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COLOR SLIDES SHOWING GEOLOGIC EFFECTS AND DAMAGE CAUSED BY THE DESTRUCTIVE GUATEMALA EARTHQUAKE OF FEBRUARY 4, 1976

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The devastating earthquake (surface wave magnitude $M_S = 7.5$) that struck Guatemala at 3:03 in the morning on February 4, 1976, took an estimated 23,000 lives, caused 74,000 reported injuries, and left more than 1 million people homeless in a country with a total population of about 5.5 million. The Guatemala earthquake sequence was accompanied by the most extensive surface faulting in the western hemisphere since the 1906 San Francisco earthquake and thus is scientifically noteworthy because 1) it permits evaluation of the relation between damage and the earthquake source, 2) it provides critical new information on the nature of a large-scale strike-slip fault rupture of the type that could occur in the future along major faults of the western United States (such as the San Andreas system), and 3) the extensive and complex faulting associated with the earthquake has dramatically provided significant new data on the present style of tectonic deformation in northern Central America.

The geologic effects and damage to the works of man produced by the earthquake of February 4, 1976, are illustrated by 54 color slides that have been placed on file at the Photographic Library, U.S. Geological Survey, Federal Center, Denver, Colorado. The slides are 35mm positive transparencies suitable for use in ordinary slide projectors and can be duplicated at private expense through the Photographic Library. The complete set of slides documents the range of geologic effects resulting from a major earthquake, and it graphically relates damage to the underlying geologic cause. As an objective photographic record showing clear-cut evidence of several dynamic geologic processes, the set provides a unique tool for classroom instruction at the college level. Many of the individual slides in the set will also be useful to research groups studying scientific and engineering aspects of the earthquake. Selected slides from the set would be suitable for high school instruction and presentations to non-technical audiences.

The slides illustrate several kinds of earthquake effects: 1) faulting and associated damage from the primary strike-slip fault and secondary dip-slip faults (28 slides; 21 of strike-slip faulting; 7 of dip-slip faulting), 2) landslides and debris avalanches (7 slides), 3) fissuring, sand-spout deposits, lateral spreading, and differential compaction, in unconsolidated deposits (6 slides), 4) structural damage from seismic vibration (10 slides; 6 of effects on buildings, 1 of highway bridge damage, 3 of damage to historical and archaeological sites), 5) volcanic effects (1 slide), and 6) maps and diagrams showing the plate tectonic setting and an interpretation of the earthquake mechanism (3 slides).

The slides are by Plafker, except for slide 41 by Seena Hoose of the U.S. Geological Survey, slides 3, 6, 10, 35, 38, and 40 by Samuel B. Bonis of the Guatemala Geological Survey, and slides 45 and 46 which were furnished by Karl V. Steinbrugge of the Pacific Fire Rating Bureau. Susan Hunt drafted the figures for slides 1, 2, 22, 52, 53, and 54.

Additional technical information and maps pertinent to the earthquake slides are contained in U.S. Geological Survey Professional Paper 1002, The Guatemalan Earthquake of February 4, 1976, a preliminary report, and in an article in the 24 September 1976 issue of the periodical Science (Vol. 193, pages 1201-1208). Additional reports on aspects of the seismicity and faulting associated with the earthquake are in preparation by the U.S. Geological Survey and will be issued as they are completed.

The primary fault and related damage. The main fault along which the destructive earthquake of February 4, 1976, and its associated surface displacement occurred was identified along the southern margin of the Motagua Valley and the mountainous area west of the valley. Ground breakage was observed in a nearly continuous, well-defined line extending for 230 km from the lower Motagua Valley on the east to about 50 km northwest of Guatemala City on the west. At the closest point, the fault is only 25 km north of the center of Guatemala City. The fault displacements followed an old established fault break in the eastern part (Motagua Valley area) but appear to have broken in a relatively new trace in the western part where the fault is generally not marked by obvious geologically youthful topographic features.

