SEISMIC ZONING

V.I. Ulomov
United Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

Keywords: earthquake hazard, seismicity, source zone, seismic effect, seismic zoning

Contents

Summary

Seismic zoning is among the most complicated and extremely important problems of modern seismology. It is the foremost link in a complex chain of an estimation of seismic hazard and seismic risk. Seismic zoning is urgently needed for the total area of the Earth without a single exception, since large damaging earthquakes have occurred and can occur in the future, even in plains, which are comparatively quiet, geologically speaking. Recent research has shown that about ten percent of Earth's surface is occupied by high or very high seismic hazard zones. These include all the countries situated along the Pacific rim, in the Mediterranean, the Near and Middle East, Central Asia, Himalayas, along the Trans-Asian belts and adjacent areas. About 70% of the land mass lies in a relatively low hazard zones. However, in such regions the seismic danger can be high also if low magnitude earthquakes occur at shallow depths because these territories are very densely populated.

Further fundamental and applied research in seismo-geodynamics and seismic zoning is to focus on development of scientific principles and techniques to be used in dynamical seismic zoning based on studies in seismicity, migration of strain waves and seismicity increases, reoccurrence of earthquakes at the same location and other problems of earthquake generation that still remain unsolved. It is important to operate with extended earthquake sources, to use of the nonlinear recurrence graph and moment magnitudes, and to calculate a spectral shake-ability. Not less important is to study features of seismic effect depending on a type of geological structures generating the

earthquakes (shear-fault, overthrust, normal fault, etc.).

1. Earthquake Hazard

Earthquakes are one of the most dangerous natural calamities influencing the human environment. They occur very frequently. Earthquakes begin very suddenly aggravating their destructive consequences. Often as destructive as the earthquake itself are the resulting secondary effects: surface faulting, tectonic deformation, landslides, tsunamis, floods, fires and blasts (Figure 1). Earthquakes and their numerous aftershocks affect the human psyche, cause serious cardiac-vascular, endocrine and other diseases. These problems as well as some new ones were encountered by medical and rescue units during the operations to mitigate the disastrous effects of strong earthquakes.

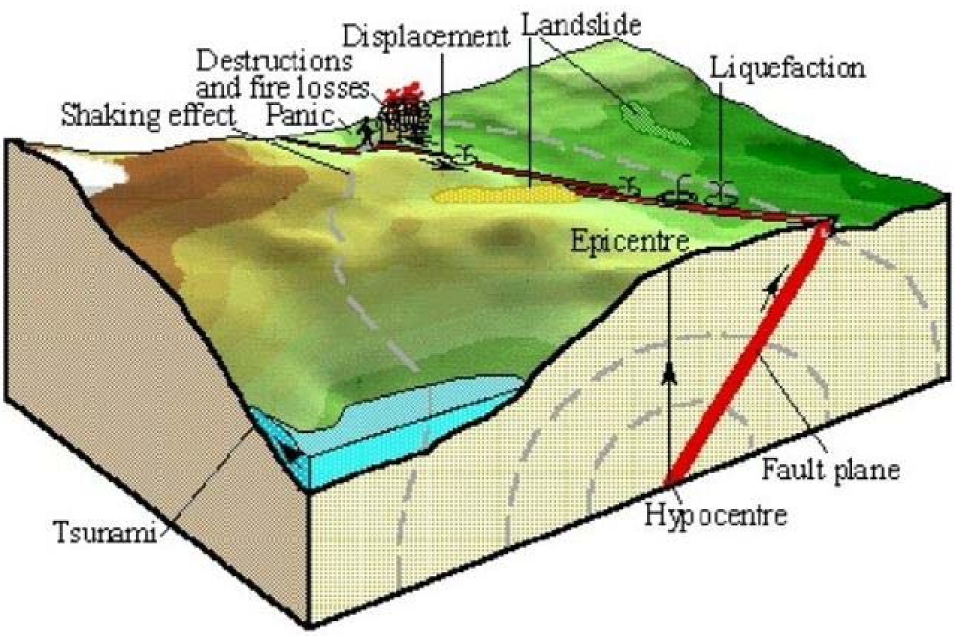

Figure 1. Earthquake source and its secondary effects

Unfortunately it is not yet possible now either to predict an earthquake and thus to avoid its consequences. However, their disastrous effects and the number of casualties can be reduced only by means of drawing up reliable maps of seismic zoning, by observing the standards of anti-seismic building and pursuing in seismic regions the long-term policy based on increasing the level of public awareness regarding the dangers involved, and the ability of the state and public services to withstand the natural calamity.

