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A Geoinformation system for estimating the hazards of catastrophic volcanic eruptions

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Abstract. Researchers from the Laboratories of Geoinformation and Petrology are engaged in developing a geoinformation system, named "Volcanic Hazard", for the purpose of predicting volcanic hazards over the territory of Russia. The system enables the user to match digital maps of different scales to see specific patterns in the spatial and tectonic settings of the volcanoes, their morphology and structure, to collect and accumulate information on changes in their states, and to model volcanic situations for the purpose of assessing the hazards of catastrophic eruptions. The choice of software for the system was guided by its comparative simplicity and low cost.

Introduction

Geological processes interfere actively in human life. Earthquakes, tsunamis, and volcanic eruptions have been and remain to be the leading natural risk factors for man and his environment. A striking example of natural catastrophes associated with volcanic activity is the explosive eruption of Krakatoa Volcano in 1883. According to the estimates available, more than 18 km^3 of a rock and ash material were ejected to the air, which covered an area of about 827 000 km^2. The loss of life was ~36 000. The fine volcanic ash rose to the stratosphere, which resulted in the several-degree decline of the average annual temperatures over the extensive territories of the Earth. The list of examples can be continued by a Tambora explosion in Indonesia (1815–1816), where ~150 km^3 of a rock material were ejected to the air, a caldera 6 km across was produced, and the loss of life ranged between 66 000 and 92 000. The lahars produced during the eruption of Ruis Volcano (1985) demolished Armera City with the population of ca. 26 000 people, situated at a distance of 45 km from the volcano. The eruption of Pinatubo Volcano on the Philippines (1991) destroyed two US naval military bases and a few settlements situated at the foot of the volcano. The eruption of Katmai Volcano in 1912, which is believed to be the greatest catastrophe of the century, though without loss of life, was accompanied by the ejection of the huge amount of ash, the particles of which rose into the stratosphere, which resulted in the weakening of the solar energy and in a climatic change on the whole of the planet. It should be emphasized that volcanic eruptions are often preceded or accompanied by earthquakes of various, sometimes very high, magnitudes, causing additional natural disasters.

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In the recent years, particular attention has been given, both in Russia [*Bogatikov et al.,* 1998a, 1998b] and in other countries [*Goward et al.,* 1982], to the integrated study of potentially active, dormant volcanoes, which can suddenly become active with catastrophic consequences for people, natural environment, and climate. Examples of such renewed activities are the eruptions of Bezymyannyi (1956) and Akademii Nauk (1997) volcanoes in Kamchatka, Russia, and of Mount St. Helens (1980) in USA, which had been ranked as extinct volcanoes. Their unexpected eruptions were accompanied by the ejection of huge volumes of volcanic materials, which caused enormous damage (billions of dollars in the case of the Mount St. Helens eruption). The US Geological Survey initiated the monitoring observations of 16 dormant volcanoes in the states of Washington, California, Hawaii, and Alaska, and also of volcanoes in Iceland, Guatemala, Salvador, Nicaragua, and Equador, in cooperation with local scientists. As to the territory of Russia, the active and potentially active (dormant) volcanoes are the numerous volcanoes of the Kuril–Kamchatka Island Arc and the volcanoes of the Elbrus and Kazbek – volcanic groups in the Greater Caucasus.

By the present time a huge amount of data has been collected for the active volcanoes of the world and Russia, including data on the types, sizes, and dynamics of volcanic eruptions and accompanying phenomena. Theoretical aspects of volcanism have been elaborated concerning the tectonic settings of the volcanoes, magma sources, the chemical and mineral compositions of their lavas, and others. This work revealed some indications of the potential renewals of volcanic activities and the possibilities of predicting eruptions, in some cases with a high degree of probability.

