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Age Dating of Karst Forms Upon Regional Assessment of Karst Hazard (A Case Study of the Tatarstan Republic, Russia)

V. A. Yolkin
Institute of Environmental Geoscience, Russian Academy of Sciences, eyolkin@mail.ru

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V.A. Yolkin

PH.D. (Engineering geology), Institute of Environmental Geoscience, Russian Academy of Sciences, P.O. Box 145, 13, Ulansky per., Moscow, 101 000, Russia
T: (7-495) 2089605, F: (7-495) 9231886, eyolkin@mail.ru

Abstract

The detailed investigations accompanied by collection of forty samples for radiocarbon and palynological analyses from six poorly and well-marked in a relief karst and karst-suffosion sinkholes, have shown, that the largest of them (diameter more than 30 m) are up to 5 - 10 thousand years, and the smaller size up to 2 - 3 thousand years. The marked karst forms - lakes, hollows and the depression reaching in diameter 200 - 300 m and more, were formed due to merging of separate forms and, most likely, have a long pre-Holocene history. The general procedure of regional probabilistic-deterministic assessment of karst hazard with karst collapse (sinkhole) intensity (cases of failures / $km^2 \cdot$ years; m^2/ $km^2 \cdot$ years) is discussed. Example is provided of corresponding map of karst hazard, made for the typical karst area of Tatarstan Republic.

Introduction

The territory of the Tatarstan Republic (Tatarstan) is located within the soluble Permian sequences mainly, limestone, dolomite and gypsum, which occur at a low depth under the surface (up to 200-300 m). In the present-day relief, carbonate rocks are more or less widespread where they are covered by poorly consolidated sediments (Figure 1, 2). Thus, the development of karst and karst-related process of suffosion is registered within Tatarstan. About 96% of studied territory is karst hazardous. From 1895 to 2005, more than 80 disastrous karst collapses occurred resulting in deformations and destruction of many economic facilities and the death of one man near Aktash in 1939.

Age dating of karst forms expressed in a relief are necessary for scientifically proved assessment of karst hazard's degree within vast territories of the Tatarstan Republic and Russia as a whole. This information can be obtained from studying the history of territory's geological development, analysis of solution process and by means of application of radiocarbon and pollen methods of dating of a filler of karst forms.

However, for the whole territory of Tatarstan Republic, the data about age of karst and karst-suffosion sinkholes are rather limited. Paleobotanic investigations carried out by V.I. Baranov and N.Ya.Ospoprivivatelev (1938) near Zelenodolsk city, have

