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Thirty Years of Geological Investigations with the Use of Space Facilities: Trends, Achievements, and Prospects

V. G. Trifonov

Geological Institute, Russian Academy of Sciences, Moscow, Russia
e-mail: trifonov@ginras.ru

Abstract—The main achievements and development trends of geological investigations with the use of space facilities during the last 30 years are analyzed, including the study of the structure of the near-surface Earth crustal layer and deep lithosphere, quest for mineral deposits, and prediction of natural hazards and effects of recent geological processes. It is shown that some methods and techniques transformed into routine geological operations with the progress in facilities of space data acquisition and processing, while new opportunities and techniques were successful. The results of space-geological investigations that have promoted solution of important geological tasks are presented.

Keywords: processing of space information, geological structure, deep structural features, metallogenic prediction, oil and gas field, neotectonics, seismotectonics, earthquake prediction, engineering geology.

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INTRODUCTION

This work presents a review of the main trends and results of geological investigations with the use of space facilities following the materials published in the journal *Issledovanie Zemli iz Kosmosa* over the 30 years of its existence. Works in this direction began in the middle of the 1960s, with appearance of first images of the Earth's surface made by Soviet cosmonauts and American astronauts. Expansion of the works was stimulated by bulk arrival of pictures of Earth from artificial satellites. They were first used in geology for surveying, which was based on the rich experience of using aerial photography in geological mapping. Satellite images (SIs) stands out against aerial ones by a larger field of view and availability of multichannel images, which were assumed to be used for analysis of the structure of mineral rocks from their spectral characteristics. Even early SIs, especially low-resolution ones from artificial satellites, revealed new structural elements, i.e., straight line lineaments and ring or oval structures, which were not seen in ground-based surveying.

Promising directions and techniques for using SIs were sought in the 1970s. A limited circle of researchers was compensated by international cooperation beginning in 1971, i.e., the Soviet–American Working Group on Environmental Investigation with the Use of Space Facilities and, later on, the INTERCOSMOC Working Group. Two important peculiarities of geological information received from SIs have been revealed.

First, it turned out that some of the lineaments correspond to faults known from ground-based studies. SIs helped to detect them more accurately and reveal relationships between faults, which is important for understanding of their origin. Some oval-ring structures were identified as orogenic central type structures (CTSs). However, many more lineaments and oval structures were not identified with faults and CTSs and, moreover, were not revealed in regions for which they are irrelevant. Therefore, an assumption arose that lineaments are zones of uniformly oriented rock fracturing, increased rock porosity, or borders between regions with different geological structure; this was confirmed in field experiments. Comparison of lineaments and oval structures with the geophysical data has shown that these forms of Earth's surface can correspond to tectonic boundaries and bodies hidden deep under the sedimentary cover or crustal layers with different deformation styles. It should be noted that surface details become less evident and deeper structural elements manifest themselves with generalization of SIs (resolution degradation) (Makarov et al., 1974; Trifonov et al., 1978).

Second, geological objects and phenomena become less pronounced with time owing to erosion, weathering, accumulation of alluvium, superposition of other phenomena and objects, etc. Therefore, traces of the most recent geodynamic phenomena and geological formations are the most pronounced on the surface. Even if objects of the study were a fortiori old structures and rock units, their indirect young manifestations in recent diastrophic movements, relief, and fluid dynamics became their key diagnostic properties (Trifonov et al., 1973).

The above circumstances determined the following main directions in the use of space information, which more or less have remained urgent up to now (Trifonov et al., 1978; Kosmicheskaya s"emka, 1979; Sadov and Revzon, 1979; *Kosmicheskaya informatsiya…*, 1983):

—refinement of geological structure of a territory for geological surveying and topical structural-geological investigations;

—study of deep geological formations, i.e., objects hidden at more or less depth under other geological bodies;

—analysis of lineaments and ring structures for metallogenic prediction;

—distinguishing of hidden structures promising for oil and gas exploration;

—neotectonics and seismotectonics—landscape indication of the recent diastrophic movements, traces of recent and Late Quaternary earthquakes;

—hydrogeology and engineering geology—lineaments as elements of fluid systems and reflection of active faults impeding construction of engineering objects; slide and karst diagnosis; laying of underground communications.

