4.3.14. INDUCED SEISMICITY IN POTASSIUM DEPOSITS: CASE STUDIES IN BULGARIA AND BELARUS

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4.3.14.1. Introduction

In many regions the large urbanized areas are overlapped with the regions of manifestations of different natural disasters. This is one of the reasons that has provoked bilateral international project exploring the problems of the natural and technogenic hazards and their possible mitigation (Aronov et al., 2005). There is a trend for quantitative assessment of the natural phenomena and their consequences analyzing different scenarios. A great problem is the formulation of the optimal measures for the possible loss reduction and particularly their effective implementation. Next items described technologically provoked problems in the salt mines Mirovo near Provadja, Bulgaria and Starobin, Belarus.

4.3.14.2. General information

Provadja. The Provadja salt deposit is the only terrestrial salt deposit in Bulgaria. It is placed in industrial area, 50km inland westwards of the Black Sea and the town of Varna.

The mining process and the exploitation have been started some 47 years ago by leaching caverns into the salt deposit. The salt is extracted by solution from three levels in depth - 700, 1000 and 1200m Fig. 4.3.14.1, using telescopic borehole system circulating water at a well head pressure of 50 bars. There are 43 underground chambers Fig. 4.3.14.2. with diameter varying in-between 100-140m and height in the range 50-200m. The roof of the chambers is controlled by floating oil layer.

During the last 15-20 years the population in the region has become increasingly alarmed by two problems - increased seismic activity and large surface subsidence, which influence the salt body, the whole underground chamber pillar system and the salt extraction installation and all the equipment in the target area, as well as the neighborhood villages.

Starobin. Mining works at the Starobin deposit of potassium salts started in the early sixties of the past century. At present four potassium mining works are operating and the fifth one is under construction. The II and III potassium horizons located at depths from 400 to 1000 m. At the first stages clearing works were performed with the chamber method. At present various kinds of mining by the wall method are used. The total thickness of impermeable layers ranges from 210 to 250 m.

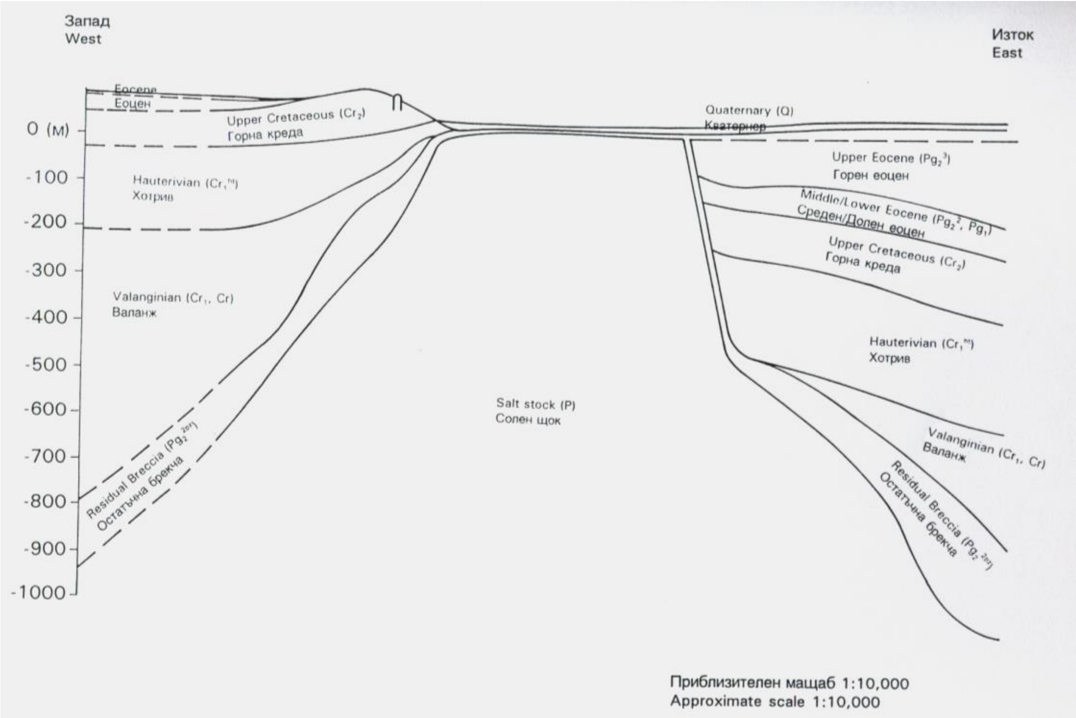

Fig. 4.3.14.1. Cross section W-E of the Provadja salt deposit

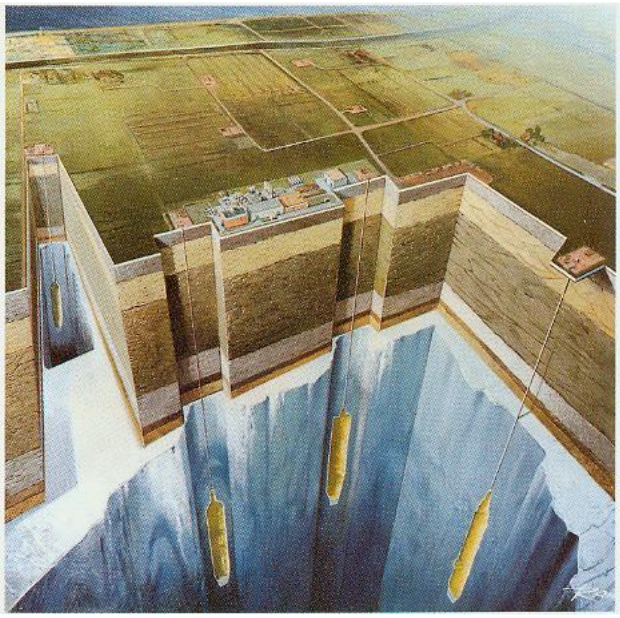

Fig. 4.3.14.2. Shem of underground chambers distribution

Potassium salt is extracted at the Starobin deposit by mining method. The potassium horizon II and the lower sylvinite bed of the horizon III are being worked out. At present the potassium ore is recovered at four mining fields which are bounded by tectonic blocks and only in the southern flanks of the deposit – by pinching-out potassium horizons. A depth of the potassium ore extraction works is 400-1000 m. The mining fields of the Starobin deposit at 1, 2 and 3 mining sites are stripped by three vertical boreholes, at the fourth one by five boreholes.