Of great advantage over the conventional earth-based methods of study are remote sensing measurements and the photographic products of space missions because of their continuous observations, global coverage, and differential scales. They return infrared photographs, detect heat radiation, and record radiation beyond the infrared region of the spectrum. The results of the remote sensing of the Earth (RSE) can help to monitor the dynamics of volcanic eruptions and rapidly evaluate their sizes and environmental consequences. The huge flows of data require extensive computer processing. In this connection, the designers of the geoinformation system discussed (GIS "Volcanic Hazard"), aimed at predicting and assessing the hazards of catastrophic eruptions, made provision for the use of information obtained by remote sensing and space missions in addition to conventional geological surveys and volcanological studies.

GIS "Volcanic Hazard" Technology and Main Functional Tasks

The "Volcanic Hazard" Information System is aimed at the constant collection of data and their accumulation in the data base of Russian volcanoes, of the data on the states and parameters of the volcanic process (derived from the results of visual observations, earth-based instrumental surveys, and remote-sensing measurements) and at the interpretation and analysis of these data for the purpose of estimating the states of their volcanic activities.

The main technological characteristic of the GIS "Volcanic Hazard" is the storage of digital topographic, tectonic, geological, seismic, and other maps of different scales, representing the state of a volcano and the precursors of the potential renewal of its activity (earthquakes, changes in ground surface tilts and in heat flow, the emergence of new hot springs and fumaroles, etc.).

The GIS technology offers the user the following options:

– perform a stratified analysis of the files of the cartographic data represented in the above maps in the form of digital images (factor maps). Using a particular interface of the system one can derive any attributive information of interest to a volcanologist from the data base;

– superpose the layers of the cartographic information in different combinations to assess the state of the volcano for a certain period of time;

– perform a paleoreconstruction of the volcano;

– derive an integral digital model of the volcano or of its volcanic group.

The principle of manipulating and managing the data stored in the form of the topical layers, geographically fixed on a topographic base map which is an information basis of the GIS "Volcanic Hazard", allows the user to perform the following operations:

– accumulate and systematize the information of the volcanoes, stored in their certificates (data on the types, morphology, time, dynamics, size, and products of volcanic eruptions, on the phenomena that preceded or accompanied the eruption, and other factors), that is, to create data bases containing the unified records of single volcanoes and volcanic groups, geological data, digital topographic data, and the results of remote sensing and space missions;

– create an array of the digital air and space photographs of the volcanoes and of the results of their interpretation;

– accumulate and analyze the data available on the state of the volcano, including the results of remote sensing, and compare them with the conventional precursors and other indications of the renewal of volcanic activity;

– estimate the probability of the volcano's eruption;

– perform the multifunctional transformation of spatially coordinated data and derive the integral digital model of the volcano for a certain period of time;

– use data on the states of the volcanoes of Russia and the world using the Internet information system.

The GIS "Volcanic Hazard" enables the user to formulate and demonstrate the solution of some scientific and practical problems for the purpose of refining the existing criteria of volcanic precursors and searching for new ones, to perform the paleoreconstruction of a volcano, to estimate the area and volume of the erupted material, and to compare individual volcanoes and volcanic groups. For example, a new digital (vector) geological map for the Elbrus volcano (scale 1:100 000) was used to estimate the areas and volumes of its age-varying igneous rocks. The analysis revealed that the Holocene lavas covered an area of $\sim$100 km^2, which is significantly larger than the areas of the Pliocene (60 km^2) and Pleistocene (60 km^2) lavas, and had a volume of $\sim$30 km^3. The volcanic products of the Late Pliocene catastrophic eruption of Elbrus had propagated over the distances of hundreds of kilometers from the volcano [*Lavrushin et al.,* 1998].

