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Coseismic and postseismic displacements related with the 1997 earthquake sequence in Umbria-Marche (central Italy)

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Abstract. We study the coseismic and postseismic displacements related with the 1997 Umbria-Marche earthquake sequence by means of leveling lines along a deformed aqueduct located in the epicentral area. Comparing the 1960 and 10/1997 measurements we obtain 0.49 ±0.10 m of coseismic displacement distributed along 3 km across the normal fault zone. Modeling of the coseismic surface dislocation is obtained from a combination of low angle (38°) faults at depth and high angle (80°) upper fault branches. The best fit model indicates that the upper branches stop at 0.4 km below the ground surface and have 60% of slip with respect to the lower faults. The postseismic displacement measured during 1998 is 0.18 m and represents 36% of the apparent coseismic deformation. Moderate earthquakes in the Apennines and related surface deformation may thus result from curved faults that reflect the brittle-elastic properties of the uppermost crustal structures.

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Introduction

The 1997 Umbria-Marche earthquake sequence was characterized by two mainshocks on 09/26/97 (00:33 UT, Mw 5.7 and 09:40 UT, Mw 6.0), another mainshock on 10/14/97 (15:23 UT, Mw 5.6) and a long-lasting series of aftershocks (Plate1). The absence of surface ruptures during the two first mainshocks, seismic moments of the order of 10^{18} Nm and low-dipping normal fault planes inferred from CMT solutions suggest the existence of blind faulting (Basili et al., 1998; Ekström et al., 1998). The mainshocks and aftershocks distribution indicates a less than 10 km-thick seismogenic layer and delineates the hanging block with the sub-surface deformation. However, fault dimensions and accurate hypocentral depths provided by near field seismic records suggest that the fault ruptures were nearly emerging (Amato et al., 1998; Zollo et al., 1999; Barba & Basili, 2000).

The correlation between the seismic source at depth and earthquake deformation is problematic in the absence of clear surface faulting. Meghraoui et al. (1999) suggested that the seismogenic low-angle normal faults were controlled by pre-existing thrusts and branched at high-angle near the ground surface. Indeed, the analysis of DInSAR images (Stramondo et al. 1999) and GPS measurements (Hunstad et al., 1999) suggest that the ruptures stopped very close to the surface.

In this study we use four sets of leveling profiles measured along the path of an old aqueduct to derive the amount of coseismic and postseismic surface deformation. The profiles run above the top-edge of the two first mainshocks causative faults. A detailed record of the aqueduct water supply allows the direct correlation between the coseismic slip and the aqueduct deformation. The coseismic modeling suggests the fault geometry at shallow depth with regards to the near-surface blind faulting. Finally, we briefly discuss the implications that moderate earthquakes may have in the understanding of surface deformation patterns and tectonic processes in the Apennines.

Data collection

The Colfiorito aqueduct connects a spring at Fonte delle Mattinate (870 m a.s.l.) with the reservoir at Pizzale (825 m a.s.l.; Plate 1). Its pipe is embedded at an average of 1.5 m depth and runs for approximately 5 km along a NE-SW path nearly orthogonal to the main normal faults. The pipeline is made of several asbestos-cement units, 80 mm in diameter, connected with steel fittings. At the main connections, there are also valves mounted on the pipe to which maintenance shafts provide access. Two types of shaft linings are present: the original type, which date back to the 1960, and a more modern type which have been added or replaced after construction. The original shaft linings, made of masonry, are up to 3 m high, have a square base of ~1 m of side, and are covered with a rugged-steel lid. The new shaft linings are all made of concrete and have a side of 0.8m. The aqueduct is also equipped with a gauge at Pizzale that monitors the incoming delivery capacity (DC). Data are picked daily at 6:00 a.m., 7:00 p.m., and 12:00 p.m. (Figure 1). The average DC before the earthquakes used to be 2.0±0.2 l/sec. The spring supply is rather regular while the fluctuations are due to few users connected between the spring and the reservoir. Although this system was initially used to monitor water supply, it is also able to detect the occurrence of possible breaks of the pipe if leaking makes the DC substantially deviate from the average.

