Technical Article

A LARGE SINKHOLE IN THE VERCHNEKAMSKY POTASH BASIN IN THE URALS

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ABSTRACT

One of the world's largest sinkholes (80 m long, 40 m wide and 200 m deep) developed in July 1986 as a result of potash mining 425-435 m below the land surface. The depth of the 3rd Bereznikovsky potash mine did not contribute to the collapse, and in fact, the sinkhole occurred in a location where the depth of the mine and the nature of the overburden were considered to be very favorable for mining. The nature and cause of the mine flooding and the collapse have been investigated and are elucidated. This case study is an example of how dangerous flooding can be in evaporite strata, even in deposits where geological conditions of mining appear to be very favorable. *Key words:* The Urals, potash mine, evaporites, collapse arch.

INTRODUCTION

The sinkhole, or sink, that developed above the 3rd Bereznikovsky potash mine (BRM3) in July 1986 is one of the largest such features known have occurred in the world's salt deposits. The depth of the cavity did not contribute to the collapse. In fact, the sink appeared in a part of the mine field where the depth of mining and the nature of the overburden strata were considered to be very favorable for mining. The appearance of such a large sink and the way that one of the world's largest potash mines flooded forces us to reconsider and revise the strategy of developing such deposits. To do this, it was necessary to thoroughly elucidate how and why the mine flooded, causing the collapse. The results of that investigation are summarized in this article.

GEOLOGICAL CONDITIONS OF THE MINE WORKINGS

Lithology and Hydrology of the Strata

At the location of the collapse, mines were located at a depth of 425-435 m (Figure 1). Above the mines, there were 100-110 m of evaporite beds (alternating beds of halite and carnallite). The upper 25 m of these beds, called the "transition zone", consisted of halite strata alternating with marls and gypsums. The evaporites are Lower Permian in age. Above the transition zone lies 50m of a clay-marl complex, which contains thin beds of gypsum. The fractured marls in this stata are filled with sodium chloride brines (from 50-70 to 300 g/dm^3 of salts) with hydrostatic heads of 150 m and more. The water was isolated from the mine workings by the salt beds in the lower part of the clay-marl complex and the evaporite strata; together, these beds were referred to as the "Waterproof Complex" (WPC). Its waterproof properties were caused by water-impermeable salts and by the brine aquifer, which protected the soluble salt rocks from more agressive weakly mineralized waters above. The evaporites did not include brine aquifers below the transition zone, but did contain small amounts of brines associated with the sedimentary and diagenetic processes of strata formation.

Above the clay-marl complex, there is another 40 m of a limestone-marl complex, which is very permeable and contains a great deal of water, especially in arches of brachianticlinal structures within the limestone strata. The lower, marlic beds are less permeable and serve to perch the limestone aquifer. Aquifer water mineralization is 0.2-0.5 g/dm^3, and dominated by calcium bicarbonate. The aquifer is recharged by atmospheric precipitation infiltration and water flow from other aquifers.

The limestone-marl rock complex is covered by 50 m of a limestone-sandstone complex. Boreholes in the limestones and sandstones produce up to 10 L/s and more of slightly (0.2-0.5 g/dm^3) mineralized water, with a calcium bicarbonate composition. Recharge is realized by precipitation and receipt from adjoining aquifers. The limestone-marl and limestone-sandstone lithological complexes of rocks are sometimes jointly referred to as the "terrigenic-carbonate complex" (TCC), while the underlying transitional and clay-marl complexes are referred to as the "salt-marl complex" (SMC). The Permian system section is completed with a parti-coloured (variegated in color) complex of argillites, aleurolites and sandstones (about 100m). Due to lithological heterogeneity, the rocks have a low water capacity (boreholes produce only a few L/s), and contain relatively isolated aquifers, connected only in part by faults. The water contained in these parti-coloured rocks is of the calcium bicarbonate type, with only 0.2-0.3 g/dm^3 of mineralization. Recharge is attributed to precipitation; the strata discharge into surface water and also into underlying beds.

About 20 m of quaternary sediments of fluvioglacial origin overlie the Permian strata. Their water capacity is comparatively small, and their waters are weakly mineralized (about 0.2-0.3 g/dm^3), with a calcium bicarbonate composition.

In the location of the sink, one sylvite bed "Red-II" (5.0-5.5 m) was being mined. The sylvite-carnallite zone thickness is diminished there as the result of carnallite substitution with rock salt and sylvite. The zone being mined (including some other beds "B" and "V") is covered with 100 m of salt caprock, including two calcareous clay beds in its upper part.

