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Radioecological studies at the Kraton-3 underground nuclear explosion site in 1978–2007: a review

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A B S T R A C T

Within this paper, radioecological data concerning the "peaceful" underground nuclear explosion Kraton-3, conducted at a remote Arctic location (65.9°N, 112.3°E) within the former USSR in 1978, are reviewed. The data and estimates published in the available literature sources before September 2008 could be grouped as following: (a) characterisation of the current radioactive contamination (γ-, β- and α-emitters) of environmental compartments in terms of radionuclides composition, activity concentration, area contamination density; (b) determination of current gamma dose rates in air, including mapping using GPS; (c) evaluation of cumulative gamma doses in air (with calculations and thermoluminiscence measurements in ceramic objects); (d) description of the visually distinguishable changes in the terrestrial ecosystem; (e) description and quantitative evaluation of morphological abnormalities in the organs of adult plants as well as in seeds and seedlings of some herbs and shrubs, and in small mammals; (f) application of countermeasures. Knowledge gaps and possible further studies are indicated.

1. Introduction

Four from a total of 81 so called "peaceful" underground nuclear explosions (PUNE), conducted by the former USSR in the period 1965–1988 within the territory of the Russian Federation, were recognized as accidental events and resulted in long-term radioactive contamination of local ecosystems (Kasatkin et al., 2004; Myasnikov et al., 2000). These explosions had code-names: Globus-1, Taiga, Crystal, and Kraton-3. The most dramatic and severe event was the Kraton-3 PUNE that occurred near the Arctic circle (latitude 65.9°N, longitude 112.3°E) in a remote area (Fig. 1) of Yakutia (the Republic of Sakha) in 1978. Due to technological mistakes and the fact that a borehole mouth was not sufficiently sealed (Burtcev and Kolodeznikova, 1994, 1997; Logachev, 2008; Myasnikov et al., 2000), the secret experiment resulted in an accidental release of radioactivity into the atmosphere and radioactive contamination of the surrounding terrestrial ecosystems. The following year, acute biological affects (mortality), presumably arising from exposures to ionizing radiation, were observed in the trees and bushes in the forest adjacent to the Kraton-3 technical zone (Burtcev and Kolodeznikova, 1994, 1997; Miretsky et al., 1997). Although the large "hot" spot with radiocaesium contamination of unknown origin had been "discovered" by Yakutian geologists during a routine aerial gamma survey in 1984 (Koltin, 1993), the regional authorities only obtained the first official data on the explosion and its consequences in 1990 (Argunova, 2004). As the site represented a potential long-term source constituting a health hazard for the local human population, the Government of Yakutia initiated complex radiological and radioecological studies in June–July 1990. Before 2008, different institutions and organizations conducted more than 25 expeditions to the site itself and to the adjacent areas. Within this paper, the major radioecological data and estimates concerning the Kraton-3 PUNE that have been published in the available literature sources are reviewed.

2. Some characteristics of the area and explosion

The Kraton-3 site is located within an uninhabited area of Western Yakutia, approximately 40 km east of the nearest

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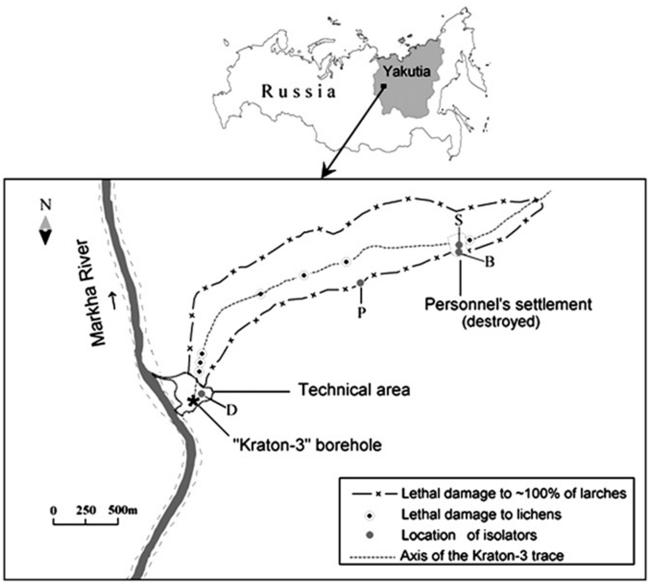

Fig. 1. Location of the "Kraton-3" area in Russia. Exact geographical position of the "Kraton-3" borehole is: latitude 65°55.66′ N, longitude 112°20.04′ E. This sketch map of the "Kraton-3" site shows the projected area of the "dead forest" with the spots where dead epigeic lichens were found and the location of porcelain isolators used for retrospective dosimetry. See the text and Table 3 for details.

settlement of Aikhal. The area under study (for details see Chevychelov and Sobakin, 2004; Mikulenko et al., 1999, 2006; Ramzaev et al., 2004, 2007c) belongs to the cool temperature zone (permafrost area). The average annual temperature is circa −12 °C. The underlying geology is characterised by sedimentary flat carbonate rocks and the average altitude of the plateau table is approximately 300 m above sea level. The area is dominated by sod-carbonate slightly alkaline soil of pH 7.05–8.45 (Burtcev and Kolodeznikova, 1997; Chevychelov and Sobakin, 2004; Petrovsky and Koroleva, 2002). The total amount of annual precipitation is low, ranging between 250–400 mm. The site (Fig. 1) is located on the right bank of the Markha River (a tributary of the Viluy River) within the North-East Siberian Taiga (boreal forest) with a high predominance (up to 96%) of larch (*Larix gmelinii*) (Petrovsky and Koroleva, 2002). Generally, sparse growth of trees is observed. Understorey vegetation is characterised by bushes and shrubs (mainly *Salix* spp., *Dasiphora fruticosa, Vaccinium uliginosum* and *Betula* spp.), herbs, grasses, mosses (*Aulacomnium acuminatum*) and lichens (*Cladonia* and *Cetraria* spp.). A thick lichen-moss carpet covers a major part of the ground surface.