The DC record shows that the first mainshock (00:33 UT; Mw 5.7) caused no significant damage to the pipe. After the second mainshock (09:40 UT; Mw 6.0) the DC drops abruptly (Figure 1) and four main pipe breaks were detected: one close to shaft G and three close to shaft I (Figure 2). For one of these last breaks, a permanent offset of a few centimeters was recorded. Significant damage to the pipeline was also recorded after the 10/03/97 and 10/06/97 events, respectively Mw 5.2 and Mw 5.4. However, some leaking could have been caused by the overpressure generated by the prompt repairing which opened-up incipient breaks. The events of 10/12/97 and 10/14/97, respectively Mw 5.2 and Mw 5.6, caused no additional damage to the pipe since no leaking was observed.

To evaluate the amount of surface displacement we compare topographic data taken before and after the 1997 mainshocks. Pre-earthquake leveling data date back to the 1960 (S0). They have been retrieved from blueprints of the aqueduct deposited at the Bureau of Civil Engineering in Perugia which provided the elevation of the ground surface surrounding the shafts against distance along pipeline. Since most BMs of the old aqueduct were not removed, damaged or affected by any kind of repair, three post-earthquake leveling surveys have been carried out on 10/10/97 (S1); 02/19/98 (S2); 10/26/98 (S3) using a Topcon GTS 700 theodolite. These surveys provided measurement of the relative elevation of vertices positioned on both original and modern shaft-heads. Since the blueprints reported only the elevation of the ground surface, the height above ground of each reoccupied benchmark (BM) was also measured. However, few BMs could not be reoccupied because the shaft lining were demolished or removed mainly by land-owners after that a new pipe was laid in late December 1997 causing some loss of data (see notes in Table 1).

Neither the technique of the survey nor the instrumentation used in the 1960 was reported in the blueprints. However, the instrumentation available to engineers at that time was precise enough to allow an average vertical error of ±0.01 m, required for the aqueduct construction. Much less accurate, instead, could have been the measurement of the shaft-lining height above ground. For the BMs surrounded by very flat terrain we assumed an error of ±0.05 m; for those surrounded by a gently inclined surface the possibility of an error of ±0.10 m was taken into account; those located in very inclined ground or suspected to have been removed from the original position were rejected. However, the soil along the aqueduct is made of a succession of thin silt-clay layers and fine to coarse fluvial gravel units and did not show any visible sign of compaction or related phenomena. On the other hand, the ground level near the old aqueduct remained undisturbed after the earthquakes. The vertical error associated with the 1997-98 post-earthquake survey technique is ±0.01 m.

Coseismic and postseismic surface displacements obtained from the four set of measurements are reported in Table 1 and Figures 2a and 3. The coseismic displacement (Δco=S1-S0) describes an S-shaped curve with a maximum vertical separation of 0.49 m distributed along 1.5 km distance. Subsequent measurements indicate an early postseismic deformation (Δepo=S2-S1) with a reversed trend and an amount of 0.10 m of vertical separation. Late postseismic deformation (Δlpo=S3-S2) reversed again with a maximum of 0.22 m. The final postseismic vertical movement (Δpo=S3-S1) is of about 0.18 m which increased by the same amount both footwall uplift and hangingwall subsidence.

The vertical displacement recorded by the aqueduct shows a systematic pattern (positive and negative movements) which clearly separates the hangingwall from the footwall of the fault and attests for the reliability of measurements of the ground deformation.

Modeling of coseismic displacement

The available earthquake fault plane solutions (Ekström et al., 1998; Zollo et al., 1999; Hunstad et al., 1999) show that the two mainshocks of 26/09/97, ruptured two normal fault planes dipping 36-40° to the SW, with a small horizontal component of slip and with negligible transversal offset between one another (Barba & Basili, 2000). Therefore, we modeled the coseismic dislocation as pure dip-slip for simplicity. The low dip-angle of the two mainshock faults yields a displacement field at the surface that does not match nor the leveling measurements nor the neotectonic features. In fact, this model pattern has a larger amplitude (~10 km), a smaller vertical separation (~0.20 m) and is nearly symmetrical on the two sides. We then explored the possibility that the surface deformation may have been influenced by an upward propagation of the mainshock faults into much steeper branches. A 2-D solution from a classical dislocation model is proposed (Figure 2b) in which the mainshock faults (F1 and F2) are embedded in a uniform elastic half-space (L1) and the upper branches (F3 and F4) propagate into the overlaying layer (L2). L2 includes 800 m of modal topography. All fault patches are assumed planar with uniform slip. Elastic parameters (Lame's constants λ and μ) were derived from the crustal model by Mooney et al. (1998). Depths of the causative faults are from Barba & Basili (2000), while dip, average slip and width are from Zollo et al. (1999). The coseismic displacement was modeled using the RNGCHN program by Feigl & Dupré (1999) which follows the formulation by Okada (1985). Vertical and horizontal surface displacements are assumed to tend to 0 at ∞.

