ANNALI DI GEOFISICA, VOL. XXXVIII, N. 3-4, September-October 1995

Retrospective analysis of the Spitak earthquake

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Abstract
Based on the retrospective analysis of numerous data and studies of the Spitak earthquake the present work attempts to shed light on different aspects of that catastrophic seismic event which occurred in Northern Armenia on December 7, 1988. The authors follow a chronological order of presentation, namely: changes in geosphere, atmosphere, biosphere during the preparation of the Spitak earthquake, foreshocks, main shock, aftershocks, focal mechanisms, historical seismicity; seismotectonic position of the source, strong motion records, site effects; the macroseismic effect, collapse of buildings and structures; rescue activities; earthquake consequences; and the lessons of the Spitak earthquake.

Key words *Armenia – earthquake – analysis – precursor – sub-sources – site-effect – destruction – lessons*

1. Introduction

Considered in the historical framework of strong earthquakes, the Spitak earthquake presents one of the recurrent pieces of evidence that the problem of strong earthquakes and the seismic risk they determine will have gained new ground by the end of the 20th century. This new quality is associated with a high probability of mass casualties, a large destruction area, economic, psychophysical and social shocks in the community.

The unsolved predictive problems lay a foundation for the new quality seismic risk. They are:

– seismic hazard prediction related particularly to seismic zonation against the background of growing population density and urbanisation of new territories in seismically active zones;

– prediction of the response of buildings and structures including critical life-line facilities;

– prediction of the behaviour of people, community and state prior to, during and after an earthquake.

The Spitak earthquake occurred on the 7th of December, 1988, 07:41:23.2 Greenwich mean time. According to the data obtained immediately after the earthquake its parameters were the following: $M_{LH} = 7.1$ (Obninsk Central Seismological Observatory, EPI) that corresponds to $M_s = 6.9$ (Balassanian *et al.*, 1993), φ, latitude 40.90°N, λ, longitude 44.20°E, h, depth of 5 ± 3 km.

The earthquake killed 25000 people, 20000 were severely injured, 515000 lost their homes and property. The state losses amounted to $ 6 billion.

2. The changes in geosphere, atmosphere and biosphere during the Spitak earthquake preparation

Preparation of a strong seismic event is known to be associated with an accumulation of gigantic elastic strain energy in the medium.

Reasoning from the above, this process could hardly be imagined without accompanying transformation of the energy into its other types and noticeable changes in the medium.

This very prerequisite serves usually as a physical basis when describing the changes in geosphere, atmosphere and biosphere preceding strong seismic events. We set a natural question of how many instrumentally recorded changes are associated with strong seismic event preparation and how much the evidence of eyewitnesses who are excited by the picture of an earthquake represents the facts.

Since the answers to these questions are directly related to earthquake precursors and the seismic event prediction problem they have been given greater or lesser attention depending on the success in this particular prediction field.

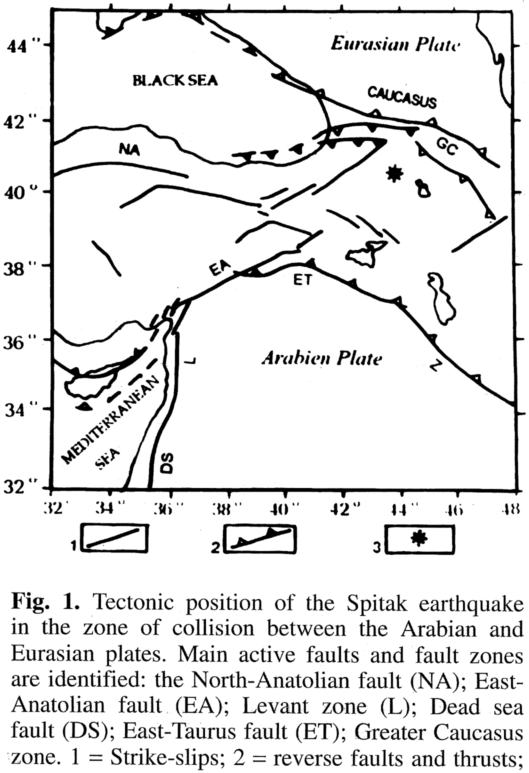

Fig. 1. Tectonic position of the Spitak earthquake in the zone of collision between the Arabian and Eurasian plates. Main active faults and fault zones are identified: the North-Anatolian fault (NA); East-Anatolian fault (EA); Levant zone (L); Dead sea fault (DS); East-Taurus fault (ET); Greater Caucasus zone. 1 = Strike-slips; 2 = reverse faults and thrusts; 3 = the Spitak earthquake epicenter.

Today the emphasis has shifted towards total scepticism and suspicion of any data interpreted as strong earthquake precursors.

The brief information about the changes in geosphere, atmosphere and biosphere during the Spitak earthquake preparation is presented in the work. In doing so we do not discuss their physical nature, but just state the facts which may be interpreted in different ways and one cannot but publish them reasoning only from the disillusionment period which set in over the solution to the earthquake prediction problem.

Figure 1 presents the tectonic position of the Spitak earthquake zone in the collision area of the Arabian and European lithosphere plates while the location of Armenian observation sites that recorded the discussed geosphere, atmosphere and biosphere changes during the preparation of this seismic event is shown in fig. 2.

2.1. *Changes in the geosphere*

One may judge the state of the geosphere during the strong earthquake preparation from the state of its solid, liquid and gaseous phases. The changes in solid state during the Spitak earthquake preparation period were monitored in seismic events each known to be followed by the rupture of rock mass continuity. The liquid phase state was assessed considering the changes in chemical compound concentration and ground water level while the gaseous phase was characterised by the changes in soil gas radon emission.

2.1.1. Seismic quiescence

The common character of the regional seismic regime is shown in fig. 3a as a map of epicenters for 1979-1983. Starting from 1984 a five year seismic quiescence period (fig. 3b) had set in the source zone of the future event. It changed over the strong earthquake with aftershocks felt up to 1991 (fig. 3c).

The seismic quiescence phenomenon is noted along the active faults that participated

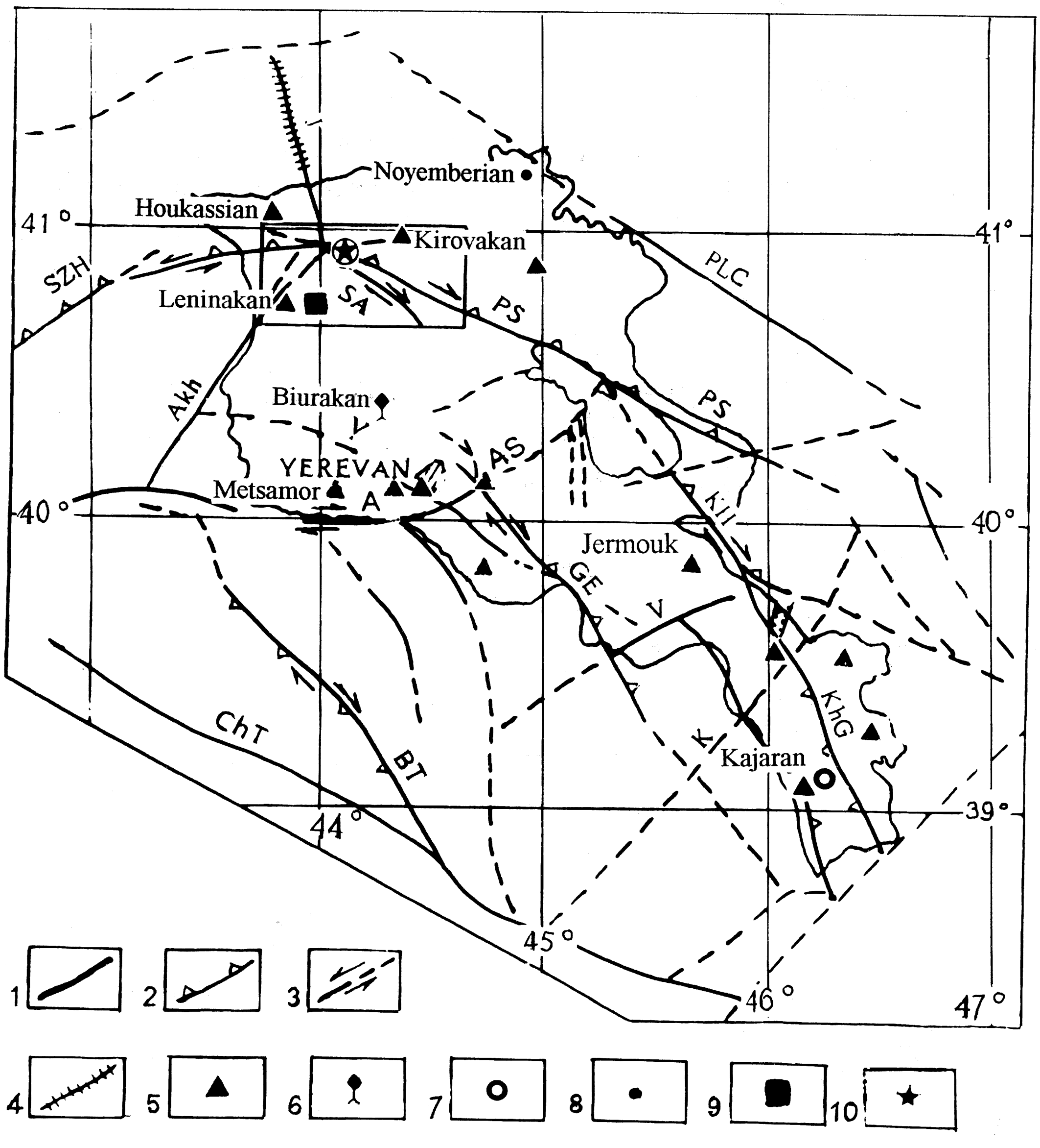

Fig. 2. Position of the observation sites on the scheme of active blocks for the territory of Armenia and adjacent territories bounded by active faults and extension zones: the Sarykamish-Zeltorechensk fault (SZh); Akhourian fault (AKh): Javakh extension zone (J); Pre-Lesser Caucasian fault (PLC); Pambak-Sevan fault (PS); Yerevan fault (Y); Arax fault (A); Azat-Sevan fault (AS); Khonarassar fault (Kh); Garni-Elpin fault (GE); Vaik fault (V); Kapoutjour fault (K); Khoustoup-Ghiratakh fault (KhG); Balikghel-Tebris fault (ChT). 1 = Active faults of obscure morphology; 2 = reverse faults; 3 = strike slips; 4 = extension zones; 5 = seismic stations; 6 = Biurakan astrophysical observatory; 7 = Kajaran hydrogeochemical station; 8 = Noyemberian hydrogeodynamic station; 9 = Leninakan radon station; 10 = the 1988 Spitak earthquake epicenter.

in the Spitak earthquake preparation: the Zheltorechensk-Sarykamish fault (since the middle of 1987); the Akhourian fault (since early 1988); and the Pambak-Sevan fault (since early 1988) (fig. 4).

It is remarkable that before the Spitak earthquake the 1.5 month short term seismic quiescence encompassed the entire region of the Armenian Upland (fig. 5) in addition to 5 years' seismic quiescence in the source zone – that fits well into Kanamori's statistics (Kanamori, 1981) – and 1.5 years' quiescence along the active faults which participated in the Spitak earthquake preparation (fig. 4). Thus, the seismic quiescence period decreased as the size of seismogenic structures got larger.

The results presented above were obtained from the data of regional seismic stations of Armenia, Georgia and Azerbaijan.

2.1.2. The changes in the concentration of chemical components in ground water

During the period of time that coincided with the Spitak earthquake preparation unusual changes in the concentration of Cl, HCO_3, pH and other chemical components were recorded in ground waters of the Kajaran seismogeochemical station located (fig. 1) in the zone of active Pambak-Sevan fault (fig. 6a-c).

The data in fig. 6a show that a year prior to the Spitak event the Cl-ion concentration dispersion had dropped sharply in the waters near the Kajaran station. The Cl-ion concentration decreased 4 months before the earthquake, while after it the Cl-ion concentration decreased almost 1.5 times.

