Известия НАН РА, Науки о Земле, 2003, LVI, №3, 14-19

DUAL NEAR-SURFACE RUPTURING MECHANISM DURING THE 1988 SPITAK EARTHQUAKE (ARMENIA)

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Received by the editorial office on 10.11.2003

We analyzed striations of various orientations and shapes formed on a fault plane of the central segment of the 1988 Spitak seismogenic rupture in Northern Armenia (Ms=7.0). This allowed reconstruction of the rupturing process on the surface during the earthquake. The variation of striae orientations is related to the multi-phase main event consisting of several pulses within 11 seconds. The earliest striations of the first group were formed on the fault plane of the secondary superficial rupture before seismic rupture from depth had reached the earth surface and were not consistent with the resulting displacement. The later striations of the first group correspond to the motion guided from the depth. These striations formed when the focal rupture reached the central segment surface; therefore they reflect motion direction at depth most precisely. Superimposed striations of the second group are interpreted as a result of vibrations (dynamic stress change) associated with propagation of the rupture on the neighboring segments. At the final phase of rupturing process, there was an additional motion with vertical component, which did not create new striation because of a distance separating the two blocks near the surface, so that the last observed sub-horizontal striations appeared above the footwall surface. The presented data indicate important near-surface variations of kinematic conditions during the rupturing process, which were not accompanied by any change of general dynamic conditions at depth.

Introduction

Slikensides (striations) observed on fault planes are geological features that are largely used in brittle tectonics to reconstruct fault kinematics and fault dynamics [e.g. 1, 17]. Numerous methods to analyze fault slip dynamics data have been published on the assumption that these slikensides represent shear stress resolved on the fault plane [17]. Striations of various orientations found on the same fault plane are commonly interpreted as reflecting different motions that result from different stress conditions changing one another in time. Statistical analysis of such striations often forms the basis for reconstruction of regional deformation histories.

However, various directions of striations associated to a single stage of deformation were also observed, for instance, during the 1957 Gobi-Altay earthquake [7], the 1980 El Asnam earthquake [H. Philip, unpublished data], the 1992 Landers earthquake [8], or the 1995 Kobe earthquake [13]. H. Cashman and A. Ellis [2] explained this phenomenon by the interaction of two stress-fields – local and regional. According to their model, the phenomenon can be explained by a non-linear relative movement and block rotation during a strong earthquake. M. Gatery and P. Spudish [8] observed the rotation of striations and explained it by the combination of low initial stress level with spatial variations in initial stress direction.

In this paper, we present observations of differently directed striations that were formed during the 1988, Ms=7.0 Spitak earthquake, and revealed the dual mechanism of surface rupturing. We propose a model to explain what these features could mean in terms of fault kinematics and fault dynamics.

Earthquake data and sampling locations

The 1988 Spitak earthquake produced surface rupture consisting of several segments of various length, kinematics and displacements rates. The earthquake, associated with the northern part of the Garni Fault, occurred in a region where main active faults of Armenia join each other to form the North Armenian Structural Arc [10, 16] (Figure 1). The hypocenter was at a depth of 11 km [10, 16, and 12.] According to seismological data, the main shock epicenter was located to the north of the Spitak city and had focal mechanism of a right-lateral strike-slip with reverse component (fault plane strike was N140°E). The 37 km-long surface rupture displayed oblique-slip (reverse motion with dextral component) and a 65° N-dipping fault plane [10, 16].

According to the broad band seismological data inversion [9], the main shock lasted for 11 seconds and was subdivided into 5 sub-events, distinguishable both in space and in time. The first rupture propagated to the northwest of the Spitak city along a N120°E-trending reverse fault with a right lateral component. Two seconds later, the second rupture propagated to the southeast from the Spitak city along the right-lateral N140°E-trending fault. Three seconds after the second rupture started, the first rupture propagated to the northwest along another segment. The rupture did not reach the surface and was a blind thrust associated to an anticline, on top of which secondary surface deformations were observed [14].

According to other authors [6, 12] the main shock lasted for 14 seconds and consisted of 3 sub-events.

The first observations of striated fault planes were reported three days after the earthquake [10, 16]. Two fragments of striated fault plane (Figure 2) were sampled at the place where the maximum vertical displacement was observed along the 8 km-long central segment, striking from the northwest of the Spitak city to the Gekhassar village [10, 14, 16].

