S. W. BILODEAU – Problemas Urbano Geológico con la Zona Agrietada de Mixco.

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URBAN GEOLOGIC PROBLEMS ASSOCIATED WITH THE MIXCO FAULT ZONE

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INTRODUCTION

Portions of the rapidly expanding urban development in and west of Guatemala City were extensively ruptured by secondary faulting along the Mixco fault on February 4th and 6th, 1976. The physical effects of the earthquake included ground shaking, fault rupture, and ground failure. The purpose of the research described here is twofold, 1) to identify the major deterrents to the implementation of a seismic hazard reduction program in the Guatemala City - Mixco area, and 2) to demonstrate the use of existing geotechnical information for the compilation of a potential seismic hazards map and for site-specific seismic hazard abatement.

Research for this study involved three phases. The first phase consisted of approximately three weeks of field mapping in March 1976 to identify and map the fault traces and ground ruptures in and north of Mixco. The second phase involved an evaluation conducted in October 1977 to see if any programs for seismic hazard abatement had been implemented. Interviews with architects, engineers, developers, and governmental officials were conducted, and areas of special interest were field checked. The third phase consisted of compilation of a potential seismic hazards map and implementation of a seismic hazard abatement plan to two development plans.

The contributions of Manuel G. Bonilla, George Plafker, Sam Bonis, and Jose Austurias are gratefully acknowledged. In addition, many thanks must go to all of the persons interviewed, for their help, insight, and generous access to files and plans. Personal funds financed the first two phases of this research, and Earth Sciences Associates generously supported the third phase.

EARTHQUAKE EFFECTS

On February 4, 1976, the Motagua fault ruptured in a left lateral strike-slip fashion along 240 km of its length, generating an earthquake of surface wave Magnitude (Ms) 7.5. Simultaneous rupturing occurred along 20 km of the Mixco fault (Plafker, 1976). The main earthquake and its aftershocks claimed more than 24,000 lives, injured more than 77,000 people, and left 1,000,000 people homeless. It is estimated that damages exceeded $1 billion. Ground shaking was the major cause of damage and death; however, the ground ruptures from the Mixco fault caused extensive damage locally.

One of the first programs the Guatemalan Government instituted, through the Emergency Committee and the Instituto Geografico Nacional, was the mapping of the fractures in and around Guatemala City and Mixco (Figure 1). The Mixco fault had been mapped prior to the earthquake and appeared on most modern published maps of the region as a 35 km long series of en echelon fault segments trending generally north-south. This fault bounds the western side of the Guatemala City graben and exhibits normal dip-slip fault displacements with the east side down (Bonis, et al., 1970). The Mixco fault is of particular interest from a seismic hazard standpoint because of its proximity to the highly urbanized areas of Mixco and Guatemala City.

Ground rupture along the Mixco fault generally was expressed by vertically oriented, nearly linear, extensional cracks 2 to 7 cm wide. The cracks typically appeared as single, well defined features, but splaying was locally expressed by branching or braided patterns of smaller fissures over ground widths of 10 to 20 meters. Vertical displacements up to 15 cm were recorded along individual fault segments, although displacements of 0 to 5 cm were more common. The cumulative vertical displacement was determined to be 37 cm down to the east, and the entire rupture zone involved an area approximately 20 km long and in places 8 km wide. The unusual width of the rupture zone and the faulting characteristics within it, make the hazard from fault rupture a serious and widespread problem throughout this area.

As illustrated on Figure 1, the mapping done immediately after the earthquake was reconnaissance in nature, and many of the ruptures noted crossing the main roads were not followed or were not evident beyond the limits of the concrete and asphalt. The resulting map is therefore somewhat discontinuous and, in some places, nonrepresentative. In addition, there is no distinction on the map between true fault ruptures and simple ground cracking, which may not be related to fault movement at depth. Some ruptures are clearly aligned in such a manner as to suggest continuity; for example, those north of the main intersection of CA 1 and CA 9. Others are so randomly oriented as to suggest non-faulting origins such as those along the eastern margin of the map (Figure 1). Utilizing the rupture patterns and other topographic indicators, an interpretation regarding probable fault traces can be made, as illustrated on Figure 2. Previous investigators (Plafker, et al., 1976) have divided the fault ruptures into three broad zones, considered to be subsidiary fault traces to the master Mixco trace. These zones have been tentatively named the Mixco Zone, the Villa Linda - Castanas Zone, and the Incienso - Santa Rosa Zone. Interpretations of the subsurface projections of these fault traces are illustrated on Figure 3. As can be seen, they are all considered to be related to the main Mixco fault at depth, but due to the extensional nature of the faulting, they tend to branch near the surface and disrupt a broad zone. There is evidence in several areas that some of these subsidiary fault traces have moved repeatedly in the in the past. Fault scarps up to 15 meters high as well as offsets in excess of 7 meters in buried pumice layers are known to exist along some of the 1976 rupture zones, clearly indicating previous movements have taken place.

Other effects from the earthquake included ground shaking and ground failure. Ground shaking was felt over an area of at least 100,000 km^2, with Modified Mercalli Intensities of VI to IX in the Guatemala City - Mixco area. Ground failure in the form of landslides and lateral spreading was also evident. Landslides occurred along the steep slopes of some of the deeply incised drainages (barancos) and in the larger road and railroad cuts. Lateral spreading involved the near horizontal movement of mobilized or liquefied deposits toward free faces in the Motagua Valley and along the Atlantic Coast (Plafker, et al., 1976). In the Guatemala City - Mixco area, lateral spreading was evident on some bluff tops near barancos.

POTENTIAL SEISMIC HAZARDS

Utilizing the data available from the February 1976 earthquakes, a potential seismic hazards map has been prepared for the Guatemala City - Mixco area (Figure 4). This map is intended to identify in a general way those areas where ground shaking, fault rupturing, and seismically induced landsliding or lateral spreading may be a problem. Site-specific geotechnical investigations within these areas could serve to refine the specific nature and extent of the hazard for input into the final project design.

Ground shaking, as analyzed by Kiremidjian, et al. (1977), is relatively uniform throughout the study area. Potential ground acceleration return periods have been estimated to be 0.25 g every 50 years, .3 g every 100 years, .4 g every 400 years, and .45 to .5 g every 500 years. This means that for any given structure with an expected economic lifetime of 50 years, it will probably experience accelerations on the order of .25 g to .3 g, and that there is a possibility, although remote, that accelerations of .4 to .5 g will be experienced (Figure 5). These accelerations were derived through analysis of all known earthquakes of the region. Ground shaking presents the principal hazard to life in Guatemala through causing the collapse of man-made structures, principally adobe. Mitigation of this hazard can be accomplished through structural design. At the time of the earthquake, no seismic-resistant design code had been officially adopted by Guatemala. Studies conducted since that time are still attempting to resolve that issue. Of interest to many here is the liability question. By granting a building permit, the government does not assume any legal responsibility for the structure (Rodger Baldizon, personal communication). Liability may rest with the planner, contractor, developer, or their engineers. However, in reality, it is often difficult and costly to attempt to get retribution through the courts. Therefore, suits of this type are not normally pursued.

The hazard resulting from fault rupture is usually confined to narrow strips of ground along fault traces. Because the Mixco fault is a normal fault and because the Guatemala City graben is bounded on the east side by the potentially active Santa Catarina fault, fault ruptures may occur almost anywhere in the valley. However, there are some areas which are more likely to fail on a regular basis than others, in particular, those areas which exhibit evidence for repeated fault offsets. Although the area affected by such rupture is small compared to the area affected by ground shaking, the results of surface faulting beneath man-made structures is usually serious. To mitigate the problem, consideration should be given to avoiding these areas whenever possible. The potential fault rupture hazard zones, as depicted on Figure 6, define the three broad zones considered to be subsidiary fault traces to the Mixco fault. Although these zones are anticipated to encompass the majority of the future fault ruptures, some new or previously unrecognized fault traces may break the surface some time in the future. In addition, more detailed study of the mapped fault zones may serve to more accurately refine the rupture hazards. As a general guideline, the California Division of Mines and Geology usually assumes that the area within 15 meters of a mapped fault break to be also involved in faulting.

The hazard resulting from seismically induced ground failures within the Guatemala City - Mixco area is generally restricted to landsliding into the barancos and lateral spreading adjacent to barancos. No areas where liquefaction-induced failures were experienced are known to be present within the study area. Generally, the amount of landsliding and lateral spreading that occurs is related to the steepness of the adjacent slope, the water content and degree of cementation of the underlying deposits, and the joint patterns within the deposits. Without a detailed site-specific analysis, it is difficult to specify seismic safety setback requirements. Therefore, through analysis of drainage patterns and topography, a generalized potential landslide or lateral spreading hazard zone can be defined as shown on Figure 4. Within these zones, there are undoubtedly areas of stable slopes where no setbacks should be required. However, there are also other areas where landslides or lateral spreading may occur. Hence, these zones and for that matter all areas adjacent to barancos, could be considered as potentially hazardous subject to more detailed investigations.

CASE HISTORIES

To evaluate the impact of the earthquakes and the resulting hazard map on specific sites within the Mixco fault zone, the following four projects north and west of Mixco were examined in detail: Colonia San Francisco, a single and multiple family residential development, San Jose de las Rosas, a 2000 lot subdivision, Colonia Carolingia, a disaster relief housing project, and the Xaya Pixcaya water filtration plant Lo de Coy (Figure 7). All of these projects are located within the fault rupture hazard zone, and some are adjacent to barancos subject to landsliding (Figure 6). Adobe structures scattered throughout the region were also examined to determine causes of failure and to evaluate rebuilding practices.