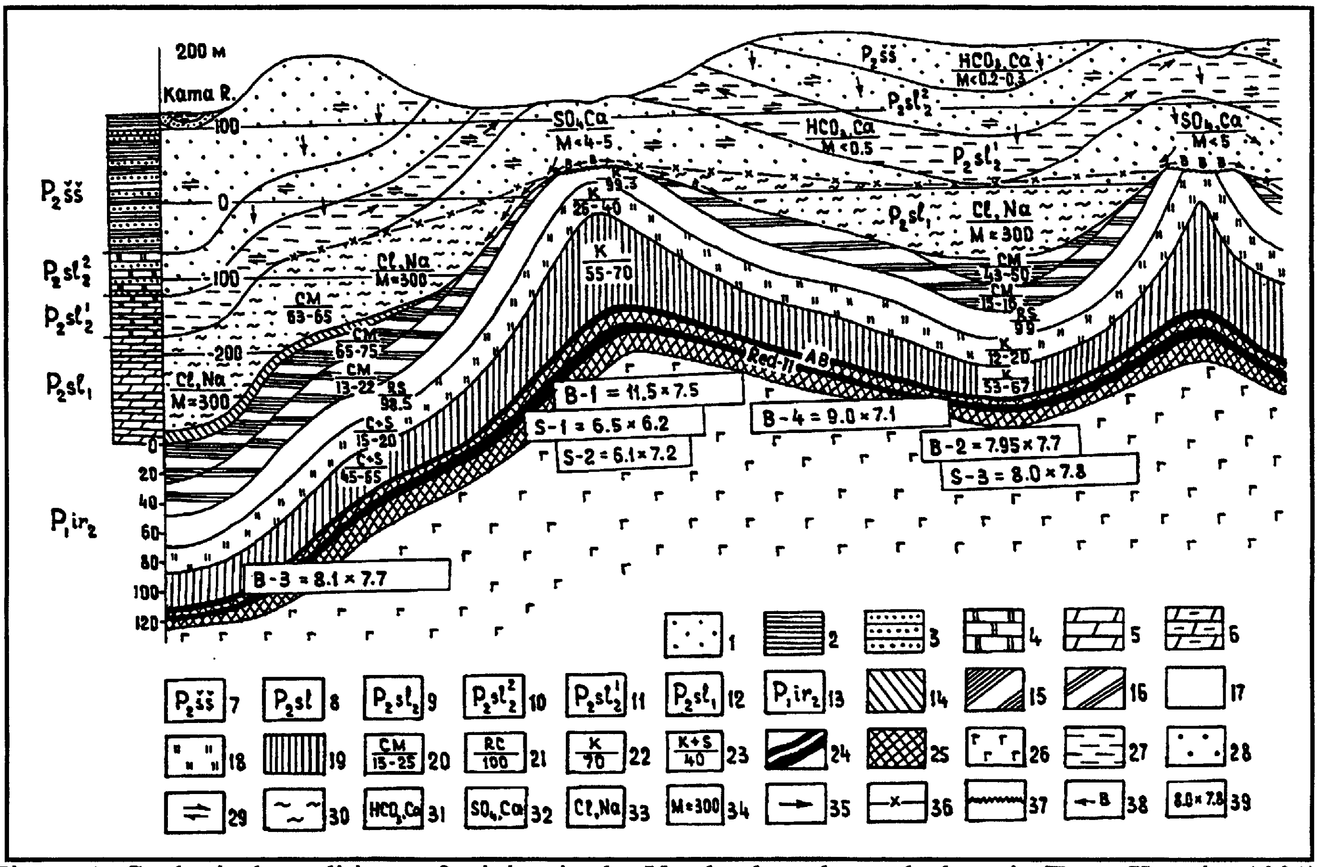

Figure 1. Geological conditions of mining in the Verchnekamskoe salt deposit (From Kopnin, 1991). The arrow indicates the 3rd Bereznikovsky potash mine. KEY: 1-quaternary deposits; 2-argillites; 3-aleurolites, sandstones; 4-dolomites; 5-marls; 6-clay marls. Lithological complexes: 7-strata capping the parti-coloured complex; 8-the parti-colored complex; 9-carbonate complex; 10-limestone-sandstone complex; 11-limestone marl complex; 12- clay-marl complex; 13-evaporites. Waterproof complex (WPC), upper zone: 14- lower part of clay-marl complex with two rock salt beds; upper transitional zone; 15- marl-salt rocks; 16-salt rock. Middle zone of WPC: 17-salt caprock; 18-halite carnallite rocks with potassium beds G, Z, I, K. Lower zone of WPC: 19-carnallite rocks with potassium beds B, H, D, E. Content of rock salt (%): 20- clay, marl; 21- rock salt; 22-carnallite; 23-carnallite and sylvite. 24-working beds AB and Red-ll; 25-sylvite zone; 26-rock salt. Hydrogeological conditions: Aquifers: 27-relatively homogenous; 28-very heterogeneous. Water exchange zones: 29-active; 30-labored. Chemical type of water: 31-$CaHCO_3^-$; 32-CaSO4; 33-NaCl. 34-mineralization of underground water (total dissolved solids), g/L; 35-water movement; 36-water borderline; 37-salt karst mirror; 38-movement of NaCl brines, 39-sampling points.

Ten-fifteen m above the first salt bed of the transitional zone, there were three aquifers that were 2, 3 and 5 m thick. Water capacity was very small (flows were 0.000022, 0.0019 and 0.0011 L/s, with boreholes producing about 7 L/h). The mineralization (total dissolved solids was about 300 g/dm^3) was dominated by NaCl, with lower amounts of $MgSO_4$ and $MgCl_2$.

Tectonically, the sink occurred within the regional Durimanskaja synclinal structure. The "Red-II" bed was in the lowest part of the mine field. [Note: The authors recognize that a plan view of the mine would have been useful to the reader, but unfortunately, the mining company would not provide one.] Due to the thickness of impermeable strata (120-140 m), the mine was considered to be very safe. In 1984-1985, sylvite excavation was realized by room and pillar excavation; rooms were 5.3 m wide and 5.5 m high, with pillars that were 3.8 m thick. Pillars yield over time due to the pressure of overlying rocks, causing the mine roof to bend and cave. In Russia, this system of extraction is called the "system of pliable pillars". The authors believe that this excavation method caused the mine to flood.

Fracturing of Rocks

According to the conventional way of thinking, the minefield's evaporite beds are plastic and relatively invulnerable to fractures, due to the impermeability of the salts. Only micro-fractures were known to occur, typically in the thin beds of halopelites (salts high in silt), due to salt bed deformation caused by physico-mechanical differences in properties of the interstratified rocks. Observations have forced us to revise this view concerning fractures and their systems in the salt rocks. Mine geologists (of the Verchnekamsky potash basin) repeatedly found them when studying the mine face and the mine shafts.

The WPC rocks contains fractures and faults formed tectonically (Andreichuk, 1989; Andreichuk and Lukin, 1989; Andreichuk and Lukin, 1992) and also localized zones of fracturing caused by salt deformations (processes of halokinesis) (Kopnin, 1991; Anonymous, 1986; Fillipov and Korochkina, 1990; Jarzemsky and Tretjakov, 1989). Faults and fractures, especially of tectonic origin, present a grave danger, since they can allow brines to penetrate into the mines. In most cases, the faults and fractures are associated with attenuated zones (formerly healed faults). The faults, which result from local (salt tectonic) and regional tectonic events, can cut into the evaporite beds, forming connections between the brines of the transitional zone and those of the clay-marl complex. The probability of joining the attenuated zones is greater, the higher the fractures penetrate or the lower the attenuated zones reach. Deep penetration of the latter also create the danger of connections with exfoliation fractures caused by the pliable pillars method of mining. We believe this explains the appearance of brines in the mines as attenuated zones caused by faults above the main gallery were "reanimated".

One must also consider the tectonic situation caused by peculiarities associated with the site's location within the Durimanskaja synclinal bowl. In the upper part of the sinkhole's geological section, we can see evidence of folding and elevated fracturing and permeability (Figure 2). Hydrodynamic data (levels of aquifers) and the nature of the faults within the salt deposit (Andreichuk, 1989; Andreichuk and Lukin, 1989; Andreichuk and Lukin, 1992) cause us to believe that the fold is associated with a fault in the upper part of the lithologic complexes. This would explain why a cavity developed in evaporite strata 100 m to the south of the sinkhole. It appears that first, the fault became a conduit for concentrated movement of fresh water downward, causing increased dissolution and collapse with depth. The fault zone, with crushed rocks in its lower part and its asscociation with the fold above, then became the controlling feature for the collapse of the salt cavity arch. Without the fault, the cavity, located at such a great depth, would (after forming a stable arch) have been stable and would not have caused an opening on the surface.

