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GEOLOGIC INVESTIGATIONS SERIES
MAP I–2772 (SHEET 2 OF 2)

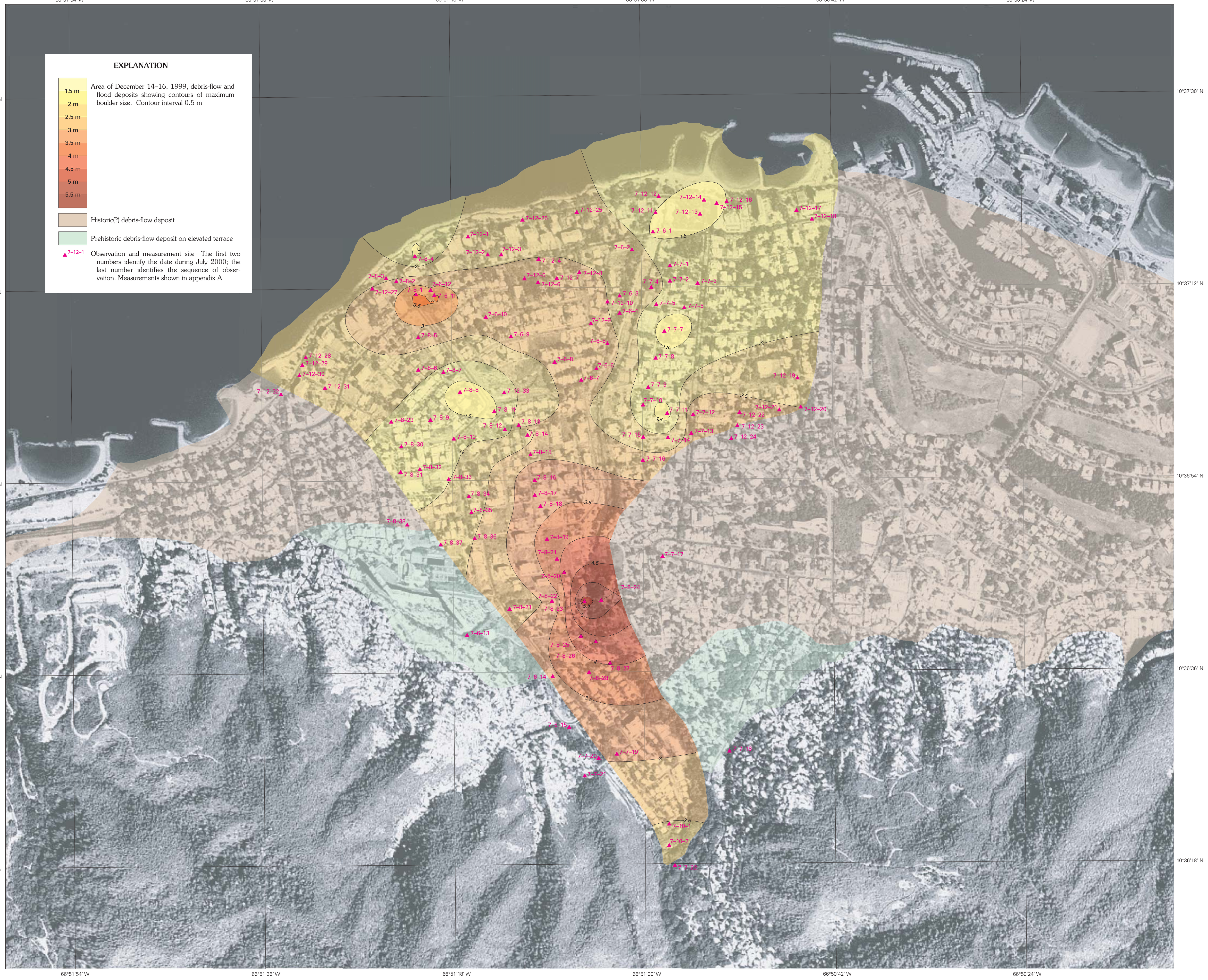

Figure 3.—Debris-flow and flooding deposits with contours of maximum transported boulder size on the Caraballeda fan.