Colonia San Francisco was 60 percent completed at the time of the earthquake; the remaining 40 percent was graded and ready for construction. After the earthquake, the project area was crossed by seven fault and ground ruptures. At least four of these are considered to represent actual fault traces. According to engineer Carlos Ahn, project director, approximately 130 lots were adversely affected by ground breakage. The seismic response of the reinforced cinder block houses was very good. Absolutely no homes collapsed, and no people were killed, although some houses were so severely damaged that they had to be abandoned. However, nearly all of the homes in this area were insured by the Fomento de Hipotuos Asegurodas (FHA). Houses situated on top of ground ruptures as small as 2 cm were wrenched apart and severely damaged. Yet homes on either side of the faults exhibited only minor cracking, which was common throughout the subdivision. According to the damage observed, the major hazards were confined to relatively narrow zones where the ground actually broke beneath the structural foundations. Because of their losses in this area, the FHA now refuses to insure any structure within 15 m of a mapped fracture shown on the published fracture map (Jose Asturias, personal communication). This action was the only official implementation of this fracture map known. Because the Colonia San Francisco development was completely designed and approved prior to the earthquake, there was little incentive to change the approved plan, especially in light of the excellent performance of the existing buildings. This development has, in fact, served as model for reconstruction engineering in the area.

The 2224 lot San Jose de las Rosas subdivision was also designed and approved prior to the February earthquakes (Figure 8a). The subdivider plans to sell these lots vacant. Improvements present at the time of the earthquakes included approximately 50 percent of the roads and pipelines. After the earthquakes, the project was crossed by two fault ruptures, one of which is at the base of a 15 m high existing fault scarp, indicating renewed movement along a pre-existing fault. A total of 192 residential lots, one school, and 15 commercial and condominium lots were adversely affected by fault ruptures. The existing roads and pipelines were severely disrupted where the fault traces crossed them. Although there was little incentive to change the existing plans, Figure 8b illustrates how some minor changes in the plans could significantly reduce the impact of renewed fault movement in this area. Three parks were already located along the fault scarps by the original plan. This type of land use is commonly considered to be compatible with high seismic risk areas such as fault zones. In the hypothetical or sample revised plan, four additional parks have been moved to the fault zone, and lot densities along the fault have been reduced by one-half. This density reduction can serve to break up the monotony of lot sizes and allows the home owner more freedom in locating their structures off of known fault traces. In the event of fault rupture, only half as many dwellings are likely to be affected, if that many. A plan revision could include relocation of the school site well away from known fault traces. However, since schools commonly have playgrounds, athletic fields, and other open space areas, it was felt that a detailed site-specific geotechnical study would reveal areas on-site that are not affected by faulting and that would be suitable for well designed, earthquake-resistant school buildings. Clustering the structures in the relatively safe areas would leave the fault rupture hazard zones free for athletic fields, playgrounds, and other recreational uses. The commercial and condominium areas could also be developed similarly with minimal risk to occupants. A cluster development concept of locating the condominiums off of known fault traces and having common open space along the potential rupture zones is one method of coping with the problem without suffering undue economic loss. Restrictions on height, use, and occupancy of some of the commercial units would serve to reduce seismic risk in this area. For example, storage warehouses could be quite compatible along this zone; however, a theater would be inadvisable. The total impact of the revisions illustrated includes 1) the realignment of several roads, 2) the addition of several parks, 3) the restriction on arrangement of the condominium + school complex, 4) restrictions on use and occupancy of 50 percent of the commercial units, and 5) loss of 116 residential and 5 commercial lots through a reduction in density along the fault. The resulting changes cause a loss of approximately 5 percent of the residential and 6 percent of the commercial lots.

The Colonia Carolingia development was not started prior to the earthquake and is actually a result of the earthquake. Refugees, predominantly from adobe structures which collapsed during the earthquake, moved away from the city and began camping in the open field north of Colonia San Francisco. The immediate need for shelter and sanitary facilities was of paramount importance, so through cooperation of the National Reconstruction Committee; BAMVI, the National Housing Bank; and CEMEC, an International World Church Service, a disaster relief housing project was started on the property. This particular project plans over 1400 homes, five schools, five parks, and one commercial center. At least 143 lots and three of the school sites are adversely affected by the present pattern of surface rupturing (Figure 9a). Because it was necessary to put as many dwellings as possible in as small an area as possible, the houses are approximately 6 x 7 meters in dimension. They are located about one-half meter apart. Most of the streets are 6 meters wide. The houses are founded on continuous concrete footings and are constructed of reinforced cinder blocks with metal roofs. The cost of a house and lot is approximately $1800 (1 quetzal = 1 U. S. dollar).

Because of the high density of the development, any plan revision to accommodate the fault ruptures or baranco setbacks will result in the loss of some home sites. Tradeoffs of this sort are very difficult to assess; however, parks and open space can serve to enhance the environment of this otherwise somewhat congested development. One form of accommodation of the fault rupture hazard through land planning is illustrated on Figure 9b. It has been accomplished by realigning one of the roads and widening it into a boulevard with trees and a park-like border. Three of the existing parks have been relocated so as to buffer the fault rupture hazard zone. Densities within 15 m of fault ruptures have been lowered by one-half to encourage house sites to be situated as far away as possible from known rupture areas. A church with a cemetery is planned where two fault traces are branching. Although this church is located 15 m from each trace, it may experience foundation rupture anyway due to the fault's proximity. Because of the occasional high occupancy, it is proposed that the church structure be of sufficient aseismic design so as not to collapse in the event of up to 15 cm of surface rupturing through the foundation. A church is proposed for this area because of its community impact as opposed to individual impact. In the event of serious structural damage, the economic burden of repair can be shared by the community at large, and it will involve only one building, as opposed to the previous 22 home sites proposed for this area.

Portions of the Colonia Carolingia development are located near the tops of barancos. These home sites are often considered valuable because of the spectacular views often enjoyed. However, in the event of strong ground shaking, seismically triggered landslides can occur and take out entire home sites. Without a site-specific analysis, it is difficult to specify seismic-safety setback distances; however, to demonstrate existence of the hazard, a small strip of open space land is shown buffering the bluff top. The total impact on the development of the revisions illustrated includes 1) the realignment and widening of one road, 2) the relocation and expansion of two parks, 3) the initiation of a common open space buffer zone along the top of the bluff, 4) the introduction of a community church and cemetery, and 5) a loss of 66 lots through the plan changes and a reduction of lot density along the faults. At a cost of $1800/lot, that represents $118,000 of a $2,500,000 project or a 5 percent impact.

The Xaya Pixcaya water filtration plant Lo de Coy was under construction at the time of the earthquake. This plant is the receiving station for water imported via aqueduct from the Xaya and Pixcaya Rivers in the volcanic highlands west of Guatemala City. This system is eventually expected to supply Guatemala City with approximately 25 percent of its water supply. At the time of the earthquake, the aqueduct was 90 percent completed; hence, they were already too far committed to the Plant Lo de Coy to consider abandoning the site. After the earthquake, the plant was crossed by three surface ruptures (Figure 10a). Geologists from the United States, Japan, and Guatemala inspected the site and determined that the middle trace was apparently the principal fault and exhibited evidence for repeated offsets during late Quaternary time in excess of 7 m. The maximum movement recorded in February consisted of 5 cm. It was therefore recommended that construction be avoided on the faults, in particular, the middle trace. The Xaya Pixcaya engineers examined several alternatives for the development and eventually decided to change the shape and design of the sedimentation tank (Figure 10b). The tank is now located 3 m off of the fault trace, and it was structurally redesigned to take higher seismic forces into account. The warehouse and other water-retention facilities are essentially unchanged; however, the filters are adjoined to the sedimentation tank via flexible, jointed pipes which have emergency shut-off valves at both ends in the event of a pipe rupture. The impact of these plan changes is to change the volume and retention time of the sedimentation tank, which reduces its efficiency to 75 percent. It is, however, still capable of purifying the water well within acceptable limits.

Because collapse of adobe structures caused the majority of the deaths and injuries in Guatemala, any practical seismic hazard-abatement program must address the issue of how to live with adobe in seismic regions. Until a cheaper or more easily available building material becomes available to the people of Guatemala, adobe will be continued to be used for most highland and lower income buildings. Although adobe structures have a notoriously poor seismic-resistance record, certain modifications in building design can help

(Jobart and Marzolla, 1976). For example, mixing the mud, straw, and sand to make adobe bricks in proper proportions so that a good, sturdy brick results. Simple field tests, as shown on Figure 11, can verify brick quality. Brick dimensions and orientation are also important. Structurally reinforcing the interior walls with available materials like barbed wire and wood can help reduce damage and serve to tie the building together (Figure 12). Choosing a roof composed of light weight, not heavy, material is also critical to favorable seismic response (Figure 13). Communication and education of the people building such structures are important if future losses from earthquakes are to be minimized. The illustrations used in Figures 11 to 13 come from a small instruction booklet designed to communicate with pictures, not words. Booklets like it were distributed throughout Guatemala as rebuilding began. A continuation of this education process should be encouraged as the memories of the devastating effects of the earthquake are forgotten.

CONCLUSIONS

The Mixco fault presents a significant seismic hazard to the Guatemala City - Mixco area. Effects from an earthquake on the Mixco fault could include ground shaking with accelerations up to .5 g, fault rupture over many linear km of ground, and ground failure in and adjacent to the barancos. The expected limits of these hazards are illustrated on the Potential Seismic Hazards Map (Figure 4).