It is particularly remarkable that analogous Cl-ion changes were observed during the Roudbar earthquake preparation (fig. 6a).

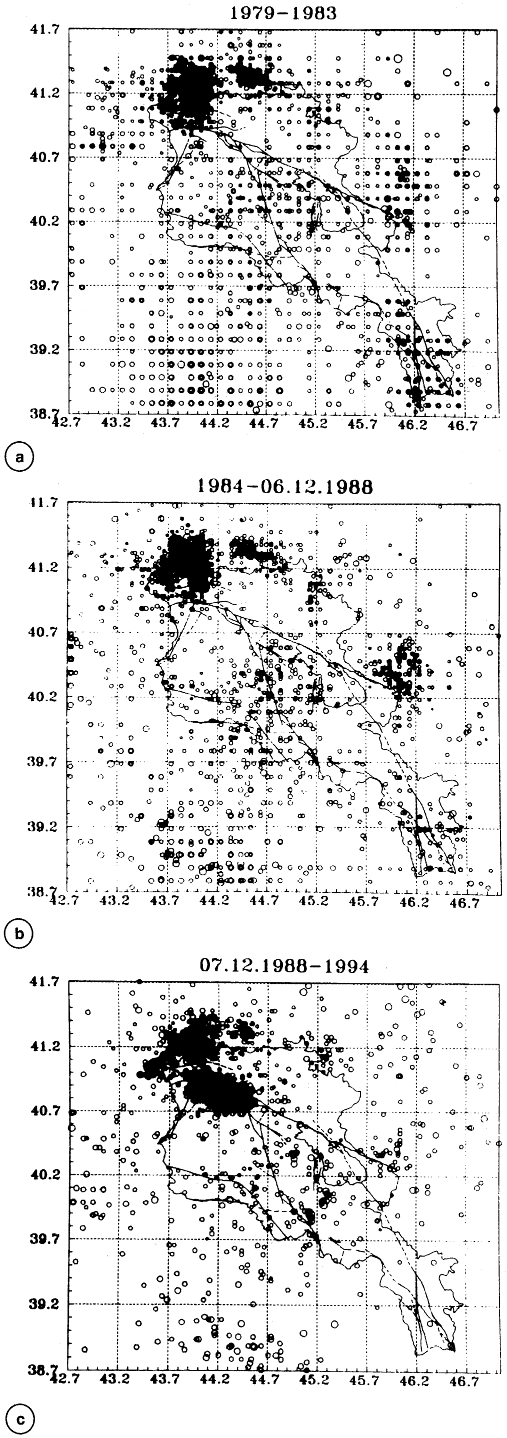

Fig. 3a-c. Map of earthquake epicentres for the time period prior to (a,b), during and after (c) the Spitak event (seismic quiescence of the source zone).

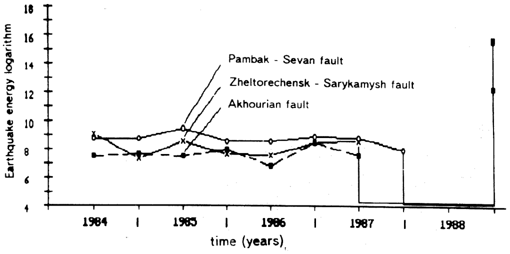

Fig. 4. Seismic quiescence along the active fault which participated in the Spitak earthquake preparation.

Figure 6b presents the changes in hydrocarbonate ions: six months prior to the Spitak earthquake the concentration dispersion had decreased sharply while after the seismic event struck the HCO_3 content in ground waters decreased (as it did for the Cl-ion). Similar changes were observed during the Roudbar earthquake preparation (fig. 6b).

Variations in the hydrogen index (pH) 4 months before the Spitak earthquake are of interest, too. The pH reading dispersion had diminished sharply (fig. 6c).

Figure 7 shows the response of He (helium) dissolved in water to the strong earthquakes in the region (Norman, 1983; Spitak, 1988; Roudbar, 1990; Racha, 1991, etc.). After each of these strong earthquakes He – content had decreased almost threefold and then the months – long process of regaining the initial concentration value started.

Certain distinctions in the response of different chemical elements to various seismic events may be explained not only by different distances from the earthquake hypocenter to the Kajaran Observation station, but different seismotectonic positions of one or another source with respect to the observation site.

2.1.3. Ground water level variations

Figure 8a,b presents long-standing period (1988-1991) results of ground water level recording at the Noyemberian observation

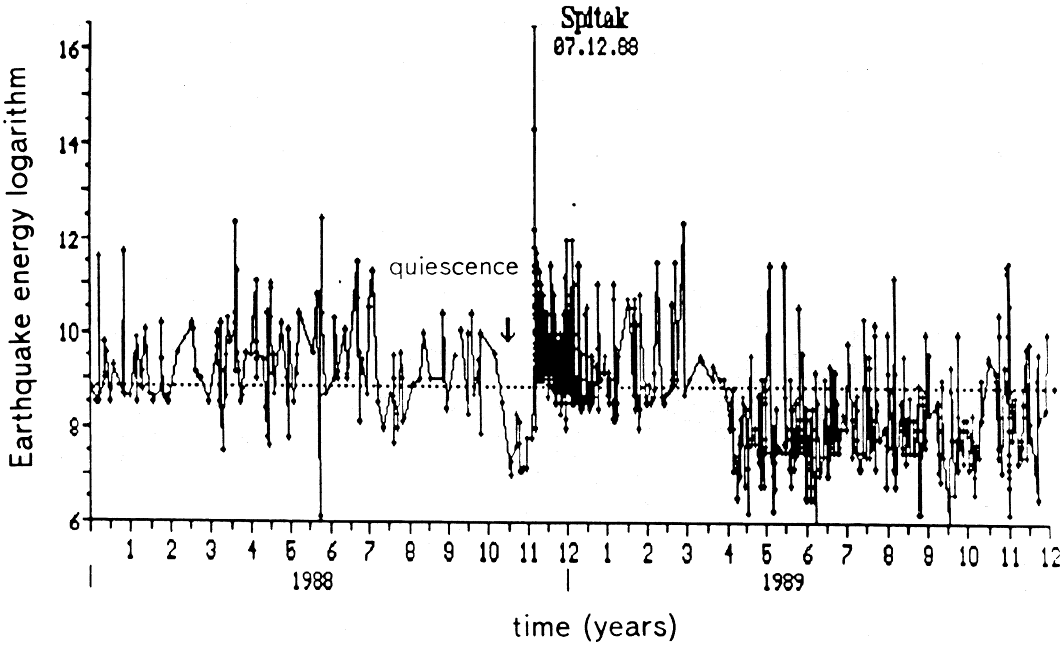

Fig. 5. Seismic quiescence in the region of Armenian Upland.

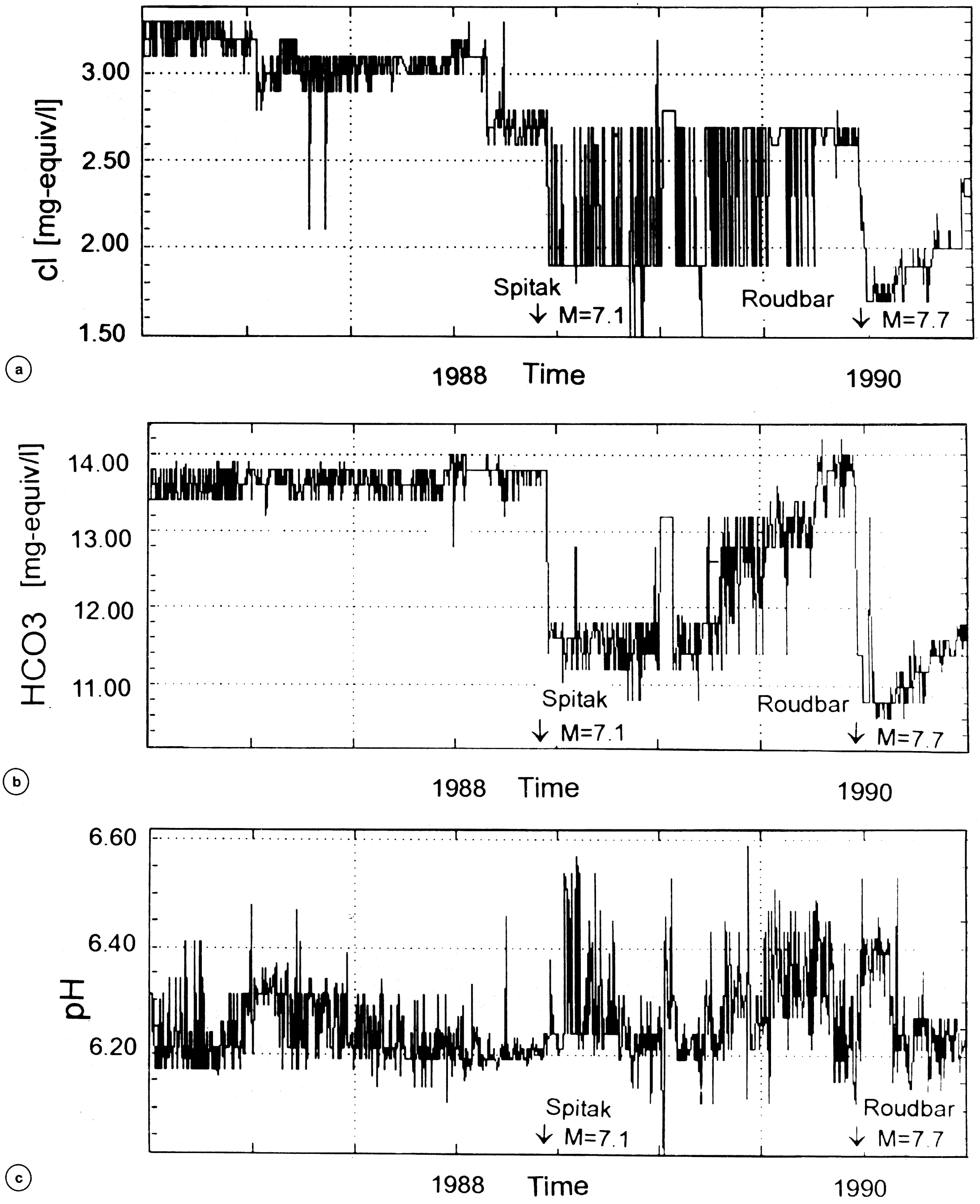

Fig. 6a-c. Hydrogeochemical anomalies at the Kajaran station during the Spitak earthquake preparation period. a) Chlorine (Cl) ion variation in ground waters; b) hydrocarbonate (HCO_3) ion variations; c) hydrogen index (pH) variations.

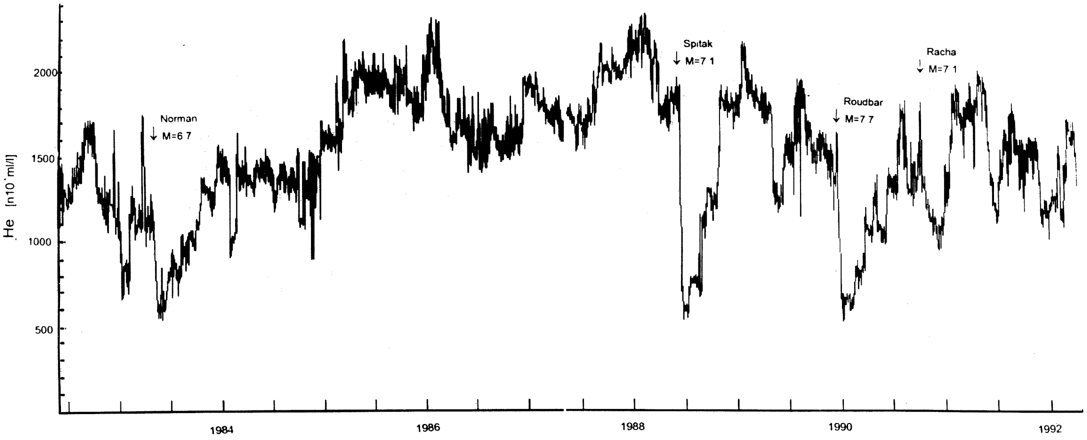

Fig. 7. Variations of the content of Helium (He) dissolved in water at the Kajaran station.

