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Some Peculiarities in Studying Fast Developed hydrogeodeformation Conditions During Strong Earthquake's Preparatory Period (Exemplified by the Spitak Earthquake in Armenia)

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Abstract

Hydrogeodeformation field changes during the strong earthquake's preparatory period are considered. These changes are the result of combined impacts of various endogenous and exogenous factors. Fast changes in the deformation field cause displacements of blocks within the geological massifs which could result in catastrophic processes in the lithosphere. Based on principles and methodology of regional hydrogeodeformatics, fine deformation changes were identified and monitored for the Caucasus region for the period August 1988 – December 1990 which includes the December 7, 1988 Spitak earthquake. Considering velocity and acceleration of deformation changes in various blocks of the region, schemes of displacement potentials during the Spitak earthquake were compiled and directions of block displacement caused the quake were identified. Based on hydrogeodeformation (HGD) monitoring data, several indicators of the forthcoming dangerous seismic event were described. The global hydrogeodeformation monitoring system is proposed as a tool providing warnings on potentially dangerous seismic events in various seismically active regions of the planet.

Keywords: Regional Hydrogeodeformatics; The Hydrogeodeformation Field; Deformation structures; The Spitak earthquake

Theoretical Basis and Methodology

An evolutionary change of Earth's volume is the main factor of the lithosphere transformation. Based on this concept, the model of the global endodrainage system (GEDS) was developed. The GEDS consists of deep «canals» penetrating into the astenosphere and probably even deeper and connects the highly heated deep zones of the Earth with its geological crust. This megastructure includes rifts, mid-ocean ridges and linear continental mountain folded areas surrounded by seismically stable regions. Accumulation and upward transport of heat, deep liquid and volatile products occur through this system. To compensate this upward movement of liquid matter, the equal mass of geological material moves downward. This global heat-mass circulation is developing in real time and is accompanied with variations of all components of Earth's geophysical field including its seismicity.

The GEDS is the main growing megastructure which manifests the Earth's volume increase [1-10]. Fast changes in pressure within aquifers due to changing stresses in geological massifs are important indicators of geodynamic catastrophes. Fundamental theoretical works on the influence of changing pressure to the water-rock system were conducted [11-15]. Numerous studies conducted in 1970s-1990s by various geological and seismological agencies in the former USSR, the USA, Japan and Denmark were focused on finding the hydrogeological features that could be used for earthquake prediction. These studies confirmed the high sensitivity of the lithosphere matrix to changing geodynamic pressure.

In 1980s-90s extensive studies on hydrogeological features associated with regional changes in dynamic pressure were conducted in the All-Union Institute of Hydrogeology and Engineering Geology (VSEGINGEO) in Moscow. These studies were based on several Russian patents and the scientific discovery which described the new type of the geophysical field, i.e. the hydrogeodeformation (HGD) field of the Earth Vartanyan and Kulikov [16]. Based on this discovery, the new discipline namely regional hydrogeodeformatics was developed. It deals with assessment of the current Earth's geodynamic activity which manifests itself in the changing HGD field. Starting from 1985 and under scientific guidance of VSEGINGEO, the regional hydrogeodeformation monitoring network was developed in seismically active regions of the former USSR. They included the Russian Federation, Caucasus and Middle Asia Republics, Ukraine, Moldavia and Khazackstan. This network provided highly accurate information on water level fluctuations which was transformed into the rock stress condition parameters. Investigations conducted in various countries allowed comparing the deformation changes and transformations occurring in distant regions of the Earth with different tectonic conditions [17-22].

These investigations confirmed that the HGD field changes within huge massifs occur in real time and very fast (in a matter of hours or days). These changes are caused by a combined influence of cosmic and endogenous factors that define displacement of the lithosphere blocks. The nature and intensity of HGD field pulsations depend on different velocity and direction of vertical displacement of geological blocks. Upward displacement causes expansion of geological blocks while downward displacement causes compaction within the blocks. Downward displacement could be caused not only by direct sinking but also by the different velocities of upward displacement within the neighboring blocks.