In addition, the problem of geological data acquisition and processing was formulated at the beginning of space-geological research.

MAIN RESULTS OF GEOLOGICAL USE OF SPACE INFORMATION IN PUBLICATIONS IN JOURNAL *ISSLEDOVANIE ZEMLI IZ KOSMOSA* (1980–2009)

Methodological Successes of Space-Geological Works Against General Scientific and Technical Progress in Earth Exploration from Space

Development trends and achievements in the above directions of space-geological research were mainly determined by the general progress in the facilities of space information acquisition and processing:

—enhancement of SI resolution in common spectral ranges and use of new ranges (thermal IR and radar survey) with accessibility of materials in digital form for broad users;

—appearance of space geophysical survey materials (MAGSAT and so on);

—appearance and wide dissemination of satellite-based ground-object positioning systems, among which GPS became the leading one, and the similar Russian system GLONASS is developing now;

—appearance of accessible materials on 3D parameters of points of the Earth's surface, first with a resolution of about 500 m (DTM-500) and, then, of 3″ (FRTM), allowing a relief model with a scale of about 1 : 100000 to be constructed;

—development of computer engineering, first of all, personal computers, software, and information acquisition and transferring facilities.

As a result, a comprehensive analysis and comparison of geological-geophysical information contained in SIs and measurement results, relief models of different scales, and materials of ground-based investigations, updatable with new exact grid data, became possible and were implemented at the current level of knowledge and computer engineering. Special purpose software oriented to geological problems was developed.

As is known, there are two main approaches to recognition and detection of parameters of natural objects with space facilities: (1) an approach based on the brightness, color, and spectral parameters as the most complete information about an object, and (2) an approach based on geometrical parameters of an object in plan, i.e., its shape, internal structure, and so-called fabric—features of spatial combination of objects.

Multizonal space surveying accounting for spectral parameters of rocks was first considered as an instrument for geological mapping of compositional complexes and revealing ore rocks (Brukhanov, 1983). Field experiments allowed optimism. Thus, spectral parameters allowed detection of surface wallrock alterations as indicators of hidden ore reserves (Il'in, 1982). As was shown during the complex aerospace-geological experiment "Tien Shan—INTERCOSMOS-88", oriented to the study of active tectonic zones (Vedeshin et al., 1989), areas of active faults are revealed by their spectral parameters even under relatively thick diluvial cover owing to their break and, correspondingly, humidity, which is manifested in heavy metal-enriched vegetation as well (Lukina et al., 1991).

However, these developments were not widely used; in addition to labor intensity of remote spectrophotometry, there were two reasons. First, various effects on rocks and superimposed information (e.g., of soil or vegetation) change spectral parameters of rocks and often make them indistinguishable. The revealed anthropogenic spectral anomalies often exceed the contrasts between geological complexes (Karputz et al., 1991). Second, a geologist perceives information based on, first of all, texture and shape of an object. Therefore, geometrical parameters of objects were used in the majority of geological investigations with the use of space facilities (Trifonov and Shultz, 1986); they were the subjects of development techniques, and this trend became stronger with time.

Algorithms for automatic detection of lineaments and oval-ring formations in SIs were suggested in (Alekseev et al., 1988, 1993). Later on, the LESSA package was used for lineament detection (Baluev and Malkin, 1999; Shkarin and Shapovalov, 2006), and the original ALINA program was proposed for ring structures (Shchepkin et al., 2007).