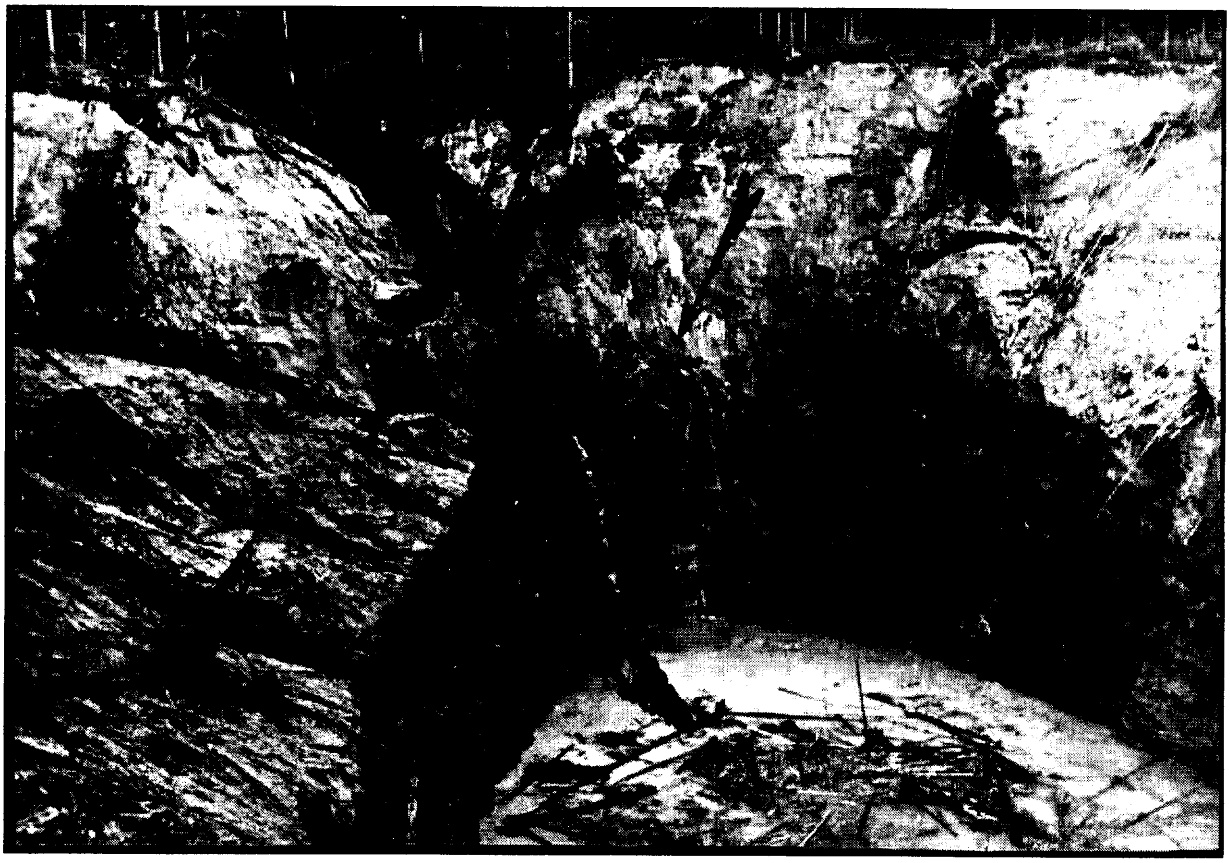

Figure 2. The view of the northwest slope of the sinkhole (June, 1987). The arrow indicates the tectonic fold in the parti-coloured rocks.

CAVITY FORMATION IN THE EVAPORITE BEDS

Appearance of the Leak

The BRM3 was one of the largest potash mines in the world, with a total volume of about 15 millions m^3 (Anonymous, 1986). On January 11, 1986, a jet of brine developed in one section (border N50, block 8) and smaller leaks also appeared in the roof of border N52. During the next two days, other small leaks of brine were noted in other section borders. The brine leaks and jet differed from sedimentogenic and condensation brines in that they were relatively low in Br and $CaCl_2$ and high in NaCl and $CaSO_4$. This indicates that the water originated in the cap-rock where there are gypsum and anhydrite strata. The force of the jet indicates that the water was under high hydrostatic pressure.

The nature of these discharges caused immediate concern, and as a result, were closely monitored from January 11 until March 8, when the inflow of water sharply increased. On March 9, all miners were safely brought to the surface, though the mining equipment had to be left underground. Figure 3 displays the dynamics of the water inflows and their chemical composition. Analysis of the water-inflow behavior, mineralization and chemical composition curves indicate that the inflows had three distinct phases, apparently associated with what was occuring in the strata above the mines.

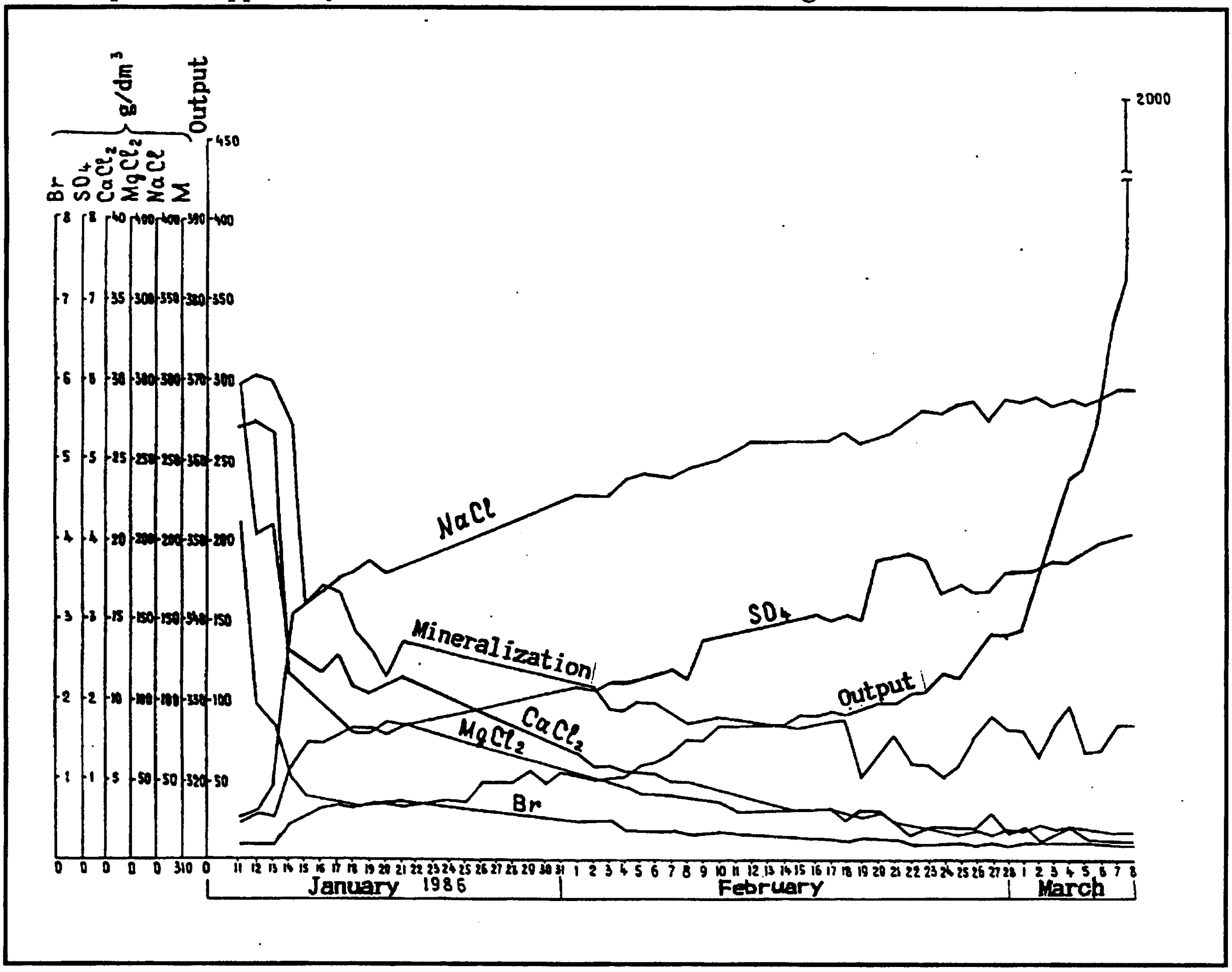

Figure 3. The dynamics of brines composition and water inflow in block 8 during January-March 1986.

1. From 11 to 15 January: relatively steep rise of water inflow (from 10 to 30 m^3 per hour), sharp drop of brine mineralization (from 370 to 343 g/dm^3) rapid increase of content of NaCl (from 25 to 160 g/dm^3), SO_4^{2-} (from 0.5 to 1.6 g/dm^3) and decrease of $MgCl_2$ (from 270 to 115 g/m^3), $CaCl_2$ (from 30 to 13 g/dm^3) and Br (from 4.2 to 0.9 g/dm^3).

2. From January 16 to February 20-23: comparatively gradual rise of water inflow (from 30 to 100 m^3 per hour), relative slow lowering of mineralization or total dissolved solids (from 345 to 323 g/dm^3) and content of $MgCl_2$ (from 115 to 25g/dm^3), $CaCl_2$ (from 13 to 2 g/m^3), Br (from 0.9 to 0.3 g/dm^3) and increased concentrations of NaCl (from 160 to 270 g/dm^3) and SO_4 (from 1.6 to 3.9 g/dm^3).

3. From February 21-24 until March 8: sharp increase of inflow (from 100 to 350 and more m^3 per hour), and fluctuations in mineralization (between 323-333 g/dm^3) and chemical composition.

We can see that the first and the third periods are relatively short (5 and 13-14 days) and the second period is longer (35-37 days). The first two periods share a decisive relationship between mineralization, chemical composition and the volume of water inflow. During the third period, this relationship becomes less significant, though to some extent it can still be seen during the sharp fluctuations that occurred.