1. Map showing the relation of segments of the Motagua and Mixco faults that moved during the earthquake of February 4, 1976 (in red) to the main shock epicenter, the larger aftershock epicenters, and major structural and volcanic features in northern Central America. Circled numbers along the Motagua fault indicate selected measured sinistral displacements in centimeters. The green lines in the western part of the map area are lineaments, some of which may have undergone minor fault displacement during the earthquake.

2. Graphs showing measured horizontal displacement (below) and vertical displacement (above) along the 230 km length of the observed surface rupture of the Motagua fault. Displacement across the fault is sinistral (left-lateral) and is almost entirely horizontal with the strike-slip component ranging up to 340 cm and averaging about 110 cm. Vertical displacements are variable and less than 30 percent of the horizontal displacements. Note the large lateral variations in both horizontal and vertical slip.

3. Aerial view westward along the Motagua fault trace in the area of maximum displacement 33 km northeast of Guatemala City. The fault trace is marked by a zone less than 3 m wide of en echelon linear cracks with connecting short pressure ridges. There is an en echelon offset of several meters where the fault crosses the creek in the upper part of the slide. Note that the meandering creek does not follow the trace of the fault, which suggests that the fault rupture is geologically young at this locality.

4. Disrupted stone fence (located in the upper part of area shown in slide 3). The fence here is offset 280 cm in a sinistral sense and 65 cm vertically with the south side relatively downthrown. View is north.

5. View southward along a row of trees offset about 325 cm in a sinistral sense where it is intersected by the Motagua fault. The amount of offset is indicated by the distance between the row of trees on the right and the stake at which the man points. The stake is alined with the row of trees in the background. The fault here is a single fissure oriented perpendicular to the line of trees; there is no measurable vertical displacement.

6. Aerial view of a broad zone of en echelon fissures along the Motagua fault trace where it passes through the village of Subinal (7 km west of El Progreso). The fissure zone, which is roughly 9 m wide, extends across the lower part of the slide. Note the complete destruction of adobe structures.

7. Near-vertical shear zone along the Motagua fault exposed in a highway cut near El Progreso. The fault here is marked by the brownish conglomeratic deposits (center of photo), which comprise a sheared sliver approximately 4 m wide.

8. Closeup of a slickensided shear plane that dips 80° N. along the margin of the fault sliver shown in slide 7. The grooves on this fault plane plunge 10° W.; sinistral slip at this locality is approximately 120 cm.

9. Aerial view east along the linear trace of the Motagua fault (dark vertical line) in farmland west of Cabañas. Sinistral displacements in this area are approximately 90 cm.

10. Mismatch of the rows in this field (shown in slide 9) is due to approximately 90 cm sinistral slip. The main fault trace (in the central part of the picture) is extremely linear and less than 2 m wide. A small subparallel fracture having only a few centimeters displacement cuts diagonally across the lower left-hand corner of the picture.

11. View north along rows in a cultivated field west of El Progreso that are offset 105 cm in a sinistral sense by slip on the Motagua fault. The thick, saturated surficial unconsolidated deposits have yielded by plastic deformation rather than rupture.

12. View eastward along the trace of the Motagua fault near Zacapa showing deformation of a thin hard adobe surface soil due to 80 cm sinistral slip. Note the prominent development of en echelon fissures oriented at about a 15° angle to the fault trace and open 27 cm in foreground with connecting pressure ridges to 40 cm high.

13. Aerial view northward at the Motagua fault trace where it crosses a soccer field at Gualán. Note the characteristic right-stepping en echelon fractures oriented as much as 20° to the fault trace in a zone about 5 m wide. Slip here was 89 cm sinistral as determined from offset of white sideline stripe at right side of field.

14. View west along Motagua fault trace where it crosses the Gualán soccer field (shown in slide 13). Note the "mole track" which is best developed in hard-packed, brittle surface materials.

