HUMAN-INDUCED ACTIVATION OF GYPSUM KARST IN THE SOUTHERN PRIANGARIA (EAST SIBERIA, RUSSIA)

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ABSTRACT: Over 25% of the area of the Siberian Platform is composed of carbonate, sulphate, and saline rock deposits that are marked by intensive karstification and leaching. Particularly intensive karst occurs under natural conditions within gypsiferous and saline rock formations in the southern part of the Irkutsk amphitheatre. Intensive economic development of the region, including creation of large industrial enterprises, man-made reservoirs, expansion of irrigation farming, and other activities, have stimulated substantial activation of karst processes, in some places with a more than a 10-fold acceleration.

GYPSUM KARST UNDER THE NATURAL CONDITIONS

The area of southern Priangaria is a high plateau, dissected to depths of 200–220 m by fluvial erosion. In 1963–64 the Bratsk Reservoir was constructed in the Angara River basin, with elongated arms of the lake occurring in the valleys of Osa and Unga Rivers. The Bratsk Reservoir extends from west to east, across a 100-km-wide zone of anhydrite and gypsiferous carbonate rock formations. The geology of this area was comprehensively described in a number of publications (Eraso and Trzcinskij 1993; Guide 1996; Trzcinski 1996; Wika et al. 2000).

The typical stratigraphic succession, including the gypsiferous rock formations, has the following pattern. A 10- to 12-m-thick bed of dense, highly fissured and cavernous dolomite overlies a gypsum/anhydrite sequence, with dolomite intercalations. At a depth of 30 to 35 m within this gypsiferous sequence is a 6-m-thick layer of gypsiferous dolomite, with some minor gypsum intercalations. The massive, fine-grained dolomite is underlain by the gypsum/anhydrite unit. Dissolution features are abundant along the contact of sulphate rocks with the dolomites, generally being represented by karst cavities that have been filled with clayey material or dolomite powder. Open cavities along the upper contact of the karstified rocks are rare.

Vologodsky (1975) distinguished three stages of karst development in this region, and these occur during the Middle Cambrian and pre-Jurassic times, and during the Quaternary.

Sulphate karst of the Quaternary Period is of a particular interest; it is widely developed in the valleys of the Angara, Oka, Belaya Rivers, and their tributaries. At present, practically the whole thickness of the Angara Member has been subjected to karstification, with the effects being most intense in the upper part of the sequence.

The solute load of runoff from gypsiferous rock areas is estimated at 170 t/km^2. Chemical denudation rates vary from 0.02 to 0.08 mm/year. The overall rate of surface denudation in geologically recent times is estimated roughly at 1 m per 10,000 to 12,000 years. The cumulative amounts of karst denudation of sulphate and sulphate/carbonate formations during the Quaternary Period are estimated to be approximately 70–80 m and 20–30 m, respectively (data obtained by V. M. Filippov).

Morphologically, gypsum karst is typified by sinkholes, caverns, blind valleys, karst trenches, and dissolution troughs (Guide...., 1996). The superficial forms are represented mainly by sinkholes of corrosional and suffosional origin. The majority of old sinkholes are in the range of 20 to 80 m in diameter (rarely 100 to 120 m) and 8 to 20 m in depth. Groups of sinkholes which have fused together commonly form depressions that are 150–200 m long (Fig. 1).

Caves are commonly located in distinct zones along the valley slopes. The largest caves are Balaganskaya and Khudugunskaya Caves. These large caves, as well as the smaller ones (commonly 20 to 50 m in length), were formed within the zones of horizontal groundwater circulation, and a multi-level structure is common, reflecting the changes of base level.

TECHNOGENIC ACTIVATION OF KARST

Intensive economic development in East Siberia has considerably enhanced karst processes, and this has produced a number of detrimental impacts upon the environment (Pulina and Trzcinsky 1994). In particular, activation of karst processes has been induced by creation of man-made reservoirs (for example the Bratsk and Ust-Ilimsk Reservoirs) which entailed considerable changes of the natural conditions along their karstic shore areas (The Problems of Protection ... 1993; Ovchinnikov et al. 1999). These changes have imposed accelerated rates of karst deformation, including the development of collapse sinkholes and subsidence trenches. Many of these have caused damage to buildings and other constructions; some shore areas have become unsuitable for industrial and even agricultural use. The creation of reservoirs has considerably changed the hydrogeological conditions in the region; for example, the flooding of earlier dry slopes, the occurrence of new aquifers, and changes in hydrogeodynamical parameters.

Experimental studies of leaching of karstic rocks on location (in the shore zone) and in laboratories (Filippov 1981;

Figure 1. Karst kettlehole in the foreground, and a Karst outlier in the background (photo by V.M. Litvin).

Trzhtsinsky and Filippov 1981) show a low dependence of the leaching rates of sulphate and limestone/dolomitic rocks upon their composition; such leaching rates are determined primarily by the hydrodynamic zonality and filtration rates. For example, the leaching rates of crystallyzed, fibrous, and bituminous gypsum, as well as dolomite and mixed limestone/ dolomitic rocks, show a 10–30% difference. This depends, primarily, not on the chemical composition of the rock, but on the structural and textural characteristics, the presence of microfractures, terrigene inclusions, and other structural imperfections.

