typhoons, *d*) the slope gradient, *e*) the presence of a well-defined natural drainage network and, *f*) a low density of vegetation in at least part of the drainage basins involved.

Further complementary aspects of mudflow evolution were the extent, geometry, shape and low roughness of the drainage network; slope gradient variations along major rivers radiating from near the cone; and shape variations of river channels with altitude and geomorphology. The loss of internal friction of the ash cover and its consequent mobilization were almost immediate, as predicted by PHIVOLCS experts, who had studied the initiation of lahars after the 1984 eruption of Mayon volcano in Legaspi (southern Luzon).

The speed of the process and the occurrence of two or more lahars per day along the same river basin were a function of the abundance and duration of rainfalls. Lahars were readily recognized by local inhabitants, due to the typical roaring sound, the gray-yellowish color, and feared because of their great destructive power.

Abundant water-borne sediments were thus deposited at distances of 20 to 45 km from the crater. Siltation begins, in fact, when slope gradient becomes minimal and a sizable reduction in the flow velocity takes place. Under these conditions the sediment load can no longer be carried and the depositional behavior prevails. This is usually associated with the widening of the riverbed and nearly level topographic conditions. When the velocity of lahars starts to decrease, water and finer suspended particles migrate upwards, while at the same time deposition of bed-load and coarser sediments begins due to the higher viscosity of the mass. A sample was taken during an on-going lahar (O'Donnel River, September 1991). After 24 hours of free sedimentation about one fourth of the volume consisted of sand and silt.

8.6.2 Hot and cold lahars and their distribution

Primary hot lahar, directly associated with the eruption, are generated during explosive phases when incandescent ash clouds carry hot rock fragments, blocks and high temperature steam. Due to the partial condensation of the steam near the surface, hot water is generated and primary hot lahars start from near the steam emission area. When this hot mixture flows during the rains or is channeled into a river, it warms up the additional cold water it gets mixed to, while the lahar progressively increases in volume. The mixed-source hot lahar can reach tens of kilometers of distance, the temperature rendering the mass less viscous and more mobile than colder mixtures.

Abundant hot lahar were described by The Manila Times on July 27, forty-five days after the most critical eruption episodes. Due to heavy rains and the fact that the Abacan River overflowed its banks, 12 villages near Mexico City (San Fernando, Pampanga) and several small villages near Angeles City were invaded by hot lahar at a distance of 25 to 40 km from the crater. The devastation induced by these hot mudflows and related flooding led to the evacuation of 11,660 people in the three provinces around the volcano, and the destruction of 7,600 houses. Small hot lahars were still occurring even at the end of September 1991 upstream of the O'Donnel River

Cold or secondary lahars occur some time after an eruption and are triggered by heavy rains. They can include pre- and post-eruption material, reach a long distance during prolonged monsoon rains and cause enormous destruction.

Both types of lahar associated with the Pinatubo eruption had properties in common: except for a limited number of trees and smaller plants, they basically carried silt and sand, the presence of vegetation being generally confined to the period close to the explosive episodes; blocks and boulders were carried along the upper reaches of rivers, where heavy ejecta had accumulated in larger quantities; sediments deposited along the downstream portions of river channels mainly consisted of fine materials; and erosion prevailed in general along upstream sections with deposition of sediments mainly in and along the downstream river segments.

The major rivers originating from the volcano, whose beds were clogged by lahars, from northwest clockwise (Fig. 8.7) are Marella-Sto. Thomas, Balin Baquero-Bucao, O'Donnel (Bangut)-Tarlac, Sacobia-Bamban (Abacan), Pasig-Potrero and Porac-Gumain. Figure 8.9 illustrates examples of major lahars at distances ranging from a few km to about 30 km from the crater and Table 8.1 shows sediment delivery rates from 1991 to 1993.

