# 30 YEARS AFTER THE SPITAK EARTHQUAKE: EXPERIENCE AND PERSPECTIVES

## *International Conference*

**December 03-07, 2018**

**YEREVAN, ARMENIA**

# CONFERENCE PROGRAM

# ABSTRACTS VOLUME

**Yerevan – 2018**

30 YEARS AFTER THE SPITAK EARTHQUAKE: EXPERIENCE AND PERSPECTIVES

SPITAK 30

International Conference

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# ՍՊԻՏԱԿԻ ԵՐԿՐԱՇԱՐԺ, 30 ՏԱՐԻ ԱՆՑ. ՓՈՐՁ ԵՎ ՀԵՌԱՆԿԱՐՆԵՐ

## *Միջազգային գիտաժողով*

**Դեկտեմբերի** 03-07, 2018

ԵՐԵՎԱՆ, ՀԱՅԱՍՏԱՆ

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**Երևան – 2018**

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***Institute of Geological Sciences (IGS NAS)***

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## *1988 SPITAK EARTHQUAKE*

The social shock caused by Spitak earthquake of 7 December 1988, Mw 6.9, (more than 25,000 people died) forced complete reconsideration of common seismotectonic knowledge in Armenia and its surroundings and practice in many aspects, including critical reevaluation of the techniques and organization of the studies of active faults, earthquake geology, and seismic hazard assessment that had been applied earlier.

Buildings destroyed by 1988 earthquake in Spitak.

Prior to 1988 Spitak earthquake, seismic hazard studies in Armenia were mainly focused on the analysis of instrumental and partly historical earthquake catalogues primarily by seismologists and geophysicists (Pirouzyan, 1972; Nazaretyan, 1984; Karapetyan, 1988). Active fault studies were not conducted, and rare monographs addressing issues of seismotectonics were published by specialists in regional geology and stratigraphy (Vardanyants, 1935; Paffenholtz, 1948; Gabriyelyan et al., 1981). Evidence available from the Armenian historical chronicles was mostly ignored because it was considered that chroniclers severely exaggerated damage and casualties caused by earthquakes (Pirouzyan, 1972). The prevailing thought was that strong earthquakes accompanied by surface ruptures were unlikely in the Greater and the Lesser Caucasus (Borisov, 1982). This attitude, as well as social reasons, contributed to severe underestimation of the magnitude and frequency of seismic hazards, both for Spitak earthquake area, and for Armenia and the Caucasus as a whole. Each of the nine strong earthquakes that occurred in the former USSR from 1948 to 1995 fell in the areas where earthquakes had been estimated to be of a much lower seismic hazard. Such inadequate hazard assessments generally contributed to unpreparedness, lack of studies, and high numbers of casualties. The Spitak earthquake has become a tragic lesson for Armenia but also an impetus for modern studies on active tectonics, seismotectonics, and paleoseismology in the country.

The 7 December 1988 Spitak earthquake occurred on the northern most extension of the Garni fault where it joins the north-eastern segment of the Pambak-Sevan-Syunik fault system.

Fragment of 37 km-long surface rupture of Spitak earthquake of December 7, 1988.


The erosion over the last 10 and 20 years after the 1988 Spitak earthquake. (photos by A. Karakhanyan)

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# CONFERENCE PROGRAM

## 4 DECEMBER

Hall of Presidium of the National Academy of Sciences of the Republic of Armenia

9:00–10:00 Registration

10:00–10:30 Opening and welcome address by:

President of the Armenian National Academy of Sciences, Academician R. Martirosyan

Minister of Emergency Situations of Armenia, Mr. F. Tsolakyan

UN Resident Coordinator/ UNDP Resident Representative Mr. Shombi Sharp

Representative of U.S. Department of Energy, Mr. W. Wanderer

10:30–11: 00 Documentary film about 1988 Spitak earthquake

11:10- 11:40 - Coffee break

11:40 –12: 10 Awarding Ceremony

12:15–13:00 Moving to Ani Plaza Hotel (by bus)

13:00–14:00 Lunch break

## Hall Ani Plaza Hotel

***PLENARY SESSION: Chairman Dr. Kh. Meliksetian***

14:00–14:20 E. Khachiyan. Spitak earthquake of 7th Dec 1988: major seismological characteristics and analysis of its devastating consequences.

14:20–14:40 S. Nazaretyan. Spitak 1988 earthquake: facts and comments.

14:40–15:00 E. Rogozhin. Spitak 1988 earthquake: complex seismological and seismotectonic study results.

15:00–15:20 Kh. Meliksetian. The Spitak earthquake: tragic lesson and impetus for modern studies and adequate assessment of seismic hazards and risks.

15:20- 15:40 - Coffee break

***PLENARY SESSION: Chairman Dr. S. Margaryan***

15:40–16:00 T. Chelidze. Signatures of strong earthquake preparation in the phase space portraits of earthquake time series of Caucasus.

16:00–16:20 L. Serva. Correlation between earthquake surface faulting and coseismic surface deformation: Consequences for FDHA.

16:20–16:40 T. Onur. Disaster risk reduction in the Caucasus through modernization of building codes.

16:40–17:00 M. Sosson. The Caucasus domain tectonic evolution: the role of inherited structural deep faults zones in the location of the seismicity

17:00–17:20 A. Avagyan. Overview of Active tectonics of Armenia.

17.20-17.40 **M**. Ashtiani. General Overview on Response, Recovery and Reconstruction of November 21, 2017 Sarpol-e-Zahab Mw 7.3 Earthquake, Iran.

17.40-18.00 Discussion

## 5 DECEMBER

### DVIN Hall (Ani Plaza Hotel)

***SECTION I. 1988 SPITAK EARTHQUAKE: FIELD OBSERVATIONS IN THE EPICENTRAL AREA; PRESENT-DAY SEISMICITY OF THE REGION; NEW STUDIES AND RESULTS AFTER 30 YEARS.***

***SESSION 1: Chairman Dr. R. Gök, Co-Chairman Dr. L. Sargsyan***

09:50–10:10 R.Tadevosyan. Seismological expedition of the IPE USSR AS in the epicentral area of Sptak, 1988, earthquake.

10:10–10:30 E. Geodakyan, M. Mkrtchyan. Aftershock process and discharge of seismotectonic stresses in the focal zone of Spitak earthquake.

10:30–10:50 R. Gök, M. Pasyanos. Seismic structure in the Caucasus region.

10:50–11:10 C. Evangelidis and G. Drakatos. European federated EIDA infrastructure for seismic waveform data archives. The regional NOA data implementation.

11:10–11:30 H. Mkrtchian, V. Mkrtchyan. New insights on the geology and seismotectonics of the Shirak basin, Republic of Armenia.

11:30-11:50 Coffee break

11:50–12:10 T. Godoladze, R. Gok, I. Bondar, M. Dzmanashvili, I. Gunia, N. Tumanova, T. Onur, G. Yetermishli, H. Babayan. Relocation of the Caucasus seismic events.

12:10–12:30 H. Petrosyan, A. Hovsepyan, S. Margaryan, A. Karakhanyan, E. Khachiyan, A. Arakelyan, T. Margaryan, S. Arakelyan, H. Babayan, Y. Abgaryan, and N.Mirzoyan. New map of probabilistic seismic hazard assessment for the area of the Republic of Armenia (seismic zoning) at the scale of 1:500000.

12:30 – 12:50 H. Petrosyan, Sh. Shahinyan and Zh. Sargsyan. Analysis of data of modern vertical crust movement in the Spitak earthquake region.

12:50–13:10 S. Akopian. Technology of global monitoring of strong earthquakes based on seismic entropy.

13:10–13:30 E. Geodakyan, S.Hovhannisyan, B. Sahakyan. Geodynamic model of the Spitak earthquake source and the analysis of the seismic processes in it.

13:30–14:30 Lunch break

***Session 2: Chairman Dr. R. Tadevosyan, Co-Chairman Dr. A. Simonyan***

14:30–14:50 J. Karapetyan, V. Grigoryan. Spitak destructive Earthquake on December 7, 1988. A brief overview of the research done and obtained results

14:50 –15:10 H. Hovhannisyan, H. Gasparyan, R. Sargsyan. Structural dynamic characteristics of the crust in Spitak earthquake epicentral zone and its adjacent regions according to geophysical and modern deformation data

15:10–15:30 A. Grigoryan, D. Likhodeyev. Response of the local geomagnetic field to the geodynamic processes during preparation of the 1988 Spitak earthquake.

15: 30–15:50 A. Simonyan, M. Ohanyan. Anomalies of the Earth’s magnetic field spatio-temporal variations and seismic activity on the northern part of the territory of Armenia (case study).

15:50- 16:10 - Coffee break

16:10–16:30 E. Sahakyan, L. Sargsyan, A. Levonyan, H. Babayan, M. Gevorgyan, H. Igityan. The current crustal stress field in the Javakheti volcanic highland.

16:30–16:50 A. Kazaryan. Detailed analysis of variations in geochemical data time series before Spitak earthquake

16:50–17: 30 Discussion

## 5 DECEMBER

### ANI Hall (Ani Plaza Hotel)

### *SECTION II. SEISMOLOGICAL AND GEOPHYISICAL STUDIES: SEISMOTECTONICS, PALEOSEISMOLOGY, ARCHEOSEISMOLOGY.*

IN HONOR OF DR. ARKADY KARAKHANYAN

***Session 1: Chairman Prof. M. Sosson, Co-chairman Dr. A. Avagyan***

09:30–09:50 Kh. Meliksetian, V. Trifonov A. Karakhanyan's scientific contribution to seismotectonic, archeoseismological and volcanological studies of the region.

09:50–10:10 J-F. Ritz, A. Avagyan, M. Mkrtchyan, H. Nazari, P-H Blard, A. Karakhanian, H. Philip, S. Balescu, S. Mahan, S. Huot, and P. Münch. Active tectonics within the NW and SE extensions of the Pampak-Sevan-Syunik fault: implications for the present geodynamics of Armenia.

10:10–10:30 H. Nazari, J.-F. Ritz. Archeoseismological analysis along the Khazar fault zone, North Alborz- South Caspian region, Iran.

10:30–10:50 V. Trifonov, A. Simakova, H. Çelik, Ya. Trikhunkov, E. Shalaeva, P. Frolov, G. Aleksandrova, E. Zelenin, A. Tesakov, D. Bachmanov, S. Sokolov. Marine Akchaghylian deposits of Caspian type in the western Shirak Basin and intensive Quaternary uplift in Armenian Highland.

10:50–11:10 A. Korzhenkov, H. Vardanyan, A. Sorokin, R.Yu. Stakhovskaya. Traces of the strong earthquakes in Holocene deposits of the Sevan lake, Armenia.

11:10–11:30 K. Abdrakhmatov. Active faults and seismic hazards of the Tien Shan.

11:30-11:50 Coffee break

11:50–12:10 A. Avagyan, L. Sahakyan, K. Meliksetian, T. Atalyan, S. Avagyan, P. Tozalakyan, E.A. Shalaeva, C. Chatainger, H. Hovakimyan, S.A. Sokolov. Holocene tectonic and volcanic activity archived in the deposits of the western part of Lake Sevan (Armenia).

12:10–12:30 L. Sahakyan, A. Avagyan, E. Shalaeva, M. Martirosyan, T. Atalyan, A. Hayrapetyan. Soft sediment deformation structures as evidence of past earthquakes in the Shirak Lacustrine basin (Armenia).

12:30–12:50 Yu. Budagov, M. Lyablin, N. Azaryan, G. Torosyan, A. Yesayan, A. Bayramyan, A. Tovmasyan, L. Hakhverdyan. Preliminary results of precision laser inclinometer installed at Garni Geophysical Observatory.

12:50–13:10 F.Cinti, P. De Martini, S. Baize, D. Pantosti, A.Smedile, R.Civico, F.Villani, L. Pizzimenti, C.Brunori, S.Pucci. 30 October 2016-type earthquakes rupturing the mt. Vettore-mt. Bove fault system (Central Italy) in the Holocene age.

13:10–13:30 G. Akhalaia, T. Godoladze, Z. Tavadze , D. Tsiklauri , Z. Javakhishvili ,G. Gventsadze, L.Tsiskarishvili. GNSS Network and Velocity field of Georgia.

13:30 – 14:30 Lunch break

***Session 2. Chairman Dr. J.-F. Ritz, Co-chairman L. Sahakyan***

14:30–14:50 Th. Tsapanos, G. Drakatos. Changes of B-values before large earthquakes in different tectonic regimes.

14:50–15:10 S. Hovhannisyan, A. Makaryan. Relation of tectonomagnetic anomalies and seismicity.

15:10–15:30 J. Karapetyan. Discussion geophysical and engineering-seismological research in Armenia main directions, achievements and prospects for development.

15:30–15:50 H. Melik-Adamyan, Kh. Khachanov. Contribution of Herman Abich into Seismology and Seismotectonics of the Armenian Highlands and its Adjacent Areas.

15:50- 16:10 – Coffee break

16:10–18:00 DISCUSSION AND POSTER SESSION

K. Ahmed, L. Gevorgyan. Encountering influence of disasters on policy makers: A theory of disaster risk governance.

H. Mkrtchian, V. Mkrtchyan. Neotectonics of 1988 Spitak earthquake epicentral area; 1989 field data revisited.

R. Houdijk, Nico van Os, Hripsime Aghagulyan. Improving local capacities for seismic vulnerability reduction.

A. O. Matossian, A. Karakhanian and H.-B. Havenith. Identification of giant mass movements in the Lesser Caucasus (Armenia) and assessment of their spatial relationship to major fault zones and volcanoes.

R. Civico, P. Baccheschi, F. Villani, V. Sapia, G. Di Giulio, M. Vassallo, M. Marchetti, and D. Pantosti. Reconstructing the geometry of a fault-bounded extensional basin by integrating geophysical surveys and shear wave splitting anisotropy: The study case of Pian Grande di Castelluccio Basin (Central Italy).

P. M. De Martini, F. Villani, S. Pucci, F.R.Cinti, R. Civico, D. Pantosti. Surface faulting following the 30 October 2016 Mw 6.5 Central Italy earthquake: Analysis of a complex coseismic rupture.

S.Baize, F. R. Cinti, T. Azuma, J. Champenois, R. Civico, C. Costa, T. Dawson, L. Guerrieri, Y. Klinger, E. Marti, J. P. McCalpin, K. Okumura, A. Sarmiento; O. Scotti, M. Takao, and P. Villamor. Towards a unified and worldwide database of surface ruptures (sure) for fault displacement hazard analyses.

A. Berezina, E. Pershina . Seismic observations in Kyrgyzstan: Stages and perspectives of development.

A. Mukambayev, N. Mikhailova. Seismic history and contemporary seismicity of the past 25 years on the territory of Dzhyungariya.

N.Toghramadjian, A. Kafka, L. Sargsyan. Cellular seismology analysis of seismicity associated with operating Armenian dams

A. Siylkanova, N. Stepanenko, A. Sadykova. Active faults of Eastern Kazakhstan

G. Boichenko, E. Cowgill, T. Stahl, C. C. Trexler, L. Tsiskarishvili, L. Sukhishvili, S. Gogoladze, T. Godoladze, M. Elashvili, G.Sokhadze, G. Akhalaia. A paleoseismic investigation of a frontal foreland thrust in the Greater Caucasus, Georgia

M. Adibekyan. Earthquake process reverberation through electromagnetic field variations.

R. Atabekyan. Estimation of the seismic resistance of buildings based on instrumental measurements.

Z.Garibyan. Interpretation of artificially-induced fields of constant electric power against the background of seismotectonic processes.

A. Karakhanyan, P. Tozalakyan, A. Avagyan and G. Alaverdyan. Gas emission in the active fault zone in Lesser Sevan Lake (Armenia).

R. Gasparyan. Geoecological problems of the territory of the city of Gyumri and its environs

A. Avanesyan, A. Kazarian. Spitak earthquake and the concept of earthquake nucleation and evolution process.

Z. Khlghatyan, N. Ghukasyan. The peculiarities of construction of Yerevan city from the point of view of seismic risk.

S. Darbinyan, S. Kakoyan. The elements of education of seismic protection in Armenian schools.

G. Grigoryan, S. Nazaretyan. Geological consequences of the 1988 Spitak earthquake and its importance from the standpoint of development of geological tourism.

J. Karapetyan, A. Gasparyan. New type seismometer.

J. Karapetyan, H. Hayrapetyan. Technical condition and vulnerability assessment of buildings using microtremor system.

A.Ghonyan, H.Tatsuhiko. Application of B-Δ and $P_d$ methods to broadband data in Armenia.

K. Harutyunyan, G. Hayrapetyan, A. Arakelyan, A. Ghonyan, A. Gevorgyan, S. Margaryan. Evaluation of the seismic risk of communities in the Republic of Armenia (example of Vardenis city)

M. Mkrtchyan. The connection of the mechanisms of the source of strong earthquakes of the Armenian Upland with geological structure.

H. Igityan, M. Gevorgyan, and E. Sahakyan. Study of near-surface active fault structures in the regional compression and extension zones of the Lesser Caucasus (by the example of the active Pambak-Sevan-Syunik fault)

## 5 DECEMBER

### Meeting Room 1 (Ani Plaza Hotel)

### *ISTC WORKSHOP*

***Chairman Prof. K. Abdrakhmatov, Co-Chairman Dr. H. Babayan***

14:30–14:50 I. Gunia, G. Sokhadze, T. Godoladze, D. Mikava, N. Tvaradze. Database of Seismic monitoring center of Georgia.

14: 50–15:10 R. Dzuraev. Using macro seismic data for the assessment of the seismic vulnerability for the area of Dushanbe City.

15-10–15:30 N. Tumanova, T. Godoladze, E. A Sandvol, S. Kakhoberashvili, S. Ukleba, K. G Mackey, J. Nabelek, H. Babayan, G. Yetermishli, A. Malovichko. Recent Development of National Seismic Network of Georgia

15:30–15:50 H. Babayan, G.Hovhannisyan, S. Babayan, M. Gevorgyan. Damage and loss assessment of large cities of Armenia caused by strong earthquake

15:50-16:10 – Coffee break

16:10–16:30 K. Abdrakhmatov. Active faults and seismic hazards of the Tien Shan.

16:30–16:50 A. Karakhanyan, H. Babayan, S. Arakelyan, L.Sargsyan. Input databases for the development of the Probabilistic Seismic Hazard Assessment for the Republic of Armenia.

16:50–17:30 Discussion

## 6 DECEMBER

### DVIN Hall (Ani Plaza Hotel)

## SECTION 3 .GEOHAZARDS, SEISMIC RISK ASSESSMENT AND SEISMIC RESILIENCE.

***Chairman Prof. H.-B.Havenith, Co-Chairman S. Nazaretyan***

09:30–09:50 A. Avagyan, A. Karakhanyan, H. Philip, J-F. Ritz, L. Sahakyan, T. Atalyan, M. Martirosyan, S. Avagyan. The Sevan basin in the epicenter of the geological hazards.

09:50–10:10 B.I.R. Müller, O. Heidbach, F. R., Schilling.The role of tectonic stress on geo-hazards.

10:10–10:30 A. Gaggioli  Earthquake Resilience and Society: the intersection of archaeology, myth, and geology at Late Bronze Age Akrotiri.

10:30–10:50 Kh. Meliksetian, R. Jrbashyan, H. Gevorgyan, G. Navasardyan, E. Grigoryan, D. Manucharyan, M. Misakyan. Volcanic hazards as an underestimated risk factor in Armenia, Georgia and Eastern Turkey.

10:50–11:10 H.-B.Havenith, A. O.Matossian. Analysing the Tien Shan and Lesser Caucasus landslide databases.

11:10–11:30 A.Braun, T. Fernandez-Steeger, A. O. Matossian, H.-B.Havenith. Applications and limitations of data mining methods – examples from landslide susceptibility mapping in Kyrgyzstan and Armenia.

11:30-11:50 Coffee break

11:50–12:10 L. Gevorgyan, K. Ahmed. Comparative analysis of socio-economic systems resilience and vulnerability frameworks: drivers, dynamics and spatiotemporal scale.

12:10–12:30 V. Grigoryan. Some methodological aspects of the assessment of seismic risk and vulnerability.

12:30–12:50 H. Petrosyan. Technique of assessment of current seismic hazard.

12:50–13:10 S. Nazaretyan, H. Karapetyan, K. Mkhitaryan, E. Mughnecian, M. Tigranyan. Methodology for seismic risk assessment of territory of small sites of Armenia.

13:10–13:30 H. Hakobyan. Lessons of the Spitak earthquake after thirty years.

13:30 – 14:30 Lunch break

## 6 DECEMBER

## DVIN Hall (Ani Plaza Hotel)

## *SECTION 4. EARTHQUAKE ENGINEERING*

***Chairman Dr. R. Atabekyan, Co-Chairman Z. Khlghatyan***

14:30–14:50 **A**. Hovsepyan. In estimating buildings and structures for seismic impacts on the allowance for complex engineering-geology conditions on the allowance for complex engineering-geology conditions in estimating buildings and structures for seismic impacts.

14:50–15:10 Z. Khlghatyan, S.Margaryan, G.Namalyan, T.Tovmasyan. Seismic Safety Assessment of the Schools of RA.

15:10–15:30 Z. Khlghatyan, G. Namalyan. New experience of applying tuned mass dampers (TMD) in Yerevan city

15:30–15:50 R. Atabekyan. About estimation of accuracy of seismic loads determination.

15:50- 16:10 – Coffee break

16:10–16:30 L. Agayeva, M. Meredova, E. Esenov. Seismic safety in Turkmenistan Ashgabat disaster of 1948: Lesson learnt

16:30–16:50 I. Kalandarbekov, D. Nizomov, I. Kalandarbekov. Studies of free oscillations of buildings taking into account seismic isolation.

16:50–17:10 S. Nazaretyan, K. Mkhitaryan, M. Tigranyan, J. Movsisyan.Special macroseismic scale on the base of damages Armenian churches

17:10 –17:30 Discussion

## 6 DECEMBER

Meeting Room 1 (Ani Plaza Hotel)

***ISTC WORKSHOP***

***Chairman Prof. T. Godoladze,***

10:00–10:30 K. Sesetyan. Earthquake Model of the Middle East Region (EMME) project. Overview of the main results.

10:30–16:00 Questionnaire of regional ISTC project

- Georgian team presentation
- Kyrgyzstan team presentation
- Tajikistan team presentation
- Kazakhstan team presentation
- Armenian team presentation

Discussion

11:30–11:50 Coffee break

13:30–14:30 Lunch break

# ABSTRACTS

## SECTION I.
## 1988 Spitak earthquake: field observations in the epicentral area; present-day seismicity of the region; new studies and results after 30 years.

### SPITAK 1988 EARTHQUAKE COMPLEX SEISMOLOGICAL AND SEISMOTECTONIC STUDY RESULTS

**E. Rogozhin**
*Institute of Physics of the Earth, RAS, 10 B. Gruzinskaya, Moscow, Russia. Email: eurog@ifz.ru*

The Spitak earthquake that occurred 30 years ago on December 7, 1988 (M = 6.8) was one of the most destructive in the USSR. The earthquake killed at least 25 thousand people. It took place in Northern Armenia (in the territory of the Lesser Caucasus) and was accompanied by the formation of a system of surface seismic dislocations, namely extensive uplift of the earth's surface (the geodetic study results); primary seismic ruptures, landslides, rock falls, talus, and subsidence of soils. The main seismogenic fault with a total length of about 35 km crosses the northern slopes and spurs of the Pambak Range in the area of Spitak town in the North-West direction. It appeared in the area of the active Alavar fault.

The near-surface structural features of the seismic rupture and the morphology of rock contact in it were studied in trenches, where the structure of the "walls" was found to be different. During the earthquake, the north-eastern "wall" was raised to a height of 0.3–0.5 m. The seismic rupture is dipping to the north-east at an angle of 40-50°, and near the surface it is at about 10-20°. In the trench walls located in the same seismic source, we found some signs of three ancient earthquakes, which had occurred about 24,000-25,000, 16,000-17,000 and 6,000 years ago with a period of recurrence ranging from 6000 to 10000 years.

The temporary international network of seismic stations located in the epicentral zone immediately after the main shock recorded several thousands of aftershocks with different magnitudes; this made it possible to reconstruct the structure of the seismic source at depth. The source was situated in the upper horizons of the crust and had a depth of 10-14 km. The field of aftershock epicenters, forming a narrow, linearly-elongated band, corresponded to the area of the surface seismic fault. The good quality of registration of earthquake aftershocks allowed the French and Soviet scientists to design a seismo-tomographic model of the foci at the depth.

According to the data of that aftershock study, the earthquake source in the tomographic image of the seismic velocities distribution looked like as a narrow zone with low seismic velocities of Vp. Usually the Vp values within such zones are about 0.5 km/s less than those in the surrounding, undisturbed blocks of the crust. This zone in the form of a narrow "pocket" penetrates into the middle crust horizons and is somewhat inclined to the North, at an angle of about 60-70° according to the general dipping of the fault surface established by geological observations conducted both on the ground surface and in the trenches. The cloud of aftershock hypocenters was developed in the crust under the same angle.

## SEISMOLOGICAL EXPEDITION OF THE IPE USSR IN THE EPICENTRAL AREA OF THE 1988 SPITAK EARTHQUAKE

**R. Tatevosyan**
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The expedition organized to the epicentral zone of the 1988 Spitak earthquake was the first attempt of international co-operation in earthquake studies in the Soviet Union. After 30 years, very few members of the expedition continue studies in seismology. In memory of the common efforts and co-operation of those days, we consider all members of the 1988 – 1989 expedition as co-authors of this presentation. Dense seismic network was installed, which made it possible to monitor the activity of aftershocks in near-real time and study their spatial and time distribution. Near-field data allowed the study of the structure of the earthquake source zone in detail, outlining the segments, and determining stress-field characteristics. This resulted in constructing the source model fitting both the geological and the seismological data. The valuable experience got in the epicentral area of the Spitak earthquake was used in the studies of the Racha 1991 (Mw=7.0), the Shikotan 1994 (Mw=8.3), the Neftegorsk 1995 (Mw=7.1), the Altai 2003 (Mw=7.3) and some other seismic events. Epicentral observations make it possible to find out peculiarities of the aftershock sequences, which are often different from worldwide observed statistical relationships.

## THE SPITAK EARTHQUAKE OF 7 DECEMBER 1988: MAIN SEISMOLOGICAL CHARACTERISTICS AND ANALYSIS OF ITS DESTRUCTIVE EFFECTS (TO THE THIRTY YEARS AFTER THE EARTHQUAKE).

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December 7, 1988 in the Northern regions of the Republic of Armenia there was a strong earthquake, which later became known as the Spitak earthquake. It caused massive destruction of buildings and structures, caused great material damage to the country and claimed the lives of thousands of people.

After 30 years, the lessons of the Spitak earthquake are still instructive, both for the engineering community and for the common man in the street. A detailed scientific account of all the features and consequences of the Spitak earthquake is given in this article.

Unfortunately, there are very few instrumental records of the Spitak earthquake. The article provides an analysis of the few accelerograms of the earthquake, which were registered both at seismic stations of the former USSR and abroad. Presented and analyzed the geophysical and energy characteristics of the focus of earthquakes, foreshocks and aftershocks of the seismic event.

The earthquake in the epicentral zone caused significant geotechnical changes on the Earth’s surface in the form of dislocations, landslides, landslides, ledges, cracks, falling large volumes of rock, soil liquefaction, destruction of the railway track. The results of studies to assess the impact of local soil conditions on the strengthening or weakening of the level of concussion of soils.

The article presents a method of instrumental assessment of the degree of damage to buildings after the earthquake, regulated by the norms of earthquake-resistant construction in Armenia. The method is based on the ratio of periods of oscillation of damaged and undamaged buildings.
The article also discusses the socio-economic consequences of the Spitak earthquake, and describes the great assistance provided by the international community to the Armenian people in the aftermath of the devastating earthquake, the feats shown by thousands of doctors, rescuers, pilots, drivers, builders and workers.

