FALLAMIENTO SUPERFICIAL Y DESPLAZAMIENTOS A LO LARGO DE

LA FALLA DEL MOTAGUA DESPUES DEL TERREMOTO DE GUATEMALA

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RESUMEN

La mayor parte de los 230 km de rajadura superficial producida por el terremoto de Guatemala del 4 de Febrero de 1976 sigue una zona de características geomorfológicas a lo largo de la falla del Motagua, que es típica de las grandes fallas con desplazamiento horizontal. Las características incluyen lechos de arroyo desplazados, charcas creadas por hundimiento, manantiales, cerros bajos y alargados.

Estas características estan generalmente ausentes a lo largo de 70 km en la parte oeste de la falla, indicando posiblemente con eso que es una rama mas recientemente activada dentro del sistema de falla del Motagua. El mapeo detallado de la superficie de ruptura se concentró en una relación descriptiva de las rupturas superficiales, variaciones cuantitativas en desplazamiento a lo largo de la falla, y medida de desplazamientos producidos después del terremoto.

Las rupturas superficiales en fallas superficiales subsidiarias y ramas a lo largo de la traza de la falla principal son notablemente escasas. La ruptura superficial está confinada a una zona angosta de grietas superficiales en escalón y otra zona de levantamiento de hasta varios metros de ancho. La exposición de la falla a profundidades de 1,5 a 2 m. bajo la superficie muestra que el desplazamiento ocurre típicamente a lo largo de una superficie cerrada de dislocación muy estrecha. La expresión superficial del desplazamiento va desde una zona lineal y angosta alterada en suelos húmedos ricos en arcilla a una zona de aberturas en escalón, conectadas por losas de suelo levantadas y sobrepuestas en áreas de suelos cohesivos. Las grietas y las losas recién mencionadas están conectadas por una superficie enroscada que se une con la superficie de deslizamiento que pasa por allí bajo la superficie. La comparación de irregularidades bien preservadas en algunas grietas en escalón muestra que el desplazamiento inicial primario implicó una componente de abertura perpendicular al rumbo de las grietas, seguido en el tiempo por desplazamiento paralelo a la dirección de la zona de falla. El desplazamiento siniestro a lo largo de la falla, medido en Abril de 1976, promedió 110 cm y varió entre un máximo de 340 cm, a 40 km del extremo oeste de la falla y un mínimo de 45 cm en la porción central, a 160 cm cerca del extremo este. Los cambios en el monto del desplazamiento a lo largo de la falla tienen la tendencia a hacerse regulares sobre distancias de hasta 50 km y fueron terminados por intervalos pequeños de variación rápida en el desplazamiento medido.

Lineas de monumentos, instalados a través de la falla, fueron usados para documentar la historia de desplazamiento continuado a lo largo de la falla por aproximadamente 2 años luego de ocurrido el terremoto. El desplazamiento en un lugar aumentó desde 60 cm el 8 de Febrero de 1976 a 91 cm el 9 de Octubre de 1977. Las variaciones del desplazamiento con el tiempo, determinadas en tres lugares, han mostrado que el desplazamiento es proporcional al logaritmo del tiempo transcurrido desde el terremoto y la tasa de desplazamiento está inversamente relacionada con el monto del desplazamiento total en el lugar.

SURFACE FAULTING AND AFTERSLIP ALONG THE MOTAGUA FAULT IN GUATEMALA

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ABSTRACT

The 230-km-long surface rupture along the Motagua fault produced by the 4 February 1976 Guatemala earthquake follows for much of its length, a zone of geomorphic features that are typical of major strike-slip faults. The features include offset drainages, sag ponds, springs, shutter ridges, elongate ridges, side-hill benches, and alined drainages. These features are generally absent along the western 70 km of the fault, possibly indicating that it is a more recently activated strand within the Motagua fault system. Detailed mapping of the surface rupture focused on a descriptive account of the surface ruptures, quantitative variations in displacement along the fault, and measurement of continuing post-earthquake displacement (afterslip).

Surface rupturing on subsidiary surface faults and splays along the main fault trace are notably scarce. The surface rupture is commonly confined to a narrow zone of en echelon surface cracks and pressure ridges as much as several meters in width. Exposures of the fault at depths from 1.5 to 2 m below the surface show that displacement typically occurred along a single, tightly-closed slip surface. The surface expression of the displacement ranges from a narrow linear disturbed zone in damp clay-rich soils, to a zone of gaping en echelon fissures connected by overthrust slabs of soil in areas of cohesive soils. The fissures and overthrust slabs are connected by a twisted surface that merges with the through-going slip surface at depth. Matching well-preserved irregularities on some en echelon fissures shows that the initial displacement primarily involved a component of opening perpendicular to the trend of the fissures, followed by displacement parallel to the trend of the fault zone.