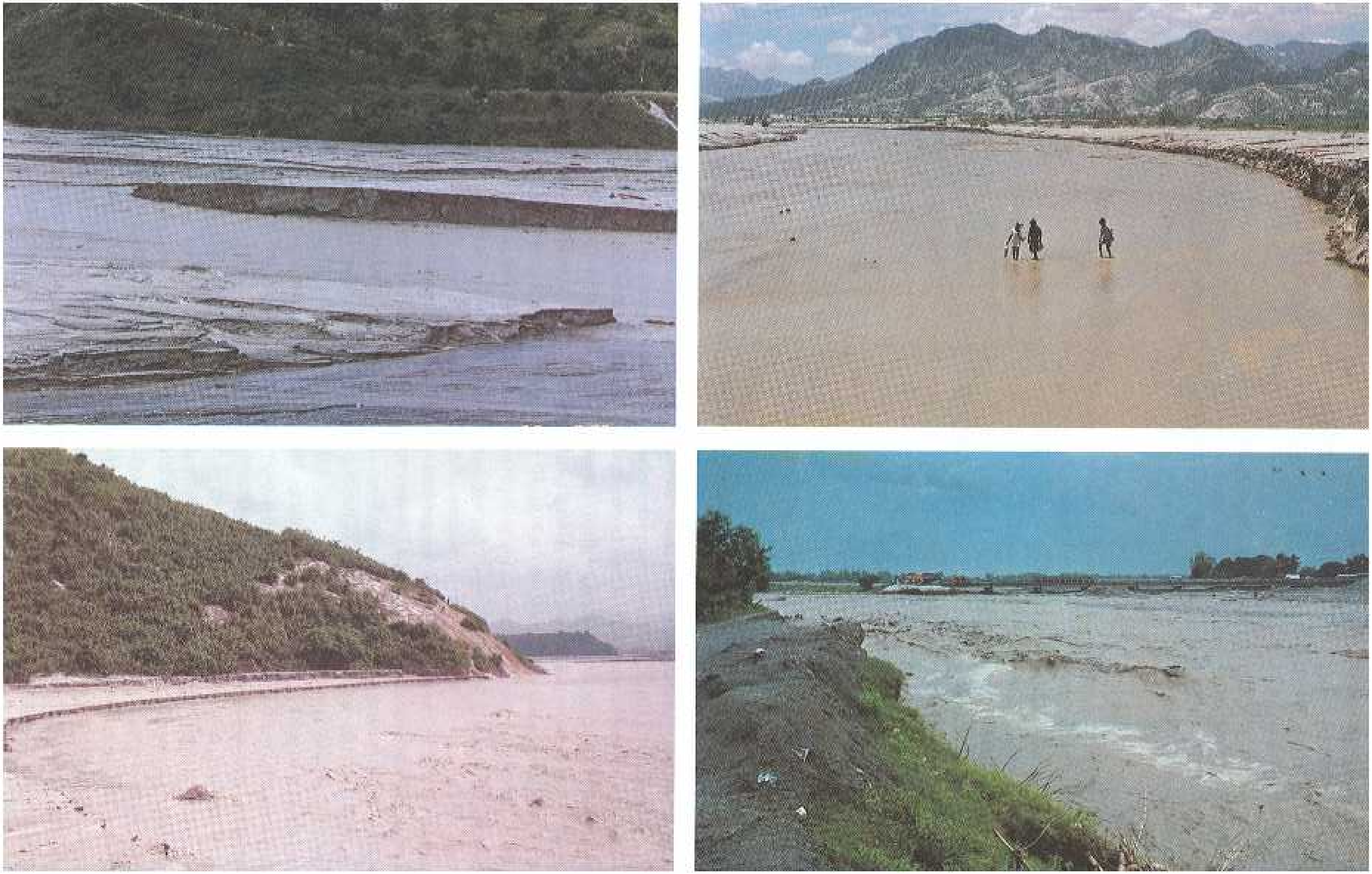

Fig. 8.9 – *Sheet-like lahar deposits upstream of the O'Donnel River a few km from the crater (top left). The deposits are entirely composed of fine sediments; neither blocks nor debris are present. Calm lahar near Angeles City (Abacan River), with the surrounding landscape blanketed by volcanic ash (top right). Cold roaring lahar about 12-km from the crater along the O'Donnel River, near Santa Lucia (bottom left). Turbulent cold lahar at Pabanlag Bridge, near Floridablanca (bottom right). The pictures were taken in July-September 1991.*

Between June and September 1991 it was not possible to reach the upper courses of the major rivers radiating from the western and southern slopes of the crater, so the quantity of blocks and heavy ejecta carried by the lahars is poorly known. It is probable that heavy pyroclastics were deposited before reaching the mid-terminal sections of the rivers. Inspections made in September along the Zambales coastal area, where rivers are already very close to the sea, confirmed that mudflow materials consisted almost entirely of fine silt and sand. Along Sto. Thomas River, at San Marcelino (Fig. 8.7) SW of the crater, both new and old mudflows (seen in eroded riverbanks), carried small-sized pumices (3 to 10 cm in diameter) in a fine sand matrix.

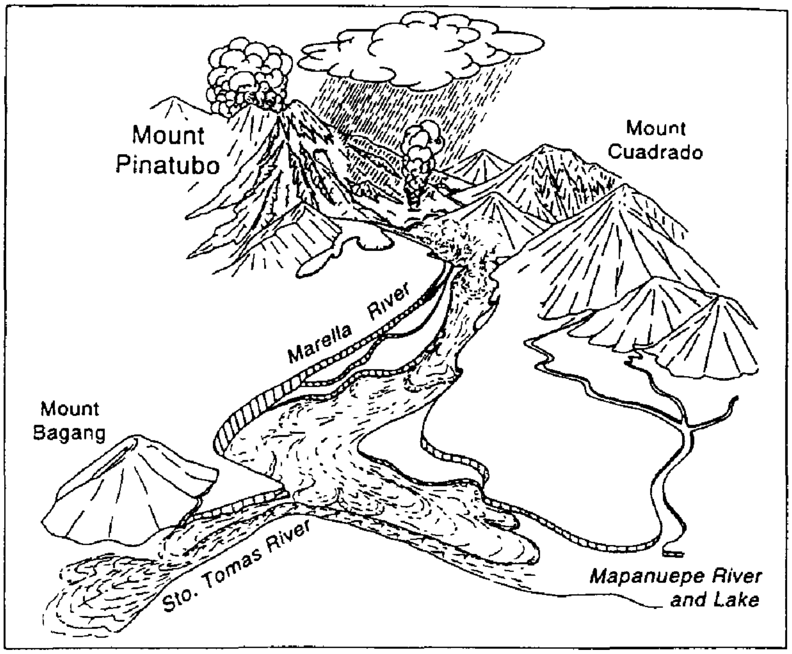

Fig. 8.10 – *Idealized sketch of Pinatubos's lahars along Marella and Sto. Thomas Rivers and Mapanuepe River damming (Umbal and Rodolfo. 1992).*

An impressive sequence of lahars along the Marella and Sto. Thomas Rivers during the 1991 rainy season was described by Umbal and Rodolfo (1992). The sizable quantity of lahars caused by the intense rainfall, due to the narrowness of the Sto. Thomas River upstream channel, was directed upstream into a tributary (Mapanuepe River) thus forming a lake (Fig. 8.10). The water volume stored by the temporary barrage later broke through the volcanic-debris dam, mobilizing the deposits of previous lahars, channeling them towards the South China Sea and heavily eroding the banks of Sto. Thomas River. This occurred during the 1991 rainy season which caused the mobilization of 185 Million cubic meters of debris along the Marella and Sto. Thomas rivers (Table 8.1) and damaged an area of 46 square kilometers.

8.6.3 Some observations on Mt. Mayon and Mt. Pinatubo lahars

The properties and behavior of mudflows generated during and after the 1984 eruption of Mayon volcano in Legaspi (southern Luzon, Fig. 2.1) were studied by PHIVOLCS researchers. Results were discussed during the First International Seminar-Workshop on Lahars and Landslides (December 1986, Legaspi) and partly summarized in the PHIVOLCS paper titled Geologic Hazard and Preparedness Systems. J.V. Umbal (1986), one of the authors, made the following observations on Mayon's mudflows. rainfall needs to be above 66 mm for lahar initiation, hot lahar have a temperature above 50 degrees C; flow is mainly laminar with boulders bobbing on top; flow velocity is between 3-5 m/sec during the initial turbulent phase; and mean grain size of particles is 0.5 mm.