## AFTERSHOCK PROCESS AND DISCHARGE OF SEISMOTECTONIC STRESSES IN THE FOCAL ZONE OF THE SPITAK EARTHQUAKE

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A detailed analysis of the aftershock process of the catastrophic Spitak earthquake (07.12.1988 M = 7.0) was carried out on the basis of modified variant of the Omori law proposed by Narteo and Shebalin:

$$\lambda_{(t)}=K/(t+c)^p$$

According to this law, the number of aftershocks per unit of time is approximated by three phases:

1. linear
2. hyperbolic
3. exponential

The first phase, which corresponds to the initial period of aftershock process (basically the initial period), characterizes the stress-strain state of the fault, the second phase basically reflects the physic-mechanical state of the geological environment; the third phase is the stage of relaxation of tectonic stresses in the focal zone. The essence of the task is to reveal the main regularities and characteristic features of the manifestation of the spatial-temporal-energy distribution of the Spitak earthquake aftershock process. With the help of the time-energy development of aftershock process, the release of seismotectonic stresses in the focal zone is estimated. The quantitative estimation of seismotectonic stresses is carried out on the basis of the theoretical relations between stress and strain in the framework of linear mechanics represented by the following form:

$$\sigma=\varepsilon\cdot\mu$$

Seismotectonic stress release has a stepwise nature with separate periods of increased values of seismic energy release and released potential associated with strong aftershocks. This type of stress release is a characteristic of the entire aftershock process. There are several stages of stepwise discharge with decreasing residual stresses in the range from 0.68 to 0.26 bar.

# GEODYNAMIC MODEL OF THE SPITAK EARTHQUAKE SOURCE AND THE ANALYSIS OF THE SEISMIC PROCESSES IN IT

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One of the main directions of the Spitak earthquake study was investigating the process of fracturing and seismic radiation at the main shock, determination of their kinematic and dynamic characteristics. Analysis of wave fields from instrument records of teleseismic and regional stations, application of inversion methods in the processing of seismic wave records allowed proving that the focal process during the Spitak earthquake had a multiplet character and represented a multi-actuation process of faulting of the focal zone. Later this conclusion was confirmed by the results of detailed geological surveys and instrumental seismological observations of the development of the aftershock process in the epicentral zone. The analysis of the structure of primary seismic dislocations that appeared in the isoseismic zone and the hypocenter locations of the first strong aftershocks revealed a complex geometry of this rupture. From this standpoint, the focus of the Spitak earthquake is a set of fracture surfaces, along which motions occurred in certain sequence and caused complex emission of seismic energy. A model that maps the geometry of these surfaces and determines the sequence of motions is usually called the geodynamic model of the source. On the basis of complex seismological and geological tectonic data, several variants of the geodynamic model of the Spitak earthquake source were proposed, consisting of different in number sub-sources. As a geodynamic model, we adopted a model consisting of 4 sub-sources, which adequately reflects the complex faulting process of the focal zone.

Our task was to investigate the course of the seismic process according to this geodynamic model for the period of time from 07.12.1988 till the present.

With the help of methodological approaches of structural and focal seismology, it was established that the space-energy development of the seismic field had complex migratory nature and areas of tectonic elements and their high-seismicity segments were identified. On the basis of seismic moments and parameters, the mechanism of earthquake sources was used to perform tensor analysis of stress-strain processes and quantitative estimation of relative seismotectonic deformations that occurred in these active areas. Using a comparative analysis of the IV consecutive stages of the kinetic the theory of strength of a solid body and the parameters of the current seismic regime, possible abnormal changes in the local stress field occurring in this complex disjunctive node, which are long-term and medium-term seismological precursors, are identified.

The obtained results make it possible, on one hand, to follow the evolutionary course of the seismic processes in the Spitak geodynamic model, and, on the other hand, to propose a generalized image of the seismogenesis of the focal zone.

# NEOTECTONICS OF THE 1988 SPITAK EARTHQUAKE EPICENTRAL AREA: THE 1989 FIELD DATA REVISITED

**Dedicated to the living memory of Koryun Mkrtchyan – Great Geologist and Naturalist**

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The main neotectonic structural features of the Spitak earthquake epicentral area are the Spitak and Shirakamut (Nalband) depressions and the Gogaran horst-uplift. The character and the rate of the post-Wurm age (12,000 yr) dislocations were studied in field by detailed mapping of the reference horizon of volcanic tuffs in the Wurm-age terrace. Most studies conducted after the December 7, 1988 Spitak earthquake were focused on the main Earthquake Rupture Fault located within the northwest-trending right-lateral oblique Amasia-Sevan Fault system. This study focuses on other faults separating the Gogaran horst from the Shirakamut and Spitak structural depressions on the West and on the East.

The eastern margin of the Gogaran horst is bounded by a number of northeast-striking sub-parallel faults, dipping to the southeast and to the northwest. Cumulative uplift on the eastern flank of the horst over the distance of 1km is 130-140 m. About half of this displacement (70 m) is accommodated along the northeast-striking, northwest-dipping reverse West Spitak Fault which outcrops at the eastern gate of the Shirakamut - Spitak highway tunnel.

Geomorphologic and borehole data indicate 25-30 meters of displacement along the northeast- striking normal Spitak Fault at the northwestern edge of Spitak Town, near the railroad crossing. West of the reverse West Spitak Fault, several northeast-striking faults with small normal-fault displacements (0.1 to 0.5m) offset the reference bed of the Wurm-age tuff.

The southwestern edge of the Gogaran horst is bounded by several faults. The largest displacement occurred along the reverse Chichkhan Fault mapped on the left bank of the Chichkhan River. Structurally, this fault follows a Wurm-age terrace, containing two prominent tuff beds seen north of the Gyumri – Spitak Highway. The Wurm-age alluvial deposits between the two tuff beds are 28 m thick. Displacement on the reverse Chichkhan Fault is 60 m, up on the northeast side. Displacement along the Chichkhan Fault decreases along the strike toward the northwest; in the area of a monastery located about 2 km farther, the fault zone represents a steep dip flexure. To the southeast, the Chichkhan Fault trends towards the city of Spitak, passing through the area of the former sugar refinery and thence toward the Spitak city center.

Twelve active normal faults, dipping to the southwest, have been mapped on the right bank of the Chichkhan River, west of the reverse Chichkhan Fault, in the sections of the highway and the railroad. Individual displacements along these faults range from 0.2m to 2m on the reference tuff beds and the Holocene-age terrace. The Holocene and the Wurm deposits are dipping 14-15° to the southwest, toward the center of the Shirakamut depression. The thickness of Quaternary deposits filling the Shirakamut depression reaches 120 m. The total post-Wurm displacement along the southwest flank of the Gogaran horst, over the distance of 3 km, is about 200 m large.

The Gogaran horst is composed of the Paleogene volcanic-sedimentary deposits. Several small-amplitude faults (0.1m to 0.5m) have been documented in the central portion of this uplift.

Several landslide fields have been identified and mapped: some of them are located in the southern part of Spitak Town, in the valleys of the Pambak River and the Chichkhan River. A big and active landslide field developed on the right bank of the Chichkhan River, at the site of Ghetik dam (currently being built).
The glacial Wurm period ended about 12,000 years ago. The post-Wurm offset by 60 meters along the West Spitak and the Chichkhan reverse faults indicates that the rate of displacement ranged up to 20 mm/yr approximately. The accuracy of this high rate of uplift could be improved when the absolute age of the tuff beds is determined.

## STRUCTURAL AND DYNAMIC CHARACTERISTICS OF THE CRUST IN THE SPITAK EARTHQUAKE EPICENTRAL ZONE AND ADJACENT REGIONS ACCORDING TO GEOPHYSICAL AND MODERN DEFORMATION DATA

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The studied area is located in the central part of the Alpine-Himalayan seismic zone – Anatolia-Caucasus segment, within the collision zone of the Arabia and Eurasia plates. According to the GPS data, the Arabian plate moves towards the Eurasian plate in the north-western direction at the rate of 18±2 mm/yr. As a result of the mentioned collision, the area of Armenia is continuously exposed to compressive stress in the north-eastern-near meridian direction at the rate of 10 mm/yr, which results in permanent crustal deformations reflected in recent horizontal and vertical movements. These deformations are usually followed by strong earthquakes such as the earthquake in Spitak in 1988.
Considering the complex geo-tectonic and mosaic-block structure of the crust in Armenia, the horizontal movement of the Earth's crust will result in different rates of deformations within individual blocks of the area. Obviously, the greatest deformations will be characteristic for the weakest zones of the Earth crust; that is for the fault zones.
This methodological approach served as a basis to apply instrumental surveys of horizontal and vertical movements of the Earth crust, undertaken by both local and foreign organizations in different pre-earthquake and post-earthquake periods, to evaluate the geodynamic activity of the structural model elements we identified in the study area. Data resulting from the correlation and analysis of the time stages indicated that the elements of the fault-block structure model of the Earth crust in the investigated area were actively involved in the change of the average velocity vector of the Earth's crust in Armenia. It has been established that the horizontal velocity vectors of GPS stations calculated with reference to the Eurasian plate undergo various modifications within the study area from the south to the north. Thus horizontal displacement velocity vectors of the GPS stations located in the center of the area are characterized by the maximum values with respect to those recorded for the stations located in the northern or southern areas. This is explained by inhomogeneous structure of the crust, represented by deep-seated active faulting and blocks, due to which the horizontal velocity vector increases and reduces from the south to the north, partially converting to modern vertical movements in the edge zones of the faults and blocks.
It was confirmed also that the epicenter of the Spitak earthquake during the post-earthquake 1989/90-2003/06 phase had been exposed to the influence of modern vertical crustal

movements with maximum annual depression speed of 9-10 mm/yr and has been subjected to the current fracture regime due to the tension in the region. It has also been revealed that apart from the regional compressive influence with South--North-eastern direction, there is also tensile strain influencing the area.
On the basis of analysis of conducted secular (1911-2006 yy) studies data that exist for the region 3 stages of modern vertical crustal movements has been revealed, when the sign of that movements was changing: Stage I - depression, which can be explained as a stage of regional bending, extension-tensile stresses, Stage II – post-earthquake stage of uplift, compressive stresses, Stage III – stage of depression bending, tensile stresses. The Spitak earthquake corresponds to Stage II and was generated predominantly due to compressive stresses.

## ROUND-THE-WORLD SURFACE SEISMIC WAVES AS A TRIGGER OF STRONG AFTERSHOCKS

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The existence of the effect of the round-the-world surface seismic waves (“seismic echo”) in the evolution of aftershock process was demonstrated in the work based on a broad-scale evidence, including hundreds of main shocks and thousands of aftershocks. The effect is that surface waves excited in an earthquake source by the main shock make a complete revolution around the Earth and excite strong aftershock in the epicentral area of the main shock. The physical nature of the effect is that critical concentration of wave energy in the epicenter is created by converging surface waves under achieving of epicentral area. Effect of the first seismic echo is manifested most clearly. For the statistical analysis of the dynamics of the seismic events flow after strong earthquakes (main shocks, shocks), we selected several datasets from a long-time series of earthquakes contained in the global USGS/NEIC catalog for the period of 1973-2014 and in the regional catalog of Northern California for the period of 1968-2007. To perform data processing and efficient detection of the seismic echo effect, we used an algorithm based on the well-known superposed epoch analysis, or synchronous detection method. Fig. 1 shows the accumulated sequences of normalized magnitude of repeated shocks.

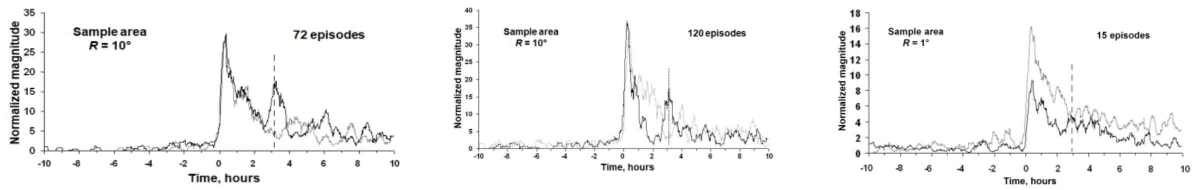


Fig. 1. Cumulative sequence of normalized magnitudes of repeated shocks for main shocks with magnitudes M≥ 7.5 (a); 7 ≤ M< 7.5 (b) USGS/NEIC catalog; M≥ 5.5 (c) Northern California catalog. The identified seismic echo effect (black line) is shown against the events, in which the effect is absent (gray line). Vertical dashed line marks the time of maximum in the effect of first round-the-world seismic echo.

The seismic echo effect (black curve) is shown in comparison with the events, in which the effect was absent (gray curve) for the main shocks with magnitudes M≥ 7.5 (Fig. 1a), 7

≤M<7.5 (Fig. 1b), and M≥ 5.5 (Fig. 1c). Vertical dotted line in the figures marks the time of the maximum effect of the first round-the-world echo. The detected seismic echo phenomenon can be used to increase the probability of a forecast of a strong aftershock in determining the seismic process scenario in the epicentral zone after a strong earthquake occurs.

This work was supported by the Russian Foundation for Basic Research, Project #18-05-00096.

## RESPONSE OF THE LOCAL GEOMAGNETIC FIELD TO THE GEODYNAMIC PROCESSES DURING PREPARATION OF THE 1988 SPITAK EARTHQUAKE

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A technique is proposed to study variations of the external-origin local geomagnetic field, related to changes of electrical conductivity at diverse depths of the Earth crust and the upper mantle as a result of evolving geodynamic processes. N(A) computation parameter representing the relation of amplitudes of external geomagnetic field variations measured synchronously at different station pairs was used:

$$N(A) = Ai/Aj,$$

where Ai and Aj were the amplitudes of synchronously-measured variations at fixed locations (i, j). Where three or more observation points are available, the technique permits identification of the zones most active in terms of geodynamics within the study regions. Applying the proposed technique in Armenia, anomalous changes in the response of the local geodynamic field before the 1988 Spitak earthquake had been revealed.

Geomagnetic variations generated by an external source enable identification of space-time changes of electromagnetic induction in the Earth crust. Applying the N(A) computation parameter, Sq and bay-form variations of the geomagnetic field components ($\delta Z$, $\delta H$, $\delta D$), we succeeded in evaluating the changes of electrical conductivity in the Earth crust up to the upper mantle and identified zones of the greatest geodynamic activity where sources of future strong earthquakes could form.

The conductivity changes are caused by movements of liquid and gaseous fluids ascending through deep faults from the crust-mantle boundary zone.

For variations at the periods of a) 5-25 and b) 30-60 minutes, synchronous difference $\Delta\delta T$ between stations Jradzor and Tovouz during 1986-1988 enabled suggesting the bottom-up directivity of development of the processes in the Earth crust, and distinguishing, against the background of regional changes in the response of the magnetic field, the local ones, which fit in the time frame of the local strong earthquakes: the Parvana (M=5.4) and the Spitak (M= 7.0). Based on the obtained data, it is possible to judge on the reversibility of the process that had been evolving within the study area before the Spitak earthquake.

Conclusions:

- The proposed technique enabled an evaluation of the electrical conductivity changes in a geological medium during preparation of strong local earthquakes;
- It was demonstrated that the process was reversible;
- The directivity of the process was established (bottom-top);
- It had become possible to identify zones of the greatest geodynamic activity.

## DETAILED ANALYSIS OF VARIATIONS IN GEOCHEMICAL DATA TIME SERIES BEFORE THE SPITAK EARTHQUAKE

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Study of the chemical and gas composition of underground water from self-pouring wells before the Spitak earthquake reveals that there were numerous geochemical precursors. More detailed studies of the precursors show that some of them are consistent prior to all major seismic events in the region. They have long duration and appear almost one year prior to strong earthquakes. There is a correlation between the statistical characteristics of the precursors and the time, intensity and location of the earthquakes that followed.
The retrospective predictive analysis of strong events demonstrates the possibility of using these types of precursors for early detection of earthquake nucleation process in real time. Comparison of data from different observation stations shows that the concentration of *He* in the underground water can be considered as the most reliable and universal precursor.
A new type of earthquake nucleation model was proposed. Determination of the time, location, and magnitude of strong earthquakes can be based on the proposed physical model of earthquake source. Gas monitoring of self-pouring wells will allow tracking both earthquake nucleation and development process long before an event. Real-time early detection of a strong event nucleation process in the region should be based on more detailed geochemical monitoring over a network consisting of 12 observation stations at least that are set 100 km apart.

## THE SPITAK EARTHQUAKE AND THE CONCEPT OF EARTHQUAKE NUCLEATION AND EVOLUTION PROCESS

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Despite the ongoing discussion on the possibility and need for earthquake prediction, this topic continues to be on the study list in many countries.
The problem of earthquake prediction has multidisciplinary character and includes the stages of:

1) Determination of precursors and
2) Calculation of earthquake parameters: Time, Location, Magnitude (TLM).

Elastic Rebound Theory (ERT) declared the entire process to be a response to an ongoing rise of tension between tectonic blocks. It assumed that tectonic forces should reach maximum levels just before the strike. However, any increase of forces between tectonic blocks prior to strong earthquakes was never measured. As a result, the rate of “tension accumulation process” was never determined. The “precursors” revealed prior to each new event have demonstrated to have different morphology and appearance in time. This makes it impossible to use them for prediction.

The ERT theory assumes that the number of precursors should increase just before the strike. Earthquake is assumed to be an anomaly impulse event. Precursors are also expected to be in the form of an anomaly or to have a tendency to be more evident close to the main event. However, any search for those anomalies have not been successful. Stein's laboratory experiments stated that earthquakes represent Self Organized Critical (SOC) processes and are considered unpredictable by many scientists.

The geochemical precursors discovered recently during the study of the Spitak event are called geochemical quiescence and show that the final stage of earthquake preparation is a relatively short period of several years and has several stages. Changes in the statistical characteristics of the measured data during the monitoring period proved to be a more reliable precursor. The constant character of newly discovered precursors makes it possible to use them for early determination of the TLM of an upcoming strong event.

The study of hydro-geochemical precursors of the Spitak earthquake and other strong events in the region leads to the determination of the character of earthquake preparation process in general. We were able to observe that this process had different stages and was well reflected in the statistical characteristics of the measured parameters. Determination of different preparation stages will help in precursor search in other studies.

## ANALYSIS OF DATA OF MODERN VERTICAL CRUST MOVEMENT IN THE SPITAK EARTHQUAKE REGION

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Data from scientific works provided by the specialists from the USA, the USSR, Japan, Armenia and other countries regarding the Spitak Earthquake were studied. The differences in the absolute benchmark elevations obtained as a result of balancing the previous leveling works at the geodynamic polygon of the Spitak region were summarized, analyzed and calculated. Based on that data, a map of the contemporary vertical movement of the Spitak earthquake zone before the earthquake (1988) and later (1989-90) was created. A map of recent vertical movements of the Earth crust between the periods of1989-90 till 2002-2006 was prepared. The maps were created according to the following principles.

The electronic data of the isogonic directions of the mapping velocity of the earth's crust were constructed in 1988 until 1989-90, 5mm, and from 1989-1990 up to 2002-2006 with a 1mm drop.

The maps of recent vertical movements of the crust before and after the earthquake were combined. It turned out that in the Spitak region, crust sedimentation took place in 1989-90 at a rate of 60 mm/year as a result of the earthquake, and after the event the crust sedimentation had the rate of 12 mm/year (near the 2002 benchmark) till 2002-2006, that is to say, the rate of earth sedimentation decreased 5 times approximately. Graphs of vertical movement of some benchmarks have been built with the graphs within 1989-2015. It is clear from the graphs that the rate of the earth crust sedimentation of 9-12 mm / year is had remained unchanged until 2015. It is assumed that currently the activity of the Earth sedimentation in the region has the same rate.

We consider the need of conducting an additional, 4th stage geodetic survey of the "Spitak Geodynamic Polygon" object, by adding the following extra works:

1. Taking into consideration that the North-Eastern region of the disaster zone is not included in Geo Polygon, it is recommended to create a new technical project for the 4th stage to have a complete pattern of the whole region (Gyumri - Akunk - Voskehat - Haykavan - Ogcheri - Meghrashat - Gtashen - Zarishat - Shaghik - Tsaghkunq - Berdashen - Aghvorik - Ghazanchi);
2. In the new technical project, particular attention should be paid to the basics installed in Classification I and II leveling works of all previously implemented objects, by including them in the new project.
3. After the completion of the geodesic works provided for by the project, analysis of the Earth's crust shall cover the periods until the 1988 earthquake in Spitak, within one year after the earthquake (1988-1990) and a later period. According to the analysis, maps of the vertical and horizontal movements in the region must be prepared. Comparing the produced maps according to the observation years, regularities in the rates of vertical movements will be established.
4. To make the technical project more complete, it should be discussed with experts from relevant geological, geophysical and seismological services. After taking into account the suggestions and comments emerged as a result of the discussion, the project shall be submitted for approval and realization in accordance with the established procedure.

## ANOMALIES OF THE EARTH'S MAGNETIC FIELD SPATIO-TEMPORAL VARIATIONS AND SEISMIC ACTIVITY IN THE NORTHERN PART OF THE TERRITORY OF ARMENIA (CASE STUDY)

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The method of identifying geomagnetic field total intensity anomalous variations connected with the dynamic properties of the Earth's crust and upper mantle was developed and applied. It is based on the analysis and removal of the regional trend of geomagnetic variations of both internal and external origin observed in the period of investigations.
As a result, the trend of the internal-origin geomagnetic field during the period 2007-2008 is revealed in the northern part of Armenia, which is neither a component of the secular variation of the global feature geomagnetic fields of internal and external origin, nor an induced part of them. It turned out that the seasonal geomagnetic variations, which have been discovered in the time series of deviations of the geomagnetic field daily mean values observed at "Bavra" station, represent a superposition of the variations of internal and external origin. The phase deviation in the seasonal variations observed in the series from "Gyulagarak" station, in relation both to the series from "Bavra" and to the series of external variations, may be caused by lateral inhomogeneity of the electrical conductivity inherent to the Earth's crust in the region of observations.
The detected annual variations of the observed geomagnetic field, which appear at maximum intensity during the summer period and at minimum during winter, evidently reflect the dynamics of the current system flowing in the ionosphere under the influence of the solar activity. In contrast, the semiannual variations are detected in the indices of geomagnetic

activity, which appear as two maxima conditioned by the dynamo-processes taking place in the magnetosphere during the period of the spring and summer equinoxes.
Complex analysis of spatio-temporal features of the local anomalies revealed in the geomagnetic variations, along with the geological and tectonic structure as well as the seismic activity of the region under investigation, allows us to conclude that the observed anomaly of the secular variations at "Bavra" Station resulted from the piezo-magnetic effect and so, may be considered as an evidence of seismic activity of the region. Whereas the anomaly of secular variations observed at "Gyulagarak" Station has relatively smaller amplitude and has most likely resulted from the currents induced in the electrically low-resistant part of the Earth's lithosphere under the influence of varying external-origin geomagnetic field.
The earthquakes that occurred during the observation period also manifested themselves in the daily variations intensity (direct correlation). Whereas, the correlation between the characteristic (regional) parameters of the investigated phenomena is inverse when we consider the variations in the middle-frequency spectrum range, i.e., in seasonal variations observed on the series of monthly mean values. There is also a correlation between the seasonal variations of the global geomagnetic activity and the seismicity of the region, both determined as an averaged over the past 50 years. Moreover, the semiannual variations are observed in the geomagnetic activity, as well as in the seismic activity assessed by the monthly values of the total energy released and the number of earthquakes observed. Analysis of the observed relationships between these phenomena allow us to conclude that their mutual dependence is possible and the mechanism of their interaction resembles the scenario of triggering by the external-origin geomagnetic variations of the active changes in dynamic processes taking place in the Earth's crust and upper mantle, which in their turn may originate tectonic earthquakes.

## GEOLOGICAL CONSEQUENCES OF THE 1988 SPITAK EARTHQUAKE AND ITS IMPORTANCE FROM THE STANDPOINT OF DEVELOPMENT OF GEOLOGICAL TOURISM

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Manifestations of seismo-gravitational processes attract attention of tourists, scientists and students, because these encompass large-scale changes in the relief (on the ground of the Earth) and the observer can comprehend the full extent of the force of the 1988 Spitak Earthquake.
The sample taken by A. Karakhanyan during the study of the Geghassar-Spitak Fault rupture is preserved and displayed at the Geological Museum after H. Karapetyan of Institute of Geological Sciences of the National Academy of Sciences. The scientific explanation and photographs of the display raise great interest among museum visitors and we are often asked to organize field trips to see the phenomenon. Despite the fault rupture has lost its original formidable look due to erosion and vegetation cover, visitors leave the site with great impressions. More often visitors go to the section of the fault rupture, which is located on the opposite slope of the village of Geghasar of Lori Marz.

The first stop of the trip is the main seismogenic fault manifested itself discontinuously on the surface. Its longest fragments located opposite to the village of Geghasar-Spitak and the village of Halavar were, respectively, 11 and 10 km long. Taking into consideration all typical fault signs, the total length was 37 km. It was a reverse and strike-slip fault with the vertical displacement of about 2.5 m, and the horizontal displacement was up to 1.5m large. The geodetic observations have shown that the vertical amplitude of the seismogenic fault has slowly and noticeably reduced after its formation. In other words, the uplifted block has slightly gone down. The size of the fault and of the vertical and horizontal displacements varies length-wise. The same is true for the dipping angle of the fault. It ranges from 60°to80°.

The next stop on the trip is made to observe large seismo-gravitational features developed in the northwestern part of the fault, in front of the village of Dzorashen. There, two rock massifs of about 2 million tons with gentle slopes moved down to the foot of the slope, creating a 5-7m-high barrier in the front part and leaving up to 200-350 m-long and 25 m-deep ravines behind them. It is important to note that water factor is absent there; hence, most of experts do not consider this as a landslide effect. The displacements did not cause much damage in that mountain area, far away from settlements and lifelines. There was only one place where the flock of sheep with a shepherd remained under the rocks. The shepherd's dog showed the location of the deceased shepherd under the rock mass.

Today, 30 years after the Spitak earthquake, despite the erosional processes, the fault rupture fragments have still preserved scientific importance, interesting appearance and can be considered as important field trip in developing geological tourism in the RA.

## THE CONNECTION OF THE MECHANISMS OF THE SOURCE OF STRONG EARTHQUAKES OF THE ARMENIAN UPL AND WITH GEOLOGICAL STRUCTURE

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Revealing regularities of earthquake generation in different geological structures is one of the most important tasks of modern seismology. Study of focal mechanisms of strong earthquakes is one of the stages of this task that allows determining specific-type movements along active geological faults, their orientation in space, and also finding out the patterns of earthquake generation in different geological structures.

To identify earthquake generation regularities for different geological structures, mechanisms of 250 earthquakes with M>5.0 in the Armenian upland and adjacent areas for the period 1965 to 2012 were studied and estimated.

For example, within the folding structures of the Spitak seismic zone, characterized by the depth of sources of approximately 20 km, the earthquake source mechanisms are represented by reverse and strike-slip faults: the Spitak earthquakes of 1975 (M =5.0) and 1988 (M=6.9). Source mechanism of the 07.12.88 Spitak earthquake (07h.41м) behaves like a reverse and strike- slip fault type with predominance of the reverse-fault component over the strike-slip one along the extent of the break. Based on the geological data, an arc of active breaks in the source area of the 1988 Spitak earthquake consists of the Amasia-Sarighamish and Pambak-Sevan Faults.