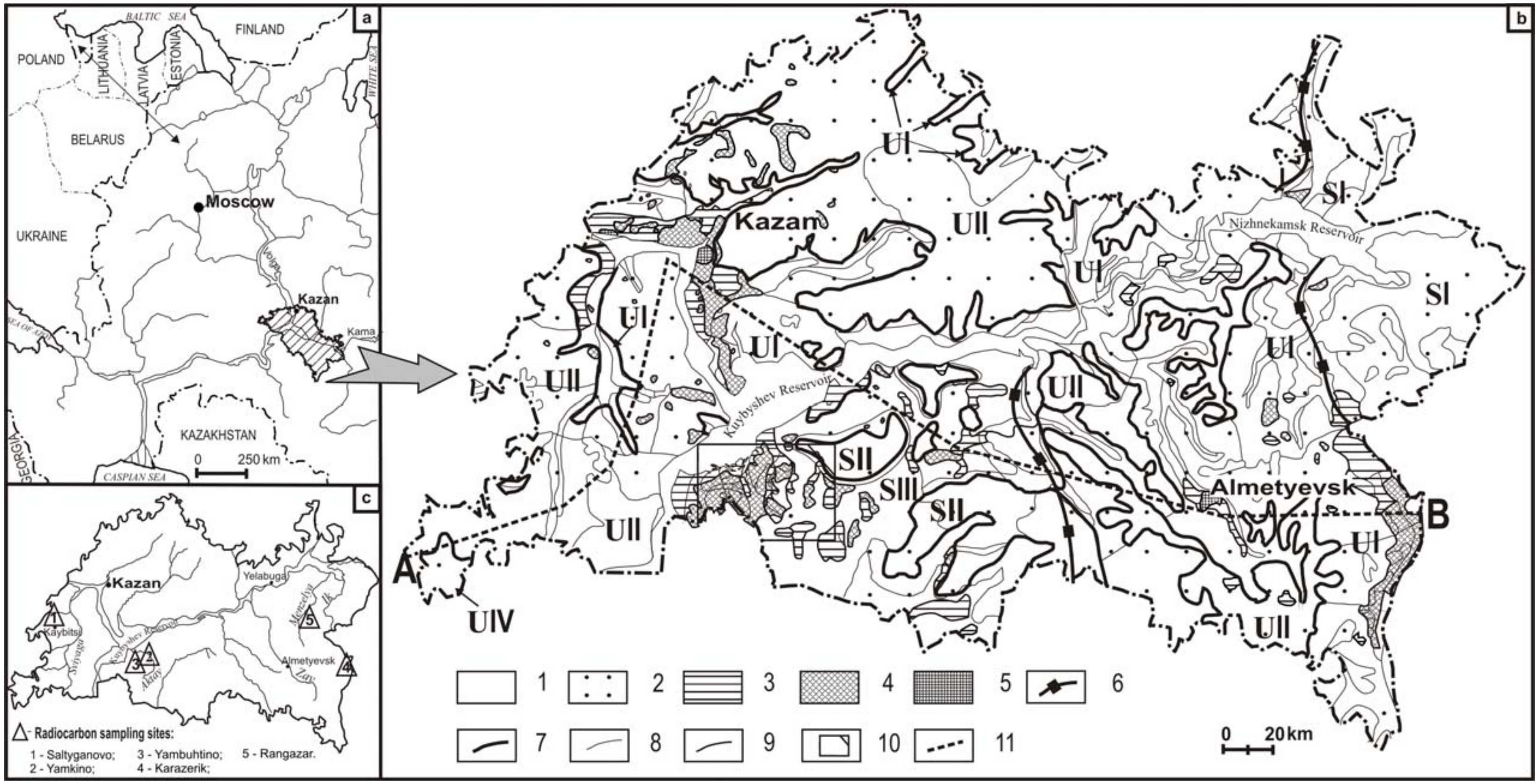

Figure 1. Karst hazard map of the Tatarstan Republic.

Territorial karst hazard categories (areal intensity of karst deformations, $m^2/km^2 \cdot year$): 1 – non-hazardous (0); insignificantly hazardous: 2 – (<0.01); 3 – (0.01 - 0.1); 4 – slightly hazardous (0.1 - 1); 5 – moderately hazardous (1 - 3). Boundaries of: 6 – territories with uplift (U) and subsidence (S) neotectonic movements, which are equal to the regions of the 1st order; 7 – stratigraphic and lithologic complexes of karst-prone bedrocks, which are equal to the regions of the 2nd order: complex of sulfate-carbonate rocks (I), complex of carbonate terrigenous rocks (II), complex of sulfate carbonate terrigenous rocks (III), complex of carbonate terrigenous rocks (IV); 8 – taxons of the cross tripple typological zoning; 9 – groups of NTS of the second order differing in karst hazard categories; 10 – a key site of detailed investigations; 11 – geological cross section.