There is a marked difference between the morphologies of Mt. Pinatubo and Mt. Mayon. Mount Pinatubo is larger, and the contours are quite fragmented, while its shape does not compare at all with the almost perfect conical symmetry of Mount Mayon. Within a radius of 20 km, between the crater of Mt. Pinatubo and Porac City to the east, elevations drop from 1,745 to 80 m with an average slope gradient of 8.3%. Mayon's crater, on the other hand, is at an elevation of about 2,500 m and has a continuous gradually decreasing slope to sea level about 10 km away, the average gradient being 25%. It is thus clear why the Mount Mayon lahars were able to carry heavy pyroclastics over long distances compared with the Pinatubo mudflows which were composed mainly of fine sediments in their downstream reaches. According to Umbal (1987) an area of 3.9 square km was affected by mudflows after 1984 Mayon eruption.

Lahar-invaded areas around Mount Pinatubo, by contrast, covered over 200 square kilometers by the end of the 1991 rainy season. This explains the order-of-magnitude difference in the post-eruption effects of the two volcanoes, as well as the destructive power of the Pinatubo lahars, due to the greater volume of sediments transported and deposited. Umbal estimates the volume of sediments transported by the Mayon lahars during the 1984 rainy season at 6 million cu. meters. In comparison, 805, 555 and 505 million cu. meters of sediments were carried by mudflows from Pinatubo during 1991, 1992 and 1993, respectively, and a further 1,86 cu. km is likely to be mobilized during the years 1994-1998.

8.7 Casualties and injuries

According to National Geographic magazine (December 1992), about 900 people lost their lives as a consequence of the Pinatubo explosion. Some belonged to the Aeta tribe, estimated to have numbered 12 thousand before the eruption, living in small villages within a radius of 20 km around the cone. When the situation near the crater became critical and evacuation was ordered, some Aetas refused to abandon their land; many of them died during the explosive phase, 12-15 June. Most casualties in cities and villages were caused by the collapse of roofs, houses and other buildings due to the weight of the ash. The early warning of critical eruption phases and preparedness measures formulated by PHIVOLCS, reduced the number of deaths. Thirty-nine people, however, were injured by rock fragments associated with the rain and sand which fell on June 14 near Subic Bay. According to PHIVOLCS (Mount Pinatubo, 1991), in addition to the casualties due to the direct effects of the eruption, 211 people died in evacuation camps as a result of disease and malnutrition; 94% of these were Aetas.

8.8 Damage assessment

8.8.1 General

The effects of the Pinatubo eruption included extensive damage to human activities and structures. The ash blanket, from several meters thick in the valleys near the crater down to 5 cm at an average radial distance of 40 km, affected an area of about 5,000 square kilometers. Lahars brought devastation to lands lying more than 40 km from the crater. The damage associated with the eruption was caused in three ways:

- the direct effect of volcanic ash. The weight of ash caused the collapse of roofs and often of two and three storey houses. Ash blocked roads, damaged infrastructure services, clogged natural and man-made drainage systems. Cultivated land, in particular, was badly affected by the nearly immediate destruction of crops and interruption of agricultural activities. The direct damage to agriculture concerned the flat land W and mainly E of Pinatubo (Central Plain) which used to be the richest farmland of the Philippines, because of the fertility of the soil (of volcanic origin), the abundance of water and the vicinity to Manila markets. Thus, the effect of the ash blanket on agriculture was catastrophic both in terms of immediate damage and loss of future income.
- the numerous lahars which brought devastation to lands beyond the area heavily affected by ashfalls (Fig. 8.7). During the 1991 and 1992 rainy seasons several dozen mudflows reached the flat land, villages and cities around the volcano, burying agricultural areas and destroying crops, vegetation and houses, while wreaking havoc on human activities. In the flat areas and depressions inundated by lahar near Bacolor (Fig. 8.2), groups of houses with their inhabitants were buried under 3-4 meters of sediments (The Manila Bulletin, September 12, 1991).
- lahar-related flooding of low-lying areas between 30 and 50 km from the crater. Floods are a recurrent problem in the southern part of the Central Plain (Pampanga and Bulacan provinces). The Plain is crossed by the Pampanga River (and by a complex network of tributaries) and drains into Manila Bay (Fig. 8.2). From Conception City (south of Tarlac), down to Manila there is a huge area of virtually flat land with little slope and numerous riverbeds. This drainage network badly suffered the direct impact of lahars and their delayed effects. Numerous floods occurred in this flat zone as a result of river siltation; depressions which had traditionally been used for farming or had served as small reservoirs for irrigation and as fish ponds, were inundated and locally clogged by sediments.

Fig. 8.11 - *Collapsed school in Porac (top left), damaged roofs (top right) and destroyed hospital (bottom left) in Olongapo City, and collapsed roof in San Narciso, Zambales, (bottom right). Light roofs in general could not withstand the weight of the ash cover*

8.8.2 Damage to buildings and city services

Over 110,000 houses were variously damaged and 40 per cent of these were destroyed by the ash deposited on roofs (National Geographic, December 1992). Its weight caused the collapse of numerous buildings in Angeles City, 25 km East of the cone. At this distance from the crater, the ash blanket was comparatively thicker on the West side of the volcano due to typhoon winds.

The US Army Clark Air Base, 20 km SE of the cone, was evacuated first, because of the abundant ash deposits and the unbreathable air during critical eruption phases; it was later abandoned by the nearly 15 thousand soldiers stationed there and shut down probably because of the high estimated cost of cleaning and rehabilitation and the fear of future explosive episodes.

It was fortunate that the ash blanket accumulated more thickly on the western side of the volcano where cities are fewer and hence the population is comparatively smaller. Because of the tropical climate in the Philippines, roofs are merely designed to support their own weight and the loads that occur during typhoons and repair works. However, an ash blanket 10 cm thick resulted in an additional load of about 150 kg/sq.m, excessive for many light structures.

Many buildings collapsed: houses, schools, hospitals and numerous markets where roofs were merely designed to offer a protection from rain and sun. Figure 8.11 shows typical damage due to roof collapse. Water supply and sewerage systems also suffered sizable damage both from the direct impact of ashfall and for the collapse of buildings in major cities around the volcano. Telephone and power lines were also interrupted during the critical eruption phase, because dust, high temperatures and ash-covered roads prevented repair works for days.