Digital processing of lineament networks, understood as a set of all deciphered SI lines (straight, arc, and oval), was developed. The main successes in this field were connected with methodological studies by a research group headed by V.M. Moralev and O.G. Sheremet directed to improvement of the metallogenic prediction criteria (Sheremet et al., 1982a and b, 1983; Artamonov et al., 1986; Androsov et al., 1992; Sheremet and Moralev, 1993; Vasiliev et al., 1994; Moralev et al., 1995). The technique included detection of geometrical parameters of lineament networks (density and orientation of lineaments, features of their combinations) and their comparison with ore-bearing samples. The most informative features were selected and then used for prediction and ground-based check of new distinguished objects. The technique was improved during investigations. It was supplemented with the cluster analysis of lineament parameters with a quantitative approach to determination of the cluster sharing level (Sheremet and Moralev, 1993). Later on, the analysis was supplemented with fractal geometry methods, which allowed differentiation between clusters with different fractal dimension (Vasiliev et al., 1994). Comparison of cluster outlines with geological maps allowed precision of tectonic zoning and revelation of hidden differences in deformation styles. The technique was used at different scale levels—from Kamchatka to the northern part of Baltic shield, where the usefulness of accounting for tectonic zoning in the lineament analysis was shown (Androsov et al., 1992; Moralev et al., 1995), to the space geological map of the entire Soviet Union, 1 : 5000000 (Artamonov et al., 1986) and was oriented to different minerals, from nonferrous metals to gold and phosphorites. The technique was the most efficient in prediction of nonferrous and rare metals.

Another direction of automated processing of space information is connected with the use of digital relief models and their analysis along with SIs of a territory. The original Lineament program is oriented to the study of the recent tectonic structure; algorithms of some procedures on the basis of these models have been implemented there, including gradient calculation and analysis, smoothing, alignment, and different filtrations and types of separation (Zagubnyi, 2004; Govorova and Zagubnyi, 2006). I.V. Florinskii used digital relief analysis for detecting linear morphostructural features, characterizing mesoforms and development of the erosion-drainage system (Florinskii, 2008).

Main Geological Results of the Use of Space Information

An important *structure-geological result* obtained with the use of SIs is deciphering of the structure of complex dislocated regions of overthrust structure, i.e., the Eastern Caucasus (Budagov et al., 1985), Polar Urals (Kuznetsov, 1988), and southeastern Baltic shield, where such structures are hidden under the sedimentary cover (Nevolin, 1989). In all cases, a specific geometric image of thrust sheets—a complicated combination of arcs with different interior texture-brightness parameters—was their main indicator. Peculiarities of the object shape in SIs were also deterministic in the separation procedure for granitoids of different composition and metallogenic specialization, suggested by S.S. Shultz, Jr. (Trifonov and Shul'ts, 1986), and in identification of the structure of the Lambert Glacier region, Antarctica (Bud'ko and Shalaev, 1986).

By the end of the 1980s, the use of traditional space survey became a routine element in structural-geological investigations, and related methodical works were no longer published. The following methodical achievements were connected with the study of new spectral ranges. Various possibilities of using radar survey materials in geology purposes were shown near Pechenga, Norilsk, and Petropavlovsk-Kamchatsky (Rundkvist et al., 1994). The possibilities of using the IR survey data in the 12–14μm range for mapping large faults and thermal water deposits were shown in (Vilor and Min'ko, 2002).

In the 1980s, there were many publications about the spatial regularities and geological nature of *lineaments and ring structures*. The review (Makarov, 1981), based on previously published map of lineaments of USSR territory (Makarov et al., 1979), showed coincidence of lineaments with deep structural elements activated in the field of current planetary fracturing. Other researchers in later works shared the opinion about lineaments as reflection of such fracturing (Bondur and Zverev, 2007). In addition, relations of mobile belt lineaments with the regional field of recent tectonic stresses and large deep faults were validated in (Gonikberg, 1983; Baluev and Malkin, 1999) and (Karakhanyan, 1985; Makarov et al., 1994), respectively. A body of increased magnetization was revealed under one of the Belarusian lineaments by means of magnetic survey and magnetotelluric sounding; it pointed out to a correlation between the lineament and inhomogeneity of the crystalline basement (Astapenko et al., 1999).