15. View north along railroad tracks that were kinked and offset approximately 107 cm in a sinistral sense where crossed by the Motagua fault, which is perpendicular to the tracks. This is one of numerous localities at which the main railroad line between the coastal port of Puerto Barrios and Guatemala City was disrupted by the faulting.

16. Aerial view southward along a repaired railroad line that is crossed at nearly right angles by the Motagua fault in a plantation area of the lower Motagua Valley. The prominent kink in the railroad line, which was straight prior to the earthquake, was caused by sinistral fault displacement of approximately 130 cm.

17. View south along a concrete-lined irrigation canal just east of Gualán that was broken and offset approximately 93 cm in a sinistral sense by the Motagua fault, which trends almost perpendicular to the canal. Many irrigation works in the Motagua Valley were damaged by movement on the fault.

18. Aerial view westward along the Motagua fault trace in the lower Motagua Valley. The trace here is marked by the dark line of fissures extending from the creek in the foreground through the giant ceiba (balsam) tree trunk and then along a prominent north-facing scarp in the background. The tree was split and toppled by fault movement of at least 72 cm sinistral and 37 cm down-to-the-north displacement. The vegetation-covered north-facing scarp behind the tree, which is 5 m high, was probably formed by many repeated earlier movements along this same trace.

19. Closeup view of the trunk of ceiba tree (shown in slide 18) which was split and toppled by faulting. Note man at base of tree for scale.

20. View north showing drainage ditch along highway CA-10 north of Zacapa offset by 60 cm sinistral and about 5 cm south-side-down vertical displacement of the Motagua fault. The man on the road is standing on the fault trace, which passes at almost right angles to the highway. Photograph taken on February 8, 4 days after the earthquake. Compare with slide 21.

21. Photograph taken from the same point as slide 20, showing effects of additional slip (afterslip) amounting to approximately 18 cm that occurred in the interval between February 8 and April 16 when this photograph was taken. Afterslip that occurred as small increments during aftershocks was a common phenomenon along parts of the Motagua fault and was still going on in late October by which time horizontal displacement at this locality had increased an additional 6 cm to 84.5 cm.

Secondary faults. Secondary faults (faults that underwent surface displacement approximately concurrent with movement on the main fault but that do not join the main fault at the surface) ruptured the ground surface in a broad zone extending from the western part of Guatemala City to Mixco (here termed the Mixco fault zone). The many faults of the Mixco zone are particularly important to Guatemala because they traverse a densely populated urban area and their future behavior should be considered with regard to present and future land use adjacent to them. Other secondary faults, suggested by aftershock concentrations, zones of intense surface cracking, and belts of extreme damage may have occurred elsewhere in the Guatemala highlands, particularly in the area southwest of the western part of the Motagua fault (along the lineaments shown in green on slide 1). Many of these secondary faults occur along preexisting fault scarps developed in thick Pleistocene tephra deposits, indicating that these faults have had recurrent vertical displacements during late Quaternary time.

22. Map of Guatemala City and environs showing the locations of the larger secondary faults of the Mixco zone associated with the February 4, 1976 earthquake (solid and dashed lines). Also shown are the major faults (dotted lines) delineated by geologic mapping in the area prior to the earthquake. All of the faults in this area are predominantly normal dip-slip faults with both down-to-the-east and down-to-the-west displacements. Numbers along fault traces indicate the maximum measured vertical displacement in centimeters. The distributive 1976 secondary faulting occurs within a broad graben as indicated in the schematic structure section (A-A').

23. Fault rupture of a road and curb in a new subdivision north of Mixco. Displacement at this locality is 12 cm down-to-the-east and about 5 cm dextral (right-lateral), or about 13 cm of oblique slip. Faults such as this one caused extensive damage to underground utilities as well as surface structures.

