# Geological conditions of Moscow subsurface development

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**Abstract:** The necessity for the greater use of the urban subsurface has been aroused lately in Moscow in connection with broadening and diversifying its urban infrastructure. The program has been now developed implying the construction of skyscrapers with deep foundations, subsurface garages, deep pipelines, transport tunnels, etc. The implementation of this program requires a comprehensive analysis of geological structure and engineering geological zoning of the city area taking into account the subsurface construction requirements.

The Institute of Environmental Geosciences of the Russian Academy of Sciences (IEG RAS) has been providing the geological support for the general plan of urban development for many years. The compilation of special maps for the city territory on the basis of the available geological database is one of the fields of scientific activity at the institute. In particular, geological and geomorphological maps to a scale 1:50 000 were created permitting us to reveal the blocky structure and the specifics of recent tectonic movements within the Moscow territory. The distinguished linear boundary zones between the tectonic blocks are the most important from an engineering geological viewpoint. These zones are formed under the impact of tectonic and planetary stresses inducing the elevated fracturing of rock. Therefore, these zones are defined by decreased rock strength, the development of karst and erosion, elevated moisture content, and geochemical anomalies.

Recently, IEG RAS has built a detailed geological map of the city territory (scale 1:10 000) with the indicated channels of ancient river valleys. If met during subsurface construction (in particular, upon driving the underground), the buried river valleys, filled with quicksand, cause many difficulties and often lead to emergencies. Taking into account these and other specific features of Moscow's geological structure, we may significantly mitigate the risk related to geological hazards, find the best ways for the arrangement of subsurface structures, and apply the most efficient excavation methods.

**Résumé:** Etant donné que le dernier temps la construction terrestre de bâtiments devient de plus en plus compacte et vu l'infrastructure très chargée de Moscou, la nécessité d'utiliser plus largement l'espace souterrain de la ville se fait fortement sentir. A l'heure actuelle, on a mis au point le programme sur l'édification des gratte-ciel de fondation fichée, la construction des garages souterrains, des collecteurs de fondation profonde, des galeries de transport etc. Pour que ce programme voie le jour, il est besoin d'effectuer l'analyse approfondie et sous tous les aspects de la structure géologique et de la zonation géotechnique du terrain en tenant compte des impératifs de la construction souterraine.

Au cours de plusieurs années L'Institut d'Ecologie Géologique de L'Académie de Sciences de Russie (IEG ASR) accorde son assistance géologique au Plan d'ensemble du développement urbain. Parmi tous les travaux menés par cet Institut on peut souligner avant tout l'élaboration des cartes thématiques du terrain urbain à partir de banque de certaines données géologiques. En particulier, la carte géologique-géomorphologique établie à l'échelle 1 : 50 000 permet de révéler la structure en blocs et de mettre en évidence la nature d'évolution des mouvements néotectoniques sur le territoire urbain. Au point de vue géotechnique, il est très important de déterminer les zones linéaires frontières entre les blocs. Le dernier temps les scientifiques de l'Institut d'Ecologie Géologique ont dressé la carte géologique détaillée du territoire et de la ville (l'échelle 1 :10 000) avec l'indication des lits des incisions anciennes d'érosion. Dans le but de diminuer considérablement le risque dû aux processus géologiques dangereux, de trouver les variantes de l' architecture optimale des ouvrages souterrains, d'utiliser les méthodes les plus efficaces pour effectuer les travaux miniers.

**Keywords:** Geology of cities, environmental geology, aquifers, erosion, groundwater contamination, geological hazards.