Left slip along the fault, as measured in April 1976, averaged 110 cm and ranged from a maximum of 340 cm, 40 km from the west end of the fault, through a minimum of 45 cm in the central portion, to 160 cm near the east end. Changes in the amount of displacement along the fault tend to be regular over distances of as much as 50 km and were terminated by short intervals of rapid variation in measured displacement.

Arrays of surveyed benchmarks installed across the fault were used to document the history of continuing movement (afterslip) along the fault for nearly 2 years following the earthquake. Afterslip at one location increased the displacement from 60 cm on 8 February 1976 to 91 cm on 6 October 1977. Afterslip time histories determined at three sites have shown the afterslip to be proportional to the logarithm of time since the earthquake, and the rate of afterslip to be inversely related to the amount of total slip at a site.

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INTRODUCTION

Detailed post-earthquake study of the surface rupture produced by the 4 February 1976 Guatemala earthquake focused on the development of a descriptive account of the surface ruptures, measurement of the displacement at numerous locations along the fault, and measurement of continuing after-slip along the fault.

Geomorphic expression of the fault zone

Along the Motagua fault, much of the 230-km-long surface rupture produced by the earthquake follows a zone of geomorphic features (fig. 1A) that are characteristic of major strike-slip faults. Left-lateral offsets of drainages crossing the fault trace, shutter ridges, elongate ridges and troughs, sag ponds, springs, side-hill benches, and alined drainages are common along the rupture (fig. 2). These features are generally absent along the western 70 km of the fault, possibly indicating that it is a more recently activated strand within the Motagua fault system.

Characteristics of the surface rupture

The surface rupture is confined to a narrow zone of en echelon surface cracks and pressure ridges commonly less than 5 m wide. Surface rupturing along subsidiary surface faults and splays along the main fault are notably scarce.

In areas of cohesive soil, displacement along the fault resulted in the development of a zone of tilted, overthrust blocks and slabs of soil or pressure ridges connected by en echelon fissures (figs. 3, 4). The fissures are at angles predominantly within the range of 16° to 20° to the overall trend of the fault zone. They are about vertical in their central portions and merge with overthrust slabs at their ends by means of a twisted surface that is inclined about 30° to the ground surface. Oppositely directed overthrust slabs of soil (fig. 5) are common in the area affected by en echelon fissuring. Numerous exposures in the bottom of the fissures showed the fault plane at depths of several meters to be a vertical, tightly closed, narrow slip surface.

Where the soil was less cohesive, the blocks and slabs crumbled, leaving the zigzag raised area of disturbed ground traditionally referred to as a mole track. The zigzag patterns of the fractures were poorly developed or absent in soil of relatively low cohesion such as in plowed fields where the surface break commonly formed a relatively inconspicuous nearly straight line (fig. 6).

Net slip on fractures was, as nearly as could be determined (probably ± 2°), parallel to the overall trend of the fault at each location rather than parallel to the trend of the fissures. Thus fissures inclined to the fault direction were opened, rather than having undergone shear displacement parallel to their walls. Only fissures parallel to the fault developed slickensides (fig. 7).

Locally, well-preserved irregularities show that the displacement at the surface, in the direction of net slip, was preceded by opening normal to, or highly inclined to the fissure. The irregularities are shaped in such a manner that displacement in a straight line, from the initial position to the final position, could not have occurred without shearing off the irregularities.

Displacements were determined by the offset of a variety of cultural features crossing the fault such as fences, roads, and building foundations, as well as by the offset of natural features such as the matching ends of broken roots and matching irregularities on opposite sides of the fractures. Left-slip along the fault, as measured in April 1976, averaged 110 cm and ranged from a maximum of 340 cm, 40 km from the west end of the fault through a minimum of 45 cm in the central portion, to 160 cm near the east end. Changes in the amount of displacement along the fault tend to be regular over distances of as much as 50 km and were terminated by short intervals of rapid variation in measured displacement (fig. 1B).