24. Offset road and repaired curb at the same locality shown in slide 23. Displacement occurred at the base of a degraded 6-m-high east-facing scarp which developed by previous movement along this same fault line during the Quaternary Period.

25. View southward along the same fault trace in slide 24 showing down-dropped brown-weathering soil horizon (left) juxtaposed against gray unweathered Pleistocene tephra. The east-dipping slope, which has been partly modified at the lower part by road construction, is a degraded scarp.

26. Damage to a house in a suburb of Guatemala City due to approximately 12 cm vertical displacement. The roof, foundation, and sidewalk have been disrupted along a fault that trends from the lower right corner diagonally across the view.

27. View south along a secondary fault of the Mixco zone that intersects an excavation for a sedimentation basin in Guatemala City's new water treatment plant. The fault, which dips 60° W. (to the right), is

visible in the wall of the excavation in the background and was exposed in the line of pits in the floor of the excavation. Soil horizons in Pleistocene tephra in the wall of the excavation are offset at least 7 m, indicating repeated movement on this same strand during late Quaternary time. Because of the faulting, the design of the settling basin had to be changed to avoid the fault trace. Available information suggests that at least part of the 5-cm displacement at this locality occurred during a large aftershock (body wave magnitude $M_b = 5.8$) on February 6, 1976, which was strongly felt in the Mixco-Guatemala area.

28. One of hundreds of open cracks that break the pavement of the Interamerican Highway in the area west of Guatemala City between Chimaltenango and Tecpan. The occurrence of these cracks, some of which had vertical displacements of up to 3 cm, in areas of very high aftershock activity and extreme damage, suggests that some of the cracking may reflect secondary faults at depth.

Landslides and avalanches. The main event and some of the large aftershocks triggered numerous landslides throughout a broad region of central Guatemala. The landslides, numbering in the thousands, were mainly falls, slides, and flows involving thick Pleistocene pumiceous pyroclastic rocks, but they also included slides of consolidated bedrock. Landslides blocked many transportation routes, interrupted surface communication lines, and in places damaged structures built on or below them. Some of the larger landslides contain several million cubic meters of material. A number of them formed natural dams behind which temporary lakes developed.

29. Landslides in steep roadcut of stratified pumice and ash deposits at the San Cristobal subdivision west of Guatemala City. The materials exposed in this roadcut are typical of much of the Pleistocene tephra deposits that extensively underlie inhabited parts of the Guatemalan highlands.

30. Aerial view southwestward of part of the Guatemala highlands showing typical terrane consisting of deeply incised flat areas underlain by rhyolitic Pleistocene tephra deposits with andesitic volcanic cones of the Middle America arc in the background. The white scars along the valley walls are landslides that occurred mainly during the February 4 earthquake. These slides are the sources of vast amounts of windblown dust, some of which obscures distant parts of this view.

31. Aerial view northeastward along Rio Pixcaya (due north of Chimaltenango) showing area of especially numerous landslides in tephra deposits. The river was partially dammed by a major debris flow that can be seen in the middle distance (see slide 22).

32. Closeup aerial view of landslide-dammed lake along Rio Pixcaya (shown in slide 31). The toe of the slide had been breached by the river at the time this photograph was taken on February 13, 1976.

33. Aerial view showing landslides and extensive headwall cracks developed along the edge of a steep-walled valley in a Guatemala City suburb.

34. Foundation failure due to landslide beneath structures built along the edge of a steep-walled valley in Guatemala City. An estimated 5,000 dwellings in this city were made uninhabitable or were threatened by sliding.

35. Aerial view of a segment of the main highway between Guatemala and the Atlantic coast at Puerto Barrios which was closed due to extensive landsliding and destruction of bridges. These slides are in Cretaceous limestone.