In general, the major deterrents to the effective implementation of a seismic-hazard abatement program within the Mixco fault zone are related to, a) the site commitment prior to the earthquake, b) the lack of basic geologic and fault data, c) the lack of an officially adopted building code, d) the lack of enforceable liability, e) economics, and f) public education.

In order to reduce future economic and cultural losses within the Mixco fault zone, certain basic studies involving geology, seismology, structural response, and land-use planning are needed. A program for evaluating the local geologic and seismic hazard from the Mixco fault should include: 1) mapping the Mixco fault in detail to determine where future ground ruptures are likely to occur; 2) evaluation of the seismicity of the fault to estimate the maximum probable and maximum credible earthquakes as well as an approximate recurrence interval; 3) evaluation of the potential ground response in relation to seismic shaking; 4) determination of the probable location of secondary ground effects such as landslides, ground lurching, liquefaction of sediments, and compaction or settlement; and 5) application of the information to site-specific land-use plans and structural designs.

Implementation of an effective seismic-hazard reduction program will require government regulation, private cooperation, and public education. In some areas where funds are not readily available for site-specific geotechnical investigations, the information currently available is sufficiently detailed to be used in a general manner to define potential seismic hazards and to initiate minimal seismic safety practices through land-use planning and building design.

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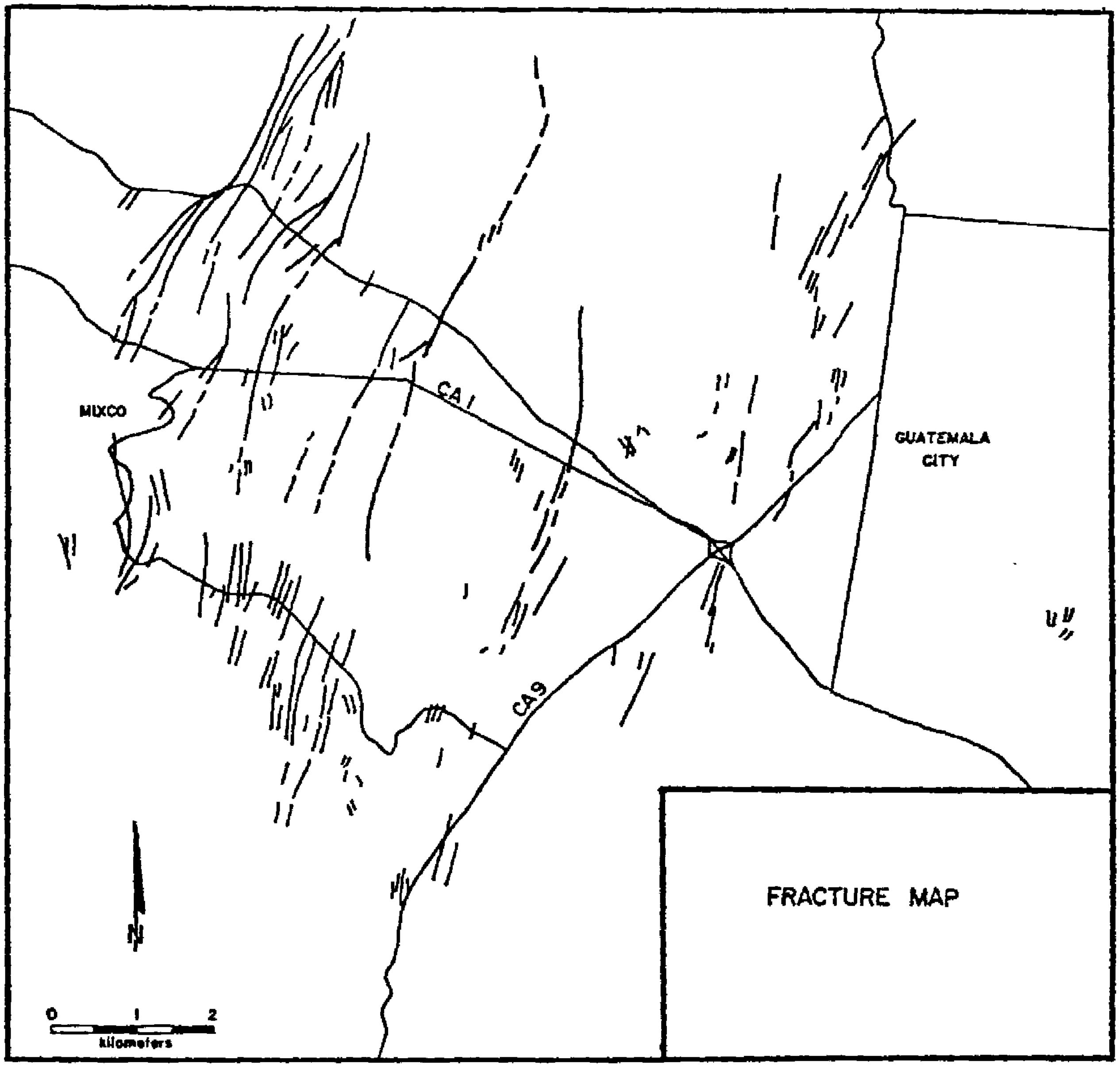


FIGURE 1- FRACTURE MAP
EARTHQUAKES OF FEBRUARY 1976
GUATEMALA VALLEY

ROADS
OBSERVED FRACTURES

FROM GUATEMALA INSTITUTO GEOGRAFICO NACIONAL, 1976.