Earthquake hazard does not decrease with time, but actually increases in direct relation with the economical assimilation of seismically active territories and with the human influence on the Earth's crust (uncontrollable pumping of oil and gas, extraction of other mineral deposits, the construction of major hydraulic structures, burial of industrial waste and the like). Enhanced seismic risk arises from nuclear power stations and other ecologically hazardous facilities installed in seismic regions, because even very insignificant earthquakes and secondary post-seismic consequences (rock slides, cracking in the ground etc.) can disrupt their normal operation.

Seismic zoning is a highly complex and extremely important challenge of modern seismology. This is to say nothing of the social, economical and ecological significance of this problem. Its scientific intricacy is based primarily on the fact that it belongs to that category of predictions based on incomplete information, on scant experimental data, not always derived from successful experiments, and on the methodological standpoints being insufficiently clear. Therefore, for example, in the United States, new seismic hazard maps are required by law every 5 years, in the Russia every 10-15 years. And although the maps of seismic zoning are being updated and improved periodically, as additional information on earthquakes becomes available and seismological knowledge is further perfected, these changes are fragmentary in that broad, universal data is not forthcoming from all corners of the globe, but is confined to those well-known, seismically active zones. Therefore, seismic zoning maps compiled in certain countries proved to be, to some extent , inconsistent with the actual natural conditions, which, together with low-quality civil engineering construction, caused many casualties and enormous material damage to the national economy.

Seismic hazard assessment is based on the observation and measurement of the ground shaking produced by seismic waves passing. The seismic effect depends on the magnitude of earthquake, the depth of its hypocenter, the distance from the earthquake source, the local ground conditions (e.g. rock or soft soil), etc.

There are two general approaches to seismic zoning: the historical records of earthquake occurrences ("Historic methods") and the geodynamical interpretations of the seismicity and earthquake source zones ("Deductive methods"). The first official seismic zoning map for a code on aseismic building was published in 1937 in Russia and initiated regular compilation of such maps as the basis for regulating design and construction in civil engineering in seismoactive regions of this country. The research conducted in the 1950-1960s led to a new paradigm of seismic zoning. It was based on a two-step method of genetic seismic zoning and a deterministic-probabilistic assessment of earthquake hazard (S.V. Medvedev, I.E. Gubin, Yu.V. Riznichenko). According to this concept, the first, seismo-tectonic step involves identification of earthquake source zones, while the second, engineering step is concerned with the calculation of the seismic effect caused by these at the surface (Figure 2). This two-step model and the probabilistic approach to seismic hazard mapping have become widely accepted in world seismology in the late 1970s, especially after the well-known papers of American scientists (C.A. Cornell and others). In recent years the ideas of deterministic-probabilistic forecasting of dangerous seismic and other geological processes have begun to influence more and more actively into seismology and into the practice of building construction.

Three database series (geodynamics, seismicity, and strong ground motion) are the basis used to develop two models: a source zones model and a model of seismic effects, which are used to calculate earthquake hazard and to map seismic zones.

Nevertheless, in spite of the high constructive value of this methodology, it is only the second, engineering, step of seismic zoning which has received much attention, i.e., calculation of seismic effect at the Earth's surface. The first step, identification and seismological parameterization of seismic source zones, which deals with deep-seated seismo-geodynamic processes and falls within the area of competence of seismologists and geophysicists, has remained less developed, being largely a subjective procedure. At the same time, already for a long time it became clear that since the zoning of earthquake hazard exclusively relies on the information concerning past earthquakes, without deep study of regional and global seismicity and without adequate earthquake source models, it is utterly hopeless. It became obvious that for seismic zoning of established local territories it is necessary to examine the features of geodynamics and seismicity in adjacent seismic regions that are genetically related to the area of interest.