Mining geological conditions of extraction of the second and third potassium horizons in general are quite favourable. The roof rocks are rather rigid and are

prone to fracturing, the soil is swelling. Waterproof strata over the horizon II consist of saliferous deposits with a thickness ranging from 0 to 130 m and rocks of clayey-marlaceous strata (CMS) up to 100 m thick. The total thickness of waterproof strata in mining fields of the Industrial Amalgamation (IA) “Belaruskaly” ranges from 210 to 250 m.

Various systems of mining development work are used at the deposit fields. Development drifts follow as a rule potassium beds. An amount of mining from those drifts constitutes 15-20 % of the bulk mining. The main type of miner is PK-8 with a rotor power unit of continuous operation performing the simultaneous destruction of the whole face area and arranging the extraction with an arched roof shape and a rectangular bed shape. A width and a height of the single working are 3×3 m. Mines are aerated using local ventilators of pressure types.

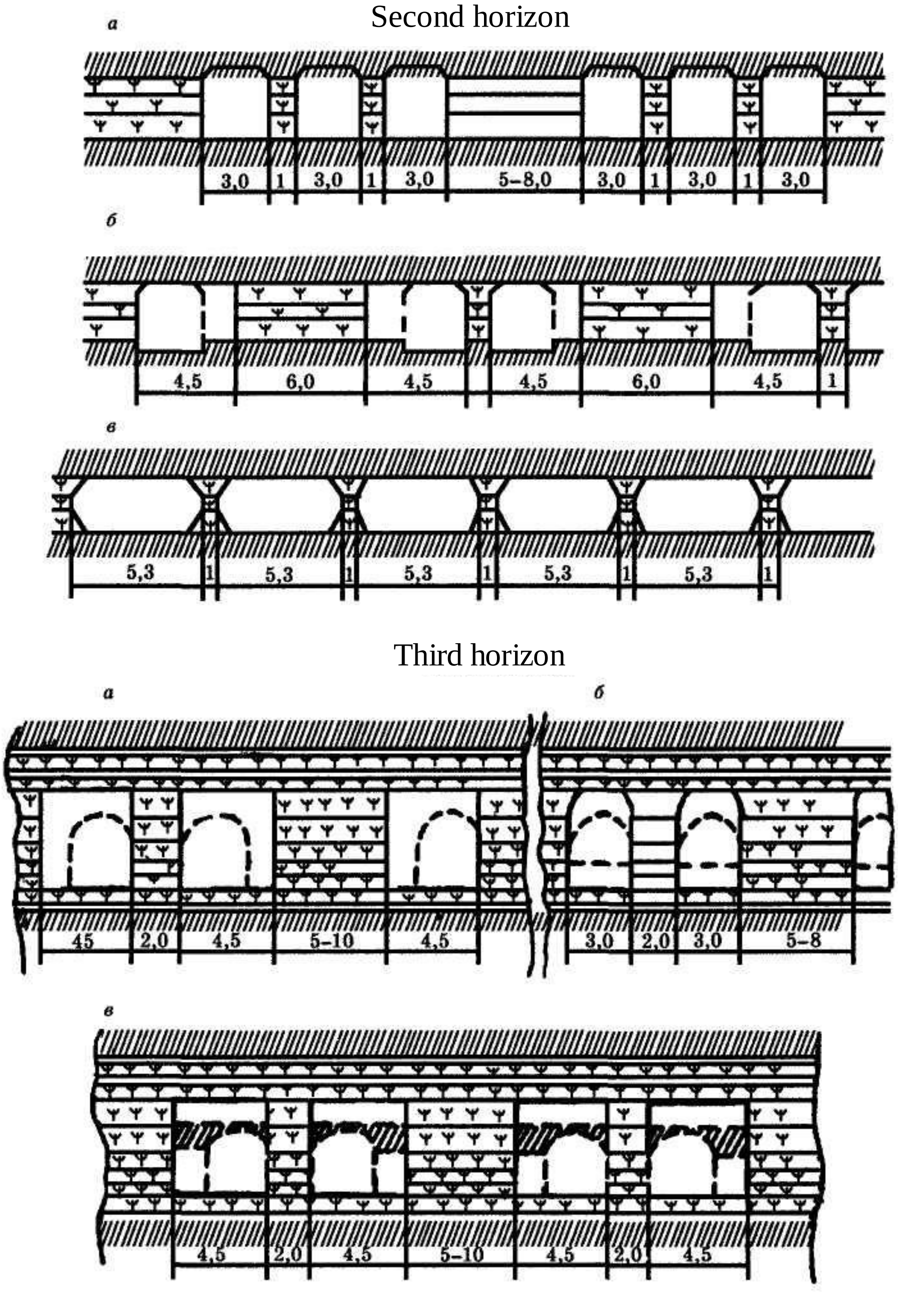

Fig. 4.3.14.3. Main methods of room mining at the Starobin deposit (Yermolenko, Bordon, 1993)

Extraction of minerals at the first stage of deposit mining began with room mining systems on rigid pillars. A few methods of room mining were used, which was due to insufficient knowledge of mining geological and hydro geological conditions there were a hazard of possible water penetration into mines. Are losses at depths amounted to 68 %. The main methods of this mining system are shown in Fig. 4.3.14.3. In general more than 30 methods were tried out.