Ring structures distinguished in SIs of bounded territories were interpreted in (Bush et al., 1983) as sections of permanent deformations of compression-rarefaction waves, propagating from a quasi-point source, on the Earth's surface. However, most researchers considered these rings and ovals as surface reflection of old isometric basement structures (Lopatin, 1981; Polkanov, 1982; Timurziev and Nugmanov, 1985), connecting there reflections in the relief and drainage network with neotectonic activization (Krotkova, 1988). A.T. Zverev and Ya.G. Kats, noting an increase in the density of ring structures with crust thinning, explained this by their deep location (Zverev and Kats, 1986). Some authors distinguished two groups among ring structures of Precambrian shields (Moralev and Clukhovskii, 1981), i.e., large structures 900–1200 km in diameter, considered as relicts of the oldest basins of volcanic-sedimentary lithogenesis, reflecting the primary divisibility of the lithosphere (the latest research knocked the bottom out of this hypothesis, showing primordial separateness of shield parts and significant lateral displacements, which distorted their original form), and structures of 50–400 km in diameter, which were formed by granite-gneiss domes and magmatic diapirs rounded by zones of ultrabasite-basic granulites.

An increased interest in lineaments and ring structures resulted in the 1980s in mapping of these morphostructure formations. The special issue of the journal *Issledovanie Zemli iz Kosmosa*, 1982, no. 2, was devoted to these maps and analysis of lineaments on the territory of the Soviet Union. It was prepared under the participation of such famous geologists as P. Bankvits (GDR), P.M. Gochev and Kh.B. Spiridonov (Bulgaria), J.F. Albear (Cuba), P. Kvet (Czechoslovakia), P. Khosbayar (Mongolian People's Republic), V.I. Makarov and S.P. Strel'nikov (USSR). Later on, similar works were published concerning territories of Poland and Eastern Cuba (Makarov et al., 1986), as well as maps of lineaments and ring structures of separate USSR regions (Belovtsev et al., 1982; Bilanenko et al., 1982; Gubin et al., 1988; Kuzin et al., 1990a). Finally, the largest lineaments were distinguished in Northern Eurasia (Lopatin, 2002). At least, their segments developed for a long period, and gigantic deposits originated at their intersections in periods of geodynamic activization.

The fact that the lineament network (broadly defined, including straight line, arcs, and oval-ring curves) reflects the deep structure inhomogeneities was the basis for studying the "deep lithospheric structure" with the use of SI information. Three megablocks were distinguished under the thick sedimentary cover and basement of the East European platform, separated by Early Proterozoic mobile belts; signs of a vortex structure were revealed within the megablocks, which are variants of large central type structures (Lopatin, 1981, 2000). The lineament analysis allowed outlining more local isometric structures, corresponding to Early Proterozoic plutons, near the Kursk magnetic anomaly (Trofimov et al., 1986). It was ascertained that lineaments correspond to deep borders between basement blocks of different density (Pugovkin and Kalashnikov, 2003). On the basis of earlier works (Makarov et al., 1974; Trifonov et al., 1978), it was shown that lineaments in the Alpine-Himalayan belt outline the cross skeleton frame of structures at different depths.

The paper (Vasiliev et al., 1999) was very important for development of the research on discrimination of structural elements of different depths. The authors presented the results of modeling the 3D block crustal structure of the Murmansk Massif in the Kola Peninsula. Lineaments deciphered in SIs of three levels of spatial resolution were analyzed. The revealed differences in block sizes, caused by different thicknesses and depths, were represented by an exponential function.

Conclusions of all the above works on the deep territory structure were based on the comparison between the results of lineament network analysis and geological-geophysical data obtained with the use of ground-based methods. The use of space-geological materials by means of transformation and numerical analysis of lineament networks for extrapolation of the results of ground-based geophysical works and drilling (Kirsanov et al., 1990; Kalinin and Terent'ev, 1992; Terent'ev, 1994) became a peculiar kind of turning point in this direction of research.