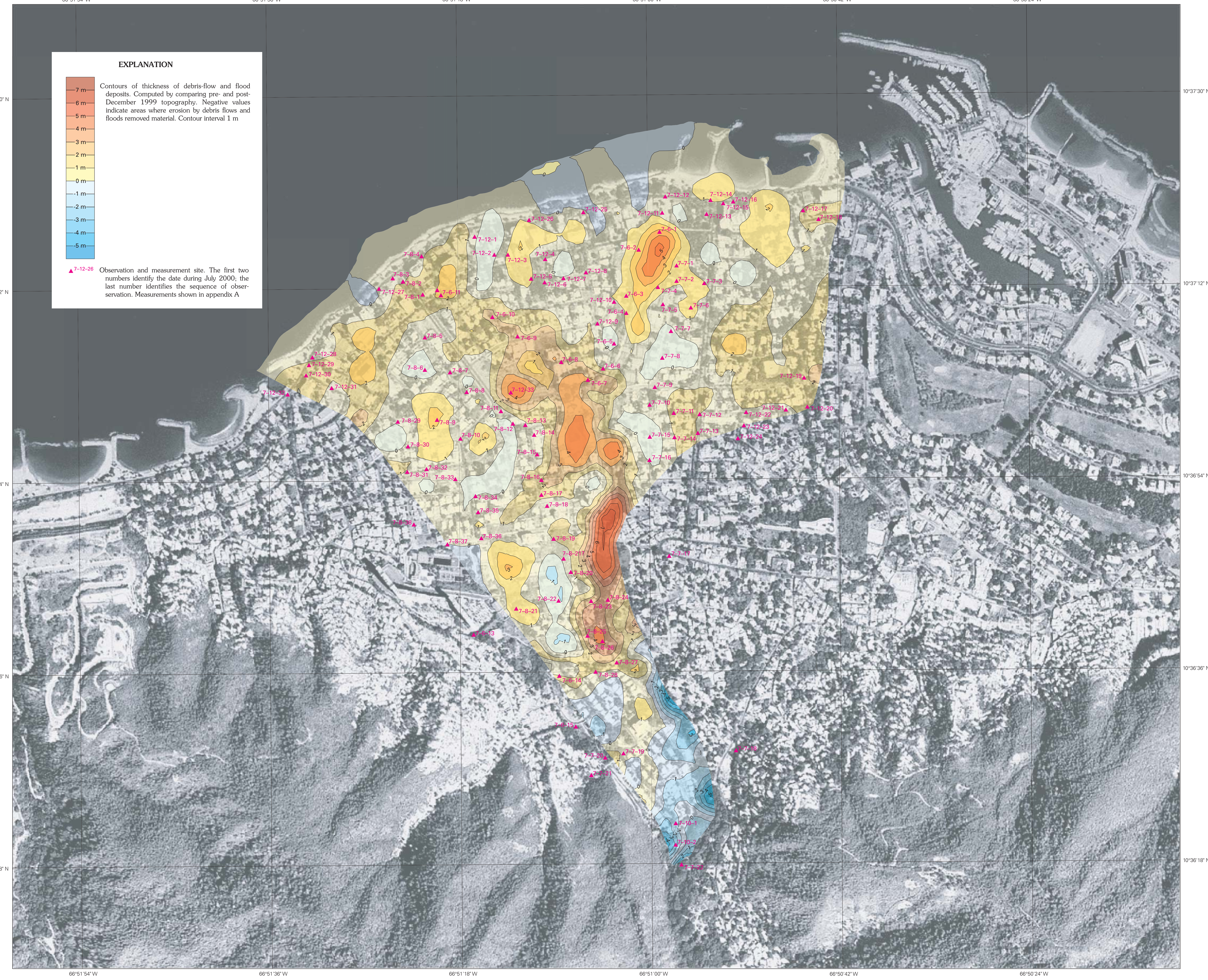

Figure 4.—Debris-flow and flooding deposit thickness determined by comparison of pre-event and post-event topography for the December 1999 storm on the Caraballeda fan.

ABSTRACT

Heavy rainfall from the storm of December 14–16, 1999, triggered thousands of shallow landslides on steep slopes of the Sierra de Avila north of Caracas, Venezuela, and caused flooding and massive debris flows in the channels of major drainages that severely damaged coastal communities along the Caribbean Sea. Within this region we characterized geologic conditions where landslides initiated on hillsides and examined the texture of debris-flow deposits in the channels of nine drainages. In one of the most severely damaged areas on a highly developed alluvial fan at Caraballeda, we measured debris-flow deposits that ranged up to 5 meters (m) in thickness, inundating structures and roads over a large portion of the fan. Boulders up to 5 m long were carried along by the flows, impacted structures causing serious damage, and were deposited on the fan. Using field measurements and comparing pre-event and post-event topography from aerial photographs, we determined the volume of debris-flow and flood deposition on the fan to be about 2 million cubic meters (m^3). The total volume of material transported and deposited by landslides throughout the Vargas region ranks this as one of the most severe historical erosional events worldwide.

INTRODUCTION

A storm on December 14–16, 1999, during which 911 millimeters (mm) of rain fell during a 52-hour (h) period caused catastrophic landslides and flooding along a 20-km (kilometer)-long coastal strip north of Caracas from La Guaira to Naiguita, along the northern coast of Venezuela (fig. 1 on sheet 1). Although a few landslides occurred inland to the south across the crest of the Sierra de Avila, damage within Caracas was minimal. Along the coast, damage to communities and infrastructure was extensive; more than 8,000 residences and 700 apartment buildings were destroyed or damaged (Salcedo, 2000). Roads, telephone, electricity, water, and sewage systems were severely disrupted. Total economic losses are estimated at $1.79 billion (Salcedo, 2000). The number of fatalities is estimated to have been about 19,000 (Larsen and others, 2001).

Many others have investigated various aspects of this December 1999 catastrophic event; much of this work was presented at an international conference held in Caracas in November-December, 2000 (University of Central Venezuela, 2000). Other investigators (Larsen and others, 2001; Merifield, 2001; Pérez, 2001; and Takahasi and others, 2001) have presented results of comprehensive on-site investigations and analyses of this event.

The topography of this region of coastal Venezuela is extremely steep and rugged. The crest of the Sierra de Avila reaches 2,700 m within about 6 to 10 km of the coast. The rivers and streams of this mountainous region drain to the north and emerge from steep canyons onto alluvial fans before emptying into the Caribbean Sea. Along the coast relatively little flat area is available for development with the exception of the alluvial fans. Land use consists of highly urbanized neighborhoods with buildings ranging in size from single-story unreinforced masonry and concrete homes to multistory modern apartment buildings. Prior to the 1950s, the alluvial fans on which these neighborhoods were constructed were used for agriculture and the population density was low. The higher portions of the drainages are part of El Avila National Park, a forested preserve established in 1958 that has had minimal human disturbance. A few unpaved roads, however, parallel the ridgeline of the mountains.

Although the severity of damage to structures and roads was extreme, the landslides and flooding that were triggered by the intense rainfall were not unique in this region. Historical records indicate that similar hydrologic events leading to severe flooding and landslides have occurred in this region in February 1798, August 1912, January 1914, November 1938, May 1944, November 1944, August 1948, and February 1951 (Röhl, 1950; Salcedo, 2000). On average, at least one or two high-magnitude flash flood or landslide events per century have been recorded in this region since the 17th century (Larsen and others, 2001).