The variations in water chemistry reflect differences in composition in different parts of the fault zone. In the lower part of the WPC (above the mines), there were sedimentary (pore) brines; in the upper part, there were brines formed by dissolution of gypsum, anhydrite and halopelite. Brines differed even within these zones due to differences caused by secondary alteration of rocks, recrystallization, etc. Reanimation of the attenuated fault zone connected pockets of previously isolated fluids, enhanced dissolution of salt, and exposed rocks to brines under high hydrostatic pressure. As permeability within the attenuated (and reanimated) zone increased, the brines began to move down to the mines. The first brines that flowed into the mine included sedimentogenic and diagenetic waters encountered along the way; these became less significant over time. This can be seen in the changes in the chemical composition of the brines and particularly the $MgCl_2$ component. After these brines were displaced from near the mines, brines from higher in the strata (the middle and upper parts of the WPC) became more important. In the middle part of the WPC, halite predominates, which is reflected by the sharp increase and then steady rise of NaCl during the second period. The rise of SO_4^{2-} concentrations may indicate the increased role of water from the upper part of the WPC, which contains gypsum and anhydrite beds. This is also indicated by the lowering of brine mineralization over time. Unsaturation of these brines would, of course, increase dissolution along all of the flow paths from the upper part of the WPC to the mines. This, in turn, caused increased circulation of weakly mineralized waters from the beds overlying the WPC, inducing the start of the third period, when water inflow increased sharply and the mineralization of the brines and their composition began to fluctuate. This period of fluctuation against a background rise of water inflow reflected the rapidly increasing permeability of the flow paths, after which nothing could avert the catastophic motion of fresh agressive waters and the flooding of the mine, which began on March 8 and 9.

The Volume of the Initial Cavity

Brines moving through the permeable zones dissolved salt along their way. This occurred primarily in the upper part of the evaporite beds (and WPC) where waters were less mineralized. Therefore, a cone or funnel model of cavity formation is appropriate for the evaporite strata above the mines. Formation of cavities like this determined the development of water capacity in the upper part of the permeable zones. The merging of waters rendered additional pressure and promoted more active advancement of waters from the cone to the mines. This is depicted in Figure 4, which reflects formation of cavities due to salt dissolution and the movement of the brines into the mines from January 11 until March 8. The increased void space volume correlates with the volume of water inflow. During the first period, 336 m^3 of cavities were formed. During the second ("evolutional") period, about 10,000 m^3 formed. The same volume of cavities had formed by the end of the last (third) period, when the output of brines began to sharply rise. According to calculation (Andreichuk and Lukin, 1992), 20,500 m^3 of cavity space had formed in the evaporite beds above the mines by March 9. Probably, it was not a common cavity but a system of vertical channels. However, the form and volume of the void space formed during that stage were made largely irrelevant by subsequent events.

Formation of the Larger Cavity

After March 8-9, when water inflow into the mines became catastrophic, brines accumulated in the mines and dissolution features increased in volume. The tectonic fault mentioned earlier enabled fresh water from spatially disconected aquifers to drain downwards. In response to the drainage of brines down into the mines, aquifers of the upper part of the WPC and the lower beds of the clay-marl complex began to receive increased recharge from above. As the water-conducting zone grew vertically, it also grew larger horizontally, capturing laterally-moving ground water. A large cone of depression of the underground water levels was formed in the brine aquifers above the draining zone,

and more weakly mineralized waters flowed into the void. The fresh waters which flowed into the evaporites had enormous capacity for dissolution. Initially, these waters flowed on the walls of karstic channels and became saturated. Successive involvement of fresh waters of the higher aquifers led to a common depression zone that extended vertically hundreds of meters up to the underground waters of the parti-colored complex (Figure 5).

In addition to dissolution, the movement of the underground waters through the crushed zone of the fault also caused erosion--washing loose sediment from fractures, and carrying suspended aleuritic and sandy material downward. Disintegration and transport of terrigenic rocks in the faulted infiltration zone promoted the formation of a cavity arch. Subsequent broadening of the cavity provoked breakdown of overlying rocks and the flow of water from fractures in the cavity arch. Freely falling streams of fresh waters began to enlarge the narrow base of the cavity, to form and widen vertical

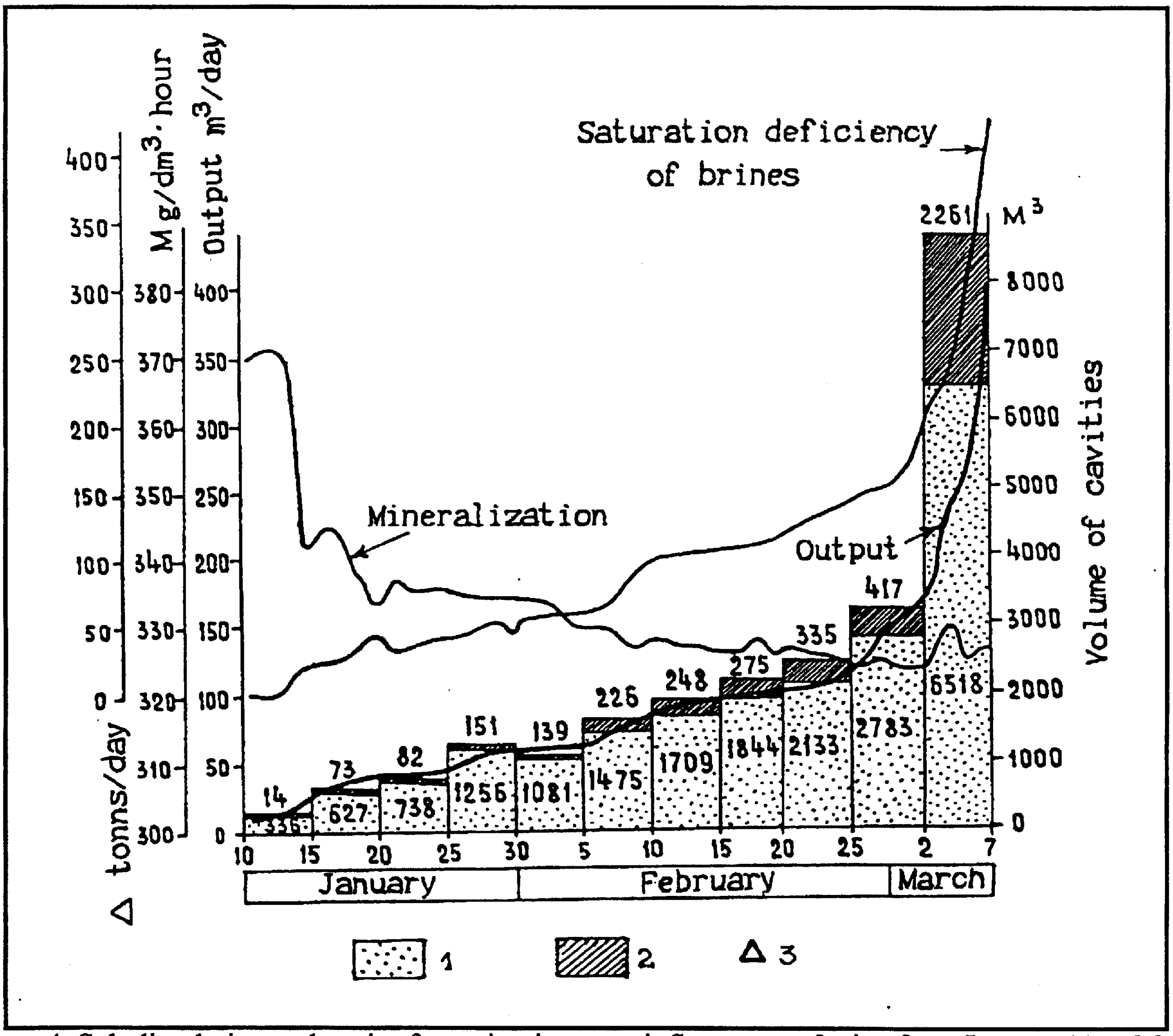

Figure 4. Salt dissolution and cavity formation in water-inflow zone of mine from January 11 to March 8, 1986: KEY: 1. The volume of cavities formed above mines owing to leakage; 2. The volume of cavities formed on the mines level owing to saturation deficiency of brines; 3. Saturation deficiency of brines that came into the mines.

channels in it and to deepen it. As a result of active stream water-inflow (from the cavity arch), the cavity shape began to change from "cone" to "cylinder", and the cavity grew until it incorporated the mine space. We believe that the formation of this enlarged cavity occurred very quickly, due to the abundance of fresh water and the existence of good pathways for their movement down into the evaporite beds.