The striated samples, still wet, were taken from the free face of the hanging wall, 60 cm above the base of

Figure 1: a -Seismicity in the region between 1977 and 1998: 1 – strike-slip fault,2 – reverse fault,3 – movement of blocks,4 – focal mechanism of Mw>4.8 earthquakes (CMT Harvard),5 – rupture mechanism solution on the lower hemisphere of Schmidt; 6 – instrumental seismicity (3<Mb<4.9) (USGS-NEIC); b – Seismogenic rupture of the Spitak earthquake in 1988 with indication of the sampling site.

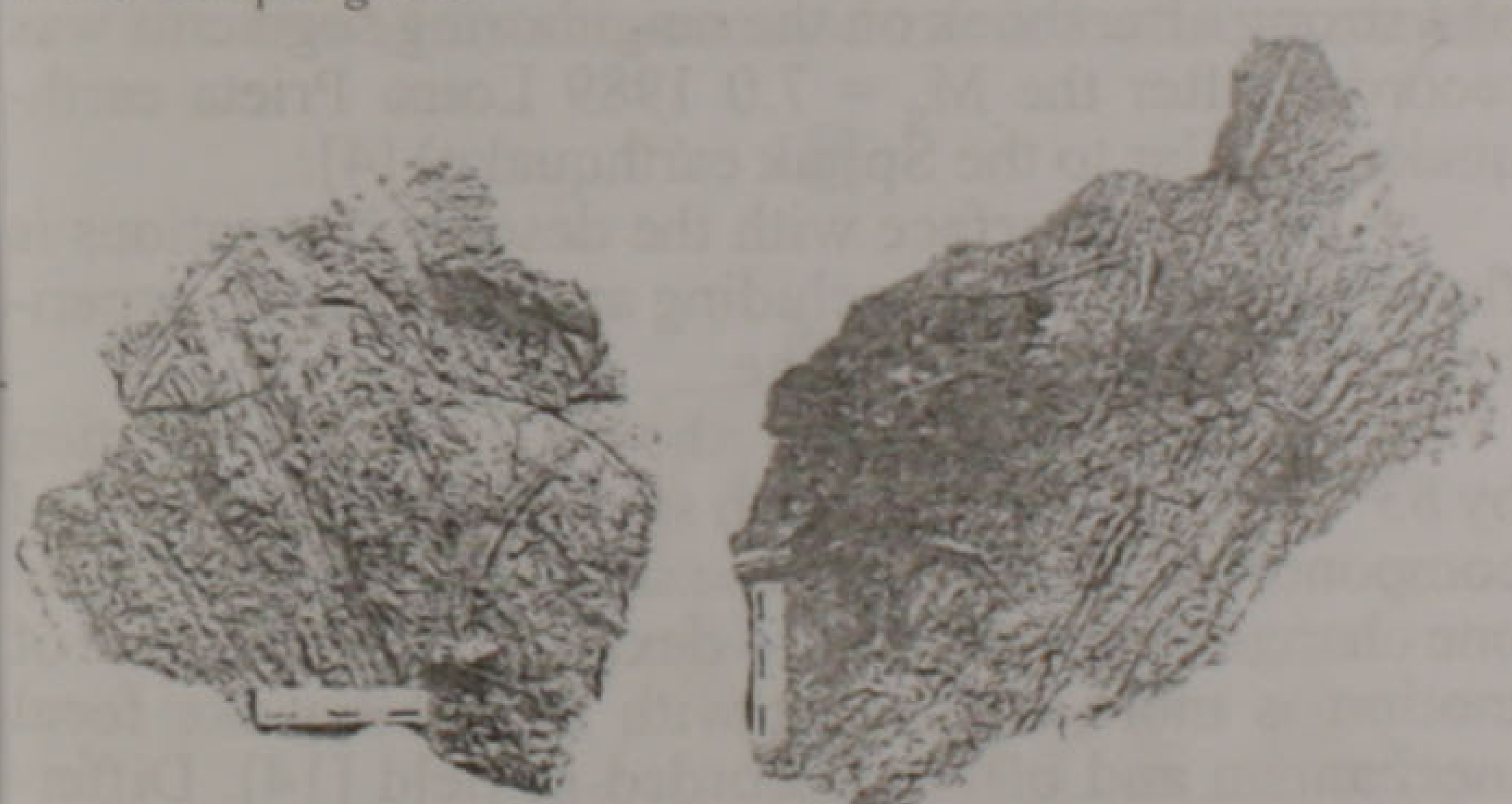

Figure 2: Two samples of the striated fault plane.

the free face (i.e., above the footwall surface), along a perfectly planar fault plane trending N140°E and dipping 50° to the northeast (Figure 3a). These samples are two tablets of plastic clay almost without clastic elements, which formed as a result of interaction between the two blocks during the rupturing.