The use of satellite-based magnetic and gravitational survey data along with analogous materials of ground-based observations was a new step in the development of the direction under consideration. It was begun by D.V. Lopatin and his colleagues (Lopatin, 1996), and its continuation was presented in a number of publications, where new data from the MAGSAT, GEOS-3, and CHAMP satellites were used (Khassan et al., 2002; 2003; Kharitonov et al., 2004, 2007). The mantle was studied under different areas of the Earth. The most interesting results were obtained in the Pacific region. Here, variations in the density and magnetization of rocks were revealed in latitude and submeridional profiles; they were interpreted as manifestations of subvertical plumes and subduction zones and indicators of existence of unistrata convection in the mantle (Kharitonov et al., 2004). Development of such investigations can make them an important addition to the global seismic tomography.

The use of space information in neotectonic and seismotectonic research developed rapidly during these 30 years. It was no wonder that a large fraction of neotectonic works studied platform territories, because small amplitudes of recent displacements in such regions made it difficult to reveal them with the use of ground-based methods, while space information opened new possibilities, connected with remote detection of landscape indicators of recent displacements, i.e., their manifestations in surface erosion and alluviation, drainage network, changes in coastlines, soil moisturing, and, hence, vegetation (Burleshin, 1983; Gubin et al., 1988; Krotkova, 1988; Kuzin et al., 1990b, Zykov and Filimonov, 1993). According to these criteria, Caspian platform regions involved in neotectonic activization in different periods were distinguished, i.e., in the Oligocene, the Pliocene, and the Quaternary (Burleshin, 1991). The rates of Holocene uplift of the Khibini and Lovozersky plutons in the Kola Peninsula were estimated in (Trofimov et al., 1989).

The regions of recent continental sedimentation, deformation of bedded formations and lateral bendings of bow areas, and manifestations of deep faults of crustal blocks actively developing at present were defined more accurately in mobile regions and, first of all, in the Alpine-Himalayan orogenic belt (Katz et al., 1987). Similar high-gradient deep zones, expressed on the surface by lineaments, have been detected on a local scale in the Faizabad geodynamic polygon; Late Quaternary displacements have been revealed along them (Ivanova, 1984). The lineament analysis allowed signs of longitudinal left-shear deformations in Tuva to be revealed (Gonikberg, 1983). The seismic control role of large lineaments of the Anatolian-Caucasian-Iranian region was ascertained; lineament intersections were recognized to be especially quake prone (Bunin, 1981; Korovina and Karakhanyan, 1981). In addition, it was found that these intersections are imaginary sometimes, since lineaments reflect disturbances at different depths, and seismogenerating stresses are concentrated at borders between differently deformed crustal layers (Makarov et al., 1974; Karakhanyan, 1985).

Several works were devoted to revealing, mapping, and parametrizing active faults as potential seismogenerating zones, with the use of large-scale SIs and radar images of territories different in structure and landscape (Lavrusevich and Bezrukov, 1984; Strom, 1987; Loziev and Urunov, 1991; Lukina et al., 1991; Makarov et al., 1994; Imaeva et al., 2006). Revelation of active displacements in SIs from displacements and bends of crossed relief forms and drainage network elements opened additional possibilities. The point is that such long-term (during the last millennia) displacements result in horizontal displacements of crossed natural and man-made objects to different values: the older the object, the larger the displacement. If displacement were caused by strong seismic impulses, then the amplitudes should be discrete. If the statistics of such displacements are sufficient, one can prove that the displacement amplitude increased along a fault line under strong earthquakes. Certain displacements allow estimation of the magnitudes of these earthquakes, since they are definitely correlated. This method, suggested in (Wallace, 1968) and implemented in Central Asia by V.G. Trifonov (Trifonov, 1985; Trifonov et al., 1988, 1990), is one of the parametrization criteria for seismogenerating zones when estimating the seismic hazard of a territory, i.e., in seismoregioning or long-term seismic prediction.

Space geodesy measurements of current movements of the Earth's surface, including seismogenic ones, became an important step in development of seismotectonics, first of all, with the use of high-precision GPS observations (Tatevyan, 1999).