<u>Sand-spout (earthquake fountain) deposits, fissuring, lateral spreading, and compaction of unconsolidated deposits</u>. At some localities where water table is close to the surface, such as the Motagua Valley and some lake deltas in the highlands of Guatemala, compaction of saturated unconsolidated materials was accompanied by ejection of water or water-sediment mixtures and the formation of sand mounds. In addition, landspreading, involving near-horizontal movement of mobilized or liquefied water-saturated granular deposits toward free faces, occurred at a number of localities in the Motagua Valley, along the Atlantic coast in Guatemala and Honduras, and along some lake shores in the Guatemalan highlands. Extension cracks and subsidence accompanied the spreading and caused damage to structures in some of these areas.

36. Oblique aerial view of farmland along the Rio Motagua in the lower Motagua Valley showing lines of light-colored sand that was ejected with water from fissures during the earthquake shaking.

37. Sand mound deposited by spouting from the row of crater-like vents that can be seen in this photograph. The slide is taken in the lower Motagua Valley in the same general area as slide 36.

38. Aerial view of ground cracks in unconsolidated alluvial deposits along the Motagua River north of Quebradas in the lower Motagua Valley. The cracks are believed to result from liquefaction of the water-saturated sediments with resultant spreading and slumping towards the river channel (see slide 39).

39. Closeup of cracks in unconsolidated deposits along the Motagua River shown in slide 38. Note that there is both extension towards the free face and down-stepping towards the river.

40. One of many large cracks in a delta at Lake Amatitlan (20 km south of Guatemala City) opened as a result of earthquake-induced liquefaction of a near-surface layer of saturated pumice sand and lateral spreading of the surficial deposits towards the lake. Such cracks caused serious damage where they intersected structures such as the one in the foreground. The front portion of the house in the background sank into the liquefied sand, tilting the brick chimney.

41. Swimming pool on the shore of Lake Atitlan (65 km west of Guatemala City) that was destroyed when deltaic deposits on which it was built liquefied during the earthquake and flowed (or slid) into the lake. Ground cracks and local sand-spout deposits occur in the lawn behind the pool.

Structural damage from seismic vibration. Most of the direct shaking damage to structures was sustained by the traditional single family adobe block homes with tile roofs on wood-pole rafters that are used in most highland villages and in older sections of the cities. Such structures have little resistance to earthquake-imposed lateral forces and an estimated 1/4 million homes were destroyed or seriously damaged. The great number of deaths (23,000) and injuries (77,000) is attributed to the fact that the earthquake occurred at night when most people were asleep in such homes. Although many well-built conventional homes and engineered buildings sustained damage due to shaking, their performance was generally good, and, with a few exceptions, there were no major failures and they did not cause casualties. In addition to buildings, a number of elevated water tanks, railroad and highway bridges, and historical and archaeological sites were damaged or destroyed by seismic shaking. Total property damage loss in Guatemala has been estimated at $1.1 billion.

42. Aerial view of a typical Guatemalan highland village (San Martin Jilotepeque) located 33 km northwest of Guatemala City that was devastated by the February 4 earthquake. Traditional adobe houses with tile roofs were almost completely destroyed, but the school buildings made of reinforced concrete block and corrugated asbestos roofs in the right-hand part of this view are essentially undamaged.

43. Typical street view in Patzicia showing adobe block rubble which is all that remains of the houses that formerly lined this street. The adobe block buildings had very little resistance to horizontal forces, and most of them were completely destroyed. Collapse of the heavy adobe walls, roof tiles, and beams caused most of the casualties. Note that many of the adobe blocks are still intact but the mortar between the blocks failed during the seismic shaking.

44. Aerial view southward of a newer part of Guatemala City where shaking damage was relatively light. Few of the typical reinforced concrete homes and multistoried buildings in this area were significantly damaged, and there were no building collapses or casualties.

45. Collapsed part of the Hotel Terminal in downtown Guatemala City. Part of this structure, which is a reinforced-concrete frame, flat-slab, six-story building, collapsed owing to failure of several columns at the third floor. Although the building was fully occupied, collapse occurred slowly enough so that the third floor could be evacuated without casualties.