As a result of experience gained and research conducted (All-Union Scientific Research Institute of Geology, JSV “BelGORKHIMPROM”) new versions of the room method were developed, tried out and adopted. These were rooms with roof lowering on flexible pillars up to 1.5 m in width (Fig. 4.3.14.4.).

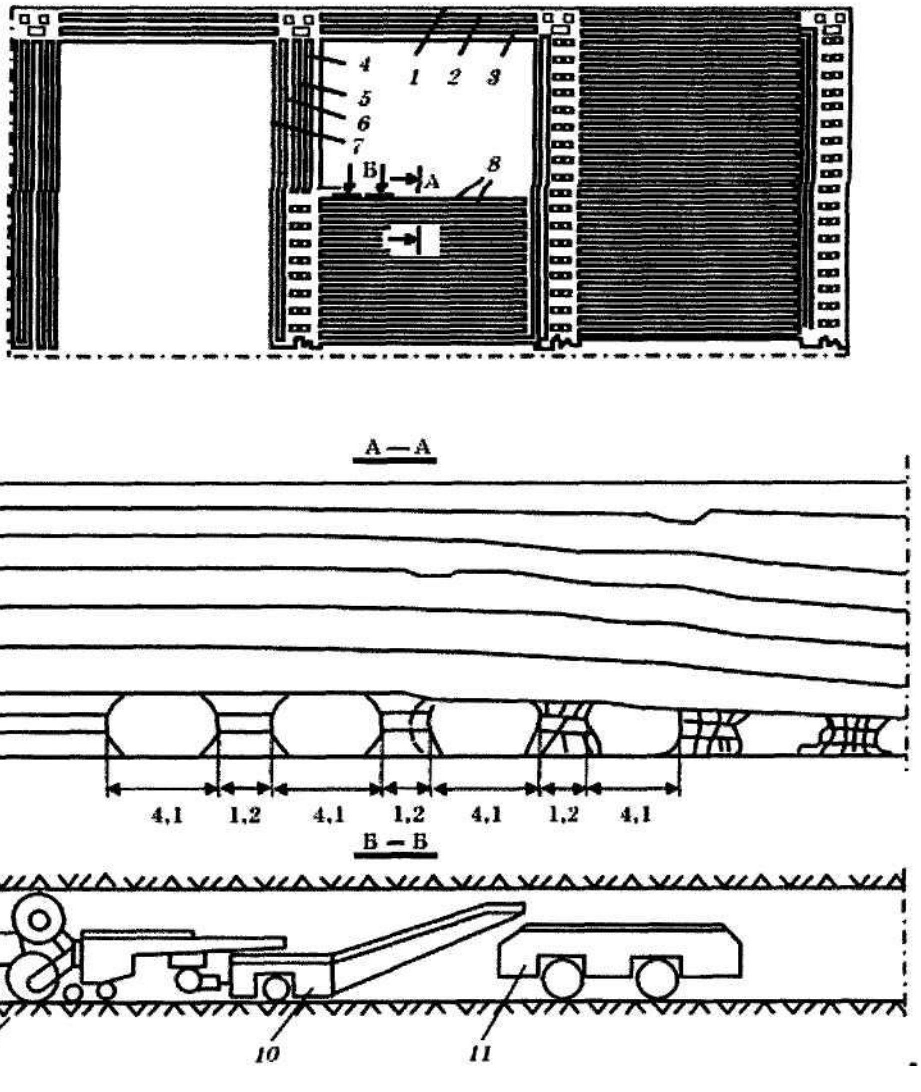

Fig. 4.3.14.4. Room mining with lowering pillars and mineral extraction by a miner “Ural-10KS” (Tomchin, Smychnik, 1998):

1, 2, 3 **– panel-spalling drifts (transport, belt and airway);** ***4*** **– heading;** ***5, 6, 7*** **- block drifts (belt, transport and airway);** ***8*** **– second working rooms;** ***9*** **– drifts miner;** ***10*** **– bunker-loader;** ***11*** **- self-propelled car**

When the lower part of clayey-marlaceous strata was determined to be impervious to water, a method of pillar mining of sylvinite beds with complete roof caving was adopted. This method suggests selective mining of sylvinite beds by two (upper and lower) extraction long walls in one extraction pillar. This mining method improved the quality of extracted ore, decreased losses connected with extraction, increased the production.

Under conditions of the potassium horizon II two-bed selective mining by four-miner long walls was used together with bulk mining. Two sylvinite beds were worked out by two duplex 180-200 long walls. The upper sylvinite bed is extracted with 4.9-6.5 m advance relative to the lower one.

The pillar system was used when the fourth sylvinite bed of the III horizon was extracted by the wall method. The underlying 2nd, (2-3) and 3rd beds were mined by the room system with miners "Ural-10KS". Such techniques (combination of the pillar and room systems) were applied for the first time in the world practice and were named integrated system.

The III horizon mining practice was improved by two walls. The main distinction of this practice from that applied at the II horizon consists in separate development and mining of the upper (fourth) sylvinite bed from 1.0 to 1.3 m in thickness, and the lower second, (2-3) and third beds their total thickness ranging from 1.9 to 2.1 m. Development working of the lower wall is carried out under the fourth sylvinite bed extracted before. An intermediate rock salt layer (3-4) 1.1-1.3 m in thickness left in the worked-out space serves as a protection from roof rocks caved as a result of an advance extraction of the fourth bed.