The products of the recent areal volcanism of the Northern Group of Kamchatkan volcanoes (excluding the products of the catastrophic ash eruptions) cover an area of 3761 km^2 (Figure 1), 2.9% of which (109 km^2) were erupted by Klyuchevskoi Volcano. The volcanoes surrounding Lake Kronotskii (Figure 2) are concentrated as a semicircular structure over an area of 2654 km^2. This structure is made up of 16 volcanoes and the products of their eruptions, which account for 19.5% ($\sim$ 530 km^2) of the area. With the addition of the area occupied by Lake Kronotskii (which is believed to be a caldera of an older volcano) the area of the volcanic cones increases to 29%, measuring about 770 km^2. These examples show that the areas covered by the products of one volcano in Kamchatka (Klyuchevskoi) and in Caucasus (Elbrus) are roughly identical in spite of their different ages.

The GIS "Volcanic Hazard" offers the user the opportunity of using different digital cartographic materials, namely, the topographic, geomorphologic, geotectonic, petrochemical, and other maps of volcanoes, refined through the in-

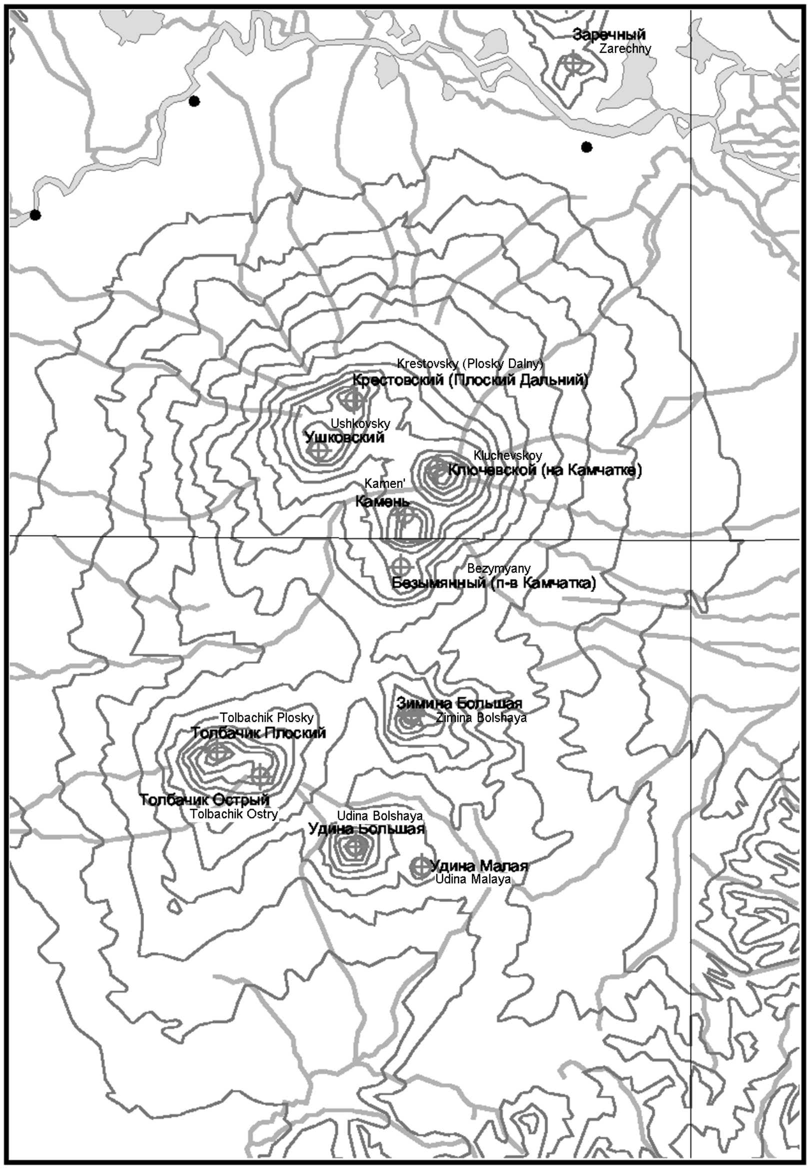

Figure 1. Northern group of Kamchatkan volcanoes (digital map).

tegrated interpretation of remote sensing data, as well as special-purpose maps containing evidence of the volcanic activities of individual volcanoes and their groups. The computer analysis of these data with the separation of maps into layers of uniform information enables the user to synthesize new maps from the factor layers available for the purpose of predicting new catastrophic eruptions.