Figure 6 defines more exactly the temporal succession and graphically presents the main events. For example, the process described above corresponds with the period beginning in March and extending to late April. That one-and-a-half month period was a critical phase in the formation of the large dissolution cavity; it continued to grow after that but at a slower rate. The end of April marks the beginning of significant cavity development above the evaporite strata and the formation of the collapse arch. It is also when the mines finished flooding, as indicated by the change of water level in the mine shafts. All 15 million m^3 of mine space were filled up with brines. On the most part, the mine field brines were already saturated so that dissolution probably only continued in the collapse zone above the mine.

Knowing the mine volume and the time of their filling up (from March 8-9 to April 15-20, about 40 days), it is possible to determine the average daily water inflow, about 375,000 m^3. In reality, the water inflow curve accelerated over time. Water inflow ranged from a few thousand (March 8-9) to 750,000 m^3 per day (April 20). Using the 15 million m^3 of brine figure, one can attempt to calculate from the quantity of dissolved salts, the volume of the dissolution cavity. Assuming a solubility of 365 g/m^3 (between halite and silvite solubility at 10ºC), the 5,475,000 tons of salts that were disssolved corresponds to 2.6 million m^3 of void space (when salt density is 2.1 t/m^3), though this assumes that all the waters were initially fresh. At least half (1.3 million m^3) of the total volume of possible cavities was formed on the mine level. However, due to the mine structure, it did not noticeably change the profile of the mine field except in the breakdown place. More important is that by mid-April, voidspace in the evaporite beds above the mines probably totalled more than 1 million m^3.

SINK FORMATION

Filling of Cavity with Water

Assuming that the flooded mines, evaporite cavity and mine shafts are hydrodynamically connected, the water level in the mine shafts should correspond to the cavity water level. As can be seen in Figure 6, the cavity appears to have flooded rather slowly. From April 15-20 until the beginning of July (about 80 days), the water level had gone only to the level of the first salt bed of the transitional complex (upper border-line of corrosion cavity). Such a long period of cavity filling (1-1.5 million m^3 in 80 days compared with 15 million m^3 of mines during the 40 days before!) is most likely due to either (or both) continued enhancement of the cavity volume, and/or a decrease in water inflow. The drilling of boreholes at the location of the future sinkhole confirmed the fact that by the summer, the fresh-water aquifers were significantly drained. The borehole NIO, which was bored in the end of May, established the absence of underground waters in the lower half of the above-saline lithological complexes (Figures 5 and 6). Consequently, from the end of April to the end of May, the output of water inflow was sharply lowered, and in the beginning of the summer it became very small. We have assumed therefore that the evaporite bed cavity volume remained fairly stable with dissolution and erosion approximately balanced with deposition of breakdown material at the bottom of the cavity. Thus, the volume of the initial cavity in salt may be estimated, as before, to be 1.0-1.3 million m^3.

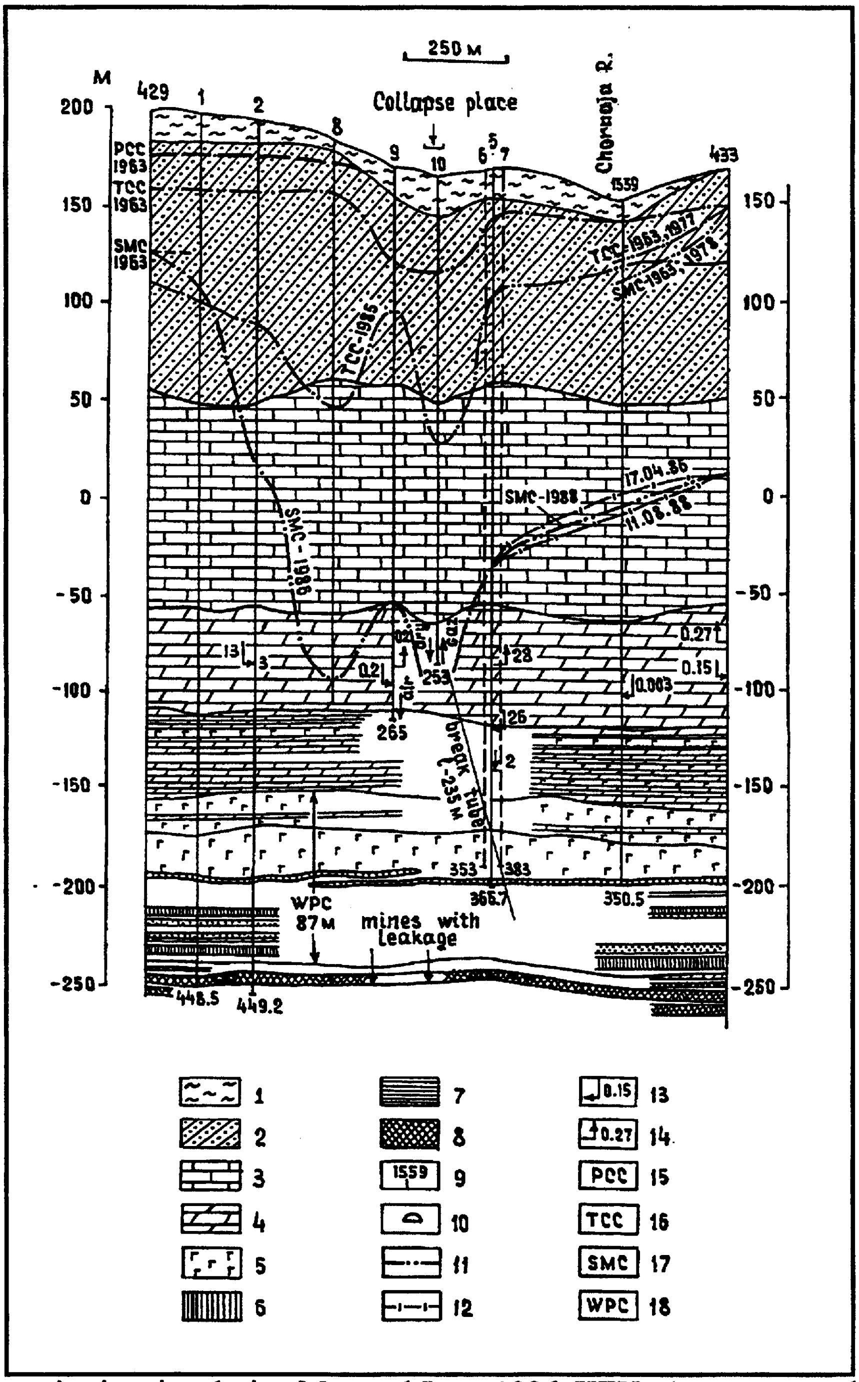

Figure 5. Hydrodynamic situation during May and June, 1986. KEY: 1. quaternary deposits; 2- parti-coloured rocks; 3- limestone; 4- marl; 5- rock salt; 6- carnallite; 7- clay; 8- sylvite; 9- borehole and its number; 10- mines; 11- aquifer levels, when boreholes were drilled; 12- level of brine aquifer after drilling of boreholes; 13- groundwater infiltrating into rock strata, L/s; 14- groundwater discharging from rock strata, L/s; levels of aquifers in; 15- parti-coloured rocks; 16- terrigenic-carbonate rocks; 17- salt-marl rocks; 18- waterproof complex.