The methodology of regional hydrogeodeformatics is focused on solving the following problems:

a) Assessment of elevations and volume changes within geological massifs;

b) Assessment of deformation process intensity within specific blocks of the geological massif and defining potentially dangerous short-living deformation structures;

c) Compiling velocity/acceleration curves of deformation structures; and

d) Calculating and mapping geological massif displacement potentials which indicate the mostly stressed blocks during the earthquake preparatory period and dangerous stages of massif displacements.

Investigations of hydrogeodynamic conditions include computerized compilation of HGD field map(s) at any specified time t_i. The next step is computerized compilation of deformograms $D_e(t)$ which show changes occurring with expansion-compaction structures for the specified monitoring period $T=t_n-t_0$. Each deformogram $D_e(t)$ is the imprint of the strong geodynamic event which includes its preparation, occurrence and post history. This imprint allows identifying event in various distant areas on the planet. The imprint's clarity depends on the power of the initial impulse and the distance between the monitoring location and the active region.

Displacement potentials could be calculated as

$$P_v = \Delta V(t)/\Delta L$$

$$P_a = \Delta a(t)/\Delta L$$

where $\Delta V(t)$ is the difference between the areas of short-lived expansion/compaction structures (in km^2) during the specific time period Δt (in hours);

P_v is the displacement velocity potential;

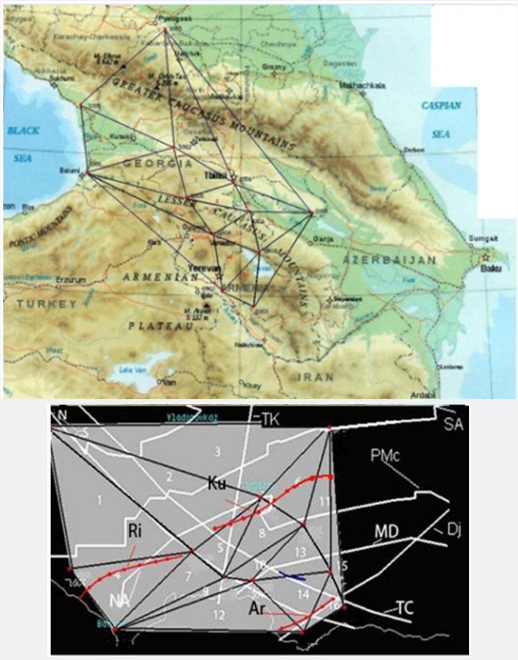
$\Delta a(t)$ is the difference between acceleration of short-lived expansion/compaction structures development (mm^2/sec^2) during the specific time period Δt (in hours);

P_a is the displacement acceleration potential (mm/sec^2) and

ΔL is the distance between central points of blocks compared.

Analysis of the Results and Discussion

The study area of about 400,000 km^2 was located in the former Soviet Republics of Russian Federation, Georgia, Armenia and Azerbaydzhan and included the Greater and Lesser Caucasus regions. At different time the monitoring network consisted of 12 to 16 HGD monitoring wells and deep oil exploration wells (Figure 1). The average depth of wells was 250 m. Each well was completed in the waterbearing bedrocks and equipped with the automatic gauge providing water level and temperature data on the hourly basis. The well's depth and construction were such that the influence of meteorological and technogenic factors on the groundwater regime was eliminated. The results of the regional HGD monitoring were applied to the analysis of the Spitak earthquake. The Spitak area is located at the crossing of the North Anatolyan fault and several sublatitudinal and meridional structural dislocations which define configuration of the deformation field in the area. Analysis of the HGD field development indicates that during the preparatory period of the Spitak earthquake fast changes from expansion to compaction and vice versa ocurred within large areas in the short time period (Figure 2).