The arrangement of and access to the data stored in the system both in the outer memory units and in the computer memory, as well as all references to the data arriving from the user's programs and from the other components of the system, are controlled by the data management subsystem. The other GIS subsystems are intended to

– access the state of volcanic hazard;

– analyze the indications of the reactivation and development of volcanic activity;

– access the potential consequences of volcanic eruptions.

Structural Arrangement and Software of GIS "Volcanic Hazard"

The block diagram of the GIS "Volcanic Hazard" allows for the use of three work stations (WS) for inputting and processing various kinds of data with the possibility of their identification on maps, updating, and transfer (see Figure 3).

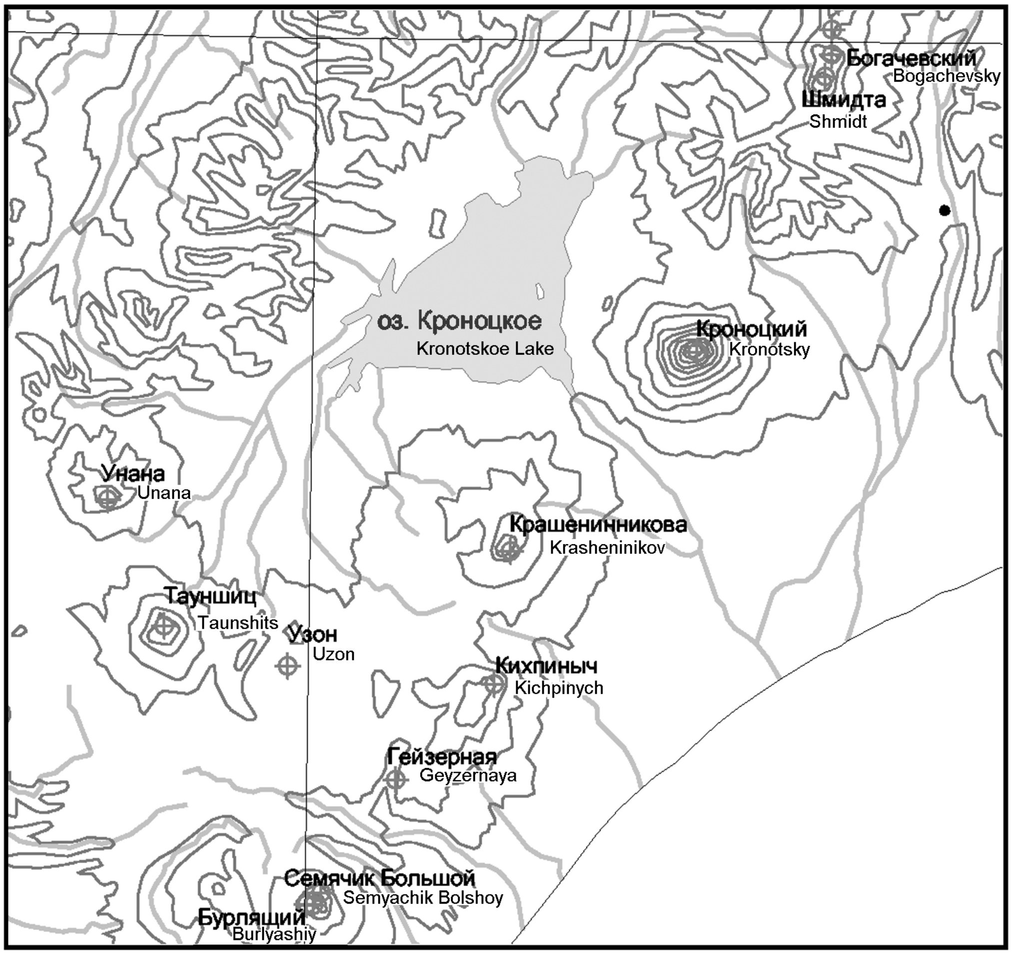

Figure 2. Volcanoes of the Lake Kronotskii semicircular structure (digital map).