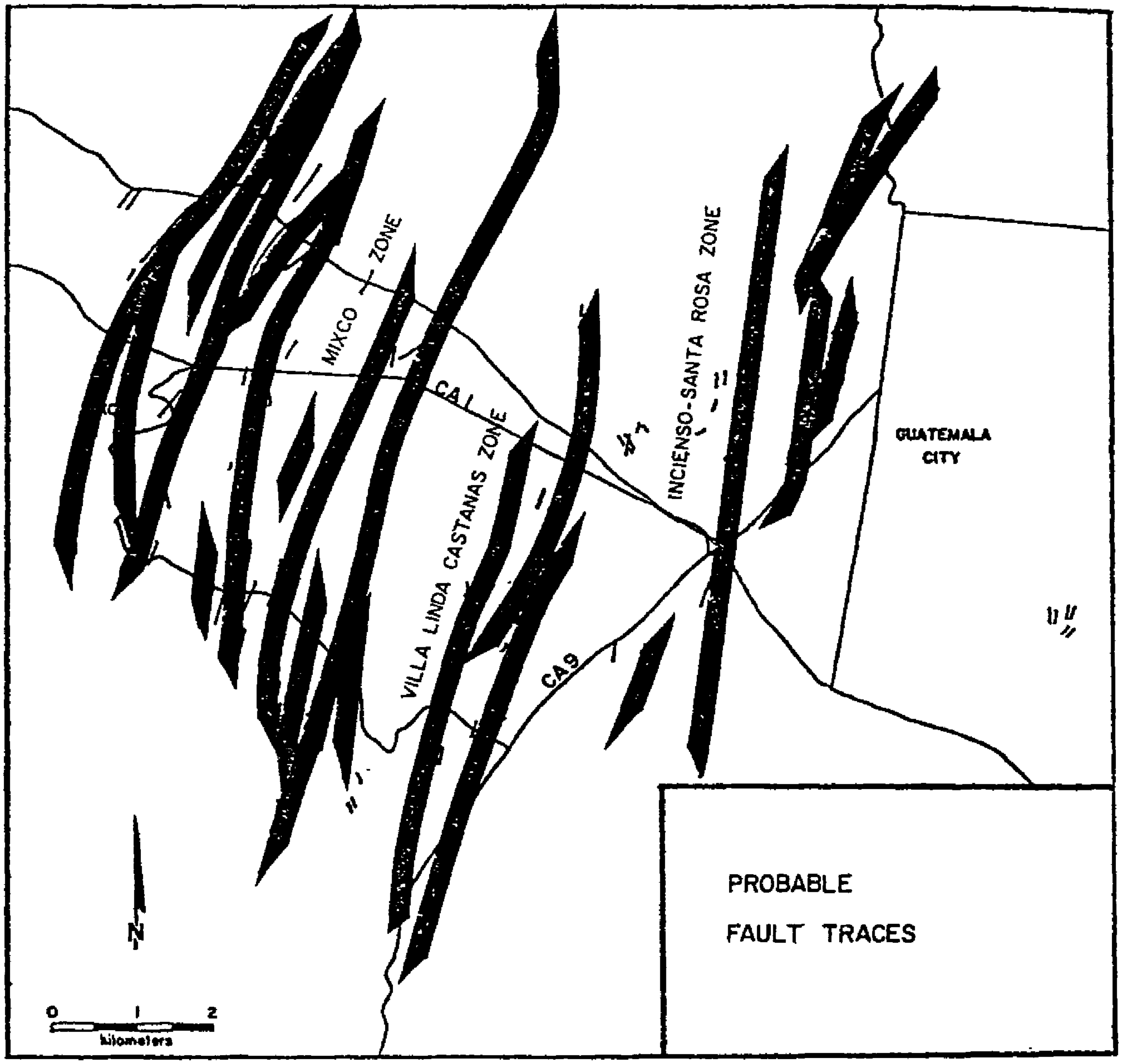


FIGURE 2

ROAD

1976 FAULT & GROUND RUPTURES

FAULT TRACE

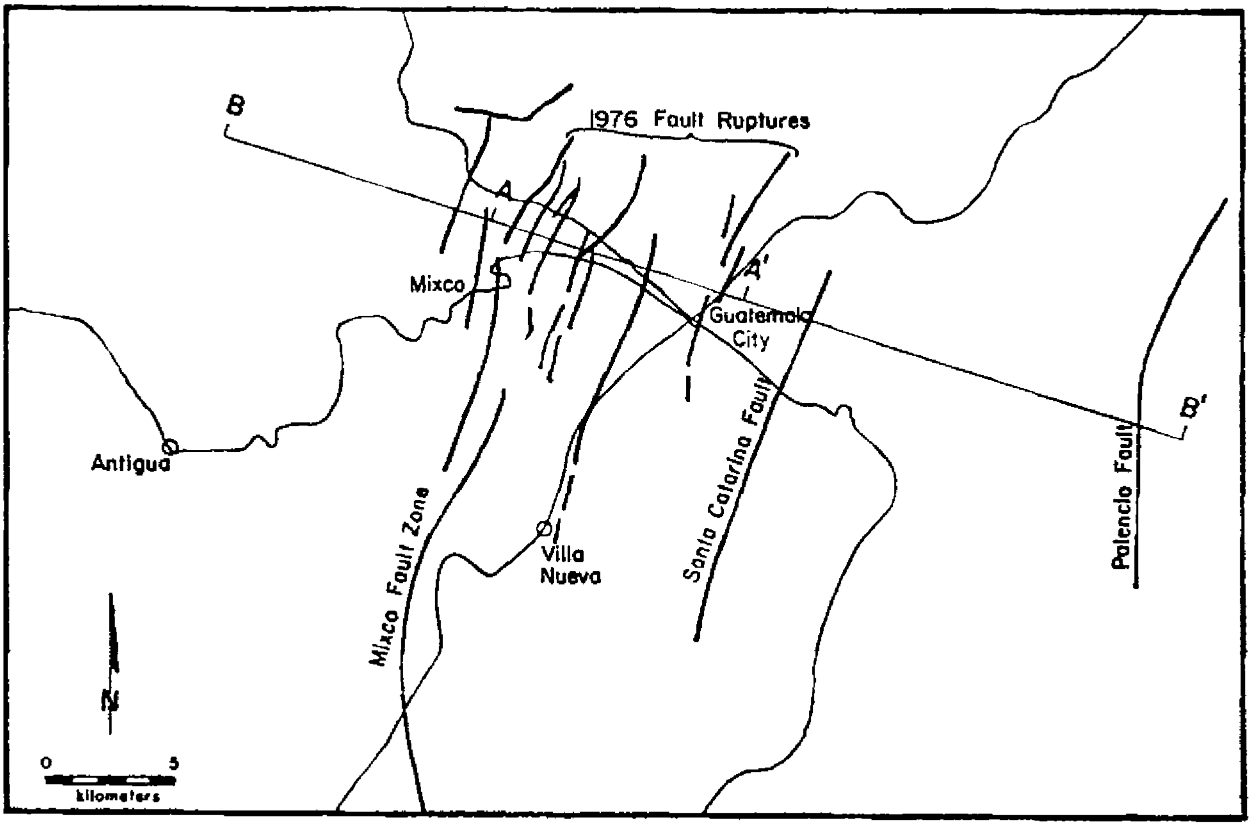
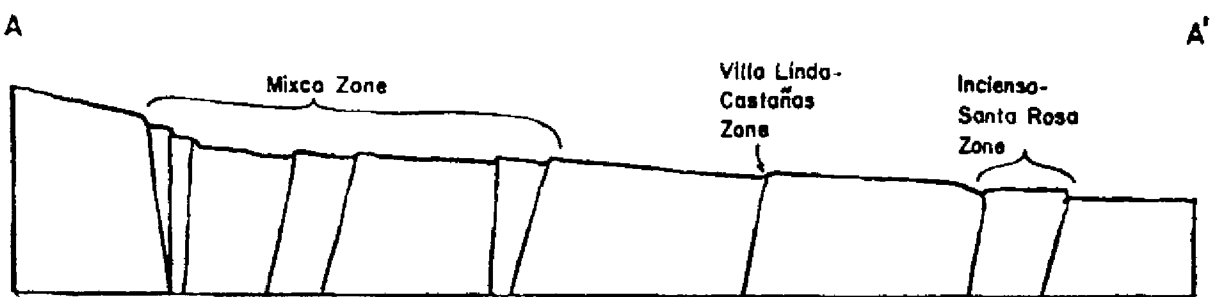
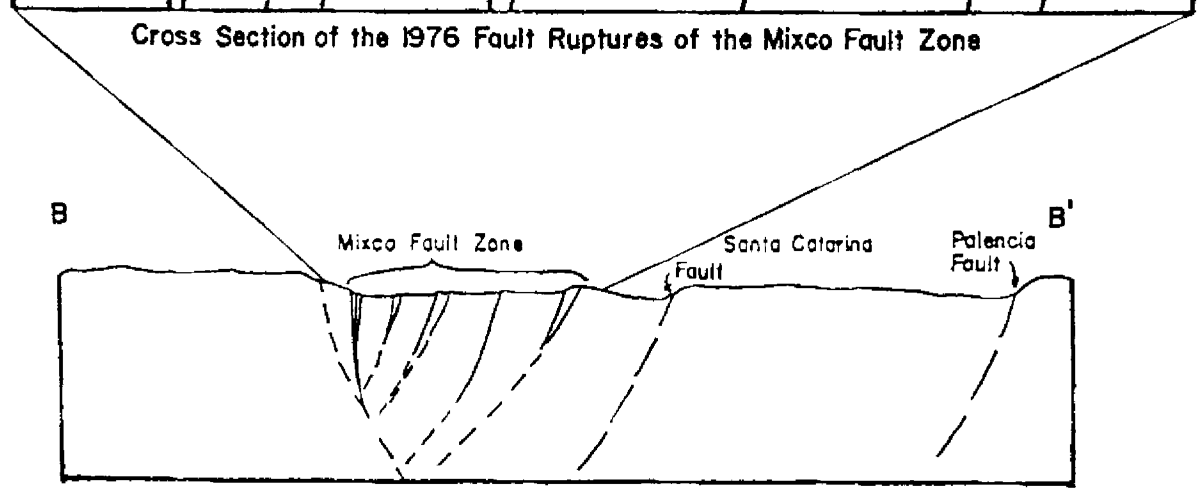


Figure 3 Regional Fault Map and Cross Sections.



Cross Section of the 1976 Fault Ruptures of the Mixco Fault Zone



Regional Cross Section

Modified from Plafker, 1977.