## INTRODUCTION

The Moscow territory increased almost by a factor of 15 in the 20th century: its area was equal to 71 sq. km in 1900, whereas now it constitutes 1080 sq. km. The city area increased at the expense of surface construction. Therefore, engineering geologists investigated mainly the upper part of the geological environment, which served the basement for all engineering structures. The exploration of the deeper horizons of the earth interior started in the 1930s in connection with the construction of underground. In last years, due to lacking space for surface buildings and increasing density of urban infrastructure, the need for urban subsurface has risen. The program of erecting high-rise buildings with deep foundations, the construction of subsurface garages, collectors, transport tunnels, etc. has been elaborated. For the implementation of this program, the comprehensive analysis of the geological structure and the engineering geological zoning of the Moscow territory is needed taking into account the subsurface construction requirements. The publication of "Moscow. Geology and the city" monograph, under the editorship of V.I. Osipov and O.P. Medvedev in 1997 (Osipov & Medvedev, eds. 1997) favoured this need to a certain extent. Nevertheless, a number of acute problems still remain, and further studies of urban geological conditions are to be conducted.

# GEOLOGICAL HISTORY OF MOSCOW TERRITORY

In Moscow region, the bottom of geological cross-section is constituted by the crystalline basement formed more than one milliard years ago. Within the city territory, the crystalline basement occurs at a depth of 1.5 - 2.5 km and it is composed of ancient metamorphic rocks. The basement is divided into blocks by numerous tectonic faults, which are inactive now.

In the course of the last 550 million years of the so-called platform stage of geological development, the Moscow territory was repeatedly raised by endogenous processes operating in the earth's crust to form a part of a continent, where water erosion developed; it also repeatedly submerged to become a sea bed, where sedimentation went on, and a thick layer of limestone, marl, sandstone, clay, and sand was accumulated.

The last marine basin quit the Central Russia territory about 80 million years ago. A general rise of the earth crust occurred then, the continent was formed, and the paleorelief with deep river valleys developed.

During the latest 2 million years, this territory was thrice covered by major glaciers. After the last glacier retreated (about 130 thousand years ago), the whole territory remained covered with glacial and fluvioglacial deposits of up to several tens meters thick, and the modern topography with the valleys of the Moscow River and its tributaries was formed.

Finally, a 1.5 - 2.5-km-thick sedimentary massif has been formed over the crystalline basement, the upper 50 - 100 m of which is of the utmost importance from the engineering geological viewpoint. This uppermost part is composed (from the bottom to the top) by marine carbonate and clay deposits of Carboniferous age, marine clay and sand of Jurassic and Cretaceous age, and sandy-clayey glacial, fluvioglacial and alluvial deposits of Quaternary age (Figure 1). The marine Jurassic clay plays a special role in the geological cross-section. The low-permeable marine clay divides the rock massif into two hydrogeological complexes. The lower one, underlying the marine clay, contains several artesian aquifers used for drinking and economic purposes. The upper complex overlying the Jurassic clay also contains several aquifers, which are, however, usually significantly contaminated.