Prospect development of mining techniques at the Starobin deposit consists in a purposeful integration of new selective extraction processes, an increase of productivity of working and drifting complexes.

An underground technological complex which envisages commercial working of the rock salt bed under conditions of an operating potassium ore mine was developed for the first time in Belarus at the Starobin deposit. The rock salt bed underlying the potassium horizon II was opened by inclined drifts in the mining field of the 1st mining site. A depth of mining work at the industrial testing site ranges from 420 to 480 m Fig. 4.3.14.5.

Rock salt production is carried out at the operating mining site of the 1st mine management of IA "Belaruskaly". Buildings and constructions available are used, constructions of some additional buildings is envisaged: shops of packaging, pressing, reloading, etc. Salt dust formed as a result of salt pouring off and packaging is a serious hazard to the environment.

Like in the case of the Provadja mining region, negative ecological consequences are considerable deformations of the ground over worked out underground mines, vast areas occupied by wastes of potassium production, as well as phenomena of induced seismicity. An intensity of individual shocks is as high as 4-5 on the MSK-64 scale. The impact of deposit mining work is responsible for troughs resulted from pushing together movements and for deformations of buildings and constructions on the earth's surface.

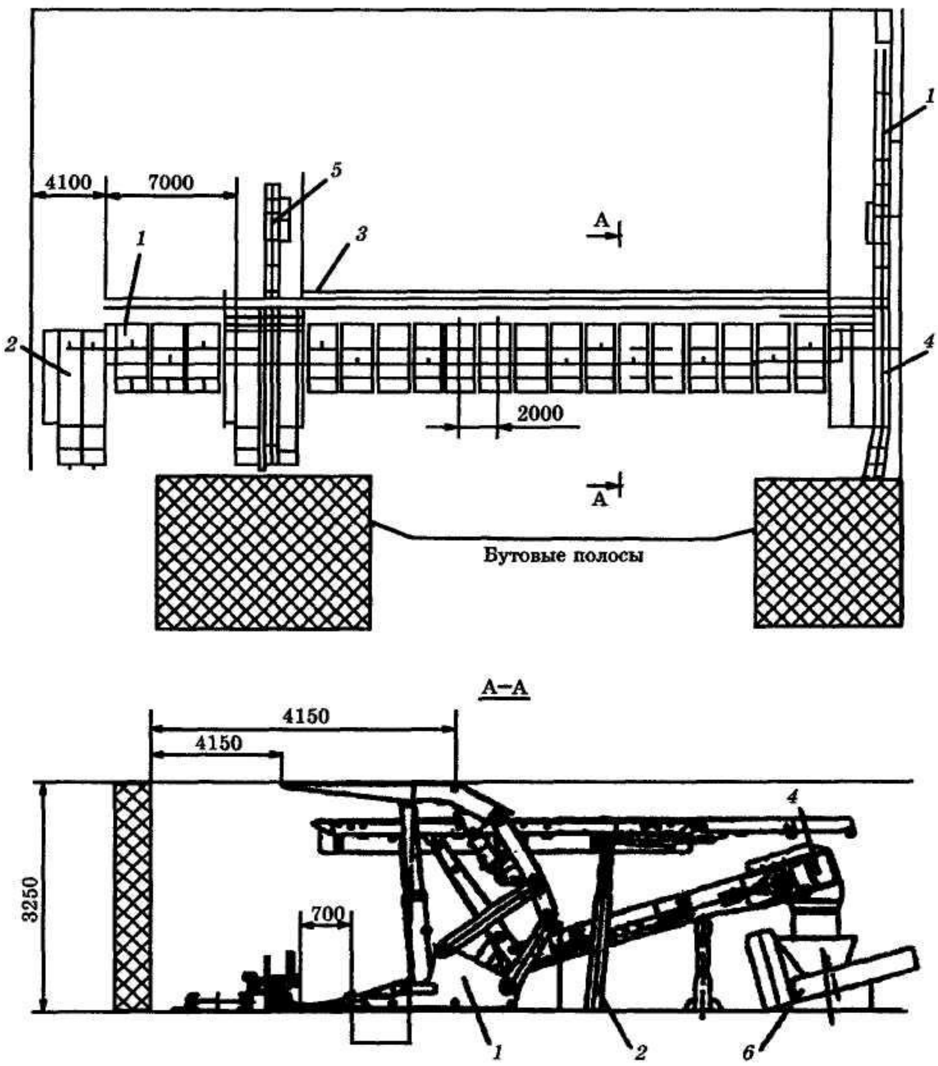

Fig. 4.3.14.5. Equipment complex for selective mining of the potassium bed. -305 m:

1 **– face support section;** ***2*** **–support section;** ***3*** **– long wall conveyor;** ***4*** **– gate conveyor;**
5 – loading elevator; 6 - thrower; 7 – power train

4.3.14.3. Geological settings

Provadja. Generally the lithosphere of the Balkans shows a rather complex tectonic structure indicating a complicated stressed pattern and differential movement of micro plates. The thickness of the crust (depth of Mohorovicic discontinuity) varies between 30 and 36km, with a maximum in the western and southern parts of the Moesian mega block (to which the salt deposit belongs), a minimum in the depression and the shelf section of the Black Sea. The salt deposit is the only terrestrial salt deposit in Bulgaria, several km across at its surface exposure, extending and broadening to depths perhaps 3500m. It passes trough the whole sediment complex including Perm to upper Eocene and is covered by Quaternary depositions. Starting from 12-20m under the surfaces, the salt, with a shape of a frustum of a cone, reaches depths of 3500-4000m, where a salt layer is formed. The deposit is imbedded in Cretaceous limestones and dolomites, and Paleocene marlstones and it is covered by quaternary sediments. The salt body is in contact with the surrounding rocks by the so called residual breccias. The rock salt

massif, built up predominantly by halite, is rather inhomogeneous. For example, the compressive strength varies from 8.5MPa to 30MPa with average values Rc=14 - 16MPa (lab tests) and Rc mass = 5.5 - 5.8 MPa (massif).