Afterslip measurements

The first field measurements of the displacement were made by Plafker and others (1976) at about a dozen widely spaced locations along the fault within a few days following the earthquake. 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-percent increase in the initially measured displacement (figs. 8A and 8B). 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. 1A); data on the variation in amount of afterslip with time are available for three of those locations (fig. 9 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 alinement of offset barbed wire fences, building foundations, and other cultural features.

The amounts of afterslip shown on figure 1A, which range between 4 and 12 cm, represent the slip occurring between late April and late October 1976. The total afterslip occurring since first measurements of displacement produced by the earthquake were made is known to be much greater at some locations. For example, 31 cm has 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. 1B). 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 9. 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 non-instrumental methods of measurement. Slip rates at time T after the earthquake are 37/T mm/day-Gualán, 60/T mm/day-Zacapa, and 69/T mm/day-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-percent reduction in the 41-cm variation in displacement between the Gualán and Marmol sites in 160 years, 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 meters on a 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. 10) 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 step-like 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 23 April 1976, sudden left-lateral slip of the broken displaced wall of a concrete irrigation canal crossing 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 (D. H. Harlow, oral communication, 1976). 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 meters away. Measurements in the 5 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 4-6 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; 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 (1/2 to 3 km thick) which 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, oral communication, 1977). 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 which 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.

References Cited

Bonilla, M. G., 1970, Surface faulting and related effects, in Earthquake engineering, Weigel, R. L., ed.: Englewood-Cliffs, New Jersey, Prentice-Hall, p. 47-74.

Burford, R. O., 1972, Continued slip on the Coyote Creek fault after the Borrego Mountain earthquake, in The Borrego Mountain earthquake of April 9, 1968: U.S. Geol. Survey Prof. Paper 787, p. 105-111.

Burford, R. O., Allen, S. S., Lamson, R. S., and Goodreau, D. D., 1973, Accelerated fault creep along the central San Andreas fault after moderate earthquakes during 1971-1973, in Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford Univ. Publ. Geol. Sci., v. 13, p. 268-274.

Plafker, George, 1976, Tectonic aspects of the Guatemala earthquake of 4 February 1976: Science, v. 193, p. 1201-1208.

Plafker, George, Bonilla, M. G., and Bonis, S. B., 1976, Geologic effects, in Espinosa, A. F., ed., The Guatemalan earthquake of February 4, 1976, a preliminary report: U.S. Geol. Survey Prof. Paper 1002, p. 38-51.

Scholz, C. H., Wyss, Max, and Smith, S. W., 1969, Seismic and aseismic slip on the San Andreas fault: Jour. Geophys. Research, v. 74, p. 2049-2069.

Smith, S. W., and Wyss, Max, 1968, Displacement on the San Andreas fault subsequent to the 1966 Parkfield earthquake: Seismol. Soc. America Bull., v. 58, p. 1955-1973.

Wallace, R. E., and Roth, E. F., 1967, Rates and patterns of progressive deformation, in The Parkfield-Cholame, California, earthquakes of June-August 1966--Surface geologic effects, water-resources aspects, and preliminary seismic data: U.S. Geol. Survey Prof. Paper 579, p. 23-40.