The comparison of sulphate and carbonate leaching by hydrodynamical section gave more contrasting results. For example, the leaching rate of gypsum within the zone of varying saturation is marked by a 3.4 to 7.7 times decrease, in comparison with gypsum in the aeration zone, and a 12.5 times decrease in the zone of complete saturation. Meanwhile, the leaching rate of dolomite increases due to a lower solubility, with longer solvent-to-rock contacts, being 2.7 times higher in the zone of varying saturation than in the aeration zone.

Comparison of the rates of karstification of gypsum and dolomite under laboratory and on-location conditions shows that the leaching rate of dolomites is by 2–3 orders of magnitude lower than that of gypsum. Homogeneous limestone rocks have a 2/3 times higher leaching rate than dolomites and mixed rocks. Sulphate rocks are most responsive to variations of hydrodynamic conditions; with higher filtration rates, the leaching rates of sulphate rocks may increase by 2 orders of magnitude. It has been proven by experiments that the highest rate of karstification is characteristic for sulphate rocks. In areas of gypsum/ anhydrite deposits, in the upper parts of the Bratsk Reservoir, the suffosional pattern of deformation changed for karst-induced features, entailing the formation of new sinkholes and pits up to 30 m deep and up to 7,000 m^3 in volume (Wika et al. 2000) (Fig. 2). Origination of large sinkholes, a typical effect during early existence of the reservoir, was due to rejuvenation of paleokarstic features. Development of sinkholes in later years was caused primarily by variations of water table, induced by water-level changes in the reservoir. Also, signs of carbonate-karst activation were observed, but they were smaller and less frequent.

Zones of sulphate- and carbonate-karst activation are, respectively, 4–6 km and 0.5–1.0 km wide. The maximum rates for appearance of new collapse features are observed along the shore zone of 1.0 km and 0.3–0.5 km widths, respectively, where the rates range between 5.9 and 3.5 collapses per km^2 per year. Figure 3 shows the greater stability of an area against karsting being related to the greater distance from the reservoir shores (Maximovich 1961). In recent years, activation of karst processes has been caused by variable impacts of groundwater backed up due to fluctuations of the water level in the reservoir.

In general, the main role in activation of karst processes belongs to variation of the hydrogeological conditions. Impounding of the reservoir, and raising of the water level by 100 m, resulted in an increase in the thickness of the existing aquifers and creation of new aquifers in the backwater zone. In areas underlain by Lower Cambrian carbonate and sulphate/ carbonate deposits, the maximum hydrostatic head is 23–28 m. Flooding of the highly fissured rock areas of the former aeration zone, with its high-filtrational character, has sharply increased the rock's water saturation here. Carbonate and sulphate/carbonate rocks of the Lower Cambrian are

Figure 2. A recent karst sinkhole.

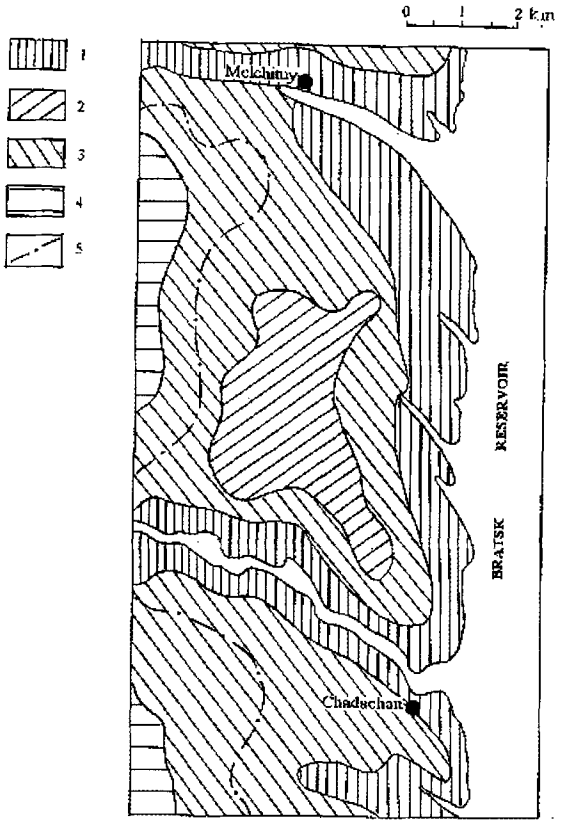

Figure 3. Zoning of the Khadakhan -- Melkhituy tract of the Bratsk Reservoir shore area in terms of sustainability against karst processes (based on the data of V.M. Filippov). Areas: 1 - rather unsustainable (formation of 10–1 sinkholes per km2 per year); 2 - not sustainable (1–0.1); 3 - low sustainable (0.1–0.001); 4 - sustainable (<0.01); 5 - zone of forecasted karst activation under the reservoir's influence.

characterized by largely uneven water saturation, due to the large non-uniformity of filtration characteristics of the karst-fissured container rocks. The variation coefficient of the specific yield of boreholes here is 162%; however, there is an appropriate decrease of the rock water saturation with increasing distance from the reservoir.