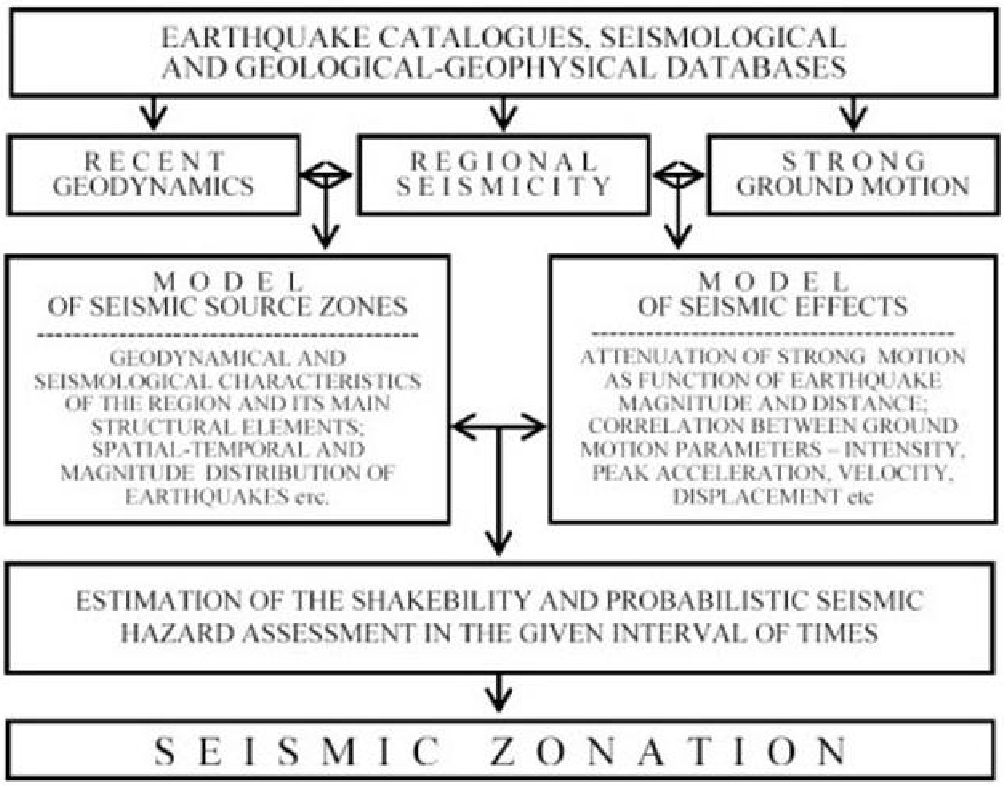

Figure 2. Structural chart of seismic zoning methodology.

There are a number of methods that have been used to estimate seismic hazard. However, these are not without their drawbacks. Here one of the methods is described, which is relatively more advanced, in comparison with others. The technique, described below, for identification of earthquake source zones and for calculating the seismic hazard is based on the seismic zoning ideas found within the approaches of Yu.V. Riznichenko in 1965, C.A. Cornell in 1968 and other scientists, but overcomes significant disadvantages of these approaches.

2. Global Seismicity

2.1. Global orderliness of seismogenic regions

The structural and geodynamic patterns observed in the extensive seismo-active regions of the Earth allow it to be treated as a global seismo-geodynamic system (SGD - system). These patterns are clearly expressed in the hierarchical heterogeneity of present-day tectonic features, ranging from the lithosphere to crust blocks of different ranks, as well as in the trends of their geodynamic evolution. The relation of regional seismicity to the structure and dynamics of the lithosphere is most clearly expressed on a global scale as three leading types of SGD-interaction caused by divergence, convergence, and transform displacements of the lithosphere plates.

The convergent lithospheric features are the most active seismically. They do not show an excessive scatter in size and are arcuate interplate boundaries extending along oceanic margins as subduction zones, as well as continental relicts of subduction zones (Figure 3). The dimensions of oceanic, hence continental, arcuate features are controlled by earth curvature, as well as by plate strength and thickness, and by the intensity of plate interaction. The mean length of all convergent regions worldwide is 3000±500 km. Roughly equal to that value are the dominant distances between the centers of two closest regions. The dimensions of these seismic regions and their spatial distribution have very direct bearing on the assessment of maximum possible earthquakes that can occur there.