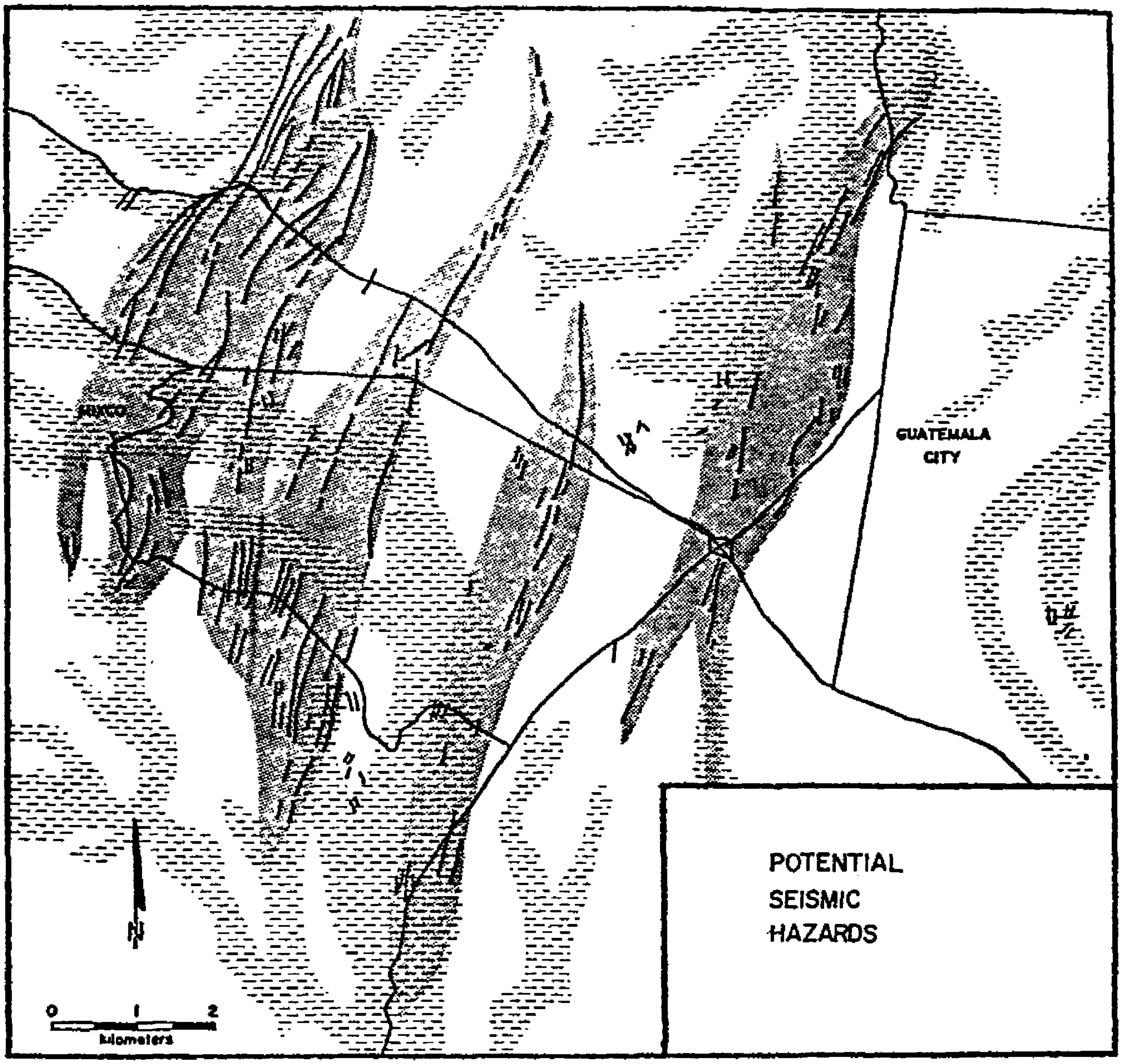


FIGURE 4

ROADS

1976 FAULT AND GROUND RUPTURES

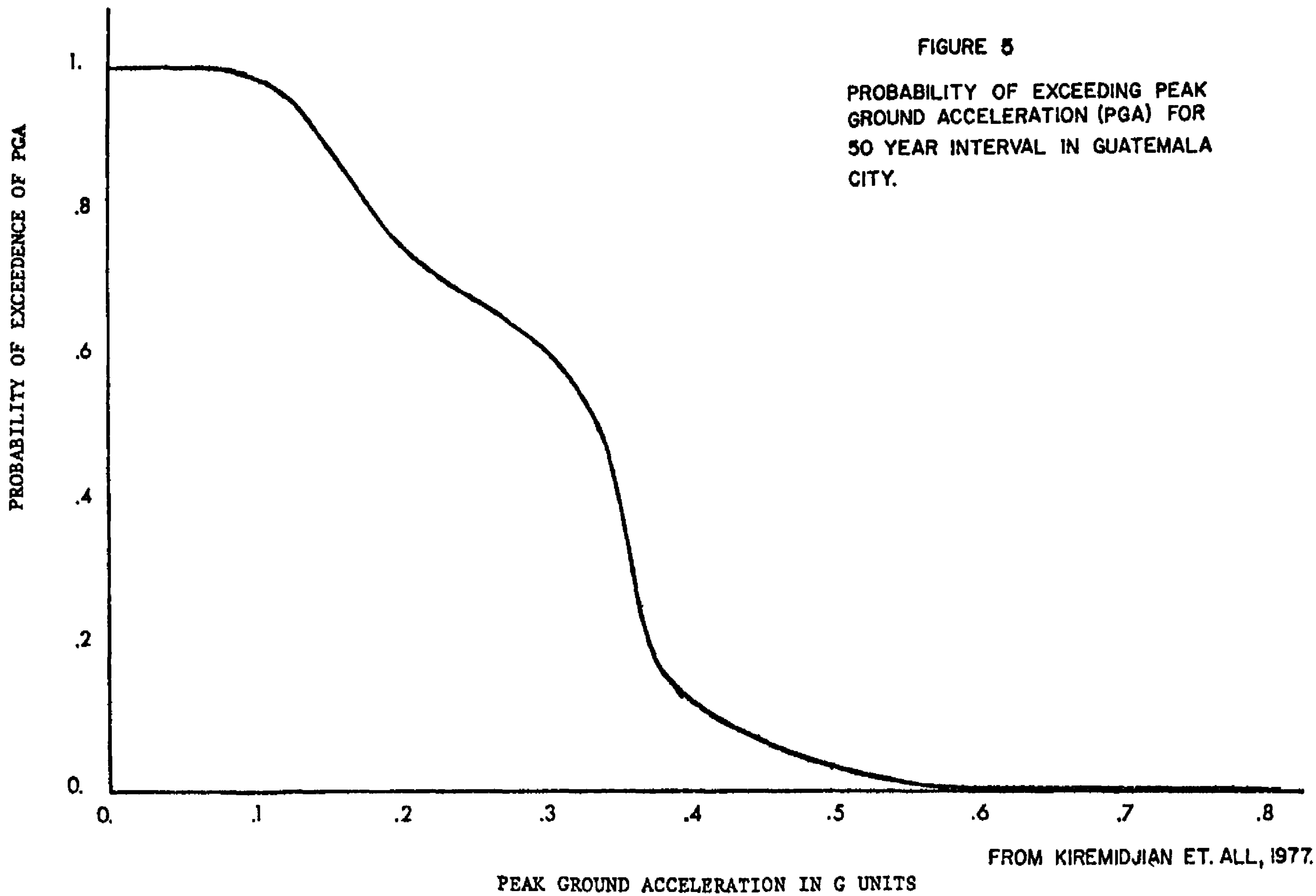
POTENTIAL FAULT RUPTURE

POTENTIAL GROUND FAILURE

POTENTIAL GROUND SHAKING - PRESENT ALL OVER STUDY AREA

FIGURE 5

PROBABILITY OF EXCEEDING PEAK GROUND ACCELERATION (PGA) FOR 50 YEAR INTERVAL IN GUATEMALA CITY.



FROM KIREMIDJIAN ET. ALL, 1977.