The Zangezur zone of earthquake sources is one of the active seismic zones in the southeast of Armenia. That was the zone of the 1968 earthquake with M=5.0. After the earthquake, deformations preserved in the epicentre zone had the form of cracks and landslides. According to this event and the 7 investigated earthquakes of the Zangezour zone, the prevailing sense of motion was thrusting.
Reverse and strike-slip fault type of earthquake source mechanisms was observed for the Van seismic zone. The analysis of all collected results and source mechanism data for the Van earthquake of 24.11.1976 and 30 aftershocks and also for the earthquake of 23.10.2011 showed that motions in the area had the type of the right-lateral strike-slip faults. In the high-seismicity Van zone, earthquakes are located on the continuation of the North-Anatolian Fault in the southeast, in the zone of junction with the Zagros zone. The epicenters of the Van earthquakes are located in the large zone, parallel to North-Anatolian Fault systems.
The type source mechanisms changes sharply for earthquakes of the Kars-Erzrum seismic zone. The Erzrum earthquake of 1983 (M= 6.8) had a source mechanism corresponding to left-lateral strike-slip fault, with steep dip angles, which is consistent with the tectonics of the system of the Anatolian faults, later examined geologically on ground surface. Strike-slip mechanisms of earthquake sources in the system of these faults are not only in perfect agreement with the tectonics of corresponding areas, but also demonstrate that the sub-vertical dip of the strike-slip faults, established geologically on the surface, is preserved to the depths of 15-30 km. The Kars-Erzrum seismic zone joins the north-eastern extension of the largest active Levant Fault, that is bent to the northeast in the south of Turkey extending up to the upper reaches of the Kura River. In the Armenian upland, the most active is the Erznka-Bingol seismic zone of earthquakes. Earthquake source mechanism for the event of 19.08.1966 (M= 6.8) and subsequent aftershocks had right -lateral strike- slip fault type of motion.
The result shows the relation between the focal mechanisms of strong earthquakes and the type of tectonic movement.

## EARTH CRUST DEEP STRUCTURE OF THE SPITAK EARTHQUAKE REGION BY PROFILE AND SQUARE INVESTIGATION ON DSS AND MCWE SEISMIC DATA

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The paper shows the main results of the Spitak earthquake region by profile and square investigation on DSS and MCWE seismic data in Armenia. As a result of the works, areas of increased seismic hazard were identified. Technical and technological solutions were recommended as an important part of the concept of integrated study of seismic zones.

# NEW INSIGHTS ON THE GEOLOGY AND SEISMOTECTONICS OF THE SHIRAK BASIN, REPUBLIC OF ARMENIA

**Dedicated to the living memory of Koryun Mkrtchyan – Great Geologist and Naturalist.**

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The Shirak basin is located in northwestern Armenia. The basin is bounded to the north by the Shirak Mountain Range, thrust to the south along the north-dipping Shirak thrust fault. The Shirak Mountain Range is composed of sedimentary and volcanic rocks of the Upper Cretaceous and Paleogene age. The Quaternary-age Lanjik Volcanic Plateau and the Pliocene-Quaternary lava flows emanating from the Aragats shield volcano are located to the south and to the southeast of the Shirak basin.

The eastern boundary of the Shirak basin is more diffuse and is marked by the north-northeast-trending Karnut Fault, separating the basin in the west from the mountain ranges to the east, which are composed of the Paleogene and Neogene volcanic and volcanic-sedimentary rocks.

The central part of the Shirak basin is filled with the Pliocene - Quaternary lacustrine deposits and volcanic tuffs and andesitic flows up to 300 meters thick. These are underlain by a Pliocene doleritic basalt flow (50 m thick), which is in turn, in the western part of the basin, underlain by the Miocene sediments (up to 1000 m thick) and, in the eastern and southern parts of the basin, by volcanic lava flows. The Miocene sedimentary and volcanic formations are in turn underlain by pre-Neogene sedimentary and volcanic rocks. The Miocene sediments thicken to the west. During the field studies, several new faults were mapped: the Shirakamut thrust fault, the Erazgavors – Karkachun, Maralik and Aygebats faults.

Below is a brief description of faults in the Shirak basin area.

- The northeast-striking Akhuryan left-lateral fault, having a length of 60 km between Digor in the southwest and Gyumri in the northeast;
- The north-northeast-striking left-lateral Karnut fault, having a length of 25 km between Artik in the south and Jajour pass in the north;
- The northwest-striking right-lateral Marmarashen fault, having a length of 15 km between Gyumri in the southeast and Kars (?) in the northwest. To the southeast, it may join with the recently identified Aygebats fault;
- The northwest-striking right-lateral Maralik fault, having a length of 30 km between the village of Mastara in the southeast and Gyumri in the northwest. It may join with the Marmarashen fault. The Quaternary-age Lanjik volcanic plateau is offset by 9 km along this fault;
- The northwest-striking right-lateral Aygebats fault, having a length of 15 km between Gyumri in the northwest and the Karnut fault in the southeast;
- The east-west-trending Shirak thrust fault zone, along which the Shirak Mountain range is thrust-faulted to the south along the northern edge of the Shirak basin. This fault has the length of 25 km between the Jajour pass in the east and the village of Kaps in the west;
- The east-west-striking and south-dipping Shirakavan thrust fault zone, forming the southern boundary of the Shirak basin. This fault was first identified during our field work in 1989. The fault zone has the length of 10 km between the village of

Shirakavan in the west and the Maralik fault in the east. Several segments of this fault were documented and mapped in road sections and in trenches. The Late Pleistocene – Holocene paleo-earthquakes associated with this fault zone are evidenced by a 50 cm- wide fault crack filled with paleosoil in a trench near the village of Gousanagyugh;

- The east-west-striking Erazgavors – Karkachoun fault zone, having a length of 18 km between the village of Erazgavors in the west and the Karnut fault in the east.

Future detailed studies of these and other regional faults will shed more light on the seismotectonics and fault kinematics, and will aid in assessment of seismic hazard risk in northwestern Armenia.

## SPECIAL MACROSEISMIC SCALE ON THE BASE OF DAMAGES ARMENIAN CHURCHES

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Abundant written information is available on strong earthquakes that occurred in Armenia for the last two thousand years. These data describe the behavior of most important monumental architectural structures that include Armenian churches, fortresses, bridges, etc. More specifically, the available valuable historical information basically concerns damages and destructions of church buildings constructed since the 4th century. Determining intensity of those earthquakes, experts treated the described facts each in own way, which cannot be objective. Therefore, to provide for more objective and systematic interpretation of the actual historical data, it is extremely necessary to draw up a scale of seismic intensity, based on the degree of the damages and destruction that buildings of Armenian churches had suffered. Drawing up such a scale, it is reasonable to keep to the basic principles of applying MSK-64 or EMS-98 scales, including 12 intensity grades.

The studies show that Armenian churches can be damaged at seismic intensity VII and more. The number of church buildings in the RA is rather large (more than 1000) and they are distributed over almost the entire area of the country, so it is possible to use any of well investigated strong earthquakes to create the proposed scale.

The new preliminary macroseismic scale is based on the analysis of damages of churches within the intensity VII-X zone of the 1988 Spitak earthquake. This earthquake is most important to draw up the scale, since there is a rather reliable and detailed map of isoseismals (1:200 000) in the range of intensities from VI to X produced by generalization of the results of detailed macro-seismic research carried out by Armenian, Georgian, Azerbaijan and Turkish experts and through technical realization of additional reliable macro-seismic studies of the condition of the church buildings. Therefore, works on the preparation of a new macro-seismic scale are required and must be started just by studying the consequences of the Spitak earthquake as it is done in the given work.

More than 50 churches located in Intensity VII-X Zone were re-investigated. A special questionnaire allowed gathering data for all churches. It includes all necessary information on any church building: name and layout, year of construction, characteristic soils and regions influencing the level of seismicity, data about basic building materials used, overlaps, availability of church dome, evidence of old damage (up to the Spitak earthquake of 1988), etc.

Based on the questionnaire filled by inspections of the churches, a table of most typical damages of the Armenian churches w on the intensity of the Spitak 1988 earthquake was prepared.
The new special preliminary macro-seismic scale was developed on the basis of the analysis of church damages in the VII-X Intensity Zone of the 1988 Spitak earthquake.

## "SPITAK 1988 EARTHQUAKE IN PHOTOS, FACTS AND COMMENTS"

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The Spitak 1988 earthquake is not an exceptional phenomenon from the seismological point of view. Globally, 15 to 20 magnitude 7.0 earthquakes happen every year. However, the Spitak event has been known for its severe consequences and is considered as one of the world's most detailed and thoroughly studied earthquakes. From this perspective, the Spitak earthquake is very instructive and is of great interest in the fight against seismic disasters. Numerous books and articles have been written, movies have been made and various content has been available in the Internet about the 1988 Spitak earthquake; however, it is difficult to extract easily the important and necessary data. Furthermore, strong earthquakes are from among hundreds of other natural disasters, the ones which affect all aspects of life without exception, which means that there is a need for a comprehensive expertise in earthquakes by a specialist. It was noticeable that the important data and even the lessons learned from the 1988 Spitak earthquake were slowly forgotten and gradually lost. It is in the nature of things, since it is difficult to keep and find the adequate materials if needed even with the powerful tools of our information era. It has long been necessary to compile, systematize and comment the main data on the Spitak earthquake; that has been needed both for experts and for general public.
A colorful album created in Armenian and English includes more than 110 photos related to the 1988 Spitak earthquake, a large number of factual data, and maps with professional comments. Special attention is paid to the severe consequences and causes of the Spitak tragedy. The materials are systematized by the important aspects of the earthquake and by stages of the disaster. The contents includes: Preface; Chapters: 1.Major Losses from the Earthquake; Earthquake Parameters and Macroseismic Effects; 2. Geological Effects of the 1988 Spitak Earthquake; 3. Damage and Demolition of Buildings; 4. Emergency Seismic Situation in Destruction Zone after the Earthquake; 5. The Merciful World; 6. Medical Assistance; 7. Rescuers and Rescue Operations; 8. Recovery and Reconstruction of the Disaster Zone; Seismic Protection of the RA; Important Results Based on the Lessons of the Spitak Earthquake for the Last 30 years in the Republic; and References.
These are all presented with the most expressive photos, facts and their brief comments. A large place is given to the lessons of the Spitak earthquake and aim to promote seismic protection in order to avoid another tragedy like the Spitak disaster. Since the Spitak tragedy, author of this album has been investigating the causes of the earthquake and its effects. A huge amount of information has been compiled and its analysis led to publication of about one hundred of scientific works, including five books.
This album contains photographs by different authors, large statistical data on the consequences of the earthquake and the results of their analysis. The author used own photos and those taken by his colleagues; there is a large number of photographs from the Internet. The comments are made by author.

# LESSONS OF THE SPITAK EARTHQUAKE AFTER THIRTY YEARS

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From the very beginning of its existence, human society is exposed to various threats and challenges, facing natural, social and technical disasters. Earthquakes cause irreplaceable losses and severe consequences that could not have been predicted until today. Located in a seismic zone, Armenia suffers from frequent shocks, the last of which was the disastrous earthquake of Spitak in 1988.

Analyzing earthquake lessons, we can record the following:

1. Even though there is a state policy, the effects of the disastrous earthquake have not been completely eliminated so far because of various objective and subjective factors and difficulties.
2. Year after year, fear of possible earthquakes and sense of vigilance and responsibility are getting weaker, when implementing construction projects, urban development acts and design-estimate documents often remain valid on paper, only; deviations and inaccuracies are increasing instead, and supervising services not always provide proper control.
3. In Yerevan and in other big cities of Armenia, in the light of western urban development and trade culture, the first floors and the basements of the buildings are turned into shops, food facilities and recreational sites, the premises of the buildings are changed and rebuilt, adapting the area to their commercial activities. Although most of required documents and justifications are mainly available, it is evident that the seismic resistance of the buildings suffers.
4. There has been almost no research addressing population migration tendencies in the area after the earthquake, the demographic pattern of the disaster zone, and the possible loss of customs and traditions.
5. There are serious social problems in the earthquake-affected communities: the number of unemployed people living on the threshold of poverty is high. The industrial cities of Gyumri, Vanadzor and other settlements have faced economic difficulties, and the economic growth rates are insufficient. Therefore, in order to improve the socio-economic situation, it is necessary to develop small and medium-size businesses, provide favorable conditions for economic activity, implement complex agricultural development programs, and apply a preferential tax policy.

Is it possible to avoid the painful effects of the earthquake? The world experience shows that yes, it is possible, if long-term and complex programs are developed and approved for emergency situations.

We suggest developing and consistently implementing a clear policy of seismic risk reduction in the Republic of Armenia as a part of the national security policy. Taking into account potential dangers of earthquakes, support and reconstruction of settlements, as well as population relocation and transfer programs should be developed. The state policy should include the RA seismic strategy, urban development norms, relevant laws of the Republic of Armenia, seismic safety regulations, and long-term national programs, which will serve as the basis for clear functioning of the seismic protection service and state-governing bodies of the Republic of Armenia.

# SIGNATURES OF STRONG EARTHQUAKE PREPARATION IN THE PHASE SPACE PORTRAITS OF EARTHQUAKE TIME-SERIES OF THE CAUCASUS

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Earthquake time-series (ETS) documented as seismic catalogs are objects of detailed statistical analysis, which show that catalogs contain both independent and correlated events (clusters), which means that mentioned data represent complex time-series. In some earlier works (Goltz, 1997; Matcharashvili et al., 2000) it is shown that at least one component of a seismic catalog, considered as a point process, namely, inter-event or waiting time (WT) series, has a low fractal dimension. This means that catalog contains some hidden nonlinear structures.

Last years, modern methods of nonlinear dynamics, applied to ETS, reveal some interesting hidden structures. There are controversial publications on revealing strange attractors in seismic time-series (which means that they can be represented by deterministic chaos model), as well as on the absence of such ordered structures. Therefore, it seems interesting to study what kind of methodology could reveal possible attractor-like structures in ETS. The study considers the spatio-temporal parameters of seismic rate, revealing nonlinear structures in the phase space plots in low seismicity areas, in the period, including intervals before, during the main event and aftershock sequence for the strongest Caucasian earthquakes: Spitak (1988) and Racha (1991). The seismic phase portraits and recurrence plots constructed for different time windows, epicentral distances and magnitude thresholds reveal certain patterns of seismic process dynamics, possibly related to precursory and relaxation patterns of strong earthquakes.

The trajectories in the phase-space portraits of earthquake time-series generally manifest two main features: a dense "source/basin" area formed by a background seismicity and (reversible) anomalous orbit-like deviations from the source area, related to swarms, foreshock and aftershock activity. Unlike the case of theoretical attractors for deterministic chaos, the “basin" area of earthquake time-series is much more diffuse (“noisy”) than in case of chaotic attractors, obtained by solution of model nonlinear equations. The same “noisy” phase portraits one obtains during processing experimental data of various origin, e.g., in biology.

Our analysis shows that before/after strong earthquakes in Spitak and Racha, there are some anomalies in ETS (large deviations from the background pattern), which generate orbit-like structures in PSPs, even using catalogs de-clustered by the Reasenberg’s approach. Presumably, these outlying orbits appear due to the presence of some nonlinear (correlated) structures in the seismic activity before/after strong earthquake remaining after declustering (Matcharashvili et al, 2015). In principle, this effect can be used for the search for strong earthquake precursors in the time domain, though the spatial resolution of anomalous area is not high, as a remote (separated by hundreds of km) strong earthquakes can result in significant changes in phase space plots of ETS even in seismically quiet areas. Further investigations are needed to reveal the EQ prediction potential of seismic phase space plotting.

# GENERAL OVERVIEW ON THE RESPONSE, RECOVERY AND RECONSTRUCTION OF THE NOVEMBER 21, 2017 SARPOL-E-ZAHAB MW 7.3 EARTHQUAKE, IRAN

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On November 21, 2017, Sarpol-e-Zahab earthquake occurred with Mw 7.3 at 18:18 GMT (21:48 local time) at the depth of 18 km, PGA of 0.697g, intensity between IX and X on MMI scale, and more than 500 aftershocks of Mn ≥2.5; it was the largest earthquake that happened in the Zagros region in the past centuries. The earthquake affected west of the Kermanshah province near Iran-Iraq border, specially the small town of Ezgeleh (5 km from the epicenter) and the city of Sarpol-e-Zahab (23 km from the epicenter) and 1900 villages. 620 were killed (560 were in the city of Sarpol-e-Zahab), 5346 were injured, around 70,000 became almost homeless and more than 12,000 buildings were damaged. The population of the Sarpol-e-Zahab sub-province and Sarpol-e-Zahab city was around 100,000 and 56,000 at the time of earthquake, respectively.

The earthquake caused variety of typical damage and failure modes were observed in structural and nonstructural components in steel frames, reinforced concrete, and masonry buildings, industrial structures, power plants, silos, dams, water and electricity lines and facilities. In general, the performance of infrastructure and lifelines was acceptable, but the building performance was not acceptable considering that the newly built buildings were damaged severely. The severe damage and widespread destruction of buildings, specially the nonstructural elements, were due to low quality of the construction, improper earthquake resistance design, low quality material, inappropriate site selection, etc.

Most of the collapses and severe damages of adobe and masonry buildings, especially in the rural area, were due to out-of-plane wall performance, diagonal and sliding shear failure of walls. The damages of masonry buildings were due to deficiencies in design and construction, inadequate amounts of bearing walls, inappropriate use of openings, deficiencies in roofs, defects in confining elements, inappropriate extension of existing buildings, and use of poor quality materials. In case of confined masonry buildings, the damage mainly was due to inappropriate out-of-plane and in-plane performance of walls. Damages to reinforced concrete buildings were due to poor quality of concrete, strong beam–weak column, stiffness irregularity (soft story), short column effect, shear wall collapse, short splice length and splices near joints in columns, insufficient stirrups, failure of beam–column joints and failure and cracks on infill wall. For moment and concentrically braced steel-frame buildings, which were mainly located in Sarpol-e-Zahab and were up to 5 stories high, the damages were due to connection failure. Papers provide an overview on these damages and lessons learned.

The overall performance of the search, rescue and relief operation and response team was good and acceptable, but it could have been better if the efforts were more coordinated. Despite the fact that the number of tents, amount of food and emergency supplies were more than was needed for the number of the affected people, but due to lack of coordination still people were not fully satisfied with the relief operation. The reconstruction of the villages is almost complete and the retrofitting and reconstruction of damaged buildings in Sapol-e-Zahab is underway, mainly funded by the government. This paper provides a general overview on the losses, reconstruction and recovery process. Even though the earthquake was the largest and its more than it was expected, human casualties were the lowest in comparison with similar earthquakes in Iran. The Sarpol-e-Zahab earthquake is just an example of natural catastrophic events that have occurred or can occur in urban area causing devastating damages in the future.

# SPITAK DESTRUCTIVE EARTHQUAKE ON DECEMBER 7, 1988: A BRIEF OVERVIEW OF THE RESEARCH CONDUCTED AND THE OBTAINED RESULTS

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The Spitak earthquake of 1988 was unique among many disastrous and destructive earthquakes in the Armenian Highland. It was unique by its strength, with magnitude ranging up to 6.9-7.1 by different estimates, and its intensity in the source zone comprised 10 and higher on the MSK scale. It was unique by the area it covered: the entire northern part of Armenia. It was unique by the caused social (about 25,000 deaths) and also economic impact (towns and villages, residential houses, schools, hospitals, and factories destroyed almost completely).

The Spitak earthquake was unique by the scale of the humanitarian help that came from other countries. And finally, it was a unique earthquake, which was thoroughly studied in all aspects -instrumental and geological, seismic, tectonic, seismological, engineering-seismological and engineering-geological.

**Instrumental records**

The Spitak earthquake was recorded by several stations in Armenia. The most records was the unique registration at the Ghukasyan station belonging to the Institute of Geophysics and Engineering Seismology after A.Nazarov of the Armenian National Academy of Sciences (IGES NAS RA) registered by accelerometer device.

It was possible to obtain very important and reliable records, which were subsequently used for various scientific analyzes, comparisons and studies by CBM & IGES multi-pendulum seismometers, located at the engineering-seismometric stations of the IGES in the city Leninakan, currently Gyumri.

It should be noted that the Spitak earthquake was also registered by telemetric stations located in a number of countries (Obninsk-RF, Skopje - former Yugoslavia, etc.).

**Macroseismic studies**

Immediately after the earthquake, large-scale macroseismic studies started in the disaster zone. The volume of research can be evidenced by the studies carried out in the city of Gyumri.

1. In Gyumri, about 3000 houses, or about 30%, were studied from around 11,000 low-rise houses existing at that moment.
2. Multi-apartment buildings still standing after the earthquake, nearly 100% (before the earthquake, there were about 850 apartment buildings, 350 of which turned into ruins);
3. Almost all preserved educational institutions, medical institutions, administrative structures, factories, etc.

As a result, a unique macroseismic map at the scale of 1: 2000 was compiled for the territory of the city (unique in its scale). Similar detailed and extensive macroseismic studies were conducted in all disaster-prone cities, including Vanadzor, Spitak and Stepanavan. Macroseismic maps were compiled for these cities also. Large-scale research was also carried out in the disaster zones to assess earthquake intensity in other locations. As a result, the isoseismal map of the Spitak Earthquake was compiled.

The results of comprehensive earthquake studies conducted by the staff of the IGES NAS RA are included in a two-volume report. The comprehensive investigation of the Spitak earthquake, and the obtained results were (and has continued to be) the basis for detailed and comprehensive scientific analyzes, interpretations and new ideas.

# SECTION II.
# Seismological and geophysical studies; seismotectonics, paleoseismology, archeoseismology
# IN HONOR OF DR. A. KARAKHANYAN

## SEISMIC STRUCTURE IN THE CAUCASUS REGION

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Seismic velocity/attenuation structure and wave propagation properties provide valuable information to earthquake hazard assessment (PSHA) studies. Amplitudes of the seismic signals vary depending on the structural properties of the crust and the upper mantle. If there are not enough strong motion records in a region these amplitudes are used to generate 2-D attenuation maps that can be used in selection of the ground motion prediction equations (GMPE). In addition, modern seismology relies on accurate velocity models, where long period seismograms are used to calculate moment tensor inversion and the source properties of earthquakes.
The Caucasus region is surrounded by major tectonic units with an abrupt change of structural properties. Armenia is situated in a region of shortening caused by convergence of the Arabian and the Eurasian plates. Number of existing broad-band stations (e.g. GNI) and recent broad-band deployments provided data for the analysis of velocity and attenuation properties in the region. As expected, the Lesser Caucasus including Armenia shows high attenuation both in the crust and in the upper mantle. Shear wave velocities are slow; however, high-resolution images of 2-D structure are needed for further investigation.
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## ACTIVE TECTONICS WITHIN THE NW AND SE EXTENSIONS OF THE PAMPAK-SEVAN-SYUNIK FAULT: IMPLICATIONS FOR THE PRESENT GEODYNAMICS OF ARMENIA

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We present a study of the active tectonics within the northwestern and southeastern extensions of the Pambak-Sevan-Syunik fault (PSSF), the major right-lateral strike-slip fault that cuts through Armenia. Quantifying the deformations in terms of geometry, kinematics, slip rates and earthquake activity - using cosmogenic $^{3}He$, OSL/IRSL and radiocarbon dating techniques - different behaviors between the two regions are revealed. Within the northwestern extension, in the region of Amasia, the Pambak-Sevan-Syunik fault (PSSF) bends to the west and splits into two main WNW-ESE-trending reverse faults, defining a compressional pop-up structure. We estimate an uplift rate and a shortening rate of 0.5 ± 0.1 mm/yr and 1.4 ± 0.6 mm/yr, respectively. This suggest that most of the ~2 mm/yr right-lateral movement of the PSSF seems to be absorbed within the Amasia pop-structure. Within the southeastern extension, the PSSF shows signs of dying-out within the Tsghuk Volcano region at the southernmost tip of the Syunik graben. There, the tectonic activity is characterized by a very slow-rate NS-trending normal faulting associated with a slight right-lateral movement. Slip rates analyses (i.e., vertical slip rate, EW-stretching rate perpendicular to the fault, and right-lateral slip rate of ~0.2 mm/yr, ~0.1 mm/yr and ~0.05 mm/yr, respectively) lead to the conclusion that the right-lateral movement observed further north along the PSSF is mainly transferred over other active faults further west within the Karabagh (Hagari fault or other structures further northwestwards. Comparing our slip rates with those estimated from GPS data suggests that most of the deformation is localized and seismic, at least within the Tsghuk region. The geometrical and kinematic pattern observed within the two terminations of the PSSF suggests that the fault and its surrounding crustal blocks are presently rotating anticlockwise, as also observed within the GPS velocity field. This is consistent with the recent kinematic models proposed for the Caucasus-Kura-South Caspian region and brings a new insight into the present geodynamics of Armenia.

## CORRELATION BETWEEN EARTHQUAKE SURFACE FAULTING AND COSEISMIC SURFACE DEFORMATION: CONSEQUENCES FOR FDHA

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Currently, the crustal deformation induced by earthquakes can be precisely measured on the surface through interferometric techniques (i.e. InSAR). Such an approach is informative for moderate and larger earthquakes; nevertheless, so far, the database of observations is poor in the region of low-magnitude earthquakes, and some issues are arising on the lower limit of detection for coseismic deformation.
Similarly, also data on surface faulting is mainly pertaining the range of Mw > ca. 5.
The available database on the size of deformed area produced by the earthquakes indicates that the limit for having measurable (significant) ground deformation is around Mw 4 to 4.5. We selected the most significant earthquakes worldwide, imaged by InSAR, trying to represent different kinematics (i.e., including both dip-slip events and mainly strikes-slip or transverse ones), depth (km 2 – 30) and magnitude (Mw 4.2 – 9.0) intervals.
It is interesting to note that this limit is also the limit for the available database on surface faulting. Consequently, also the probability of surface faulting is increasing from the similar values of Mw.

This good correlation between the surface faulting and the deformation of the crust on the surface, implies some consequences on the assessment of the surface faulting potential and, more in general, the capability of a fault, sensu IAEA (2010): a crucial point of the seismic hazard evaluation and feasibility of nuclear power plants. In fact, in the case the capability cannot be assessed because reliable dating is not possible by any method, including the more updated geochronological dating methods, the fault is considered capable if: a) it could be linked with a known capable fault. (i.e., it has been demonstrated that a movement of the capable fault may cause movement of such a fault); b) the maximum potential magnitude associated with a seismogenic structure is sufficiently large and at such a depth that it is reasonable to conclude that, because of the significant crustal deformation produced by the event also in the site vicinity area of the NPP, surface faulting can occur also on faults here located.
Point a) indicates the capability of a fault non-dated if it has a structural relationship with a known capable fault. This structural relationship in many cases could be questionable; therefore, an important step forward for a reliable assessment could be the following. First, it is necessary to identify the deformed area due to the maximum earthquake produced by the capable fault, using the correlation cited above. In the case the deformed area is including the fault under investigation its potential capability becomes significant. On the other hand, it becomes insignificant in the case the fault is outside the deformed area.
Point b) indicates a situation where the maximum potential earthquake associated to a seismogenic structure, close or not to the fault under investigation for capability, could produce deformation affecting also the area where this fault is located. To verify this situation, it is necessary to calculate the deformed area using the correlation cited above and, if including the fault under investigation, it is necessary to consider properly this possibility and an ad hoc FDHA could be necessary. In point b) it is also possible to include the case when the seismological database indicates that for an earthquake of such Mw surface faulting is expected, but there are no geological and geophysical data that could indicate, to which structure this earthquake can be associated. In this case, the earthquake should be located in the epicenter/s given by the seismological database or in its vicinity, where potential geological structures could be hypothesized, then the potential deformed area can be calculated following the logic exposed above for this point.

## MARINE AKCHAGHYLIAN DEPOSITS OF THE CASPIAN TYPE IN THE WESTERN SHIRAK BASIN (NE TURKEY) AND INTENSIVE QUATERNARY UPLIFT IN THE LESSER CAUCASUS

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Vertical component of displacement in earthquake focus (and, correspondingly, on the ground surface, if the focus reaches it) is characteristic for the majority of instrumental earthquakes. Even if the displacement is completely lateral, the existing tectonic topography causes secondary gravitational earthquake effects like landslides and rock falls. Thus, estimates of vertical Quaternary movements are important for seismic hazard assessment.

