Fault movement (afterslip) following the Guatemala earthquake of February 4, 1976

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ABSTRACT

Field studies of surface faulting associated with the Guatemala earthquake of February 4, 1976, have documented the occurrence of afterslip at seven locations along the 230 km of surface rupture. The total displacement across the fault as measured in April 1976 averaged 110 cm. Displacement at one location increased from 60 cm on February 8, 1976, to 91 cm on October 6, 1977. Afterslip time histories determined at three sites show the afterslip to be proportional to the logarithm of time since the earthquake, and that the rate of afterslip is inversely related to the amount of displacement at a site. The regular variation in total slip and afterslip along about 50 km of the fault trace suggests that the afterslip is not controlled by local, near-surface geologic factors such as alluvial cover.

Figure 1. (A) View north along Highway CA-10 near Zacapa showing drainage ditch offset by 60-cm left-lateral and 5-cm south-side-down displacement on the Motagua fault, February 8, 1976. Black line drawn on north side of offset is aligned with the upper inside edge of the section of ditch in the foreground.

(B) View from same point as Figure 1A, taken on October 6, 1977. Afterslip during the time interval February 8, 1976, to October 6, 1977 amounted to 31 cm at this locality. Black line has same alignment as in Figure 1A.

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The 230-km surface rupture along the Motagua fault, produced during the Guatemala earthquake of February 4, 1976, is the longest in the western hemisphere since the 1906 California earthquake. Left-lateral horizontal displacement across the fault averaged about 1.1 m over the 230 km. The first field measurements of the displacement were made by Plafker and others (1976) within a few days following the earthquake at about a dozen widely spaced locations along the fault. Some of those were remeasured and more closely spaced additional measurements were made during follow-up studies in April and May 1976. Comparison of the April and May measurements at several locations with the earlier measurements showed that left-lateral movement on the fault was continuing, resulting in as much as a 42% increase in the initially measured displacement (Figs. 1A, 1B). Afterslip on a fault following an earthquake has been documented for many earthquakes, notably the Borrego Mountain, California earthquake of 1968 (Burford, 1972) and the Parkfield, California earthquake of 1966 (Wallace and Roth, 1967; Smith and Wyss, 1968). Additional examples are tabulated by Bonilla (1970, p. 61).

By early October 1977, we had documented afterslip at eight locations along the Motagua fault (Fig. 2); data on the variation in amount of afterslip with time are available for three of those locations (Fig. 3 and Table 1).

Locations where afterslip has been observed are distributed along nearly the entire length of the fault. The total amount of afterslip varies widely along the fault, as does its proportion of the total slip at a site. The smaller amounts of afterslip are near the limit of precision of some of the measurements, commonly made by visual alignment of offset barbed wire fences, building foundations, and other cultural features.

The amounts of afterslip shown on Figure 2A, which range between 4 and 12 cm, represent the slip occurring between late April and late October 1976. The total afterslip occurring since the first measurements of displacement produced by the earthquake were made is known to be much greater at some locations. For example, 31 cm have been measured at the Zacapa Highway site. Reference marks in the area of maximum slip near the west end of the fault were not suitable for an accurate determination of afterslip. However, measurements made there in April 1976 and October 1977 show that afterslip, if any, during that period was less than about 10 cm.

No instruments to record afterslip were installed. However, at three locations from Gualán to Marmol, well-defined reference points were readily accessible and were measured over a 20-month period providing a general picture of the time history of afterslip. These three sites are located along a segment of the fault trace where there is a conspicuously regular change in displacement with position along the fault (Fig. 2B). The regularity suggests that the fault segment might have behaved generally as a unit during the period of seismic slip and subsequent afterslip.