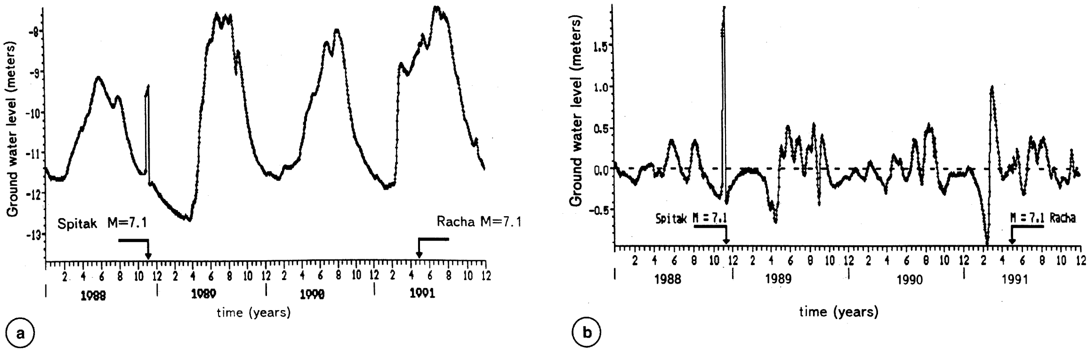

Fig. 8a,b. Ground water level alterations at the «Noyemberian» station: a) initial data; b) the data after Fourier analysis.

station (fig. 1) situated 75 km north-east of the Spitak earthquake source zone. After Fourier analysis had eliminated the annual ground water level variations (fig. 8b) it became evident that anomalous changes in ground water level took place from December 1 till December 10, 1988, *i.e.* during the Spitak earthquake preparation and realization, and further during the Racha earthquake (M_{LH} = 7.1, April 29, 1991, Western Georgia) preparation. The Spitak earthquake was well pronounced in annual cycles too, while the Racha event was concealed in them.

2.1.4. Variations in the soil gas radon emission

Long-standing series of observations on the soil gas radon emission at the Jermouk station located 150 km south-east of the Spitak earthquake source zone (fig. 1) compared to the variations in atmospheric pressure (Bassentsian and Roudakov, 1989) are presented in fig. 9. It is clear from the data that starting from 1987 the amplitude of radon gas emission annual cycles had increased sharply against the background of dropping amplitude of atmospheric pressure annual variations.

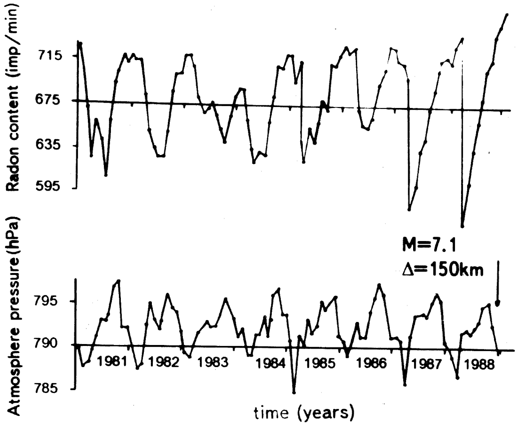

Fig. 9. Variations of subsoil gas radon content at the «Jermouk» station compared to the atmosphere pressure variations (according to the data of Bassentsian and Roudakov, 1989).

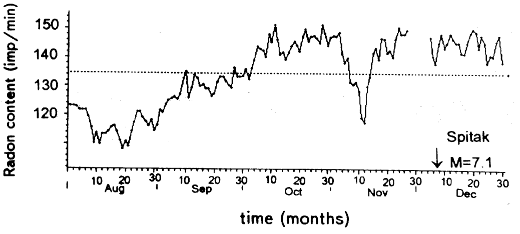

Fig. 10. Variation in gas radon content at the «Leninakan» station.

Figure 10 shows the radon gas variations at the Leninakan station four months prior to the earthquake and immediately after it.

2.1.5. Other changes in the geosphere

In addition to the above data, different authors described various anomalous effects after the Spitak earthquake (from Spitak-88 International Seminar, Abstracts, 1989). These are intense regional vertical Earth crust movements revealed by repeated geodetic surveys several years prior to the earthquake; intense sign-converting deformations of rock masses starting from 1988 and recorded by strainmeter at the Garni Geophysical Observatory underground 96 km away from the earthquake source, in the region of Garni active fault (fig. 1); anomalous slopes of the Earth's surface noticed at the same Garni site; long-period and short-period electrotelluric field anomalies since August 1988; a sharp decrease in electric resistance pronounced 10-12 h before the earthquake at the Parackar observation site (75 km far from the earthquake source in the Near-Yerevan hypogene fault zone); intense acoustic noise within the range of 800-1200 Hz recorded 25 h prior to the main shock at the stations installed in Georgia and Azerbaijan.

According to the evidence of witnesses, the changes in spring debits (from disappearance of water to its spouting), appearance of new springs, temperature and airation build-up in the outgushed waters had been noted in the Spitak earthquake epicentral zone.

2.2. *Changes in the atmosphere*

Such atmospheric changes as a sudden warming in the autumn and summer seasons of 1988-1989, atmospheric pressure drop (fig. 9), disturbed propagation of very long radio waves, sharp build-up of the radio-noise situation in the metric band, and anomalous radio radiation fluctuations in the MHz frequency range coincided with the period of Spitak earthquake preparation.

The results of the recording of «Omega» Radio Navigation system signal phases along the Liberia-Omsk (f, frequency = 10.2 kHz) and Reunion-Leningrad (f = 12.3 kHz) radio routes are presented in fig. 11 (Gufeld *et al.*, 1992).

From November 27, 1988 to December 8, 1988, *i.e.* starting 12 days prior to the earthquake, nocturnal anomalous variations of the $(\bar{\varphi}-\varphi)/\sigma$ parameter ranging up to 4 had been observed along the routes passing 1000 km far from the epicenter, *i.e.* up to three zones of Freznel (Liberia-Omsk), and immediately through the epicentral area (Reunion-Leningrad).

Note that $\bar{\varphi}$ is an hour monthly mean value

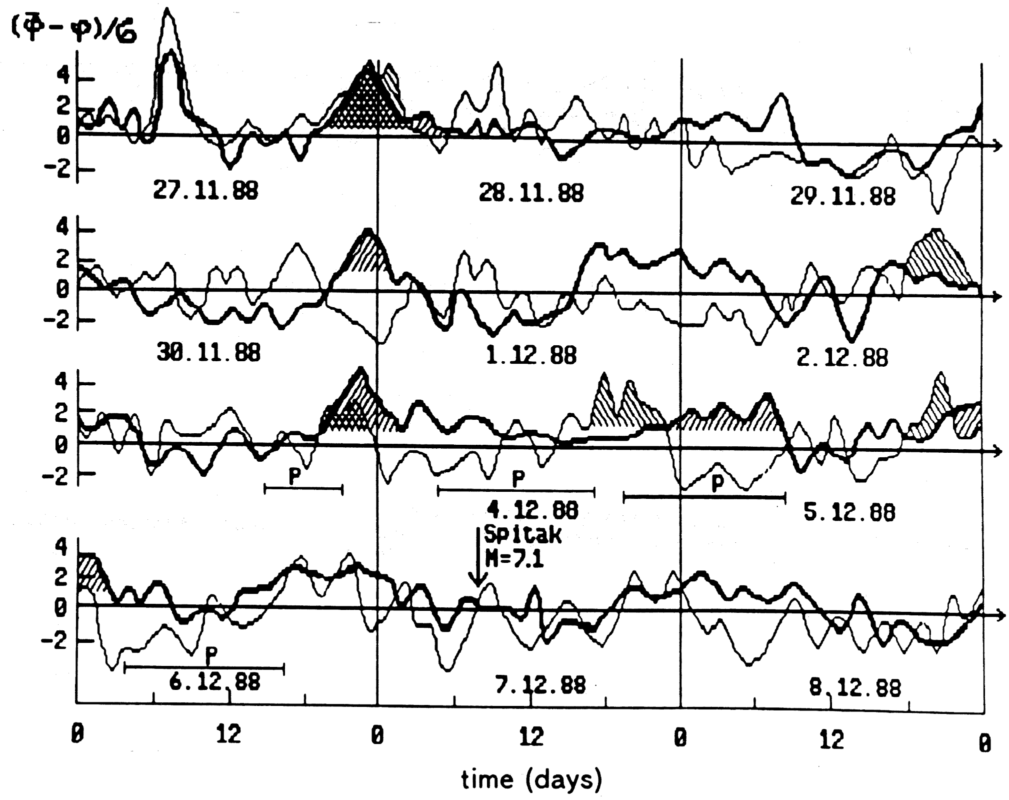

Fig. 11. Results of registration of the «Omega» Radio Navigation system signal phases along the «Liberia-Omsk» (bold line) and «Reunion-Leningrad» (thin line) radio routes together with the time interval of anomalous radio noise observed on radars (according to the data of Gufeld *et al.*, 1992).

of the spreading very long radio wave, while φ is the current value of its phase and σ is the dispersion.

This phenomenon, in the opinion of Gufeld *et al.* (1992) is connected with a normal very long radio wave splitting at the inhomogeneities which appeared in the lower ionosphere and interference of modes at the receiving point.

The same fig. 11 shows the period of active noise situation according to the data of circular scanning radar stations in the metric range of radio waves. The mentioned stations were situated near the epicentral zone. It is clear from fig. 11 that the active noise situation had been observed on December 3-6, 1988. As to the data of meteostations in Georgia and Armenia, the situation was not due to the thunderstorm activity.

Figure 12 illustrates the results of monitoring the ionospheric scintillations of the Lebed A space radio source at the range of 74 MHz (Panarjian *et al.*, 1989) using the receiving antenna with an effective area of $\Delta \approx 40$ m^2 and narrow, 2 $\Delta f \approx 100$ kHz, passage band radiometer set in the Biurakan Astrophysical Observatory 50 km to the south of the earthquake source (fig. 1). From the data given in fig. 12 it is evident that intense anomalies associated with an appearance of active radio radiation sources in the controlled zone over the territory of Armenia were observed on December 5-7, 1988, with the maximum value noted on 6th of December.

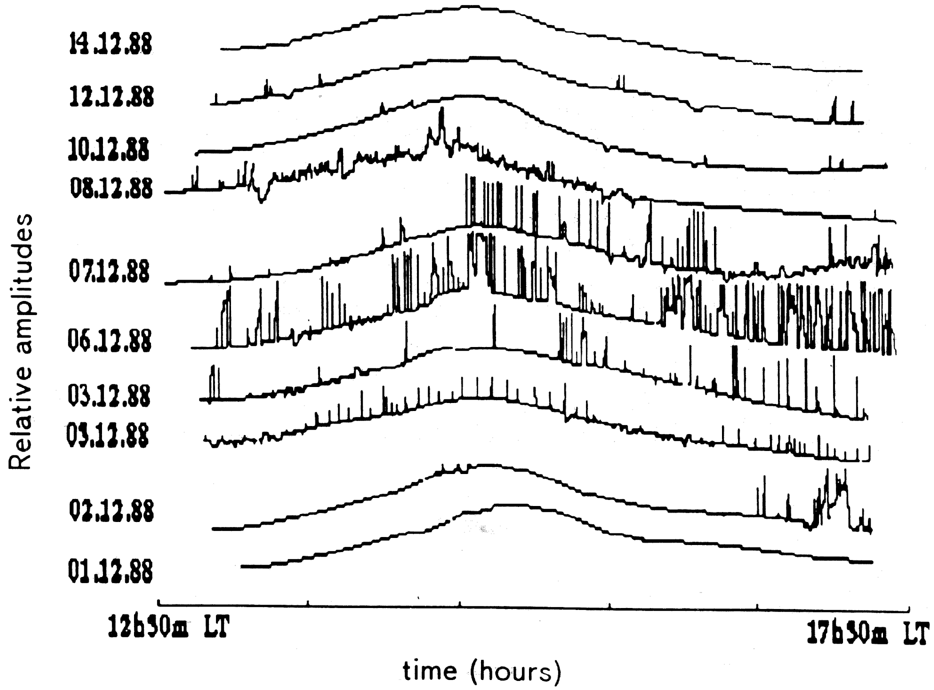

Fig. 12. The results of observation over the Lebed A space radio source ionospheric scintillations at the Biurakan Astrophysical Observatory (according to the data of Panarjian *et al.*, 1989).