The neotectonic and recent features of the Provadja region's formation are conditioned by its location. The recent vertical movements (state geodetic network data) of this region are influenced more by Balkanidi development features than the Moesian platform ones. There is a positive correlation between the neotectonic and recent vertical movements, showing the continuation of the general trends of the tectonic regime, occurred during the neotecotnic stage of the discussed region development, in the recent epoch (Paskaleva et al., 1992, 1994).

During the period 1981-1991 extensive geodetic measurements have been carried out to monitor the vertical movements. They show that, there are movements along some faults in the salt deposit region. The central part of the deposit goes down and the velocity decreases going far from the center. This means, that the movements along the faults limiting the deposit continue. The geodetic observations have been processed on large and close net. A constant subsidence with average velocity 3 - 4.5 cm per year and horizontal block movements have been observed in this region for the recent few years. The largest subsidence is observed in the central part where the top of salt body is located.

Starobin. The Starobin deposit of potassium salts is situated in the northwestern centroclinal part of the Pripyat Trough, which is a sublatitudinally striking palaeorift.

Saliferous strata are interbedded members of potassium salt and carbonate-clayey rock, as well as of sandstone and siltstone layers. The deposit territory is of clearly defined block structure. It is bounded by the sub regional Liakhovichi and Glusk faults with amplitudes of 150-350 m on the north, and by a set of faults forming the Southern tectonic zone on the south. The Central, North-Western, Northern (Guliayevo) faults are running immediately within the deposit and divide the territory into the eastern, central, western and northeastern block. Four potassium horizons are found within the saliferous strata; the II and III ones are mined. The II potassium horizons occur in the depth range from 250 to 700 m, the III potassium horizons – from 350 to 1000 m.

In the region of the Starobin deposit the crystalline basement occurs at depth of 1700-2100 m. Upper-Proterozoic formations overlie it conformably and are represented by Riphean and Vendian complexes. The Paleozoic erathem involves the middle and upper divisions of the Devonian.

Saliferous strata with abundant potassium horizons are of Lebedian-Streshin age (D_3^2 lb-str).

A thickness of sub salt clayey-marlaceous deposits varies between 230 and 560 m.

The Mesozoic erathem comprises deposits of the Jurassic and Upper Cretaceous. The Palaeogene is represented mainly by sandstones. The Neogene is restricted in area. Quaternary deposits are 20 to 150 m thick.

Some active faults were identified from a series of aerospace survey and geologic and geophysical data obtained in the region of the Starobin deposit. Systems of lineaments distinguished show correlation with the preplatform and platform faults, as well as with dislocations of disjunctive nature. The Stockhodsk-Mogilev super regional fault belongs to the preplatform age structures, and the Liakhovichi, Chervonaya Sloboda, Rechitsa,

Glusk and Mikashevichi faults are structures originated at the platform stage of evolution.
When potassium ores were mined in the Starobin deposit region a number of geological features were revealed, such as:

1) **rock fissuring,**
2) **zones of rupture dislocations,**
3) **zones where sylvinite was replaced by potassium salt in productive beds,**
4) **subsidence troughs and their associated gas-dynamics phenomena,**
5) **squeezing-out brine inflows into mine works (Vysotsky et al. 2003).**

As regards seismic processes, their effect on mining works was not appreciable until the present.

4.3.14.4. The regional seismic situation and monitoring

Provadja. The Provadja region is considered to belong to a zone with moderate seismicity between 1900 and 1970 (Ranguelov, 1994). The seismicity of this region is determined mainly by the Devnya fault in the north of Provadja. The region is characterized by compression stresses in NE-SW direction which is in agreement with the general situation in northern Bulgaria (Knoll et al., 1995, Karaguleva et al., 1974). According to the potential seismic source map the maximum expected magnitude at this site is M=5.6-6.0 and depth 5-10km. Within the time, since 1900 there were only few events felt near the Mirovo salt deposit (in 1901, with M=3.14 and epicentral intensity I_0=V MSK-64; 1901, M=3.6, I_0=V; 1902, M=3.6, I_0=V; 1903, M=2.6, I_0=III). Up to 1964 there are not other data concerning the seismicity of the Mirovo district. Generally the seismic regime of the whole Bulgarian territory is characterized by a recurrence rate with relatively low slope, which is 0.36 for the period 1900-1930 and 0.34 for the period 1931-1970.

The nearest seismological station, PRV (Provadja), was established somewhere in 1980. In 1981 a strong ground motion network with five instruments SMA-1 was built. The digital Reftek station was installed and calibrated by the GTU IngenieurBuro Knoll specialists.

About 81 events within epicentral distance up to 27km occurred in the last 20 years. More than 200 strong ground motion components registered by the SMA-1 instruments were processed. All the records are “saturated” with high frequency vibrations. According to the response spectra for the accelerations and 5 % damping the maximum periods are in the range 0.085-0.2 sec for the vertical and 0.1-0.57 sec for the horizontal components. Another feature of these events is their short duration (0.12-2.97 sec); most of these earthquakes act as impact excitations. The peak ground accelerations are quite high, in some records they overcome 0.5g. The dynamic effect of single events obtained from the response spectra with 5% damping varies from 1.2 to 6.0 for the horizontal components and reaches up to 7.0 for the vertical components. The ratio between the peak accelerations, vertical and horizontal, is 0.17-2.26, which shows the predominant influence of the vertical component and confirms the local origin of the earthquakes. The duration of the intense part of the accelerograms is about 3 sec. Such short duration means that these events act as single short-time impulse load on the chamber-pillar system. The fact that the peak vertical accelerations are often higher than the horizontal (50 % of the registrations) has to be considered when perform a dynamic analysis of the stress-strain state of the system too, since there is a possibility for pillar

failure due to vertical cracks occurrence. The available records can be efficiently used for the vulnerability analysis of the structures in the region of Provadja, for pillar capacity reestimations.