Afterslip time histories for the sites of Gualán, Zacapa, and Marmol are shown in Figure 3. The displacement at each site is approximately proportional to log T (where T is time in days since the earthquake). Standard deviations of displacement on log T for least-squares regression of the data are 1 cm or less and are of the size expected for the noninstrumental methods of measurement. Slip rates (in mm/day) at time T after the earthquake are $37/T$ at Gualán, $60/T$ at Zacapa, and $69/T$ at Marmol. There is an inverse relationship between the total displacement (coseismic slip plus afterslip) and the rate of afterslip at a site; the largest total displacement (Gualán) is associated with the lowest rate of afterslip, and the smallest total displacement (Marmol) is associated with the highest rate of afterslip. This relationship is of a form that would equalize variations in displacement along the fault, although at the observed rates the time required would be quite long. For example, there would only be a 53% reduction in the 41-cm variation in displacement between the Gualán and Mar-

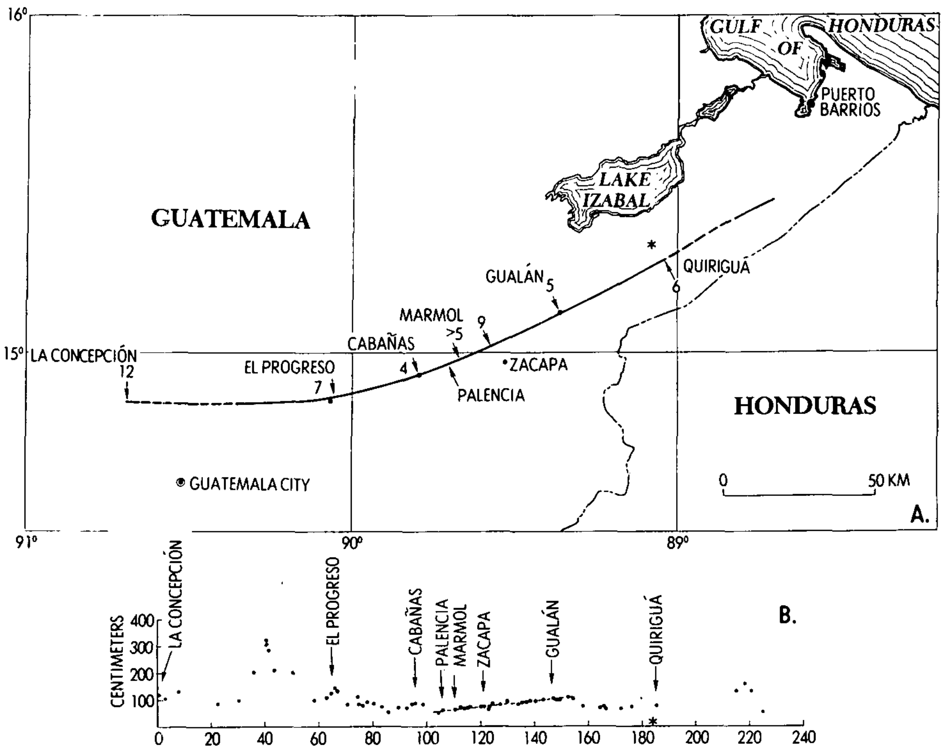

Figure 2. (A) Locations of afterslip measurements along zone of surface breakage (solid line) on the Motagua fault. Afterslip values (in centimetres) are for the period May to October, 1976. (B) Total displacement across the fault as measured in April 1976. Epicenter shown by asterisk.