The GIS operator's work station is designed to input and process data, to prepare and update the data bases of the certificates of volcanoes, to model volcanoes and volcanic processes, to solve the applied problems of assessing volcanic hazards, and to provide reference information for the user.

The work station for processing remote sensing data is intended for the decoding and interpretation of aerospace information.

The structural core of the GIS "Volcanic Hazard" is a server controlling the data resources and operation modes of the whole system. It also stores digital maps (topographic, tectonic, geological, and others) for various volcanic areas and individual volcanoes of Russia from 1:1 000 000 to 1:100 000 and larger scales and transmits them to the work stations. The server incorporates means for remote (telecommunication) data processing. Recently a remote (Essentuki City) work station for the formation and updating a local data base for Elbrus and Kazbek has been linked to the GIS "Volcanic Hazard" via Internet (using the system of the "Mineral" Center) [*Laverov et al.,* 1997], as the first step of creating a distributed system.

The technology of the GIS "Volcanic Hazard" allows one to use the Windows 95 and 98 operation systems and process scan patterns exceeding the RAM of a computer. The user can choose any algorithm of scan transformation (magnification, reduction, and matching) and has access to the vector unit of the geoinformation system via a file structure.

Each work station includes a Pentium III PC with a frequency of 800 MHz and a random-access memory of 128 megabytes, input units (digitizer and scanner), a laser printer, and a fax-modem to communicate with global information networks. The server is also based on a Pentium III computer with an operation memory of 128 megabytes.

The use of a GIS-technology based on the hardware including personal computers requires the use of known operation systems and applied software packages with an environment, e. g. such as Arc Info, Arc View, and Arc SDE. The basic software of the GIS "Volcanic Hazard" includes ArcInfo 3.5.2 and ArcView GIS v.3.2 for Windows, chosen for the simplicity of information exchange with domestic and foreign information systems dealing with volcanism. The software can be adapted for particular problems to be solved by the system with the creation of the user's supplements using conventional programming languages. Geographical coordinates are used in the main operation modes.

The well-known Access 2000 program is used to control

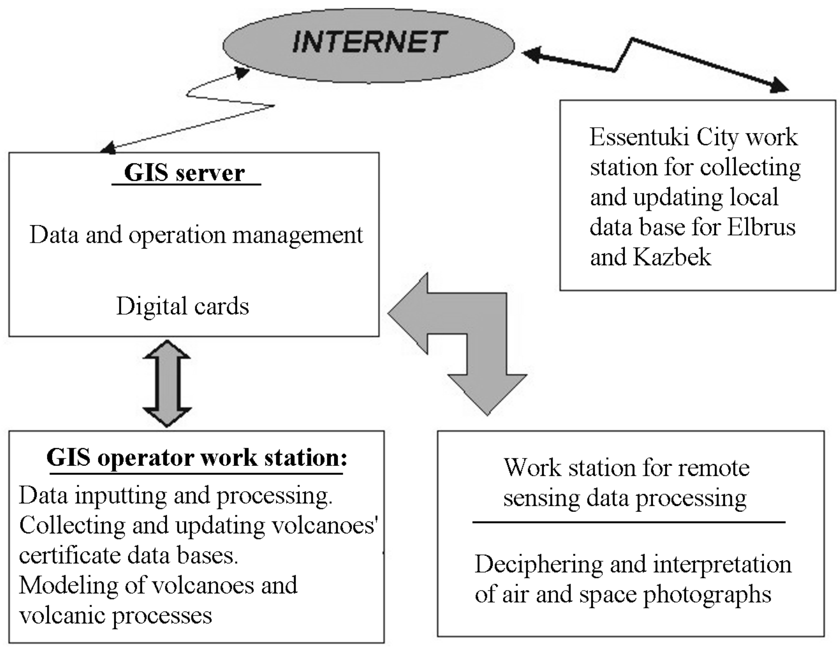

Figure 3. Structure of the GIS "Volcanic Hazard."

the factographic data base for accessing the hazards of volcanic eruptions.