2.3. *Changes in the biosphere*

Mass questioning of witnesses after the Spitak earthquake indicates – as Ignatossian *et al.* state (1989) – that from two days to several minutes prior to the earthquake many domestic animal and bird species displayed an increased vocal and motor activity; most animal species were found in either an excited or depressed state; some farm animals rejected the food; interspecific phobia disappeared in mice and rat communities; premature awakening of snakes, worms and bees from winter hibernation, etc. With respect to plants the appearance of fresh grass in that unusual season as well as the changes in colouring, fading of plants, excessive swelling of algae and changes in colouring had been observed. Noticable changes of general condition – most frequently for women and younger children – had been observed a day and less prior to the main shock.

One of the important phenomena noticed in the biosphere was vegetation burned along the main seismic dislocation of the Spitak earthquake (fig. 13).

3. The Spitak earthquake

The catastrophic Spitak earthquake occurred on December 7, 1988, 07:41:23.2 Greenwich mean time. According to the data obtained immediately after the earthquake it had the following parameters: $M_{LH} = 7.1$, that corresponds to $M_s = 6.9$ (Balassanian *et al.*, 1993); the epicenter coordinates were $\varphi = 40.90°$N, $\lambda = 44.20°$E; the hypocenter depth, h, was equal to 5 ± 3 km.

The peculiar feature of that strong seismic event was that it had foreshocks, a complex multi-phase main shock with the consequent

Fig. 13. The vegetation burned along the Spitak earthquake main seismic dislocation (photo by A. Karakhanian).

strong aftershock and prolonged aftershock activity.

3.1. *The foreshock*

According to the data of the Armenian regional seismic network the Spitak earthquake was preceeded by three foreshocks characterized by the main parameters given in table I.

Table I. The main parameters of the Spitak earthquake foreshocks.

Date	Time	Lat.	Long.	LgE
03.12.88	15.54.19	40.54.00	44.15.00	7.8
06.12.88	15.27.15	40.55.12	44.13.12	9.8
06.12.88	18.44.35	40.52.12	44.15.00	8.0

In addition, the stations situated in the zone remote from the source and particularly the IRIS station (Garm, Tadjikistan) recorded a weak foreshock 4 s prior to the main shock.

3.2. *The main shock*

Figure 14a-c presents the recording of the Spitak earthquake main shock made by the IRIS station located in a remote area at the Garm Observatory in Tadjikistan, the epicentral distance $\Delta = 20.0°$, the azimuth from the source to the station Az = 87°, (Panarjian *et al.*, 1989). Figure 14a shows that the *P* wave recording made at the long-period recording channel of the IRIS station (60-30 s, digitization frequency is 0.1 Hz) looks like an unilateral pulse. A more complex structure of the source signal emerges at the shorter periods. It can be noted in fig. 14a that the process started

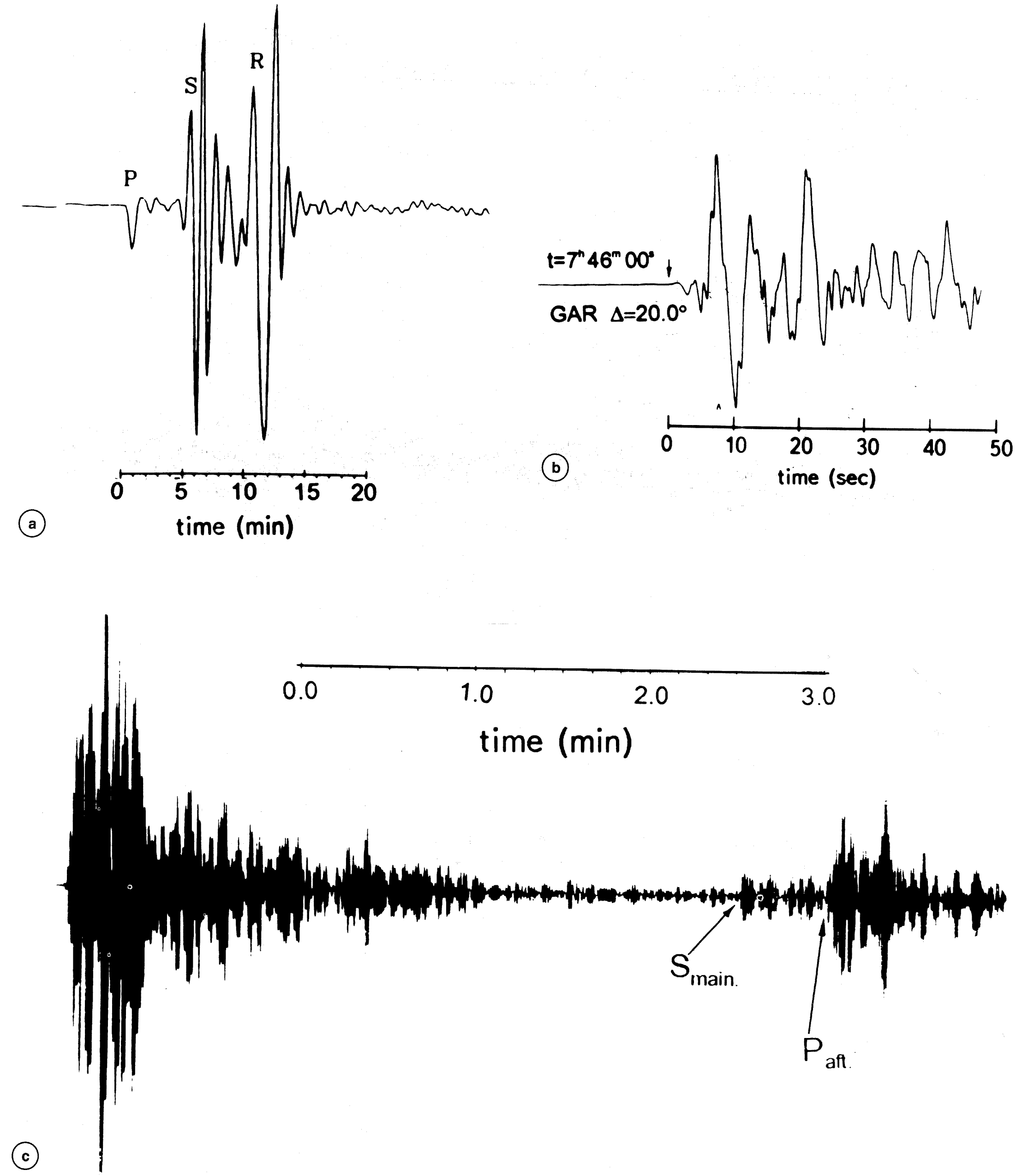

Fig. 14a-c. The Spitak earthquake record in a remote area Garni station (according to the data of Novikova and Rauthlan, 1991). a) Long-period channel vertical component (60-30 s, 0.1 Hz digitization frequency); b) vertical component of the Spitak earthquake record onset; c) main shock and aftershock (after 4 min 17 s) band filtration (1.1-1.6 Hz) of the IRIS record.

from the weak, smoothly arriving foreshock which 4 s later was followed by the main shock. The main shock direct *P* wave was of 25-45 s duration at different stations. Further analysis shows that the *P* wave consisted of several pulses. The first strong aftershock with $M_{LH} = 5.9$ took place 4 min and 17 s after the first main shock pulse (fig. 14c).

The Spitak earthquake recording obtained at the Leninakan seismic station, *i.e.* immediately in the source nearby area, is shown in fig. 15.

Numerous studies (Novikova and Rauthlan,

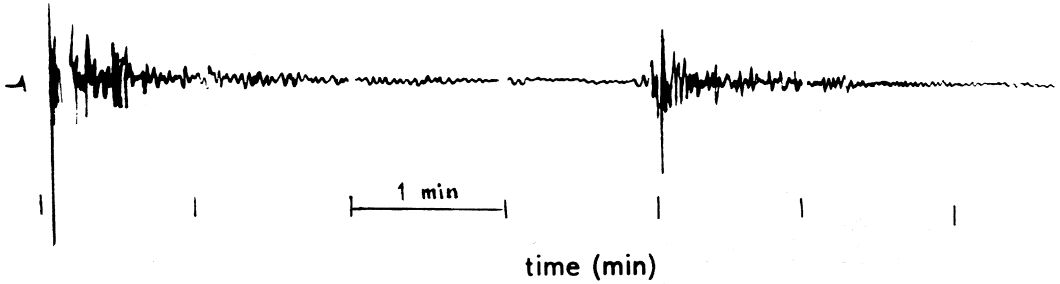

Fig. 15. The Spitak earthquake record in a near-by area at the Leninakan seismic station.

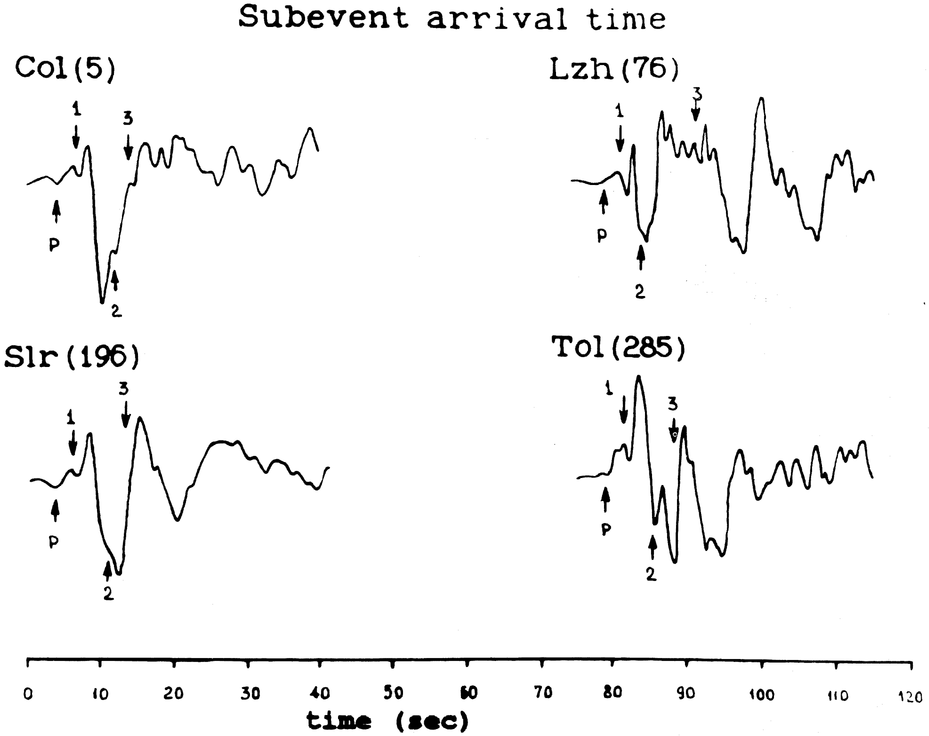

Fig. 16. Record of the three sub-events of the Spitak earthquake main shock in a remote area (according to the data of Pacheco *et al.*, 1989).

Table II. Parameters of the main shock sub-events.