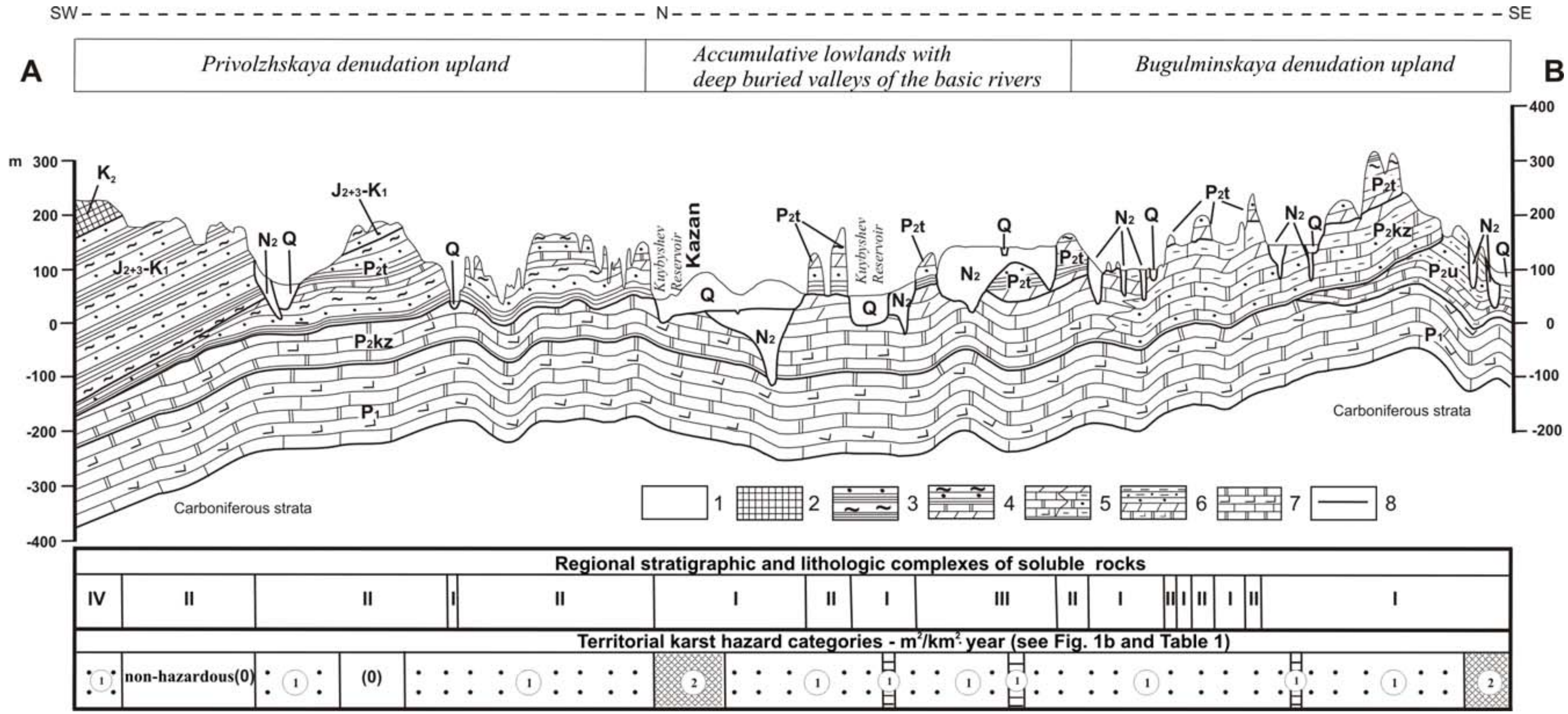

Figure 2. Geological cross section and hazard categories of the karst region of the Tatarstan Republic.

1 – Quaternary and Neogene deposits (sand with siltstone and clay interbeds and lenses); 2 – Upper Cretaceous chalk-like marls; 3 – Mesozoic terrigene deposits (J_{2+3} - K_1): stratification of sandstones, clays, and loams; 4 – Upper Permian Tatarian stage (P_2t): loams, sandstones, clays, dolomite, and marls; 5 – Upper Permian Kazanian stage (P_2kz): stratification of dolomites, limestones, and gypsum layers, which shows facies changes from west to east across the area (i.e. increasing of terrigenous rocks in the stage - siltstones, sandstones, and marls); 6 – Upper Permian Ufimian stage (P_2u): siltstones, mudstones, sandstones, marls, dolomites, and lens of gypsum; 7 – Lower Permian (P_1): succession of dolomites, limestones, and gypsum. 8 – borders of stratigrafic and lithological complexes.

shown that peat at the bottom of the ancient collapses which formed on the second and third terraces of the Volga River, is referred to pre-Holocene or to the beginning of Holocene time (Boreal and Atlantic periods). In opinion of Yu.V. Sementovsky (1986), a significant part of collapses located on the second and fourth terraces of the Volga River near Kazan city was formed during Odintsovo and Mikulino interglacials along deep buried valleys. At present, the lakes with diameters ranging from 15 to 200 m at the maximal depth up to 26 m have been formed on the place of these collapses.

Thus, it is possible to note that until recently within the limits of investigated territory the complex investigations of age of karst forms were not carried out. Another aspect of the problem of karst hazard assessment concerns little attention of researchers at a regional level. In this situation, the problems of karst hazard identification upon the territory's stability assessment appear to be significant and urgent, and are partially considered in present paper.