The GIS "Volcanic Hazard" applied software package consists of the following five subsystems:

– data input and verification;

– data storage and data-base management;

– data output and representation;

– data transformation;

– interaction with the user.

The data transformation subsystem includes a block for the cartographic and analytical modelling of a volcanic situation. An important property of this unit is the ability to provide a 3-D description and representation of a volcano, necessary for the analysis of its state. The basic programs used in 3-D digital modelling are the GIS programs, such as ArcInfo and ArcView with the units of ArcView 3D Analyst, ArcView Spatial Analyst, MapInfo, and GeoGraph.

The GIS "Volcanic Hazard" has the following standard characteristics:

– the input of cartographic information is performed mainly in a vector form using a digitizer and in a scan form using a scanner;

– the factographic database is compiled using the arrays of data recorded on optical and magnetic memory disks;

– the data are retrieved from the system to printers of various types in a black and white or a multicolor form; the information recorded on optical and magnetic memory discs is transmitted in a network mode over commutated telephone communication channels and to the Internet;

– the modeling of volcanic situations requires the layer-by-layer representation of factographic data reflecting the indications of the renewals of volcanic activity. This information is supported by factographic data (georelation models) containing the results of visual, earth-based instrumental, and aerospace observations.

Structure of the GIS "Volcanic Hazard" Data Bases

This system is able to store, edit, update, and distribute a great variety of data (tables, maps, air- and space photographs) for volcanic belts and individual volcanoes. Data arrive in a digital form and are tied to the geographical coordinate system. This enables the user to integrate the data arrays of different contents, necessary to estimate the state of the volcano of interest.

Structurally, the GIS "Volcanic Hazard" consists of the main data base, residing in the Institute of Ore Deposits, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences (Moscow), and the data arrays stored at remote terminals (work stations). Instructions and software packages are sent to the sites of volcanic hazard monitoring located in the vicinities of active and potentially hazardous volcanoes. All information which is accumulated in the main data bank and at the local work stations constitutes a collection of attributive data, digital maps, air and space photographs, and the results of remote sensing, which are arranged into the following data bases:

– volcanoes of the world;

– the passports of active volcanoes of Russia;

– the indications (precursors) of the volcanoes' reactivations;

– air and space photographs;

– evidence derived through Internet.

The data base management and the integration of data in response to the arriving inquiries are accomplished by the GIS server which transmits the required information to the regional organizations via Internet.

Information Resources of the System

At the present time the system contains about 40 digital maps of various scales and contents and numerous photographs. Based on these materials, a demonstration film was made, reflecting the main features of volcanic processes in the Greater Caucasus (Elbrus and Kazbek volcanic groups) and Kamchatka.

The main part of the system's data array consists of the graphic and attributive data of the federal digital topographic maps, scale 1:200 000. In the case of Caucasus this is a collection of 41 sheets embracing the territory of 40° to 44°N and 39° to 48°E. The system also includes vector topographical maps, such as a Digital Chart of Russia (1:3 000 000) and a Digital Chart of the World (1:1 000 000), and also a Geological Map of Russia (1:2 500 000), and fragments of maps for Russia and the adjacent territories of various contents: a gravity map (1:1 000 000) and a heat flow map (1:1 000 000).