	Source parameters				
Sub-event	Moment (10^{18} N×m)	Centroid depth (km)	Strike	Dip	Rake
1	6.4	2.5	290	44	131
2	5.8	6.0	314	83	151
3	5.1	7.3	269	71	142

1991; Pacheco *et al.*, 1989; Kikuchi *et al.*, 1988; Graiser *et al.*, 1991) pursued after the Spitak earthquake suggest that this strong seismic event consisted of three sub-events at least. These three sub-events were associated with three sub-sources that acted sequentially within 15 s.

According to the data of Pacheco *et al.* (1989), which were obtained based on the analysis of body waves recorded at 14 digital seismic stations in different regions of the globe, the first sub-source appeared 3 s after the first weak arrival distinguished at the seismograms and interpreted by the authors as a main shock precursor (fig. 16). The second and third sub-sources acted 4 and 10 s after the main shock, respectively (fig. 17). The three sub-sources were all similar in size and had the parameters given in table II.

3.3. *The aftershocks*

The Spitak earthquake is characterised by the prolonged aftershock activity that lasted right up to 1991, attenuating gradually.

The first shock occurred 4 min 17 s after the main shock and was of $M_{LH} = 5.9$. Afterwards, up to 3rd March 1989, 6 aftershocks with magnitude of $M_{LH} \geq 4.1$ were recorded.

The detailed investigation of the aftershock activity was started by the seimologists of different countries (the U.S.S.R., U.S.A., and France) with the organization of provisional observation networks since 1988. The observations covered various time intervals all beginning from mid-December, 1988 (Arefiev *et al.*, 1991; Borcherdt *et al.*, 1993).

In addition to stationary seismic stations, four movable stations were installed in the epicentral area on the Soviet part, 25 different type stations were set up on the French part and 32 (12 analog and 20 digital) stations were installed by Americans.

From December 6, 1988 till December 31, 1989 – in a time of Soviet-French observations – 2804 events had been recorded. The American seismologists observed 135 events from December 23 to January 4, 1989.

As one can see in figs. 18a,b the distributions of the Spitak earthquake aftershocks derived using French-Soviet (fig. 18a) and American (fig. 18b) observation networks respectively, are alike despite the different number of events recorded. The overwhelming majority of the aftershocks is confined to the Pambak-Sevan and Alavar faults with their depth ranging up to 13 km.

The distribution of aftershocks given in fig. 18b reveals comparatively isolated groups that coincide with the three main shock sub-sources in space. This is one of the arguments in favour of the main event model put forward by Pacheco *et al.* (1989).

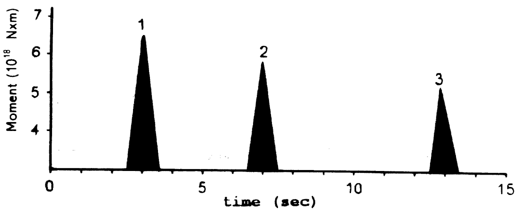

Fig. 17. Distribution of the main shock sub-events in time.

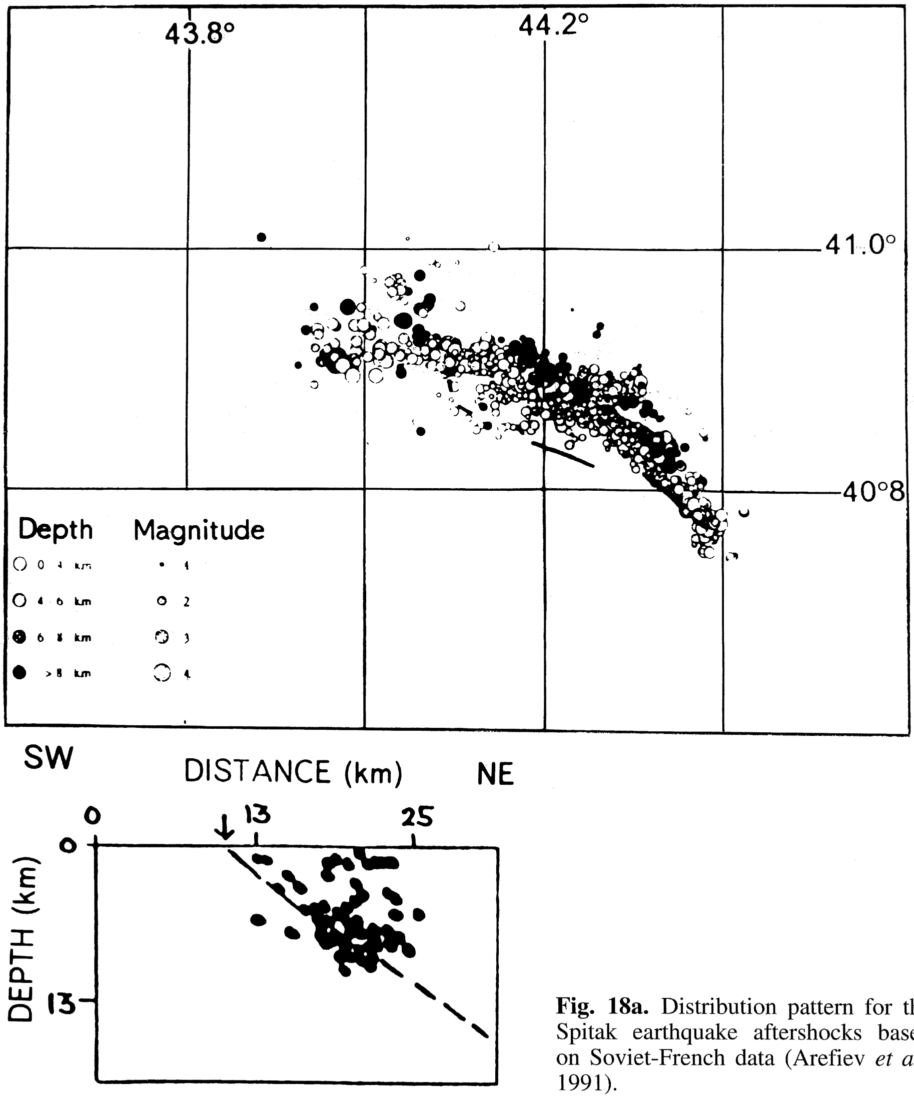

Fig. 18a. Distribution pattern for the Spitak earthquake aftershocks based on Soviet-French data (Arefiev *et al.*, 1991).

3.4. *The past strong earthquakes in the epicentral area*

The following strong earthquakes with $M \geq 5.0$ are known in the Spitak earthquake region for the instrumenal period – the 14.11.1916 earthquake, epicenter coordinates $\varphi = 40.8$°N, $\lambda = 44.4$°E, $h = 26$ km hypocentral depth, $M_{LH} = 5.3 \pm 0.5$, 6-7 MSK-64 scale intensity in the epicenter; the 30.01.1967 earthquake, epicenter coordinates $\varphi = 41.03$°N, $\lambda = 44.32$°E, $h = 5$ km hypocentral depth, $M_{LH} = 5.0 \pm 0.2$, 6-7 MSK-64 scale intensity in the epicenter.

Historical seismicity has been poorly investigated, particularly in Northern Armenia. The Spitak tragedy urged the start of detailed seismological investigation. Even the first systematic works initiated in 1989 revealed numerous

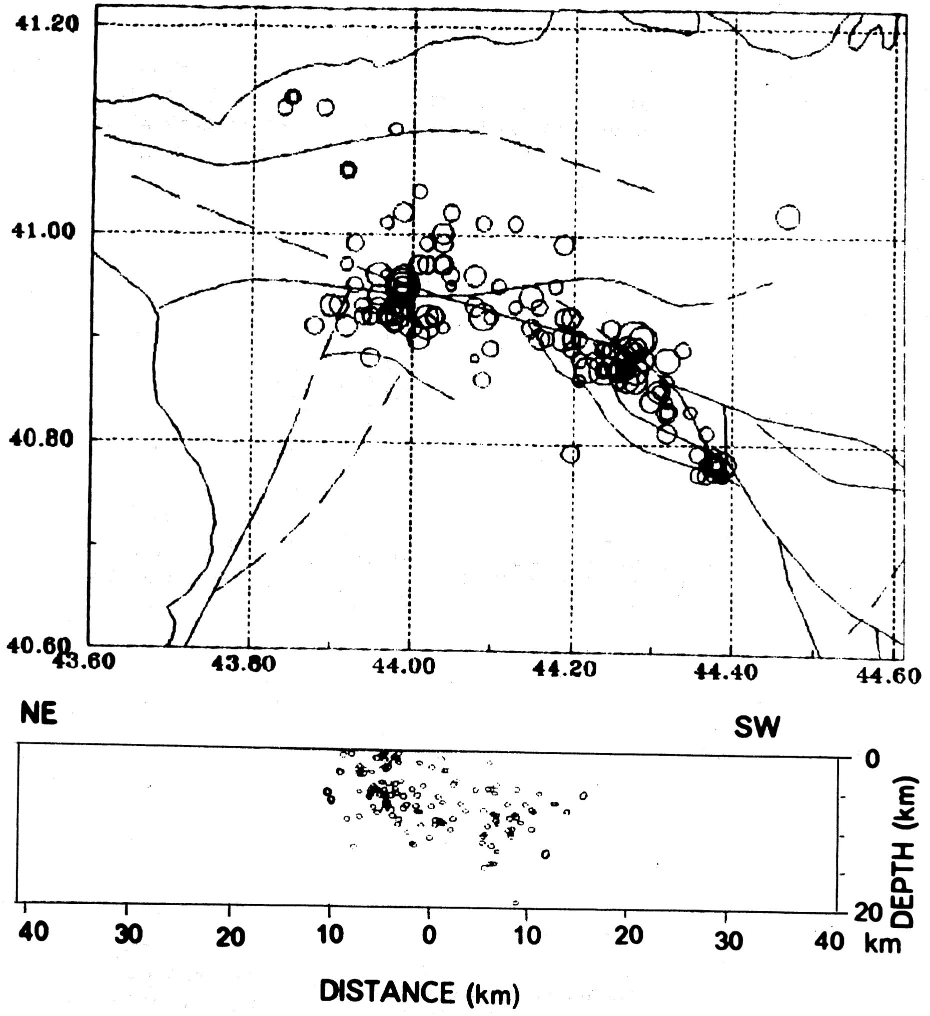

Fig. 18b. Distribution pattern for the Spitak earthquake aftershocks based on American data (Borcherdt *et al.*, 1993).

paleoseismotectonic dislocations in the Spitak earthquake zone (Rogozhin and Philip, 1991; Alberde *et al.*, 1991; Trifonov *et al.*, 1994). They offer evidence of $M \geq 7.0$ catastrophic earthquakes in the region that occurred repeatedly in the historical past. The Soviet-French group of researchers had thus revealed that there was a strong paleoseismodislocation at the south-eastern flange central segment (near Spitak) (Novikova and Rauthlan, 1991). Based on its age estimated by carbon-14 dating at 17-20 thousand years and the vertical displacement amplitude, the authors concluded that a strong $M \geq 7.0$ earthquake with its source outcropped to the surface occurred at the edge of Upper Pleistocene and Holocene in the Spitak region. The formed rupture had an upthrusted north-eastern wall like the 1988 rupture did.

The same authors (Pacheco *et al.*, 1989) suggested that a large seismic event had probably occurred at the same fault 2-3 thousand years before the 1988 Spitak earthquake. In Nikonov's opinion (Graiser *et al.*, 1991) the factual evidence permits one to link the fault activation at the considered site and the four strong seismic events (including the 1988 Spitak earthquake as well) for the last 25 thousand years approximately.

3.5. *Focal mechanisms*

Different authors defined focal mechanisms for the Spitak earthquake main shock (that had three sub-sources), foreshocks and aftershocks using different seismic networks, data processing procedures, wave groups, and programs (Graiser *et al.*, 1991; Arefiev *et al.*, 1991; Borcherdt *et al.*, 1993; Rogozhin and Philip, 1991). The solutions obtained are in satisfactory agreement and include the following.