8.8.3 Damage to roads and bridges

The road network (DPWH Report, September 1991) was directly damaged by the deposition of ash, which had to be removed like snow to enable traffic to circulate. The clogging of side drains and minor structures soon became a major problem and with the beginning of the rainy season by mid-June 1991 numerous roads were inundated.

Lahars posed a major threat to bridges by eroding around piers, by the lateral pressure on piles and by the overtopping of bridge decks. Lahars are characterized by high velocity and low viscosity upstream and by the reverse situation downstream, where riverbed gradients are minimal. Most bridges are located in areas of nearly flat topography where the speed of the flow is naturally low and the viscosity comparatively higher. When the silting process begins, before the sediment mass becomes motionless, lahars assume the consistency of a fresh and dense concrete mix, so the pressure exerted on piles can become excessive and eventually cause the collapse of the structure. Any heavy volcanic ejecta which may be carried by lahars increase the danger to man-made structures, such as houses or bridges.

Lahars are powerful landform-molding agents because of the huge quantities of sediments they carry In the case of Bamban Bridge (Fig. 8.12) the existing structure was destroyed, the channel clogged with fine sediments and the drainage pattern of the site markedly modified. Soon after the collapse of the road and railway bridges, it was evident that new bridges would have to be longer. The geomorphological changes in other cases altered the drainage pattern by laterally moving the riverbed and hence imposing a different location for the new bridge.

Deforestation played an important role in the change of the hydrologic regime and the riverine landscape since it facilitated runoff and downslope movement of huge quantities of volcanic ash.

Damage to roads and bridges is evident from Figures 8.12-8.14, which illustrate the different types of problems caused by lahars. The sequence of figures concerns bridges located counterclockwise around the periphery of the volcanic edifice. Figure 8.12 shows the huge lahars along Bucao and Sto. Thomas rivers in Zambales (top and middle), and the damage to the road and railway bridges along the Bamban River (bottom). Figure 8.13 shows the condition of the Santa Rosa bridge (top left) in Cabangan (Zambales), about 34 km west of the Crater, where siltation clogged the river almost entirely, leaving a mere 40 cm clearance beneath the deck-beams. Maculcul bridge (top right) north of San Narciso (Zambales) suffered a similar problem. The bottom figures show the partly and totally collapsed

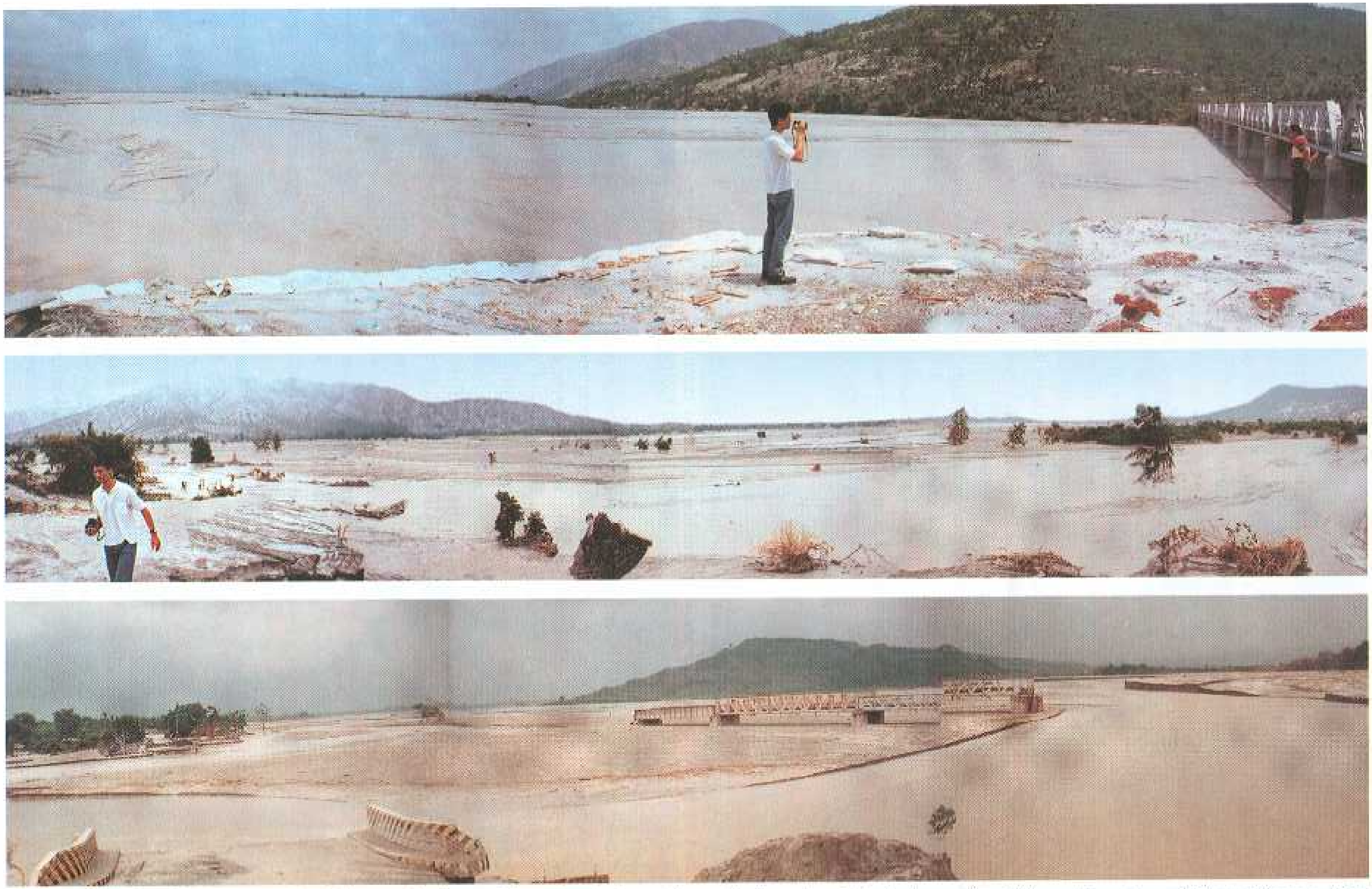

Fig. 8.12 – *Enormous lahars in Zambales at the Bucao River (top) where the road along the right bank was buried by sediments, and Santo Thomas River (middle) where a long concrete bridge was destroyed. Catastrophic lahars at the Bamban Bridge (Pampanga), about 10 km N of Angeles City (bottom). Both the railway and the highway bridges were washed out by the destructive power of lahars, the riverbed being clogged by about 2 m of sediments.*