Intensive Quaternary uplift is testified in the western Turkish part of the Shirak Basin that extends to NW Armenia around the city of Gyumri. The 90-m thick section of clays, silts, and fine-grained sandstones is exposed in the western side of the Akhurian River valley near the village of Tazekent to the south of the town of Akyaka (N 40°42.897′; E 43°40.367′). The section is covered by 5-m thick gravels and pebbles representing a cover of terrace that is 1570-m high above sea level (a.s.l.). Simakova found the cysts of dinoflagellate in the lower part of the section (about 1500 m a.s.l.). Aleksandrova identified them as the brackish-water Caspian-type dinocysts of the Lower Akchaghylian (Upper Pliocene) aspect. The presence of dinocysts in several layers excludes their accidental arrival within the deposits. Normal magnetic polarity of the whole fine-grained deposits of the section confirms their Upper Pliocene age. The maximum Early Akchaghylian transgression level was probably about 100 m higher than the world sea level and decreased up to 0 a.s.l. by the Quaternary (~ 2.58 Ma). Therefore, the western Shirak Basin rose during the Quaternary to 1400–1500 m that yields the average rate of the Quaternary uplifting of about 0.6 mm per year.

This rise was caused mainly by total uplift of the region, but was partly related to vertical movements on the Akhurian Fault. Sayadyan (Sayadyan, Yu.V., 2009) reported results of studies of the borehole drilled near the Marmashen Monastery (the elevation is 1516 m a.s.l.). The fine-grained deposits similar to the Tazekent section were found under the basaltic andesites with estimated K-Ar dates of 2.0-2.3 Ma (Trifonov, V.G., et al 2017). The top of these deposits is situated at the elevation of 1440 m a.s.l. The mollusk fauna was found in the drilling samples. Akramovsky dated the mollusks to the Upper Akchaghylian at 4–8 m under the top and to the Lower Akchaghylian at 43–126 m under the top of the fine-grained deposits (Sayadyan, Yu.V., 2009). The correlation of the Tazekent and the Marmashen Monastery borehole sections shows that the vertical offset on the Akhurian Fault is about 170 m.

The Tazekent section composes the basement of the same terrace as the Ani unit in the Armenian part of the Shirak Basin. The fine-grained part of the Tazekent section is covered by the same alluvium as the fine-grained lacustrine deposits of the Voghji section of the Ani unit. We date these lacustrine deposits to the Calabrian and the alluvium to the latest Calabrian – earliest Middle Pleistocene. The Arapi unit composes the terrace that is incised into them and is dated to 0.75–0.65 Ma (Melik-Adamyan, G.U., 2004, Sayadyan, Yu.V., 2009). Therefore, the mentioned offset along the Akhurian Fault occurred in the Early Pleistocene after accumulation of the Lower Akchaghylian deposits and before the Ani unit lacustrine sedimentation finished.

There are the estimates of the uplift in NW Armenia during the last 0.6 Ma [Trifonov, V.G., et al. 2016, Trifonov, V.G.,et al, 2017]. The magnitudes of uplift reach 700 m in the eastern part of the Lori Basin and ~900 m in its western part relative to the middle Debed River near the town of Alaverdi. The Upper Akhurian Basin is uplifted by 200 m more than the Lori Basin. The adjacent Bazum and Javakheti Ridges rise to 1230–1400 m. These data show that the Quaternary uplift varies in different structures of NW Armenia and its rates probably increase in time. The rates reached the rates of 1.1–1.8 mm per year in the basins and 2.0–2.3 mm per year in the adjacent ridges during the last 0.6 Ma.

The data on significant Quaternary tectonic uplift are available also for the eastern Greater Caucasus. T. Kengerli, Trikhunkov, Frolov, and Shalaeva identified the Caspian-type Akchaghylian deposits in the south-eastern eroded termination of the axial ridge of Greater Caucasus to the ESE of Mount Shakhdagh. These deposits are situated now at the elevation of 2200–2300 m. Filippova (2007) reported on the finding of dinocysts of the Akchaghylian-Apsheronian aspect in the upper part (1615 m a.s.l.) of the section of Muhkai II Early Paleolithic locality (Amirkhanov, H. A., et al, 2016) in the Dagestan north-eastern slope of the eastern Greater Caucasus.

# ARCHEOSEISMOLOGICAL ANALYSIS ALONG THE KHAZAR FAULT ZONE, NORTH ALBORZ- SOUTH CASPIAN REGION, IRAN

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The active tectonics in Central Alborz is characterized by two thrusting fronts to the north and to the south. The Northern Alborz defines an E-W trending fold and thrust zone, striking obliquely with respect to the Caspian Sea shoreline. To the West, the Caspian Sea abutes against the range while to the East, a 20-25 km-wide coastal plain separates the sea shoreline from the reliefs. Geologically, the Northern Alborz includes a large variety of Paleozoic-Mesozoic detritus-calcareous rock units that are all deformed by folding and faulting processes, which is known as an active complex and poly-phased orogenic belt surrounded by the South Caspian Basin to the North and the Central Iran block to the South.

It shapes a 500 km-long, 100 km-wide "V"-shaped mountain range, trending WNW-ESE in its western part and NE-SW in its eastern part. Generally, it is described as some kind of a crustal-scale flower structure with a double verging fold-and-thrust system both to the north and to the south. The Khazar fault defines the northern-most border of the Central Alborz mountain range. In the eastern part of the Central Alborz, it has been described as a fold propagation fault.

GPS data for the Central Alborz suggested that the Khazar fault that was mapped as an active one could be divided into two segments kinematically. Its western segment with a slip rate of ~6 mm/ yr is mainly a thrust with a slight left-lateral component, with a ratio (compressional/ sinistral) of ~3 mm/ yr, respectively. They considered also the eastern segment as a strike-slip fault with a greater left-lateral component (~5 mm/ yr) than thrust fault (2–3 mm/ yr). Many earthquakes may have been associated with the Khazar fault system.

The paper also raises the question of the recent geodynamical evolution of the Northern Iran-Southern Caspian basin. The deep South Caspian Sea is interpreted as a remnant of a Mesozoic marginal sea that included the Black Sea to the west as well as the Caspian Sea in the east.

Within the northern flank of the Alborz mountain range, preliminary morphotectonic and paleoseismology studies, which were carried on along an eastern northward-propagated fault segment (Nazari et al., unpublished data) indicate active shortening, in particular, along the Khazar Fault zone.

We studied the geometry and the kinematics of the active faulting along the Khazar fault by means of a morphotectonic analysis, e.g., by surface and sub-surface observations in the South Caspian in its onshore and offshore areas, as well as by archeoseismological trenching. Our study allows us to present an updated seismotectonic setting for the north Central Alborz-South Caspian Basin region, and provides a basis for seismic hazard assessment for this highly populated region. It also allows discussing the question of the geodynamical evolution of the Northern Iran-Southern Caspian Basin during the Quaternary.

# ACTIVE FAULTS AND SEISMIC HAZARDS OF THE TIEN SHAN

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The report is devoted to the results of studying the active tectonics of the Tien Shan and Dzungaria - the area of interaction between the two largest lithospheric plates: Indo-Australian and Eurasian. Interest in this area is due to the fact that its study can provide evidence to answer some questions of the modern theory of tectonics of lithospheric plates, among then the problem of intra-continental mountain building. Indeed, the newest orogeny of these major structures develops at a distance of more than 1000 km from the direct interaction of these plates, which began about 55 million years ago. This distinguishes it from the situation of the subduction zones, where the thrust zones mark the boundary between the two slabs and the situation in typical conflict zones, where one continent sinks under the other along the main thrust, as happened in the Alps or the Himalayas. In this respect, the Tien Shan is more similar to some other inland regions such as Altai, Nanshan, Gobi-Altai in Asia or Atlas in Africa, Sierra Pampenas in the Argentine Andes, and Laramie Rockies in the western part of the United States.

Despite the detailed study of the Tien Shan and Dzungaria, many questions of its resent geodynamics remain vague or poorly elucidated, among them: What is the distribution of current stresses within the orogenic belt? Are the main stresses within the marginal parts of the orogen concentrated or evenly distributed within the belt? What is the slip rate of the Late Quaternary tectonic displacements in the zones of active faults?

In addition, GPS methods established (Abdrakhmatov et al, 1996) that the slip rate of the current shortening of the Earth crust in the Tien Shan is about 20 mm / year, which is about half of the total reduction between India and Eurasia. This fundamental fact requires a geological interpretation and the question to be answered is what part of the present reduction of the Earth crust is realized in the displacements along the zones of active faults of the Tien Shan.

Seismotectonic rupture of individual segments of active faults in strong earthquakes is one of their most important properties. Therefore, we attach importance to the study of paleoseimology of Tien Shan and Dzungaria. The main attention is paid to the results of trenching, i.e. opening of active fracture zones by deep trenches with detailed description and dating of faulted layers. Paleo-seismic data is intended to provide a link between the long-term displacement velocity in fault zones, which is the cumulative effect of displacements at several seismic events, on one hand, and geodetic measurements of the rate of contraction that characterizes the inter-seismic stresses accumulating since the time of the closest major seismic events, on the other hand.

This study is focused on the faults showing direct evidence of the Holocene and the Late Quaternary displacements over the past 140,000 years, indicative of a relatively high rate of displacement. This approach is consistent with the recommendations of the International Lithospheric Program (Inter-Union .., 1990), according to which active faults should be understood as faults with signs of tectonic movements that have occurred over the past 100,000 years. Obviously, some difference in duration is associated with a different approach to determining the lower boundary of the Late Pleistocene.

The paleoseismological data obtained by our investigations in different parts of the Tien Shan and Dzhungaria (Chu, Naryn, Atbashin, Dzhungar and other depressions) show that strong seismic events occurred there with an average interval of recurrence of 1000-5000 years,

leading to the appearance of surface discontinuities with the mean displacement of 2-4 m. Calculations show that generally, events with M = 6.9-8.2 can occur within the studied region.
Within the studied area, which includes the areas of the Tien Shan and Dzungaria, the "fault related fold" methods calculated displacement rates for the eight main active faults. According to the mapping results, these eight faults are characterized by the highest rates of movement in the Late Quaternary. The dip-slip rates along individual faults range from 0.2 to 3.1 mm per year and accumulate a significant part of the sub-meridian compression, although the methods used can measure the dip displacement only.
The highest values of the Late-Quaternary compression are observed within the Kochkor and Naryn basins located in the center of the Tien Shan. The least compression is typical for the southernmost and topographically high intermountain Aksay depression. The displacement velocity of the Alma-Ata Fault in the Late Pleistocene-Holocene is 1.6 mm / year.

## TRACES OF STRONG EARTHQUAKES IN THE HOLOCENE DEPOSITS OF THE SEVAN LAKE, ARMENIA

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With the purpose of investigation of the geo-ecologic and paleogeographic features of existence and development of high-mountain lakes, we have conducted field study of geological sections of loose deposits in the western part of the Sevan lake depression (Armenia). As a result of investigation of the mentioned sections, we have revealed characteristic lithologic signatures of significant lake transgressions, stratigraphic layers with numerous remnants of human activity, as well as signs of ancient earthquakes – horizons of seismogenic convolutions in lacustrine deposits (seismites). For determination of the absolute age of the mentioned stratigraphic units, we used 4 radiocarbon dates estimated at the Radiocarbon Laboratory of the Lomonosov Moscow State University for the samples from the geological section near the Norashen village. They provided accurate ages of the lacustrine deposits in the age interval of 2020±120 – 6270±110 years BP for the 4.5 m-thick section. Using these data, we have calculated the average rate of sedimentation in the studied region at 0.34 mm/year. The materials of the radiocarbon dating of the lacustrine deposits demonstrated two significant lake transgressions that occurred in the Middle and the Late Holocene. During the field study, special attention was paid to a section of lacustrine deposits near the Norashen village, because the layers found there had a significant content of human life remnants such as ceramics and bones. Archeological investigations and radiocarbon dates of the Norashen section have shown that this region was populated during two periods - one in the 3rd and one in the middle of the 2nd century BC. Analysis of the data of the study of seismogenic convolutions in the lacustrine deposits has brought us to a conclusion that the regime of transgressions and the 500 year-long break in human occupation of the study region could be possibly related to a strong earthquake in the Sevan lake depression that occurred approximately 4400 years ago. The obtained data can be used to determine the long-term trend of high-mountain lake level oscillation during the Holocene and revealing its causes, as well as for a more precise assessment of the seismic hazard in the Sevan lake depression.

## SOFT SEDIMENT DEFORMATION STRUCTURES AS EVIDENCE OF PAST EARTHQUAKES IN THE SHIRAK LACUSTRINE BASIN (ARMENIA)

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The analyses of sedimentary successions, particularly soft-sediment deformation structures (SSDs), can be a strong tool for detecting the evidence of past earthquakes (e.g. Seilacher, 1969; Sims, 1973; Alfaro et al., 1997).
The Shirak lacustrine basin had been developing as a depression since the Upper Pliocene up to the early Middle Pleistocene and later was drawn into the uplift (Trifonov et al., 2017). In the Quaternary stratigraphy of the depression, the Karakhach (the episode of the Olduvai and the Lower Calabria ~ 1.9-1.7 Ma), Ani (the Upper Calabria and the Lower Ionian ~1.25-0.75 Ma) and Arapi (lower Middle Pleistocene ~ 0.75-0.65 Ma) suites are distinguished. The earliest Karakhach unit is exposed within the northernmost part of the basin. It is about 20m thick and consists of sand-gravel alluvium in the upper part and mostly of fine-grained deposits in the lower part. The Ani (1.25-0.75) and Arapi (0.7±0.05) sedimentary units were formed mostly in lacustrine conditions and are composed of clays, silts, and clayey diatomite downwards and of alluvial sands, gravels and pebbles upwards.
SSDs are observed within the Ani and Arapi formations in alluvial coarse-grained gravel, lacustrine sandy, silty, clayey, and clayey-diatomite layers of the palaeo-Shirak basin. In this study, the SSDs were classified based on the morphological features as contorted structures (simple convolute bedding, ball and pillow structures) and load (flame structures). Spherical or semi-spherical structures are observed in clay, silty, sandy and gravel deposits. Gravel and pebble layer has grown like flame structure in the upper silt layer. Flame structures are observed in sandy and silty deposits as well. They are formed by penetration of sandy sediments to the silty deposits. Generally, flame structures develop under pressure, but they can also be formed by seismic tremors (e.g. Dasgupta, 1998).
The seismites are observed in different levels of lacustrine deposits: eight levels in the Ani and four-fives levels in the Arapi unit. The existence of seismites is an evidence of continuing tectonic activity ($M \geq 5$) that affects the Lake deposits (Avagyan et al., 2017).

## STUDY OF NEAR-SURFACE ACTIVE FAULT STRUCTURES IN THE REGIONAL COMPRESSION AND EXTENSION ZONES OF THE LESSER CAUCASUS (BY THE EXAMPLE OF THE ACTIVE PAMBAK-SEVAN-SYUNIK FAULT)

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As a consequence of collision between the Eurasian and Arabian plates, folding zones have developed mainly in eastern Anatolia and the Caucasus. High rate of seismicity is typical for such sites. Approximately, respective orientations of the regional compression and extension forces in the Lesser Caucasus are to the North-South and to the East-West. The Pambak-

Sevan-Syunik Fault is among the main active faults of the Lesser Caucasus. It originates in the north-western Armenia and strikes to the SE up to the Iranian border. The fault is composed of segments that are located within the zones exposed to the impact of versatile regional forces. During the study, the Fioletovo and Syunik segments of the active Pambak-Sevan-Syunik Fault, located in the regional zones of compression and extension, respectively, were investigated.
The purpose was to study near-surface tectonic structure elements in the regional compression and extension zones of active faults. The studies were conducted by means of geological and GPR surveys. The near-surface tectonic elements of the Fioletovo and Syunik segments of the active Pambak-Sevan-Syunik Fault were identified and mapped. The contribution of the regional compression and extension forces in the process of formation of those structures was analyzed, and the tectonic settings for the development of the Fioletovo depression were clarified. For this purpose, the north-eastern slope of the depression was studied and a fault was identified there. The presence of this fault supports the suggested pull-apart basin-type structure of the Fioletovo depression.
The results of the study will enable upgrading the accuracy of the seismotectonic model, eventually leading to reduced rates of seismic risk and hazard.

## GAS EMISSION IN THE ACTIVE FAULT ZONE IN THE LESSER SEVAN LAKE (ARMENIA)

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Gas emission has been revealed at the specified site during the geophysical profiling of 2017 (Humminbird 898c SI Combo SONAR) conducted in the zone of the active Pambak-Sevan-Sunik fault in the Lesser Sevan Lake. After additional sonar inspection performed in 2018, underwater investigations that were realized in the same period confirmed the emission of gas bubbles.
At least 3 gas components were identified from the collected gas bubbles: methane (72.9%), carbon dioxide (0.1%) and oxygen (5.6%). Physical and chemical parameters of the ambient lake water were measured at the depth of 42m (diving activities were realized with the help of the Armenian Center of Diving and Subaqueous Research). It is shown that the near-bottom level of dissolved oxygen is high of 97% sat. This aerobic condition is not favorable for biogenic origin of the methane.
The obtained data are in agreement with our earlier observations of methane emission from the surface of Lake Sevan in the zone of the active fault.

# PRELIMINARY RESULTS FROM THE PRECISION LASER INCLINOMETER INSTALLED AT THE GARNI GEOPHYSICAL OBSERVATORY

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In the complex of inclinometer studies, the share of monitoring increases rapidly due to the study of modern tectonic movements enabling one to monitor slow deformations of the Earth crust, which makes it possible to reveal in future the dynamics and the causes of tectonic phenomena occurring in the Earth crust and in the upper horizons of mantle, as well as to assess the forces that cause them.

Precision laser inclinometer (PLI) developed by the physicists of the Joint Institute for Nuclear Research (JINR) in Dubna is the first angular seismograph registering microseismic fluctuations on the surface of the Earth with an accuracy of 2.4 x 10-11 rad/Hz ½ in the frequency range of 10-6 Hz,4 Hz, which allows registration of all known microseismic phenomena.

One of the professional PLI of the JINR is installed at CERN (European Organization for Nuclear Research) in the territory of the Large Hadron Collider, where seismic activity monitoring has been started since the autumn of 2017. The second specimen of this device was installed in the tunnel of the Garni Geophysical Observatory in February 2018.

The conclusions based on the data available from the GGO are the following:

- The inclinometer operates is stable mode and the management program registers daily data from all the signal photo-detectors. Through processing these data, the inclinations of the Earth surface in the directions with an azimuth of 266° in the vertical plane and with an azimuth of 356° in the horizontal plane were determined.
- The sensitivity of the registration is estimated through Fourier analysis based on the daily data and is 2.5 10-11 rad/Hz 1/2. It coincides with the data received earlier from the PLI at the JINR in CERN.
- All the known types of microseismic signals were registered, including those:

1. From remote earthquakes;
2. From deformations of the Earth surface related to the Moon and the Sun;
3. Microseismic signals from "Microseismic peak" occurring in the waters of the Black Sea and the Caspian Sea;
4. Narrow-band and broad-band signals of industrial noise.

A relatively low level of "Microseismic peak" at '50-100nrad is observed. This fact enables monitoring nearly all earthquakes at the distance of 300-400 km higher than 1.5 m.

## GNSS NETWORK AND VELOCITY FIELD OF GEORGIA

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Continental collisions are a fundamental part of the Wilson Cycle and play a significant role in the evolution of the Earth's continents, including being responsible for many major mountain belts. Only two active continent-continent collisions occur today - India-Eurasia and Arabia-Eurasia (AR-EU). Because of its young age (less than 30 Ma), limited spatial extent (~600 km across the entire collision zone), and less than 20 years of geodetic studies, the AR-EU continental collision zone offers the opportunity to determine the detailed kinematics of active deformation for the entire region of plate interaction, from the stable Arabian Plate in the south to the stable Eurasian Plate in the north. The Caucasus region is a broad zone of convergence that forms part of the Alpine–Himalayan collision belt. The mountains of the Greater and the Lesser Caucasus extend roughly between the Caspian Sea and the Black Sea, and are separated by an inter-mountain depression. The region is tectonically and structurally complex. Thus, quantifying the distribution of crustal strain within the collision zone, a principal objective of this research, is important both for clarifying our understanding of the dynamics of continental deformation, and for developing an improved physical basis for estimating and mitigating earthquake hazards in this rapidly developing region

We used the available GPS data throughout the collision zone obtained throughout the Caucasus region and enhanced the existed GPS network by means of installing new permanent stations and performing trans-section GPS surveys from the western part of the Caucasus mountains up to the very eastern edge of the main Caucasus thrust. This effort was utilized and built upon a new GPS velocity field (1994-2018) including all GPS sites of the Caucasus countries (Armenia, Azerbaijan, Georgia) and further constrained by geodetic observations available in Turkey, the northern part of the Arabian Plate, the northern Caucasus in Russia, and Iran. Our study provided new constraints on: 1- convergence across the Greater Caucasus (spatial distribution of active faults and their associated slip rates and locking depths) from the Black Sea to the Caspian Sea, 2- faulting and block rotation in the Lesser Caucasus.

## SURFACE FAULTING FOLLOWING THE 30 OCTOBER 2016 MW 6.5 CENTRAL ITALY EARTHQUAKE: ANALYSIS OF A COMPLEX COSEISMIC RUPTURE

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Surface-rupturing earthquakes represent a unique opportunity to investigate the impact of faulting on landscape evolution, and to refine models of coseismic brittle deformation affecting the upper crust in active tectonic environments. The Mw 6.5 Norcia normal faulting earthquake that hit central Italy on 30 October, 2016, was one of the strongest seismic events to occur in Europe in the past thirty years, causing complex surface ruptures over an area of >400 km$^2$. Thanks to the collaboration of several European teams (*Open EMERGEO Working Group*; about 130 researchers) coordinated by the Istituto Nazionale di Geofisica e Vulcanologia, the observations (>7000 measurements) were collected by performing detailed field surveys in the epicentral region in order to describe the geometry and kinematics of surface faulting (*Villani et al., Scientific Data, 2018*), and subsequently of those of the landslides and other secondary coseismic effects. Detailed rupture mapping is also based on almost 11,000 oblique photographs taken from helicopter flights that have been verified and integrated with field data (*Civico et al., Journal of Maps, 2018*). The ruptures follow the NW-trending normal fault splays of the Mt. Vettore - Mt. Bove fault-system (VBFS). They form a fracture network comprising hundreds of strands striking N135°-160°, with complex stepping relationships and bends. The investigated surface rupture is ~22 km-long, with average surface slip of ~0.44 m. The inversion of coseismic slip vectors provides consistent N230°-N240° extension. Overall, the ruptures length and surface offset frequency distributions follow power-law and exponential scaling, respectively. The surface slip profile is markedly asymmetric, with a high gradient in the southern part. Here, the ~5 km-long Mt. Vettore fault displays average vertical offset of ~1 m (peaks of ~2.4 m), accounting for 40% of the overall coseismic surface slip. The correspondence between surface ruptures and cumulative fault scarps and the matching location of coseismic slip peaks and long-term fault displacement maxima, suggest a progressive trend towards strain localization along the VBFS (*Villani et al., Tectonics, 2018*). The geometric properties of the Norcia earthquake coseismic ruptures obey the general power-law scaling of surface rupture length vs. seismic moment observed for dip-slip earthquakes worldwide over several orders of magnitude.

## 30 OCTOBER 2016-TYPE EARTHQUAKES RUPTURING THE MT. VETTORE-MT. BOVE FAULT SYSTEM (CENTRAL ITALY) IN THE HOLOCENE AGE

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A campaign of paleoseismological investigations was performed on the nearly 22 km-long coseismic surface rupture of the 30 October 2016 Mw 6.5 normal-faulting earthquake in Central Apennines. The main goal was the definition of the maximum magnitude, the average rate of displacement and the frequency of seismic events on the Mt. Vettore-Mt. Bove fault system (VBFS hereinafter). We show the results from the analysis of three trenches at different sites, one dug across a synthetic rupture strand and two across antithetic strands, as well as the integration of other paleoseismic data collected along the VBFS at different time. A major finding of our field campaign is the recognition of slip events associated with individual earthquakes affecting deposits of Holocene age based on radiocarbon dating. The paleoevents are very similar in geometry and size of deformation (up to 0.5 m of throw) to the 30 October 2016 event and re-ruptured the same fault portions within thousands time-windows. Then, paleoseismicity confirms that the VBFS growth develops during large seismic events where surface slip tends to concentrate on the same splays involved in the 2016 October earthquake rupture process, including minor antithetic faults.

Moreover, the 30 October rupture traces overprinted and magnified those produced by two previous spatially and temporally clustered main shocks of lower magnitudes, like the 24 August Mw6.0 to the south and partially the 26 October Mw5.9 to the north (Villani et al. 2018 Tectonics and references therein), involving previously activated faults as well as additional strands of the VBFS. This proves that surface ruptures can re-occur on the same portion of a fault system even within a few days/months, a scenario that has been seldom documented so far. From a paleoseismic perspective, this extreme case of very short lapses of time between surface faulting events and the observed complexity of rupture traces highlight how critical can be the reconstruction of discrete slip events in trenches stratigraphy.

## HOLOCENE TECTONIC AND VOLCANIC ACTIVITY ARCHIVED IN THE DEPOSITS OF THE WESTERN PART OF LAKE SEVAN (ARMENIA)

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The investigation of Lake Sevan recent sediments allows a better understanding of the history of recent tectonic and volcanic activity. The paper summarizes underwater investigations (with diving) of the active tectonics of Lake Sevan undertaken for the first time in Armenia. More than 30 aligned underwater source-related gas emission points were discovered, which allows defining the trace of the Noratus-Kanagegh fault segment below the recent lake sediments. The discovery of a subaqueous segment of the active fault indicates that there is another natural risk of tsunami related to potential fault rupture in future.

The recent Lake Sevan sediments of the north-western coastline are sandwiched between two blocky lava flows. The radiocarbon dating of bones of bovine mammals (with entire skull) that are found about 15 cm from the upper limit of the lake sediments suggests that the upper blocky basaltic-andesite layer can be a result of lava flow eruption younger than 3900 years BP.

About 80 m-thick portion of sediments in the Noratus strata sequence has been sampled for paleomagnetic study and the age of 3.1-2.3 Ma was estimated for the lower part (42 m). The upper and post-Gelasian activity of the Noratus-Kanagegh fault is proven by the cut pumice layer of 2.30±0.15Ma K/Ar age.

## TECHNOLOGY OF GLOBAL MONITORING OF STRONG EARTHQUAKES BASED ON SEISMIC ENTROPY

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The technology is based on the concept of Seismic System (SS) (specific volumes of the geological environment) and the law of seismic entropy production. The developed computer technology allows us to describe the dynamics and the development of instability in the SS. The computer program works in real time on the basis of seismic statistics, automatically processes information, analyzes and delivers results to the Situation Center of the Ltd. SeiEn. Current input data is generated on the basis of information on earthquakes from the global seismological networks. Monitoring of earthquake preparation is conducted simultaneously in all SS (287 in the world and 45 in the territory of the Russian Federation) over all stages of preparation (long-term, medium-term and short-term). The method of seismic entropy has been developing since 1985 and includes 32 years of experience in different seismically active regions of the world. Since 2007, the first stage of fundamental development of the software product and the mass determination of earthquake monitoring and prediction algorithms in reference to 150 seismically active regions of the world has been conducted at the Earthquake Prediction Center (EPC) "GeoQuake", the legal successor of which is Ltd. SeiEn. From 2007 to 2011, the technology had been successfully tested on-line at the www.geoq website: 7 strong earthquakes of the world (including Tohoku, March 11 and Van, Oct. 23 in 2011) were predicted. Starting from 2012, quarterly Bulletins of earthquake prediction have been submitted to the National Crisis Management Center of the Ministry of Emergency Situations of the RF. At the present, the technology allows monitoring almost all significant seismically active regions of the world. SS were identified, which could control, at the regional level, the operating NPPs located in seismic zones (examples for nuclear power plants in Iran, Armenia, California, Japan are given). The possibility of monitoring induced and triggered seismicity of natural and man-made nature is demonstrated by the example of China and the Korean Peninsula. A technology has been developed to control the occurrence of cracks under the platform of NPP and facilities in other areas.