The red dot indicates the monitoring well and its number. Solid black lines indicate block boundaries. Bold red lines indicate the Rioni valley (Ri), the Kura valley (Ku) and the Ararat lowland (Ar). The blue line indicates the new fault formed after the Spitak earthquake. White lines indicate main structural dislocations: TK-Tshinvalo-Kazbecksky, SA- North Adzharsky, NA-North Anatoliysky , PMc-CisLessercaucasian, Dj-Dzhulfarsky, MD-Mrovdagsky, and TC-Transcaucasian. 1,2,3…16 - block numbers.

Figure 1: Study area, monitoring well locations and main dislocations.

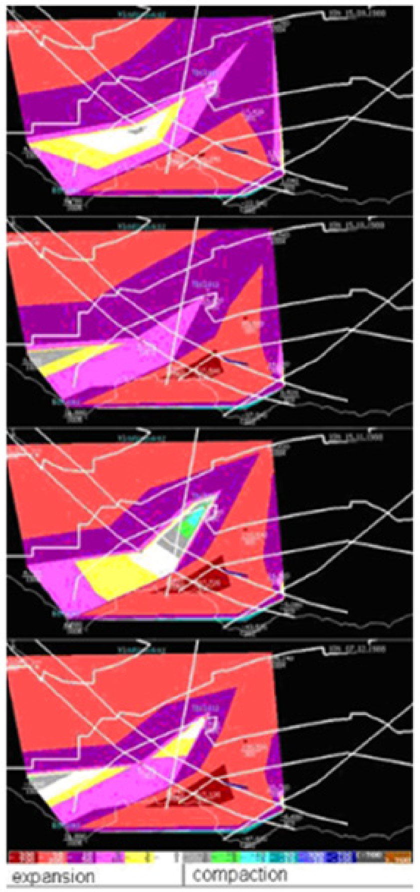


Figure 2: The general maps of hydrogeodeformation field at 10:00 September 15, October 15, November 15 and December 7, 1988.

The deformogram $D_e(t)$ for the entire study area shows the influence of local and distant seismic events on fast changing expansion-compaction conditions in rock massifs. As a rule, most of the extreme values on the $D_e(t)$ curves for the Caucasus region coincide with preparatory periods or occurrences of strong earthquakes in various distant areas on the planet (Figure 3).

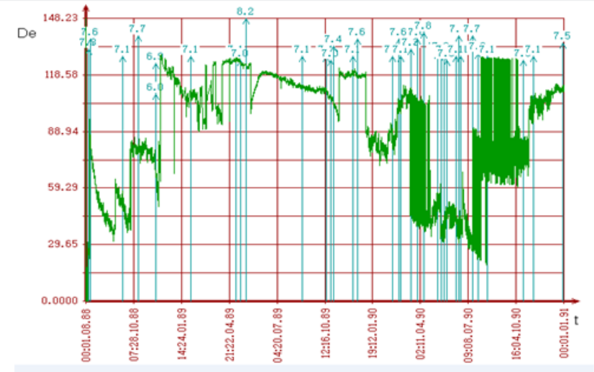


Figure 3: The deformogram $D_e(t)$ (km^2 *.10^6) for the Caucasus region for the period from August 1988 till December 1990. Blue lines indicate strong seismic events. A,b,c and d-earthquakes in Spitak (Armenia), Makauri (New Zealand), Loma Prieta (USA) and Rudbar-Manjil (Iran).

The similar analysis was conducted for the separate geological blocks and indicated significant differences in deformation evolution of each block (Figure 4). They were defined by different velocities and directions of blocks vertical displacements which occurred constantly but intensified significantly at the final stage of earthquake preparation. Block's deformograms for the Caucasus region also indicated high sensitivity to powerful distant seismic events such as earthquakes in the Tasman Sea (May 23, 1989.

