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Introduction

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On March 5, 1987, two earthquakes (M_s=6.1 at 2054 local time and M_s=6.9 at 2310 local time) occurred along the eastern slopes of the Andes Mountains in northeastern Ecuador. The epicenters were located in Napo Province (Figure 1.1), approximately 100 km ENE of Quito and 25 km N of Reventador Volcano (Figures 1.2, 1.3). Modified Mercalli Intensity (MMI) values as high as IX have been estimated for the epicentral area (Espinosa et al., this report). The shaking damaged structures in towns and villages near the epicentral area, particularly in the town of Ibarra (50 km NW of the epicenters), where two brick churches were severely damaged; several other brick buildings in Ibarra had to be reinforced subsequent to the quakes because of structural damage. In addition, considerable damage occurred to reinforced concrete buildings and foundations of wooden buildings in the village of Baeza (60 km SSW of the epicenters). In El Chaco village (50 km S of the epicenters), a steel-frame gymnasium, which was under construction, collapsed (Hakuno et al., 1988).

In spite of the seriousness of this structural damage, the economic and social losses directly due to earthquake shaking were small compared with the effects of catastrophic earthquake-triggered mass wasting and flooding in the area adjacent to Reventador Volcano (Figure 1.2). Rock and earth slides, debris avalanches, and debris and mud flows E of the Andes resulted in the destruction or local severing of nearly 70 km of the Trans-Ecuadorian oil pipeline and the only highway from Quito to Ecuador's eastern rain forests and oil fields. The total volume of earthquake-induced mass wasting has been estimated at from more than 75 million m^3 (Crespo et al., 1987) to about 110 million m^3 (Hakuno et al., 1988; Okusa et al., 1989). Economic losses have been estimated at $1 billion; the effects of widespread denudation on the agricultural and hydroelectric development of the