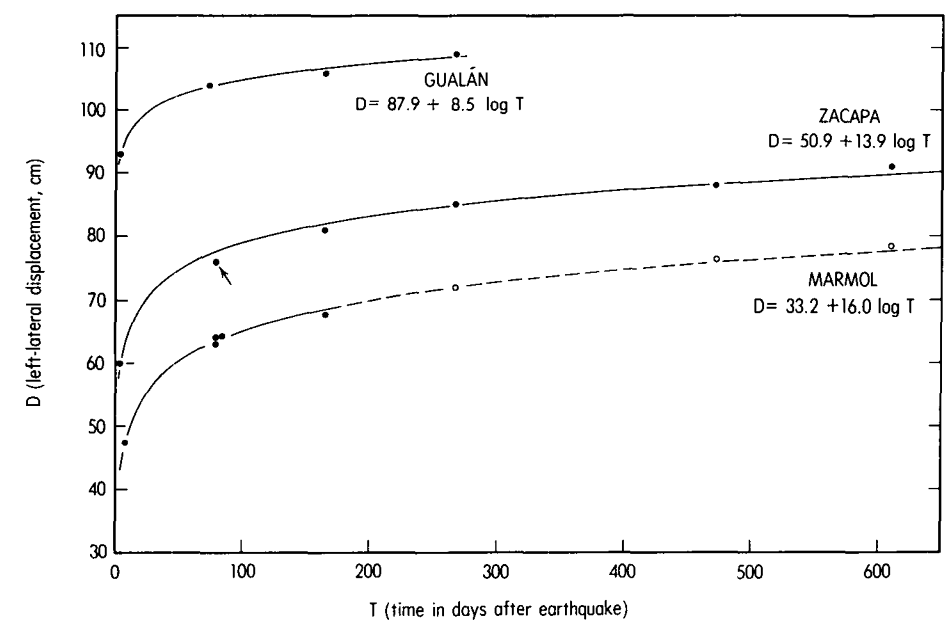

Figure 3. Variation of total amount of left-lateral slip with time in the central part of the Motagua fault. See Figure 2 for location of measurement sites. Equations are based on least-squares regression of observed displacement on logarithm of time since the earthquake. The reference used for measurement at the Marmol site was destroyed in August 1976, which resulted in a gap in the data. The open circle symbols for the site refer to measurements using monuments installed October 28; the total displacement on that date was assumed to lie on the least-squares curve derived from the earlier data. Arrow on the Zacapa site curve refers to corresponding observation of Figure 4.

mol sites in 160 yr, a period estimated by Plafker (1976) to be the minimum recurrence interval for earthquakes on the Motagua fault with lateral displacement comparable to that of the 1976 event.

Although the long-term slip-rate curves are quite regular, there is some evidence that significant temporal variations in the rate of afterslip did occur. During field studies in May and April 1976, a quadrilateral monument array several metres on each side and spanning the fault trace was installed about 500 m east of the Zacapa Highway site. The quadrilateral was measured to the nearest 0.5 mm with a steel tape, allowing measurement of changes occurring there during a 10-day period in April. The measurements showed a rate of slip of 1.4 mm/day (Fig. 4) during that interval compared with the average rate for the same period from the long-term measurements at the nearby Zacapa Highway site of 0.8 mm/day. Remeasurement of the quadrilateral in late October showed that long-term changes closely corresponded to those at the Highway site. The significant changes in rate indicate possible short-term displacement surges or episodic afterslip activity similar to that observed on the San Andreas fault in central California (Burford and others, 1973).

A steplike increase in fault displacement associated with an aftershock was observed at one site. Within several minutes of measuring the total displacement at the Marmol site on April 23, 1976, a sudden left-lateral slip of the broken, displaced wall of a concrete irrigation canal crossing

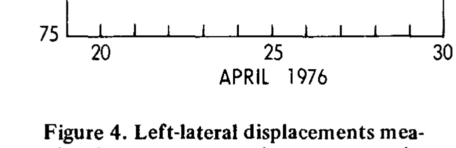

Figure 4. Left-lateral displacements measured at 2-m square surveying array spanning the Motagua fault northwest of Zacapa (see Fig. 2). Dashed line is the average slip during the observation period April 19, 1976 to April 29, 1976–average slip rate = 1.4 mm/day. Solid line is a least-squares fit to the long-term data at the nearby Zacapa Highway site (Fig. 3)–average long-term slip rate = 0.8 mm/day. Arrow refers to corresponding observation of Figure 3.

