The Spitak (Armenia) earthquake of 7 December 1988: field observations, seismology and tectonics

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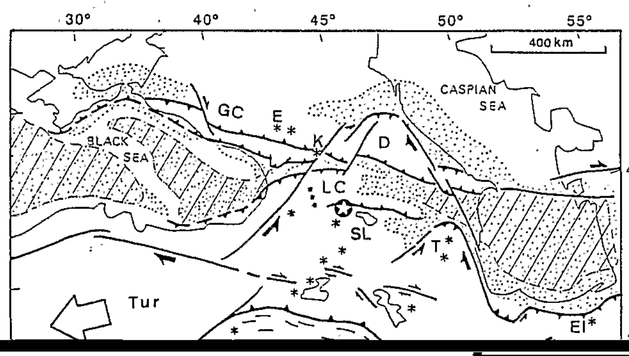
The epicentre of the destructive earthquake that devastated northern Armenia, the strongest in the region since historical times, is located within the Lesser Caucasus, a mountain country subjected to north-south compression by the push of the Arabian plate. A French-Soviet field expedition studied surface breaks and aftershock activity. The fault scarp could be followed for 13 kilometres and showed a reverse dislocation of 1.6 metres. Aftershocks are shallower than 13 kilometres, and delimit a ruptured surface of about 300 km^2.

A DESTRUCTIVE earthquake devastated the region around the cities of Spitak, Leninakan and Kirovakan in northern Soviet Armenia on December 7, 1988, at 07:41 UT (latitude 40.94° N, longitude 44.29° E, depth 10 km according to the US National Earthquake Information Center (NEIC); 41.15° N, 44.25° E after the Euro-Mediterranean Seismological Centre; 40.84° N, 44.32° E, depth 10 km using 19 local Soviet stations). Its magnitude was 7.0 according to the Seismological Centre of Obninsk[1], 6.9 according to NEIC and 6.7 according to the Institut de Physique du Globe de Strasbourg. This was the largest earthquake in this region since historical times. Official figures give 25,000 people dead, the city of Spitak being destroyed to 90%, Leninakan to 50% and Kirovakan to 20%. The maximum

between the northern front of the Arabian wedge and the Russian Platform.

The Lesser and Great Caucasus are located to the north of this region. Caucasian tectonics is characterized by reverse faulting and folding associated with large strike-slip faulting. Present and neogene tectonics of northern Armenia shows that north-south compression coexists with east-west extension related to recent volcanism along north-south-oriented normal faulting, and with the Borjomi-Kasbeg left-lateral strike-slip fault[3].

The earthquake fault belongs to the approximately east-west Sevan-Akera deep thrust zone, the old Tethys suture, which borders the Lesser Caucasus to the south, running along the northern border of the Sevan Lake and to the north of the Aragat volcano and volcanic plateau. The Pambak river runs along the fault zone, the structural disposition of its basins suggesting a right-lateral component of the motion across the fault.



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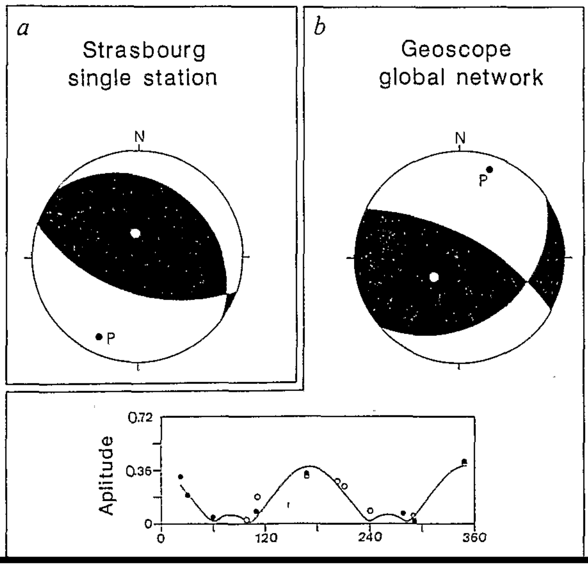
The main shock