Principal outlines of the structure of karst sinkholes and its ages

For studying regularities of karst process on the territory of Tatarstan, first, the data on spatial distribution of surface karst forms were obtained with GIS (MapInfo) by means of interpretation of spectral zonal space images, and, second, the field investigations have subsequently been carried out within key-sites differing in principal karst factors. Within boundaries, the karstification coefficient (the number of collapses per km^2, m^2/km^2) is specified; the age of typical karst forms with radiocarbon and pollen methods is determined.

On Figure 1c, the sketch of key sites' location is shown where the samples for radiocarbon and pollen analyses were extracted from pits (up to the depth 4 - 5 m). Radiocarbon analyses were performed by L.D. Sulerzhitsky and M.M. Pevzner, researchers of the laboratory of isotope geochemistry, Geological Institute (GIN), Russian Academy of Sciences. As a result, a total six key-sites within the studied territory have been selected and surveyed. The description of the some of them is given below (Figure 3).

Key-site № 1 – "Travkino". The first site – "Travkino" is located within the limits of the third alluvial terrace (Middle Pleistocene) of the Volga River of 90 - 100 m asl. Karst phenomena are related to carbonate and gypsum dissolution ($P_1 + P_2kz$) at this site. The succession is concealed by Quaternary deposits, mainly sands and loams, which attain 50 - 100 m in thickness.

A saucer-shaped sinkhole was chosen as a typical karst form up to 55 m in diameter and 0.3 m deep located in the vicinity of the village Travkino. Two samples (samples 1 and 2) from depth of 0.7 and 1.9 m were collected which consisted of clastic material, and sapropel. These samples contained the radioactive carbon insufficient for the laboratory analysis. Therefore, the estimation of karst sinkhole age across the considered site was based only on palynological investigations.

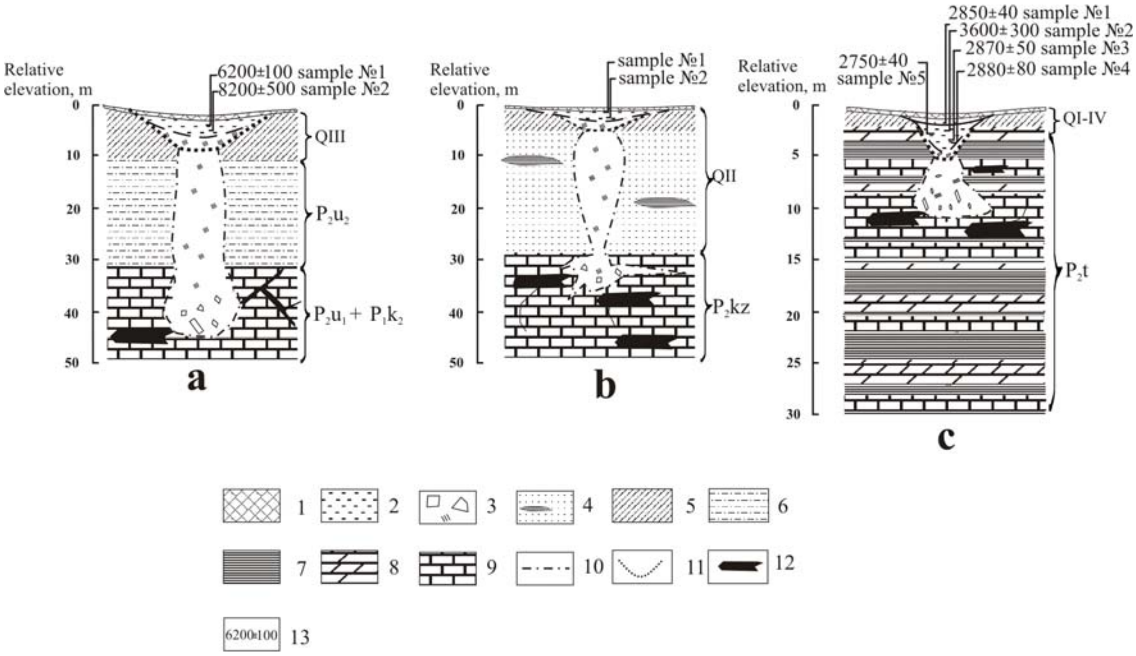

Figure 3. Cross-section of karst and karst-suffosion sinkholes (collapses) within key-sites: Karazerik (a), Travkino (b) and Saltyganovo (c).

1 – soil; 2 – lacustrine and bog sapropel; 3 – caved material; 4 – sand with clay interbeds and lenses; 5 – loam; 6 – siltstone; 7 – clay; 8 – dolomite; 9 – limestone; 10 – break down area; 11 – hypothetical sinkhole's profile; 12 – cavity; 13 – radiocarbon dates.