The PUNE Kraton-3 was conducted at 3 a.m. (local time) on August 25, 1978 for seismic sounding of the Earth's crust. The depth of the bore-hole was estimated to be about 584 m (Mikulenko et al., 2006). The device was detonated at a depth of 577 m, and the energy output was equivalent to about 22 kt of TNT (Myasnikov et al., 2000). Mikulenko et al. (2006) present a somewhat smaller explosive power, i.e. 19 ± 1.5 kt. An unknown proportion of products from the explosion reached the earth surface via the destroyed bore-hole shortly after detonation and formed a radioactive plume (Logachev, 2005). Besides radioactive noble gases, the plume contained the volatile radionuclides ^{131}I, ^{140}Ba + ^{140}La and the refractory radioisotopes: ^{141}Ce, ^{106}Ru, ^{95}Nb, ^{95}Zr, as well as ^{134}Cs and ^{137}Cs (Burtcev and Kolodeznikova, 1994). The cloud of radioactive debris was dispersed downwind in a northeasterly direction, and twelve minutes after the detonation, the plume passed over a temporary settlement (about 2.5 km from bore-hole, see Fig. 1) where the participants of the experiment were staying. Despite an urgent evacuation precipitated by extremely high gamma-dose rates in air of more than 2 Gy per hour (Dubasov and Kasatkin, 2000), the personnel received up to 300 mSv of acute external irradiation (Logachev, 2001, 2005, 2008). Contamination of the ground occurred by wet deposition (Antonov and Dekhtarenko, 1999; Chomchoev, 1993). The initial length of the radioactive trace was reported to be 31 km, and its maximum width was about 1.5 km (Antonov and Dekhtarenko, 1999; Burtcev and Kolodeznikova, 1994; Logachev, 2001).

It is worth noting that in 1974, another PUNE (code named "Crystal") was conducted in the study area (Myasnikov et al., 2000; Ramzaev et al., 2007c). The site of the Crystal PUNE (latitude 66.5°N, longitude 112.5°E) is located near the town of Udachny, about 60 km north of the Kraton-3 site. The Crystal PUNE also resulted in significant radioactive contamination of the environment by long-lived radionuclides. The radioactive traces of these PUNEs do not overlap one other, and therefore in principle, Crystal and Kraton-3 explosions and their consequences might be reasonably treated as spatially separate events with respect to terrestrial ecosystems. At the same time, as the Crystal site is located within the Daldyn River basin (a tributary of the Markha River), it is difficult to distinguish the contribution of each source to the radioactive contamination of the Markha River ecosystem downstream from the confluence of the Daldyn and Markha rivers.

3. Alteration of forest ecosystem and other biological effects

In June 1979, it became clear that the trees and some bush species had been killed over an area covering approximately 1 km^2 (Burtcev and Kolodeznikova, 1994; Miretsky et al., 1997). In 1990, mortality effects were observed for grasses and even for relatively radioresistant lichens and mosses (Gedeonov et al., 2004). The sum of these phenomena, reported for the Kraton-3 site, is commonly referred to as "dead forest" (Burtcev and Kolodeznikova, 1994; Gedeonov et al., 2002, 2004). In the years following the turn of the millennium (early 2000s), the length of the "dead forest" area was about 3.5 km, and its maximum width was 600 m. A sketch map of the "dead forest", as well as aerial and on the ground photos from the area are given in the published literature (Ramzaev et al., 2004, 2007c; Ramzaev and Göksu, 2006). A collated sketch map of the site is given in Fig. 1. Newly formed vegetation cover consists of bush and shrub plants (*D. fruticosa*, *Salix* spp., *Betula* spp.) and micro-groups of grasses (*Poaceae* spp., *Carex* spp.) and herbs. Among herbs, *Campanula langsdorffiana, Chamaenerion angustifolium* and *Gentiana barbata* were reported (Petrovsky and Koroleva, 2002). In 2001–2002, young larches of different ages (2–20 years) were mostly found on some spots occupied by dead epigeic lichens (Ramzaev et al., 2004) that are located exclusively on the axis of the radioactive trace (Fig. 1). The major part of dead lichens decayed in the period 1993–2007, but some residuals of *Cladonia* lichens have served as a substrate for the development of regenerating lichens (Ramzaev et al., 2007b).

Besides lethal and recovery-compensation effects, some morbidity alterations and deviations from normality have been observed in plants that have survived or have re-established, in the area. These observations included: partial loss of needles and dryness of the main branches and apexes of larches (Ramzaev et al., 2004), increased levels of fluctuating asymmetry of the leaves of some bush species (Shadrina et al., 2004), morphological abnormalities in flowers and seeds of the herb *C. langsdorffiana* and the shrub *D. fruticosa* sampled in the "dead forest" and the Kraton-3 technical area (Batygina and Titova, 2003).

The seeds that were collected from some plant species grown at the control and contaminated areas at the Kraton-3 site have been used to study the germination of seedlings under laboratory