## TOWARDS A UNIFIED AND WORLDWIDE DATABASE OF SURFACE RUPTURES (SURE) FOR FAULT DISPLACEMENT HAZARD ANALYSES

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Fault Displacement Hazard Analysis is based on empirical relationships from historic fault ruptures. These relationships establish the likelihood of co-seismic fault displacements values for a given earthquake magnitude, both on-fault (i.e. along the primary earthquake fault) and off-fault (i.e. distributed surface rupture off the primary rupture), and predict the amount of surface slip. These relationships are useful for land use planning and structural design of infrastructure and critical facilities located on, or close to, an active fault. The current empirical equations are based on sparsely populated data sets, including a limited number of mainly pre-2000 events. Earthquake data sets include the detail of segment map and series of measurements of fault slip.

Based on the above, in 2015, an international effort started to constitute a new worldwide and unified surface rupture database (SURE) to improve further fault displacements estimations.

To date, two workshops have been held and discussions on how to build such a database started. Outcomes from the first workshops discussions are: (1) the first step should be to unify the existing data sets; and (2) the database will include recent and future cases of deformation that has been captured and measured with modern techniques (e. g., InSAR, LiDAR, Optical correlation or Structure From Motion), potentially yielding very rich data sets. Moreover, the SURE database includes parameters that are relevant to properly describe the complexity of a rupture, such as surface geology that potentially strongly changes along a rupture and partly controls its pattern. This kind of "site-specific" information would be useful to derive ad-hoc empirical regressions in future.

Up to now, we could gather a database that includes rupture segment maps and slip data of 41 earthquakes (23 strike-slip, 9 normal and 9 reverse events) in the magnitude range of Mw 5 to 7.9. The quality and amount of data are very heterogeneous and vary from one event to the other, between historical (e. g., 1891 Nobi earthquake, Japan) and remote-sensing era earthquakes represented by thousands of observations (e. g., the 2010 El Mayor Cucapah earthquake, Mexico). To date, the Alps-Caucasus-Himalaya collision belt and forelands are poorly represented in the database, despite its significant activity and wealth of recent and historical surface-rupturing events (e. g., the 1905-1957 M~8 Mongolia; 1968 Dasht-e-Bayaz, Iran; 1988 Spitak, Armenia; 2005 Kashmir, Pakistan, and 2008 Wenchuan, China, earthquakes). Data are available in journal publications, but a significant work is needed to convert them into the SURE format. Next steps will obviously consist in populating the database, but also in taking decisions on how to rank (primary or distributed) each rupture segment for each event of the database, in order to later derive the empirical relationships.

The database will be published in 2019 and will require regular updating. This common effort would imply a large and open community of earthquake geologists to populate and update this free and open-access tool, including people from Middle East, Caucasus, Central Asia and Himalaya. Welcome to be part of it!

## RECONSTRUCTING THE GEOMETRY OF A FAULT-BOUNDED EXTENSIONAL BASIN BY INTEGRATING GEOPHYSICAL SURVEYS AND SHEAR WAVE SPLITTING ANISOTROPY: THE STUDY CASE OF PIAN GRANDE DI CASTELLUCCIO BASIN (CENTRAL ITALY)

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The Pian Grande di Castelluccio (PGC) located in the central Apennines of Italy is a Quaternary intermontane basin bounded by a normal fault-system responsible for the 30 October 2016 Mw 6.5 Norcia earthquake. Following this event, coseismic surface breaks occurred along one of the basin-bounding faults and a further splay in the inner part of the plain. To constrain the shallow and deep geometry of the PGC, we integrate electrical resistivity tomography (ERT) and time-domain electromagnetic soundings (TDEM), focusing on a transect oriented across coseismic ruptures within the plain. Here, the top-bedrock displays a bumpy topography and it deepens down to ~260-300 m below the ground level, due to the presence of previously unreported subsurface fault zones: they are characterized by a low-resistivity signature and throws of several tens of meters.

We also analyze seismograms recorded by temporary stations to calculate horizontal-to-vertical spectral ratio (HVSR) curves of ambient vibrations and to estimate the splitting anisotropic parameters from small-magnitude earthquakes. The retrieved peak resonance frequency varies from about 1.5-2.0 Hz down to 0.4 Hz according to the topography of the top-bedrock as suggested by TDEM results. The pattern of shear wave splitting parameters indicates a dominant fault-parallel fast polarization direction for stations close to the basin borders and near the inferred subsurface fault zones, suggesting that crustal anisotropy in the PGC basin is likely controlled by the geological structures and, also, by the presence of a broad zone around the faults with fault-parallel cracks or shear fabric.

By combining surface and geophysical data with shear-wave splitting analysis, we propose a geological cross-section depicting the PGC basin structure. The latter is a complex half-graben related to the interference of two fault systems of different age (possibly Early-Middle Pleistocene), the older one trending about N30° and the younger one trending about N150°. The latter is currently active and responsible for the present-day seismicity; moreover, it episodically displaces the topographic surface during M > 6 earthquakes.

## CHANGES OF B-VALUES BEFORE LARGE EARTHQUAKES IN DIFFERENT TECTONIC REGIMES

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It is well known that the b-value is influenced by the tectonic regime of each region. Therefore the changes of b-values, as an indication of tectonic changes, are examined before the occurrence of large earthquakes in different seismotectonic regimes.

Specifically, we examine the seismicity and the b-value variations of two regions: a) South America (N. Chile to S. Peru) and b) Nepal. Both maximum likelihood and least square methods are applied for the purpose of the present investigation.

The data sets are extracted from the NEIC seismicity catalogs and are restricted to shallow depths. The data sets include earthquakes with $M \geq 4.0$ for S. America and events with $M \geq 4.5$ for Nepal. The final data sets do not include foreshocks or aftershocks, which have been removed from the initial data set following the method introduced by Mousson (2000). The spatial distribution of the events and their analysis is restricted to areas with radius dependent on the maximum earthquake magnitude, according to relations given by Wells and Coppersmith (1994).

The final results show that in both seismotectonic regions, the b-value decreases (up to b=0.70) with respect to time. Specifically, in the case of South America, the fluctuations of b-value were examined immediately after the occurrence of the 1995 earthquake, M=8.0. The initial b-values were relatively high and a decrease started after 1999. The b-values continued to decrease up to the occurrence of the 2001 earthquake (M=8.4). In the case of Nepal, the distribution of b-value was examined after 1998. The general trend shows a decrease, up to the occurrence of the April, 2015 earthquake (M=7.8).

## EUROPEAN FEDERATED EIDA INFRASTRUCTURE FOR SEISMIC WAVEFORM DATA ARCHIVES: THE REGIONAL NOA DATA IMPLEMENTATION

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The European Integrated Data Archive (EIDA), an initiative within ORFEUS (Observatories and Research Facilities for European Seismology), is the federated European data center that archives and provides access to seismic waveforms and their related metadata from the European and neighboring research infrastructures. Eleven distributed EIDA nodes contribute data from specific regions and have committed resources for the support, operation and development of EIDA. Access to waveform and station metadata is achieved through modern APIs and interfaces. Waveform data from seismic stations located in Greece, the Balkans and the eastern Mediterranean are included to the new regional EIDA node hosted by the National Observatory of Athens (NOA). At present, NOA is hosting and serving all the seismic networks that belong to the Hellenic Unified Seismic Network (HUSN) and the national networks of Cyprus and Montenegro and FYROM. The node archives a total number of 190 stations from networks: CQ, EG, HA, HC, HL, HP, HT, ME, X5 2015. Among those data are provided from 167 broadband stations, 36 strong motion stations or collocated sensors and two permanent Ocean Bottom Seismometers. The implementation and operation of the NOA EIDA node is an attempt at national and European level to provide unlimited and unrestricted access to waveform data archives from the region to the global scientific community. Wider usage of public available data is strengthening the scientific background and increases visibility for international cooperation and collaboration.

## DATABASE OF SEISMIC MONITORING CENTER OF GEORGIA

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The Caucasus is one of the active segments of the Alpine-Himalayan collision belt. The region needs continuous seismic monitoring systems for better understanding of the tectonic processes going on within the region. The Seismic Monitoring Center of Georgia (Ilia State University) is operating the digital seismic network of the country and is also collecting and exchanging data with neighboring countries. The main focus of our study was to create seismic database, which is well- organized, easily reachable and is convenient for scientists to use.

The seismological database includes information about more than 100 000 earthquakes from the whole Caucasus. We have to mention that it includes data from analog and digital seismic networks.

The first analog seismic station in Georgia was installed in 1899 in the Caucasus in Tbilisi city. The number of analog seismic stations had been increasing during the next decades and

in the 1980s about 100 analog stations were operated all over the region. From 1992 due to political and economical situation the number of stations has been decreased and in 2002 just two analog equipment sets were operated.
New digital seismic network has been developed in Georgia since 2003. The number of digital seismic stations was increasing and in current days there are more than 25 digital stations operating in the country. The database includes detailed information about all equipment installed at the seismic stations.

## RELOCATION OF THE CAUCASUS SEISMIC EVENTS

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The Caucasus is one of the most active segments of the Alpine-Himalayan continent-continent collision. High seismicity of the area reflects general tectonics of the region. The Southern Caucasus countries started a joint project on “Probabilistic Seismic Hazard Assessment in the Caucasus” supported by LLNL, USA (Lawrence Livermore National Laboratory). The major goal of the project was to compile regional seismic data in order to provide reliable input for the Hazard map calculation.
Earthquake catalog is the backbone of any PSHA study. We saw a potential to significantly improve the number of events in the catalog using former Soviet monitoring network data (1955-2004).
The Caucasus has a documented historical catalog stretching back to the beginning of the Christian era. Most of the largest historical earthquakes prior to the 19th century are assumed to have occurred on active faults of the Greater Caucasus, but size and location of those events have high uncertainties and cannot be directly assigned to one or another active tectonic structure in the area. Instrumental seismic observation in the Caucasus began in 1899, when the first seismograph was installed in Tbilisi (Capital of Georgia). Seismic network grew over the years. During Soviet era number of stations increased in the region, providing better network coverage and valuable data set for the research. Data of many thousands of earthquakes recorded by the regional network were stored as the seismic bulletins in a paper form.

- We were able to combine bulletins from neighboring countries. Improved location accuracies paved the road for future collaboration and data exchange. Ability to measure direct Mw values from small events to improve magnitude relationships.
- First arrival and amplitude data from the old bulletins for 15 000 earthquakes were digitized. Participant countries provided data for the events with magnitude more than 3.7 of both the analogue and digital seismic networks. Data was stored in the web database, developed particularly for the project.
- In this study, we present 15 000 relocated regional events for 118 years of the observation period in the Caucasus as the major input for hazard analyses. Compiling Soviet magnitude data K, MLH, MPV, we derived new relation formulas of Soviet and modern magnitude scales. Newly compiled catalogues have unified Mw magnitude scale.

- The results of this study will tremendously improve the National Seismic Hazard maps of the Southern Caucasus Countries.

## SEISMIC HISTORY AND CONTEMPORARY SEISMICITY OF THE PAST 25 YEARS IN THE TERRITORY OF DZHYUNGARIYA

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The region of Dzhyungar Alatayu in Kazakhstan is one of the most seismically active areas. On the map of seismicity-generating zones of Kazakhstan, this region includes the zones with maximum possible magnitudes greater than 8, and expected seismic intensity of shakings can reach 9 (Kurskeyev A.K., 2003). This region still preserves its activity in the present time. Figure 1 shows the map of earthquake epicenters in the Dzhyungariya region for the past 25 years indicating all events with magnitudes more than 3 (mb) by the KNDC data.

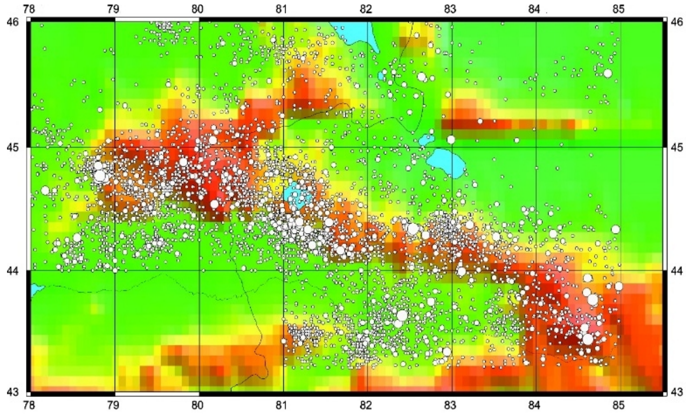


Figure 1: The map of earthquake epicenters in the Dzhyungariya region for the past 25 years.

The report describes new features in the seismic history of Dzhyungariya related primarily the data on the Lepsy earthquake. The observations, analysis of satellite images and field works of the international expedition in the past years (Campbell, G et al, 2003; Abdrakhmatov K.Ye., 2016) demonstrated that the eastern Balkhash part of the Lepsy fault striking to the E-W over ~ 120 km from Dzhyungar Alatayu to the Kazakh Platform has experienced the largest earthquakes. Age dating of the most recent surface events at the Lepsy fault suggests there were two large earthquakes: the first one occurred at least 5000 years ago in the west part of the fault, and the second, occurred about 400 years ago in its east part. Measurements of the earthquake size by different empirical relations allow assuming that the last event could have had the maximum magnitude of Mw 7.5 – 8.2.

Campbell et al (2003) and Abdrakhmatov (2016) are inclined to believe that the Lepsy earthquake is the one mentioned in the catalogue by Mushketov and Orlov, 1893, and consider it as the first known 1715 large earthquake of Dzhyungariya.

However, we think that these are two different events. The catalogue issued in China (Inland Earthquake, 1997) has information on the 1716 earthquake with a magnitude of 7.5 (the Tekes earthquake). It is located directly southward of the assumed Lepsy earthquake at the distance of about 300 km. For the Tekes earthquake, the same work provides the isoseismal

map that shows the rupture line during the earthquake and isoseismal values with points in the territory of China and Kazakhstan. In addition, it shows collapses, caving and landslides caused by the earthquake, and the rupture in the origin. So, it is necessary to assume that in the near-historical time, about 400 years ago, there were two earthquakes of almost similar energy in one seismic active zone: the Lepsy event with the magnitude of Mw=7.5-8.2 and the Tekes event with Mw=7.5. It is noted that the North Tien Shan feature is a spatial-temporal grouping of the largest earthquakes during one activation period as it was, for instance, at the end of the 19th – beginning of the 20th century. For 26 years, the same seismicity-generating zone included the Verny earthquake (1887), the Chilik (1889), and the Kemin (1911) earthquakes; two of them with magnitude greater than 8.
Having performed a comprehensive consideration of the seismicity of the entire large region of Dzhyungariya in Kazakhstan and China, we observe a chain of deep earthquakes along the mountain ranges striking in the SE – NW direction (Figure 2).

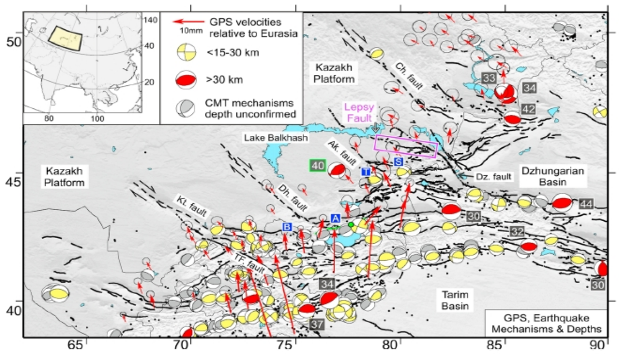


Figure 2: The general view map from the study of Campbell et al (2003). The Figure shows the main faults, focal mechanisms, depths, and GPS-velocities.

The depth of all these earthquakes is more than 30 km. In the north, the chain is ended by the Bakanas earthquake with the depth of origin of 40 km (Mikhailova N.N., Poleshko N.N., 2016). Over a long period of time this earthquake that occurred in 1979 was considered unique due to several reasons, among which were: location of the origin on the platform, extremely large depth for the Northern Tien Shan, and other. However, these issues can be are removed when we look at its position in the tectonic settings on the map of a larger region, which  makes its position and depth quite logical. The Lepsy earthquake having a large depth (30 km) and located on the platform fits into the same chain, but along another fault of the same extension.
New seismic data on large earthquakes provide the basis for geodynamic calculations and tectonic interpretations in Dzhyungariya; the revealed origins of the largest earthquakes should be considered while making the maps of seismic zoning of the next generation.

## THE CURRENT CRUSTAL STRESS FIELD IN THE JAVAKHETI VOLCANIC HIGHLAND

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The Javakheti Volcanic Highland, located in the central Caucasus, is part of the Arabia-Eurasia continental collision zone. This area is characterized by increased seismic activity and volcanism where earthquake distribution is diffuse. In this study, we investigated source mechanisms of the earthquakes using digital waveform data recorded by seismic stations of the Armenian, Georgian, and adjacent seismic networks. The focal mechanisms of a set of earthquakes that occurred within 2005–2017 were resolved with high reliability, based on the polarity of the first motion of the P-wave. A re-location for selected seismic events during this time period was also performed. The azimuth, angle of incidence, and polarities of the P-phase were used to obtain initial focal mechanism solutions.

Analysis of the distribution of focal mechanisms demonstrates the present-day tectonic activity in the study area. The solutions of the different mechanisms vary between strike-slip, thrust, and normal, but are mainly thrusts.

The events characterized by strike-slip faulting mechanisms occurred in the north-eastern part of the study area largely, along both sides of the Javakheti Ridge, where the supposed faults are located.

The fault plane solutions of the recorded earthquakes were used to determine the actual fault geometry, faulting type, and stress regime of the study area.

The resolved earthquakes have a variety of focal mechanisms, and the fault planes of those events have different compression and dilatation distributions. The kinematic Compression (P) and Dilatation (T) axes of the fault planes have been determined to be the predominant sub-meridian directions for P axes, and sub-horizontal directions for T axes. According to the orientations of P- and T-axes, the region experiences NE-SW compression, and NW-SE tension.

For the investigation of the current crustal stress regimes in the Javakheti Volcanic Highland the reliably determined focal mechanisms across the dozens of earthquakes were combined.

The study area is characterized as a thrust (with strike-slip component) stress regime with a radial compressional field ($\sigma 1$-NE-SW; $\sigma 3$-NW–SE).

## THE NETWORK OF GEODYNAMIC AND SEISMOLOGICAL OBSERVATIONS OF THE INSTITUTE OF GEOLOGICAL SCIENCES, NAS OF RA

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Studies of geodynamic processes and seismicity and their interaction in the region have been carried out utilizing the newly-established seismological and geodynamic monitoring networks. The results serve the basis for the study of seismicity and tectonic structure of Armenia and adjacent areas.

Since 2012, deployment of the seismic network has been based on the joint research program between the Taiwan National University and the IGS. During this project, 6 GPS stations

(Trimble Net R9 receivers) and 14 Guralp CMG-6TD seismic stations were installed. As the Javakheti Highland was selected as a trans-border test-zone for this project, the selection of observation sites was concentrated mainly in the northern and central parts of Armenia.
Additionally, 21 Guralp CMG-3T and STS2 stations were installed in the framework of the Project on the Uplift and Seismic Structure of the Greater Caucasus in 2017-2018.
We describe the IGN NAS geodynamic network consisting of stationary GPS observation points and broadband seismic stations. The methods and results of the processing of local and near earthquakes are described. The earthquake parameters established according to the European-Mediterranean Seismological Centre (EMSC) and the data calculated using DIMAS and HYPO71 programs are compared.

## SEISMOTECTONIC MODEL OF THE M5.8 PERNIK EARTHQUAKE OF 22 MAY, 2011

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The M5.8 Pernik earthquake of May 22, 2012 was an unexpected seismic event, in an area with no prior indications and/or well-documented history of earthquakes. To elucidate the state of stress in the area and help explaining the main event and its numerous aftershocks, an onsite SIMORA Project was deployed and its data were analyzed. Here we present the results of the measurements of several geophysical fields and post-seismic activity along with their interpretation as pertaining to the parameters of the main shock. The new proposed geodynamic model, based on this complex geophysical investigation, supports the need for deployment of an Early Warning System in the area.

## CHRISTMAS TREE FAULTING IN NW HIMALAYA

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The tectonics of eastern Pakistan, which is a portion of NW Himalaya, is complicated primarily because it represents the region where major Himalayan faults strongly curve. Previous works have shown various active faults in the region, but details are missing and this includes geomorphic evidence of active faulting. For example, the Jhelum fault is mapped either as a sinistral fault or a dextral fault or a thrust. Herein we try to solve this ambiguity by mapping of all the regional faults in this region using freely available satellite data that include Google maps, coupled with seismological data from the Incorporated Research Institutions for Seismology (IRIS) Earthquake Browser, and moment tensor solution from GeoMap App. The initial mapping is achieved by identification of active geomorphic features on Google images that includes fault scarps, triangular facets, wine-glass canyons, displaced channels, alluvial fans, river terraces, faulted ridges and folded and faulted Holocene to Recent sedimentary deposits. Our results show a series of ~NW to North-

dipping thrust faults, which seem to root from the two major sinistral strike-slip faults: one previously known as the Jhelum fault (JF) and the other newly discovered (herein) fault that we have named as the Tarbela fault because it runs under the Tarbela Dam. The regional Himalayan thrust faults (e.g. Main boundary thrust, Main central thrust) sharply curve at the Jhelum fault, and this curvature largely satisfies the sinistral slip on the JF. This means that the JF is younger, and have displayed, and rotated the major Himalayan faults, and caused the clockwise rotation of the region east of the JF. This has created characteristic tectonic landforms in the region where ~NE-dipping thrusts east of the JF curve at the JF and then turn into ~NW-dipping planes in the west of this structure. This peculiar pattern of faulting resembles a typical pine-tree structure and, therefore, we have named it as Christmas-Tree (CT) faulting.

## ACTIVE FAULTS OF EASTERN KAZAKHSTAN

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The East Kazakhstan region is characterized by an exceptional variety of geological settings and is located within the Tarbagatay-Altai seismic region.
The geological structure of the Tarbagatay-Altai region is a product of the intensity and uniqueness of repeatedly manifested tectonic processes. There are three stages of the Alpine cycle of transformation of the Earth crust and formations of morpho-structures identified within the region include: the Early Alpine (lasting over 100 million years), Middle Alpine (110 million years) and the Late Alpine (30 million years). The latest neotectonic stage is identified with the Late Alpine, which is associated with the highest rate of crustal deformation, pre-Orogen surface alignment and all the contrasts observing the current morpho-structures. One of the characteristic features of tectonic processes of this stage is earthquake.
There are four major mixed-age fold systems within the region consisting of well-defined structural-formational zones, which are associated with regional fold elements of megasynclinorium and mega-anticlinorium, separated by large discontinuous dislocations.
Discontinuous dislocations are limiting movable blocks of various sizes and forming naturally oriented systems. The study of the region creates prerequisites for the identification of structural criteria for localization of earthquake epicenters. There is a set of deep faults within Kazakhstan, which are described in the literature addressing both general theoretical issues and fault characteristics in specific geological regions. Interpretation of remote sensing data allowed us to clarify the alignment of the faults significantly.
Faults play an important role in the formation of orogenic, as well as new structure platforms (morpho-structures) in Kazakhstan. They are the most important structural deformation elements of the Earth crust. As a rule, they are confined to the earthquake epicenters occurring in the study area.
This paper presents a map of active faults and their description. The Map of Active Faults collectively with the complex of geophysical, geological, tectonic and seismological data is designed to develop a regional seismotectonic model of actual and potential earthquake epicenter zones (seismicity-generating zones). These zones are the sources of possible seismic impact capable to affect residential and industrial facilities in the territory of Kazakhstan.

# CONTRIBUTION OF HERMAN ABICH IN THE SEISMOLOGY AND SEISMOTECTONICS OF THE ARMENIAN HIGHLANDS AND ADJACENT AREAS

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An outstanding German geologist, academician Otto Wilhelm Hermann von Abich (1806-1886) largely contributed to all the areas of geology of the Armenian Highlands and its adjacent areas including pre-instrumental seismology and seismotectonics. He was the one to coin the scientific term of the *Armenian Highlands*, which is commonly known to cover the territory of modern Armenia, the Republic of Artsakh (Nagorno-Karabakh Republic), a considerable part of eastern Turkey, etc. (Melik-Adamyan, Khachanov 2011; Volkova, Tikhomirov 1959; Mandalian 2005; Malkhassian 1974).

In July 1945, he climbed Ararat, thoroughly investigated its geological formation and proved that despite the then-dominant views by Voskoboynikov, Helmerson and other nature scientists, the large-scale catastrophe on the Greater Ararat that occurred on July 2, 1840 (M - 7.1, H - 20km where M is the magnitude and H is the hypocenter) was not a volcanic eruption, but a “bright red flame-like” emission witnessed by many, which he explained by unoriginal light effect against the background of the setting sun (Abich 1846, 1862; Malkhasyan 1974; Yankovskaya 2014; Batyushkova 1974; Babayan 2006). In June-July 1859, Abich examined the consequences of the earthquake around the city of Shamakhi (June 11, 1859, M -5.9, H - 10) in Azerbaijan and that of the Turkish city of Erzurum (June 2, 1859, M-6.5, H -10), (Abich 1862; Trifonov, Karakhanyan 2004; Abdulsalamli, Panahi 2007; Babayan 2006).

On the basis of his field research and analysis of data published in the *Caucasus* (a newspaper), Abich compiled a map of isoseimal lines of the Shemakhi earthquake and was the first to scientifically substantiate the correlation between mud volcanism and earthquakes, by rightfully considering that the linearly-located mud volcanoes mark the active tectonic fault of earthquakes (Abich 1939). This was proved by further research, which showed that a considerable part of mud volcanoes erupted immediately after strong M>5 earthquakes (Aliev, Kermova 2007). Abich also studied earthquakes in the midstream basin of the Kura River (May 24, 1861, M – 6.2, H – 30), which had caused considerable damage to the city of Shusha located in the Republic of Artsakh (Trikhonov, Karakhanyan 2004). The earthquake comprised two shocks; it lasted for 15 seconds and is currently estimated at 7-8 points. It immediately followed the emergence of the mud volcanic island named after Captain M. Kumani and located 95km SW of the city of Baku (Abich 1939).

As a whole, Abich related all earthquakes of the south-eastern areas adjacent to the Armenian Highlands to the fault system stretching from NW to ESE, i.e., parallel to the direction of the main Caucasus Mountains. By thoroughly collecting all data on the historical earthquakes of the Armenian Highlands, Abich in fact laid the basis of historical seismology with some help from the outstanding Armenian historian Ghevont Alishan (1820-1901).

## RELATION OF TECTONOMAGNETIC ANOMALIES AND SEISMICITY

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The proposed method represents a tool for practical application of theoretical and practical knowledge of tectonomagnetism in earthquake forecasting. This can become a basis for applied tectono-magnetism, a new direction in the Earth science. As a result of summarizing the scientific data from the net of geomagnetic observations, a tectono-magnetic method of earthquake prediction was developed and tested over 10 years in assessment of the parameters of formed sources of strong earthquakes, such as the Van (23.10.2011; M=7.3), Racha (07.09.2009; M=6.1) and other seismic events. The prediction of strong earthquakes of any magnitude has shown that the suggested method can be surely applied both for the inspection of tectonomagnetic processes in the lithosphere, and for the assessment of expected seismic hazard.