The vertical and horizontal displacements measured at the studied site are 1.60 m and 0.90 m respectively. On the free face, one can observe a 10-15 cm-thick black layer of modern soil that is lying directly on the weathered volcanic bedrock.

Description of striations

The observed striations can be divided into two main groups depending on the shape, size and depth of striae (Figure 3b). One can easily distinguish a group composed of thin and long rectilinear striations (Group I) covering a larger part of the surface (1, 2, 3, and 4 in

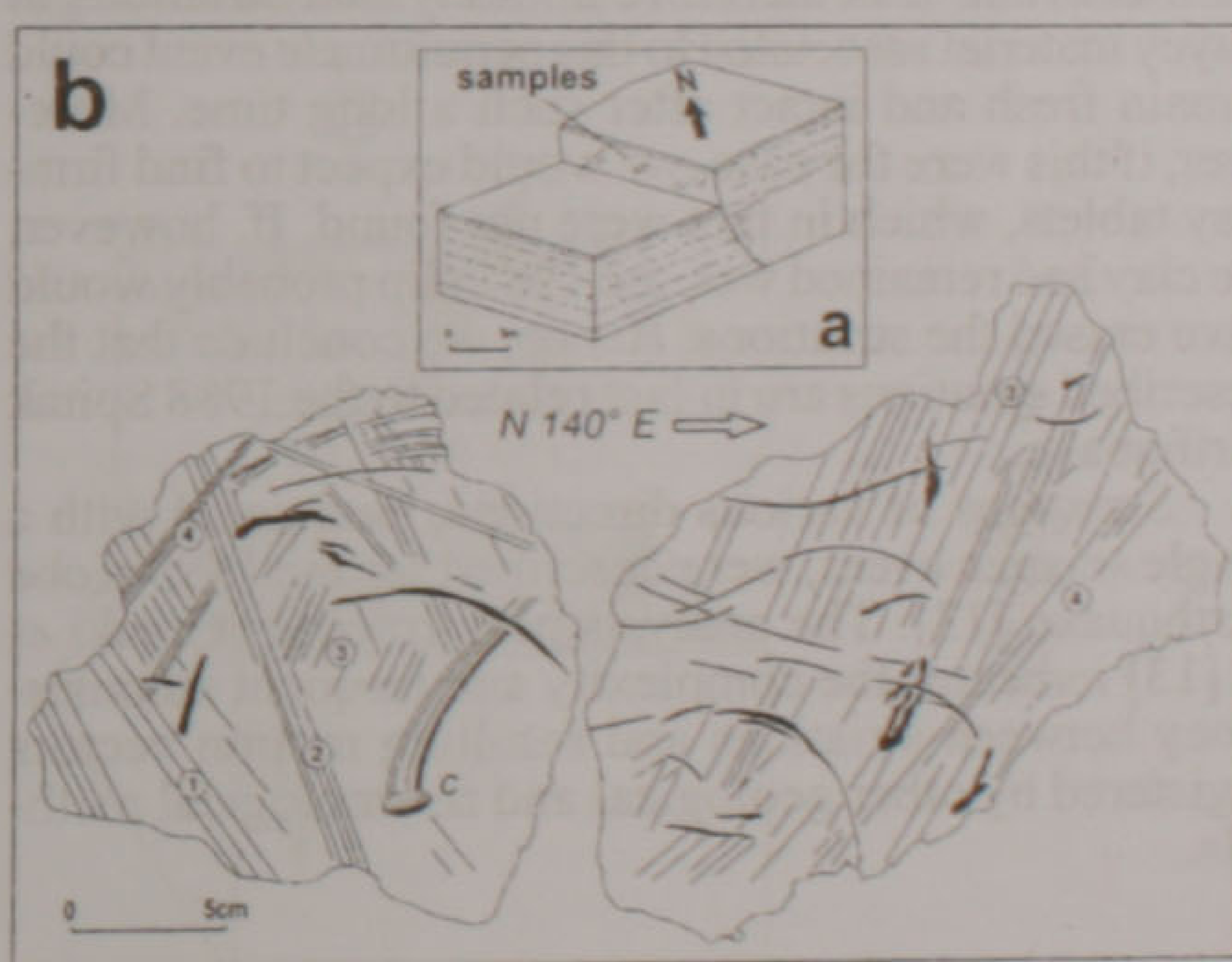

Figure 3: a – location of striated samples, b – samples (numbers indicates striae of the first group, c indicates clay accumulation).