1) The main shock sub-source mechanisms are peculiar for different types: the first mechanism presents a reverse fault with small right-lateral slip component, the preferred nodal plane is of 290° azimuth and dips 44° to the north. This fits well into the field observation results and distribution of the aftershocks. The second sub-source presents right lateral slip with small reverse fault component, the preferred solution is a plane striking 314° and dipping to the north-east at an angle of 83°. The third sub-source is a right-lateral slip with 269° strike azimuth and northward dip at an angle of 70° (fig. 19).

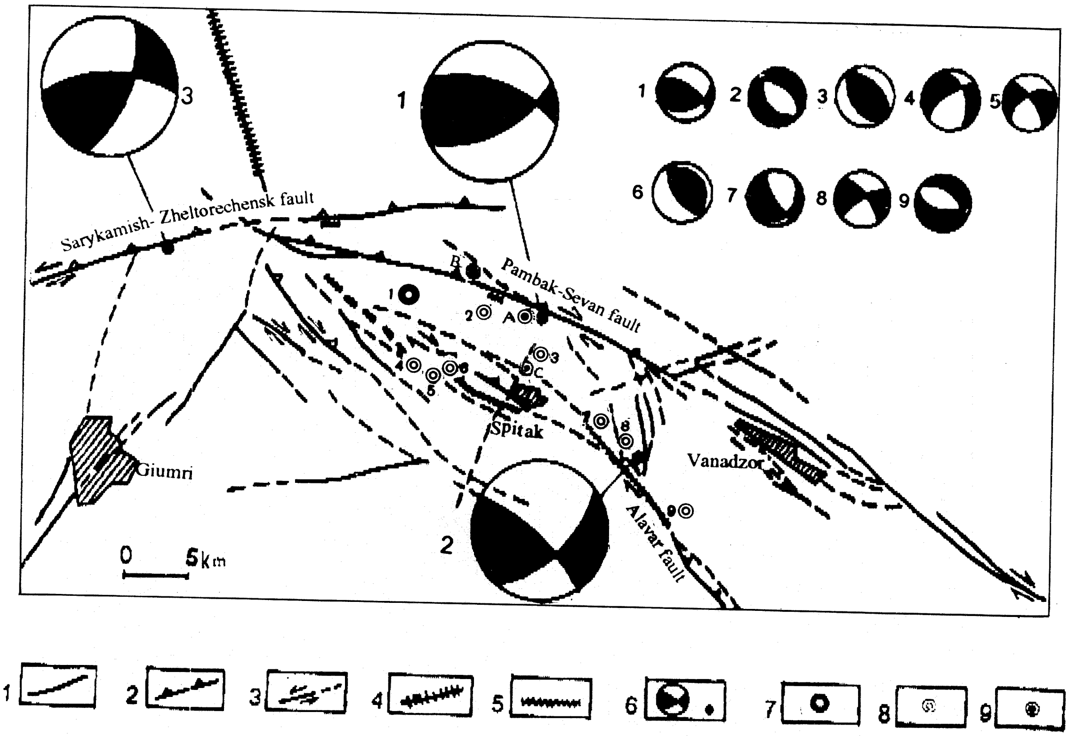

Fig. 19. The main shock focal mechanisms and those for aftershocks along the seismogenic rupture on the source zone seismotectonic scheme (according to the data of Pacheco *et al.*, 1989; Trifonov *et al.*, 1994, as well as the data kindly provided by M. Danilova): 1 = active faults of obscure morphology; 2 = reverse fault; 3 = strike slip; 4 = extension zone; 5 = seismogenic ruptures; 6 = sub-source epicenters and their mechanisms; 7 = the 1967 earthquake epicenter; 8 = aftershocks; 9 = foreshocks.

2) After December 7, 1988, the aftershock focal mechanisms were normal faults, normal and strike slip faults and strike slips. Starting from December 8, 1988, the character of movements in aftershock sources had changed significantly, that is reverse and reverse-slip type mechanisms became predominant (Graiser *et al.*, 1991; Rogozhin and Philip, 1991; Geodakian *et al.*, 1989).

3) The aftershock focal mechanisms December 7-31, 1988, with their coordinates differing by ± 2' from the central coordinates of the main shock sub-source epicenters were reverse faults, normal faults, normal and strike-slip faults all slips being right-lateral. The same pattern is derived for the aftershock sources with epicenters located at the seismogenic rupture: there were strike-slip and normal faults, reverse faults, strike-slip faults, normal fault, and brim (with a vertical movement on the near-vertical plane).

4) The rupture plane for the first and strongest main shock sub-source approximately coincides with the rupture planes in the sources of January 30, 1967 and March 21, 1975 Spitak earthquakes.

3.6. *Seismotectonic position of the source zone*

The Spitak earthquake struck at the junction of four active blocks of Northern Armenia that are confined by the Pambak-Sevan, Sarykamish-Zheltorechensk and Akhourian active faults and the Javakhet extension zone represented by a series of smaller submeridianally striking ruptures (fig. 2).

The Pambak-Sevan and Sarykhamish-Zheltorechensk faults display deep slope to the north and are characterized by right and left lateral and reverse fault displacements, respec-

Fig. 20. The Spitak seismogenic rupture (photo by A. Karakhanian).

tively. The Akhourian fault displays sub-vertical left slip character (Kikuchi *et al.*, 1988).

The formation of above active structures went on against the background of general submeridianal compression of the Earth's crust in the collision zone of Arabian and Eurasian plates.

As follows from the seismological description, the Spitak earthquake was of multi-phase nature and consisted of three strong sub-events at least.

The sub-source of the strongest shock is situated at the junction of the Pambak-Sevan and Hankavan-Spitak (Alavar) faults. Its formation was accompanied by the exposure of a tectonic cross-piece between these faults and the outcrop of 27 km long seismogenic rupture to the surface along the Hankavan-Spitak (Alavar) fault (fig. 20). This rupture displayed maximum displacement on a right slip for 1.8 m and 2 m reverse fault. In addition to that, a seismogenic fracture with a right slip for 3 cm and reverse fault for 6 cm was formed along the Pambak-Sevan fault. The sub-source of the second shock that took place 4 s later was located 15 km to the south-east of the first one, towards the Alavar fault. A seismogenic rupture that was 10 km long was formed at the extension of the latter.

Fig. 21. Rock specimen taken from the formed seismogenic rupture displacement surface bearing fresh forrows that attest multi-phase character and complex, versatile direction of movements in the Spitak earthquake source (photo by A. Karakhanian).

The sub-source of the third shock which followed 10 s after the second one is situated 30 km west from the first. It is confined to the junction zone of Akhourian and Sarykamish-Zheltorechensk faults. The formation of this source was attendant with the Sarykamish-Zheltorechensk fault outcropped over 350 m with a left slip of 15 cm.

The multi-phase nature and complex, versatile orientation of movements in the Spitak earthquake source is well illustrated by fresh forrows on the displacement surface of the formed seismogenetic rupture (Alberde *et al.*, 1991) as seen in fig. 21.

Thus, the Spitak earthquake was due to tectonic strain accumulation up to a critical level in the zone where active blocks of Northern Armenia join. The strain discharge was featured by a multi-phase character and occurred along the Pambak-Sevan, Alavar and Sarykamish-Zheltorechensk active faults.

3.7. *Strong motion records*

One of the main problems complicating a comprehensive study of the Spitak earthquake resides in an acute deficiency of strong motion records. This is owing to the absence of a developed and properly operating network of strong motion stations in Armenia prior to the Spitak earthquake.

Figures 22a-c show all of the three main shock records made by accelerographs set at the Houkassian station (fig. 1), in the building of Yerevan Earthquake Engineering and Architecture Institute and at the observation site of Armenian Nuclear power plant in Metsamor.

Table III presents an analysis of these records together with the response spectra obtained for their most intense horizontal components. R is the epicentral distance, PGA is the peak ground acceleration, T_a is the predominant acceleration period on the response spectra with 5% attenuation; $\tau_{0,5}$ is the ground motion duration at the 0,5 PGA level. The given data

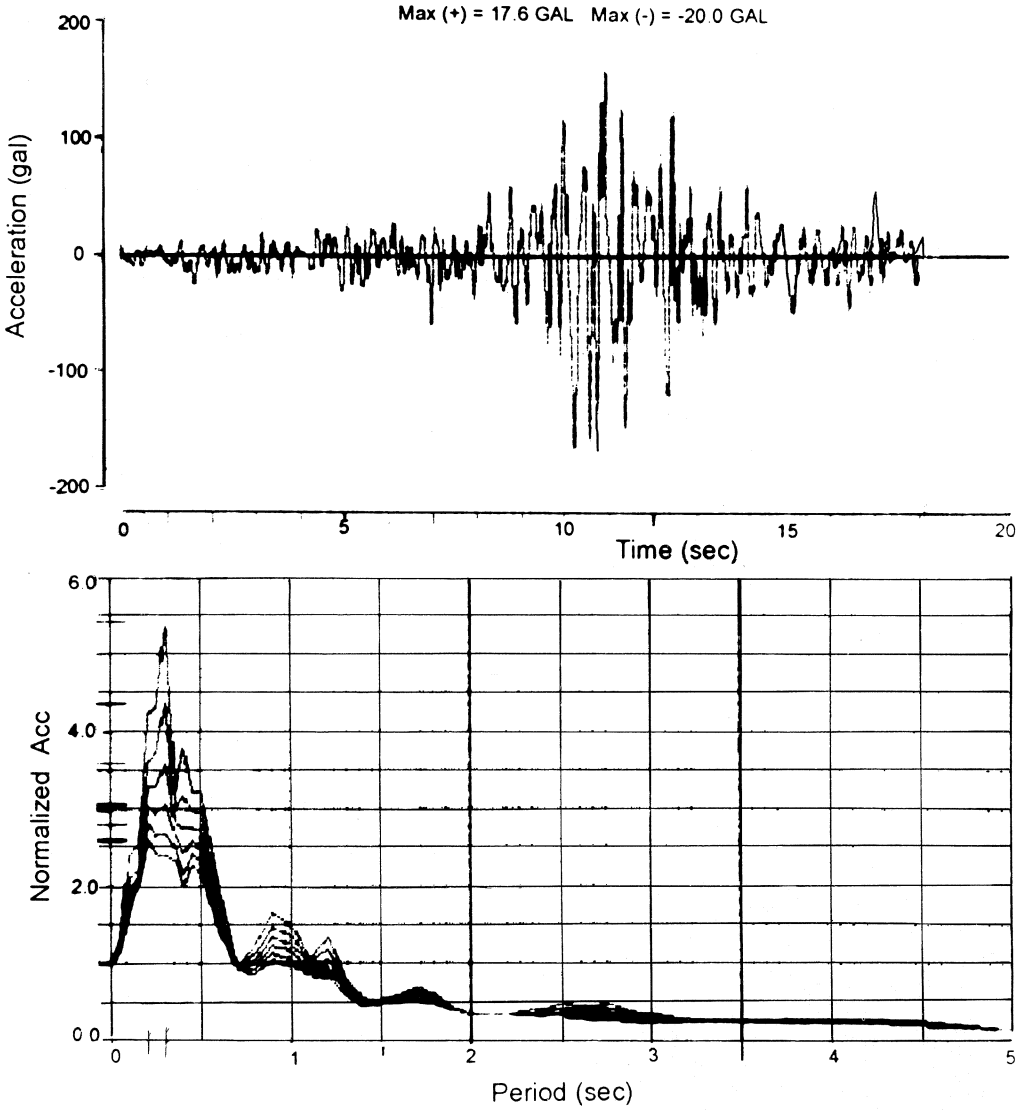

Fig. 22a. Records of the Spitak earthquake main shock and response spectra at the Houkassian station.

depict certain remarkable features of the main shock. It consisted of several movement portions with different periods and was noted for abnormally short duration compared to the motions recorded in Leninakan. Moreover, its frequency spectrum was shifted towards relatively higher frequencies. The mentioned peculiarities are often observed under strongly pronounced influence of local conditions (site effect).

As to the data of Borcherdt *et al.* (1989) peak accelerations recorded for the aftershocks are approximately 1.8 times greater in Leninakan than at hard rocks given the equal epicentral distances. Reasoning from the above, maximum peak accelerations, according to the accelerogram made in Houkassian, are estimated at 0.4 g.