The latter analysis was conducted by Dr. M.M. Pakhomov, the head of the Palynological research laboratory for the Evolution Nature at the Vyatka Pedagogical University.

It is necessary to note that samples contained the so-called selective spore-pollen spectrum, because the test points in pits were selected, mainly, in humus layers. Palynological investigations show a strong predominance of spectra of temperate-warm flora, especially gramineous and forb meadow representatives (Asteraceae, Cichoriaceae, Apiaceae etc.). Such paleographical conditions with absence of precisely expressed maxima of broad-leaved species were typical to Upper Holocene. Thus, it is possible to draw a conclusion that formation and filling of sinkhole at the site "Travkino" occurred about ~ 3000 years ago.

Key-site № 4 – "Karazerik". It is located within a flat surface of the first alluvial terrace of the Ik River which formed in Upper Pleistocene at 90 - 100 m asl. Karstified Permian rocks comprise sulfate-carbonate sediments ($P_1 + P_2kz$) such as limestone, dolomite, gypsum, and anhydrite. They are overlapped by alluvial deposits, mainly sands and loams, which reach 50 m in thickness. A saucer-shaped sinkhole was selected as a typical karst form with 20 m in diameter and 1.5 m deep located in the vicinity of the village Karazerik.

Two samples (samples 1 and 2) from depth of 1.48 and 2.71 m respectively were selected, which consisted of humus (paleo-soil) and sapropel. Results of the radiocarbon dating of samples № 1 and 2 (6200 ± 100 years, GIN - 12304 and 8200 ± 500 years, GIN - 12305, respectively) allow us to conclude that the sinkhole developed in early Holocene, circa 9000 years ago.

Key-site № 4 – "Saltyganovo". The area is set within the interfluvial surface of Early Pleistocene with 140 -150 m asl. Karstified Permian rocks comprise carbonate layers (limestone, dolomite) within clayey and marly subsequences of Tatarian stage (P_2t). It is overlapped from a surface by stratum of loamy-rubbly eluvium (Quaternary) which attains 5 m in thickness.

A saucer-shaped sinkhole was chosen as a typical karst form up to 15 m across and 1 m deep. Samples have been selected from the deepest central part of studied sinkhole (see Figure 3), including the fragments of wood (sample №1) from the depth of 0.67 m, the sapropel samples (№2 and 4) from the depth of 1.5 and 2.8 m, respectively and, finally, the fragments of wood (sample №3) from depth the of 2.7 m. Also, the fragment of wood from the depth of 2.1 m was collected (sample №5) at the distance of 2 m from the central part of sinkhole.

It is important to emphasize some inversion of dates of the radiocarbon dating, e.g. samples №2 and 4. The later sample was taken just below a wood fragment, which was also dated. The vicinity of the decomposed wood, has obviously played the "rejuvenating" role for the enclosing stratum of sapropel from which the younger date was obtained as compared to the overlying one (see Figure 3).

A special attention is paid to a surface layer of peat with the wood fragments (sample №1), which manifested the age dates of the same order. It was similar to ones at the depths of 2.1 and 2.7 m. Proceeding from the above, we may conclude that the wood was initially on a surface of lake, developed in contours of the sinkhole. Having been dipped into deposits, they were buried gradually in depth.

Palynological investigations (samples №2 and 4) show the predominance of wood vegetation, e.g., a treelike birch, a linden, an oak, an elm etc., i.e. filling the sinkhole that occurred under the conditions of thermophile wood flora, probably, in the Atlantic period of Holocene. Thus, on the basis of results of the radiocarbon and palynological analysis it is possible to conclude that the saucer-shaped sinkhole was formed in the middle Holocene, about 5000 years ago.

The detailed investigations accompanied by collection of forty samples for radiocarbon and palynological analyses from six poorly and well-marked in a relief karst and karst suffosion sinkholes, have shown, that the largest of them (diameter more than 30 m) are up to 5 - 10 thousand years, and the smaller size up to 2 - 3 thousand years. The marked karst forms - lakes, hollows and the depression reaching in diameter 200 - 300 m and more, were formed due to merging of separate forms and, most likely, have a long pre-Holocene history.