This study examines the landslides, debris flows, and flooding produced during the storm of mid-December 1999 along coastal northern Venezuela. Measurements were made of the initial size, inclination, and geologic character of shallow landslides that initiated debris flows on steep slopes. Observations also were made of channel and alluvial fan width, gradient, and depositional depth, as well as the maximum size of boulders transported by the flows. Measurements of flow inclination around bends in the channels were used to estimate flow velocity. The stratigraphy and texture of deposits were examined to identify the type of deposits as well as the sequence of flooding and debris flows in December 1999. Detailed measurements were made of debris-flow deposit thickness and boulder sizes on the alluvial fan of the Río San Julián near Caraballeda (figs. 3 and 4 on sheet 2). To calculate the volume of deposits and compare it with volumes calculated from field measurements, topographic maps prepared from aerial photographs taken before and after the December 1999 event were analyzed. A categorization of historical debris-flow depositional events worldwide made it possible to compare the severity of this event with other catastrophic debris-flows triggered by storms, earthquakes, and volcanic eruptions.

STORM OF DECEMBER 1999

The timing and intensity of rainfall of the storm of December 14–16, 1999, was unusual because the rainy season in coastal Venezuela normally lasts from May through October. Beginning in early December of 1999, the interaction of a cold front with moist southwesterly flow from the Pacific Ocean towards the Caribbean Sea resulted in an unusually wet period over coastal northern Venezuela. Moderately heavy amounts of rainfall during the first week of December were followed by extremely heavy rainfall beginning on December 14 and lasting through December 16. The total 3-day rainfall along the coast at the International Airport at Maiquetía (see fig. 2 on sheet 1) for a 52-h span between December 14 and 16 totaled 911 mm (from 1945 on Dec. 15 to 2345 on Dec. 17, Coordinated Universal Time (UTC)). Hourly rainfall from 6 to 7 a.m. on the morning of December 16 measured 72 mm, which has a 50-year (yr) return interval (Salcedo, 2000). As noted by Grases and others (2000) the daily totals (380.7 and 410.4 mm, respectively) for December 15 and 16 at Maiquetía exceeded the 1000-yr average return period of rainfall for this location as previously determined by Ayala (1978). When the maximum daily 1999 storm total rainfall (410 mm) is included in the analysis, the return period decreased to 270 yr (Bello and others, 2000). Mean annual precipitation over a period of record of 51 yr (excluding 1999) at Maiquetía (43 m above mean sea level) is 523 mm (Bello and others, 2000). In previous storms, ground-based rainfall measurements in this region indicate that the higher elevations towards the crest of the Sierra de Avila received about twice as much rainfall as along the coast (Salcedo, 2000).

Few ground-based rainfall measurements of this storm were available, particularly within the heavily damaged region (Wieczorek and others, 2001). A spatial and temporal representation of distribution of estimated rainfall was available from the Geostationary Operational Environmental Satellites (GOES–8) from the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS) rainfall estimator. These rainfall estimates have been computed by using a relation between rainfall rate and cloud top temperature determined from infrared sensors on the GOES–8 satellite (Vicente and others, 1998). A map of rainfall contoured from the GOES–8 data with a cell size of 4 x 4 km shows that the heaviest rainfall occurred within 8 km of the coast and the higher elevations of the Sierra de Avila roughly centered over the middle to upper part of the San Julián basin upstream of Caraballeda (fig. 2). Rainfall decreased towards Caracas on the southern side of the crest of the Sierra de Avila and to the east of Naiguata and to the west towards Maiquetía along the coast. These areas of heavy rainfall centered over the San Julián and adjacent drainage basins roughly corresponded to the areas that suffered the most abundant landslides and most severe flooding and debris-flow damage. The results of comparing the few ground-based rainfall measurements with GOES–8 rainfall estimates are highly variable. In this storm, ground-based cumulative rainfall measurements along the coast at Maiquetía (911 mm) greatly exceeded the GOES–8 value (~180 mm); whereas, at Observatorio Cajagal southward over the crest of the Sierra de Avila within Caracas, the GOES–8 rainfall value (~100 mm) exceeded the ground-based measurement (76 mm).

GEOLOGY

The Sierra de Avila is composed mainly of metamorphic rocks dissected by channels that drain to the Caribbean Sea across alluvial fans mantled with Quaternary sediment. Although bedrock is exposed in some channel reaches, most channels contain extensive Quaternary sediment deposits up to several meters thick.

Exposures of the Tacagua Formation of Mesozoic age, consisting of graphitic epidote schists, parallel the coast and extend about 1 km inland (Urbani and others, 1997). The soils developed over these schists are relatively thin, 0.5 to 3.0 m thick (Salcedo, 2000), red, and fine grained. Clayey colluvial soils cover partially to deeply weathered, strongly foliated bedrock. Further inland of the Tacagua Formation, quartz-plagioclase-mica gneiss and feldspar schist of the San Julián Formation of Paleozoic age and augen-quartz-mica gneiss of the Peña de Mora Formation (Precambrian age) extend to the crest of the Sierra de Avila (Urbani and others, 1997). Soils developed over these two formations are likewise thin, sandy, and tan gray in color. The soils developed over these metamorphic rocks are thin because of the higher rates of erosion induced by the steep topography.

In many drainages young terraces consisting of prehistoric debris-flow and flood deposits are elevated 10 to 20 m above the current stream channels, suggesting contemporaneous tectonic uplift of the coastal range combined with accelerated incision of the channels (fig. 5 on sheet 2). Older and higher terraces have been identified within several of the drainages by Urbani and others (2000). An arid period associated with the late Pleistocene has been correlated with elevated terraces having similar deposits of bouldery debris over bedrock located about 100 km west of the this region (Schubert, 1985). Scouring of channels and removal of alluvium in the December 1999 event exposed eroded bedrock benches above the apices of the fans, with apparent vertical steps ranging from about 0.5 to 2 m high above the current levels of the channels. These benches are suggestive of tectonic uplift and accelerated bedrock channel incision in this region. Stallard (1988) has suggested an uplift rate of 2 to 5 m/1000 yr for terraces at the northern terminus of the Andes in northwestern Venezuela.