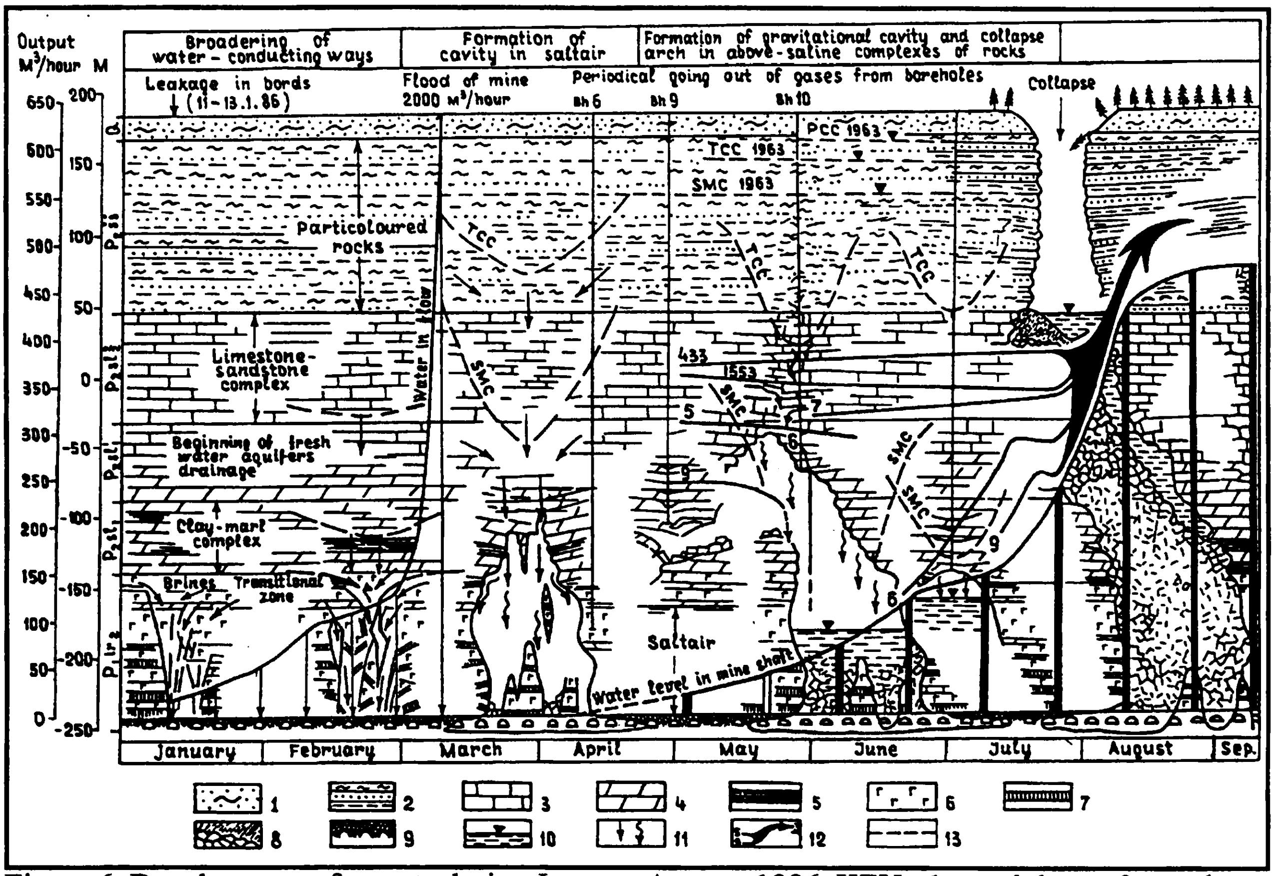

Figure 6. Development of events during January-August, 1986. KEY: 1- sand, loam; 2- sandstone, aleurolite, argillite; 3- limestone; 4- marl; 5- clay; 6- rock salt; 7- carnallite; 8- breakdown material; 9- mines; 10- water level in cavity; 11- underground drainage of aquifers; 12- exchange of aquifers water level; 13- water levels. The term "saltair" refers to the evaporite beds.

Formation of Collapse Arch

Starting in May, roof caving became the dominant process in subsequent development of the main cavity. By the second half of May, when borehole 10 was drilled, the arch (cupola) of the cavity was located 100m above the top evaporite bed. By the end of June, the evaporite bed cavity was filled with breakdown material to a height of approximately 150m. This confirms that by that time, development of the main cavity was occuring gravitationally rather than by dissolution.

However, based on borehole data, dissolution was still going on elsewhere. Boreholes were drilled at the beginning of May into the cavity and variability in gas composition and pressures were monitored. It is possible that some of the methane diffused into the mine from a working oil field under the salt strata, but it was established that gases, such as methane, were being released by dissolution of salts. However, according to our data, only gravitational process were taking place from May-June above the cavity. Gravitational processes would not cause gases to accumulate. Concequently, salt dissolution had to be occurring at some location within the evaporite strata, spatially connected to the main gravitational cavity. Borehole 9 was drilled about 200 m from boreholes 5 and 6, which were drilled above the mine locations where the original leakage of brines ocurred. Borehole 9 had been drilled into a cavity that was a breakdown branch, not a dissolution cavity, but the gases released indicated that the main gravitational cavity was probably connected with a corrosional cavity (illustrated in Figure 7). Borehole 8, 150 m further away, provided additional information. Although no gases were detected in the mines beneath borehole 8, gases were detected at the borehole, which indicated that there probably was a dissolution cavity nearby. Depression in brine aquifers in the vicinity of borehole 8 also testified to the existence of a nearby dissolution cavity (Figure 5). The development of this cavity explains the