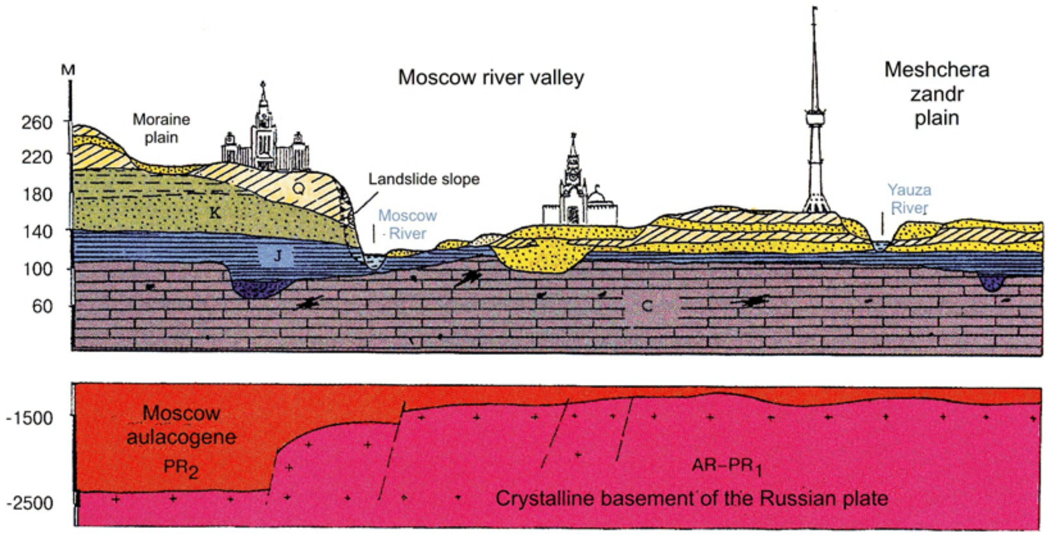


**Figure 1.** Schematic geological cross-section of Moscow

# MODERN GEODYNAMICS

The Moscow territory developed as a typical platform with moderate geodynamic activity in recent geological time (Osipov & Medvedev, eds. 1997; Makarov 1997). Therefore, there are no grounds to speak about either possible strong seismic activity in Moscow or active faults with large displacement amplitudes. As proceeds from the geodynamic map (Figure 2), compiled at the Institute of Environmental Geoscience RAS under the guidance of Dr. V.I. Makarov, the geological environment in Moscow consists of hierarchically built blocks of the earth's crust differing by the general direction of modern tectonic movements. The rates of the modern lateral and vertical displacements do not usually exceed 1-2 mm per year. These displacements are of alternating sign. However, to a geological time scale, some blocks manifest a descending trend; in the map, these blocks are shown in blue and green; and the lowermost areas in the city are confined to these blocks (for example, the Moscow River valley). Another group of blocks shows a rising tendency (they are coloured in yellow and pink in the map). As proceeds from the map, the highest elevation above sea level is registered in the Teplyi Stan district.