Regional karst-hazard assessment

Assessment of karst and also any other natural hazard begins with its identification or determining regularities of a space-time variability in the area under consideration. For this purpose, we first collected all available data on karst manifestation and controlling regional-geological, zonal-climatic, and technological factors for the Tatarstan Republic area. Next, we performed zoning of the considered area based on the main factors of formation of karst hazard and risk. Final taxons of the cross tripple typological zoning of the area (natural-technical systems (NTS) of the first order) with quasi-uniform engineering geological, zonal-climatic, and technological conditions and processes responsible for a karst hazard and corresponding risk at the regional level were isolated as a result of this procedure.

After zoning, the karst hazard was estimated from the following formulas for determining a degree of hazard or physical risk of area damage (Ragozin & Yolkin 2003):

$$H(K)= \sum_{i=1}^{n} \mathrm{P}^{*} (K_i) \cdot S_i \approx S_k/t; \qquad (1)$$

$$H_s(K)= H(K)/S \approx S_k/S \cdot t, \qquad (2)$$

where $H(K)$ и $H_s(K)$ – are the total and normalized (over area) karst hazards, which are identical to the total $R_f(K)$ and specific $R_{fs}(K)$, respectively, physical risks of damage by karst deformations (m^2/year and $m^2/km^2\cdot$year); $P^*(K_i)$ – is the frequency of development of the *i*th-type karst forms (event/year); S_i – is the average area destroyed by this deformation (m^2); S_k – is the total area of karst deformations within the considered territory (m^2); t – is the time interval of generation of these deformations (years), S – is the area of the considered territory (km^2).

The predicted values of the areal intensity of karst deformations (sinkholes, collapses) obtained in such a way were referred to one of the six categories of karst hazard, according to the classification presented in Table 1, and are shown in the final map of hazard (see Figure 1b).

The analysis of the map presented in Figure 1b shows that all territory of the Tatarstan Republic (96 %) is practically karst hazardous. Throughout the territory (91.5 %) an areal intensity is less than 0.1 $m^2/km^2\cdot$year, i.e. insignificantly hazardous category (see Table 1). Slightly hazardous and moderately hazardous territories cover 4.3 and 0.2 %, respectively.

The areal intensity of collapse formation varies from 0.11 to 0.92 $m^2/km^2\cdot$year at territories of slightly hazardous category. They coincide with the areas marginal, as a rule, buried and modern river valleys of the Volga and Kama and their inflows in the Aznakaevsky, Alekseevsky, Alkeyevsky, Arsky, Bavlinsky, Vysokogorsky, Zelenodolsky, Kamsko-Ustyensky, Laishevsky, Sarmanovsky, Spassky, and Yutazinsky districts.

Table 1. Classification of territories with respect to the degree of a hazard of formation of karst collapses and ground surface subsidence within these collapses (Ragozin & Yolkin 2003).

Territorial Karst Hazard Categories	Areal Intensity of Karst Deformations ($m^2/km^2 \cdot year$)
I – Insignificantly hazardous	< 0.1
II – Slightly hazardous	0.1-1
III – Moderately hazardous	1-10
IV – Hazardous	10-100
V – Very hazardous	100-1000
VI – Extremely hazardous	> 1000

Within 4 % of the territory located in the southwest of Tatarstan (Bouinsky, Drozhanovsky, and Tetyussky districts) the karst collapse formation is practically impossible because of low karstification degree of bedrocks, which are overlapped by terrigenous deposits (J_{2-3}; K_1) of thickness more than 100 - 150 m, see Figure 1b, 2. At present time, the largest karst hazard (up to 1.6 m^2/km^2 a year) is specified for the territory of Kazan and others large towns. It is generally explained by man-caused influence, which led to the change in subsurface water regime and intensification of anthropogenic karst-suffosion process.

By *karst risk* we mean the probable index of hazard formation of karst and karst-suffosion collapses and ground surface depressions established for a certain object as it possible losses in various spheres for given time. Depending on kinds of losses, karst physical, economic, social and ecological risks are distinguished. At the same time, the areal intensity of karst deformations is an integrated quantitative measure of the first risk of physical losses of territory (also as for karst hazard). In such kind, the karst physical risk of losses is a basis for prediction of other types of karst risk. The assessment of karst economic and social risk at a regional level has been performed during 2003-2004, by the example of Spassky, and Alkeyevsk districts of the Republic Tatarstan (Ragozin & Yolkin 2004).

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