To facilitate various analyses and modelling, the vector maps contain stratified attributive information. For instance, the geological map of Elbrus Volcano, based on a topographical map of scale 1:100 000, is stratified into layers reflecting the volcanic history of the volcano in the Pliocene, Pleistocene, and Quaternary. On this basis models of the volcano were derived for these periods of time [*Bogatikov et al.,* 2000].

The semantic information of the system is represented by individual files containing information depicted in the digital charts and their individual "layers". Using the interface of the system the user can retrieve a particular file using a respective digital map or its layer displayed.

The digital topographic maps are supplemented by maps of various contents including the maps of instrumental earth-based (seismic) surveys and space photography. The space data for the territory of the Greater Caucasus with its Elbrus and Kazbek volcanic groups were recorded in 2000 by the Ocean-O No. 1 spacecraft using an MSU-SK equipment.

The scan maps of the system show the tectonic positions of the Greater Caucasus and Kamchatka volcanoes, and also the morphology and geographic distribution of volcanoes in the Kamchatka volcanic belt. Numerous maps and photographs illustrate the particular patterns of the Klyuchevskoi, Shiveluch, and Karymskii eruptions and the formation of New Tolbachik volcanoes (Great Tolbachik Fissure Eruption).

The GIS "Volcanic Hazard" contains data on the precursors of volcanic eruptions and on the methods of their monitoring. It includes the photographic images obtained as a result of the interpretation and photogrammetric processing of the remote-sensing observations of the Klyuchevskoi, Bezymyannyi, and Malyi Semyachik volcanoes [*Dvigalo et al.,* 2000]. The system illustrates the particular patterns of earthquakes that precede volcanic eruptions (earthquake swarms, volcanic tremor). A digital map is presented for Elbrus Volcano, which depicts the positions of hot springs in the saddle between its western and eastern cones and maps the area of the rocks altered by the recent and present-day solfatara and fumarole activity. A space-returned photograph illustrates the thermal field of the volcano. A scan map shows the distribution of floods that may be caused by the potential renewals of Elbrus and Kazbek volcanic activity.

The data base "Certificates of Russia's active volcanoes" includes the records of 75 active volcanoes from the Greater Caucasus, Kamchatka, and the Kuril Islands. The form of a certificate was worked out proceeding from the present-day view that the type of the volcano remains the same irrespective of the time of its eruption. Therefore any evidence of the historic evolution of the volcano is important for estimating its present-day state and the consequences of its potential eruptions. The certificate consists of four data blocks (Table 1):

– general data: name, topographic elevation, geographic coordinates, geographic position, geomorphologic setting, type, and the main series of its igneous rocks;

– historical data on previous eruptions: the type, kind, and size of each eruption; the direction of the propagation of eruption products, the morphology of the newly formed cones and their sizes; the evidence of the phenomena that preceded and accompanied the eruptions;

– consequences of each eruption: the types, composition, and volumes of its products;

– present-day state of each volcano: the crustal structure of the region (depths of the asthenosphere, Benioff zone, and intermediate magma sources);

– geological structure of the basement; the morphology of the volcano and the sizes of the major elements of its cone; indications of the present-day activity: solfataric and fumarolic activities, hot springs, heat flow, etc.; ice cover.

The data-base fields are connected through their common fields. Data on any dynamics in the state of a volcano can be added. The certificates were compiled using numerous literature [*Active...,* 1991; *Aprodov,* 1982; *Catalog...,* 1957], to name but a few, and an Access 2000 program.

The system also contains a "Volcanoes of the World" data base which includes 2300 active and potentially hazardous volcanoes with their geographic coordinates and brief characteristics [*Aprodov,* 1982; *Volcanoes...,* 1994]. This data base is supported by the cartographic data presented in the topographic map of the world (DCW). These data bases interact through the Arc View program, v. 3.2.

The "Volcanic Hazard" system is technologically open for new data bases; new fields can be added to the tables available, the data bases can be updated, and the production of the hardware and software of the system can be upgraded.