The alluvial fans in Vargas are not deeply incised. Typically they are slightly higher in elevation (about 5 m) towards the axis of the fan than on the flanks, with only relatively shallow incision of a couple of meters by the active stream channels. The minimal stream entrenchment suggests that the long-term rate of delivery of material from the upper watersheds to the fans is equal to or exceeds the rate of removal. The steep mountainous topography with basal accreting fans is consistent with a youthful geomorphic stage of alluvial-fan development (Sorriso-Valvo, 1988).

Figure 5.—Prehistoric terrace of flood and debris-flow deposits about 20 m thick above current channel of Río San Julián. Note people on left for scale among recently deposited large boulders in channel. Recent landslides from storm of December 14–16, 1999, on hillside in background.

MEASUREMENTS AND OBSERVATIONS

During field examination in April and July of 2000, nine watersheds were examined: the Camurí Chiquito, San Julián, Cerro Grande, Camurí Grande, Alcantarilla, Seca, El Cojo, San José de Galipán, and Osorio (fig. 1). Sites of field measurements and observations are identified and located on figures 1, 3 and 4; values of measurements from these sites are included in appendixes A and B (sheet 1).

LANDSLIDES

Abundant and widespread shallow landslides occurred on steep slopes within areas underlain by schist and gneiss from near the coast to slightly over the crest of the Sierra de Avila. Some hillsides were almost entirely denuded by single or coalescing failures (fig. 6 on sheet 2). Most landslides initiated as thin earth (soil) slides or debris slides (soil with pieces of rock), as indicated by shallow sliding surfaces within soil or weathered, foliated, and jointed rock. As these slides moved further downslope and deformed with the incorporation of additional water, many mobilized into debris flows. Types of slope movement were classified according to Varnes (1978).

In most cases, debris flows entrained additional colluvium while traveling down steep hillside paths. Upon entering main channels, the debris flows incorporated stream alluvium from the channel and colluvium from channel banks, ranging in size from fine-grained material to extremely large boulders (fig. 7 on sheet 2).

Figure 6.—Coalescing shallow landslides initiated on steep hillsides in soils developed over bedrock of Tacagua Formation. Shallow slides that initiated on concave or planar slopes coalesced with other slides as they traveled into main channels. Transmission tower, 30 m high (upper right), for scale.

The undermining and collapse of prehistoric debris-flow deposits along the banks of channels was one mechanism by which large boulders became incorporated into the 1999 flows (fig. 8 on sheet 2). Subrounded to subangular large gneissic boulders derived from the Peña de Mora Formation, which crops out at higher elevations within the Sierra de Avila, were found in channels and alluvial fan deposits near the coast, in areas underlain by the Tacagua Formation. The underlying geology and in situ weathering characteristics suggest that these boulders have been transported at least several kilometers, probably by multiple episodes of flood/debris flow over a period of many thousands of years.

Measurements of hillside morphology included hillside inclination and initial slide thickness, width, and length. The composition of materials involved in sliding and whether the site showed evidence of previous sliding were noted. Most slides occurred within the top 0.5 to 2.0 m of soil and (or) weathered schist or gneiss, but deeper earth slumps or rock block slides were noted. The width of slides varied greatly, with a mean of 19.5 m (landslide source data included in appendix B). Some smaller slides coalesced to denude larger sections of hillsides. Stratigraphic sequences exposed in main scarps indicated some examples of reactivation of previously active landslides.

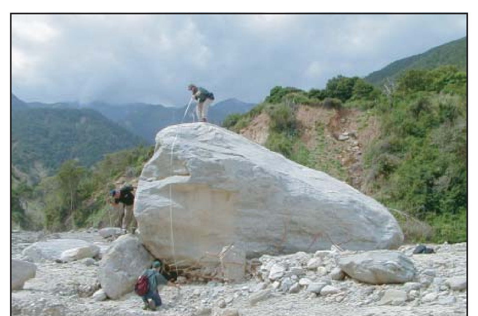

Figure 7.—Large (11.3 x 5.0 x 3.5 m) subrounded gneissic boulder deposited in center of channel of Quebrada Camurí Chiquito. Boulder was deposited atop reinforced concrete pad with strands of steel rebar visible along base of boulder.

Measurements indicated that landslides initiated on slopes ranging from 30° to greater than 60°, and the slopes that failed had a mean value of 41° with a standard deviation of ±7.8° (N=26). Landslide measurements by Salcedo (2000) reported similar values with a mean initial slope value of 38.5° with a standard deviation of ±5.1° (N=15).

Bedrock structure in this region strongly influences slope stability. In locations where the direction of steeply dipping foliation of the schist and gneiss is towards an open slope face, conditions are more favorable for sliding. The steeply dipping foliation in many parts of this region (Dengo, 1953), in combination with exceptional storms, has inhibited the development of thick soils. The steep inclination of the slopes frequently exceeds the frictional resistance (angle of internal friction) of the sandy soils in this region, suggesting that other sources of strength, such as internal cohesion, soil suction (negative pore pressure), soil structure, or contribution of vegetative root strength, must contribute to the stability of the steep slopes. In his observations of landslide failure scars in this region, Merifield (2001) found that root penetration was generally confined to the thin topsoil layer, except in a few cases where roots penetrated bedrock along open fractures of joints or foliation.