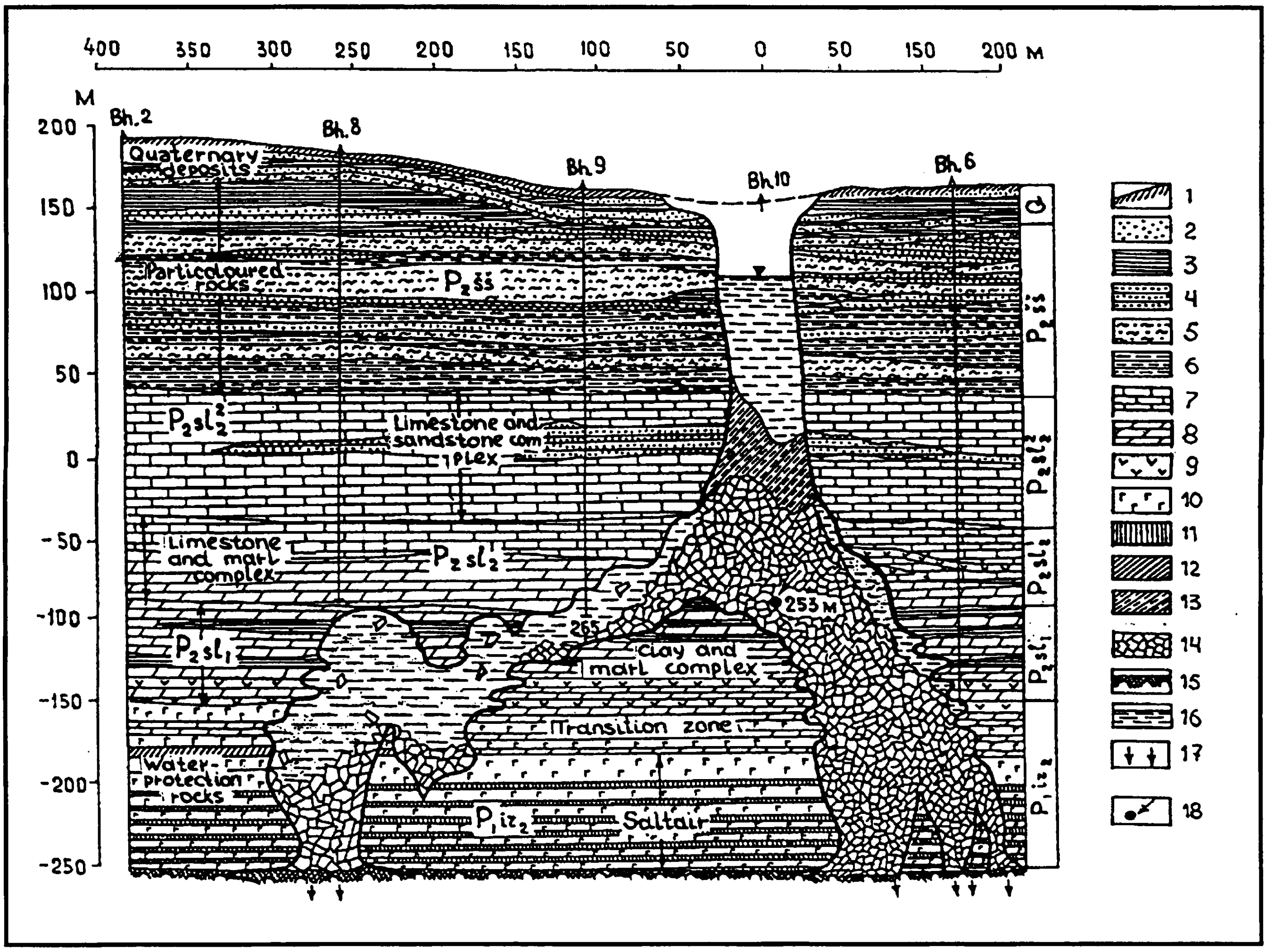

Figure 7. General view of the corrosional and gravitational system of cavities in the vicinity of the sinkhole just after sink formation. Key: 1-salt; 2-sand; 3-clay; 4-sandstone; 5-aleurolite; 6-argillite; 7-limestone; 8-marl; 9-gypsum; 10-rock salt; 11-carnallite; 12-sylvite; 13-loam, sandy loam; 14-collapsed material; 15-mines; 16-water; 17-places of brines infiltration in January 1986; 18-points of borehole tube break.

periodic appearance of gases from the boreholes before the formation of the sinkhole and the opening of the gravitational cavity-branch by borehole 9. By the beginning of July, the two cavities--a large gravitational cavity (with its peak at the limestone-sandstone complex level) and a corrosional cavity (with its peak at the clay-marl complex level)--had joined.

The joining of cavities is very important because it created a "common arch" geodynamical effect. The common arch was less stable than the two relatively stable arches of the disconnected cavities. In addition, the fractured and crushed rock in the fold-faulted zone added to the instability. By the middle of July, the cavity arch had moved along the fault zone and had reached the base of the parti-coloured complex. After that occurred, the collapse process accelerated sharply as the thin-bedded and loosely aggregated parti-coloured rocks began to fall. Water levels in the shafts and boreholes were affected as the gravitational cavity rapidly filled with breakdown materials, which displaced water upwards. Ground water rose to 120-130 m above sea level (Figure 6). Caving of parti-coloured rocks was very active during the 10-30 days prior to the collapse, with an average speed of about 10m per day. During the last day before sink formation, the drillers of borehole 11 reported feeling periodic underground shocks and hearing hollow rumbles from underground. The shocks were undoubtedly caused by large blocks falling to the bottom of the void space (karstic earthquake). However, it is important to note that based on the borehole records, although the accumulation of gases in the void space was significant, it was not sufficient to generate an explosive pressure to overlying rocks (above the cavity arch), as some have speculated. An explosion did occur at the moment of collapse, but it did not cause the event.

Surface Collapse

At midnight, between July 24-25, the quaternary deposits (20-25 m) collapsed and a violent explosion took place. The percussion wave activated the safeguard sensory elements installed on the mine office windows (1.5 km from the collapse). The explosion threw fragments of parti-coloured rocks (aleurolite, sandstones) out of the hole and up to 200 m away. The fragments were variably sized but ranged up to 0.8x0.4x0.2 m. As the fragments fell, they formed small craters up to 1 m deep and 2 m in diameter.

The explosion and accompanying light flash in the final moment of collapse caused some specialists to believe that the sinkhole was formed by a large gaseous outburst in the cavity. They drew the following picture: dissolution caused a large gas-filled cavity to form in the evaporite bed. Gravitational caving then caused the cavity (and a "gas bubble") to move up to the surface. When the cavity reached the parti-coloured (or fluvioglacial) rocks, the enormous pressure of gases caused an explosion. After the explosion, the sinkhole was left where the bubble had popped.

However, we disagree with this eruptive hypothesis. First, the gas pressure in the gravitational cavity could not have reached such an anomalous level because the cavity was joined to the surface through the ventilative boreholes. In fact, sometimes the boreholes sucked air into the cavity. Even if we assumed that high quantities of gases had accumulated, despite the borehole evidence, the fractured rocks and the ground water should have provided a boundless permeable environment.

Second, it is not unusual for explosions to accompany sinkhole formation, in particular in events in which gravitation caving has lost spatial connection with a deeper-located "mother" cavity. Isolated near-surface cavities, which "lose touch" with the underlying cavities due to momentary filling with breakdown materials are vulnerable to dust explosions. The mass of material falling down acts as piston, compressing the air in the reduced volume. The compressed air is then released, shooting up dust with a deafening sound. Loud bangs can be heard sometimes even when small collapse sinks are formed. In our case (Figure 8), the cavity (in the parti-coloured rocks) was already separated with breakdown material from neighboring cavities. The falling-down of the huge mass of breakdown materials caused a strong and sharp compression of the cavity air. However, that would only have caused a loud sound-and-dust effect. The cavity air though was also saturated with inflammable gases, which exploded, providing the light flash and the amplified sound effect. Gas inflammation could have resulted from sparking caused by metal (borehole tubes) and rock fragments falling down together.