Figure 3a), which is cut by the second group composed of short, deep and discontinuous striations having various orientations. Detailed analysis of Group I striations on the samples using the principle of superposition allowed us to determine four main motion directions that sequentially in time produced striation pitches of 48°S, 59°S, 65°N, and 49°N (1, 2, 3, and 4 in Figure 4). Using the graphical method proposed by Ritz [15] for the stress ellipsoid parameters obtained from geological data [14], we determined the theoretical slip-vector for the studied fault plane (5 in Figure 4). For Group II striations we could not establish the chronological sequence.

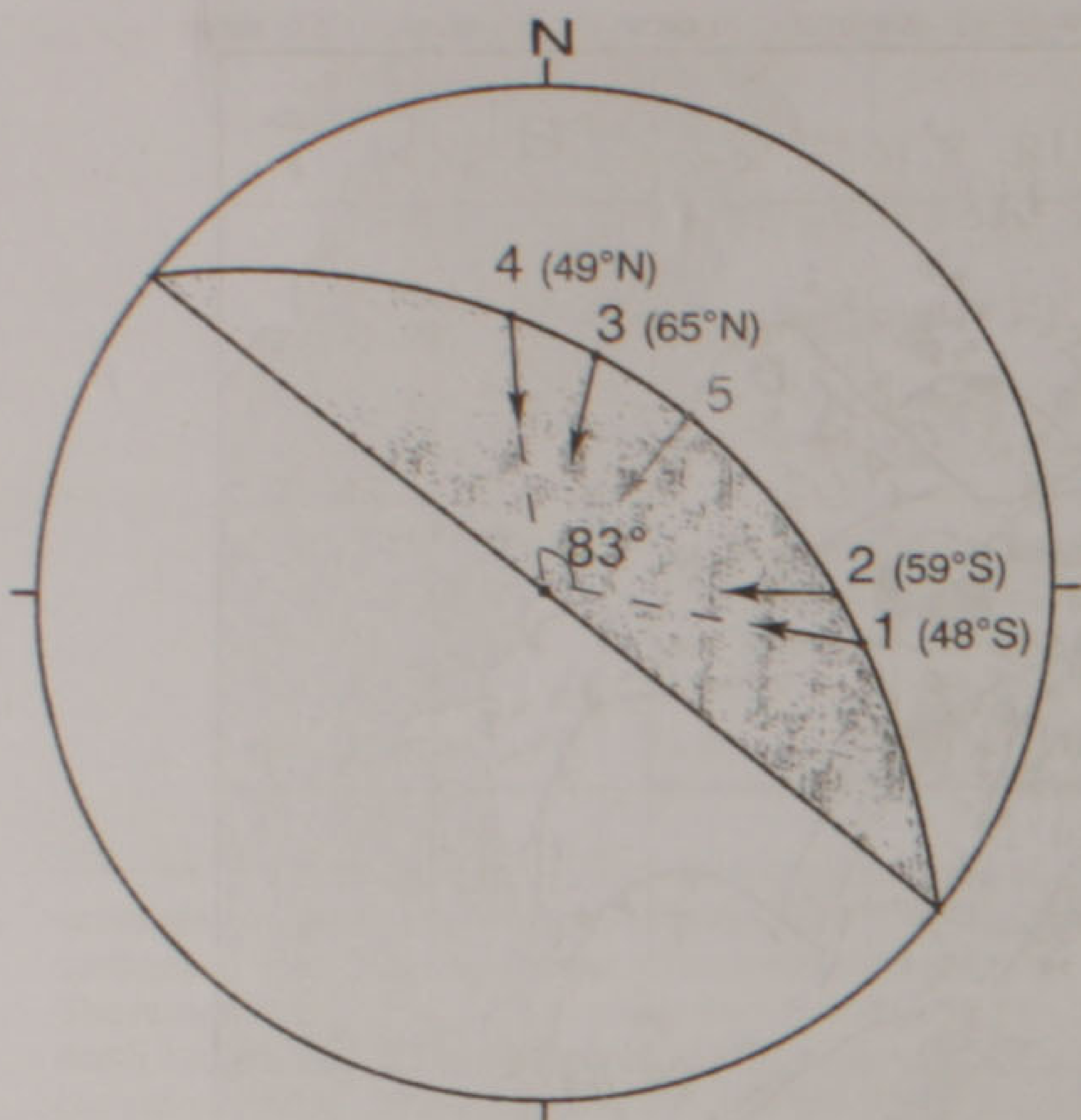

Figure 4: Representation of the striae on the lower hemisphere of Schmidt; 1 to 4 are the measured striae and 5 is the calculated one.