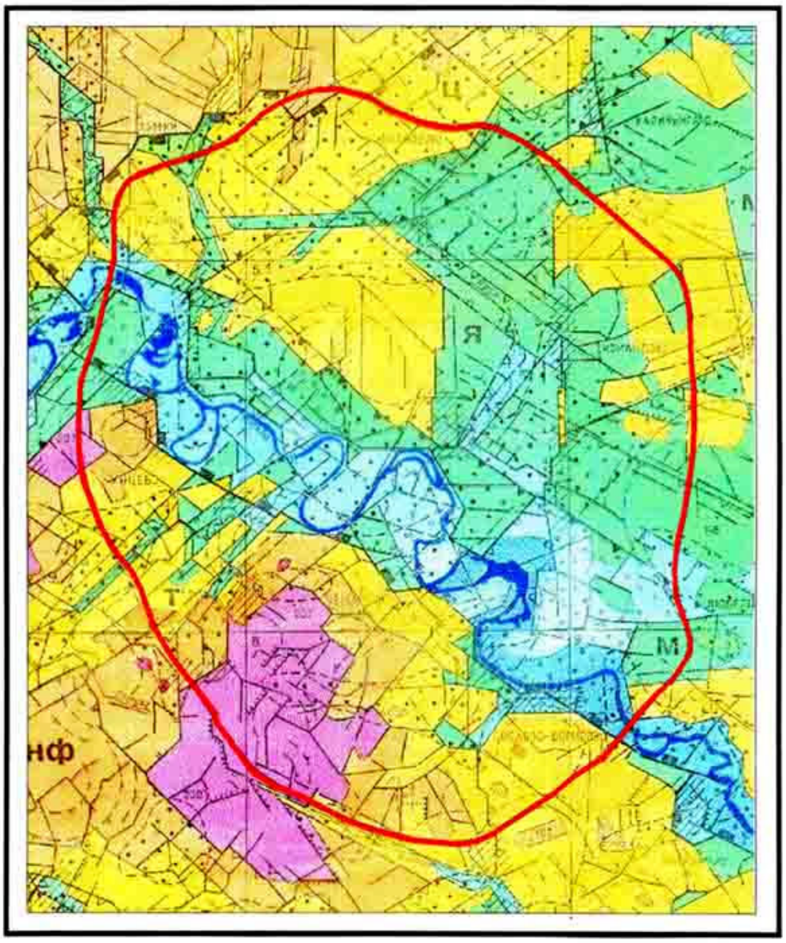


**Figure 2.** Structural geodynamic map of Moscow (see text for designations)

The boundary linear zones dividing the blocks rather than the blocks properly are most interesting from the engineering geological standpoint. These are geodynamically active linear zones related to the planetary stresses existing in the earth's crust (Nesmeyanov 2000). Due to stress concentration, the rocks within these zones are highly fractured, karstified, weak, and prone to erosion. Hence, the blocks boundaries represent highly permeable zones, along which gases and fluids ascend from the earth's bowels to the surface. Within these zones, the elevated concentration of radon, helium, and hydrogen is registered, as well as various geochemical anomalies in ground water. Therefore, these areas may be regarded as potentially geopathogenic zones. However, actual facts are needed to prove their pathogenic effect.

## ANCIENT EROSION CUTTINGS

Ancient river valleys, i.e., erosion cuttings, formed during the continental stages of geological development of the territory, and occurring in a buried state now, play an important role in urban planning and construction. We distinguish PreJurassic paleovalleys with the cutting depth reaching 40 m as related to the modern river network, and two generations of the preglacial paleovalleys, i.e., Tatarovskaya and Khoroshevskaya paleovalleys, with the depth of cutting up to 20 m. (Figure 3). From the geological viewpoint, paleovalleys (preglacial paleovalleys, in particular) are of interest in two respects (Kutepov, Osipov & Kozhevnikova 1999; Osipov 2000). First, the Jurassic clay dividing the two above-mentioned water-bearing complexes appears to be completely eroded within these valleys. This produces the so-called “hydrogeological windows” connecting these two hydrogeological complexes, through which the artesian aquifers are contaminated with the above-lying groundwater.

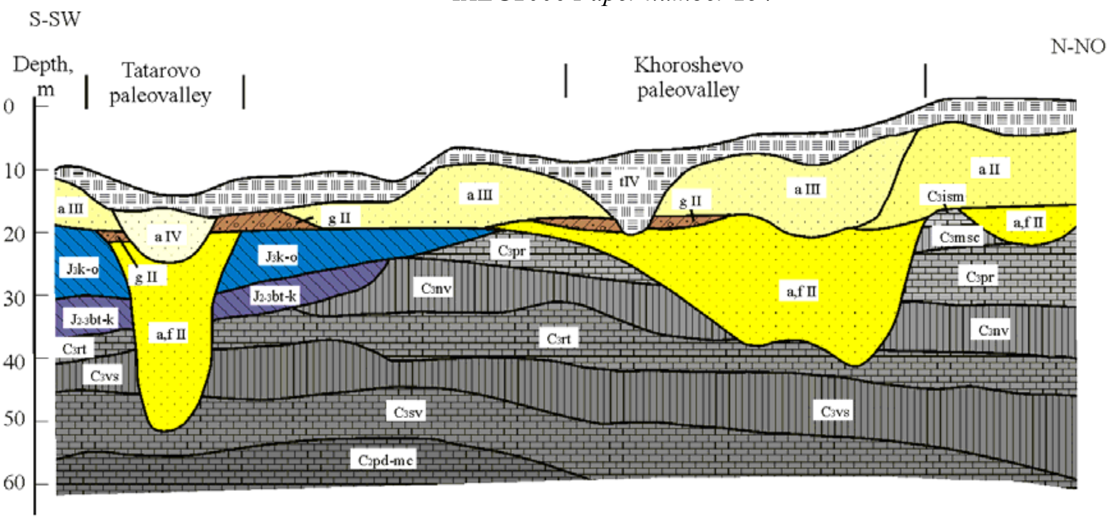


**Figure 3.** Geological cross-section of the central part of Moscow

Unfortunately, the degree of potable groundwater protection has never been taken into consideration upon urban planning. Therefore, the engineering objects polluting groundwater, e.g., petrol stations, when located above these "hydrogeological windows", will contaminate deep aquifers.

