ences cohesion (Brand, 1982; Ho and Fredlund, 1982), which, as noted previously, affects the pseudostatic factor of safety. The area around the Reventador cone has a wetter microclimate than the rest of the zone (E. Aguilera, personal communication, 1987); the INECEL station near Reventador Volcano has a mean annual precipitation of 6,868 mm.

Last, but not least, the materials near Reventador Volcano, being mostly residual soils formed on pyroclastic materials, may simply be more susceptible to failure.

## EVOLUTION OF MASS-WASTING PROCESSES

One of the more striking characteristics of the mass wasting caused by the March 5, 1987, earthquakes was the effectiveness of the transport of materials from the slopes of the lowest-order tributaries to the flood plains of major streams. As mentioned previously, some reaches of the main rivers received as much as 20 m of sediment (measured in the center of the flood plains), most of which was landslide-generated. If we assume a triangular cross section for sediments in the valley bottom, an average width of 600 m for the Coca River floodplain, and a valley length of 20 km between the mouth of the Salado River and San Rafael Falls, we calculate a total volume of $120 \times 10^6$ m$^3$. If we now assume an average depth of landsliding of 2 m (a reasonable value based on field observations), the denuded area was about 60 km$^2$. The calculated volume compares well with the total volume ($110 \times 10^6$ m$^3$) of the mass wastage obtained by Hakuno et al. (1988). This volume attests to the fluidity of the debris flows and the effectiveness of the tributaries in transporting the debris materials. We suggest that two factors may have contributed to this large volume. The first is the nature of the soils involved in the slope failures, and the second is the general morphology of the Reventador area.

In general, the vast majority of the soils involved were tropical residual soils or relatively recent pyroclastic materials of various grain sizes (ash, lapilli, cinders, and pumice). Both of these types of soils have characteristically open structures, and hence high water contents when saturated. The natural water content is typically very close to or higher than the liquid limit. The pyroclastic materials have relatively low liquid limits and plasticity indices. However, the residual soils, being usually at advanced stages of laterization, have high liquid limits (up to 300 percent) and plasticity indices (up to 150 percent). The plasticity of such soils is the result not of high-activity clays, but of the presence of hydrated sesquioxides of Al and Fe in a gel state. In fact, residual laterites have very small or no clay content (Mitchell and Sitar, 1982). If present, clays tend to be of the halloysite type. Both the sesquioxides and halloysite suffer irreversible changes upon drying, and the soils undergo dramatic decreases in plasticity (Mitchell and Sitar, 1982). These hydrated materials, which provide plasticity, behave as cementitious elements that impart physical cohesion to the soils. The open structures are preserved and the result is a brittle, open soil with high capacity to absorb water.

As shown in tests by Hakuno et al. (1988), the soils in the Reventador area fit this characterization well. These authors found natural water contents equal to or higher than the liquid limit, a wide range of plasticities, and absence of clay minerals. Pyroclastic materials, particularly those of fine grain size, also have open structures and relatively low plasticity. These two types of soils exhibit extreme loss of strength if they fail under undrained conditions. The first factor in these dramatic strength losses is the collapse (in the dehydrated residual soils); the second factor is the increase in pore pressures and the attendant decrease in effective stress.

The scenario postulated for the transport of the landslide materials is as follows: (1) Failure at a basal shear surface with an average depth of 2 m, probably at the bottom of the residual soil profile and at the top of the weathered rock. (2) Contractive behavior of the failed soil. Contraction decreases effective stresses until a steady-state strength is reached (Poulos et al., 1985; Ellen and Fleming, 1987; Fleming et al., 1989). Given the highly contracted behavior of the soils in this area, we can surmise that the steady-state strength of these soils is very low. (3) High-velocity flow down steep slopes that are several tens of meters to a few hundred meters long. (4) Movement of debris flows to the thalwegs of tributaries that do not have floodplains. Flow then was channeled and effectively conducted to channels of higher-order streams.

## FLOODING OF RIVER VALLEYS IN THE VICINITY OF REVENTADOR VOLCANO

Crespo et al. (1987) roughly estimated that "ground shaking triggered mudslides and rock avalanches near the volcano involving more than 100 million cubic yards [76 million $m^3$] of soil and rock." Based on airphoto study of denudation of slopes in the vicinity of Reventador Volcano, Hakuno et al. (1988) estimated the total volume of slope failure at about 110 million $m^3$, but noted that this approximation easily could have been in error by as much as 50 percent. Whichever of these estimates is the more accurate, a large percentage of this huge mass of material combined with water in the Coca and Aguarico Rivers and their tributaries to form thick debris flows that descended these tributaries of the upper Amazon.

Because these debris flows occurred at night, and thus were not easily observed, we are not sure of their character. We do not know whether they acted as true debris flows, or whether they might better be designated as "hyperconcentrated flows" or "mud floods." However, based on (1) depths of sediment deposited in the rivers, (2) "trimlines" on the lower valley walls, which indicated the heights to which the rivers rose when charged with the debris flows, and (3) damage to the Trans-Ecuadorian pipeline and highway due to deposition and erosion, we know that considerable flooding occurred (Figures 5.16A,B, 5.17A,B, and 5.18). Figure 5.19 indicates

FIGURE 5.16A

FIGURES 5.16 Aerial oblique views looking downstream at the confluence of the Salado and Quijos rivers to form the Coca River. (A) 1978 view (photograph by William Savage, Pacific Gas and Electric). (B) April 1987 view illustrating that braided debris-flow and flood deposits (as much as 20 m thick) have covered much of the