the fault was observed during the shaking accompanying a small aftershock. The shock was not recorded in Guatemala City and was probably less than magnitude 3 on the Richter scale (D. H. Harlow, 1976, oral commun.). Remeasurement after the shaking stopped showed that a 1.1-cm slip had occurred at the irrigation canal as well as at another previously measured site in a field a few tens of metres away. Measurements in the five days following the slip event showed only 1.5-mm additional slip—less than the 4.0 mm expected from the average rate based on long-term measurements. This is in contrast to the observations of Smith and Wyss (1968) who found four 6-day intervals of rapid creep following local aftershocks of the 1966 Parkfield earthquake. The slip associated with the aftershock did not appear at the Zacapa Highway site 10 km to the east. The quadrilateral at Zacapa Highway had been measured the morning of the aftershock. It was remeasured the following morning; a 1.5-mm slip had occurred, an amount consistent with the 1.4 mm/day average rate for late April.

Several studies of afterslip in California (Smith and Wyss, 1968; Burford, 1972) have led to the conclusion that a significant component of afterslip is due to the presence of relatively thick sections of alluvium (0.5 to 3 km thick) that attenuate and delay the upward propagation of seismic displacement from the underlying bedrock. The three sites in the Motagua Valley for which we have afterslip history data are on poorly consolidated Quaternary alluvium estimated to be less than 100 m thick (D. P. Schwarz, 1977, oral commun.). The contribution of such a thin veneer of alluvium to the mechanism of afterslip should be minimal in this case. Also, the regular variation in total slip and the inverse relationship that we observed between total slip and afterslip along about 50 km of the fault trace suggests to us that afterslip on the Motagua fault involves some process that affects large areas of the fault surface and is not controlled by local, near-surface geologic factors such as alluvial cover.

A more general mechanism of afterslip proposed by Scholz and others (1969) is more consistent with the Guatemala data. Based on their study of the Parkfield earthquake, they suggested that creep (afterslip) occurred by stable frictional sliding in a 4-km thick surface layer that they felt probably did not correspond to a geologic layer. Unfortunately, however, no geodetic data are available from Guatemala to help define the depth to which creep extends along the Motagua fault.

Table 1. Afterslip data, Motagua fault, Guatemala. Locations shown on Figure 2.

Location	Reference used and remarks	Days after earthquake	Measured total slip (cm)	Measured afterslip (cm)
Finca La Concepción	Rows of small coffee trees	79	120	
		271	132	
El Progresso	Cactus fence	4	104	
		269	111	
Cabañas	Wall of house	72	88	
		267	92	
Finca Palencia	Array of alined monuments installed 30 October 1976. Measurement of total slip made 1 km to the east.	73	62	
		269		0
		[2]472		3.8
		610		5.2
Marmol	Broken concrete-lined canal. Temporary concrete patches dated 12 February 1976 allow determination of afterslip subsequent to that date. Total slip based on measurements in a fissure in field adjacent to canal. Patched section removed and relined 20 August 76 destroying reference marks.	8		0
		79	63	15.6
		80		16.7
		83		16.7
		84		16.9
		[1]165		20.5
	Array of alined monuments installed 70 m to the east 28 October 1976.	267		0
		[2]473		4.4
		610		6.5
Zacapa	(a) Offset concrete-lined drainage ditch (see Figures 1a and 1b). Nails alined with edge of ditch on 8 February 1976 used for subsequent measurements.	4	60	0
		79		16
		[1]165		21
		267		25
		[2]472		28
		610		31
	(b) Quadrilateral array of nails across fault at a point 0.5 km E of a). Only afterslip measured at this array. Measurements of total slip on fissures near the array and at highway all consistent within several cm. Value of total offset measured at highway used for scale for Figure 4.	75		0
		79		0.30
		80		0.45
		85		1.35
		267		8.90
Gualán	Concrete-lined canal.	4	93	
		74	104	
		[1]165	106	
		268	109	
Quirigua	Steel fence.	74	80	
		268	86	
		[2]474	90	

[1]Measurements by R. A. Page, M. G. Bonilla, and S. B. Bonis.

[2]Measurements by C. J. Langer and R. F. Henrisey.

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