## EARTHQUAKE PROCESS REVERBERATION THROUGH ELECTROMAGNETIC FIELD VARIATIONS

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Aiming to apportion earthquake precursors, the manifestations of preparation of the VARDENIS (Armenia, 29.04.2008, M=3.7), ERZRUM (Turkey, 28.03.2004, M=5.4) and BORISAKHO (Georgia, 09.06.08, M =4.1) earthquakes in the time-series have been studied using the geomagnetic, ionosphere and Irreversibility of Non – stationary Processes (INP) techniques.
With the purpose of earthquake forecasting, anomalies in the ionosphere plasma are investigated by a radio-astronomical method. Some results produced earlier allow distinguishing seismogenic anomalies of the ionosphere from the longer anomalies related to the magnetic activity of the ionosphere by the method of vertical reconnaissance of the ionosphere.

## INTERPRETATION OF ARTIFICIALLY-INDUCED FIELDS OF CONSTANT ELECTRIC POWER AGAINST THE BACKGROUND OF SEISMOTECTONIC PROCESSES

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The Republic of Armenia is situated in a highly active seismotectonic zone. A series of disastrous earthquakes, leading to unrecoverable losses in economy, culture and architecture and in many other fields, have been recorded and documented in the area of Armenia and adjacent countries.

The 1988 Spitak earthquake was a disastrous blow felt in the period the sovereignty of Armenia had been established, and the damages caused by that seismic event have not been recovered up today.
Identification of precursory phenomena is among important tasks in resolving the problem of prediction of catastrophic earthquakes. The endogenous processes, among them tectonic motions and seismicity, having long-term character and directivity, can contribute to deformation of strata in the Earth crust, leading to abnormal changes in the investigated geophysical fields.
The work presents the results of many years' study of anomalous manifestations of artificially-induced fields by means of dc electrical sounding method.
The results of the studies demonstrate that a series of abnormal changes may reflect manifestations of seismotectonic processes quite objectively and certain relation to the ongoing seismic processes is revealed.
It is possible to conclude that study of electrical conductivity within the upper layers of the Earth crust is undoubtedly promising in the quest for earthquake precursors.

## SEISMIC MONITORING AND DAM SAFETY MEASURES OF LARGE HYDROELECTRIC INFRASTRUCTURE IN GREECE

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The Public Power Corporation (PPC), S.A. ensures the renewable energy efficiency of Greece through its vast hydroelectric power plants, totaling more than 3.200 MW, interconnected with the mainland power grid. For this reason, 21 large dams (according to ICODS) have been built since 1950 by PPC at the country's major rivers in order to exploit its hydrodynamic potential. The Dam Safety sector of PPC has established a regional seismic network that monitors the seismicity in the vicinity of the major reservoirs. Thus, any potential induced seismicity due to abrupt water level fluctuation that might affect the existing local stress field is continuously assessed. The 1966 Kremasta earthquake sequence, shortly after the dam reservoir was filled, is the most prominent example of induced seismicity in the country. Currently, 16 seismic stations, constructed according to NMSOP standards, are operating. The Seismological Unit of PPC is also monitoring the structural response during earthquakes of its major large dams by operating arrays of strong motion sensors installed on them. There's a plan underway to upgrade equipment at existing seismic stations and dam strong motion arrays and to expand the network around new reservoirs.

# GEOPHYSICAL AND ENGINEERING-SEISMOLOGICAL RESEARCH IN ARMENIA: MAIN DIRECTIONS, ACHIEVEMENTS AND PROSPECTS FOR DEVELOPMENT

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This study presents the main lines of scientific research (Geophysics, Engineering Geophysics, Environmental Geophysics, Earth’s Magnetic Field, Seismology, Predicting Earthquakes, Engineering Seismology, Strong Ground Motion Database, Analysis & Modeling, Seismic Hazard & Risk Assessment, Earthquake Engineering & Structural Dynamics, Developing & Manufacturing of Geophysical Instruments) performed by the scientific departments (department of geophysics, department of seismology and earthquake prediction, department of engineering seismology and earthquake engineering, department of geophysical instrument engineering) of the Institute of Geophysics and Engineering Seismology after A. Nazarov (IGES NAS RA). The main direction of scientific research in the department of geophysics is the creation of integrated geophysical model of the deep structure of the Earth's crust on the territory of the Republic of Armenia, development of electrometric and nuclear geophysical study methods when exploring ore bodies on the flanks of metal deposits of the Republic of Armenia, and evaluation of the geo-ecological condition by geophysical methods; comprehensive studies of space-time variations of the Earth's magnetic field and related geological and geophysical phenomena. Scientific studies carried out in the department of seismology and earthquake prediction are aimed at studying seismicity and seismic regime, assessing the stress-strain state of the Earth crust in Armenia and adjacent areas, as well as studying foreshock and aftershock processes anticipating and accompanying strong earthquakes in the region. Scientific research carried out in the department of engineering seismology and earthquake engineering addresses assessment of seismic hazard and risk in the area of the RA, improvement of methods for assessing quantitative parameters of seismic impacts, and improvement of the theory and methods of seismic resistance, considering the real effect of buildings and structures and the deformation features of the foundations. In the field of engineering of geophysical instruments, a number of seismic sensors (accelerometer, velocimeter) and auxiliary equipment such as recorders (loggers) were designed at IGES NAS RA, providing wireless transmission of information to the data collection and processing center. On the basis of the developed equipment, instrumental observation systems have been created in order to ensure the integrated safety of important objects. These systems can be converted to conduct seismic monitoring on seismic prognostic sites of large reservoirs, as well as important objects such as nuclear power plants, bridges, overpasses, tunnels and technological pipelines of chemical and oil refineries. Also at IGES NAS RA we have developed a complex of seismo-hydro-geochemical equipment for aquatic ecosystem monitoring. Herein we will present the technical characteristics of the above-mentioned equipment and the possibility of its mass application in foreign countries.

# RECENT DEVELOPMENT OF THE NATIONAL SEISMIC NETWORK OF GEORGIA

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Southern Caucasus is tectonically active and structurally complex region. It is one of the most active segments of the Alpine-Himalayan collision belt and world's youngest mountain system. It is the natural laboratory to study early stage of Montanan formation. For the high-resolution seismic studies, countries of the southern Caucasus have been developing regional seismic networks. Seismic Monitoring systems and the data quality is the major tool to study active tectonic structures of the area.

Seismic network coverage has been tremendously increased in the framework of the joint regional project on "The Uplift and Seismic Structure of the Greater Caucasus", supported by the USA Department of Energy, IRIS Passcal and Science and Technology Center in Ukraine (STCU). Project has started since April 2017. Scientific teams from Armenia, Azerbaijan, Georgia and USA (Michigan State University, Oregon State University, Missouri State University) jointly deployed 53 seismic stations in the region. Our seismic array has two components: (1) a grid of stations spanning the entire Caucasus and (2) two seismic transects consisting of stations spaced at distances of less than 10 km that cross the Greater Caucasus. In addition to the temporary stations, data are integrated from the national networks to produce high-resolution images of the seismic structure.

In Spring of 2017 forty new broadband stations (10 additional stations in the country and 30 in the transect line) were deployed in Georgia. At the same time 9 stations were deployed in Armenia and 4 in Azerbaijan. The Russian National Seismic network has extended the line in the northern direction of the transect. To select the sites for the stations, we used standard network optimization techniques. To choose the optimal sites for base stations, first we have taken into account the geometry of the existed seismic network and topographic conditions of the site. Campaign stations were deployed at the profile starting from the uppermost point of the Georgia-Russia state border at Larsi up to the end of the line hitting the border with Armenia. Distance between campaign stations was approximately 5 km. For each site, both base and campaign, we studied local geology (Vs30 was mandatory for each site), local noise level and seismic vault construction parameters. Due to the complex topography of the country, stations were installed in the high mountains, poorly accessible in wintertime due to the heavy snow conditions. To secure online data transmission from CNET (Caucasus Network) stations, we used cell data network coverage from the different local companies. In Autumn 2018, part of the CNET campaign stations were moved to Armenia and Azerbaijan (12 to Armenia and 12 to Azerbaijan).

Continuous data streams from 46 stations are acquired and analyzed in the real time. National Seismic Network of Georgia is planning to install more stations to improve seismic network coverage.

## A PALEOSEISMIC INVESTIGATION OF A FRONTAL FORELAND THRUST IN THE GREATER CAUCASUS, GEORGIA

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The Caucasus defines the northern margin of the Arabia-Eurasia collision zone between the Black and Caspian Seas within the Alpine-Himalayan collision. Most orogen-perpendicular convergence within this sector of the Arabia-Eurasia collision is absorbed within the Greater Caucasus, as indicated by the seismicity, GPS velocity gradients and the Neotectonic geology. Despite significant historical seismicity in the region, important earthquakes include the Lechkhumi-Svaneti earthquake of 1350, Ms~7.0, I0=9; and the Alaverdi earthquake of 1742, Ms~6.8, Io=9. Active faults with the potential for seismogenic rupture remain poorly characterized. Earthquake focal mechanisms in the Greater Caucasus generally have thrust mechanisms, with recent earthquakes on the main thrust of the Caucasus region being the 1991 Racha Mw=7.0 and the 1992 Barisakho earthquake Mw=6.4. GPS data indicate 2-10 mm/y of convergence across the Greater Caucasus. To investigate potential coseismic rupture along the southern margin of the Greater Caucasus, we are conducting a paleoseismic study in the ShidaKartli foreland fold-thrust belt, 40 km NW of Tbilisi. In 2015 we excavated a 24 m-long and 5 m-deep trench across a potential fault scarp on the southern limb of a south-vergent fold near the Tbilisi-Gori highway between the villages of Okami and Igoeti. This fold deforms deposits mapped as Meotian-Pontian in age. The following soil layers were excavated: the deepest horizon is Unit 1, which is buried topsoil (?), Unit 2 yellow sandy-clayey layer and Unit 3 dark-brown topsoil. In addition, we identified a fault in middle of this trench: this is a thrust fault that dips 345° 3450 to the north and cuts all layers, except the first one. The Unit 1 horizon shows about 3-4 meters of separation along the fault. Unit 1 in the hanging wall is deformed by an overturned anticline. We interpret this thrust fault to have ruptured the surface cutting Unit 1 during one or more significant earthquakes. We have constructed photo mosaics using Structure from Motion and detailed log of the trench.

## A NEW-TYPE SEISMOMETER

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A broadband seismic sensor was developed to be used at seismic stations when establishing seismic systems, to carry out seismic prospecting studies of buildings, reservoirs, tunnels and bridges. This seismic sensor is designed to replace the widely used CM-3 seismometer.

In our seismic sensor, unlike the CM-3 seismometer, the weight was reduced, it has simpler design solutions, which are lighter, more technologically advanced and simplified.

Technical characteristics of the proposed seismic sensor: the natural oscillation range of the pendulum was increased from 1.7 to 2.0 seconds to 2.5 seconds, the damping coefficient from 0.5-0.6 was brought to a critical value: 1, the sensitivity was doubled. Stabilized pendulum is maintaining zero position. For installation of the device and its setting in the zero position, the opening of the cover has been eliminated. These advantages have been achieved through the use of modern information technology capabilities and relevant materials.The weight of the sensor is 1.5 kg, and similar seismometer CM-3 weighs 7.7 kg. In future we plan to organize mass production and wide applicationof the instrument.

# SECTION III.
# Earthquake Engineering

## DISASTER RISK REDUCTION IN THE CAUCASUS THROUGH MODERNIZATION OF THE BUILDING CODES

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Many urban centers in the Caucasus are subject to high seismic risk as evidenced by the Spitak earthquake and the devastation it caused in 1988. Hence, it is important to better understand and quantify the potential for damaging earthquake shaking across the region. There are broadly two questions that need to be answered in order to achieve this: 1) where and how frequently do various types and magnitudes of earthquakes happen? and 2) when these earthquakes happen, how much does the ground shake in various locations? Probabilistic Seismic Hazard Assessments (PSHA) provide a quantitative solution to the problem of evaluating earthquake shaking potential by integrating across these two components (seismic sources and ground motion) in a probabilistic framework. PSHA currently forms the basis for seismic provisions in most contemporary structural design codes around the world. There are currently efforts ongoing in Armenia and Georgia to conduct PSHA and update building codes. Up-to-date building codes ensure that future earthquake risk is reduced in Armenia and other countries in the region through reduction of structural vulnerabilities, resulting in lower risk of casualties, increased resilience, and better economic stability.
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## VERIFYING THE CHOICE OF A NUMERICAL MODEL OF A BUILDING BY IN SITU INVESTIGATION AFTER REALIZATION

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The choice of the structural system, the spatial position of the supporting elements, as well as their section, are defined in the state of project to take the solicitations generated by the exploitation of the structure and the environment of the implantation site. In the case of seismic design, the dynamic parameters of the structure are fundamental. The construction of the numerical model of the structure of a building is based on a choice of hypotheses, such as the mechanical characteristics of the concrete and the steel, the level of embedding, the taking into account or not of the soil-structure interactions, the dynamic characteristics of the structure, in relation to the inter-floor displacements to be respected.
In practice, often all the assumptions are not respected and, it becomes dangerous when the situation leads to a critical state of the work, which is sometimes difficult to make a diagnostic.

In this paper, a building under construction located on the periphery of Algiers, is taken as an example to illustrate a proposal for experimental verification of a theoretical model. The non-destructive investigation technique called the ambient vibration noise technique is used to identify the dynamic characteristics of the building structure.

## ABOUT ESTIMATION OF ACCURACY OF SEISMIC LOADS DETERMINATION

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An attempt is made to evaluate the accuracy of determining seismic loads by the alternative universal method proposed by the author, which makes it possible to take into account the strength characteristics of the soils, the size of the foundations, and a number of other factors. The following basic initial assumptions are adopted, which, in the opinion of the author, may more accurately reflect the behavior of structures under seismic influences.

- The building is considered as free-standing on the ground with one horizontal, conditional connection. The strength of the horizontal connection with the base is limited by a number of real factors.
- On the *foundation - ground* contact, compressive forces act only (tensile forces cannot be considered, except for pile foundations). This approach does not exclude the overturning of buildings without destruction of structures, which is often observed in strong earthquakes.
- It is assumed that in an earthquake, the impulse action – displacement of the soils - leads to some displacement of the foundations, and oscillations of the structure depend on its dynamic characteristics and interaction with the base. In order to determine the seismic loads, the mechanical and dynamic characteristics of the soils and structures are used only, without applying any implicit coefficients, including the dynamic factor β.

The solution of the problem leads to the determination of the unknown external load P (x), which corresponds to the ultimate strength of the load-bearing elements of a structure when it oscillates. These same loads are taken as seismic impacts. The condition of general equilibrium of transverse forces - Q0 due to shear and bending of the bearing elements is used.

$-By^{III} + Ay^{I} = Q_0$ or $By^{IV} - Ay^{II} = P_1(x)$ where -*y* is the total movement at point *x* along the height of the building.

A particular solution of this equation is represented in the form of

$$y = (C_1 chr_1 x + C_2 shr_1 x + C_3 \cos r_2 x + C_4 \sin r_2 x)(C_5 \cos w_i t + C_6 \sin w_i t)$$

$C_1$, $C_2$, $C_3$. $C_4$ and $C_6$ constants are determined from the extreme and initial conditions, and to determine $C_5$ we proceed from the law of momentum conservation of the soils and buildings.

$$C_5 = D_i = -\frac{F_0^{\max} T_0}{2 w_i \sum_1^n m_n X_1} = -\frac{F_0^{\max} T_0 T_i}{4p \sum_1^n m_n X_1}$$

The comparison of calculation results produced by SNiP II-7-81 and those performed according to the proposed method shows sufficient accuracy of the calculations for the fundamental tone of the oscillations and the suitability of this method for analyzing seismic impacts on structures. For higher tones, existing norms distort the results because of the uncertainty of the dynamic coefficient - β for small periods. Seismic loads at the level of foundations are also identified, which leads to redistribution and reduction of general seismic influences on the elements of the structure.

## ESTIMATION OF THE SEISMIC RESISTANCE OF BUILDINGS BASED ON INSTRUMENTAL MEASUREMENTS

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Assessment of the technical condition of buildings affected by an earthquake has own characteristics, and the main part of the existing macroseismic data is based on visual surveys. However, visual survey of some buildings often does not show any significant damage (cracks, wall separation, uneven sediment, etc.); however, their strength characteristics could have suffered significant changes after the earthquake. In such cases, it is practically impossible to assess the seismic resistance of a building without instrumental studies, among which determination of the periods of natural oscillations is the most effective approach. This is especially true for stone buildings with *midis* stonework type. During the Spitak earthquake of 1988, due to low quality of construction works, many residential buildings with this type of stonework were destroyed or severely damaged. Thus, a quantitative assessment of the actual earthquake resistance of buildings exposed to an earthquake is important for assessing seismic risk.

With this purpose, measurements of natural oscillation periods have been carried out for some types of buildings in Vanadzor (Kirovakan). The results of the measurements showed that for frame and for stone buildings, the periods of natural oscillations increased by 15-17% and up to 42%, respectively.

To quantify the effect caused by changed natural oscillation periods of buildings in terms of the strength and seismic stability, some formulas are used to determine the natural oscillation periods. The general rigidity of the buildings under study before and after the 1988 earthquake was estimated for stone buildings and for frame buildings.

According to the data produced, the initial conclusion is that strength and deformability, i.e., seismic resistance of stone multi-apartment buildings decreased 3.03 times, and for frame - panel buildings the decrease was 1.33 times compared to their condition before the earthquake. As far as MMSK-86 and MSK-64 scales assume that an earthquake intensity increase by one point corresponds to approximately doubled seismic actions, actual reduction of the seismic resistance of buildings is 3.03 times corresponding to a decrease by about 1.5 points. For frame buildings, respectively, there is a decrease in seismic resistance by 0.66 points.

The results were used to assess the risk of damage to buildings in case of possible earthquakes of intensity 8 and 9 points on the MSK-64 scale. For areas built over with buildings of different types and having different degrees of damage, seismic risk is determined taking into account their weight in total.

# SEISMIC SAFETY ASSESSMENT OF THE SCHOOLS IN THE RA

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There are 1,363 state public schools in the RA. Most of them had been built before the devastating 1988 Spitak earthquake, and it is obvious that the volumetric-design and design solutions of those buildings do not meet the modern requirements of earthquake resistant construction, which threatens the safety of children and educational staff.
There had not been any definitive database for schools buildings in the RA in terms of their seismic risk assessment. Besides, it is noted that any results of macro-seismic examinations of the behavior of school buildings after the devastating Spitak earthquake were either lacking or were very limited in number. The reason was that in fact school buildings in the disaster zone either collapsed totally, or were damaged to a degree making their reconstruction impossible.
In 2013, with the support of the UNICEF Armenia, RSSP implemented a Project on "Preventing disaster losses and reducing vulnerability of children in Armenia" in line with the 2005-2015 Hyogo Framework for Action, Priority 4 (reducing the underlying risk factors) in particular.
The work carried out within the framework of the project is aimed at prevention of disasters in Armenia and intends to increase the seismic safety of school-aged children. Special attention is given to the works of seismic vulnerability assessment for school buildings and structures as an important stage in the activities aimed at seismic risk reduction.
As a result of the complex analysis of the typical school buildings, they have been classified into the following 5 main design types: (A) bearing walls of stone masonry, complex construction, (B) external bearing walls, internal RC precast or monolithic frame, (C) external RC frame, internal precast RC bearing walls, (D1) precast two-storey RC frame (IIS-04 series), and (D2) precast three-storey RC frame (IIS-04 series).
Vulnerability curves were developed for each type based on the European MSK-98 scale, RABC codes, international experience, results of seismic calculation, data on the damage in the 1988 Spitak earthquake, natural period of buildings and soil category.
To select schools most vulnerable and hazardous in terms of earthquakes, an evaluation scale was developed, which included the following 7 main indicators: seismic hazard level of an area (I), vulnerability degree of the typical building (II), number of students (III), school construction date (IV), technical state (according to the existing database) (V) existence of secondary hazards in the school area (landslide, rock fall, mudflows, flood, etc.) and (VI) existence of highly vulnerable buildings, structures or objects adjacent to the school (VII). Considering the importance of an indicator, corresponding weight (in regard of 1 unit) was given to each indicator of the scale.
In general, the following assessments were given in terms of seismic safety: schools having high level of safety-14.5, medium level of safety -14.5-30.9, and low level of safety -30.9-54.6.
The existing school databases were analyzed and school seismic safety database was developed, in which the above indicators were taken into consideration.
The results of the project served the basis to approve of the N 797-N Resolution of the RA Government of July 23, 2015 on "The 2015-2030 Program for the Improvement of the Seismic Safety of State Comprehensive Schools of the Republic of Armenia". The

Government has identified the required resources and started with the reconstruction and reinforcement works of the prioritized schools.

## NEW EXPERIENCE OF APPLYING TUNED MASS DAMPERS (TMD) IN THE YEREVAN CITY

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For the Republic of Armenia, improvement of seismic resistance is a crucial problem of national security demanding urgent solution.

The number of residential buildings built in Yerevan before the devastating Spitak earthquake comprises about 4765: they were designed for seismic resistance to 7-8 points on MSK-64 scale and their design solutions do not meet a number of requirements of the Earthquake Resistant Building Codes. Around 70% of Yerevan population lives in such buildings. It has been revealed that depending on the year of construction, structural features and damages suffered in the course of maintenance, about 45% of the buildings have high level of vulnerability, i.e., they can be destroyed in case of a potential earthquake with a seismic intensity value of up to 7-8 points (0.2 g).

It has been proved that the seismic risk in Yerevan is very high. In case of financial and economic opportunities, the best solution to the problem would be to demolish the buildings that are physically and morally depreciated and do not meet modern requirements, and to replace them with new ones, which is currently being done in developed countries. However, this is not realistic for our Republic yet. Therefore, the only justified way to minimize the seismic risk for Armenia is to enhance the seismic resistance of the buildings that have high or average rates of vulnerability.

According to preliminary calculations, enhancement of the seismic resistance of each building with traditional methods will comprise at least 40% of its value, and besides, the residents will have to be temporarily evacuated. In case of applying these methods, long time and huge amount of financial investments will be required to cover the whole city of Yerevan, which makes implementation of the project not feasible within the framework of the RA state budget currently and in the coming years.

Implementation of an advanced and effective method proposed to solve the problem may help to minimize the investments from the state budget. Unlike conventional methods, it is suggested to apply special seismic protection systems, which are set out in paragraph 7.15.1 of RABC II-6.02-06 Code. Among these methods, TMD has been already applied in the RA.

Unlike other special seismic protection systems, TMDs have the remarkable advantage as they can be mounted in a building that is already used, without interrupting its normal operation and without interfering with its interior volume ( they are mainly mounted on the building roof). In addition to the main function, TMDs can offer the following features: "extra weight", "useful weight-pool", "green roof", and "one or two extra floors".

The article presents the experience of using TMDs during the recent years on the residential building at 18/3 Amiryan str. and "Baghramyan Apart Hotel" building.

In case of the residential building at 18/3 Amiryan str., the cover of the additional technical floor on the building served as the weight. In case of the hotel building, the pool and the green garden on the flat roofs served as the weight. Unlike previous similar work carried out in Armenia, laminated rubber steel bearings produced in Armenia (RSB, AST 261-2007) served as an element of rigidity for the TMD. They have horizontal rigidity of 0.81 kN/mm.

The bearings were placed one on the other in one junction, in which case the total horizontal rigidity of one junction comprised 0.405 kN/mm (0.81/2).
As a result of relevant experimental studies, joint work of two RSBs in a single junction and their stability under the minimum vertical load in case of maximum deviation was substantiated.

## THE PECULIARITIES OF CONSTRUCTION OF THE YEREVAN CITY FROM THE POINT OF VIEW OF SEISMIC RISK

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The devastating Spitak earthquake of 1988 showed that the level of seismic resistance of buildings and structures in Armenia is considerably lower than the level of seismic hazard, so almost entire area of the country is in the zone of high seismic risk.
Beginning from 1989, huge work has been done to reduce the seismic risk in the northern part of Armenia that was damaged by the earthquake. The level of seismic hazard of the region has been re-evaluated; buildings and structures damaged during the earthquake have been strengthened to meet the level of seismic resistance according to the requirements of the National Seismic Resistance Construction Code established in Armenia after the Spitak earthquake. The compilation of the inventory of buildings and structures affected by the Spitak earthquake has been finished.
In the meantime, Yerevan city, the capital of Armenia, located in an active seismic zone, has not received sufficient attention. Taking into consideration high density of city population, it is clear that next strong earthquake may be hazardous for Yerevan.
Yerevan was the first city in the Soviet Union for which a General Layout was developed. The General Layout developed by academician Alexander Tamanyan was approved in 1924: it was designed for a population of 150.000. Since that time, the administrative area of the city has increased 5 times. The construction of Yerevan started with buildings of basalt, granite and marble. The most widely used construction material was rosy tuff. As this construction material gave a unique vividness and specific tint to the city, Yerevan was called a “Rosy City”. During the next 70 years, the area of the city enlarged even more.
Residential buildings in the capital city of Yerevan are considerably diverse by both the number of floors and design solutions, and by provision for the required seismic resistance.
Large-scale construction of residential buildings in Yerevan, where more than one third of the population of the Republic is concentrated, has been conducted mainly during the last 50-55 years. Compared to the rate of 1940, the housing stock in the capital has increased more than 20 times and covers about 13.5 million sq. km. Conditionally, development of the large-scale state (public) residential construction, in Yerevan and over the Republic as a whole, can be divided into stages conditioned by the development of the construction industry, establishment of the normative database of earthquake resistant construction, as well as by the policy the former Soviet Union adopted in different periods.
In this study, we address the features of Yerevan city-planning: multi-storey residential buildings, low-rise houses, schools and hospitals are classified according to design solutions and date of construction. The design features of typical multi-storey residential buildings and their behavior during the destructive Spitak earthquake are presented. The seismic resistance of typical buildings is estimated. In total, 103 multi-storey residential buildings, 31 low-rise

individual buildings, 13 schools and 8 hospitals were studied. The passports of the studied buildings were compiled.
Based on the results of the study, rate of seismic risk was calculated for the Yerevan city within the framework of "The Project for Seismic Risk Assessment and Risk Management Plan in The Yerevan City of the Republic of Armenia" carried out by JICA in 2012.

## STUDIES OF FREE OSCILLATIONS OF BUILDINGS TAKING INTO ACCOUNT SEISMIC ISOLATION

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The numerical solution of the dynamic problem of the "platform- model of the building" system is considered. On the basis of a direct numerical integration method, free and forced oscillations of the dynamic model of a building with and without seismic isolation were studied. The results of the numerical solution of the test problem of the system "platform-model of the building" were obtained using a computer program developed in the FORTRAN language.
At the present, seismic isolation is one of the most promising methods of active seismic protection of buildings and structures.
The superstructure motion equation of the dynamic model is presented in the matrix form:

$$M_S \ddot{W}_S + C_S \dot{W}_S + K_S W_S = -M_S I(\ddot{x}_g + \ddot{w}_b) \qquad (1)$$

where $M_S, C_S, K_S -$ correspond to the diagonal matrix of masses, damping and stiffness matrices, $W_S = \{w_1, w_2, ..., w_n\}^{\mathrm{T}}$, $\dot{W}_S$, $\ddot{W}_S -$ are vectors of relative displacements, velocities and accelerations, $\ddot{w}_b, \ddot{x}_g -$ are the relative acceleration of the mass of the base slab $m_b$ and acceleration of the ground, respectively, and $I -$ is a unit vector. The equation of mass motion $m_b$ is presented in the form

$$m_b \ddot{w}_b + f_b - k_1 w_1 - c_1 \dot{w}_1 = -m_b \ddot{x}_g, \ (2)$$

where, $f_b -$ is the restoring force of seismic isolation, $k_1, c_1 -$are the coefficients of stiffness and damping of the first floor.