3.8. *Site effect*

The great distinction between the destructions in Leninakan and Kirovakan is one of the Spitak earthquake mysteries. Although Kirovakan is closer to the earthquake instrumental source and the outcropped rupture part, the destruction in Leninakan appeared to be more significant than in Kirovakan given the same type of structures and construction quality in both cities.

This seemingly paradoxical fact invokes explanation in the comparison of geological cross-sections of the cities.

As seen from the data in fig. 23a,b Leninakan is situated in a wide valley composed of loose sedimentary material while Kirovakan is in a narrow valley surrounded by high mountains. As a result, the largest portion of the built over area in Kirovakan city is on hard rocks.

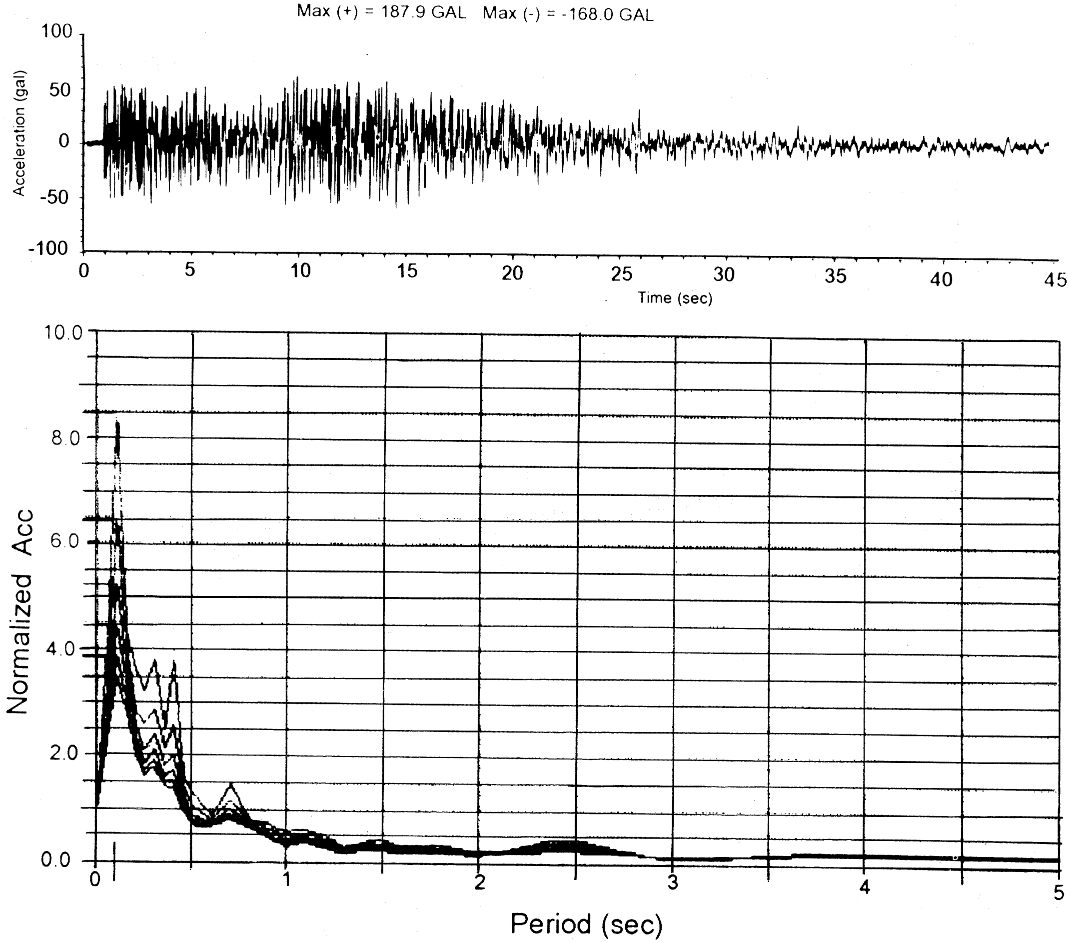

Fig. 22b. Records of the Spitak earthquake main shock and response spectra at the station in Yerevan.

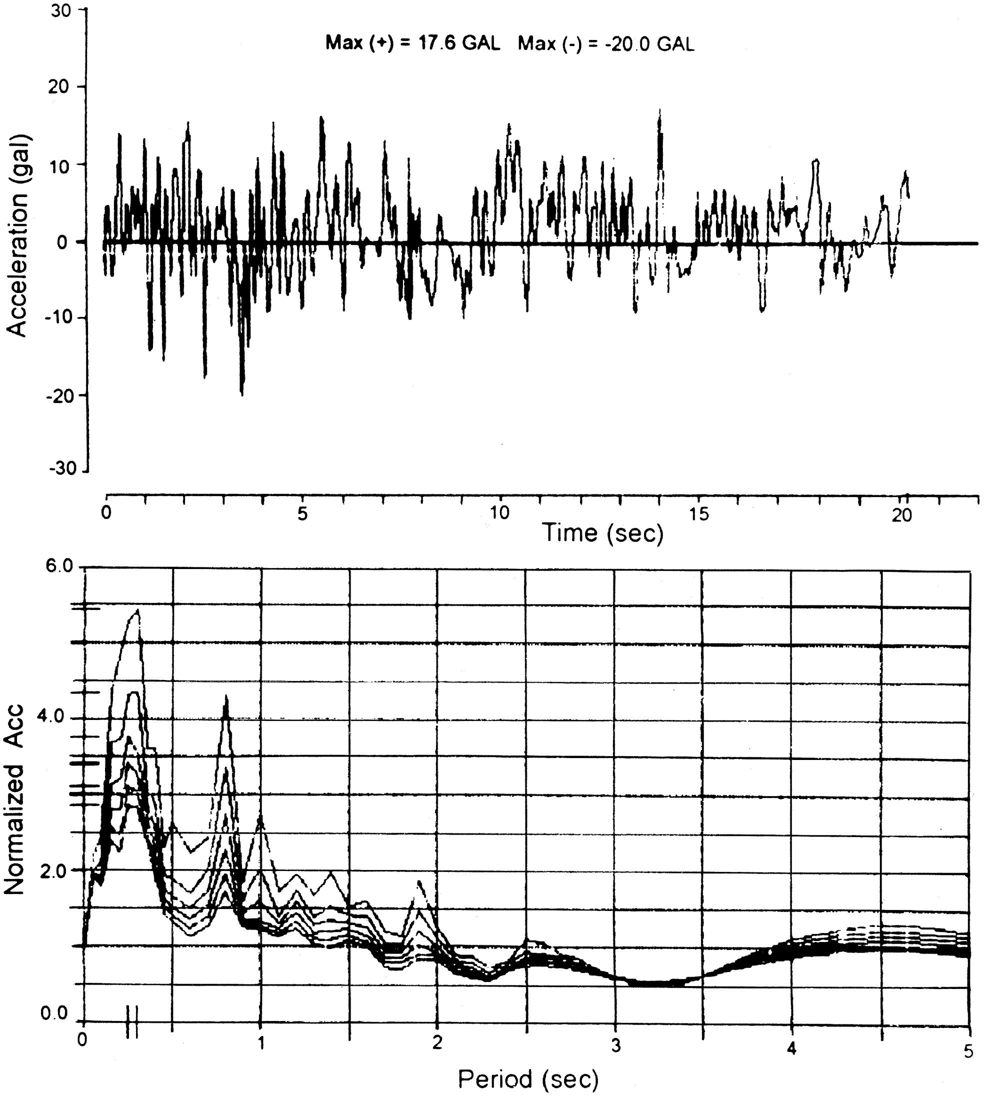

Fig. 22c. Records of the Spitak earthquake main shock and response spectra at the Metsamor observation site.

Figure 24 displays two records of an $M = 5.0$ aftershock that were obtained (Borcherdt *et al.*, 1993) at about the same distances (Δ) from the epicenter: in Leninakan ($\Delta = 24$ km) and Ketti settlement ($\Delta = 20$ km). The Leninakan record was made on sedimentary formations while in Ketti it was done on hard rock.

It is not difficult to note the significant acceleration of long period ground motions in Leninakan examining fig. 24. The effect is particularly well demonstrated in fig. 25 where the

Table III. Parameters of recorded strong motions during the main shock of the Spitak earthquake.

	R km	PGA gal	T_a s	$\tau_{0.5}$ s
Houkassian	35	188	0.2	5
Yerevan	80	62	0.1	25
Metsamor	80	20	0.25	20

relationships of the motion spectra are shown: horizontal component amplitude for 0.5-2 s periods increased up to 23-25 times on the sedimentary soils in Leninakan compared to that on hard rocks in Ketti (Borcherdt *et al.*, 1993).

From the above it is suggested that the local effect of ground motion amplification in Leninakan during the main shock at the cost of local geological conditions led to great destruction in the city as against the situation in

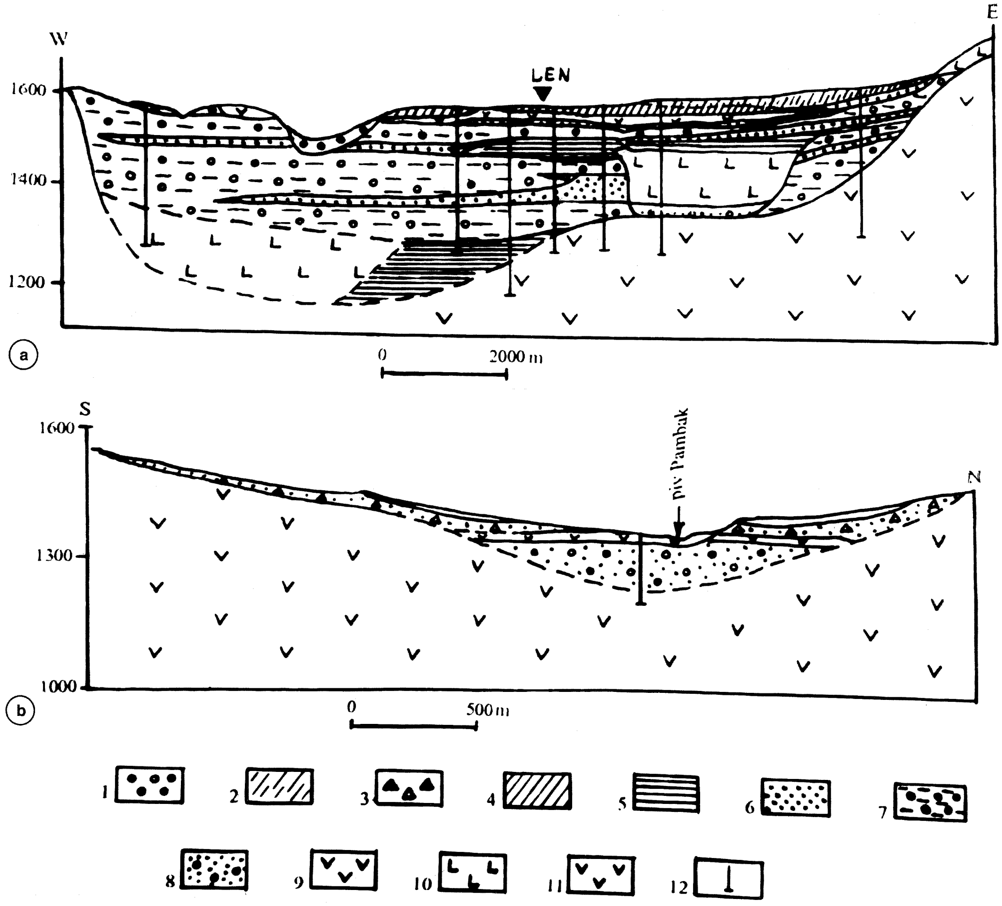

Fig. 23a,b. Geological cross-sections in the area of Leninakan (a) and Kirovakan (b) cities. 1 = Modern alluvial deposits; 2 = sand loam; 3 = gravel, broken stone, gruss with sand loam and loam aggregate; 4 = loams; 5 = clays; 6 = sands, sandstones; 7 = conglomerates, gravel, sands, clays (lakustrine); 8 = old alluvium of the paleo river bed of the Pambak river; 9 = tuffs; 10 = basalts, andesite-basalts; 11 = Eocene tuffs, tuffites, tufsands; 12 = boreholes.