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M8.2), Loma Prieta (October 18,1989, M7.1), Solomon Islands (October 27, 1989, M7.1), and the Honshu Island (November 1, 1989, M7.4). These quakes manifested themselves on the $D_e(t)$ curves as distinctive signals with lag time of several days after the seismic event. This lag time was due to the relatively low velocity of the initial impulse migration which is usually less than 100 km/hour. The impulse migrates from the west to the east in direction of Earth's rotation [9,10]. A few hours prior the main shock of the Spitak earthquake the differences in velocity and directions of vertical massifs displacement were most evident.

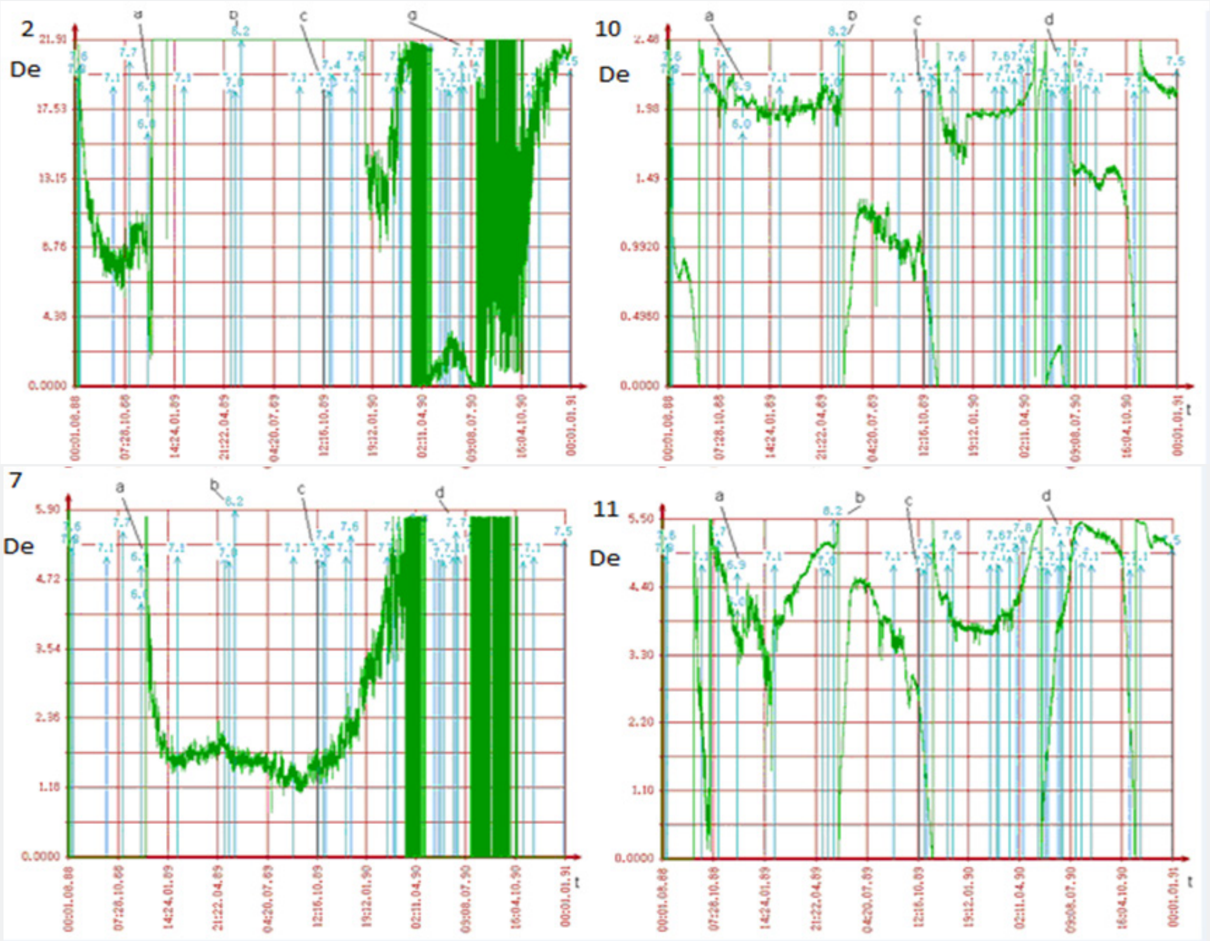

Figure 4: The deformograms $D_e(t)$ (km² *.10⁶) for blocks 2,10,7 and 11. Blue lines indicate strong seismic events. a, b, c and d - earthquakes in Spitak (Armenia), Mackuari (New Zealand), Loma Prieta (USA) and Rudbar-Manjil (Iran).

At the earthquake's epicenter the upward displacement was maximum: from August to December 1988 the increase of ground surface elevations at the well № 0304 was 247cm. The similar results were obtained by N. Shebalin. This significant rise within the epicentral area was associated with development of main expansion structures. For example, at the well № 0304 expansion was 20600cm³/m³, or +2.06% compared to the initial state in August 1988. At the distance of 