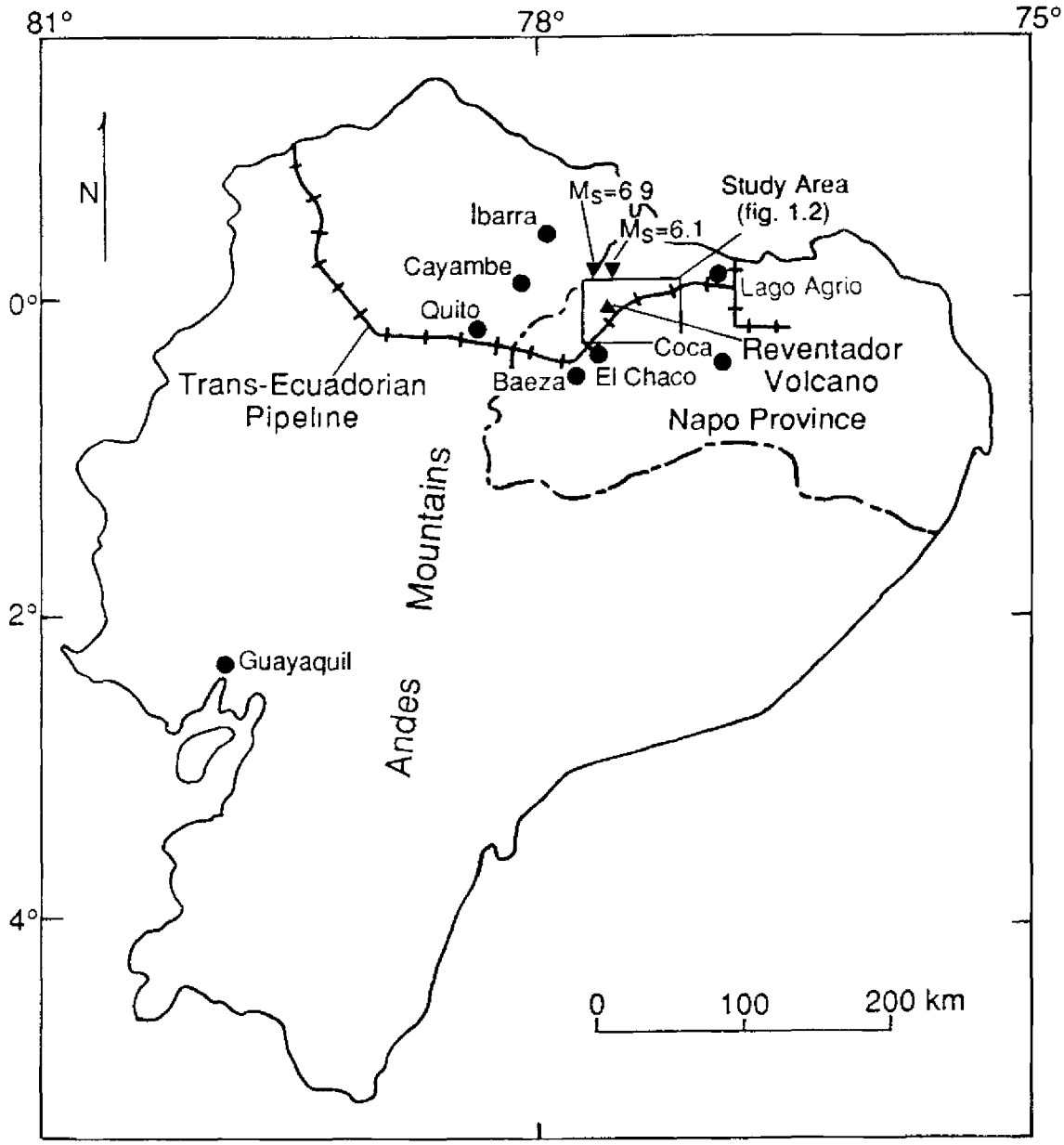

FIGURE 1.1 Index map of Ecuador showing locations of Napo Province, the Andes Mountains, Reventador Volcano (upright triangle), epicenters of the 1987 earthquakes (inverted triangles), the Trans-Ecuadorian oil pipeline, towns and villages (solid circles) that suffered structural damage from the earthquakes, and the mass-wasting study area (open rectangle; Figure 1.2).

region are difficult to evaluate, but undoubtedly were very large (Nieto and Schuster, 1988). Nearly all of the estimated 1,000 deaths from the earthquakes were a consequence of mass wasting and flooding. Because the mass wasting and flooding produced a high percentage of the economic and human losses resulting from these earthquakes, this report deals primarily with these processes, their socioeconomic effects, and the resulting social