A forward modeling procedure was performed by varying only the width of the upper fault branches between 3.4-4.0 km (i.e. top edge about 0.2-0.8 km below ground) and the amount of slip between 50-100% of the average slip at depth. The dip was kept fixed at 80° according to location of maximum deformation along the aqueduct. A summary of model parameters is reported in Table 2. The modeling results are shown in Figure 2a. The best-fit model (see inset) suggests that the upper branches have the top at 0.4 km depth and an amount of slip of 60% of the average slip on the deeper faults. Residuals between the measured displacement and the model may either result from benchmark measurement errors that unpredictably exceed those inherent in the survey procedure or be generated by a more complex geometry of secondary ruptures at shallow depths.

Discussion

One of the main observations of the leveling survey is that the maximum coseismic displacement was found in coincidence with the pipe breaks (Figure 2). Indeed, most of it directly correlates with the second mainshock of 09/26/97 (09:40 UT), because the pipe broke only after this event. The total amount of coseismic displacement (0.49 m), however, includes a significant contribution from the first mainshock (00:33 UT). Another contribution (few cm?) to the total displacement may also come from the events of 10/03-06/1997 which both occurred before the leveling survey. In fact, these events are located quite close to the leveling line and caused further damage to the pipe (Figure 1). In addition, considering the date of pre-earthquake leveling (1960), the contribution of a considerable amount of displacement may come from pre-seismic slip. Indeed, De Martini & Valensise (1999) studied the elevation changes of the 1951-1992 period, along a leveling line that crosses the active zone further north of the epicentral area, and observed 0.025 m of subsidence.

Early postseismic deformation (0.1 m) shows a reversed movement followed by an increase of the total displacement (0.18 m). Such a reversed trend was also observed in other moderate earthquakes (e.g.: the 1979 Homestead Valley earthquake, Ms 5.6; Stein & Lisowsky, 1983) and may correspond to relaxation movements that follow the coseismic slip. Cumulative coseismic and postseismic displacements present comparable curves with a ratio of 36%. This ratio could reflect a combination of two phenomena: an important visco-elastic deformation of the uppermost rock layers and postseismic slip related with the long sequence of aftershocks.

Regarding the results of coseismic modeling, it is worth noting that previous models obtained from GPS and SAR interferometry also refer to a low-angle fault plane and infer a coseismic surface deformation comparable to our results (Hunstad et al., 1999; Stramondo et al., 1999). However our modeling approach suggests that the surface displacement may be explained by rather deeper low-angle main faults that branch upward, at least locally, at a steeper angle. Salvi et al. (2000) proposed a similar solution to the displacement pattern observed in the area of the 10/14/1997, Mw 5.6, event which agrees field observations of tectonic ruptures (Basili et al., 1998) and suggest that the causative fault may be curved.

Although steepening-upward and puzzling branched normal faults are quite common both in field examples and in seismic reflection profiles, their occurrence as earthquake faults is much less documented. However, this fault geometry seems to develop into multi-layer media with different mechanical properties causing the narrowing of the deformation zone at the ground surface (Liu & Hagman, 1978; Withjack et al., 1990; Bray et al., 1994).

The complex structural architecture of the Apennine mountain belt and related topography inherited from older tectonic episodes may hidden the surface deformation. However, moderate earthquakes contribute to the crustal deformation and seismic strain release which can be measured along small faults at the ground surface. The identification of such small faults capable of producing moderate earthquakes is decisive for a better assessment of the seismic hazard in central Italy.

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Table 1. Coseismic and postseismic displacements.