Within the shore zone (up to 2.0 km wide), which is marked by maximum influence of hydraulic head, very high specific yields are predominant in existing boreholes (the average values varying from 5 to 25 L/s). The rock water saturation decreases substantially with increasing distance from the reservoir (at distances >2 km away), where the maximum value of specific yield in boreholes does not exceed 0.5 L/s. Also, similar relationships within the section can be observed. The zone of high rock permeability is confined to the depths of 30–50 m below the bottom of the reservoir.

Formation of backwater was accompanied by infiltration of fresh groundwater into the shore area. Karst development here resulted from the leaching of gypsum/anhydrite rocks; it is accompanied by lowering of the water level in the reservoir, and consequently by lowering the groundwater table and increasing the travel times of groundwater. Since the initial impounding of water in 1967, the intensity of karst processes has not diminished, and the area influenced by karst has expanded.

The technogenic intensity of carbonate karsting is much lower; however, the maximum danger in areas of carbonate karst comes from joints, landslides, and suffosion processes, which approach the impacts of gypsum karst. In the shore areas of the reservoir, the activation of karst processes is most prominent. Karst-suffosional processes, however, may be intensified also by other kinds of technogenic impacts. For example, in the BAM area numerous small and middle-size sinkholes (ranging from 0.5 m to 8.0 m in diameter, and up to

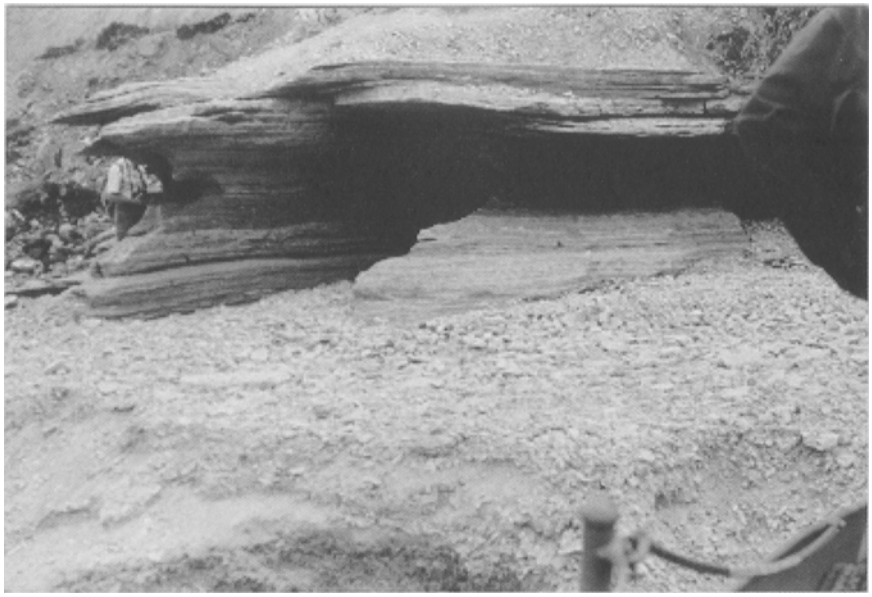

Figure 4. Leaching of sulphate rocks in the area of variable water level of the reservoir.

2.5 m deep) of suffosional nature appeared due to opening of the karsting gypsiferous rocks by excavations, quarries, and other means. Origination of sinkholes was the result of increased infiltration of surface water into the exposed bedrock, and suffosional transfer of products of the karst-induced destruction into corrosion-tectonic joints. The development of karst is associated with an enhanced leaching process which is more intensive than in similar areas with undisturbed turf cover.

The analysis of leaching rates shows that karsting rocks will retain the inherited character of karst activation at least until the next century. In the shore areas, cave-like hollows develop in the areas where gypsum/anhydrite rocks are penetrated by backed-up groundwater.

The probability-statistical prognostication of karst development is the most effective method of local karst prognosis in the southern area of East Siberia. On the basis of ongoing investigations of karst dynamics, degree of karsting, and activation of karst processes, the probability and frequency of occurrence of sinkholes and their size can be predicted; this enables us to establish zones that show an area's sustainability. Such investigations currently are underway in the area of Khadakhan settlement; here the horizontal cavities extend about 20 m into the gypsiferous bedrock (Fig. 4).

Analysis of conditions and factors contributing to activation of karst in the vicinity of the reservoir indicates that the intensity of sinkhole development will not vary during the next 15–20 years. Sharp fluctuations of the water level in reservoirs will result in considerable intensification of the origination of sinkholes.

CONCLUSION

The changes of geological conditions in the southern area of Priangaria have resulted in considerable activation of karst. In particular, the activation of karst processes has been induced by construction of the Bratsk Reservoir; fluctuations of the reservoir's water level has locally caused intensive development of evaporite karst.

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