The main shock was preceded by a foreshock of magnitude $M_L = 3$, on 6 December at 15:27, and was followed 4 min 20 s later by a large aftershock of magnitude $M_L = 5.8$ (ref. 1). Different focal mechanisms have been calculated by different groups, the first being obtained by the analysis of surface waves. Two days after the earthquake, a mechanism (Fig. 2*a*) was obtained[4] using Love and Rayleigh waves at periods ranging from 20 to 50 s (ref. 5). This result (azimuth = 309°, dip = 29° for the fault and slip vector = 107°) was conveyed to NEIC in Golden, Colorado, and to the Institute of Physics of the Earth in Moscow. The thrust component was shown clearly on this first solution, although there was no resolution of the horizontal component of the slip, and the half-depth of the source was found to be 7 km. A week later, the global Geoscope[6] network permitted a more constrained mechanism[7] to be obtained by using Rayleigh waves retrieved by dial-up teletransmission from eight stations at a longer period ($180 < T < 320$ s) and at a fixed depth of 10 km. Figure 2*b* shows this solution, which is remarkably close to what was observed in the field (azimuth = 299°, dip = 72° for the fault and slip vector = 135°). The residuals for the amplitude at different azimuths were small, and the phase was well explained except at those azimuths where rapid variations occur. The seismic moment was 1.6×10^{26} dyne cm for the single-station Strasbourg solution, and 2×10^{26} dyne cm for the Geoscope determination. With these values, the expected length of the fault should be of the order of 20 km if we estimate a mean slip of 2 m and a fault width of 15 km from field observations. Broad-band body-wave modelling, obtained four months later when the records became available, is shown in Fig. 2*c* (azimuth = 30°, dip = 60° for the fault plane and slip vector = 110°). The P and SH waves from broad-band and long-period stations, low-pass-filtered at 6 s, are well explained by two pulses, each with a duration of 3 s and a seismic moment of $\sim 0.4 \times 10^{26}$ dyne cm, separated in time by 12–16 s. A small precursor is needed to fit the beginning of the signal. Separation between the pulses is larger in the Chinese stations than in the African, European and American ones, suggesting that the rupture propagated from east to west.

Besides the tectonic evidence, we observed that focal mechanisms in the Caucasian region, those calculated by Jackson and McKenzie[8] for example, are compatible with a north–south compression. The mechanism of the Spitak earthquake thus gives new, high-quality additional information to confirm the general features of the tectonics of the region.



Surface breaks

Surface breaks oriented roughly 120° N have been observed

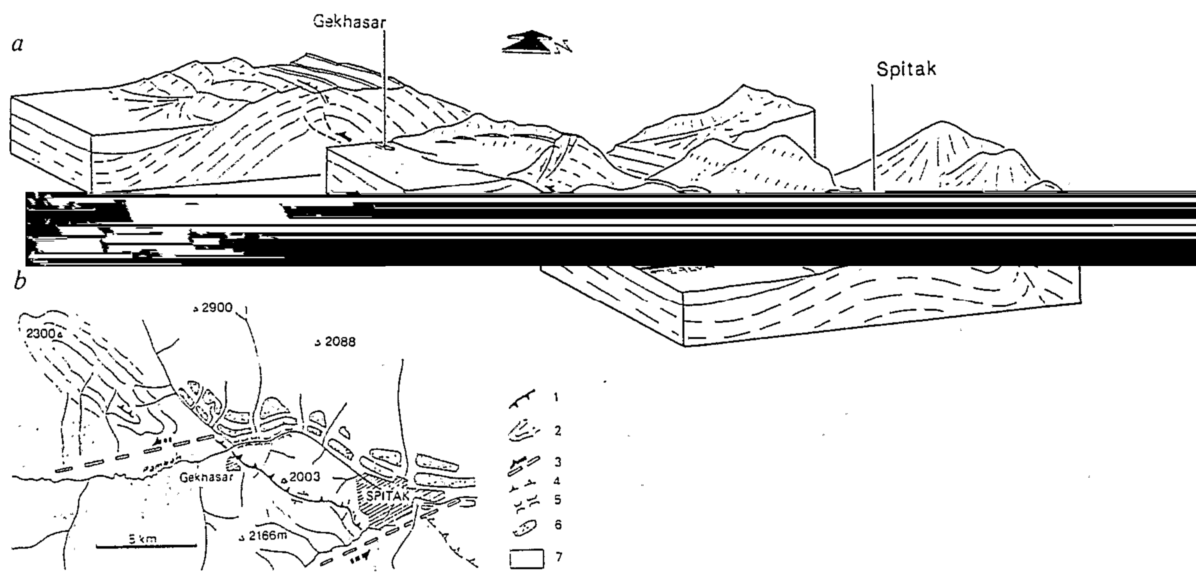


FIG. 3 Surface breaks and deformation related to the main shock. *a*, Block diagram showing surface ruptures between Spitak and Gekhasar and the fold to the west of Gekhasar. A geological fault exists to the east of Spitak but was not activated during the earthquake. *b*, Same as *a* but on the horizontal plane. High points are indicated, along with their elevation in metres. 1, Thrusts activated during the earthquake. 2, Layering within the anticline west-northwest of Gekhasar. 3, Inferred left-lateral strike-slip faults offsetting the segments of the thrust. 4, Thrusts not activated during the main shock. 5, Pambak river gorge. 6, Uplifted Quaternary terraces. 7, Quaternary sedimentary filling in subsiding valleys.

and upper Cretaceous limestones to the south). Therefore it is likely that the fault acted as a normal fault in the past, and that the motion later changed to reverse. The limestones are distorted and folded against the fault gauge at the contact, in agreement with the recent sense of motion (Fig. 3). There is no geomorphological evidence for a fault scarp along this geological contact. Nevertheless this fault has been an active thrust during Quaternary times, as indicated by the exposures along the road from Spitak to Leninakan, near Gekhasar. In fact, Quaternary volcanic tuffs and alluvial deposits are faulted and tilted near the fault trace. A further and more striking piece of evidence is the overall disposition of fluvial deposits on both sides of the fault. To the north of the fault trace, or its continuation, there is a system of well developed successive terraces that have been elevated and then eroded by the Pambak river and tributaries. On the other hand, south of the fault trace, the valleys are smoothly filled with sediments, swamps are present and no terraces are observed. This disposition indicates that during Quaternary times the southern compartment of the fault subsided but the northern one was uplifted. As this earthquake is the largest observed during historical times, it is certain that no conclusions regarding seismic hazard may be obtained from the historical record alone. It is then necessary to appeal to palaeoseismic studies to estimate maximum possible earthquake and recurrence times.