BM	Dist	Δco	Δepo	Δlpo	Δpo	Notes
A	5.80	-0.230	0.021	-0.097	-0.076	
B	5.98	-0.360	0.057	-0.098	-0.041	
C	6.05	-0.327	0.058	-0.156	-0.098	
D	6.21	--	0.035	-0.085	-0.050	(1)
E	6.32	--	0.036	--	--	(3)
F	6.39	--	--	--	--	(1); (3)
G	6.45	-0.205	0.033	-0.057	-0.024	
H	7.11	0.131	-0.021	0.036	0.015	
I	7.58	0.063	-0.048	0.053	0.005	
J	7.75	--	0.018	0.050	0.068	(2)
K	8.12	0.088	-0.045	--	--	(3)
L	8.34	--	-0.036	0.124	0.088	(1)
M	8.41	0.012	-0.018	--	--	(3)
N	8.65	-0.040	-0.002	--	--	(3)
O	8.79	--	--	--	--	(4)
P	8.81	--	-0.011	0.114	0.103	(2)

Distance in km; displacements in m. Notes: (1) added after 1960; (2) moved after 1960; (3) demolished after Feb 1998; (4) demolished before 1997.

Table 2. Model parameters.

Fault/ Layer	λ GPa	μ GPa	Depth km	Dip deg	Slip m	Width km
F1/L1	17	34	8.8	38	0.370	7.5
F2/L1	17	34	7.8	38	0.380	6
F3/L2	10.5	21	4.2	80	0.370-0.185	4-3.4
F4/L2	10.5	21	4.2	80	0.380-0.190	4-3.4

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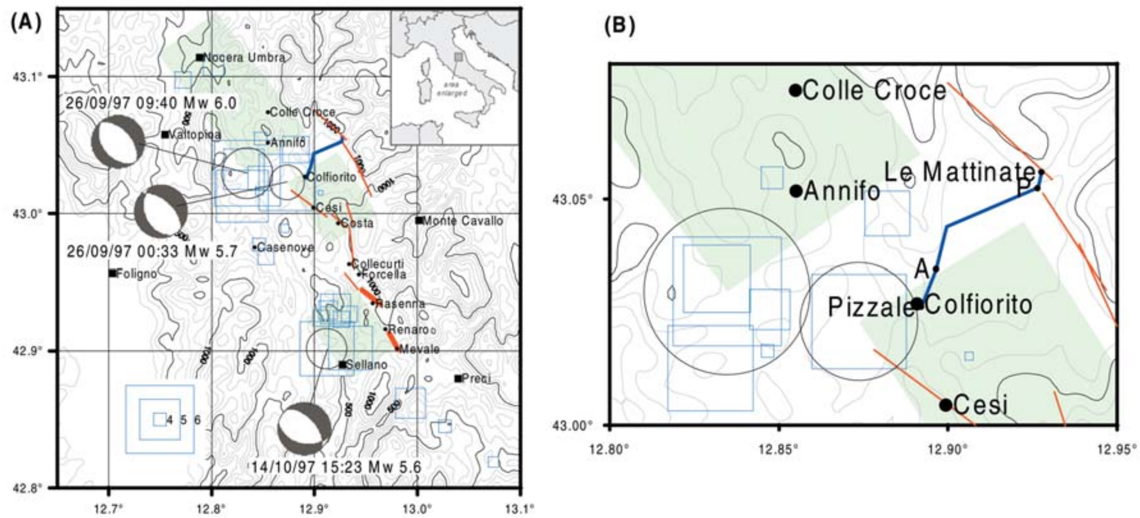

Plate 1. Location of aqueduct (blue line). Distribution of M>4 earthquakes (blue squares) and projection to surface of the mainshocks fault planes (green rectangles) along with location horizontal error (black circles) from Barba & Basili (2000). CMT solutions from Ekström et al. (1998). Main normal faults (thin red lines) and surface ruptures correlated with the 10/14/97 earthquake (bold red lines) from Basili et al. (1998).