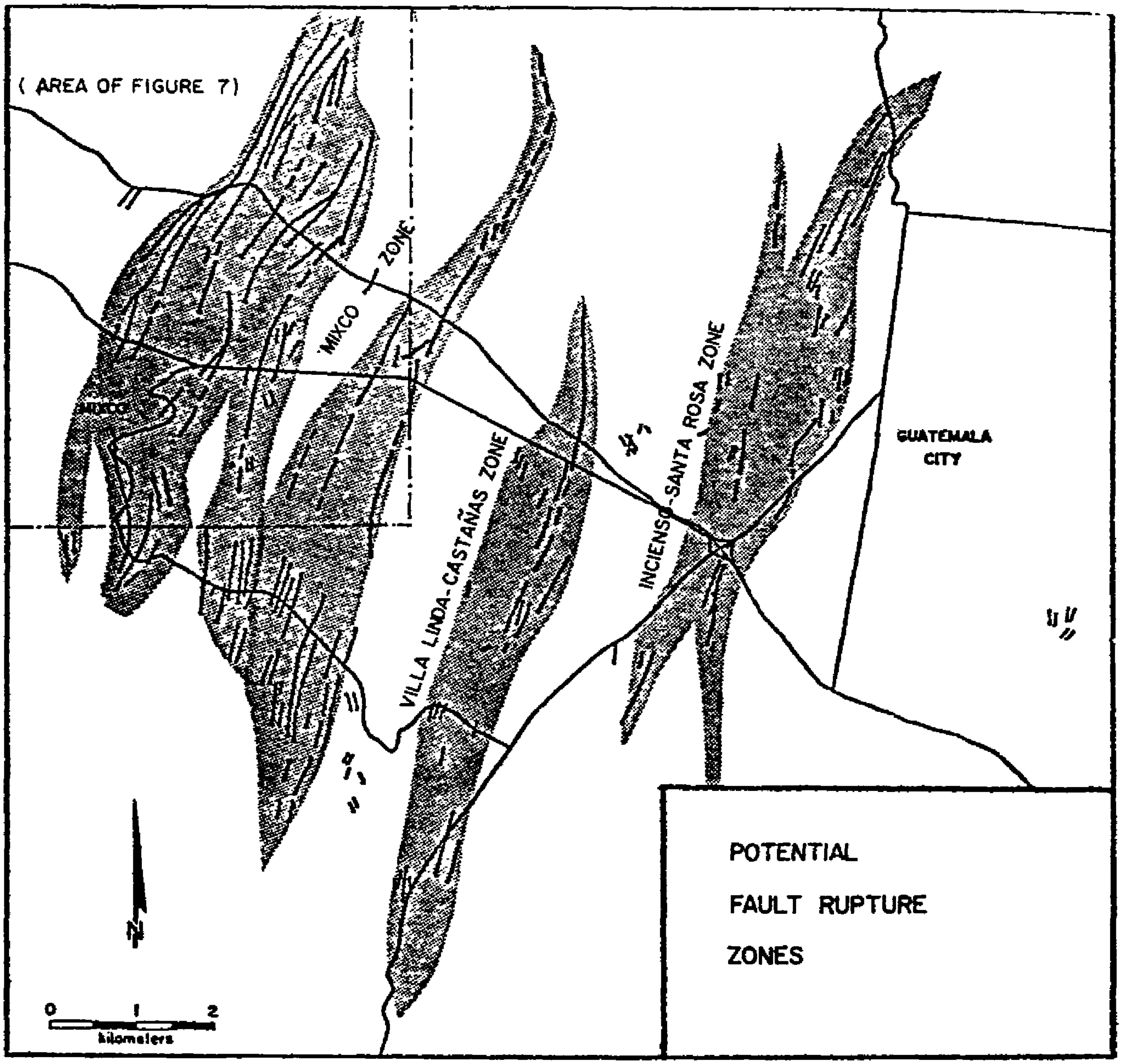


FIGURE 6

ROAD

1976 FAULT & GROUND RUPTURES

POTENTIAL FAULT RUPTURE ZONE

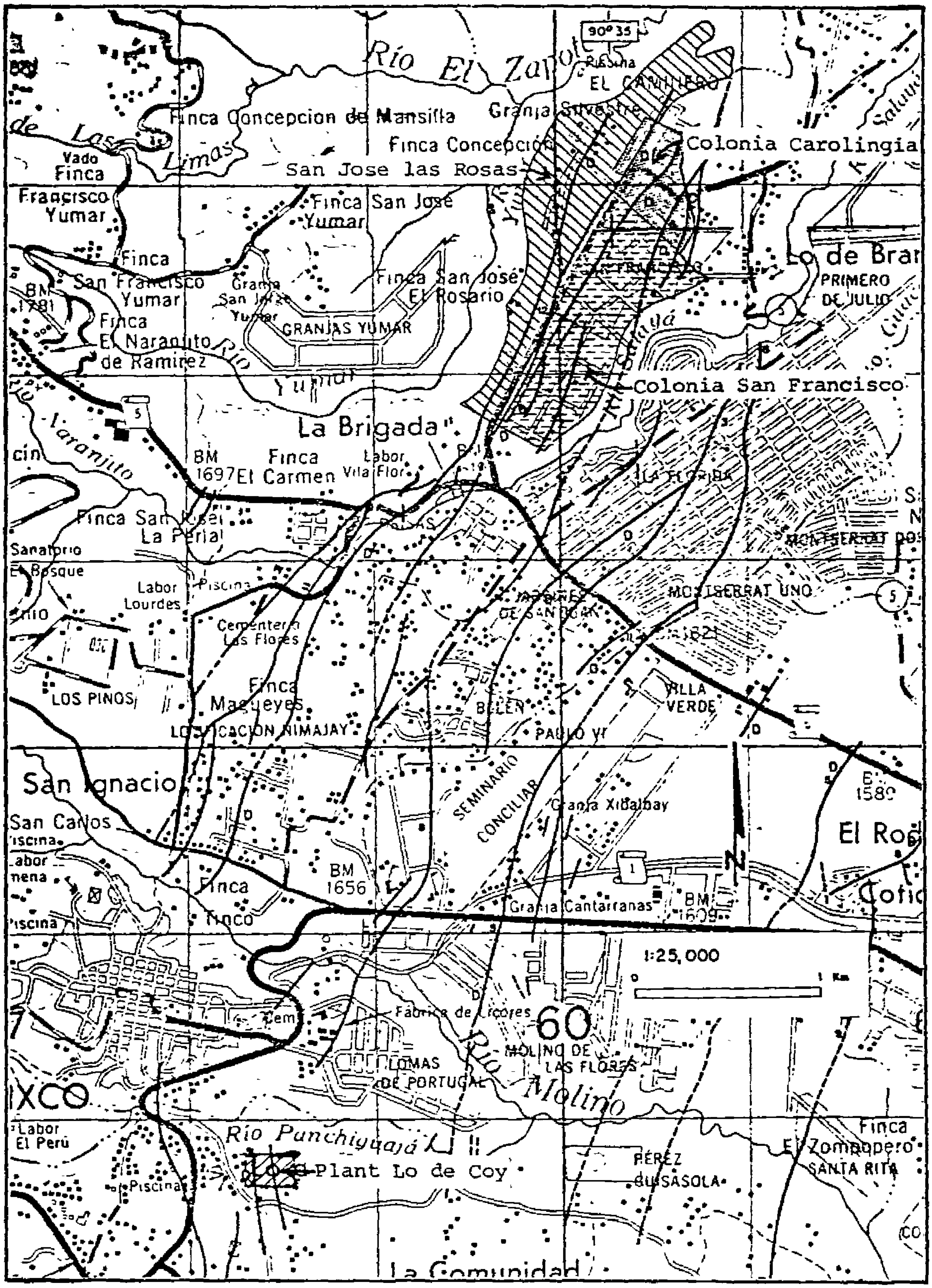


FIGURE 7

INDEX MAP

1976 Fault and Ground Ruptures

Base Map from Guatemala Instituto Geografico Nacional, 1976.