Age of striations

According to historical and paleoseismological evidence, the penultimate event on this segment occurred several thousands of years ago. Philip *et al* [14] established a date of 17,000 years BP as the lower time limit for this event. It is therefore unlikely that striations in clayey material associated to this penultimate event could remain fresh and intact after such a long time. Moreover, if this were the case, we would expect to find firm-clay tablets, which in fact were not found. If, however, the clay had remained wet, the 1988 slip probably would have erased the striations. Hence, we conclude that the described striations are in fact related to the 1988 Spitak earthquake.

Striations of various directions, associated with a single seismic event, were described for the 1995 Kobe earthquake [13]. The analysis performed by Otsuki *et al* [13] indicates the complexity and frequent inconsistency between striations and resulting motion vectors registered by other geological and seismological methods.

Analysis of the striation pattern

The complex pattern of slickensides can be partly explained by the presence of small clastic and rigid fragments in the clayey material, which would remain fixed to one or the other of the two fault walls alternatively during the relative movement of the blocks. As a result, striation patterns on both walls of the fault would not reflect the complete pattern of motion. Figure 5 presents different theoretical patterns of striations during a single fault movement. Figure 5a shows striae reflecting complete relative displacement between the two blocks, since a single rigid object remained constantly affixed to one of the blocks not shown in the figure. Figure 5b presents striations left by several rigid objects, distributed along the fault plane, which were affixed to the not-shown block during a part of the displacement and scratched the opposite wall. For the same relative movement, Figure 5c shows the striation left by a fragment, which, in the course of motion, was successively fixed to one fault wall or the other. The trace of the striation appears somehow reduced due to the irregular scratching and forms an arc with a smaller radius with respect to the complete record shown in Figure 5a.

To reconstruct the history of deformation, we consider the following facts:

• The striated samples were taken from the central segment, where seismogenic rupture was initiated earlier than on the other ones: therefore it could reflect all later static and dynamic stress changes during the earthquake.

• The rupturing during the Spitak earthquake included different pulses that in total lasted for 11 seconds, and created different segments of rupture. We suggest that the ensemble of described striations was created during these pulses. Based on the analysis of the Spitak earthquake aftershock parameters, Dorbath *et al* (1992) concluded that no one of the strong aftershocks could trigger surface rupture process [5]. However, the influence of a strong aftershock on the neighboring segments was recorded after the M_s = 7.0 1989 Loma Prieta earthquake (similar to the Spitak earthquake) [4].

• The fault surface with the described striations is flat enough to permit excluding any effect of its asperities on the direction of striae.

• Striations of Group 1 show a clockwise rotation by 83° (Figure 4). Along with such rotation, the vertical component is always a reverse slip, while the horizontal one changes from sinistral to dextral. The latter sense of motion is more consistent with the earthquake focal mechanism and offsets recorded in field [14]. Differently oriented striations of Group 1 have a rectilinear form (not wavy), which suggests that the movement was discrete (i.e., it had individual pulses). What this means is that there was a discrete pulse for each striation. Such change in the orientation of striations can not be a result of relative rotation of the compartments during the earthquake, because in such case the final amplitude of the vertical motion would be unreasonably large compared to the observed one (the radius of motion must be large enough to allow for the observed rectilinear shape of the striation).