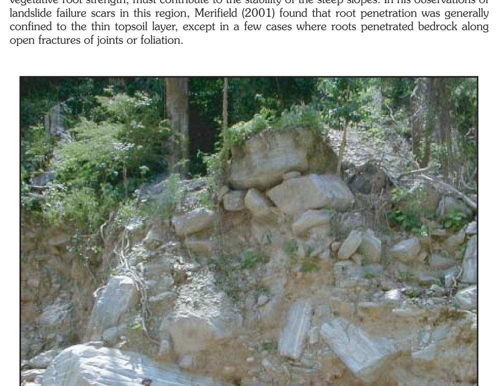

Figure 8.—Prehistoric debris-flow deposit (7.7 m thick) exposed in channel bank of Quebrada San José de Galipán. Matrix-supported texture with randomly oriented subangular large gneissic boulders from the Peña de Mora Formation gneiss deposited in a sandy matrix. Top of deposit is matrix free and was produced by winnowing of debris flow by recessional and (or) secondary overland water flows.

CHANNELS AND FANS

The main channels and fans of the nine watersheds we examined displayed a complex sequence of deposition. The sediments exposed in most channels suggested evidence of both flooding and debris-flow processes; however, the types of flow processes, stratigraphy, and thickness of deposits typically varied along the length of a channel and onto the fan. Deposits in most channels and fans showed that flooding had preceded debris-flow activity. Many of the fans experienced multiple pulses of debris flows and large boulders and tree trunks were deposited amidst a sandy matrix on nearly all the fans. Flooding in the later stages of the storm subsequently incised these fluvial and debris-flow deposits. Measurements at individual stations of the range of thickness of deposits and depths of flow are included in appendix A and are summarized for each watershed in table 1 (on sheet 2).

The degree of matrix support of coarser clasts observed in deposits varied from full matrix support to full clast support (fig. 9 on sheet 2). The association between flow processes and depositional texture was gradational as characterized by Keaton and others (1988) with debris-flow deposits having fully matrix-supported, unsorted, unstratified clasts; transitional flow deposits having partially matrix-supported clasts; and hyperconcentrated sediment flow deposits having a fully clast-supported texture. The surface of some deposits was matrix free as a result of winnowing of debris-flow deposits by recessional and (or) secondary overland water flows (Moscariello and Deganutti, 2000).

In most drainages the sequence of flooding and debris-flow deposition during the storm was confirmed by eyewitness accounts (table 2 on sheet 2). Flooding was generally observed in many drainages beginning after 8 p.m. local time (Atlantic Standard Time (AST)) on the evening of December 15. Some residents fled from the vicinity of the rivers and remained atop nearby houses, watching the events unfold as the rivers overtopped their banks. At Caraballeda on the fan of the Río San Julián the first eyewitness reports of debris flows or events with descriptions of crashing rocks occurred about 8:30 p.m. on December 15. At Caraballeda another large bouldery debris flow occurred about 2 a.m. on December 16, followed by a mudflow before 3 a.m. Along the San José de Galipán possible debris-flow events (for example, "rumbling noise and vibration of rocks"), occurred between 2 and 3 a.m. Another series of debris flows was observed between 5 and 7 a.m. on the Uria, Cerro Grande, Seca, San Julián, Camurí Grande, and San José de Galipán; the last series of debris flows was reported on the Camurí Chiquito, San José de Galipán, and Osorio between 8 and 9 a.m. on December 16. Flooding was reported in a few channels between 7 and 9 a.m. on December 16 that persisted until late in the afternoon of December 16, eroding many of the debris-flow deposits within channels.

The variation of flood/debris-flow depositional processes along the channels can be attributed to various factors, particularly the location of the junctions with tributaries and whether these tributaries were experiencing debris flows or flooding. In the upper parts of the drainages that were accessible, about 4 km inland, bedrock channels had been severely scoured and had been left almost devoid of sediment. Although vegetation trim lines could be identified on the channel sides, it was not possible to determine whether the channel sediments had been removed by flood, debris flow, or an intermediate variety of flow (transitional flow or hyperconcentrated flow, see Pierson and Costa, 1987; Keaton and others, 1988; and Scott and others, 2001). The dilution of debris flow by inflow from a flooding tributary to a transitional flow or hyperconcentrated sediment flow also could have occurred in the upper drainages. In almost all examined drainages debris-flow deposits could be traced from the distal ends of the fans up the channels to about 2 to 4 km from the coast. The deposition extended for some tens of meters beyond the shorelines as subaqueous fans (Larsen and others, 2001). The thickness of subaqueous deposits from the 1999 event could not be determined because of the lack of sufficiently precise pre-event bathymetric surveys. The subaqueous deposits were probably generally less than 1 m thick, reasoned from observations of subaerial, thin-bedded, dominantly fine-grained deposits grading into the coast. A characterization of the types, sequence, and thickness of deposits, and maximum boulder size within channels and on fans is given in table 1.

Methods of estimating the average flow velocities during flash flooding have been developed by Costa (1983) and Clarke (1996) based on empirical relations between boulder diameter and average velocity accompanying flood discharge. These methods determine the critical (competent bed) velocity required to initiate boulder movement. Because of slightly different means of measuring the boulder diameter, Costa's equation results in a velocity estimate about 40 percent greater than that of Clarke. Velocities also were estimated from superelevation of flows around channel bends where flows reached higher elevations on the outside of channel bends than on the inside. Based on the cross-channel flow surface angle, radius of curvature of the channel bend, and channel slope, the approximate mean velocity of flow can be calculated (Costa, 1984). Estimated velocities using these methods based on boulder sizes and superelevation are listed in appendix A.