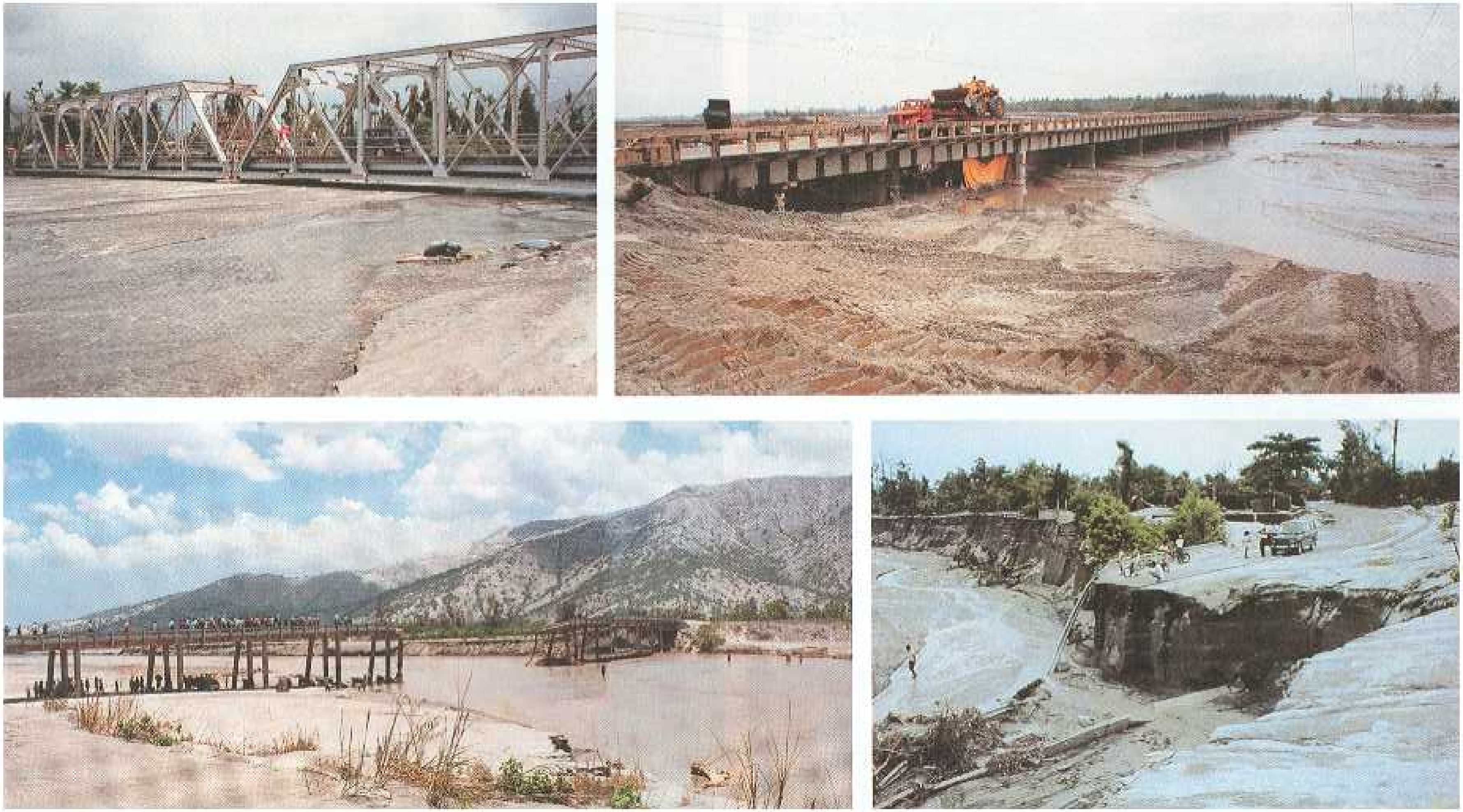

Fig. 8.13 – *Damage to bridges in Zambales, between San Narciso and Botolan (see also Fig. 8.2). Clogged riverbeds by lahars in Santa Rosa (top left) and Maculcul Bridge top right), where the clearance was reduced to 40 cm and 2 m, respectively. Partly (bottom left) and totally destroyed (bottom right) Sto. Thomas bridge near San Marcelino.*