140-160 km from the epicenter the expansion values were much lower (6400cm³/m³, 1500cm³/m³, 860cm³/m³ at wells №№ 0301, 0308 and 1001 correspondingly). Due to different intensity of blocks vertical displacement, the regional HGD field demonstrated significant heterogeneity which indicated the role of particular faults in preparation of the Spitak earthquake.

In August-September 1988 large expansion structures were observed in the Greater and Lesser Caucasus regions (Figure 5). By early December the Z-shaped compaction structure was formed in the region. Its northern part coincided with the Rioni valley while its southern part was controlled by the Ararat hollow. Both parts were connected by 100-110km long, 10-15km wide isthmus. This part of Z-shape structure was squeezed between two strong expansion areas which played important role in preparation and occurrence of the Spitak earthquake. The new fault which was formed immediately after the earthquake, was located at the above mentioned isthmus (Figure 5).

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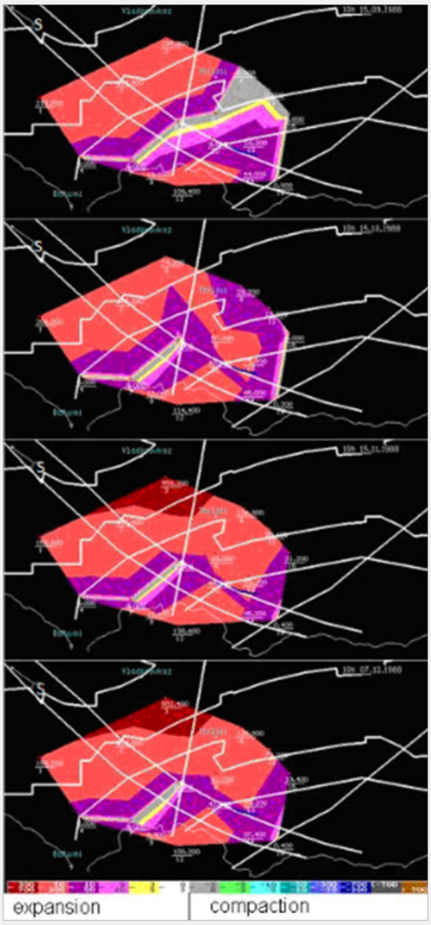


Figure 5: The maps of hydrogeodeformation field at 10:00 September 15, October 15, November 15 and December 7 1988. The fraction numerator indicates increase of block's volume (cm^3/m^3). The fraction denominator indicates the block's number. The blue line indicated the new fault formed after the Spitak earthquake.