The average estimated velocities of the flows ranged from 4 to 14.5 meters/second (m/s) using methods by Clarke (1996) and Costa (1983) based on measurements of the largest transported boulders at particular sites. A slightly lower range of velocities from 3.3 to 13.6 m/s was independently determined at several dozen sites based on superelevation measurements on channel bends. Direct comparison between these two methods was possible at only six sites. At these six sites the velocities based on boulder size (Clarke, 1996; Costa, 1983) overestimated the velocity based on superelevation by about 28 percent and 68 percent, respectively. The velocity based on superelevation probably better represents the actual flow velocity of a debris flow or flood because the calculation is independent of fluid density (Costa, 1984, p. 304). The methods of Costa (1983) and Clarke (1996) are based on average velocity necessary for initial movement of a boulder along the channel bed in a clear water flood. This technique probably overestimates the velocity because a debris flow suspends boulders within a matrix and has a density greater than clear water, making it capable of transporting boulders at a lower velocity.

Figure 9.—Debris-flow deposit, 2.9 m thick, incised by subsequent flooding of channel in Río Camurí Chiquito. Fine-grained matrix supports coarser particles.

The heterogeneous nature of a debris-flow surge (Hungr, 2000), which includes a high, steep, bouldery front followed by a lower slurry of coarse particles in suspension and finally a dilute tail, suggests why equations for velocity based on bedload transport of large boulders during flooding are inadequate to represent such a complex process. In addition, velocities based on boulder size should be used with caution because it was not known how the largest boulders had actually been transported, whether by fluvial transport of rolling or sliding along the bottom of the channel in a dilute fluid, or whether suspended in a granular matrix by a debris flow. Where the large boulders were found deposited within a matrix, the evidence strongly supports transport by debris flow. At other sites the largest boulders are isolated in the channel and all other sediments removed by subsequent flooding, so that it is not possible to determine the mode of transport.

The dimensions of the largest boulders found in prehistoric deposits and their estimated velocities based on size for fluvial transport are shown in red type in appendix A. Evidence showed that prehistoric deposits were not only thicker, but contained larger boulders than documented in the December 1999 event.

CARABALLEDA FAN

The large fan of the Río San Julián at Caraballeda was one of the most severely damaged areas in the December 1999 event (fig. 10 on sheet 2). The thickness and volume of deposits, maximum size of transported boulders, and size of inundated area were all notably larger in this drainage than in other watersheds.

Caraballeda was one of the more intensively developed communities along the coast with large individual multistory structures, many residences, and a complex infrastructure. At the fan apex, the peak volume of flow, probably during a debris-flow surge, exceeded the channel capacity resulting in multiple stream avulsions and subsequent flows spreading bouldery debris over the center of the fan. The flow overcame the channel in several places, notably wherever sections or lineaments of the channel changed direction. Pre-1951 topographic maps show the channel of the Río San Julián taking a more or less straight path across the western part of the fan. Photographs of the February 1951 event available from the Venezuela Ministry of Environment and Natural Resources (MARN, 1999) show deposition limited to the vicinity of a recently constructed channel through the eastern part of the fan. In the events of December 1999 the river overflowed its banks high on the fan and followed the pre-1951 course. Whereas the 1951 event was adequately contained within the constructed eastern channel, the flows of 1999 greatly exceeded the channel capacity.

Flows inundated the second story of several apartment buildings, causing their partial collapse (fig. 11 on sheet 2), and also buried or completely destroyed many two-story residential structures. Further down the fan, flows followed the paths of streets and openings between houses; the deposition of debris thinned, but still exceeded 1 m in thickness at most locations. Only about one-third of the total area of the fan was inundated by deposition in this event.

We measured degree of slope, depositional thickness, and boulder size from the fan apex to the distal end of the fan near the coastline (appendix A). Data collected of the extent and thickness of the deposits were used to map the distribution and thickness of deposits and to estimate the total volume of deposits on the fan. In addition, we obtained pre-event and post-event digital topography on the Caraballeda fan from the MARN that enabled us to determine topographic changes due to the storm event and to numerically model the total depositional volume on the fan for comparison with the field derived estimates of volume.

Figure 10.—Aerial view of debris-flow deposits up to 5 m in thickness and totaling about 1.8 million m^3 on the fan of the Río San Julián at Caraballeda. Avulsion at the apex caused flow through center of fan to the lower right of photograph (Photograph by Lawson Smith, U.S. Army Corps of Engineers).

Total depositional volume on the subaerial fan was calculated by using two different methods. In the field we measured deposit thickness, or if necessary, indications of the depth of flow where material had been removed by cleanup. Where material had been removed, mudlines on structures were used as an approximate measure of deposit thickness. Total depositional volume of 1.9 million m^3 was determined from field measurements by using Earth Vision Version 5.11 software for three-dimensional modeling. This volume is a minimum because it neglects the amount of material that remained in the main channel after the event, but was removed by the time of our visits. The same software also was used for comparison of pre-event and post-event topography on the fan derived from aerial photography, and the results show a depositional volume of 1.8 million m^3. Figure 4 shows a plot of contoured thickness of deposits using the comparison of pre-event and post-event topography. The determination of volume by comparison of pre-event and post-event topography is the preferred method due to modifications on the fan by the time of our field visit in July of 2000, although both values vary by only about 10 percent.

Figure 11.—Apartment building in Caraballeda extensively damaged by passage of debris-flow front at least 3.5 m in height, depositing boulders (>1 m long) on second floor of structure. Note apartment building in background similarly damaged by debris flow.

The significance of the volume of deposits on the fan at Caraballeda can be ascertained from comparison with other large debris-flow events worldwide (table 3 on sheet 2). Using a magnitude scale, M, of the log of depositional volume suggested by Keaton and others (1988), the magnitude of debris-flow deposits on the fan at Caraballeda (M=6.3) is amongst the largest individual rainfall-induced debris flows within a single watershed. López and others (2000) evaluated the cumulative volume of flood and debris-flow deposition along the coast in December 1999 as amounting to 20 million m^3 (M=7.3). The December 1999 Venezuela depositional event is at least an order of magnitude smaller than the largest documented depositional debris-flow events worldwide triggered by volcanic explosions, eruptions, or earthquakes (table 3).