Data on remote recording of effects of recent earthquakes are given in (Ishanov et al., 1990; Bogachkin et al., 1993). New types of *earthquake precursors* have been suggested, recorded with space facilities. Thus, gas emissions can probably precede strong earthquakes and cause cloud formation (Grigoriev and Kondratiev, 1996). The authors presented NOAA pictures showing origination of such cloudy anomalies above active faults during and near the epicenter of the Spitak earthquake on December 7, 1988, in Armenia and strong earthquakes in the east of Turkey in March–April 1992 (Morozova, 1993). Temperature anomalies near foci of strong earthquakes were recorded during space surveys in the IR range before the events in China in Yunnan Province in November 1986 and Shaanxi Province in October 1989 (Grigor'ev and Kondrat'ev, 1993), as well as in Middle Asia, Kamchatka, Japan, Spain, Italy, Saudi Arabia, and California (Tronin, 2005). According to A.A. Tronin, the most probable cause of thermal anomalies is changes in the soil humidity owing to release of fluids during earthquake preparation. Data on variations in gravity anomalies before strong earthquakes in oceans are given in (Ivanov, 2004). They are expressed in variations in the sea level of up to 1 m in amplitude at distances of up to 50 km (MGDR files), which exceeds the effect of ocean currents by an order of magnitude. Magnetospheric and ionospheric disturbances were considered in (Sergeenko and Kharitonov, 2005) as earthquake precursors. Despite the importance of the fact that they precede earthquakes, these disturbances originate on areas much larger than pleistoseismic regions, and no correlation has been ascertained between the earthquake magnitude and disturbance parameters. This does not allow consideration of these disturbances as effective earthquakes precursors so far.

A new technique for earthquake prediction was suggested in (Bondur and Zverev, 2005, 2007). Analyzing lineament systems in SIs of California and Peru in 2001–2004, they revealed that the manifestation rate of lineaments begins to increase 2–3 months before a local earthquake and reaches its maximum about 20 days before it; after the earthquake, it decreases and becomes normal in 2–3 months. The effect repeated during five seismic events with magnitudes of 4.2–6.5 in vicinities of the San Andreas Fault in California (on 1
September 4, 2001, M = 4.2; February 22, 2002, M = 5.2; December 22, 2003, M = 6.5; September 18, 2004, M = 5.5, and September 28, 2004, M = 2004) and was noted in Peru during the earthquake of January 27, 2004 (M = 5.2). No such short-term variations in the lineament manifestation rate were discovered in aseismic regions; it remained stable independently of survey type. It was assumed that an increase in the lineament manifestation rate is connected with changes in the stress-deformed state of the medium and, correspondingly, its fluid conditions during earthquake preparation and occurrence.

Many works were devoted to space study of another hazardous geological event, i.e., *volcanism*. Such advantages of its space monitoring as due notice about the beginning of an eruption, information about its conditions, and estimation of the global effects of aerosol and gaseous emissions in the atmosphere were noted in (Grigor'ev and Kondrat'ev, 1996). Some attention was paid to IR survey, recording thermal anomalies and their variations in volcanic regions even through thin clouds. As an example, materials on the Pinatubo (Philippine Islands) eruption in 1991 were considered in (Kondrat'ev 1993). The monitoring results of volcanoes in Kamchatka were considered in

(Khrenov et al., 1999). The Klyuchevskaya group of volcanoes in Kamchatka was studied with the use of radar survey in the 23.5 cm range (Shkarin and Shapovalov, 2006). Lava flows of different ages and types were distinguished. A zone of areal volcanism was distinguished on the stratovolcano flank via lineament analysis with the use of the LESSA program.

The use of space information for "metallogenic prediction" has been of stable interest during these 30 years (Baratov et al., 1981; Bagrov and Antonov, 1987; Gan-Ocir et al., 1988; Skublova, 1989; Skublova et al., 1990; Pugovkin, 2000; Lopatin, 2001; Milovskii and Galkin, 2002; Milovskii et al., 2002, 2004, 2007). Like the above-mentioned works by V.M. Moralev and O.G. Sheremet, also oriented to metallogenic prediction, these studies were based on geometric images of different structural elements shown in SIs, among which ore controlling and ore concentrating structures were distinguished via comparison with ground-based geological and geophysical data. New prospective regions were predicted on the basis of similarity with known deposits. Deposits, as bodies with multiply increased concentrations of chemical compounds, are natural anomalies; therefore, their structures and, hence, geometric images on the Earth's surface are distinctive, and this "image" approach seems promising.