For defining areas with most active kinetics of the HGD field hodographs V(t) and accelerograms a(t) were compiled for some specific blocks. Their analysis allows defining the periods of regular fluctuations caused by the gravity forces variations and periods when gravity related fluctuations were disturbed and muffled. The latter indicated the presence of activated endogenous processes which could cause dangerous seismic events. For example, the hodograph for the block 10 (the epicenter of the future Spitak earthquake) is characterized by the low amplitude and the irregular cyclicity caused by activated endogenous processes (Figure 6). The gravity related cyclicity with the amplitude much higher than those in the block 10, was presented on hodographs for blocks 1, 2, 3 and 12 before November 23, 1988. After this date and prior to the quake's occurrence (December 7, 1988) the gravity related cyclicity became very irregular and practically disappeared. This godograph feature could be used as short-term indicator of the forthcoming seismic event. Analysis of the regional HGD field development and hodographs shows that the Greater Caucasus structures play significant role in the deformation field kinetics. Blocks 1 and 2 were characterized by the strongest and fastest changes in deformation conditions and, therefore, could be considered as generators of deformation changes in the whole study area.

Figure 6: Hodographs V(t) (km^2/hour) for blocks 10 and 2 for the period from August 1988 till December 1990.

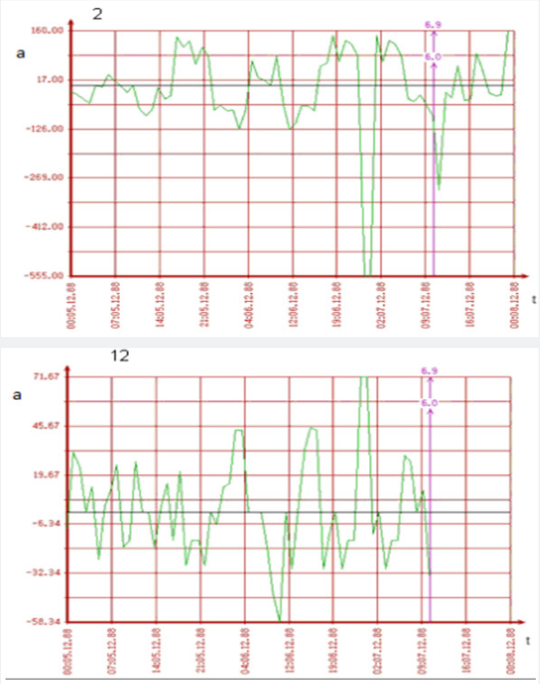


Figure 7: Accelerograms a(t) (mm^2/sec^2) for block 2 (the Greater Caucasus region) and block 12 (the Lesser Caucasus region) for the period from August 1988 till December 1990.

The stagnation period (from 23:00 December 6 to 01:00 December 7, 1988) was observed on all block's accelerograms and could be considered as the important prognostic feature. During this time preceding the Spitak earthquake, the a(t) curves were completely still. In the northern blocks (for instance, in the block 2) the stagnation period was preceded by sharp decline of the deformation process and coincided with the lowest a(t) values. In the southern blocks (the block 12) it was preceded by sharp acceleration of the deformation process and coincided with the highest a(t) values (Figure 7).

Fast changes of HGD field in the whole region could cause significant displacements of geological massifs. They occur under the influence of the displacement potential from the area with high expansion acceleration to the area with high compaction acceleration. Based on the a(t) data the displacement potentials were calculated and the scheme of potentials was compiled (Figure 8). By 10:00 December 7, 1988 the area with the high displacement potential was formed in the northern part of the study area. The block №5 was characterized by the maximum displacement potential. There is a connection between vertical and lateral displacements of geological massifs. Apparently, the heterogeneity in vertical displacements defines the deformation field and lateral movements of massifs.