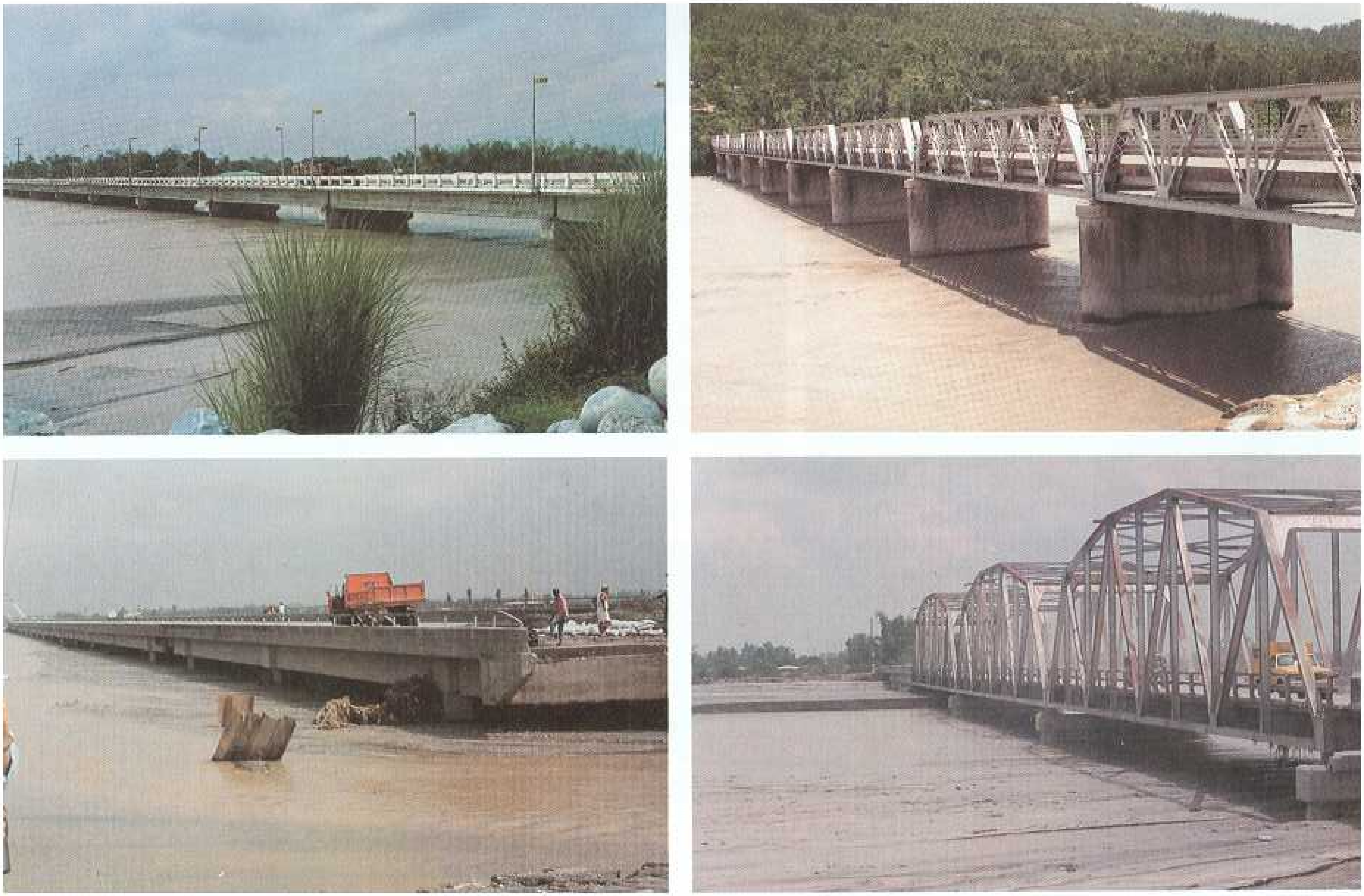

Fig. 8.14 *Clogged riverbed in Tarlac (top left), and partially filled riverfloor of the Bucao River (top right), on the Zambales side. Collapsed bridge span and clogged riverbed along the Superhighway around 30 km N of Manila (bottom left), and clogged floor of the Apaya River with only 1 m clearance (bottom right), north of Manila.*

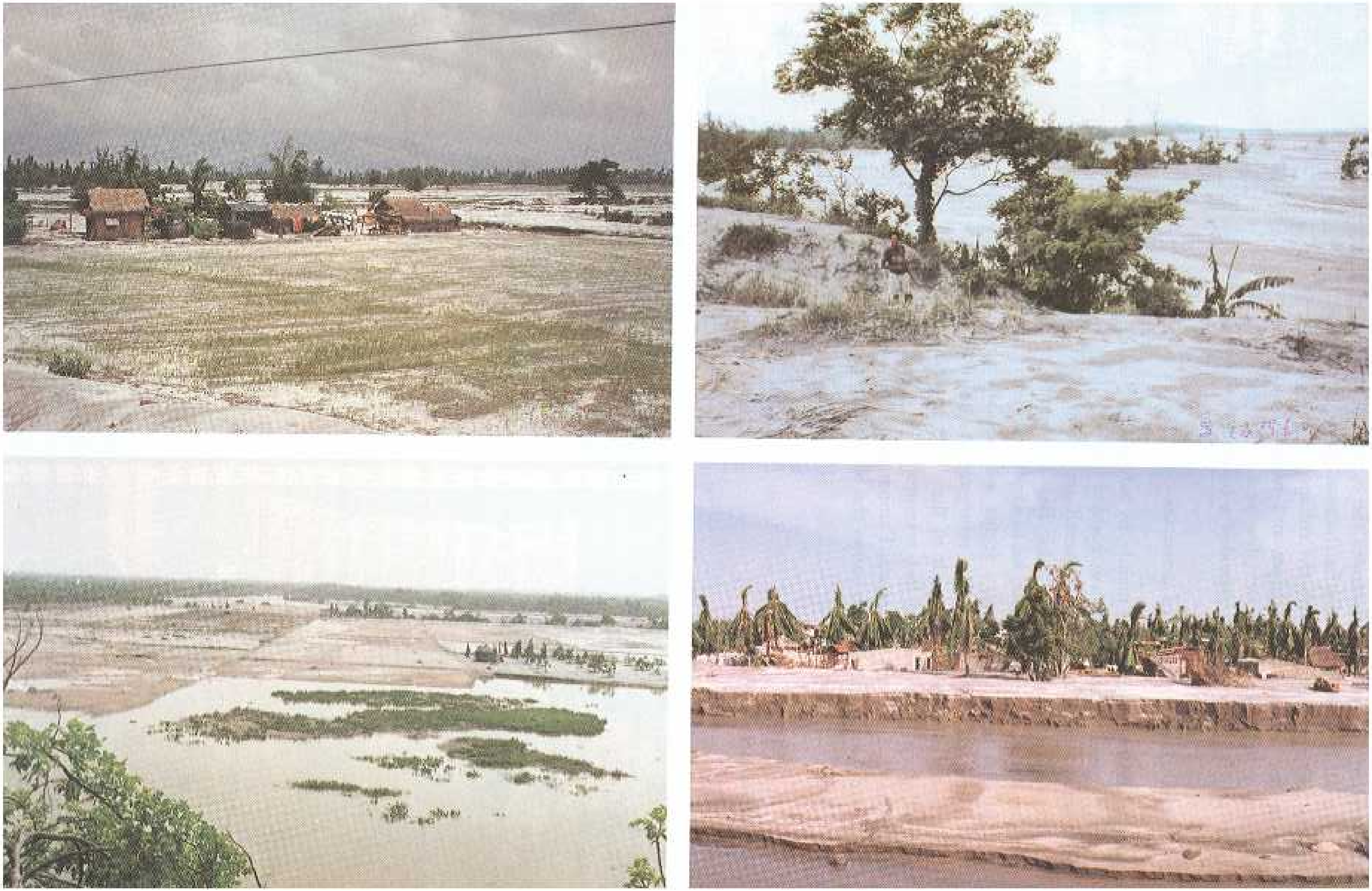

Fig. 8.15 – *Farmland blanketed by the volcanic ash between San Narciso and Botolan (top left), and near San Marcelino (top right), Zambales side. Partially submerged ricefield (bottom left) by grayish ash-rich waters (Zambales side), and village in Porac affected by ashfall and later on by lahars (bottom right). Due to the ash deposited during the eruption, trees look like closed umbrellas.*