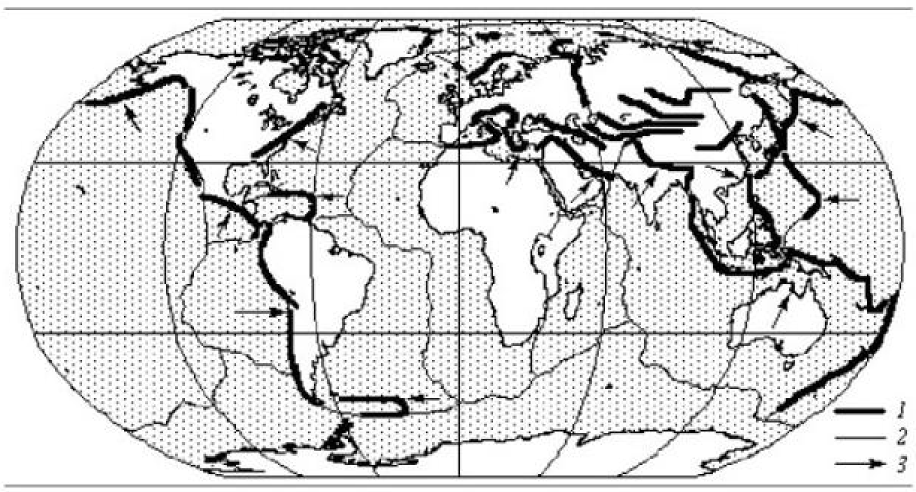

Figure 3. Generalized tectonic map of the Earth showing boundaries (1 and 2) of major lithospheric plates and the global orderliness of earthquake-generating regional features: 1 - axes of convergent subduction zones and their relicts in continents; 2 - axes of divergent rift zones in oceans; 3 - direction of motion of plates.

Each region has its own seismic regime and seismicity structure; for this reason, as will be shown below, it is a region of the dimensions indicated above which is taken as the "basic" seismogenic structural unit to develop the model of earthquake source zones. The patterns that have emerged can become a basis for the appropriate seismic regionalization of the Earth.

Global seismicity is caused by the intense geodynamic interaction between several large lithosphere plates—the Eurasian, African, Arabian, Indian, North- and South-American, Antarctic and Pacific plates. Horizontal motion of the plates can be 10 centimeters and more per year.

Earthquake sources can occur in the region 0–700 kilometers below the Earth's surface. This earthquake source depth range is, as a rule, divided into three zones: shallow, intermediate, and deep. "Shallow" earthquakes are between 0 and 70 km deep, "intermediate" earthquakes, 70 - 300 km and "deep" earthquakes, 300 - 700 km deep. Earthquakes with depth up to about 700 km are localized within convergent subduction zones that are sinking into the Earth's mantle. The sources with intermediate depth occur mainly in relicts of such zones inside continents. Shallow earthquakes are distributed practically everywhere. Most of the intra-crust earthquake sources are in the upper crust within 15 km of the ground surface. The vertical distribution of the hypocenters is controlled by the dimension L_M and vertical extent H_M of the relevant sources, which are related to magnitude M of the respective earthquakes.

Annual occurrence of earthquakes on the Earth is as follows: one with $M \geq 8.0$, about three with $M \geq 7.5$, about 15 with $M \geq 7.0$, about 60 with $M \geq 6.5$, , and more than 200 with $M < 6.5$. Certainly, these mean that the yearly seismicity rate (V_M) is highly variable and longer period of observation could give quite different results.

2.2. Regional Structure of Seismicity

The seismic sources are not distributed chaotically. They arise in the most compliant inter-block contact zones and most often occur, in a regular manner, in fixed sites that are least favorable for creep displacements and thereby seismically most hazardous. Commonly, these seismogenic structures are intersections of faults or displacement zones, their sharp bends, or other features (asperities and barriers) that prevent slow tectonic movement on faults. If such delays are long, more elastic energy is collected; the large volume of rocks become potentially stressed and the next earthquake will be stronger. The dimension of such areas is determined by the sizes of interacting blocks bounded by active faults or displacement zones. These sizes control the upper threshold of the earthquake magnitude, and the number of blocks is responsible for the intensity of the tectonic movements and seismic regime (average number of seismic events per unit time). The fault ranks J, and the distances between their dislocated nodes δ_j, as well as block sizes are determined by the thickness and strength of the related layers faulted in the past geological epochs. The thicker the layer divided by faults into blocks, the larger and longer the faults and the greater the distances between them. This results in an increase in block sizes and, consequently, in the magnitude of the related earthquakes. Conversely, the number of faults, blocks and earthquake sources increase as the layer thickness decreases.