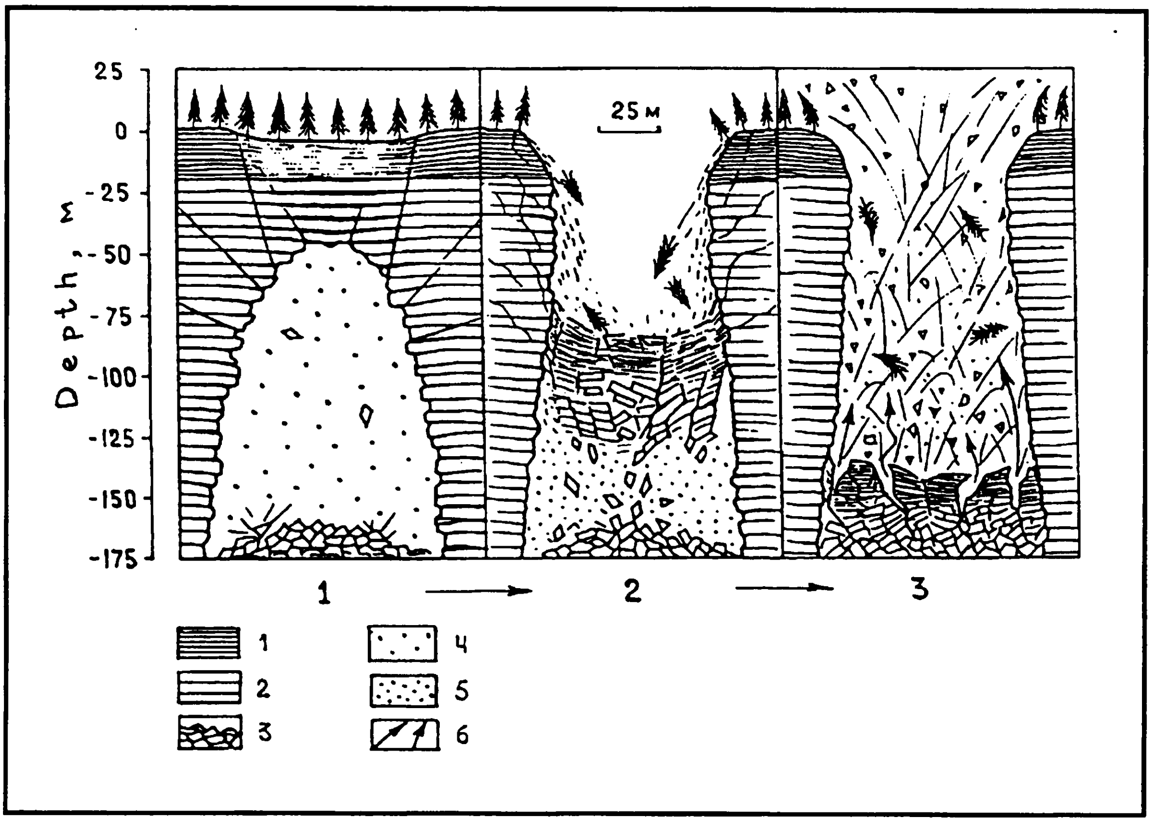

Figure 8. Arch collapse of isolated gravitational cavity and expulsion of rock fragments. KEY: 1- quaternary deposits; 2- parti-coloured rocks; 3- collapsed material; 4- gas mixture; 5- compressed gas mixture; 6- directions of gas spurts.

In this hypothesis, the piston effect compressed the explosive gases and promoted the burst. As a result, the total power of the burst proved to be sufficient to throw out not only small clay and sand particles but also relatively large fragments. The wave blast was directed up, as is typical in cases of karst sinkhole formation. Therefore, the trees surrounding the sinkhole were not brought down or burnt.

Thus, the burst was not the cause but the consequence of the cavity arch collapse. An asymmetric sinkhole with steep (on the fluvioglacial rocks level) and vertical (on the parti-coloured rocks level) walls was formed (Figure 9). Its initial diameter was 80m (along the long axes) and 40m (along the short axes). The long axes of the sinkhole was directed NW-SE, aligning approximately with the fault directon and with a surface ravine genetically connected with the fault. It was initially very difficult to determine the depth of the sinkhole because the sinkhole was filled with grey fog, presumably consisting of after-explosive gases, dust and mist. After 15 days, it became possible to see the water in the sinkhole, which at that time was located 100-110 m from the surface. The large black arrow of Figure 6 illustrates how, in connection with the further collapse of rocks during the 10 days after sinkhole formation, the increase in water level (in the boreholes and mine shafts) accelerated. By the end of August, the ground water was fixed at a depth of 60-70m from the surface. The sinkhole filled with water as it drained ground water from the parti-coloured rocks and quaternary deposits, and received rainwater and runoff.

Our investigations indicate that the sinkhole formation in potash mine N3 was not simply bad luck. Although it required the coincidence of a series of natural (faults) and artifical (system of extraction) preconditions, the same concurrence of circumstances are also likely elsewhere in Berezniki salt deposit, especially above the synclinal depression. This example should point out the potential dangers associated with mine flooding and sinkhole formation and how possible they are in salt deposits, even where geological conditions of mining are very favourable.

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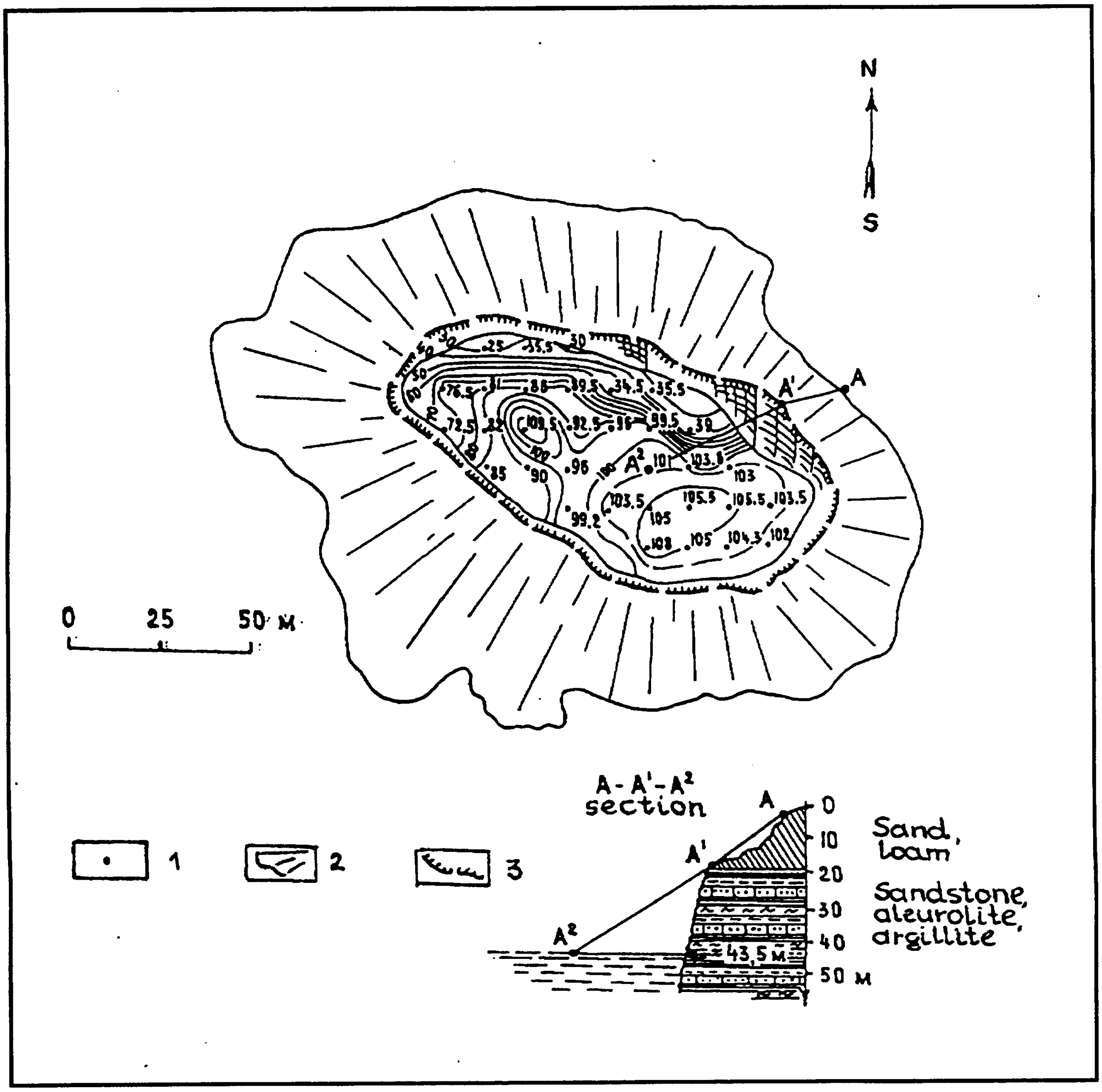

Figure 9. Sinkhole on the mine field of BRM-3 in the beginning of 1986. KEY: 1-depth measure points (from the water surface) and depth of collapse lake; 2-sloping part of sinkhole (in loose quaternary deposits); 3-precipice (in parti-coloured rocks).