• As a rule, striations in Group 2 are shorter, bent

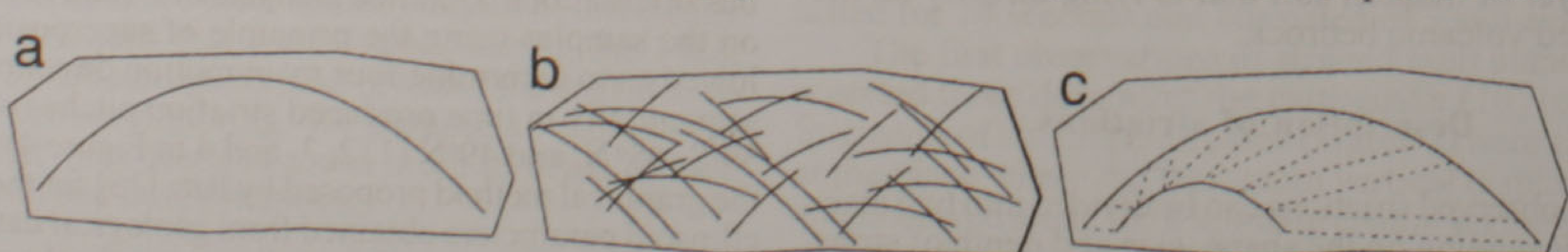

Figure 5: Theoretical pattern of striations during the same relative movement. Dashed line in c shows corresponding movements.

and more versatile than in Group 1. Their individual orientations vary, while the traces are wavy. We think that the second group of striations represents discrete displays of the same wavy movement (Figure 5b). The last of recorded striations in Group 2 was sub-horizontal (Figure 3b) and totally different from the resulting slip vector. This and the rest of striae in Group 2 can not reflect the last motions, because they are sub-horizontal and found 60 cm above the free face base. In other words, 60 cm of the total 180 cm of vertical movement took place after the last of the recorded striations had formed.

• Striations of Group 2 are deeper and larger than those in Group 1, i.e., they were produced by larger clasts (striatiors). One of such clasts left a 6-7mm-high clay accumulation at the end of its trace (*c* in Figure3). This suggests that the latest striations of the second group formed when an opening appeared between the two blocks.

Discussion and conclusion

During an earthquake, rupture propagates at a speed of about 3 km/s [e.g., 9]. For the Spitak earthquake, it would take more than 4 seconds for the rupture to reach the surface. The rupture propagated in pulses both at the depth, and on the surface, and different pulses formed their respective striations.

Therefore, as the rupture approached the ground surface at early stages of its propagation (the first pulses), the secondary ruptures were formed on the surface favored by the absence of an upper formation load (Figure 6a).

The law of conservation of momentum can explain these phenomena by analogy with a billiard-balls example. A strike from one end of a straight row of billiard-balls moves the last balls in the opposite end of the row, while those in the middle do not move. The motions on the secondary surface ruptures could reproduce orientation and amplitude of source motions at depth not in a precisely same manner. The first generation of striations appeared only on the surface, and was induced by the initial displacement at depth at the beginning of the rupturing process. The orientation of these striations is probably controlled by the location of the site with respect to the earthquake hypocenter. Later striations in Group 1 correspond to, and are consistent with, the movement and initial displacement at depth (i.e., with the focal mechanism), and the resulting surface slip (Figure 6b). On the surface, ruptures of early rupturing stages were observed also in the northwest part of the Spitak seismogenic rupture, which formed after the central rupture segment was generated. Folding and secondary superficial ruptures were also recorded there [14]. Therefore, Group 1 striations reflect this early stage of rupture formation. The late striations of the first group were formed more than 4 seconds after the rupturing started, by the time when the rupture had reached the surface. The orientation of these striations is consistent with the displacement observed at the surface. A significant part of the displacement took place during this stage.

As described above, once the central seismogenic rupture was formed, another rupture segment propagated to the southeast of Spitak and then to the northwest of the central segment. We believe that the second group of striations was created at this moment due to the passing of seismic waves. Since rock friction laws are insen-