We measured a maximum thickness of deposits between 4 and 5 m thick in the center of the fan at Caraballeda at station 7–12–33 (fig. 4). At this same locale, the fan slopes ranged between 5° and 6°, and the maximum thickness of deposits was 5.3 m as determined by comparing pre-event and post-event topography. Elsewhere, comparision of pre-event and post-event topography identified areas with deposits up to 7 m in thickness (fig. 4). Mapping the shoreline from post-event aerial photographs showed that deposition in this event had extended the shoreline at Caraballeda by about 40 to 60 m. Deposits on slopes of 2° to 4° near the (pre-event) shoreline were predominantly fine grained and less than about 0.5 m thick. Although post-event bathymetry exists, no pre-event data of sufficient resolution were available to determine the thickness of subaqueous deposits. The volume of subaqueous deposition beyond the new shoreline is probably not significant with respect to the total volume of subaerial deposits.

We measured about 100 boulders deposited in the center of the fan along short traverses (10–40 m in length), recording the lengths of the major three axes for all boulders (defined as >256 mm). In terms of nominal diameter, equal to the cubic root of the product of these dimensions, the mean nominal diameter of boulders deposited at stations 7–8–14 and 7–12–33 was 0.75 and 0.99 m, respectively, with larger boulders being deposited slightly further down the fan towards station 7–12–33 (fig. 3). The slope gradient at station 7–8–14 was 4°, whereas at station 7–12–33 the slope steepness was 6°. For comparison, 11 boulders deposited about 2 km upstream in the Río San Julián channel on a slope of 5.5° (station 4–5–7, fig. 1) had a mean nominal diameter of 1.20 m.

PREVIOUS FLOOD/DEBRIS-FLOW EVENTS

Previous flood/debris-flow deposits were exposed along channel banks in most of the observed watersheds. The dimensions of large boulders in these prehistoric deposits as well as the deposit thickness were recorded (appendix A). The sizes of boulders and thicknesses of prehistoric deposits are at least as large as those of December 1999 and in several areas, greater, indicating that the December 1999 event was not necessarily the event of greatest magnitude to have occurred in this region.

Aerial photo interpretation and field examinations indicate that previous debris-flow deposits cover much of the fan at Caraballeda with a thickness and size of boulders comparable to the 1999 event (figs. 3 and 4). Although a flooding/debris-flow event occurred in 1951 on this fan, its extent visible in aerial photographs (MARN, 1999) was minor in comparison to the 1999 event. Since 1951, extensive development has occurred on this fan and is reflected in the severity of damage in 1999.

Prehistoric flood and debris-flow deposits are exposed along the banks of the Río San Julián and on the flanks of the fan. At Plaza de Piedras, located above the active channel on the eastern side of the fan (station 7–7–17, fig. 4), a house built in 1917 sits on a boulder terrace; the largest boulder is approximately 2.9 m^3 (A-axis=2.8 m) (fig. 12 on sheet 2). On the western side of the fan at about the same elevation (stations 7–6–13, –14, –15, fig. 4), a thick (~17 m) sequence of multiple flood/debris flow deposits includes gneissic boulders (A-axis=1.5 m) in a brownish-yellow, slightly cemented sandy matrix. Thick deposits with large boulders in a sandy yellow matrix could be roughly traced upstream from the western side of the fan for about 0.5 km along the western banks of the Río San Julián. In a fresh exposure (between stations 7–10–5 and 7–10–7) located on the western channel banks we found organic carbon in paleosols above and below a thick (10 m) debris-flow deposit, containing large subrounded gneissic boulders (A-axes =2–3 m) suspended in a sandy matrix. The dates from the carbon samples recovered from these paleosols bracketed the age of debris-flow deposition between the upper dates of 3,720±50 yr B.P. (years before present (1950)) and 3,750±40 yr B.P., and the lower date of 4,267±38 yr B.P. Closer examination of this exposure and mapping the lateral extent of this deposit is necessary to determine if this sequence of coarse bouldery deposits represents a single episode or separate debris-flow events within the span of about 500 yr. Although we observed prehistoric debris-flow deposits in other watersheds, exploration for dateable materials to bracket their ages was not conducted.

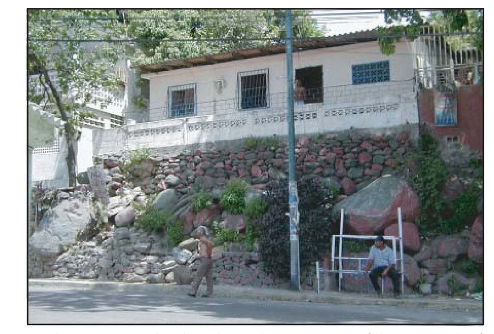

Figure 12.—Structure at Plaza de Piedras on the eastern portion of the Río San Julián fan (station 7–7–17). This "House of Stones" built around 1917 predated the flood and debris-flow events of 1951 on the Caraballeda fan.

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Table 1.—Characterization of flood and debris-flow (DF) deposition in examined watersheds. As contrasted with a debris flow (DF) which transports boulders or clasts in a fine-grained matrix, a hyperconcentrated sediment flow (HSF) moves boulders without matrix support.