The restoring force, $f_b$ in general, has a non-linear nature of change, depending on the displacement of the isolation. The nonlinear law of variation of the restoring force can be replaced by an equivalent linear model based on effective elastic stiffness and effective viscous damping

$$f_b = k_{eff} w_b + c_{eff} \dot{w}_b, \ (3)$$

$$k_{eff} = k_2 + f_0 / \Delta_2, \quad c_{eff} = 2\xi_{eff} \mathrm{M} \omega_{eff}, \omega_{eff} = 2\pi / T_{eff} \ T_{eff} = 2\pi \sqrt{\mathrm{N} / k_{eff} g},$$

where $\mathrm{M}$ – is the mass of the superstructure, $\mathrm{N} = \mathrm{M}g$, $\xi_{eff}, T_{eff} -$ are the effective damping factors and the main period of free oscillations of the isolation. The system of differential equations (1), (2) is solved by numerical method. At the first stage, free oscillations of buildings for different number of stories were studied. At the second stage, the results from seismic impacts were studied and obtained.

- The results of numerical simulation, based on the developed algorithms and programs, confirm the effectiveness of seismically isolating rubber-metal bearings.
- The use of seismic isolation leads to a significant reduction in the acceleration and relative inter-storey shear, but at the same time, the absolute displacement of the building increases compared to the building without seismic isolation.

## TECHNICAL CONDITION AND VULNERABILITY ASSESSMENT OF BUILDINGS USING MICROTREMOR SYSTEM

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The problem of studying the peculiarities of vibrations of a building of the Typical Series 538 erected on basalt soils is considered. Spectral analysis was performed by means of microtremor registration on the building and its soils. The features of dynamic behavior caused by design solutions in the building were revealed.
The aim of the study was to investigate the features of dynamic behavior of a 15-storey residential building of the “Badalyanian” structures related to the Typical Series 538 and erected on the basalt soil, based on the results of the experiments implemented during field tests from microtremor measurements, using the super-sensitive seismic sensors and the logger developed by the IGES NAS RA. The following tasks were addressed:

1. obtaining their main actual dynamic characteristics;
2. investigating the assignment of the peak values of natural vibration amplitudes to design elements; and,
3. identifying the features of the joint work of the building and the soil.

The tested building, which was designed for intensity 7 seismic zone is located at 89 Raffi Str and was built on basalt soil in 1983. The building has square layout 18.3 × 18.3 m in size, one entrance, the basement and 15 over-ground floors with the total height of 45.8 m; floor height is 3 m.
The building has a reinforced-concrete framed structure with a spatial precast-monolithic system that is built of the Badalyanian-type factory frames. The foundations are isolated with spread footings under individual columns of prefabricated reinforced concrete. The columns and beams are from prefabricated reinforced concrete 500 × 500 mm and 500 × 570 mm in size. Shear walls and internal staircases are also from prefabricated reinforced concrete. The covers are executed with precast voided floor slabs. The interior walls were installed with the masonry of hollow concrete blocks. The roof is flat with bituminous waterproofing systems and with organized water drainage.
Measurements were made by means of a mobile seismic station consisting of three receivers - seismic sensors SM-3 (two horizontal (H) - X, Y and one vertical component (V) – Z), 8-input logger, powered by IGES, with the wireless network that provides connectivity with a laptop. This device (logger) enables online visualization of the records that are displayed on the laptop monitor by using the specially developed software. The registration frequency is 200 samples per second.

Instrumental observations, measurements and microtremor recording were performed on each floor of the building and on soil over the surrounding area to study the dynamic characteristics of the structure and the soils. Spectral analysis was performed based on data from instrumental recordings and Fourier spectra (48 pcs) were constructed.
The analysis of the data obtained shows that the average free vibration period values of the building correspond to 1.036 Sec in the X direction (frequency: 0.892 Hz); 1.122 Sec in the Y direction (frequency: 0.892 Hz) and 0.188 Sec in the Z direction (frequency: 5.318 Hz). The average value of the logarithmic decrements of the basic tone of free vibrations of the buildings is 0.198, 0.20 and 0.045 in the X, Y and Z directions, respectively.
The value of the dominant vibration periods of the soil is 0.06 Sec (frequency: 16.604 Hz) in the direction of all components, with a striking peak. The value of the logarithmic decrements of the basic tone of the natural soil vibrations in 0.007 in the X direction, and 0.006 in the Y and Z directions.

## ON THE ALLOWANCE FOR COMLEX ENGINEERING-GEOLOGY CONDITIONS IN ESTIMATING BUILDINGS AND STRUCTURES FOR SEISMIC IMPACTS

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To provide for earthquake resistance of buildings and structures in complex and unfavorable engineering-geology conditions, irregular deformations of the basement must be considered among the main factors affecting the bearing capacity, deformability and stability of buildings and structures.

The results of studies of strong and damaging earthquake effects (including the findings of the detailed macro-seismic observations conducted in the zone of the December 7, 1988 Spitak earthquake within the cities of Spitak and Gyumri) attest that in some cases the greatest damage and destruction of buildings or structures built under complex or unfavorable engineering-geology conditions can be considered not as a simple result of local amplification of the seismic effect due to unfavorable soil conditions in compliance with the “classical” approach of the seismic micro-zoning, but rather an effect of long-term and gradual reduction of their bearing capacity, hence, of the reserve of resistivity to seismic impacts, caused by the pre-*loading* of design elements determined by irreversible deformation processes in builing bases.

According to the classification of standards by loads and impacts, basement deformation impacts like seismic impacts shall be related to the category of special impacts. It is clear that natural combination of any basement deformation impacts (regardless of their origin) with a seismic impact is possible (which is not allowed for by the effective standards on the grounds of “low” likelihood of combination of two kinds of special impacts). This creates ***doubled***-complexity conditions for construction.

Engineering analysis of the results produced by the study enables the conclusion that to provide for comprehensive invulnerability of buildings and structures under doubled-complexity conditions, earthquake resistance calculation shall be based on the estimated design seismicity of the construction site and then, it is necessary to add internal loads developing in structural elements under specific irregular deforming impacts of the basement that have been standardized in the specified way.

## APPLICATION OF B-Δ AND $P_d$ METHODS TO BROADBAND DATA IN ARMENIA

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We applied two onsite methods for earthquake early warning, the B-Δ and $P_d$ (peak initial displacement amplitude) methods, to broadband waveform data from the IRIS GNI station in Armenia to investigate their performances. We reviewed the widely used three onsite earthquake early warning methods, which are the B-Δ, Tau_c, and $P_d$ methods. Considering the data availability and the characteristics of the methods, we selected the two methods to be applied in this study. First we calculated B values for 220 events that occurred from 2010 to 2014. The magnitude range is from 3.0 to 7.1 and the epicentral distance range is from 15 to 270 km. We compared our results to the previous studies. Most of the B values are smaller than the expected values from the formulas obtained by previous studies except for larger events (M≥5.0). This result suggests that the B-Δ method may work for larger events. Second we applied the $P_d$ method to data for the selected 220 events. We integrated velocity data to obtain displacements using a high-pass filter to remove long-period drift following previous studies. We found a good correlation between $P_d$ with PGV (peak ground velocity) and obtained the relation between $P_d$ and PGV by the least squares method. We also found a good correlation between $P_d$ and PGD (peak ground displacement), which is consistent with previous studies. The results of this study indicate that these onsite methods will work for large earthquakes to estimate epicentral distance, PGV, and PGD using waveform data recorded in Armenia.

## EVALUATION OF THE SEISMIC RISK OF COMMUNITIES IN THE REPUBLIC OF ARMENIA (EXAMPLE of VARDENIS CITY)

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Assessment of seismic risk in communities is a very important scientific and practical issue. It has a social-economic, specific and strategic meaning, since it is linked to the preservation of human lives and material values. In the recent years, the seismic risk of major cities in the country has been assessed, using different assessment methods.
In this study, the seismic risk assessment of the study area was conducted using two approaches: intensity-based and spectral acceleration-displacement-based damage and loss assessments. For damage and loss calculation, we used the ELER (Earthquake Loss Assessment Routine) methodology and software for a rapid estimation of the earthquake shaking.

Three scenarios were identified for the province, and, for each of them, the possible epicenter, which could cause great damage to the area under study, was fixed. Subsequently, the study area was divided into cells. In each of the cells, the population and the number of buildings were placed.

As a result, we obtained the expected losses, based on seismic hazard obtained from definite earthquakes magnitudes.

# SECTION IV.
# Geohazards, seismic risk assessment and seismic resilience

## THE ROLE OF TECTONIC STRESS FOR GEO-HAZARDS

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Tectonic stress changes and the associated strain in the upper crust have significant influence on the processes of long-term or short-term large-scale natural geodynamic processes, resulting in geo-hazards such as seismicity or volcanism. On regional and local scale, human activities, such as mining, building of hydropower dams, withdrawal and injection of fluids in porous reservoirs can also cause geo-hazards. This induced hazard can also occur in areas, which had been characterized by absent or very low natural seismicity in advance of human activities.

In contrast to natural hazards, the induced hazards can be mitigated by smart geo-engineering. However, the control of these anthropogenic geo-hazards requires an improved process understanding. In recent years, the combined effect of tectonic stress and stress-changes due to human activities has been identified as one of the key causes. For instance, gas extraction in the Groningen Field in the Netherlands has increased the felt and damaging seismicity, which has finally led to a gradual shut-down of gas production within the next decades. Injection of fluids e.g. in EGS projects is frequently associated with mostly minor earthquakes, whereas the long-term massive injection of waste water in mid-continental U.S. has led to earthquakes of magnitudes $M>5$. In most cases, the changes of pore pressure and the associated changes of stress caused reactivation of those faults that are close to a critical condition in the natural tectonic stress environment.

Similarly, in mining areas of tunnels for infrastructure, the opening of these underground structures modifies the existing state of stress, which can lead also to fault reactivation, wall failure and surface subsidence. In Germany, for coal mining the water table had to be lowered significantly with severe costs for the pumping. Now, with closure of the coal mines the water tables are rising again and low to moderate magnitude earthquakes occur – presumably because the rising pore pressure meets a modified state of stress around the mines.

Future challenges are linked to safe energy supply and activities to reduce green-house gas emissions. The renewable energy sector requires large storage potential (TWh) to compensate the fluctuations in generation and demand of power. Furthermore, the geological storage of CO2 (CCS) requires large storage volumes in the underground as well. For both, porous aquifers or former gas reservoirs could be used. For CCS, but also for underground gas storage, the activities do not only change the characteristics of the reservoir rocks, but also those of the infrastructure and nearby fault zones. In this context the natural in situ stress state and the induced stress changes are a key parameter that needs to be quantified.

## THE SEVAN BASIN IN THE EPICENTER OF THE GEOLOGICAL HAZARDS

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With its 4900 km$^2$, the Sevan basin represents 16.4% of the Armenian territory. The Sevan lake, in its center (1240 km$^2$ of freshwater) is a region where various geological hazards occur. The lake is surrounded and crossed by active faults of various kinematics. Situated at the northern limit of the South-Armenian micro-block, the north-eastern part of the Sevan basin corresponds to a suture zone, Middle Jurassic-Lower Cretaceous ophiolites, controlled by the active Pambak-Sevan-Syunik Fault (PSSF) crossing the axial part of the Sevan lake. The evidence of historical seismicity and paleoseismicity shows that the PSSF can produce earthquakes with moment magnitudes of Mw>7.0.
Normal and oblique-slip active faults with lower seismic potential characterized the mountainous areas within the western part of the lake and its southwestern limit. In the Gegham (westward) and Vardenis (southward) regions, the Holocene volcanic activity produced eruptions and lava flows that reached the bottom of the lake.
In the lake, underground water and gases reach the surface through fault planes with emission points linearly distributed along the fault lines.
Within its northeastern and southwestern limits, the Sevan lake displays the potential of landsliding along steep slopes that are controlled by tectonic triangular facets and listric faults, respectively.
Therefore, the Sevan basin corresponds to a region where not only tectonics and volcanism, but also landsliding and, possibly, lake tsunami effects can interact. Hence, the occurrence of these various geological hazards and their possible interactions imply that the related risk is more important than for each hazard taken separately. This involves a specific evaluation of the sum of hazards.

## CHARACTERIZATION OF FAULT PARAMETERS PREDESTINED FOR SEISMIC HAZARD MAPPING OF THE SOUMMAM REGION, EASTERN ALGERIA

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The purpose of this work is to provide the geological parameters (direction, length, type, dipping) of the active Soummam fault. These parameters are integrated to evaluate the seismic hazard assessment of the area surrounding the fault in the radius of 50 km. The probabilistic approach is used to estimate the maximal magnitude of credible probable earthquake (MCE), which can affect the Soummam region.
For seismic hazard assessment, it is primordial to reconstruct the neotectonic model. Moreover, the Soummam fault is an authentic case, which deserves neotectonic evidences. This is a regional Miocene border fault connecting two tectonic contexts of the Kabylian domain. This one belongs to Algerian Maghrebides. The mean is to describe tectonic

structures associated to the regional context of the Soummam fault, which seems to be characterized by slow crustal deformations and the seismicity seems weak for quite short periods.

## IDENTIFICATION OF GIANT MASS MOVEMENTS IN THE LESSER CAUCASUS (ARMENIA) AND ASSESSMENT OF THEIR SPATIAL RELATIONSHIP TO MAJOR FAULT ZONES AND VOLCANOES

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The Vokhjaberd and Garni landslides (of assumed seismic origin) located in the vicinity of Garni, Armenia, were investigated during a geophysical field campaign in September 2016 (within the framework of a master thesis). On the basis of the geophysical prospection (ambient noise measurements, also called the H/V method), the thickness of the landslide deposits was estimated and a 3D model was developed. The original trigger of those ancient landslides is not known – but one major reactivation by an earthquake in 1679 has been proved (see below).

Additionally, the spatial distribution of Armenian landslides was analyzed with respect to the location of major fault zones and volcanic areas, and landslide susceptibility maps were created considering the morphological, geological, tectono-geological and geo-morphological factors. For this research, a spatial GIS analysis was carried out on the basis of two landslide catalogues: the GEORISK inventory (provided by the GEORISK Scientific Research Company, Yerevan) and our catalogue. Both catalogues cover the entire area of Armenia, but the study zone covers only the areas near the Garni and Pambak-Sevan-Syunik faults, as well as several volcanic areas. These faults are mainly marked by dextral strike-slip movements locally combined with reverse mechanisms. Strong historical earthquakes occurred along these fault zones, as for example the 1679 Garni earthquake, which caused widespread destruction and reactivated landslides located near the Garni Fault, including the two investigated landslides. The volcanic areas on the other hand include the Ghegham and the Vardeniss ridges. Some of the volcanoes along these ridges erupted during the Holocene. Nowadays, more than 80% of Armenia is covered by Quaternary volcanic rocks or friable deposits, which are favorable for formation of landslides. Actually, the analysis revealed that our catalogue indicates an indirect spatial link between the location of landslides and the presence of the volcanic deposits: landslide susceptibility increases with distance from volcanoes. This indirect link could be due to the fact that slope instability is more widely developed in the finer volcanic deposits that are deposited far from the eruption center (while this link is less obvious if we use the GEORISK inventory as an input). We also noted that many landslides are located very far from any mapped fault zones – this behavior is atypical for seismotectonic regions (e.g. for the Tien Shan we could show that the spatial relationship between presence of faults and increased landslide susceptibility is very clear). Therefore, we think that in some regions of the Lesser Caucasus, higher densities of landslides may hint at the presence of faults that have not yet been mapped. If this can be proved, landslides could also help in other regions of the world to map faults that have no clear surface signature (besides the landslides).

## ESTIMATION OF SEISMIC HAZARD IN PART OF WESTERN REGION OF HIMALAYA, INDIA

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Destructive effects of earthquakes are becoming alarming day by day because of growth in population, rapid rate of industrialization, large-scale engineering activities and their impact on the environment, which now call for increased efforts to minimize the resulting seismic hazards. Seismic hazard analysis involves quantitative estimation of ground shaking at a particular site or for a particular region. In the present study, Deterministic Seismic Hazard Analysis (DSHA) was carried out for the states of Himachal Pradesh & Uttarakhand. The study region is one of the most seismically active regions in the western part of Himalaya, India, and there are numerous major seismic faults present in this region. Eighty-nine seismo-tectonic sources in and around Himachal Pradesh &Uttarakhand were identified. Using an appropriate attenuation model, the peak horizontal accelerations, peak vertical accelerations and ratios of peak vertical to horizontal accelerations were computed. For this purpose, the study region was divided into grids of 0.5° by 0.5°. The estimated peak horizontal accelerations vary from 0.02g to 0.60g and peak vertical accelerations vary from 0.01g to 0.47g. The ratios of vertical to horizontal accelerations vary from 0.27 to 0.78. The PGA contour maps prepared for the region show that larger Peak Ground Accelerations are present in the region, where there is a higher density of larger faults and vice versa.

## INPUT DATABASES FOR THE DEVELOPMENT OF THE PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE REPUBLIC OF ARMENIA

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The scientific activities were performed in order to deliver the input databases for the Probabilistic Seismic Hazard Assessment for the Republic of Armenia.
The project was performed by the Consortium composed of the Air Worldwide Corporation (AIR, USA), Georisk Scientific Research Company (GEORISK, Armenia), and Global Earthquake Model Foundation (GEM. Italy) led by AIR. The Consortium delivered a PSHA over a wide range of return periods and intensity measures and a new seismic zonation map that enables the Government of Armenia to produce a more informed update of the national seismic building code. The project incorporated the latest scientific data related to seismic hazard, state-of-art PSHA methodologies, and explicit treatment of key uncertainty.
All relevant geophysical, geological, and seismological data were collected, analyzed, and interpreted during the construction of the Input Database associated with this project. GEORISK established input databases to be utilized in the development of the Probabilistic Seismic Hazard Assessment for the Republic of Armenia. The databases contain available data from a variety of geophysical, geological, and seismological sources including data from the Institute of Geological Sciences (IGS) and Armenian National Survey for Seismic

Protection (NSSP). The majority of data were collected within the 150 km buffer enclosing the national boundaries Republic of Armenia (RA). In brief, these databases contain: (1) general data such as digital elevation and hill shade data; (2) geological data such as active fault data, geological maps; (3) geophysical data including borehole and gravimetric data, and GPS data; (4) seismological data including focal mechanism and macroseismic data; and (5) ancillary data such as previously developed regional seismic hazard models. All datasets are contained in digitized GIS format and are combined into a single multilayer database.

## ENCOUNTERING INFLUENCE OF DISASTERS ON POLICY MAKERS: A THEORY OF DISASTER RISK GOVERNANCE

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The paper investigates disaster risk governance in the context of development and disaster recovery. The historical catalogue comprising up of natural hazards and associated disasters developed for Pakistan suggests that the country has enormous economic exposure to the hydro-meteorological events, and is highly vulnerable to undergoing significantly huge losses at least once every decade. The study also proposes a new theory, called dis-fluence theory of disaster risk governance. The term is coined by the authors of the paper and is an amalgamated version of ‘disaster’ and ‘influence’, representing the influence of a disaster on policy makers. The crux of the theory lies in the idea of the probability of disaster influence in triggering a discretionary action. The probabilistic expression of the theory explains how the magnitude of the events and discretionary actions, in turn define and explain governance. The theory inherits the assumption that it takes only an event that has the capability of posing intensive risk to trigger the influence rather than the one posing extensive risk. It is so that the cost of an event associated with extensive risk is minute in the short-term for its impact is much localized and therefore, influence is not likely to be triggered. By contrast, the damage from the intensive risk events may or may not be localized; nevertheless the damages are huge and the economic costs are enormous in the short-term, thus increasing the probability of an influence trigger.

## IMPROVING LOCAL CAPACITIES FOR SEISMIC VULNERABILITY REDUCTION

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Reducing risk and improving disaster resilience are common international challenges that should not only be addressed at national level, but even more so locally. To supplement the ongoing ‘top-down’ efforts to improve national and transnational resilience as part of the implementation of the Sendai Framework, also a ‘bottom-up’ strengthening of local

competence and action is needed. Impacts of disasters are felt the first at local level. Local governments are the 'first line of defense', both in terms of prevention and preparedness.
The philosophy is that reducing disaster risks and increasing resilience requires a long-term local strategy that can outlast the short-term political agenda, as well as a local system of governance, capacities and resources that is realistic and sustainable. This starts from 'understanding risk' to inform a concrete and holistic DRM strategy. To reduce disaster risks, local governments have some of the most fundamental policy instruments, if multi-hazard Disaster Risk Management (DRM) can be effectively mainstreamed into local policies such as spatial planning, building code enforcement, economic development and local infrastructure investments. However, local governments across the world struggle with mainstreaming DRM, because of budget constraints and limited capacities and capabilities.
To be able to assess risks, to use this to develop DRM strategies and actions, as well as to mainstream DRM in a participatory process with local stakeholders, cities need to develop their capacities and capabilities. This is a gradual process of acquiring skills and knowledge, using existing good practices and gaining practical experience by actually starting to work on a structured DRM cycle. The CapaCities project (www.drm-capacities.eu), funded by the European Union Civil Protection, assists cities in Armenia, Georgia and Moldova with such a capacity development process. The project provides a curriculum to develop the competences of local 'DRM focal points' that is combined with actual local actions such as a self-assessment of current local capacities, a multi-hazard risk assessment and development of a holistic DRM strategy.
The local risk assessments and DRM strategies will include seismic hazards and vulnerabilities, because those are of great significance in all three countries. To reduce seismic vulnerabilities, implementation and enforcement of seismic building codes requires local action, in coherence with local efforts on risk communication, community resilience and preparedness of local emergency services. The project shares its lessons on capacity development and mainstreaming and in turn hopes to acquire additional, practical insights from seismic experts. By bringing together local governments and seismic experts, a coherent and realistic approach can be devised for local seismic vulnerability reduction and resilience improvement.

## COMPARATIVE ANALYSIS OF SOCIO-ECONOMIC SYSTEMS RESILIENCE AND VULNERABILITY FRAMEWORKS: DRIVERS, DYNAMICS AND SPATIOTEMPORAL SCALE

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This article reviews definitions of socio-economic and human-environment systems resilience to natural hazards in addition to comparing the frameworks that elaborate the resilience and vulnerability concept of the human-environment systems. The diverse variety of the concepts used in different disciplines is summarized to have a common ground for further deliberation. Series of comparative discussions and analyses of nine selected frameworks (used in disaster risk management, climate change adaptation, and sustainable development etc.) reveal the respective limitations as well as extent of the frameworks in addressing three main aspects of resilience and vulnerability analysis. These aspects are a)

Drivers and pressures in terms of their origin as exogenous and/or endogenous, b) dynamics of the human-environment systems, and c) spatiotemporal scale of analysis.

## EARTHQUAKE RESILIENCE AND SOCIETY: THE INTERSECTION OF ARCHAEOLOGY, MYTH, AND GEOLOGY AT LATE BRONZE AGE AKROTIRI

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Disaster research is concerned with the resilience of social, economic, and political systems in human societies, especially in urban contexts, at the face of environmental risks, such as earthquakes. The history of human activity in the Aegean and eastern Mediterranean region intimately involves encounters with disasters related to the tectonic environment. This project first examines methodologies and theories applicable to the study of disasters occurring in the ancient Mediterranean, which include approaches from archaeology, literary and historical textual studies, the natural sciences, and also resilience theory and the adaptive cycle from ecology. Resilience theory and the adaptive cycle can be applied across many scales in time and space, and when applied to completed cycles of past environmental stresses, such as earthquakes and climate change, it can provide insight into similar problems prevalent in contemporary society. Using these multidisciplinary approaches, this project secondly explores the case study of the Late Bronze Age (c. 1700-1200 BCE) Aegean island of Akrotiri with a primary focus on the complexities of earthquakes leading up to the c. 1630 BCE eruption of the Thera volcano. Analysis of the case study of Akrotiri reveals both the short- and long-term effects of earthquakes and associated disasters on society not only at the site level, but also at the level of the entire eastern Mediterranean region. Seismic phenomena impacted cultural adaptation, complexity, and innovation at Akrotiri as observed through architectural and technological changes in response to earthquake events. Patterns of restoration and reconstruction activities highlight the capacity and resources of the inhabitants to engineer seismic resilient architectures and to develop building regulations. Similar earthquake responses seen in building patterns in other Mediterranean urban contexts both ancient and modern, such as Pompeii (79 AD) and Lisbon (1755), highlight convergent patterns of inhabitants in local seismic cultures to innovate building technology and develop building regulations not only through codified written policies, but also through ideologies and knowledge passed between local members and generations. Overall, the case study of Akrotiri aids in the reconstruction of socioeconomic and political effects of earthquakes and associated disasters, while also revealing the advantages of applying multidisciplinary approaches to disaster research.

# METODOLOGY FOR SEISMIC RISK ASSESSMENT OF TERRITORY OF SMALL SITES OF ARMENIA

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The main characteristics of the method developed for assessment of seismic risk of the areas of Armenian cities with population less than 30 000 are the following:

1. The most important components of seismic risk are estimated: a) damages of buildings; b) possible human losses; c) emergence of fires; d) active geological processes (landslides, falls, ground liquefaction effects, faults, etc.); e) damages of internal and external life lines;
2. It is expedient to use the map of seismic micro-zonation as an indicator of seismic hazard;
3. Statistical data and results of the analysis of the effects caused by the 1988 the Spitak earthquake were used widely in the assessment of seismic vulnerability of buildings. The same approach was applied in the vulnerability assessment for both external and internal life-lines of the settlements. Such methodology is justified and proved, otherwise it is impossible to estimate the influence of low-quality construction of the multi-room, public and other buildings built before 1989.
4. There are certain difficulties related to risk assessment for infrastructures of the cities and external life-lines. The matter is that the underground life-lines (especially cables and pipelines) are generally old and the associated seismic risk is very high. Their vulnerability rates are especially high in the zones of faults, active geological processes, on the borders with soils having different physical mechanical properties, etc., which makes it even more difficult to estimate the risk for the old life lines.
5. Assessing the risks, areas of the cities were conditionally divided into individual sites not in the form of squares or other geometrical figures, but rather based on the prevailing types of buildings, building floor numbers, destination, time of construction, etc. The analysis of data on buildings in 12 cities of Armenia demonstrated that certain regions were built up with buildings of almost the same type and during specific period of time. Such regional subdivision of the city (micro-zonation) allows one to facilitate assessment of different risk components considerably, especially damage risks for buildings of various types.
6. The risk assessment study for Gyumri comments that illegal changes of building layouts, weakening of bearing wall structures, digging of cellars to depths below the bases and similar facts that had reduced seismic stability were responsible for about 10% of destruction of 4-5-floor multi-apartment stone buildings.
7. When calculating human losses, a series of statistical data of the 1988 Spitak earthquake was also considered. Our inquiry in Gyumri made it evident that the rate of casualties in one destroyed apartment was 1.2. Take into account the fact that the greater part of multi-apartment buildings (9-storey buildings mainly) were not fully occupied in the day-time, it is logical to assume that number must be 1.5. Taking into account the statistical data for night-time earthquakes, the number of victims in one destroyed apartment could be estimated at 3. After the Spitak tragedy the ratio of the victims and hospitalized people made 1.5.

The data are taken as the basis for the methodology of assessment of human losses.

# SOME METHODOLOGICAL ASPECTS OF THE ASSESSMENT OF SEISMIC RISK AND VULNERABILITY

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Seismic hazard and seismic risk assessment is of great importance, as social and economic protection of the population are conditioned by it. It should be specially noted that when evaluating these parameters it is very important to have a relatively homogeneous system - characterizing their qualitative indicators, to develop such a classification principle that actually reflects the existing features of town planning, without violating the main provisions of the current regulatory and technical documents.