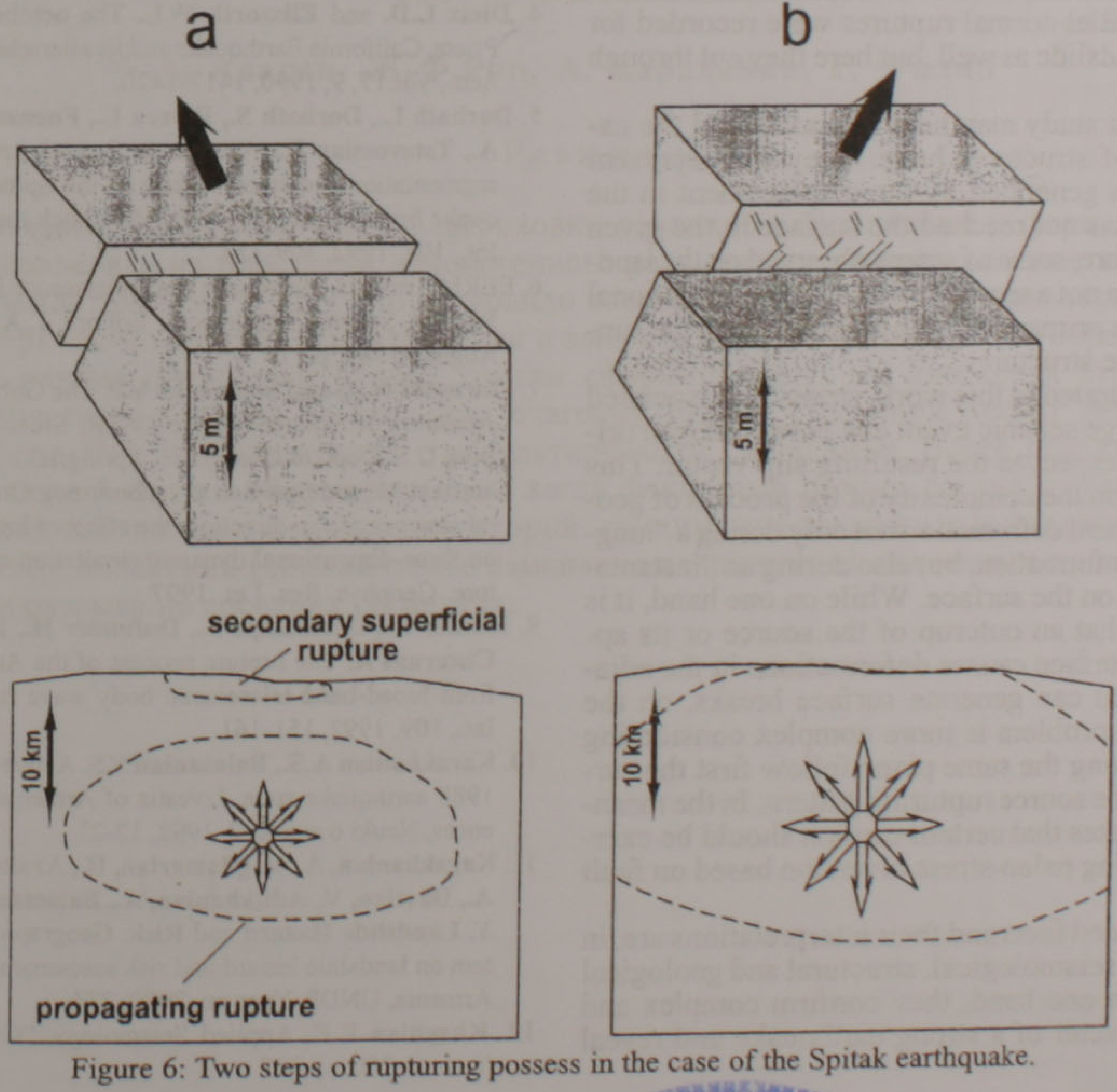

Figure 6: Two steps of rupturing possess in the case of the Spitak earthquake.

sitive to transient stresses, the stresses in seismic waves are not as great as necessary to trigger rupturing [3]. On the other hand, as mentioned above, the effect of a strong aftershock influence on the neighboring segments was also observed [4]. These factors determined the limited length of striations in Group 2.

During this final stage of rupturing, the scarp height grew by about 60 cm without any friction between the two flanks near the surface, and the last observed sub-horizontal striae appeared above the footwall surface.

The described stages of the seismogenic destruction are all accommodated within the interval of 11 seconds, during which the shocks, jointly considered the main event of the Spitak 1988 earthquake, were recorded.

For some seismogenic surface ruptures it is still not clear whether they owe their origin to a primary effect, i.e., hypocentral rupture outcrop, or secondary one, i.e., seismic shaking. We have recorded such structures in the areas of giant seismogenic landslides in Garni and Artavan (Central and Southern Armenia) [11]. Flatly cut planes of clastic elements in medium cementation breccias, suggesting instantaneous motion along such plane, were recorded on the main scarp of the Garni Giant-Landslide located in the zone of the Garni active fault. Rectilinear and parallel normal ruptures, which have almost perpendicular orientation with respect to the strike of the right-lateral strike-slip Garni Fault, located to the north, were recorded on the body of this landslide.

The Artavan Giant Landslide is located in a region characterized by numerous landslides, forming an oval zone elongated NW-SE. This expansion of landslides across a seismically active region indicates presence of a seismogenic fault. Fragmentary breaks discovered till the present do not compose a continuous structure. Rectilinear and parallel normal ruptures were recorded for the Artavan Landslide as well, but here they cut through landslide flanks.