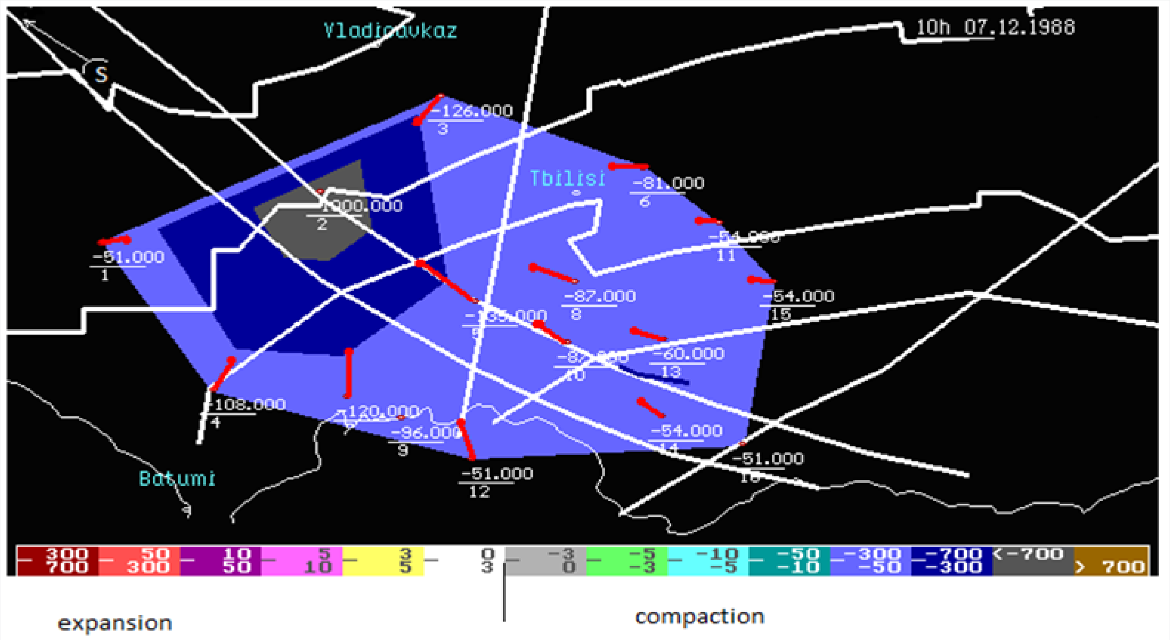
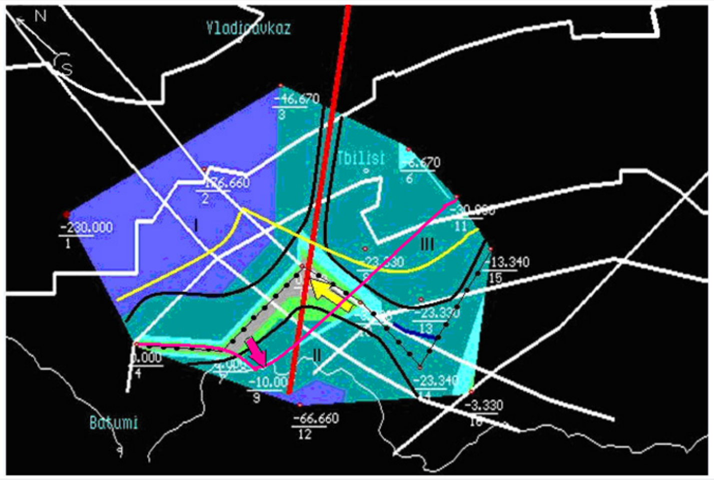


Figure 8: The scheme of block displacement potentials at 10:00 December 7, 1988. The fraction numerator indicates the displacements potential Δa(t) (mm/sec^2). The fraction denumerator indicates the block number. Red arrows indicate direction of block displacement.



Numbers I, II and III indicate the areas with different deformation kinetics. The bold black line indicates the short-lived Z-shaped deformation structure within Rioni and Ararat lowlands. The dotted black line indicates the axis of the Z-shaped structure. The red line indicates the front of blocks displacement at 3:00 December 7, 1988. The red arrow indicates direction of blocks displacement at 3:00 December 7, 1988. The yellow line indicates the front of blocks displacement at 11:00 December 7, 1988. The yellow arrow indicates direction of blocks displacement at 11:00 December 7, 1988. The bold red line - the Tshinvalo-Kazbecksky structural dislocation.