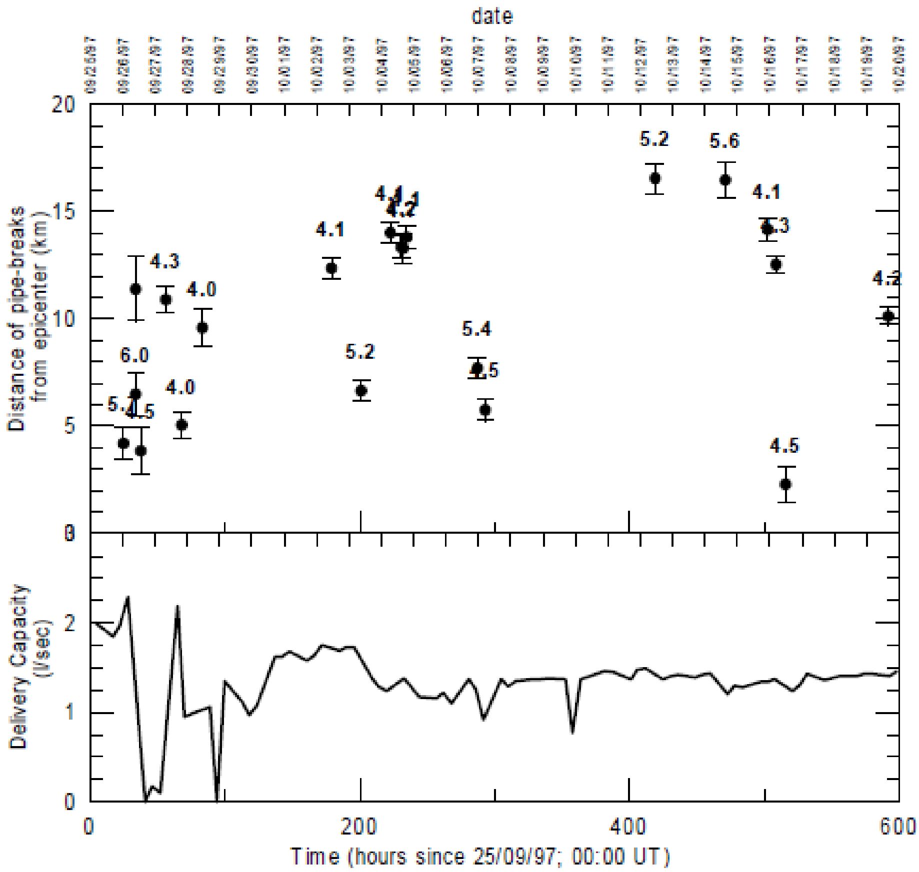

Figure 1. Delivery Capacity (l/sec) measured between 09/25 and 10/20/1997 (lower panel) and relative distance of earthquake epicenters from the pipe breaks (upper panel); Mw values are also indicated.