Aftershocks

A seismic network of 25 portable stations and 3 accelerometers was arrayed around the source region by the French team 10 days after the main shock (Fig. 5). The network, with a diameter of about 50 km, consisted of 10 MEQ analog recorders with L4C Mark Product seismometers, six Geostras digital three-component autonomous stations recording on magnetic tape, and a portable digital telemetric network, built in Strasbourg, with one three-component and eight vertical-component stations centred at Spitak.

Day-to-day location of the aftershocks was routinely performed during the field experiment together with magnitude determination and observation of other parameters of the seismic regime. In Fig. 5 we show the distribution of 259 well recorded aftershocks corresponding to the period from 22 December 1988 to 1 January 1989. The relative disposition of the events with respect to the surface deformations and breaks indicates that most of the activity is concentrated to the north of the surface scarps. The aftershock cloud is elongated along the trend of the fault. One notable feature is the very low level of activity

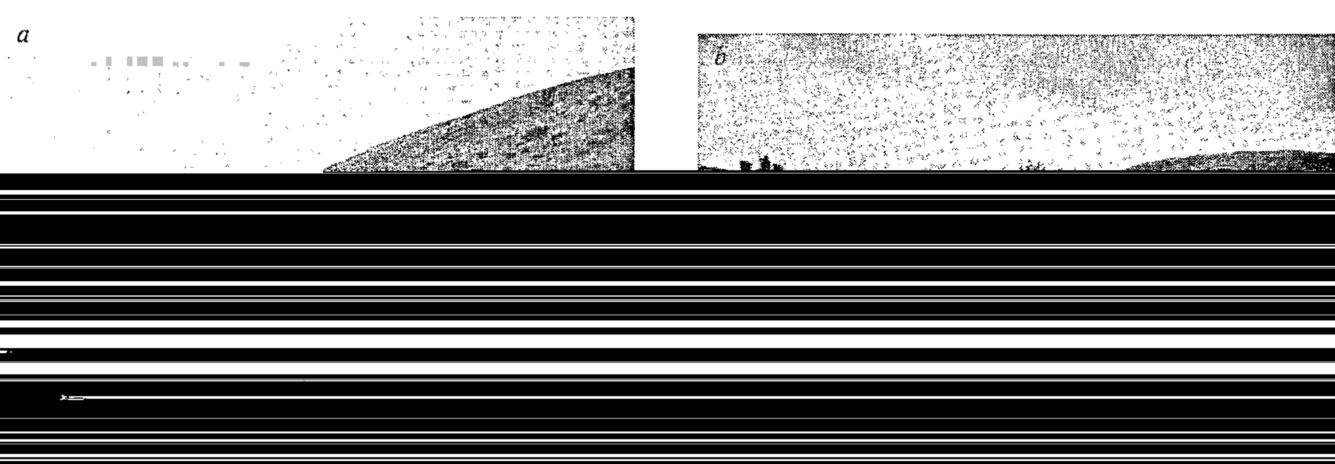


FIG. 4 Representative surface breaks looking towards the west. *a*, Pressure ridges on soil. Extension cracks indicate a right-lateral component of slip. *b*, Scarp in volcanic rock showing 1.6 m of reverse vertical offset. Bushes were burnt next to the fault trace, possibly because of escape and ignition of gases through tension cracks.

of magnitude 5.3 in 1911 and Leninakan was the site of an earthquake of magnitude 5.7 in 1926. Few seismologists believed that an earthquake as severe as that of 7 December 1988 was possible in this region. It is clear that seismic history alone is not sufficient to arrive at such conclusions. One way to improve the assessment of seismic hazard in this region, where continental collision is dominant and seismicity is confined to the crust, is to increase the knowledge of active faulting, for example by improvement of the permanent seismic network, neotectonic mapping of Quaternary deformation, analysis of aerial and satellite images, and the use of palaeoseismology in appropriate sites to give an insight into past activity.

Pattern-recognition analysis of earthquake-prone areas made by the Soviet group for events of magnitude $M > 6.5$ in Armenia classified as dangerous an object around Leninakan that included the epicentre of the 7 December Spitak earthquake[12]. Further study[13] established an object close to Erevan as being dangerous for earthquakes of magnitude $M > 7$. It is now recommended that this latter region also be subjected to short-term prediction studies, because a nuclear power plant is operational there. □

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Phosphorylation of RNA polymerase by