Starobin. According to a division of the east European platform west into seismotectonic regions, the territory of the Starobin deposit of potassium salts is related to the Pripyat potentially seismic super zone with a magnitude M=4.0 and a focus depth H=5 km(Garetsky et al., 1997).

As to induced earthquakes, the first of them was recorded in 1978 (K=9 I_0=V) by the seismic station "Minsk" located at a distance of 170 km from it. Continuous instrumental seismic observations in the deposit region were carried out in 1983 by equipment with short period seismographs. Operating frequency bands were 1-10 Hz with analog recording. Besides within 1983-2000 observations were carried out by self-contained seismic instruments with operating frequency bands of 0.5-60 Hz and duration of independent work of 20 hours, and the information was recorded on magnetic tape. About 1000 seismic events were recorded in the region within this period (Aronov et al., 2003).

A seismologic telemetric complex was installed in 2004, and the information was transmitted into the computer. At the first stage the complex was composed of four observation stations. A total of 6 observation stations were envisaged. Each station was instrumented with three-component short-period seismic detectors with capacitance-type transducer and magnetic-electrical feedback. The operating frequency band was 1-70 Hz. The information was continuously transmitted to a computer in the real time network and then to a computer when it was accumulated, processed and stored. Observation stations were located both in mines, and on the ground surface. A dynamic range was at least 120 dB. A reception range was at least 30 km.

A three-level database was the result of long-term seismic monitoring based on an automated telemetric complex:

- **level 1 contains general geological and geophysical information on the territory under monitoring, specific data on the seismograph network, tectonic blocks, velocity models, seismic wave travel time curves, etc.**
- **level 2 contains digital seismograms of recorded seismic events, digital event Seismograms, arrival times and amplitudes of seismic phases, major wave groups with maximum amplitudes, etc.**
- **level 3 contains the main results of interpretation, i.e. space and time, energy parameters of foci of seismic events as well as some other parameters.**

The data are considered to be most important for studying geodynamics of the Soligorsk industrial region.

4.3.14.5. Results

The map of epicenters of the Soligorsk seismic events recorded in the period since 1983 till 2004 is presented in Fig. 4.3.14.6. Over the period mentioned more than 1000 seismic events have been registered in the area monitored, 4 of which produced a tangible effect: 10 May 1978; 2 December 1983; 17 October 1985; 15 March 1998. The energetic class which is connected to the magnitude correlating K=1,8M+4 for those events is located within the diapason of 8,0- 9,5. The intensity of soil shaking raised up to 4-5 scores. All the earthquakes were accompanied by macro-feelings: rumble, window glass rattling, swaying of hanging objects, furniture and floor creaking on the ground floors

of wooden constructions. The scattered plaster cracks were observed. During the earthquakes 1978 and 1998 roof collapse took place.

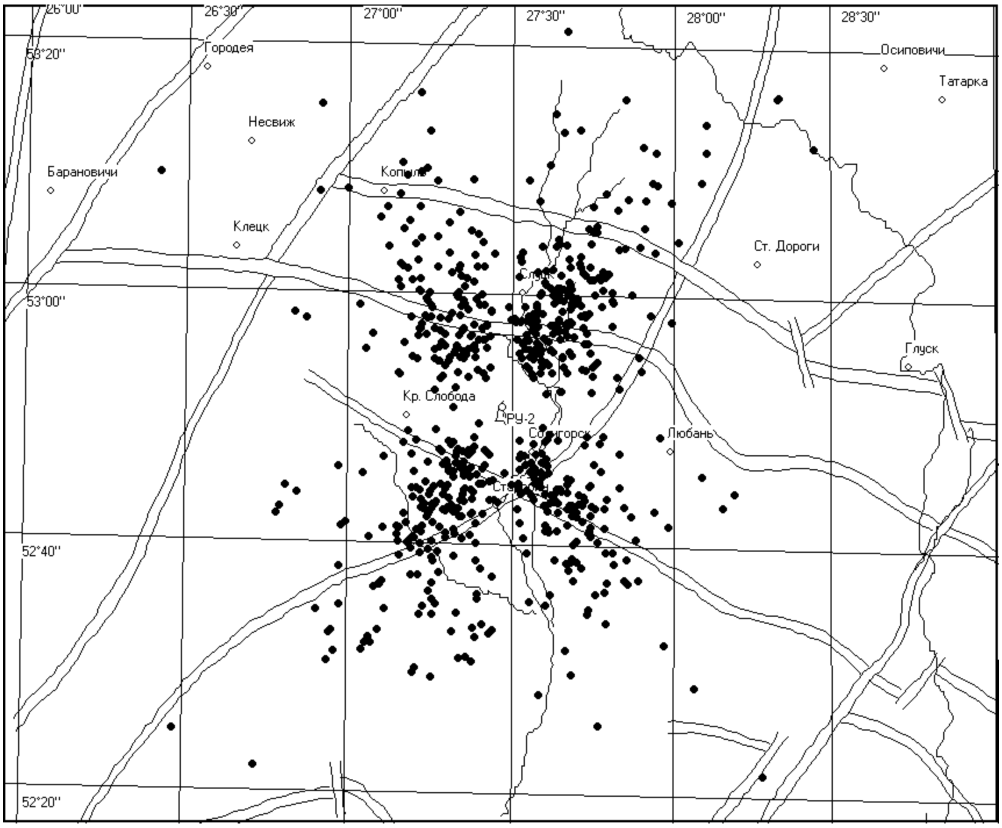

Fig. 4.3.14.6. Map of epicenters of seismic events in the Soligorsk region

This map also shows rupture dislocations active at the present-day stage. The strongest seismic events recorded recently in the Soligorsk region are confined to zones of tectonic disturbances active at the latest stage. These are a set of the North-Pripyat super regional faults, the Chervonaya Sloboda and Stokhodsk-Mogilev fault systems. This is also evidenced by the prevailing fracturing orientation measured immediately in mines and by the regional stress system of the East European Platform west.