bridge in San Marcelino. Figure 8.14 illustrates the condition of bridges with a significant reduction in clearance (top); two bridges North of Manila (bottom) underwent a severe reduction of the clearances. and the one on the left also suffered with the collapse of a span.

In addition to the above, other bridges and minor drainage structures were condemned: their collapse can occur any time during the next few years. The dredging of riverbeds upstream of endangered bridges, in fact, is likely to have provided a temporary extension of life only for some of them.

8.8.4 Damage to agriculture and related activities

The damage to agriculture, caused mainly by ashfalls and lahars, was estimated at over half a billion US$ (Chapter 9 gives details). The ash blanket and its partial conversion into lahars (mudflows) during the 1991 rainy season involved an overall area of 385,000 hectares, roughly bounded by Iba, Tarlac, La Paz, Mt. Arayat, Sto. Thomas, Subic Bay and San Antonio. Out of this total (ADB, 1991*b*) 326,000 ha were devoted to forestry, 43,000 ha to agriculture (rice, vegetables, fruit trees and sugarcane) and 16, 000 ha to fisheries. The forestry sector was spoiled mainly in the provinces of Zambales (193,200 ha) and Tarlac (83,000 ha) and 302 reforestation projects (9,595 ha) were involved.

Considerable losses occurred as a result of the destruction of agriculture facilities. irrigation systems, agri-based industrial activities and lost revenues from agricultural production.

About 16,000 ha of fishponds in Bataan, Pampanga, Tarlac and Bulacan were affected by siltation due to the ashfall and lahars. Figure 8.15 shows the effect of the ash blanket and flooding of croplands around the volcano.

8.9 Environmental impact

One major effect of the eruption was the physical impact on the environment, with widespread modification of pre-eruption landscape and destruction of the vegetation mantle. After the eruption the environment around the crater, with scattered dark- gray branchless trees, looked completely inhospitable to life. Vegetation in tropical regions recovers fast, but the recovery of rain forest which originally covered Pinatubòs landscape will take decades to centuries.

With the significant changes brought by the eruption the hydrology of the region was altered and the natural drainage system partly modified. First, a number of incised valleys near the crater were clogged with pyroclastics and heavy ashfalls. Part of this material is likely to be subject to accelerated erosion during the coming rainy seasons until a stable topography is re-established. This process of reshaping the landforms will proceed in parallel with the weathering of the newly deposited volcanic products, the growth of spontaneous vegetation and the formation of a new topsoil Reforestation could contribute greatly and at the same time provide job opportunities for the local inhabitants.

According to the Task Force Report (ADB, 1991b) «*The DENR-Region III reported that the volcanic eruption damaged a substantial area of established forest lands in the provinces of Zambales (193,200 ha), Tarlac (83,100 ha), Bataan (33,000 ha) and Pampanga (16,800 ha) amounting to approximately 326,000 ha. This includes several DENR reforestation and social forestry projects covering about 19,402 ha in the provinces of Zambales, Tarlac, Pampanga and Bataan. A rough estimate of the cost of damage is approximately 117.87 million US$, but considering the vast devastated area and the number of years to re-establish the forest lands, the value of production loss will undoubtedly be more substantial. The DENR-PAWB also reported that perhaps the single largest unaccounted casualty in Mt. Pinatubòs recent eruption is the Philippine wildlife (flora and fauna) which are found on Mt. Pinatubo and its surrounding environs. The destruction of the endemic species in the area will surely result in the alteration of the ecological balance between flora and fauna. Endemic species in the area are the following: bats, insectivores, rodents wild boar, deer and several other species of birds, reptiles, and lesser known fauna species. Most birds and fast moving mammals have moved to safer ground, possibly northward to Tarlac, Pangasinan and Bagac-Morong area. However, the smaller species such as frogs, lizards and snakes may have been caught in the eruption. Alteration*