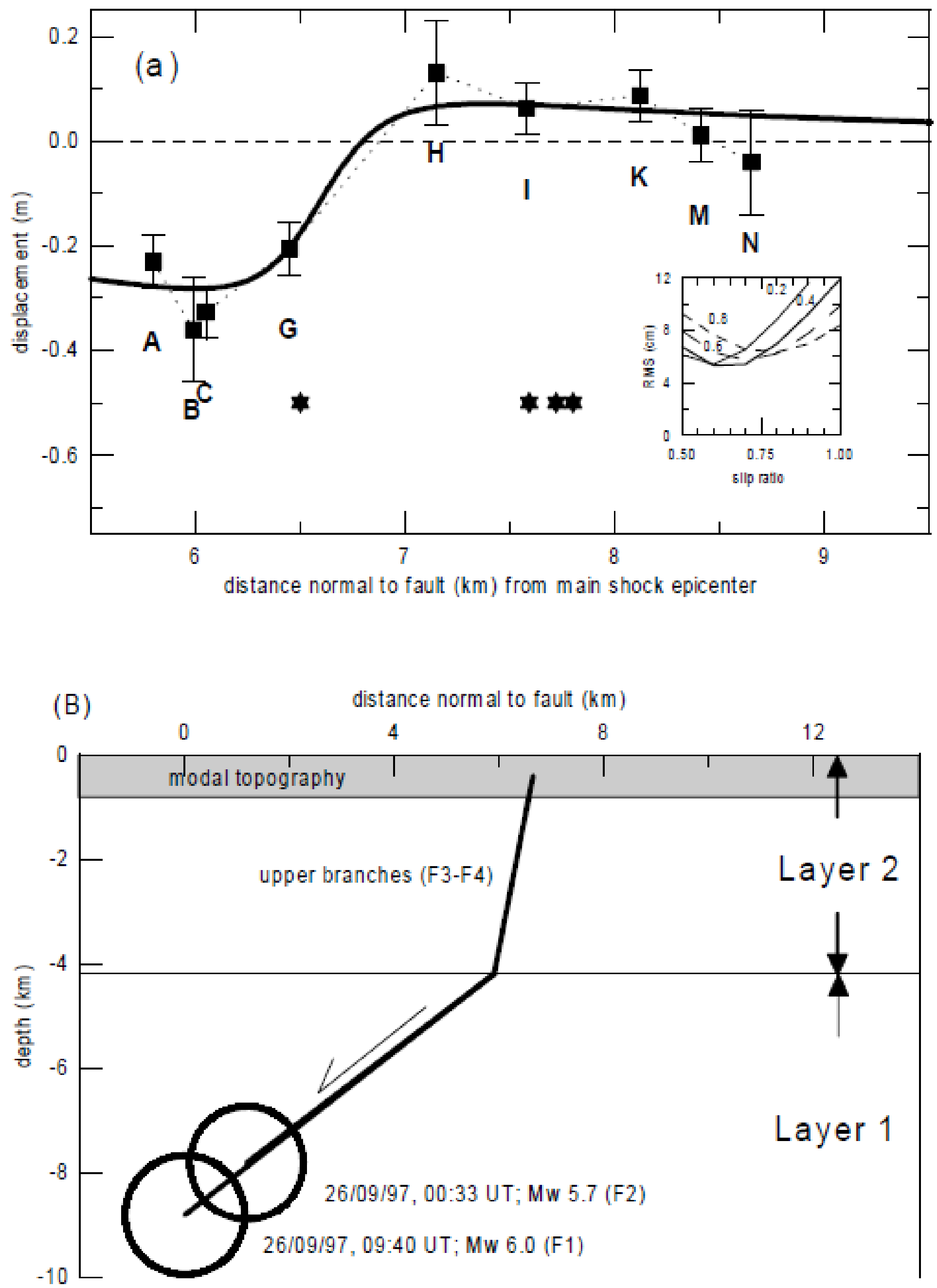

Figure 2. (a) Displacement at the aqueduct benchmarks reoccupied on 10/10/97 (squares) and best-fit model (bold line). Stars indicate location of the main pipe breaks. RMS vs. slip ratio for different trial depths of fault tip (inset); (b) Sketch of the adopted model, see also Table 2 for more details.

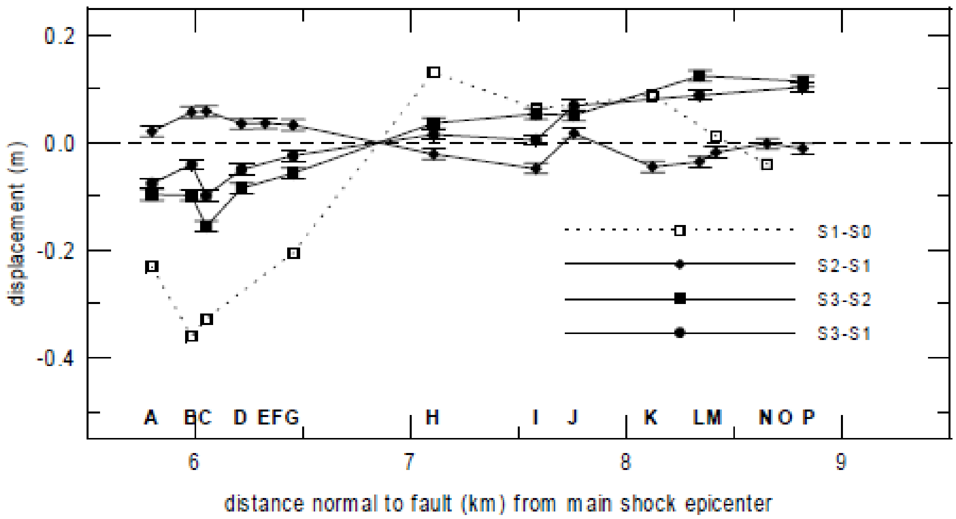

Figure 3. Post-earthquake relative elevation changes across the fault zone. S0, S1, S2, and S3 refer respectively to 1960, 10/10/1997, 02/19/1998, and 10/26/1998 surveys.