At present continuous seismic observations at the Soligirsk geodynamic testing ground are carried out with an automated telemetric seismic complex intended for prompt monitoring of space and time distribution of seismicity and assessment of the geodynamic environment by outlining seismically active areas (tectonic blocks).

The Provadja deposit area is situated in the eastern part of Bulgaria. Seismic observations have been carried out there since 1994 by a local network of five stations.

The map of epicenters of seismic events in the Provadja region is presented in Fig. 4.3.14.7. This map also shows the location of local seismic stations that are operating there. The distribution of epicenters suggests that they are tending to linear arrangement in a direction from southwest to northeast along the profile joining the settlements of Dulgopol and Tolbukhin. Most of epicenters are confined to a zone measuring 20 km across and situated between the settlements of Markovo, Dulgopol and Momino. The strongest earthquake of this region with a magnitude of 4.4 also took place there in December 18, 2003.

The other smaller zone where epicenters are abundant is situated 30 km southwestward of the settlement of Tolbukhin. The area of epicenters extends to approximately 70 km sublatitudinally and 65 km submeridionally. In the first epicentral zone events with a magnitude of 1.5÷2.4 are slightly prevalent, and in the second zone events with a magnitude of 2.5÷3.4 are dominant.

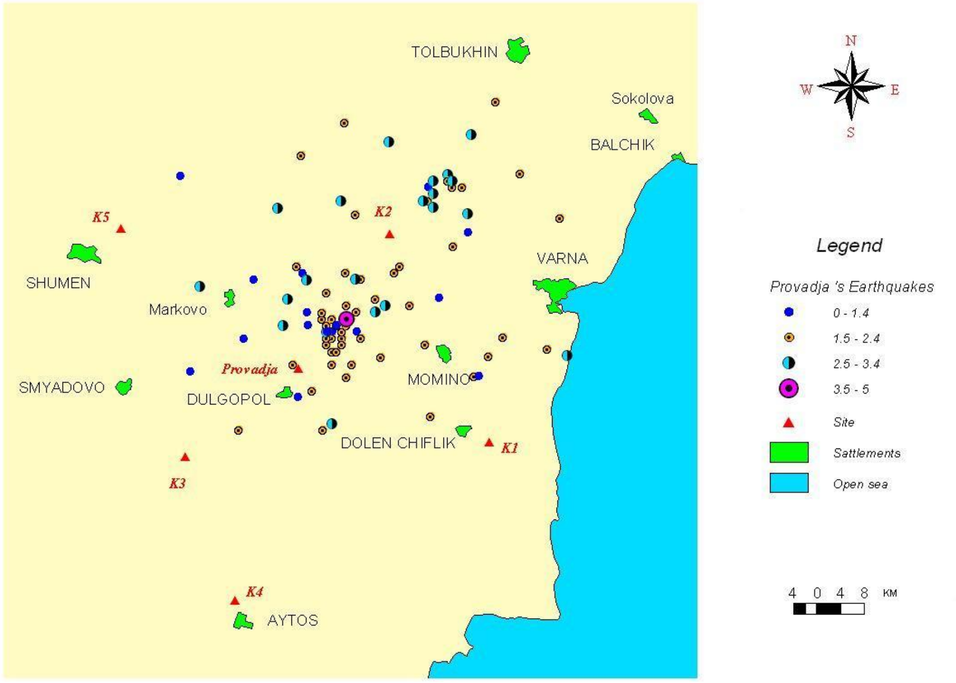

Fig. 4.3.14.7. Map of epicenters of seismic events in the Provadja region

In both deposits epicentral areas of seismic events overstep the limits of mine workings. This is typical of induced seismicity zones.

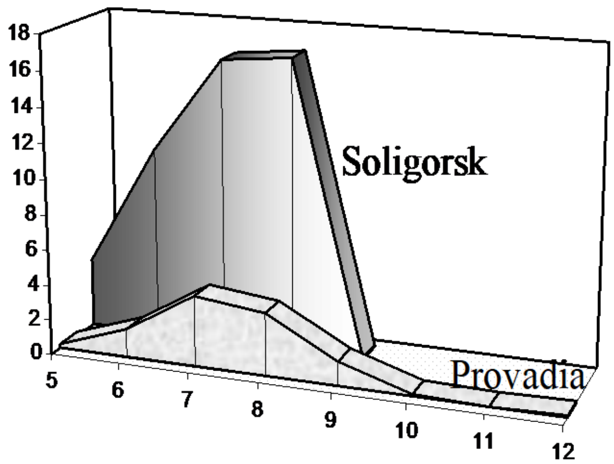

Fig. 4.3.14.8. The curve of recurrence for the Soligorsk and Provadja regions

The Fig. 4.3.14.8. presents a curve of recurrence calculated by the method of intervals for both regions. The average annual value of a number of seismic events is plotted as ordinates. This curve shows that in the region of Soligorsk the seismic activity is higher for a range of energy classes 4÷9. The curve shape in this range is almost uniform. It should be noted that this range of energies correspond to rock-tectonic shocks according to Malovichko classification (Malovichko et al., 2000). A quasi-similarity of curves suggests the similar origin of seismic events.