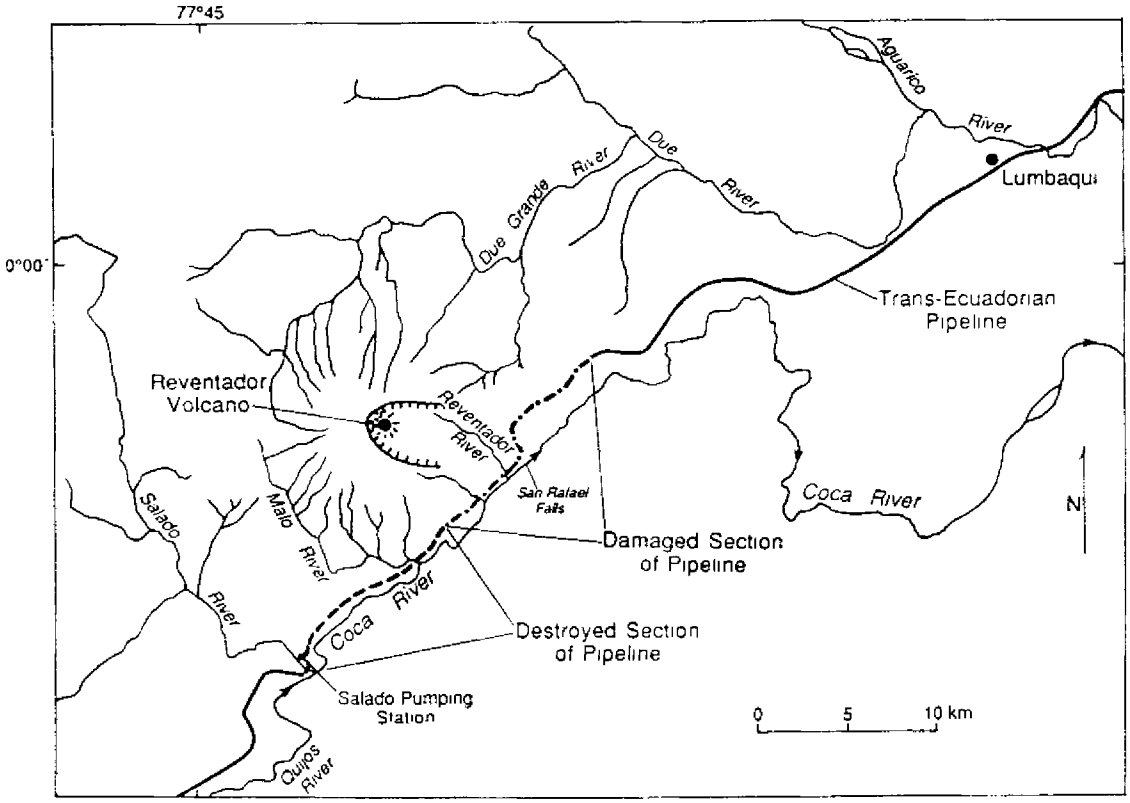

FIGURE 1.2 Area of study of mass wasting and flooding caused by the 1987 earthquakes, showing sections of damage to the Trans-Ecuadorian pipeline.

FIGURE 1.3 Reventador Volcano (elevation 3,562 m). (1978 photograph by S. D. Schwarz.)

implications. Observations related to these factors were made on site in Ecuador by the National Academy of Sciences/National Research Council (NAS/NRC) research team during the spring and summer of 1987.

Earthquakes are a major cause of mass wasting in many parts of the world. Earthquake-induced landslides have been documented for thousands of years; the earliest on record are landslides that dammed the Lo and Yi rivers in Hunan Province, China, in 1767 B.C. (Xue-Cai and An-ning, 1986). During the twentieth century, earthquake-induced landslides have caused tens of thousands of deaths and billions of dollars in economic losses (Keefer, 1984). In some cases, they have denuded thousands of square kilometers of unstable hillslopes. Particularly striking has been the denudation of jungle-covered, saturated slopes in tropical areas (Pain, 1972; Garwood et al., 1979).

A secondary hazard caused by earthquake-induced landslides is the formation of landslide dams. These natural stream blockages cause upstream flooding by stream impoundment, and they often breach catastrophically, causing major downstream flooding. Some of the world's most devastating floods have resulted from failure of large landslide dams that were formed by earthquake-induced landslides (Schuster and Costa, 1986; Costa and Schuster, 1988). In a review of more than 400 cases of historic landslide damming, Costa and Schuster (1991) have noted that about 35 percent of these blockages have been formed by landslides triggered by earthquakes.

The area of eastern Ecuador hardest hit by mass wasting due to the March 5, 1987, earthquakes was S of the epicentral area in the vicinity of Reventador Volcano (Figure 1.2). Most casualties from the earthquakes occurred in this region (Figure 1.4); the greatest damage to the Trans-Ecuadorian oil pipeline and highway occurred along the Coca River immediately SE of Reventador Volcano, upstream from beautiful San Rafael Falls (Figure 1.5). Because of the volcanic activity and river downcutting, the region exhibits strong relief. The average valley slopes range from 35 to 45°; before the 1987 landsliding, these slopes were generally covered by residual soils of variable thickness and by a dense, subtropical jungle.

The earthquake-induced slope failures were very fluid. About 600 mm of rain fell in the region in the month preceding the earthquakes; thus, the surface soils had a high moisture content. The slope failures commonly started as thin slips, which rapidly turned into very fluid debris avalanches and debris flows. The surficial materials and the thick jungle vegetation covering them flowed down the slopes into minor tributaries and then were carried into the major rivers (Salado, Quijos, Malo, Coca, Dué, Dué Grande, and Aguarico: Figure 1.2). Millions of tons of silty, gravelly sand, as well as tree remains and other organic matter, were deposited in the rivers (Figure 1.6). Many of the slopes were almost entirely denuded of their soil and jungle covers (Figure 1.7).