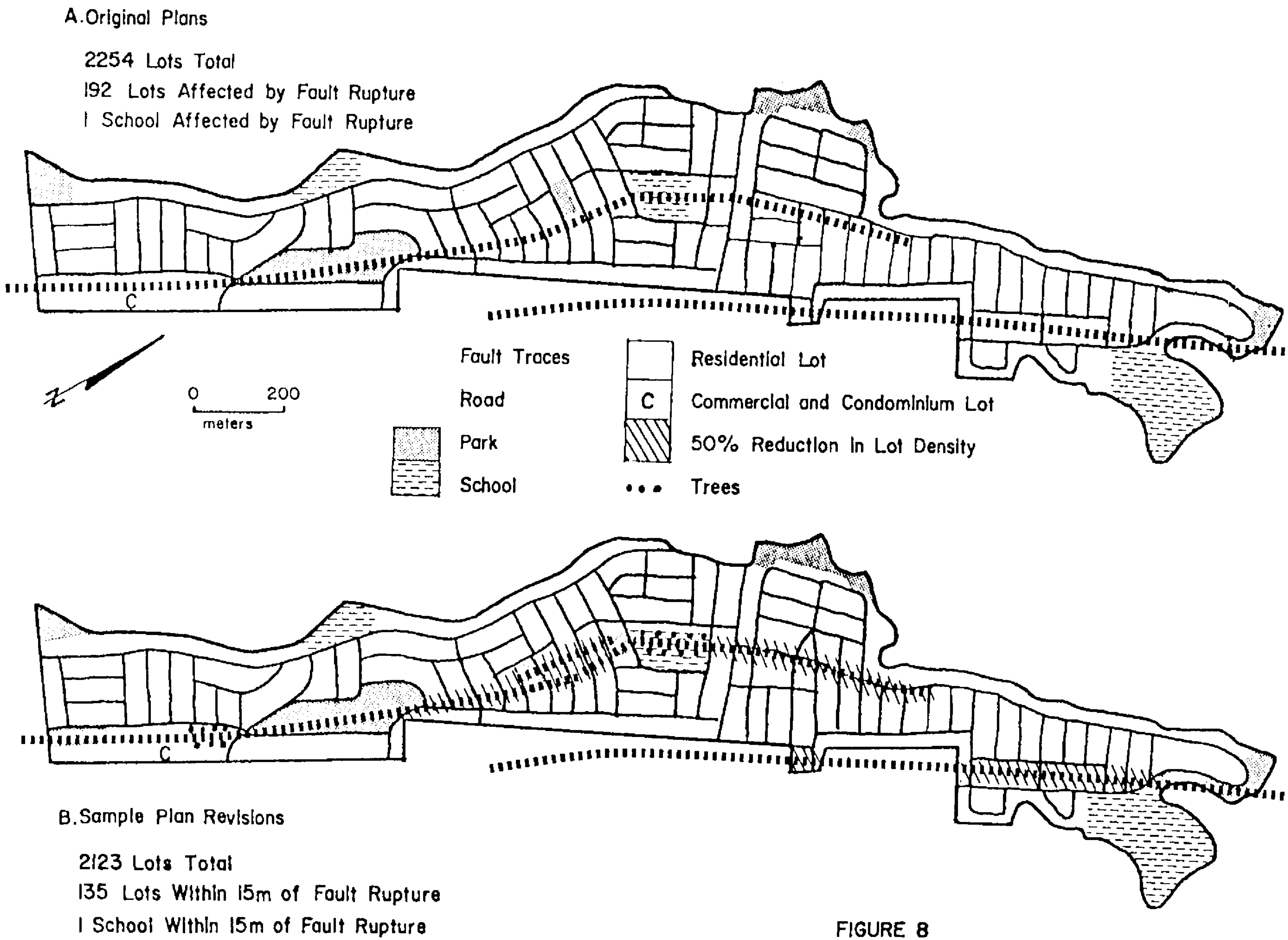


FIGURE 8
SAN JOSE LOS ROSAS

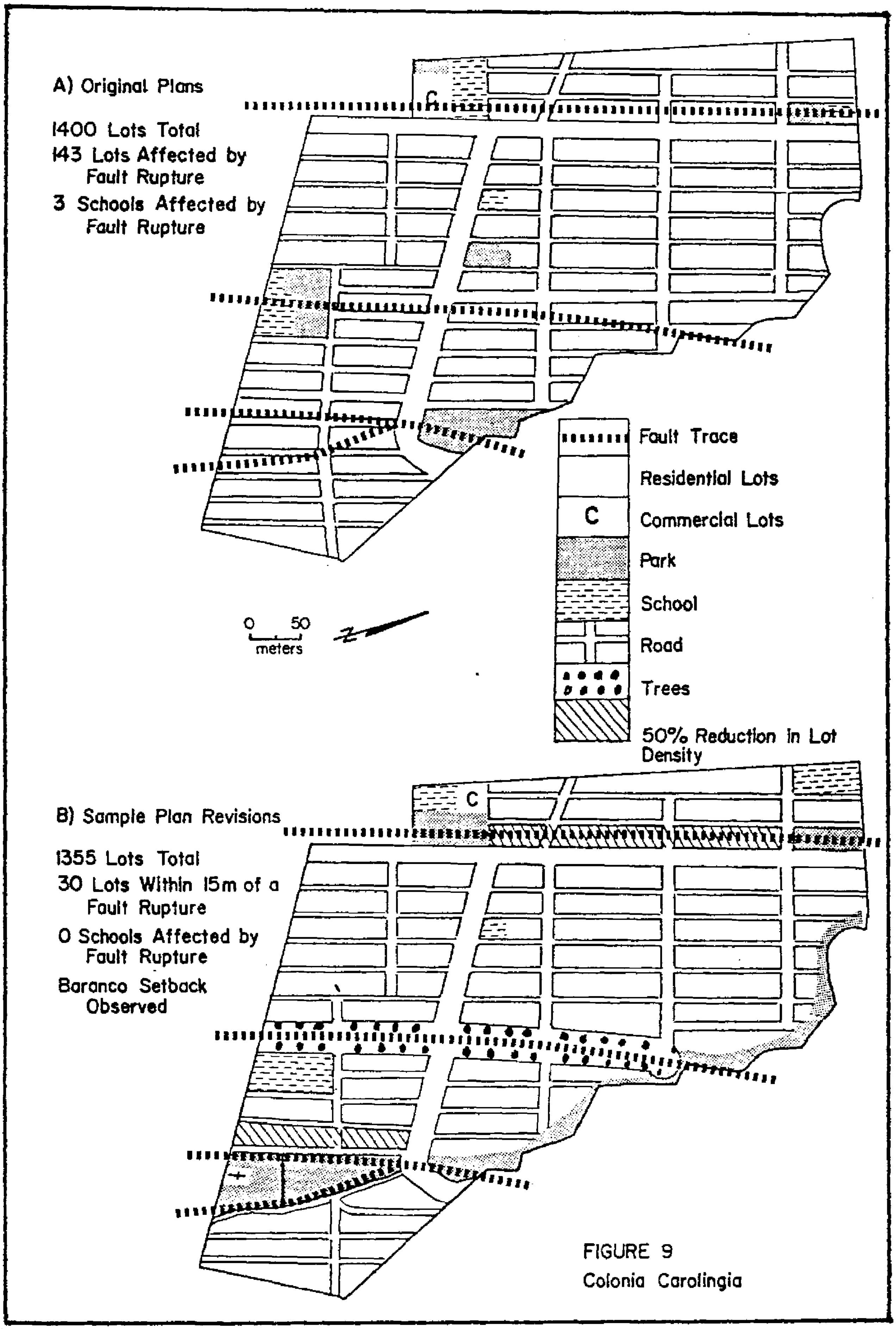


FIGURE 9
Colonia Carolingia

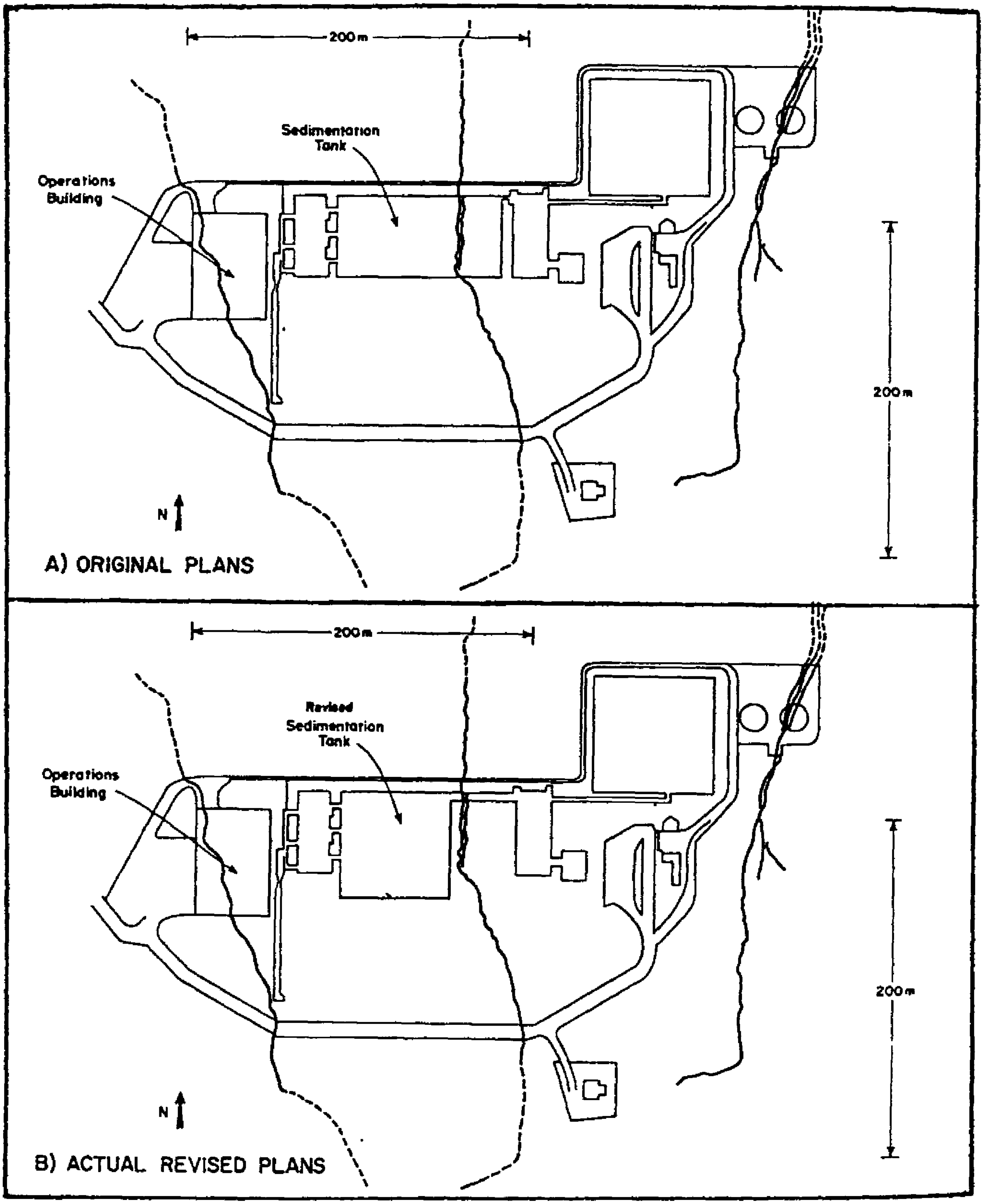


FIGURE 10 PLANT LO DE COY

Fault and Ground Rupture

Modified from Husid, 1976.

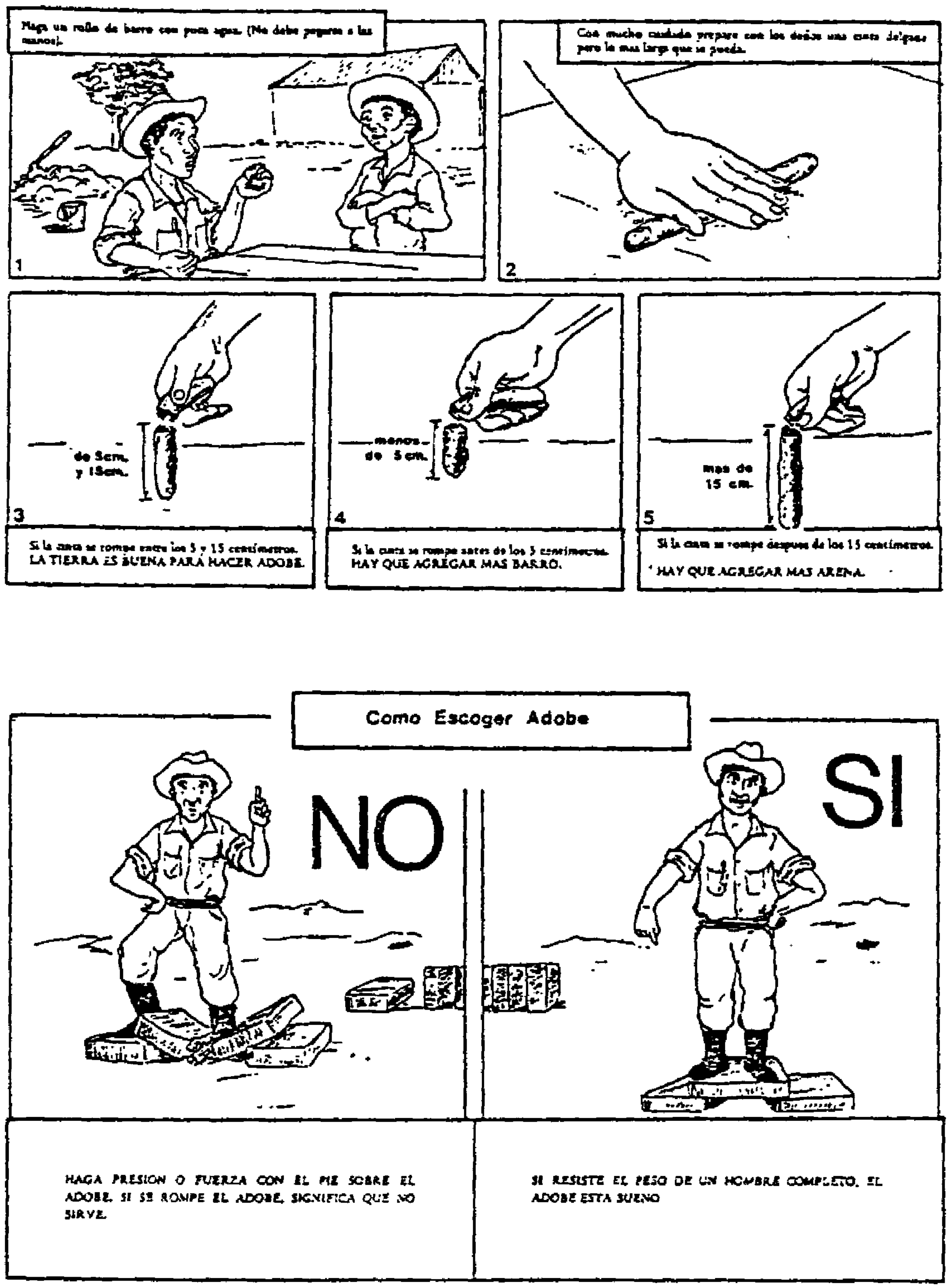
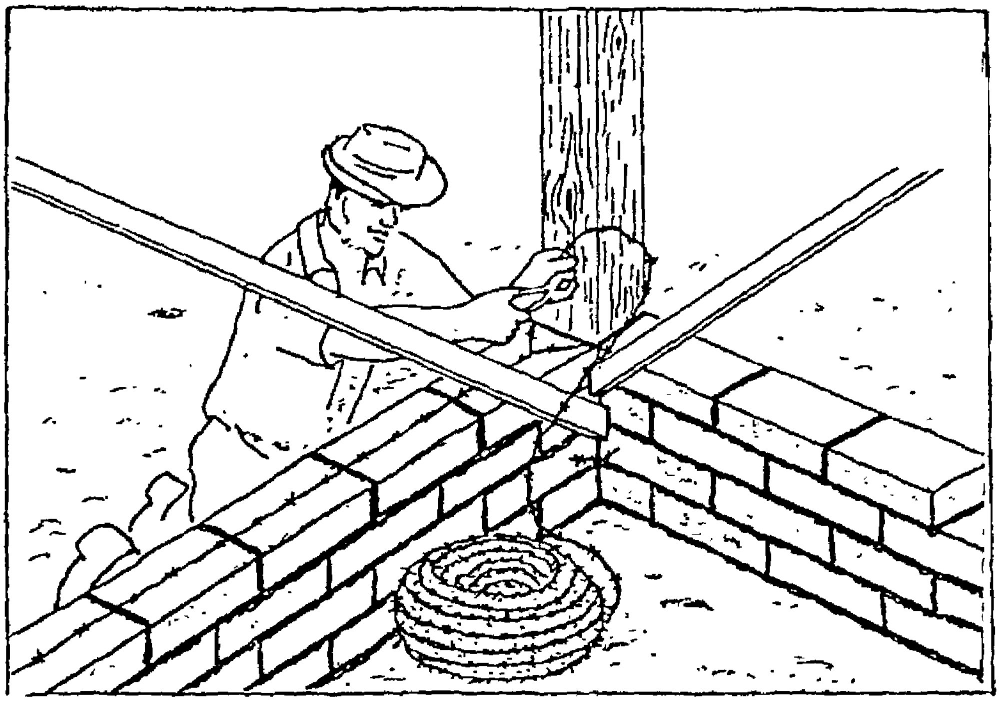