However, in the Provadja region seismic events with energy class of 9 and higher, i.e. in the energy range related to technogenic earthquakes (4) are more abundant. One earthquake which took place between the settlements of Markovo and Momino in December 18, 2003 had a magnitude of 4.4 (K≈12). The time distribution of the seismicity in Provadja and Soligorsk regions is given in Fig. 4.3.14.9A. In Fig. 4.3.14.9B released energy vs. extracted salt quantities, considered period - up to 1995 in Provadja region is given. Fig. 4.3.14.9C shows total annual values of seismic energy (E) for the Soligorsk and Provadja regions.

A quasi-periodic character of a number of seismic events with the general tendency to increase is characteristic of the Provadja and Soligorsk regions. The summary annual energy value agrees in general with a number of events. This regularity has been slightly disturbed since 1996 in the Soligorsk region. When a number of events increase there the summary annual energy is tending to decrease. For the curves drawn from the Provadja data two extreme points are not quite informative as during 1994 and 2004 the observations were not carried out regularly there.

In the Soligorsk region events of the less energy class are dominant suggesting a technogenic effect. Besides, there are suppositions that the seismicity in the Soligorsk is influenced (though to a lesser extent) by the other factors, e.g. lunar-solar tides (Seroglazov, 2003). In the Provadja region tectonic processes seem to play the more important part, which is confirmed by the stronger seismic events that occur there. This is due to the fact that the Provadja region is situated in the seismically active zone.

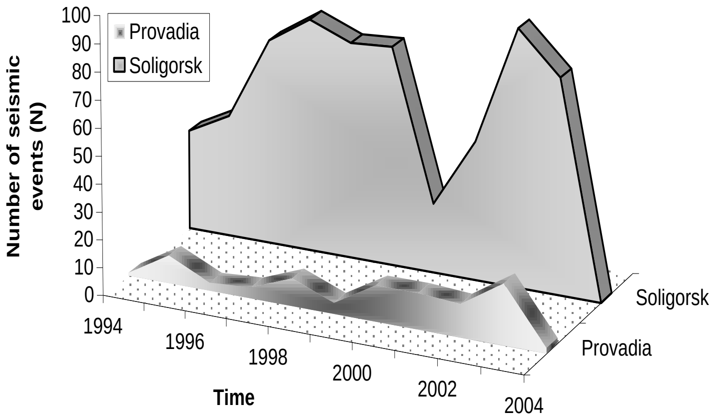

Fig. 4.3.14.9A. Annual number of seismic events (N) for the Provadia and Soligorsk.

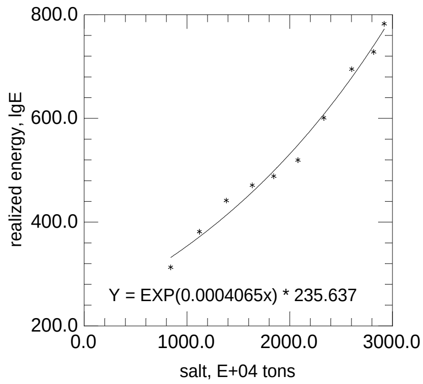

Fig. 4.3.14.9B. Released energy vs. extracted salt quantities, considered period - up to 1995.

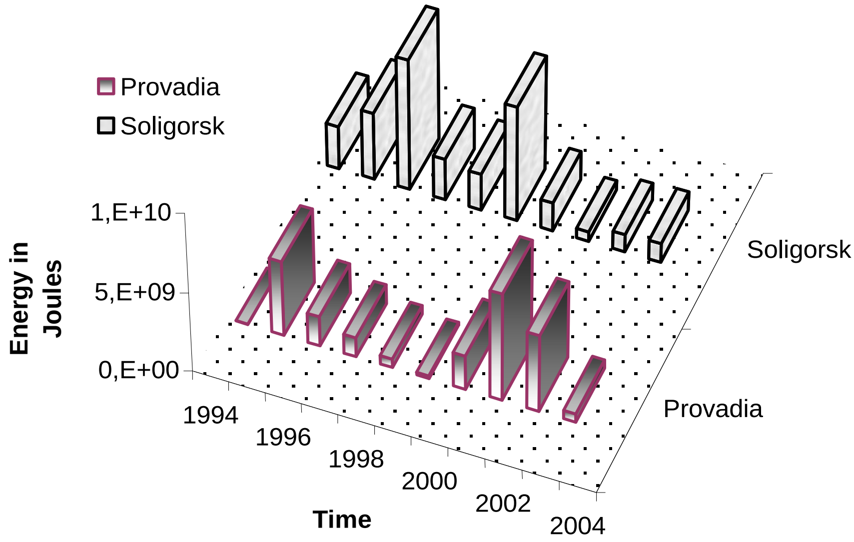

Fig. 4.3.14.9C. Annual values of seismic energy (E) for the for the Soligorsk and Provadia regions

4.3.14.6. Conclusions

Seismic processes in the regions of potassium salt deposits of Provadja and Soligorsk show the following characteristic features: a) the identity of the curves of recurrence of seismic events of the energy range of 4-8; b) a quasi-periodic character of the seismicity activation in time against the general trend of seismicity activation increasing; c) zones of epicenters of seismic events are larger that mining areas.

There are some differences in the pattern of seismic processes, such as: a) seismic activity in the range of small energies (K=4÷8) is higher in the Soligorsk region; b) events of the higher energy class K>9 are characteristic of the Provadja region.

4.3.14.7. Acknowledgements

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