Also important is the fact that the ancient erosion valleys are as a rule filled with fine silty sand, which easily acquire quick-sand properties. It often causes difficulties upon subsurface construction, especially, upon laying underground tunnels, in case the construction route crosses a paleovalley. It may even result in emergencies, as it happened, for instance, upon the construction of the "Borovitskaya" underground station in Moscow. This accident resulted in the deformation of the building of the Lenin's library and neighbour buildings. This was also the reason for the emergency situation in the subway tunnel between the "Lesnaya" and "Ploshchad' muzhestva" stations in St. Petersburg.

The collapse that happened in the B. Dmitrovka Street in Moscow on May 13, 1998, is also related to the ancient river valley, i.e., the buried right tributary of the Neglinka River. Upon driving a deep manifold pipeline under the thalweg of this valley, quicksand burst into tunnel to result in a collapse funnel on the surface. To say, similar geological conditions are revealed in other parts of Moscow, for example, at the Bol'shoi Theatre site. It should be especially taken into account now, when the project of the theatre reconstruction is under design.

Taking into consideration the important role of the buried river channels in the engineering geological conditions of Moscow, Institute of Environmental Geosciences of the Russian Academy of Sciences by the order of the Moscow Architectural Committee in collaboration with the Moscow Geological Trust for three years have been compiling the geological map of Moscow with the indicated ancient erosion channels under the guidance of Dr. V.M. Kutepov. The map was based on more than 24 thousand boreholes borrowed from the Moscow Geological Trust archives. This map appears to be the first map of the Moscow territory built to a scale 1:10 000, which meets the state requirements for the support with actual data. In this map, the ancient erosion network is mapped precisely for the first time, which is of great importance for urban planning and rational use of territory, as well as for planning engineering geological survey at particular construction sites.

## HAZARDOUS GEOLOGICAL PROCESSES

The strong economic impact of the city on the geological environment induces the intensification of many hazardous exogenous processes in urban area. Four processes pose the most serious danger for the urban development, i.e., karst, karst-suffosion, landslides, and groundwater level rise (waterlogging).

Karst in Moscow was studied for a long time (Kozhevnikova 1980; Kutepov 1980). Until recently, the karst-suffosion hazard was mainly discussed, which is spread at about 15% of the Moscow territory and is expressed in the possible development of sinkholes (collapses) at the surface. This problem is particularly acute for the north-western region of Moscow, where 42 karst-suffosion sinkholes have been formed for the last 40 years.

In recent years, an increasing volume of subsurface construction and erection of buildings with deep foundations demands for revealing karstified rocks lying at a depth of 15-20 m and deeper. These rocks are nonhazardous for the surface construction; however, they pose danger for the subsurface facilities. There is a well-known geological phenomenon: the slopes of river valleys (including paleovalleys) composed of soluble rocks are usually affected by karst. Hence, the data on the accurate position of ancient erosion channels gives us a key to learning regularities of karstified limestone distribution. Even now we may say that the most karstifed areas in Moscow border the ancient river valleys. Proceeding from this fact, as well as from geological conditions and numerous borehole data, we may assess the karst hazard in Moscow.

Landslides are widespread in the valley of the Moscow River and its tributaries. Fifteen landslide-prone zones where deep landslides are developed are distinguished within the city boundaries, the sliding surface of these landslides occurring at a depth of up to 100 m (Paretskaya 1971). These landslides usually manifest a rather complex structure. These are usually blocky bodies with a multistage structure. In addition, the banks of numerous tributaries of the Moscow River are often subjected to minor landslides (of mudflow type). Lately, an ever-growing number of investors aim at developing landslide-prone sites in construction and other purposes. However, the development of these sites is connected with high natural risk and is possible only after undertaking special engineering and other slope-stabilization measures.