The lattice of the intra-continental faults is predominantly of the rectangular, or more often square shape determined by the tangential compression. It was found that the distances δ_j between the intersections of faults and, accordingly, the dimensions of geological blocks (geoblocks) exhibit a well-pronounced tendency of clustering in ranks, their vertical and horizontal dimensions being in a ratio of roughly two to one between adjacent ranks. This phenomenon seems to have its origin in the persistent doubling of the depths to major discontinuities in the crust and upper mantle, the faults of respective ranks penetrating as deep as the discontinuities. To take an example, the top of the "granite" layer in the continents lies at a mean depth of ~10 km, the Conrad discontinuity is at 20-25 km, the crust-mantle interface is at 40-50 km, the bottom of the lithosphere at ~100 km, that of the asthenosphere at ~200 km, these being followed by the ~400-km and ~700-km discontinuities. This fundamental pattern of discontinuous change in material properties as the depth is multiplied by two governs all geological depths up to and even including the soil.

The orderliness thus emerging dictates a corresponding orderliness, not only in systems of tectonic faults and geoblocks, but also in the hierarchy of earthquake sources: the larger the earthquakes, the farther are their sources from one another. Thus, earthquake sources when ranked according to magnitude M and elastic energy radiated E are distributed in a regular manner, not only in time ("frequency-magnitude relation"), but also in space ("the law of inter-source distances"). It has turned out that the mean distances δ_M (km) between the epicenters of two closest-lying earthquake sources of length L_M (km) and magnitude M are well described by the following relations:

$$\delta_M = 10^{(0.6M - 1.94)} \quad (1)$$

$$L_M = 10^{(0.6M - 2.5)} \quad (2)$$

As is apparent, the factor 0.6 at M implies that the source sizes L_M and distances between epicenters δ_M change approximately by a factor of two with a 0.5 increase in magnitude. From the above relations it follows that the quantity $\delta_M / L_M = 3.63$ is independent of magnitude, thus reflecting self-similarity in the size hierarchy of geoblocks and the associated earthquake sources in the entire magnitude range investigated (from M = 6.0±0.2 to M = 8.0±0.2). Also independent of magnitude, to some degree at least, is the ratio of earthquake sources length L_M to the vertical sources plane extent H_M, which is identical with the respective thickness of the geoblocks.

Relations (1) and (2) are still neater when earthquake energy is expressed in the SI system, where $E = 10^{(1.8M+4)}$ is measured in Joules, L_E and δ_E in meters:

$$L_E = 2^{\lg E} / \sqrt{3.5}; \qquad \delta_E = 2^{\lg E} \sqrt{3.5}. \quad (3)$$

In that case $\delta_E / L_E = 3.5$.

The quantity δ_M (as well as δ_E) is none other than the mean horizontal size δ_j of geoblocks that can generate earthquakes of the respective maximum magnitude M_{max}; $\delta_M = \delta_j$ is the diameter of the area responsible for M_{max}, a very important quantity for the assessment of earthquake hazard; this is related to δ_j as follows:

$$M_{\max} = 1.667 \log \delta_j + 3.233. \quad (4)$$

Interrelationships in the orderliness of faults, geoblocks and earthquake sources, as well as in the evolution of seismo-geodynamic processes are just more evidence in favor of a structural and dynamical unity of the hierarchical geophysical medium and the seismogeodynamic processes that are going on in it. Orderliness obtains also in the hierarchy of soliton-like strain waves (the so-called G waves, or geons) of seismicity increases. These provide for the dynamics of interacting geoblocks and for directivity in the evolution of synergistic seismo-geodynamic processes. Geons propagate along faults of their respective ranks, creating and removing various barriers and so provoking earthquake sources of appropriate magnitudes. Since these geodynamic processes are evolving more or less independently at each hierarchical scale, they possess the same fractal dimension as for the fault-blocky medium and its seismic regime. When the external geodynamic excitations are low, the seismicity in the region is close to the steady state, involving small shallow earthquakes that are being generated by a denser network of smaller faults. When the external forces become greater, e.g., as a result of major coseismic or creep movements, the SGD-system passes to a qualitatively different and better organized state. Larger fault zones begin to "operate". This can be inferred from ordered changes in seismic activity in many regions worldwide (migration of earthquake sources, periodic seismic rate increases, localization of quiescent areas and the like) which are caused by synergetic self-organized phenomena typical of many hierarchical multi-component non-equilibrium systems.

-
-
-

Bibliography

Cornell C.A. (1968). Engineering seismic risk analysis, Bull. Seis. Soc. Amer., 58, p. 1583-1906. [The most famous publication which has begun world researches of seismic hazard assessment.]