Based on this principle, we have classified the seismic risk and vulnerability with the corresponding descriptions and quantitative indicators.

The classification of the degrees of seismic risk of destruction (SRD) and vulnerability took into account national-traditional and architectural-building features in the Republic of Armenia, as well as the results of inspections of damages and destruction of buildings and structures of the Spitak earthquake on December 7, 1988.

For a relative assessment of the seismic risk of destruction (SRD), the following simplified relationship is adopted:

$$K_{SRD}=\frac{I_{\text{экп}}}{I_{s.a}}$$ , where

$K_{SRD}$ characterizes the degree of seismic risk of destruction;

$I_{exp.}$is the expected intensity for a given territory expressed in intensity points; and

$I_{s.a}$is seismic reinforcement of the studied objects, also expressed in points.

Thus, proceeding from the above relation for seismic risk assessment, we propose to apply the following classification of the KCPP degrees:

1. Practically no risk - $K_{SRD}$=1,0;
2. Moderate level of risk - $K_{SRD}$=1,06;
3. Average risk level - $K_{SRD}$=1,12;
4. Risk level above average - $K_{SRD}$=1,20;
5. High level of risk - $K_{SRD}$=1,30.

While maintaining the classification structure of the degrees of damage to buildings and structures on the MSK-64 scale, we propose the following classification with the corresponding estimates of possible damages (in percentages):

- virtually invulnerable - damage 0%;
- slightly vulnerable - 5% damage;
- moderately vulnerable - 10% damage;
- significantly vulnerable - damage of 50%;
- high degree of vulnerability - 75-100% damage.

The developed classification criteria are recommended for use when drawing up maps of seismic risk of destruction (SRD) for large settlements in the RA, as well as in general and at the country level.

# GEOECOLOGICAL PROBLEMS OF THE TERRITORY OF THE CITY OF GYUMRI AND ITS ENVIRONS

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Geological vulnerability of urban territories in the Spitak earthquake zone is redoubled by the fact that it is exposed to a multitude of impacts of natural as well as man-made (technogenic) origin. Scientific substantiation and the choice of appropriate specific measures required to improve the ecological conditions of life of the population are possible through the analysis of problem situations in the republic from the general system positions and understanding of disaster zone restoration as natural-social-ecological-economic integrity.

The range of the main geo-ecological problems in the limits of the above-mentioned areas is reduced to the following: pollution of air and water pools, degradation of soil; presence of numerous seismic-gravitational and man-made origin landslides; activation of subterranean processes over densely built-up sites of the areas; presence of heterogeneous underground cavities of various genesis (*qariz*, karst-suffosion sinks and cavities, tunnels, etc.); intensive geo-filtration processes taking place in reservoir banks and expansion of heat zones stipulated by them; presence of active, highly-permeable geodynamic zones creating favorable conditions for exhalation and accumulation of radioactive emanation in habitable premises.

Geological environment of the Gyumri city represents a multi-component system; in its structure underground mines are included as a specific system-forming element, added with the presence of *qariz* (underground water canals), underground openings formed as a result of excavation of construction material, bomb shelters, underground ways arranged for military and other unknown purposes, and karst-suffosion cavities. Deformations of unconsolidated soil layer and distructions of constructions taking active place in different parts of the city are provoked by underground mining and voids of technological and natural origin as well. The marked activation of ground caving processes has been observed lately in the central and south-eastern parts of the city, which are characterized by dense net of qarizes.

It is necessary to note that the presence of underground mining is the necessary, but not sufficient condition for rock shift, as disruption of rocks stability takes place under the influence of the integrity of natural and man-made factors having casual character in the overwhelming majority.

To develop methods of protection against rock dislocation processes in urban areas, in particular in the limits of Gyumri, it is important to understand the origin and mechanism of these effects and provide for their early identification, which constitutes an applied-science problem.

Features of the geophysical investigations aimed to resolve the listed tasks are illustrated by the results of research works carried out on the areas of heterogeneous exogeneous and man-induced processes: landslides, karst-suffosion phenomena, radonic pollution, etc.

# NEW MAP OF PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE AREA OF THE REPUBLIC OF ARMENIA (SEISMIC ZONING) AT THE SCALE OF 1:500000

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The new probabilistic seismic hazard assessment map (seismic zoning) of the RA at the scale of 1:500000 was prepared with the financial support of the World Bank by the international Consortium composed of three companies, namely, «AIR Worldwide Corporation» (AIR, Consortium leader, USA), «Global Earthquake Model» Foundation (GEM, Italy) and «GEORISK Scientific Research» (Armenia).
An inter-governmental Working Group was established to render technical assistance to the preparation of the map on the part of concerned national authorities and professional institutes.
The Consortium fully completed the complex of studies required by the Terms of Reference of the Probabilistic Seismic Hazard Assessment (PSHA) for the area of the RA, conventionally distributed among six components according to Project tasks: (1) collection of the input GIS database, input data quality assurance and control, (2) selection of ground motion attenuation models from models for various tectonic settings, and justification of the selected model, (3) development of a comprehensive seismotectonic model, (4) selection of PSHA computation software, hazard calculation and processing of hazard results, (5) preparation of seismic zoning maps for different return periods, map annexes and explanatory note, and (6) Final Report and presentation of the deliverables.
The Consortium delivered the set of updated RA seismic zoning maps for a range of earthquake return periods and intensity non-exceedance values, which would serve the baseline for revision and update of the effective national earthquake engineering code.
The 1:500000 seismic zoning map of the RA is based on the same-scale probabilistic seismic hazard map for the return period of 475 years of given intensity earthquakes and for 90% probability of non-exceedance of the peak ground acceleration (PGA) intensity value in 50 years.
According to the seismic zoning map, the area of the RA was subdivided into Seismic Intensity Zones I, II and III in ascending order of intensity covering, respectively, 50%, 40% and 10% of the total country area. The PGA values expected within Zones I, II and III comprise, respectively, 0.3g, 0.4g and 0.5 g.
Suggestions and recommendations of the inter-governmental Working Group were considered when drawing contours of the zones. For large cities, computation results for the 90% of PGA non-exceedance probability in 75 years for the given earthquake intensity return period of 712 years were studied and considered additionally. Based on the analysis, seismic zone boundaries were adjusted. In particular, the Yerevan city area was fully encompassed within Seismic Zone II (0.4g). The map is supplemented by the summary list of RA cities and Marzes according to the seismic zones.

# TECHNIQUE OF ASSESSMENT OF CURRENT SEISMIC HAZARD

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1. Creation, adjustment and supplementation of the database on:
-The seismotectonic structure of the area of the RA and the study region;
-Various precursors of strong regional ($M \geq 6.0$) and local felt ($M \geq 4.0$) earthquakes (seismological, geodynamic, hydrogeodynamic, hydrogeochemical, electrical, electromagnetic, radon, geomagnetic, ionospheric and biological);
2. Studies of observation networks:
-Establishing the main principles of deploying observation networks;
-Establishing the capabilities of different monitoring parameters and methods;
-Determining the responsiveness of observation points to the preparation and realization of seismic events;
3. On-line processing of the monitoring data:
-Screening man-made anomalies and identification of useful anomalies;
-Determining parameters and characteristic features of the useful anomalies.
4. Earthquake testing:
-Selection of strong regional ($M \geq 6.0$) and local felt ($M \geq 4.0$) earthquakes;
-Earthquake testing technique;
-Supplementing the catalogue of precursory anomalies of the tested earthquakes;
-Determining the forms of test-anomaly manifestations;
-The physics of earthquake preparation and the test precursory anomalies;
-Developing typology of the precursory anomalies.
5. Determining criteria to suggest seismogenic nature of an anomaly by:
-The presence of pre-seismic, co-seismic and (or) post-seismic periods in the anomalies;
-The presence of anomalies in fields of different nature;
-The presence of anomalies over relatively big area;
-The correlation of anomalies with a specific physical model of earthquake preparation.
6. Determining space and time regularities in the manifestation of earthquake precursors in Armenia:
-The Spitak earthquake (1988, $M=7.0$);
-Strong regional $M \geq 6.0$ earthquakes;
-Locally felt earthquakes of $M \geq 4.0$.
7. Assessment of the current seismic hazard:
-Application of seismic catalogue;
-Analysis of monitoring data time-series;
-Determining the likelihoods of seismic realization of the on-going anomalies;
-Application of seismotectonic and seismic zoning maps;
-Preparation of an operational map of current seismic hazard assessment for the area of the RA;
-Stress analysis for different sites of the Earth crust.

# VOLCANIC HAZARDS AS AN UNDERESTIMATED RISK FACTOR IN ARMENIA, GEORGIA AND EASTERN TURKEY

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Since pre-historic times, societies have been continuously affected by various natural hazards such as earthquakes, violent explosive volcanic eruptions, floods, and landslides. Generally, explosive volcanism is characterized by significantly lower recurrence rates compared to strong earthquakes. About 800,000 deaths related to earthquakes were confirmed during 2010-2015. The majority of deaths occur in developing countries, while the confirmed number of deaths caused by earthquakes during 1990-2012 in the US is 70. There are different estimations of recurrence rates of volcanic eruptions during the Holocene and the Quaternary. Eruptions with magnitude equal to or greater than 5 may cause significant local and global climate changes, catastrophic tsunamis and a big number of deaths as it happened several times during the 8th-20th centuries. On the other hand, even Magnitude 3 eruptions may cause disasters and result in a big number of deaths, as it happened in 1985 during the eruption of Nevado Del Ruiz volcano in Columbia, where lahar triggered by volcanic eruption killed about 23,000 people in the towns of Armero and Chinchiná. Total number of fatalities related to volcanism during the last five centuries is estimated 278,368 (Brown et al., 2017).

As for the region of the South Caucasus and Eastern Turkey, a number of monogenetic volcanic fields and stratovolcanoes with signs of activity in Mid-Upper Pleistocene and Holocene-Historical times exist within the territories of Armenian Highlands and Georgia (Karakhanyan et al., 2002, Yilmaz et al., 1998, Meliksetian et al., 2015, Skhirtladse, 1958 and others). Besides the fact, that major natural hazard and risk factor in the region is seismic hazard, and even considering that the recurrence rate of volcanic activity is lower than for the seismic activity rate, volcanism may produce high-magnitude events and can be considered as an underestimated risk factor for the population and infrastructure of the entire region. Geological evidence, such as the Holocene-Historical volcanism, the presence of volcanic tephra layers originated from Nemrut and Ararat volcanoes (Eastern Turkey) discovered in Armenia, as well as the appearance of volcanic and volcano-tectonic earthquake swarms across the region strongly support the assumption that volcanic eruptions may occur in the region in future. When such eruptions occur, many populated places and infrastructure in the region will be at significant risk from a variety of volcanic phenomena and accompanying seismic activity. In contrary to seismic hazards, most of the volcanic phenomena cannot be mitigated by application of engineering solutions. Quaternary volcanic features of regional volcanoes include ignimbrite deposits and lava flows. The distant tephra fallouts in Armenia, deposited hundreds of kilometers far from the vents, indicate that volcanism is among trans-border natural hazard factors.

Considering recent age determinations, estimations of eruption recurrence rates for the extended lava flows in the southern part of the Gegham Ridge having the potential of damaging the infrastructure are in the range of ~$3.1\text{-}5.7\times10^{-4}$ per year. At the same time, if we consider the presence of younger flows and volcanoes are hitherto undated in the northern and watershed part of the Gegham Ridge, the frequency of occurrence of effusive volcanism in the highlands as a whole, can be much higher, increasing up to $2\text{-}4\times10^{-3}$ per year.

Another argument in proving the activity of volcanic and volcano-tectonic processes within the Gegham Highlands and potential volcanic hazard is also the presence of a seismic swarm within the watershed part of the highland (Sargsyan et al., 2018).

## ANALYSING THE TIEN SHAN AND LESSER CAUCASUS LANDSLIDE DATABASES

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This paper presents a comparative landslide analysis applied to the Tien Shan and to the Lesser Caucasus, on the basis of recently compiled full landslide inventories, as well as geographic, geological and geomorphological data. We first determined landslide densities with respect to morphological, geological, river distance, precipitation, earthquake, and fault distance factors. Respective landslide density values were used to compute landslide susceptibility maps according to the conditional analysis.
From the comparison of the results with actual landslide distributions we infer that the local slope angle and the distance to rivers strongly constrain the susceptibility of slopes to landsliding in both regions, while the proximity to active faults essentially influences landslide susceptibility in the Tien Shan only. For the Lesser Caucasus, landslide distributions do not really spatially correlate with the presence of the two main (known) fault systems, the one of Garni and the one of Pambak-Sevan-Syunik. There are three possible reasons why landslides do not preferentially occur near mapped faults in the Lesser Caucasus: a) first, the geology of the Lesser Caucasus is significantly different from the one of the Tien Shan, notably due to the presence of (recent) volcanoes and volcanic deposits (which are absent in the Tien Shan) – those modify local slope stability conditions which may interfere with the seismotectonic influence on regional landslide distributions; b) second, the weak spatial correlation of the landslide distribution with the known active faults in the Lesser Caucasus could be related to their strike-slip character; actually, in the Tien Shan most landslides are located near thrust faults; c) third, several landslide clusters in the SE and NE of the Lesser Caucasus, far from mapped faults and volcanic centres, can only partly be explained by known environmental factors, such as by the presence of thicker Loess deposits (notably in the NE). Indeed, thick Loess deposits in the foot hills around the Tien Shan proved to be extremely susceptible to slope instability. Nevertheless, we believe that some of those clusters in the Lesser Caucasus (especially those of rockslides – which are less influenced by the stability of surface deposits) hint at the presence either of unknown active faults or of major paleo-structures.
Alongside the outlined differences with respect to landslide susceptibility characteristics in both mountain ranges, there are also common features such as the formation of multiple large (breached/non-breached) rockslide dams along deep valleys – and many of those rockslides are marked by smooth surface morphologies, which are indicative of their old age. For both mountain ranges, the most important question is ‘what triggered those large rockslides?’ This question is all the more important, because there are no comparable recent events, which might help understand those giant paleo-landslides. And, they cannot simply be explained by glacier retreat and post-glacial processes, such as similar mass movements in the Alps. Both, the Tien Shan and the Lesser Caucasus are characterized by a relatively arid climate and most likely have been far less glaciated than the Alps. For these reasons, many researchers believe

that in those two mountain ranges large rockslides have most likely been triggered by very strong earthquakes. Yet, also this consideration is problematic as even the M>>7 events in the Tien Shan of the last century had not triggered >>100 Mio. $m^3$ rockslides (the probably largest single mass movement triggered by an earthquake in the Tien Shan is the Khait rock avalanche of 1949, with a volume of about 75 Mio. $m^3$). Therefore, the origin of those old mega-landslides still needs to determined, and researchers will most likely have to develop very complex coupled climatic-seismic scenarios to explain their occurrence in 'pre-historic' times. In this regard, we think that large ancient mass movements might represent key elements allowing us to reconstruct ancient paleo-seismic and paleo-climatic conditions.

## APPLICATIONS AND LIMITATIONS OF DATA MINING METHODS – EXAMPLES FROM LANDSLIDE SUSCEPTIBILITY MAPPING IN KYRGYZSTAN AND ARMENIA

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In a cooperation between the University of Liege, previously RWTH Aachen University and now TU Berlin, data mining methods and strategies have been applied to landslide analysis in several regions, such as Central Asia, China, and now also Armenia. The aim of the research was to evaluate if and how data mining with its wide range of tools may support landslide susceptibility mapping and knowledge discovery regarding the causes of landslides. In contrast to classical modeling attempts or statistical analysis, data mining is opportunistic and output-driven. This means that each successful strategy is allowed if it fulfills the previously defined aims and respects the requirements of the applied tools. Although, data-driven landslide susceptibility mapping has been developed now for three decades, application is still limited and no standards have been established. However, due to the rapid development and availability of geo-data and earth observation, as well as to the increasing need for tools supporting landslide hazard management, it is still an important research topic. Current challenges in landslide susceptibility analysis are for instance the growing amounts and extents of available data and new types of sensors and data. One problem that still has not been solved is the differentiation between characteristics of climatic and seismically-triggered landslides. This is especially of importance for landslide hazard management, as climate and seismic dynamics are in most regions considerably different and do not develop harmoniously.

This study provides a short introduction in the data mining concept, shows the strength of the approach and how it may be applied successfully. Finally, limits and problems, which might occur, are discussed.

## DAMAGE AND LOSS ASSESSMENT OF LARGE CITIES OF ARMENIA CAUSED BY STRONG EARTHQUAKE

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There are 2 types of risk assessment in terms of its use in decision/policy making:

- event scenario-based risk assessment, and
- hazard-based risk assessment.

Event scenario-based risk assessment is generally designed for disaster preparedness, in particular, for contingency planning, pre-disaster recovery planning, evacuation simulation exercise, DRR action planning, etc.

The damage and loss assessment is the main result of the event scenario-based risk assessment.

In 2010-2017, deterministic seismic risk assessment (earthquake scenario-based) had been implemented for the biggest cities in Armenia – Yerevan, Gyumri, Kapan, Goris, Sisian, Stepanavan and Dilijan by the IGS and “Georisk” Scientific-Research company.

Seismic risk assessment for the investigated cities was conducted using two approaches: intensity-based and spectral acceleration-displacement-based damage and loss assessments. For damage and loss calculation, we used the ELER (Earthquake Loss Assessment Routine) methodology and software. The expected rates of building damages were estimated using different methods, and the results provided by using the Chiou and Young’s GMP model, as the one yielding the most destructive damages, were chosen as the final ones. This estimated number of damaged buildings was applied as the basis to calculate the monetary losses associated with each building damage state, as well as to produce the expected number of casualties. Considering that the worst-case (night-time distribution) scenario was chosen for risk assessment conducted under the study, the calculations did not take into account non-residential buildings and structures such as health-care, education, community and consumer, and cultural purpose facilities.

The results demonstrated high level of seismic risk for the Armenian cities, especially for Yerevan and Sisian.

## SEISMIC SAFETY IN THE TURKMENISTAN ASHGABAT DISASTER OF 1948: THE LESSON LEARNT

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Turkmenistan is located in the Central Asian region, which is characterized by high seismic activity. The catastrophic Ashgabat earthquake of 1948, along with its sad consequences, caused the development of seismological science and practice. Analysis of the earthquake effects provides valuable material for assessment of the seismic stability of new construction and buildings and their actual behavior under seismic effects. These studies serve as the basis

for improving structures and methods for construction in seismic area. In this sense, the Ashgabat earthquake of 1948 is indicative, and urges improvement of seismic design methods and approaches.
The report shows the consequences and lessons of the Ashgabat disaster of 1948, identifies and analyzes the main factors determining the seismic hazard and risk in the Turkmenistan region. It is shown also that the seismic hazard and risk assessment methodology must be improved, taking into accounts the regional characteristics of Turkmenistan.

## CELLULAR SEISMOLOGY ANALYSIS OF SEISMICITY ASSOCIATED WITH OPERATING ARMENIAN DAMS

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Reservoir-triggered seismicity (RTS) has been observed globally in large dam operations since the mid-twentieth century. Addressing the threat posed by RTS is critical, especially for reservoirs located in seismically active regions with high-population densities. Armenia is one such area. Situated in the Caucasus continental-collision zone, almost all of the country is subject to high levels of seismic activity, and its numerous large reservoirs in densely populated areas make it especially susceptible to damage from RTS. Here, we analyze RTS for the three highest risk reservoirs in Armenia: Azat, Akhuryan, and Tolors. We apply modified versions of “Cellular Seismology” (CS) to analyze the associated RTS activity and explore how spatial patterns of seismicity change with reservoir impoundment. In this study, we explore the possibility that CS might provide new insight into RTS. CS is a statistical method that seeks to measure the tendency for past seismicity to forecast likely locations of future earthquakes. Here, we explore repurposing CS for RTS analysis, experimenting with five types of application of CS to the study of RTS, and we discuss how some variation of a modified CS method might be useful for analyzing RTS.

## SEISMIC OBSERVATIONS IN KYRGYZSTAN: STAGES AND PERSPECTIVES OF DEVELOPMENT

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High seismic activity of the Central Asia is specified by the extremely complex geological structure of the Tien Shan and Pamirs and corresponding tectonic processes. Over the last 150 years, the strongest earthquakes with magnitudes exceeding 8 have occurred there. Therefore, seismic monitoring has been and remains one of the most important problems of the region, having both scientific and applied significance. The correct initial data and their subsequent scientific analysis are the basis for seismic hazard assessment and, as a consequence, for the planning of appropriate preventive measures, especially in case

epicentral zones of strong and destructive earthquakes traverse the most densely populated areas.
The instrumental seismic observations in Kyrgyzstan have begun since 1927 on the basis of analogue stations that essentially influenced network efficiency. In 1990, thanks to the assistance of the IRIS Consortium (USA), the first digital seismic station AAK was installed in the Republic. In 1991, the first digital seismic network KNET (Kyrgyz Seismic Telemetry Network), consisting of 10 stations and equipped with broad-band high-sensitive devices, was installed in the north and northwest of Kyrgyzstan. In 2008, within the frame of CTBT capacity building, Norwegian Seismological Service, NORSAR, with support from the Ministry of Foreign Affairs of Norway, provided the NAS KR Institute of Seismology with10 digital broad-band stations. In 2009 the new network of stations was registered in the FDSN as KRNET (Kyrgyz Republic Digital Network). At the present, the KRNET network consists of 18 seismic stations, most of which have been installed in the highly-active seismic areas south of Kyrgyzstan. Otherwise, the National system of seismic monitoring consists of 28 seismic stations, providing good enough coverage of the Kyrgyz territory. It allows significant improvement of the accuracy of seismic event locations in the region. Owing to carefully conducted site surveys of the geology and seismic noise characteristics, all new sites are highly sensitive both to local, and regional events. Moreover, it is necessary to observe that the advantage of seismic stations in Kyrgyzstan is that they are located at regional distances according to all Asia nuclear test sites. Besides, most of these stations are located on solid rock outcrops, in tunnels that allowed record of even small underground nuclear explosions.
It should be noted that for an adequate analysis of seismic regime and creation of a seismic catalog it is necessary to use the data not only from the National Monitoring System of Kyrgyzstan, but also the seismic data from other regional and international seismological organizations.
International cooperation is known to favor development of any scientific school, but it is necessary to notice that it is of special importance for seismology, so far as there are no state borders for earthquakes, and only close cooperation of seismological organizations in the region will allow correct analysis of seismic regime and will enable local authorities, such as the Ministry of Emergency Situations, to react more adequately and operatively to any seismic catastrophe, and through that to save human lives and reduce the level of damages.

## USING MACRO-SEISMIC DATA FOR THE ASSESSMENT OF THE SEISMIC VULNERABILITY FOR THE AREA OF DUSHANBE CITY

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Seismic vulnerability of the urban areas is the one of the most complicated tasks of seismology and earthquake engineering. It is especially important for Tajikistan, which is located in a very seismically active part of the Earth. Seismic safety of settlements and objects depends on the seismic activity (Mmax, Iomax) of the areas of their location and on the technical condition of buildings and other structures.
Macro-seismic data are important for evaluation of seismic safety of big urban areas. Sufficient quantity of macro seismic data allows one to find the conformity of strong

earthquakes in the study area, and create models of possible scenarios based on the given magnitudes, focal depths and intensities. In case of a destructive earthquake, up-to-date operation of rescue teams is one of the effective mitigation options. Creation of the maps of possible earthquake effect scenarios allows planning and realization of the top-priority mitigation tasks very quickly.
All existing macro-seismic data from the past strong earthquakes with epicentral intensity of Io ≥ 6 around Dushanbe city were collected and analyzed to determine the seismic situation around the area, and to estimate the seismic risk for the existing building and structures as well. The technical inventory of the existing structures was made.
The three most probable zones of seismic sources that can affect the Dushanbe city area were identified. The first and the biggest one is located to the north from Dushanbe city and connected with the Hissar-Kokshaal fault zone, where the strong Karatag earthquake with epicentral intensity 9 on MSK-64 scale occurred in 1907. The other two are connected with the Ilyak fault zone to the south-west and south-east from Dushanbe city, where earthquakes with epicentral intensity 7 – 8 on MSK-64 scale took place in the past. Sixteen models of the theoretical isoseismal for the earthquakes with different magnitudes and focal depths were created based on the macro-seismic data, and these models may be used for estimation of potential shaking intensities for the Dushanbe city area.
The special GIS software “Quake-Dushanbe” developed by specialists from the Center of the Extreme Situation Study (ESAS) and the Seismological Center of the Institute of Geology of the Russian Academy of Sciences was used to develop possible scenarios of earthquake consequences in the Dushanbe city area. The developed models of the theoretical isoseismals were used as the basis for such estimation, and the seismic conditions, engineering-geological and hydrogeological conditions, and data on the state of the existing structures were taken into account as well.
At the next stage, software input data must include the date, local time, longitude, and latitude of the earthquake, its magnitude and focal depth. After data processing, possible scenario map is produced with indicated rates of potential damages of the residential buildings in colors.
Developed possible scenarios of the consequences of strong earthquakes allow one to plan and carry out the required mitigation measures, and to reduce the seismic risk as well in the Dushanbe city.

## THE ELEMENTS OF EDUCATION ON SEISMIC PROTECTION IN ARMENIAN SCHOOLS

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We use some essential approaches for the education of pupils in the field of seismic protection:

- The pupils as a target category have been divided in groups such as pupils of elementary school, secondary school and high school.
- They have been taught based on the experience and lessons of the Spitak earthquake (1988) and also on the international experience of this field, where the main accepted approach is to divide the program into three phases: What to do before an earthquake? What to do during an earthquake? What to do after an earthquake?

We took into account some important features. For example, the type and the level of seismic vulnerability of the buildings were considered. Also, possible intensity and duration of strong earthquakes, possible prediction of the situation immediately after the earthquake in the settlement are taken into account along with the level of preparedness and skills of the rapid response forces of the RA. We consider also the seismic vulnerability of the specific residential area, including life- lines, etc.

- The use of didactic and video materials was essential. For this purpose, the RSSP has prepared a lot of educational manuals, posters, booklets, video clips, etc., which are widely used for the trainings.
- Most pupils are involved in the training process. International and local experience shows that the interactive method is more effective; hence, we involve the trainees in the learning process, where they are not only passive listeners, but also active participants based on their general knowledge and logic, etc.
- In addition, we use various game quizzes, instructional drillings and logical games. Those are more interesting ways of learning process. Another crucial point in our activity is that we give children a chance to use their creativeness via solving some cases and developing their guiding skills. This approach is very effective, especially when the games are interesting. The service has a lot of ready materials and experience of effective teaching.
- The practical part of the training is crucial, where we create situations of an imaginative earthquake. The main cases are taken from the earthquake of Spitak (1988) about the situation after the earthquake, correct actions, and finding solution in difficult situation. Subsequently, we use various scenes, from which children should find out solutions, for instance, how to evacuate from vulnerable building etc.
- Another important point is the social-psychological preparedness, which is essential for quick and accurate action in possible traumatic situation.

As a result of above mentioned activities conducted from 2016 to 2017, the Department of RSSP Activities of the RA taught and trained 51.177 people, of which 48.150 were pupils.

## PROTECTION OF CHILDREN AGAINST STRONG EARTHQUAKES

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The results of a survey about the vulnerability of children in case of a strong earthquake are presented. A statistical model based on several case studies shows that about 1/3 of the victims in such a case are children. The time of occurrence (day/night), the density of population (towns, cities, villages), the level of education on how to protect our children and ourselves are the most important parameters established during the study. The Spitak earthquake is a remarkable example of the vulnerability of citizens and their children in case of a strong earthquake occurrence.

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