Kirovakan and other populated areas located primarily on hard rocks.

Another phenomenon that again stemmed from the local geological conditions and contributed to the significant destruction is an unusually prolonged strong ground motion observed in Leninakan.

It is known that strong shakings caused by the main shock lasted for about 50 s according to the records made in Leninakan (fig. 15) and were accompanied by noticable ground motions of more that 1 min duration. The strong shakings from the aftershock followed 4 min 17 s after the main shock lasting for, approximately, 20 s and were attendant with marked ground motions of more than 40 s duration as well. So the total duration of strong motions comprised about 3-3.5 min with a 1.5-2 min interval.

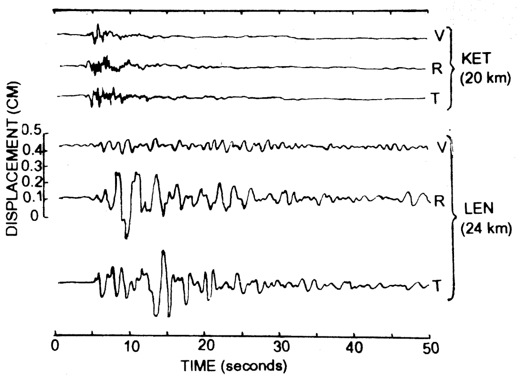

Fig. 24. Records of the $M = 5.0$ aftershock in the Leninakan city and Ketti settlement region (according to the data of Borcherdt *et al.*, 1993).

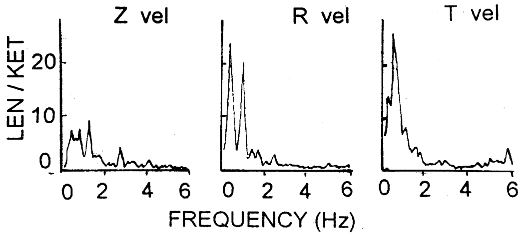

Fig. 25. Relationship of motion spectra recorded in the region of Leninakan city and Ketti settlement (Borcherdt *et al.*, 1993).

4. The macroseismic effect

The Spitak earthquake destructive effect was pronounced over an enormous area. The destruction area encompassed the 3 largest cities – Leninakan, Kirovakan and Spitak – amongst the total number of 21 towns and regional centers as well as more than 300 villages.

As seen from fig. 26 the 10-intensity and 9-intensity isoseisms which are 46 × 11 km and 77 × 30 km in size, respectively, spread NW and narrowed at the SE termination (Shebalin *et al.*, 1991; Geodakian *et al.*, 1991; Sobolev *et al.*, 1993).

The shape of 8-intensity isoseism is stretched in a near-latitudinal direction and covers an area of 116×65 km.

The isoseism dimensions and shapes reflect the focal depths and focal dimensions, motion type in the source, soil types as well as earthquake resistance of buildings and structures.

5. The destruction

The Spitak seismic event went down in the history of natural disasters as an earthquake whose parameters were not adequate to the tremendous scope of destruction.

The probability of an anologous disaster being repeated in the future depends on how correctly we are able to unravel the reasons of the Spitak catastrophe, *i.e.* to explain why the destruction was so great.

Besides the factors mentioned above – great duration of strong motions and amplification of the oscillations at the sedimentary formations of Leninakan – the resonance effect contributed badly to the collapse of buildings.

The data in fig. 25 show that periods of 0.5-2 s predominate in the ground motion frequency spectrum for the Leninakan region. In compliance with the calculations made by the

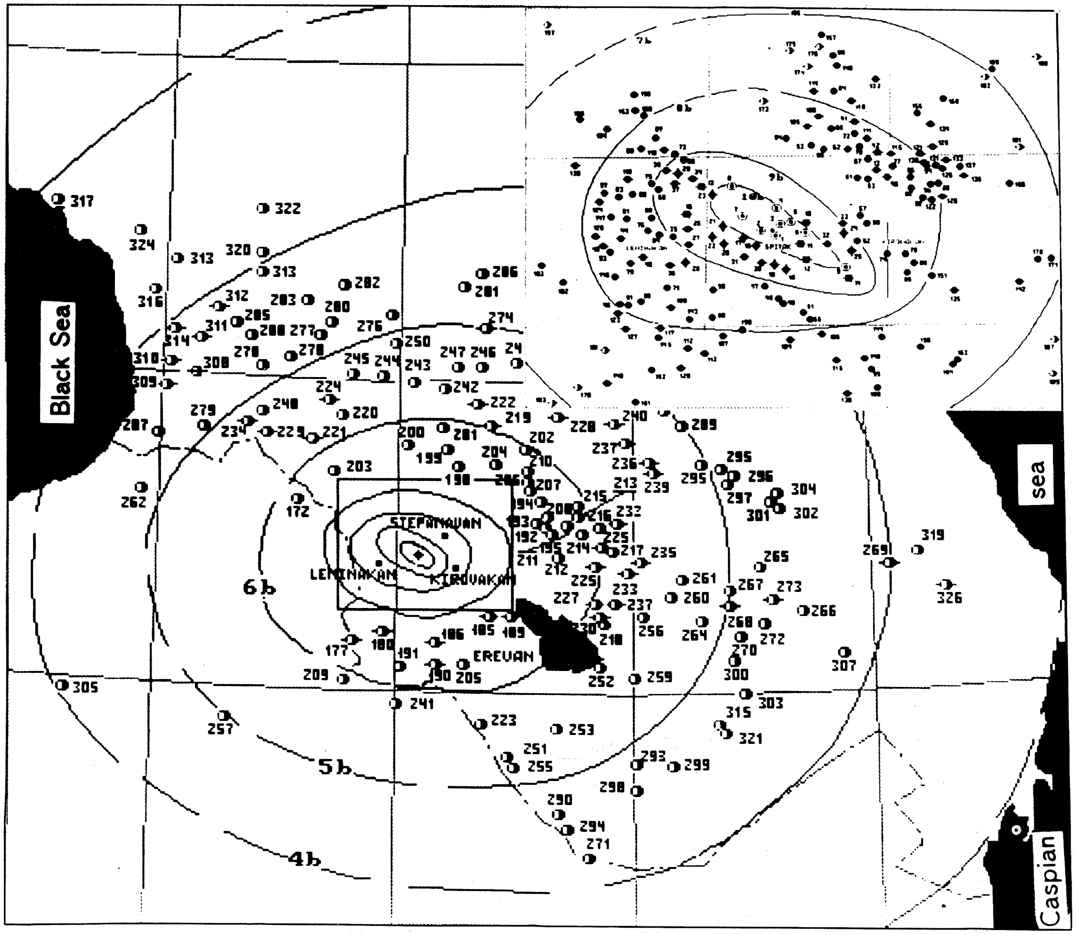

Fig. 26. The Spitak earthquake macroseismic effect (according to the data of Sobolev *et al.*, 1993).

specialists of the Earth Physics Institute, U.S.S.R. Academy of Sciences, (Aizenberg, 1989) the predominant ground motion periods strongly varied at the different sites in Leninakan and comprised 0.3; 0.6; 0.9 and 1.5 s. The Japanese specialists' measurements affirmed these data (Khachian and Melkoumian, 1989). The predominant period for the microseisms in northern and central parts of Leninakan was equal to 0.6 s according to their information. The same group measured natural oscillation periods for the main building types. As a result it was established that 9-storey frame-and-panel buildings in Leninakan display a natural oscillation period close to 0.6 s; the one for large-panel 9-storey buildings is equal to 0.35 s. This period is 0.3 s for the complex 5-storey stone buildings with reinforced concrete elements, while for stone and complex stone 1-4-storey buildings it comprises 0.1-0.2 s.

The analysis of the state of buildings in Leninakan after the 7 December, 1988 earthquake showed (Khachian and Melkoumian, 1989) that the 9-storey frame-and-panel buildings, *i.e.* the ones with natural oscillation period (0.6 s) coinciding with the ground motion predominant period (0.6 s), were damaged to a larger extent (89%) (fig. 27). It is particularly remarkable that this type buildings did not collapse in Kirovakan.

Therefore, the resonance effect in a «soil-structure» system again played a destructive role as was already noted for the earthquakes in Mexico (1957, 1962, 1985), Bucharest (1940, 1977) and other places.

The reasons listed above form a basis for the activities on seismic microzonation of cities. Unfortunately only now has it become apparent that this work had been poorly performed prior to the Spitak earthquake.

Other and even grosser errors existed in addition to the above:

- bad errors in the seismic zonation map, where the 10-intensity Spitak zone was indicated as a 7-intensity zone (fig. 27);
- code of earthquake proof construction that needed sufficient development;
- poor construction quality;
- poor quality of construction materials;
- infringement of maintenance rules in buildings and structures;
- lack of an adequate control over the earthquake resistant construction.

The errors related to the above were in a large part caused by the social and economic problems of society, while the ones of the seismic zonation map bore profound methodological and technological gaps as well.

Due to the errors in seismic zonation the structures corresponding to high Japanese building rules and standards collapsed in the Kobe earthquake ($M_S = 7.2$, January 16, 1995). That was a striking illustration of the latter conclusion.

Therefore, the gross errors in the Armenian seismic zonation map that manifested in underestimating the seismic hazard of the Spitak earthquake zone by 3 points of the MSK scale may be considered a major reason that would

Fig. 27. Destruction in the 10-intensity isoseism zone.

have led to mass destruction regardless of what the construction and construction code quality were.

6. Prompt response

The prompt response presents an important component of seismic risk reduction in seismically active zones. The Spitak tragedy showed that neither people nor the Government were prepared for a strong earthquake. And again it was the seismic hazard, underestimated in the territory of Armenia, that became a basis for that situation.

Due to the absence of special professional rescue teams and a rescue activity management system the main burden fell on the people who appeared near those buried under the ruined buildings during the first days after the earthquake. The rescue as well as other types of activities became more targetted as military divisions and special rescue teams from different countries became involved in the work.

7. The earthquake consequences

As a result of the 1988 Spitak earthquake 21 regional centers and towns and 342 villages were damaged; 515000 people lost their homes, 20000 people were severely injured and 25000 died.

The city of Spitak, 58 villages and 21000 houses were destroyed totally. The disaster area covered 3 million square meters. The operation of 170 industrial enterprises with 82000 work places stopped. Amongst the 8461 architectural and historical monuments of the zone 155 were destroyed totally, while 984 were damaged severely.

Particular damage was caused to schools and school-age children: 917 schools where 20000 pupils had studied and 22000 teachers worked were destroyed. Of the mentioned total number 190 schools collapsed and 6000 pupils were killed in them. The Spitak earthquake is one of the most tragic natural disasters of the 20th century.

8. Conclusions

The lessons of the Spitak earthquake are those related to seismic risk reduction. The risk is particularly high in the countries situated within seismically active zones and experiencing economic difficulties.

Accurate seismic hazard assessment forms a basis for seismic risk reduction. Only after this assessment is made do all the rest elements of risk reduction – from earthquake resistant construction to population training – become efficient. Correct seismic hazard assessment is a correct prediction of potential earthquakes. The most important stage in the prediction is represented by seismic zonation of a seismically hazardous zone.

The successful solution of the seismic risk problem is possible only through the concerted efforts of seismologists, geotechnical engineers, constructing engineers, urban planners, psychologists and sociologists, mass media, leading businessmen, leaders of executive and legislative authorities, authoritative international organisations, etc.

In a word, in so far as the community of the states situated in seismically active zones is totally exposed to seismic risk the problem should be solved by the community as a whole. In doing so, the efforts undertaken nationally should be supported by international level efforts. In our opinion, this is a sole key to a safe future.

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(received November 21, 1994;
accepted June 27, 1995)