Oval-ring structures and lineaments, mainly identified with faults and fracture zones, were the main structural elements distinguished in SIs for metallogenic analysis. Such identification was rather hypothetical in earlier works; hence, relationships and, especially, junctions of lines of different curvature were of main interest there. Later on, the morphostructural content of rings and ovals was also considered (Skublova et al., 1990); an increase in the SI variety and resolution served to distinguish morphokinematic types of faults, dike fields, paleovolcanoes, metasomatosis zones, and other geological formations important for exploring for deposits (Milovskii and Galkin, 2002; Milovskii et al., 2004). Space-metallogenic investigations covered many ore regions of the former Soviet Union; different minerals were their subjects. A specific geometric image of blow holes (potential kimberlite) was noted in the north of the East European platform (Bagrov and Antonov, 1987); their geometric, landscape, and phototone indicators in SIs were formulated in (Lopatin, 2001). Regions especially promising for exploring for uranium deposits of "nonconformity" type stand out by distinctive diagnostic features (Pugovkin, 2000). Modeling of ore objects became a separate direction in space-metallogenic prediction (Pertsov et al., 1994; Kuznetsov and Samsonov, 1995).

A significant number of works were devoted to the use of space information in *predictive-search prospecting for oil and gas*. Earlier works noted a significance of lineaments identified with faults and increased fracturing favorable for vertical migration of formation fluids, including hydrocarbon ones (Amurskii and Bondareva, 1981). Later on, attention was paid to geoidentification of isometric relief forms for detection of local petroleum-bearing structures, which are defined by minor surface neotectonic elevations (Guschin, 1986; Yakhimovich, 1986; Milovskii et al., 2005). Morphological, orographic, and morphometric structural features were pointed out as indicators in (Trofimov et al., 1990). Specific lists of geological indicators of faults as zones of vertical fluid migration and local structures promising for oil and gas exploration were given in (Aksenov and Mozhaeva, 1990) for arid territories; the importance was justified and approaches to remote detection of the deep structure of petroleum-bearing territories were described. The results of the use of SIs for reconstruction of the tectonics of subsalt deposits of the Cis-Caspian depression were shown in (Mokienko, 1985); a wide spread of hidden local elevations was assumed. The capabilities of using SI for distinguishing inferred petroleum-bearing reef knolls were shown by the example of Chardzhou step in the Southern Sub-Aral area in (Smirnova, 1995).

The airborne IR-thermal sensing experiment of the
Tengiz oil field in Northwestern Kazakhstan was an 3
important step in the development of this research
direction (Zlobin et al., 1993). The experiment 2
showed the capabilities of direct petroleum prospect-
ing in arid and subarid conditions, previously pointed
out by V.I. Lyal'ko.

A number of publications were devoted to the use of space information in *hydrogeology*. The importance of distinguishing lineaments as zones of increased fracturing was validated by examples of the Caspian Platform (Burleshin and Vilkovich, 1990) and Central Afghanistan (Ob'edkov and Zurmati, 1992). The algorithm for detection of the underground water level from the complex of remote and ground-based data was proposed in (Komarov et al., 1998) for the region of the Belovo water reservoir.

The use of space information for the *study of exogenous geological processes and solution of engineering geology problems* was extensively discussed. The importance of remote estimation of tectonic break and related exogenous processes dangerous for building was validated in (Revzon and Yurovskii, 1983). The automatic mapping technique for exodynamics of mountain relief during underground laying of communications was suggested in (Revzon et al., 1988). The map of mudflow hazard in the Issykul basin was presented in (Chalmaev and Abdullaeva, 1989). The capabilities of satellite monitoring of recent exogenous processes were shown for the dry part of Aral Sea (Budnikova et al., 1996) and evolution of the estuary of the Sefidrud River on the Iranian coast of the Caspian Sea (Krasnozhon et al., 1999).