Waterlogging appears to be one of the most widespread natural hazards in Moscow causing the greatest damage. It results from a rise in groundwater level to a depth of less than 3 m. At present, 29% of urban area occurs in a permanently waterlogged state, while 38 and 33% of area are seasonally waterlogged and not subject to waterlogging, respectively (Osipov & Medvedev, eds. 1997). Waterlogging causes huge economic damage to the city, giving rise to premature ruining and deformations of buildings, engineering structures, and subsurface pipelines; it also raises the seismicity of the area, and it significantly worsens the environmental conditions. According to the data of State Construction Committee of the Russian Federation, waterlogging of 1 ha of urban area causes damage ranging from 15 to 200 thousand US dollars.

The disturbance of natural balance between the percolation and groundwater discharge under the urban conditions is the main reason of waterlogging. The mean value of percolation alimentation is 1.5-2 times higher within the city boundary as compared to the country area. The water leakage from water-bearing pipelines constitutes a considerable share in percolation water recharge. Levelling of the urban surface and filling up minor river channels and gullies for construction purposes (which operate as natural drains) is also one of the causes of waterlogging.

## CONSTRUCTION UNDER GEOLOGICAL RISK

The above-discussed specifics of geological structure and natural hazards predetermine the existence of geological risk for construction within the Moscow territory. Urban development under these conditions should provide for the security of inhabitants and safety of urban infrastructure by the prediction of natural hazards development, undertaking the preventive measures and duly managerial decisions, as well as the insurance risk regulation, etc. (Osipov 2001).

The construction practice should proceed from the permissible risk concept. This means that the construction is allowed almost everywhere provided the appropriate measures are undertaken to mitigate the existing risk down to the permissible level. Therefore, urban development with the account of natural risk implies, above all, the economic expediency of developing sites of high geological risk. In doing so, the additional expenses for geological risk mitigation should be taken into account already at the early stages of construction planning, in order investors should be aware of the necessity for these expenditures from the very beginning. The map of city territory zoning according to the geological risk degree is required for this purpose. On the basis of this zoning, the entire territory of Moscow was subdivided into 5 types of areas differing by the geological risk degree, i.e.:

- extremely hazardous (2.3% of area);
- very hazardous (2.3 %);
- hazardous (26%);
- low hazardous (54%);
- nonhazardous (12%).

Proceeding from the permissible risk concept, the construction at the sites with geological risk should be accompanied by the risk-mitigation measures. This includes the soil and rock reinforcing, land drainage, slope stabilization, filling of karst cavities, etc. The cost of these measures may exceed 20-30% of the cost itself. Investors will have to pay 5-15% higher than the object for the construction in very hazardous territories, and 3-5% higher, for the construction in low hazardous areas as compared to nonhazardous areas.

## FURTHER RESEARCH

In conclusion, it would be appropriate to say some words about the future tasks. Two problems should be solved for the future urban planning taking into account geological risks, i.e., (1) monitoring of geological environment and hazardous processes; and (2) special geological mapping of the city territory and building large-scale engineering-geological and geoenvironmental maps.

The arrangement of monitoring system for natural hazards has already begun. In December 1994, the Moscow Government adopted the Decision on the organization of monitoring of geoecological processes in Moscow. The work on this decision implementation has already started.

Simultaneously, we should proceed to compiling a set of large-scale topical maps and GIS of Moscow geological environment. This set should include the following maps:

- a map of engineering geological zoning;
- a hydrogeological map;
- a map of karst hazard;
- a map of interrelation between aquifers;
- a structural geodynamic map, etc.

Compilation of a series of engineering geological maps to a scale of 1:10 000 will provide a new informational basis for urban planning and environment protection. These maps may be used in the further development of the general plan of Moscow, building an ecological map of Moscow, solving construction problems and rational use of the urban territory, as well as the prediction of geological hazards, the elaboration of risk-mitigation measures, and undertaking managerial decisions. In addition, these maps will permit experts to draw adequate conclusions on engineering survey at the particular construction sites.

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