Figure 9: The kinematic scheme of block displacement potentials during the Spitak earthquake.

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At the final stage of the Spitak earthquake preparatory period geological massifs changed direction of their displacements within the short period of time. By 11:00 December 7, 1988 displacement potentials were maximal and direction of block's displacement was mainly northward following the Transcaucasus structural dislocation system (Figure 9). According to reconstruction conducted, the HGD field in the Caucasus region experienced several fast intensive changes associated with preparations of both local and distant earthquakes. These modifications reflected the global kinetic process of Earth's shape evolution and the adjustment of regional structures to the globally changed deformation field.

Large geological structures including regional fault systems also made their «input» into formation of regional stress-strain field. Therefore, the regional deformation field could be considered as self-organized system within the global Earth's lithosphere. During the final stage of the Spitak earthquake's preparatory period, fast changes of lithospheric block boundaries were observed. They were due to uneven vertical displacements of geological massifs which caused fast changes of the deformation field in the region.

The short-lived Z-shaped structure (Figure 5) along with the Tshinvali-Kazbeksky fault divided the region into three large sub-systems with different intensity of deformation processes (Figure 9). They were as follows:

a) The central part of the Greater Caucasus (blocks 1, 2 and 3) was characterized by the most intensive deformation activity that strongly influenced deformation processes in the entire region;

b) The Lesser Caucasus (the Dzavahet highland, blocks 9 and 12) was characterized by the elevated deformation activity which was, however, less than those in the central part of the Greater Caucasus area; and

c) The eastern part of the Greater Caucasus and the Kura valley (blocks 6, 11and 13) with low deformation activity.

These three kinetic systems along with the sublatitudinal faults created prerequisites for the massif displacement along the Transcaucasus dislocation system. Prior to this catastrophic displacement, the two hour period of stagnation was observed in all blocks followed by rapid development of geodynamic processes in the Greater and Lesser Caucasus. The rapid expansion processes were observed in the Greater Caucasus while the strong compaction processes occurred in the Lesser Caucasus.

As a result of these oppositely directed developments, the rupture of the geological massif occurred approximately 11 hours after the stagnation period. Therefore, the Spitak earthquake was the result of the fast and intensive changes in the deformation fields which occurred within the huge area and were observed at the HGD monitoring network.

Conclusion

a) The HGD field demonstrates deformation changes within the geological matrix. These changes are caused by combined impacts of variable endogenic and exogenic factors on the lithosphere;

b) Based on the principles and methodology of regional hydrogeodeformatics, several indicators of dangerous seismic situations were identified. They allowed defining blocks with the disturbed gravity related cyclicity and activated endogenous processes;

c) Different fine movements were observed within blocks using velocity and acceleration curves. They made possible defining the short-lived deformation structures which were responsible for development of dangerous processes within the blocks. Such structures could not be identified by any other means;

d) Changes in the deformation field occur more intensively within the global endodrainage system (GEDS) presented by mountain folded structures, mid-ocean ridges and rifts. The Greater and Lesser Caucasus system is one of the components of the GEDS.

e) Distant seismically active areas are interconnected through the GEDS. The initial impulse migrates through the GEDS from the west to the east, i.e. its migration coincides with Earth's rotation.

f) Fast changes in the deformation field cause subhorizontal displacements of huge geological massifs. These displacements could cause catastrophic processes in the lithosphere.

g) The global HGD monitoring network is proposed as the tool to follow the seismic preparatory processes. It will consist of several (5-8) monitoring stations located within the GEDS system (the Italian peninsula, the Japanise Islands, Caucasus, Cordilleras, Pyrenees regions). Each station will provide assessment of the HGD field and the possibility of dangerous development in geodynamic conditions in the specific region. This information will be forwarded to the International Centre for further processing and issuing warnings on potential dangerous seismic events.

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