The present study may help to understand the nature this kind of structures have. They can represent surface ruptures generated by the displacement in the source, which has not reached the surface in the given sections. Therefore, some of scarps observed on the landslides could have not a secondary, or seismogravitational nature, but just a primary one. This may explain the limited size of these structures.

As demonstrated in this work, striations associated with a single large seismic event can have different orientations with respect to the resulting slip vector. This bears evidence on the complexity of the process of geological environment deformation not only during a "long-term" stage of deformation, but also during an "instantaneous episode" on the surface. While on one hand, it is not surprising that an outcrop of the source or its approaching the surface causes deformations in the adjacent volume and can generate surface breaks, on the other hand, the problem is more complex considering that ruptures along the same plane follow first the surface, and then the source rupturing pattern. In the meantime, this indicates that certain caution should be exercised in analyzing paleo-stress inversion based on fault slip data.

The presented facts and their interpretations are, in our opinion, of seismological, structural and geological importance. On one hand, they confirm complex and combined character of a strong earthquake and reveal the contents of diverse processes of geological environment destruction during a strong earthquake. On the other hand, they demonstrate cinematic diversity of surface motions along a fault plane occurring instantly within a single tectonic stress field condition. The history of such motions can be reconstructed by the final pattern of breaks and displacements appeared. Therefore, it is with certain reservations that various striations on rupture surfaces should be used as indicators of changes in kinematic and geodynamic conditions during the geological history of the region.

Acknowledgements

This work was supported by the NATO post-doctoral award. The authors would like to thank Dr. V. Trifonov (Geological Institute of Russia) for promoting this research, Dr. Sosson (GeoSciences Azur, Sophia Antipolis, Dr. J. Chery (Université Montpellier II), Dr. H. Bagdassaryan («Georisk » Scientifc Research Company) for their valuable advice and Y.Abgaryan for translation.

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ՄԱԿԵՐԵՍԱՅԻՆ ԽԶՎԱԾՔԻ ԵՐԿԱԿԻ ՄԵԽԱՆԻԶՄԸ ՍՊԻՏԱԿԻ 1988Թ. ԵՐԿՐԱՇԱՐԺԻ ԺԱՄԱՆԱԿ (ՀԱՅԱՍՏԱՆ)

Ա. Ավագյան, Ժ-Ֆ. Ռից, Ա. Կարախանյան, Հ. Ֆիլիպ

Ամփոփում

Անալիզի է ենթարկված Սպիտակի 1988թ. երկրաշարժի խզման կենտրոնական սեգմենտի հարթության տարբեր ձևերի և կողմնորոշման քերծվածքավորումը: Այն թույլ տվեց վերականգնել մակերեսային խզվածքի պատռման ընդացքը և վեր հանել նրա երկակի մեխանիզմը: Նախնական քերծվածքավորումը ձևավորվել է երկրորդային մակերեսային խզման հարթության վրա մինչև հիպոկենտրոնային խզման մակերես դուրս գալը և չեն համընկնում գումարային տեղաշարժի ուղղության հետ: Հետագա քերծվածքավորումները առաջացել են հիպոկենտրոնային խզման մակերես դուրս գալու ժամանակ: Նրանց վրա վերադրված այլ տեսակի քերծվածքավորումը հետևանք է դինամիկ լարվածության փոփոխությունների:

ДВОЙНОЙ МЕХАНИЗМ ПРИПОВЕРХНОСТНОГО РАЗЛОМООБРАЗОВАНИЯ ПРИ СПИТАКСКОМ ЗЕМЛЕТРЯСЕНИИ 1988 г. (АРМЕНИЯ)

А. Авагян, Ж-Ф.Риц, А. Караханян, Г. Филип

Резюме

Авторами проанализированы штриховки различных ориентаций и форм, которые сформировались на плоскости сейсмогенного разрыва центрального сегмента Спитакского землетрясения 1988г. Это позволило восстановить процесс разрывообразования на поверхности в период землетрясения и выявить двойной механизм его образования. Самые ранние штриховки первой группы сформировались на плоскости вторичного поверхностного разрыва до того, как очаговый разрыв с глубины достиг земной поверхности. Они не согласуются с результирующим смещением. Более поздние штриховки первой группы сформировались, когда фокальный разрыв достиг поверхности. Наложенные на них штриховки второй группы предположительно возникли в результате колебаний (динамическое изменение напряжения), связанных с распространением разрыва на соседних сегментах.