TRENDS AND PROSPECTS

The main successes in the use of space information in geology are connected with the general progress in data acquisition and processing. The expansion of new facilities, methods, and techniques become routine operations common and even required in geological investigations and industrial activity and are no longer subjects of scientific publications. This occurred with the use of SIs in geological surveying and is happening now with their use in seismotectonics, in particular, in mapping and parametrization of active faults—potential sources of strong earthquakes and zones of maximum seismic impacts.

In addition, the development of space engineering and processing facilities of space information opened capabilities for solution of new geological and geophysical problems or for new approaches to old problems. Among them are automated complex analysis of SIs, relief parameters determined from satellite sensing, and ground-based data; deciphering of deep crustal and mantle structures with the use of space-geophysical sensing; IR-thermal surveying for the study of recent geodynamically active regions and direct exploration for hydrocarbon deposits; and monitoring of recent endogenous and exogenous geodynamic processes and estimation of their environmental effects.

Both of the above trends in development of geological investigations will be evidently pronounced in the future. There is one other trend in current earthquake prediction: revelation of related phenomena on the ocean surface and in the atmosphere, in particular, in the magnetosphere and ionosphere, located beyond the application area of geological and geophysical investigation techniques proper. Though correlations of these effects with earthquake parameters are understudied and cannot be considered as precursors so far, such an approach (like geoindication detection of geological structures and interest in environmental effects of their development) reflects profound understanding of interrelations between natural processes.

The number of space-geological publications in the journal *Issledovanie Zemli iz Kosmosa* is less than half as large in the last two decades as in the 1980s. Besides social and economic causes, this is connected, in my opinion, with a loss of interest in works which have no methodical specificity and oriented only to receiving geological and geophysical results. Only works discovering new techniques and capabilities of using space information are of interest, but they were rare in the 1980s as well.

A number of new ideas important for solution of geological problems proper appeared in course of works on using space information. Here are some of them.

1. An increase in the degree of generalization of SIs of the Earth's surface results in poorer visibility of the details characterizing the geology of near-surface layers and better visibility of deep structure features. This concerns structural elements active in the recent period of geological development. Thus, interpreting SIs of different degree of generalization and comparing the results of interpretation with the available geological and geophysical data, one can compare structural elements of approximately equal age at different crustal depths and sometimes in the whole lithosphere and reveal their similarity and differences. Such an approach, suggested by V.I. Makarov and V.G. Trifonov, resulted in the concept of tectonic layering of the lithosphere in a number of mobile regions, which is an important element of modern tectonic theory.

2. Mineral specialization of a territory is determined by its structural and material properties, which are displayed on the Earth's surface in geometrical images decipherable in SIs. This idea has been realized by V.M. Moralev and O.G. Sheremet by means of lineament network analysis and provides for additional criteria of metallogenic prediction.

3. An oil or gas deposit in a trap of one or another type (mostly structural elevation) gives such a structure additional thermal properties. Microorganism activity inside a deposit increases its temperature, and an increase in the fluid porosity owing to recent fracturing activization and, partly, isostatic elevation because of the fact that a deposit is lighter than enclosing rocks results in an increase in the moisture of the soil above it. This can be detected by special filtering of IR thermal signals. The idea belongs to V.I. Lyal'ko and has been implemented in the Tengiz oil field by 3
E.L. Zlobin, B.N. Mozhaev, and colleagues. It opens 2
a way to direct revelation of deposits in structures promising for petroleum exploration.

4. Changes in the stress-deformed conditions of the medium in the focus region of a future earthquake are manifested in fracture activization and an increase in their fluid porosity before the earthquake. This is reflected in the enhancement of the manifestation of the lineament network visible in SIs. The idea belongs to V.G. Bondur and A.T. Zverev; they validated it in focus regions of several earthquakes in California and Peru. The idea gives an additional precursor of seismic events.

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