Giardini D. and Basham P. (1993). The Global Seismic Hazard Assessment Program (GSHAP). *Annali di Geofisica*, Vol. XXXVI, N 3-4, June-July, Special issue: Technical Planning Volume of the ILP's "Global Seismic Hazard Assessment Program" for the UN/IDNDR, 257 pp. [Presents the Proceeding of the GSHAP Technical Planning Meeting, Rome, June 1-3, 1992.]

Gubin I.E. (1950). Seismo-tectonic method of seismic zoning, *Trans. Geophys. Institute*, Moscow: AS USSR, N **13** (140), 60 pp. (in Russian) [Informs about new seismotectonic (“seismogenetic”) method of earthquake source zones identification for general seismic zoning]

Gusev A.A., Shumilina L.S. (1995). Certain aspects of the technique of general seismic zoning. *Seismicity and seismic zoning of North Eurasia* (edit. V.I. Ulomov), Issues 2-3, Moscow, UIPE RAS, p. 289-300. [Informs about new technique of seismic danger calculation for general seismic zoning]

Medvedev S.V. (1947). To a question on the account of seismic activity of area with construction, Proc.

of the Seismological Institute, AN SSSR, N 119 (in Russian). [Presents the first, but not well-known in the world, publication about a probabilistic seismic hazard assessment.]

Riznichenko Yu.V. (1965). From the activity of seismic sources to the intensity recurrence at the ground surface, Izv. AN SSSR, Fizika Zemli, 11, p. 1-12 (in Russian). [The most developed methodology of a probabilistic seismic hazard assessment and calculation of spectral "shake-ability".]

The Global Seismic Hazard Assessment Program (GSHAP) 1992 – 1999. Summary Volume. (1999). *Annali di Geofisica*, **42**, N 6, December, 1230 pp. [This work edited by Domenico Giardini presents the first-ever quantitative Global Seismic Hazard Map, provides updated seismic hazard values for nearly half of the world's nations.]

The practice of earthquake hazard assessment. (1993). International Association of Seismology and Physics of the Earth's Interior and European Seismological Commission. 284 pp. [This work edited by R.K. McGuire presents fifty-nine reports covering 88 countries, which comprise about 80 percent of the inhabited land mass of the Earth.]

Ulomov V. and Working group. (1999). Seismic hazard of Northern Eurasia. *Annali di Geofisica*, **42**, N 6, 1023-1038. [Presents the new methodology and seismic hazard map for N 7 GSHAP region of Northern Eurasia in PGA value.]

Ulomov V.I. (1999). Seismo-geodynamics and Seismic Zoning of North Eurasia. *Vulcanology and Seismology*. N 4-5. p. 6-22 [in Russian]. [Presents the new methodology of seismic hazard assessment.]

Biographical Sketch

Valentin I. Ulomov was born in 1933, in Tashkent, Uzbekistan Republic. He is Professor of geophysics, Doctor of physics and mathematics, and Member of the Uzbekistan Academy of Sciences. His scientific interests are as follows: deep structure of the lithosphere; processes in earthquake sources; regional and global seismicity; seismo-geodynamics; seismic zoning; earthquake prediction. In 1955 V.I. Ulomov received the specialty of a mining engineer-geophysicist and was invited to work as a scientific researcher at the seismic station of "Tashkent". In 1959 he became the head of this station. In 1963 he was the Deputy Director of the Institute of Geology and Geophysics, Uzbekistan AS, and the Director of the Tashkent Seismology Observatory. In 1966, he initiated creation of the National Institute of Seismology and became its Deputy Director. In 1966 V.I. Ulomov headed the complex studies of the Tashkent earthquake, whose source was located beneath the central part of the Uzbekistan capital. His scientific paper from 1967 about the prognostic properties of radon emission became widely known, and the radon method of searching earthquake precursors was quickly propagated all over the world. On the basis of many-years seismologic and strain observations, V.I. Ulomov officially predicted (in scientific publications of 1966 – 1974) the strongest Gazli earthquakes of 1976, on the Turan plate. In 1990 V.I. Ulomov moved from Tashkent to Moscow on invitation of the Institute of Physics of the Earth, where he became the head of the Laboratory of Continental Seismology created by him. From 1990 to 1997 V.I. Ulomov headed the studies on general seismic zoning of the territory of the former USSR and adjacent regions; in 1992–1999 he was one of the main participants of the Global Seismic Hazard Assessment Program (GSHAP). V.I. Ulomov is the author of more 300 publications.