The system can be upgraded by way of adding a module for the computer interpretation of air and space photographs. This will provide new information of the Earth's lineaments that control the distribution of volcanic regions, refine the positions of faults, and map blocks with different fracturing patterns, this information being extremely valuable for the regions of recent and present-day volcanic ac-

Table 1. Form of a Volcano Certificate

Main characteristics	Supplementary characteristics
General information	
Volcano's name Alternative name Topographic elevation Coordinates Category Name of volcanic group Geographic position Geomorphologic environment Type of volcano Main igneous rock series	
Eruption data	
Date of eruption Preeruption state Eruption type Eruption kind Eruption magnitude Eruption site or name Trend of eruption material propagation Morphology of newly formed structures Size(s) of new structure(s) Eruption dynamics Activity before eruption Activity during eruption	
Consequences	
Types of erupted products	
Amount of erupted products	length thickness height volume
Composition of erupted products	petrography size of fragments color of gas–ash clouds
Modern state of volcano	
Tectonic setting	
Crustal structure	mantle–crust blocks gravity asthenosphere Benioff zone peripheral magma sources
Geothermal state of surrounding rocks	
Basement	
Structure	morphology caldera crater sizes
Ice cover	position size
Precursors	fumarole activity solfatara activity hot springs heat flow

tivity. Stereophotogrammetric methods of study are known to provide valuable information on the precursors of catastrophic volcanic eruptions, such as changes in the state of active volcanic craters, in the growth dynamics of extrusive domes, and in lava-flow parameters [*Dvigalo,* 2000].

The prospects of the further development of the system include the use of remote-sensing data obtained by radiophysics methods in addition to the space photographs of the Earth's surface. This information will refine the evidence of the morphology, structure, and petrochemistry of the volcanoes and their products and will help to monitor the precursors of new volcanic eruptions [*Khrenov et al.,* 1999].

Conclusion

The "Volcanic Hazard" geoinformation system (GIS) is designed to collect, process, and transmit (including telecommunication means) data on the states of the active and potentially hazardous volcanoes located on the territory of Russia. The system includes three automated work stations where data bases are accumulated to store the certificates of the volcanoes of Russia and the world, remote-sensing data are processed, and space photographs are interpreted. The GIS server controls the information resources and operation modes of the system. It also accumulates and transmits to the work stations various (topographic, tectonic, geological, and other) digital maps for the volcanic regions and individual volcanoes of Russia. The server has means for remote (telecommunication) data processing. The first local (Essentuki City) work station, intended to form and update a data base for Elbrus and Kazbek is linked to the GIS "Volcanic Hazard" via Internet with the help of the GIS "Mineral".

The information resources of the GIS "Volcanic Hazard" include about 40 digital maps of various scales and contents, numerous photographs, grouped into a film and accompanied by necessary attributive information, and also data bases for the volcanoes of the world, the certificates for all active volcanoes of Russia, including the precursors of volcanic eruptions, air and space photographs, and data obtained via Internet.

The package of digital maps includes a recently plotted geological map for Elbrus (1:100 000) which is supplemented by maps of various contents including the maps based on the instrumental earth-based (seismic) surveys and space photographs of the volcano and adjacent regions of the Greater Caucasus.

To facilitate various analyses and modeling of the volcanoes and hazardous (catastrophic) situations, the vector maps are stratified into different information "layers". The semantic information containing the evidence depicted on the digital maps and their "layers" is represented as individual files. The interface of the system is able to call and retrieve a needed file if the respective map or its layer is shown on the display.

The use of the digital cartographic data arrays and data bases of the volcanoes allows one to use the methods of analogy in deriving the cartographic models of the volcanoes and real and hypothetical volcanic situations over the extensive territories of Caucasus, Kamchatka, and the Kuril Islands.

The continuous updating of the system will make it a good instrument for predicting and assessing the hazards of catastrophic volcanic eruptions.

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