46. Collapse of the dormitory-classroom unit of the newly built Catholic boy's school (Collegio San Javier) owing to failure of some second-story columns in the part of the building on the right. This three-story framed reinforced-concrete structure was designed and built to California Seismic Code specifications. There could have been major loss of life in these flattened second-floor classrooms had the earthquake occurred during the day, rather than at night.

47. Collapse of three central spans of the Agua Caliente bridge on the road to the Atlantic Ocean. This bridge was constructed in 1959 and its loss, together with many landslides, cut the highway connection to the Atlantic. Several other large railroad and highway bridges were badly damaged but did not collapse.

48. Damage to the ruins of the San Agustín Cathedral in Antigua, Guatemala. This cathedral was originally destroyed during the earthquake of 1773 at which time Antigua was the capital city of Guatemala. Many other historical monuments were weakened and damaged by the 1976 earthquake.

49. Aerial view of part of the Mayan site of Mixco Viejo near the Motagua fault trace. This archaeological site, which had been recently beautifully restored by the Guatemalan government, was severely damaged by the earthquake of February 4, 1976. Mound structures and stone walls visible in this view have been cracked and in many cases crumbled as a result of the seismic shaking.

50. A Mayan stele at Quirigua in the Motagua Valley that cracked near the base as a result of rocking during the February 4, 1976 earthquake. The wooden braces were installed to protect the stele from further damage by seismic shaking during the aftershock sequence.

<u>Volcanic effects</u>. There is no indication that the main event or any of its aftershocks were related to volcanic activity. After the earthquake numerous reports were received of new volcanic activity, steam suddenly venting from the ground or changes in hot spring flow, and there was widespread fear that such activity could be related to the onset of major volcanic eruptions. Those reported anomalies that were checked by geologists, however, provide no evidence of dramatic new volcanic activity initiated by the earthquake that could be a hazard to life or property.

51. View of Pacaya Volcano 25 km south of Guatemala City during an ash eruption shortly after the February 4, 1976 earthquake. Although the amount of ash erupted from the volcano may have increased slightly as a result of the earthquake, the apparent increase is well within the limits of the variation in the volcano's activity that had been observed for roughly a year prior to the earthquake.

<u>Tectonic setting of the earthquake</u>.

52. Map showing the Motagua fault (labeled) in relation to the boundaries of the Cocos and Caribbean plates. Large arrows indicate the relative plate movement directions, and numbers in parentheses indicate the inferred annual rate of movement in centimeters. Note that the Motagua fault is part of the transform fault system that comprises the northern boundary of the Caribbean plate. Plate boundaries and motions from Jordan, T. H., 1976, Jour. Geophys. Research, v. 80, p. 4433-4439.

53. A suggested model showing combined relative movement between the North American (green), Cocos (blue), and Caribbean (yellow and orange) plates and within the Caribbean plate to account for the

complex tectonics of northern Middle America. Predominantly extensional faulting (blue zones) has caused fragmentation of the western part of the Caribbean plate. As a consequence, the northern part of the plate (yellow) may be breaking up along north-south-trending graben, and it may be decoupling from the southern part (orange) along the major northwest-southeast-trending system of graben that follows the volcanoes (black dots) of the Middle America arc. White arrows show the directions and relative amounts of long-term movements of the plates and plate fragments; black arrows, relative movements along the Motagua fault system.

54. Block diagram showing the relation of the Motagua fault zone and the inferred zone of decoupling within the Caribbean plate to major tectonic and volcanic elements in Guatemala and contiguous countries. Guatemala is subject to earthquakes that are generated by movement on 1) the transform fault system between the North American and Caribbean plates (which includes the Motagua fault), 2) the megathrust zone between the Cocos and Caribbean plates, 3) extensional faults within the Caribbean plate, and by 4) earthquakes associated with volcanism along the Middle America volcanic chain.