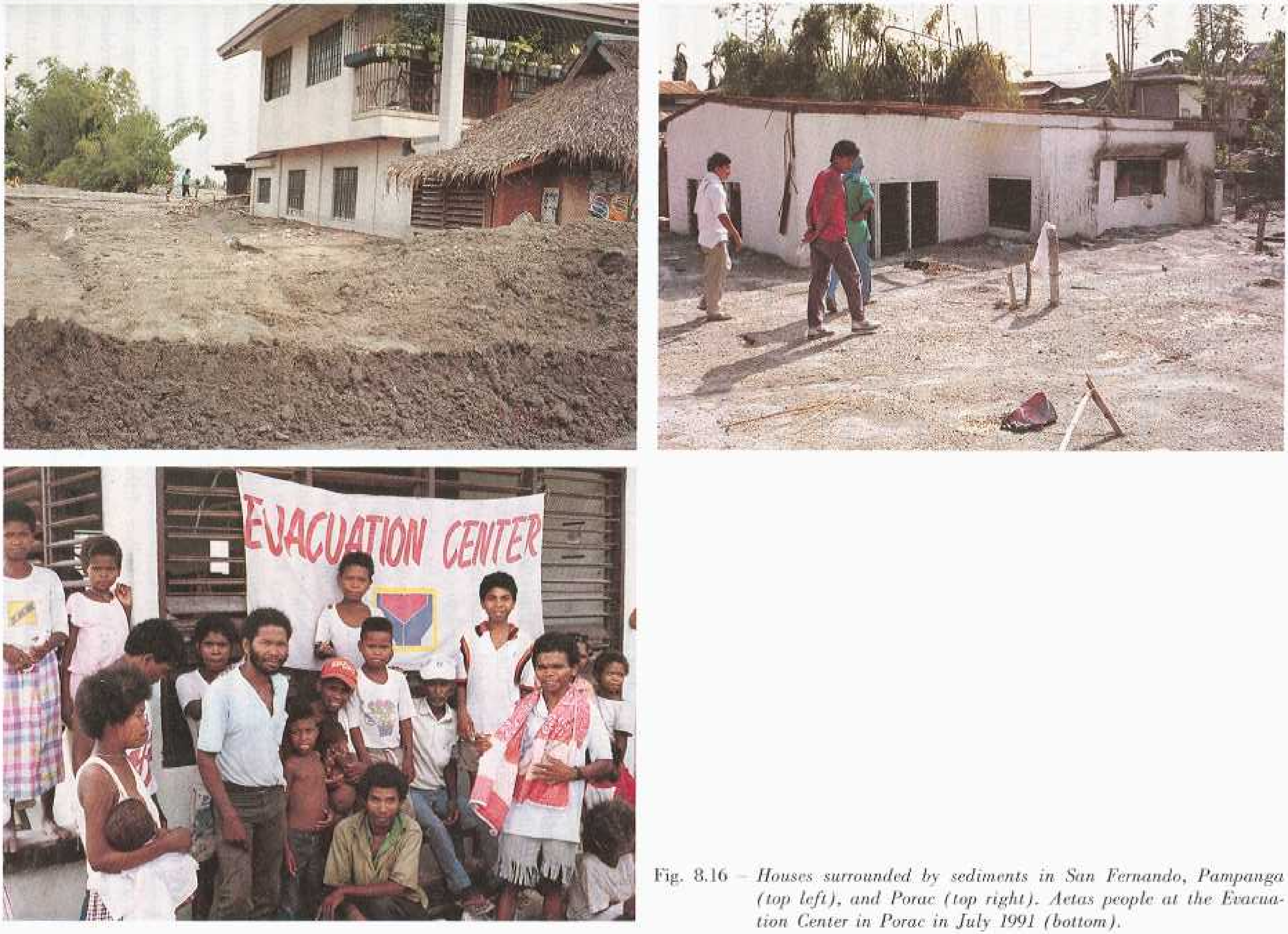

Fig. 8.16 – *Houses surrounded by sediments in San Fernando, Pampanga (top left), and Porac (top right). Aetas people at the Evacuation Center in Porac in July 1991 (bottom).*

in the hydrologic regime of rivers and streams is also inevitable due to filling up of river channels by lahar and other volcanic debris. Thermal pollution in areas directly affected by mudflow/lahar could render rivers and streams biologically dead. Streams quality monitoring is still being undertaken by the DENR to document changes in the physico-chemico-biological structure of freshwaters».

Long-term alteration occurred in the riverine habitat due to the abundant ashfalls and lahar-erosion upstream and to silting downstream. A negative influence of ash on the chemistry of river waters must have at least temporarily affected the riverine ecosystems.

Topsoil composition was altered both by the variable thickness of the ash deposits and the new minerals brought by the eruption, while shallow water tables are thought to have suffered some pollution by ash-carried chemicals.

There will be a different evolutionary trend on lands with 10-12 cm or less of ash, compared to the zones covered by heavy ashfalls. Where the cover was thin, combined effects of vegetation recovery and human agricultural activity will soon produce a higher fertility soil. Where the ash blanket is thicker a new vegetation will have to adapt to this virtually uniform, fine, nitrogen-poor material. Thus the formation of a new humus will probably take decades.

Through a comprehensive study of the potentials and limitations of the agricultural, industrial and residential areas unnecessary and uneconomic investments for social purposes can be avoided. The impact recorded on the South China Sea waters was also great. Along the Zambales shoreline fine ash from the eruption and sediments brought by lahars temporarily altered the chemistry of the waters. Corals in the area were also damaged by the turbidity induced by the finer fraction of the sediments.

Figures 8.15 and 8.16 (top) give an overview of impacts resulting from lahars on flat lands.

8.10 Social impact

There are two main social groups in the area: the Aetas predominantly living on the south-western slope of Mt. Pinatubo and the farmers mainly residing on the flatlands around the volcanic edifice. According to the DPWH (DPWH Report, 1991) nearly two million people are thought to have been affected in various ways by the eruption and its secondary effects.

An estimated 678,000 employed workers were displaced as a consequence of the eruption, thus almost doubling the number of the unemployed in the region. Primary damage due to ashfall also disrupted the activities of Clark Air Base and Subic Naval Base with immediate consequences on the purchase of local goods and the interruption of contractual services.

The 12,000 Aetas, were forced to evacuate during the main eruption episodes. According to Hiromu Shimizu (1989), who recently published an ethnographic study on the social and religious life of the Aetas, this tribe belongs to the Negrito ethnic group. Shimizu, who studied the Aetas world, sharing his life with them for a long time, reports they were forced to settle on the southwestern slopes of Pinatubo by the waves of migrants who arrived during the past century. Organized in families, small groups or temporary villages, they were used to move from place to place on the slopes of Pinatubo every five to ten years. The Aetas acquired a thorough knowledge of fauna and flora in the volcanic environment.

With their forced migration from Pinatubo and relocation in distant areas with different environmental conditions, the Aetas have suffered more heavily from the eruption than the farmers. Some of them died during the explosive phase having refused to abandon their bamboo houses. Many of them, however, gathered in evacuation camps where they suffered from malnutrition and a variety of diseases. Figure 8.16 (bottom) shows Aetas at the evacuation camp in Porac a month after the eruption.

Lowland farmers also suffered from the almost complete disintegration of their environment, as well as the destruction of their property and failure of their activities. Within a few weeks of the eruption, the natural resources on which about two million people depended were temporarily annihilated, and productive activities, agriculture and commerce as well as social life were completely disrupted.

Part of the flatland agricultural environment some distance away from the crater will recover in a few years, and farmers will resume their activities. The restoration of the Aetas environment will take much longer and the habitat will not be the same.