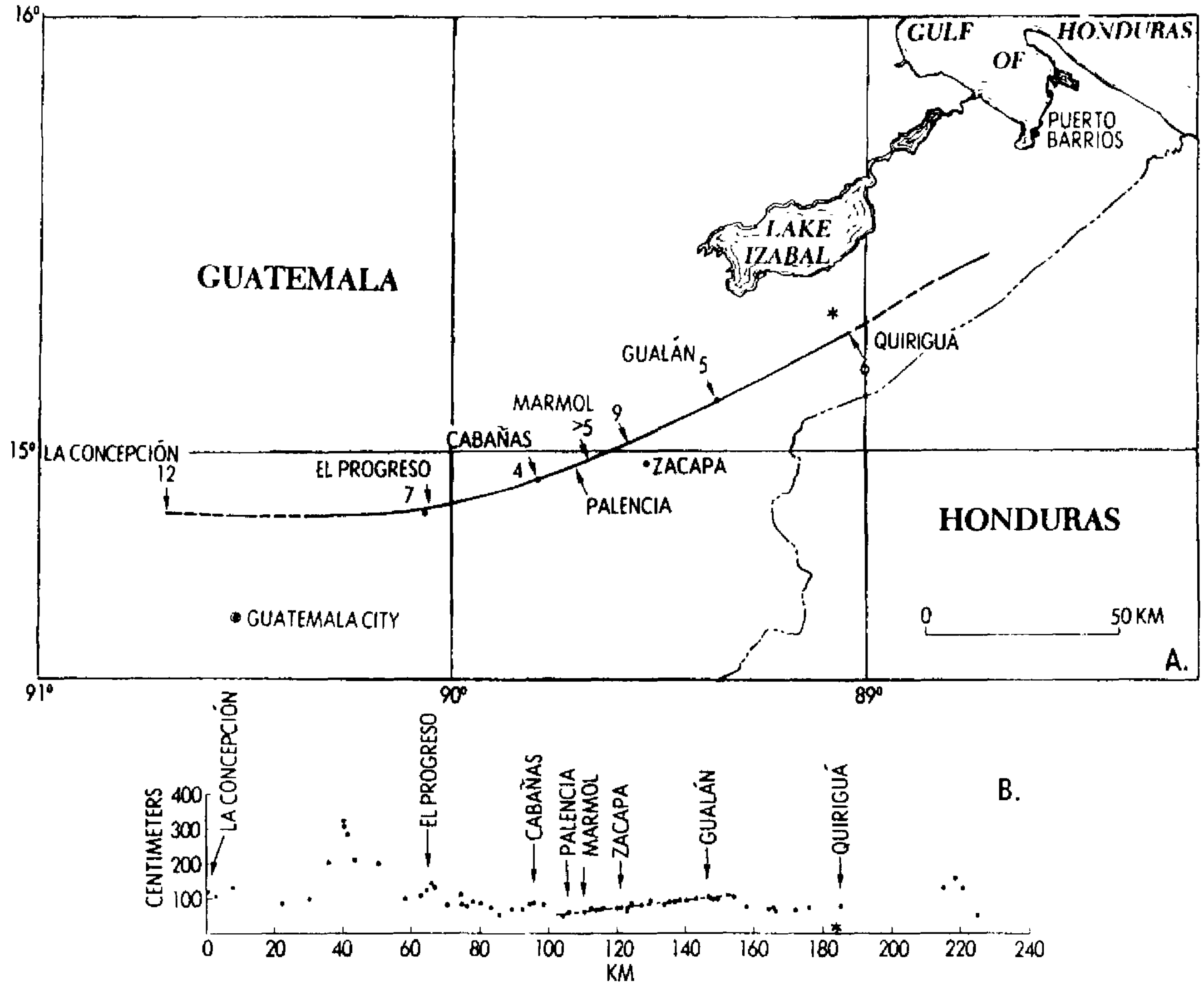

Figure 1. (A) Locations of afterslip measurements along zone of surface breakage (solid line) on the Motagua fault. Afterslip values (cm) are for the period May to October, 1976. (B) Total displacement across the fault as measured in April, 1976. Epicenter shown in (A) and (B) by asterisk.

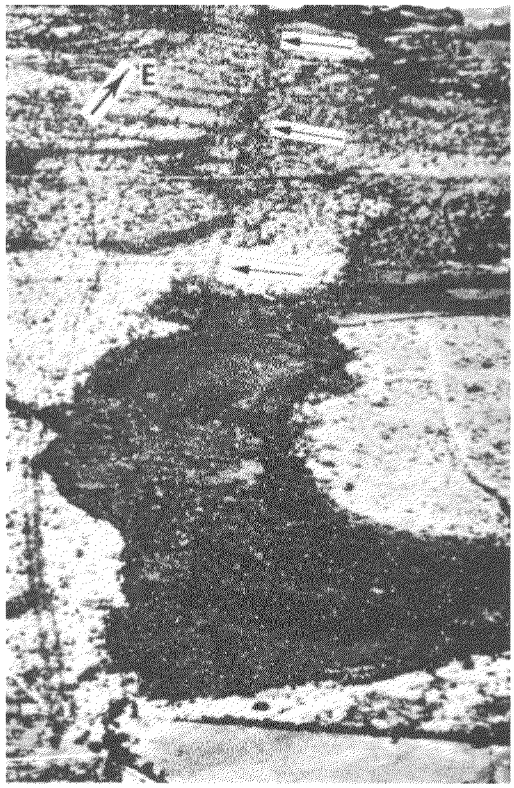

Figure 2. Sag pond (Laguneta los Yajes) along Motagua fault northwest of Zacapa. Surface ruptures of the earthquake follow the dark line of vegetation along arrows.

Figure 3. Zone of tilted, overthrust blocks and slabs of soil along surface rupture of the Motagua fault. Left-lateral slip at this site north of Zacapa was 75 cm.