FIGURE 11

FIELD TESTING OF ADOBE



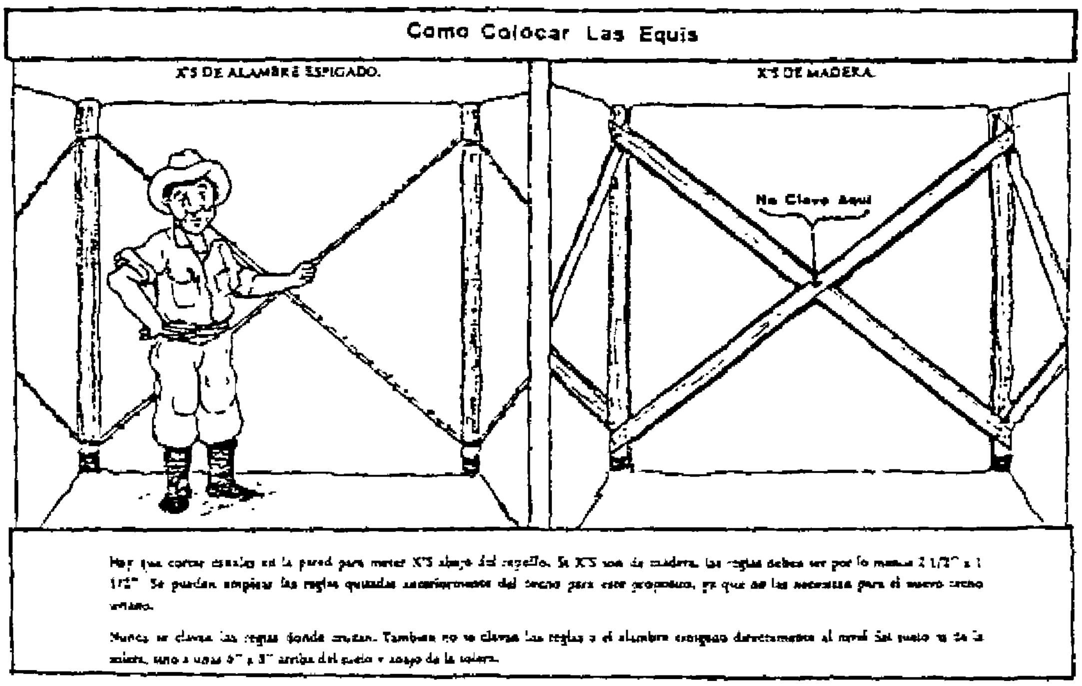
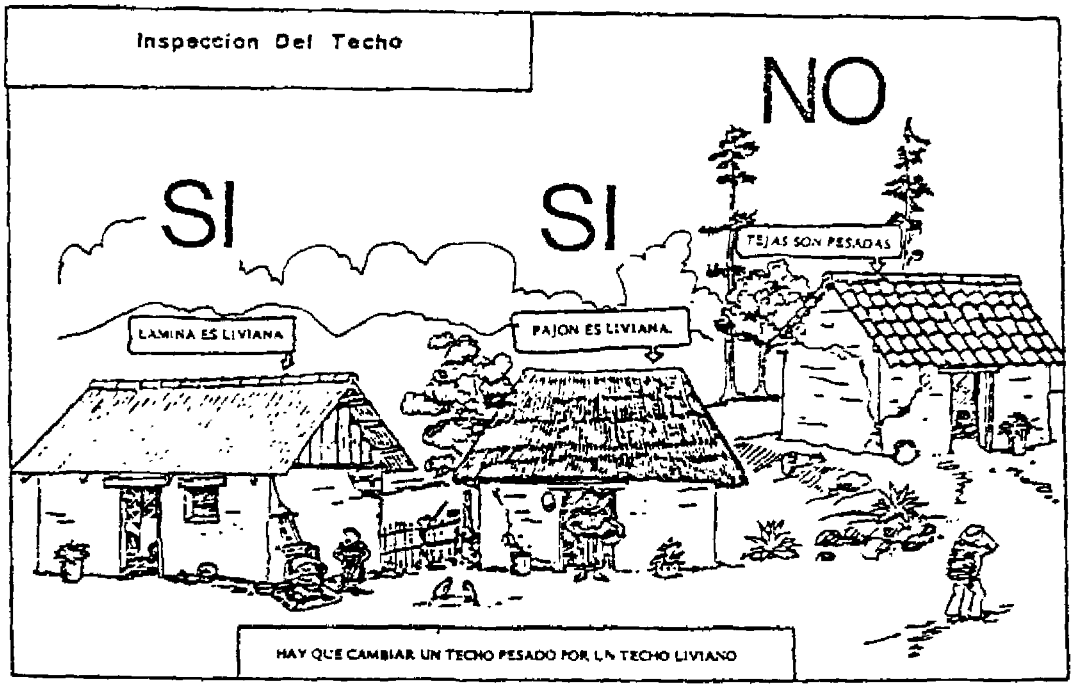


FIGURE 12

STRUCTURAL REINFORCEMENT OF ADOBE



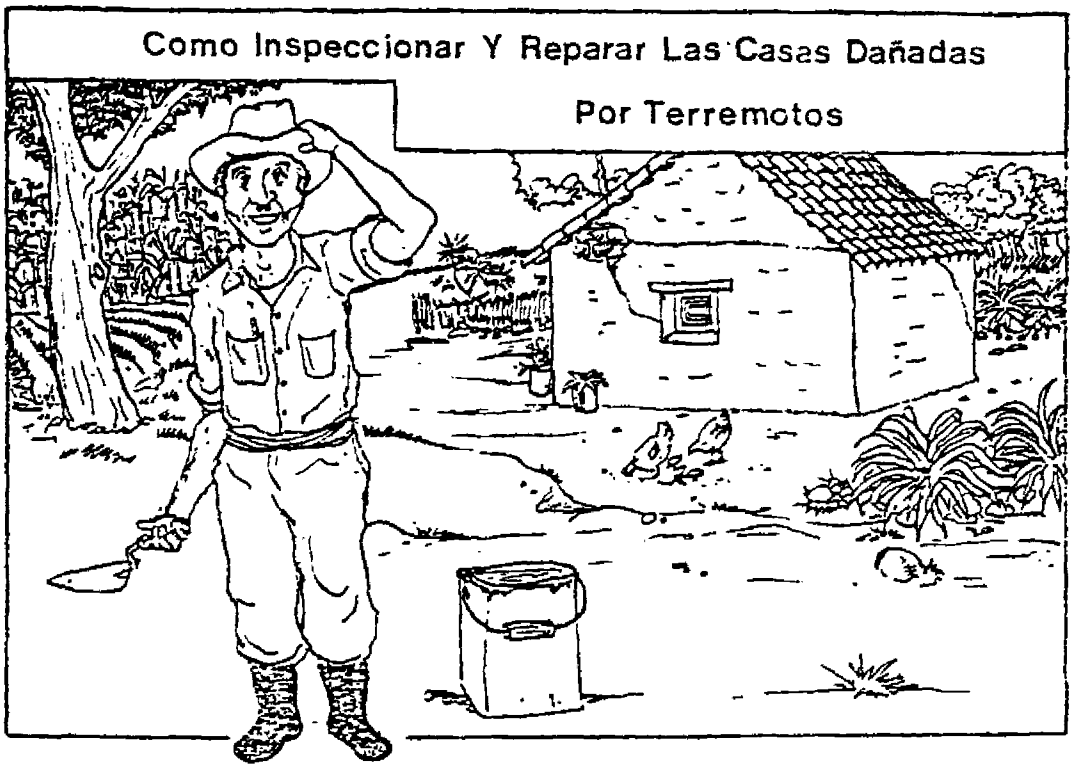


FIGURE 13

HOW TO INSPECT AND REPAIR HOMES FOR EARTHQUAKES