[Size of drainages is from MARN (1999). Velocity estimates are calculated from evidence of superelevation. Values of volume of deposits from López and others (2000) shown in parentheses. N/A indicates no data available]

Drainage	Size, in km^2	Sequence and type of deposition (top to bottom)	Volume deposits, in $m^3 \times 10^6$	Deposit thickness, in m	Max. boulder (A-axis), in m	Velocity, in m/s	Fabric
Camurí Chiquito	10.2	Coarse DF/Fine DF/Flood incision	(1.6)	3.0–4.0	5.1–12.0	5.8	Matrix supported to grain to grain support.
San Julián	21.3	Coarse DF/Flood/Fine DF/Flood incision	1.8–1.9	4.0	1.0–5.6	N/A	Grain to grain support.
Cerro Grande	25.4	Flood/Flood incision	(1.5)	2.0	0.2–0.4	4.2–7.0	Graded.
Camurí Grande	45.3	Coarse DF/HSF/Flood incision	1.6	3.0–6.0	2.7–4.1	N/A	Grain to grain support.
Alcantarilla	1.5	Coarse DF/Sandy Flood/Flood incision	N/A	3.2–4.5	1.7–2.7	3.5–13.6	Matrix supported.
Seca	3.0	Coarse DF/Flood incision	(1.5)	2.5–4.0	1.8–7.5	3.3	Grain to grain support, partially imbricated.
El Cojo	6.5	DF/Flood incision	(0.3)	2.0–3.6	2.5–9.5	3.2–5.2	Matrix supported.
San José de Galipán	15.0	DF/Flood incision	N/A	1.0–4.0	3.2–5.3	4.4	Grain to grain support.
Osorio	4.7	DF/Flood incision	N/A	3.0–3.6[1]	3.2–7.1	4.1–5.8	N/A
Carmen de Uria	11.6	N/A	(1.6)	N/A	N/A	N/A	N/A

[1]Flow depth reported where evidence of deposit had been removed.

Table 2.—Times of observed flooding and debris flows from eyewitness accounts.

[Locations in parentheses refer to sites of communities within identified drainages. Parenthetical terms in last column are inferred from context]

Time	Drainage (location)	Description
12/16/99	Camurí Chiquito	
9:00 a.m.		Major debris-flow event in drainage burying bus along eastern margin of fan.
12/16/99	Osorio (La Guiara) (E)	
7:20 a.m.		Water flooding on eastern part of fan.
8:00 a.m.		Water flooding on eastern part of fan.
9:00 a.m.		Rocky (debris-flow) event.
12/16/99	Osorio (La Guaira) (W)	
5:00 a.m.		Flooding.
9:00 a.m.–3:00 p.m.		Rocky debris flow followed by water flooding.
12/15/99	San Julián (Caraballeda)	
8:00 p.m		First wave of flood water, 1.5 m high.
8:30 p.m.		Crashing of rocks (debris flow?).
12/16/99		
2:00 a.m.		Water flooding shortly followed by large bouldery debris flow.
2:00–3:00 a.m.		Water and mud (flows) observed.
6:00 a.m.		Three (debris) flow episodes, with the last one at 6:00 a.m.
10:00 a.m.		Flooding recedes.
12/16/99	Camurí Grande	
2:00 a.m.		River levels (running) high.
6:00 a.m.		Rumbling sounds like (debris-flow) boulders crushing buildings.
12/15/99	San José de Galipán (Macuto)	
8:00 p.m.		River flooding over banks; flow travelled down street.
12/15/99 8:00 p.m.– 12/16/99 3:00 a.m.		Rumbling noise of vibration of rocky (debris flow); row of houses removed.
12/16/99		
6:00–7:00 a.m.		Surge of debris flow destroyed houses.
9:00 a.m.		Major (debris-flow) event, with pulses of sand, but no boulders.
12/15/99	Seca	
Evening		Flooding during night.
12/16/99		
1:00–2:00 a.m.		Rising water levels and flooding.
5:00–6:00 a.m.		Debris flow.
6:00 a.m.		Single debris-flow event carrying cars; most people near stream evacuated their homes and fled up hills.
6:00–7:00 a.m.		Debris (flow) with boulders.
12/16/99	Cerro Grande	
1:00 a.m.		Torrent with lots of sediment.
6:00–7:00 a.m.		Debris flow with four large surges (Shucheng and others, 2000).
12/16/99	Uria	
6:00 a.m.		Flooding following by large surge (Shucheng and others, 2000).

Table 3.—Comparison of depositional volume of historical debris flows worldwide.

[Magnitude, M, equal to the logarithm of depositional volume in cubic meters, as proposed by Keaton and others (1988) used for comparison]

Location (Year)	M	Trigger	Reference
Rudd Canyon, Utah (1983)	4.8	Snowmelt	Keaton and others (1988).
Whitehouse Creek, California (1982)[1]	5.1	Rain	Wieczorek and others (1988).
Fountain Green, Utah (1983)	5.2	Snowmelt	Lips and Wieczorek (1990).
Ophir Creek, Nevada (1983)[2]	5.2	Snowmelt	Glancy and Bell (2000).
Wollinitzbach, Austria (1966)	5.5	Rain	United Nations (1996).
Campania, Italy (1998)[3]	6.2	Rain	Calcaterra and others (2000).
Casita, El Salvador (1998)	6.3	Rain	Scott (2000).
Caraballeda, Venezuela (1999)	6.3	Rain	This report.
Malaya Almatinka River, Kazakhstan (1921)	6.5	Rain	United Nations (1996).
Nevados del Ruiz, Colombia (1985)	7.2	Volcanic explosion	United Nations (1996).
State of Vargas, Venezuela (1999)	7.3	Rain	López and others (2000).
Mt. Ontake, Japan (1984)	7.5	Earthquake	United Nations (1996).
Nevados Huascaron, Peru (1970)	7.7–8.0	Earthquake	Plafker and Ericksen (1978).
Mt. Pinatubo, Philippines (1991)	8.9	Volcanic eruption and rain[4]	Newhall and Punongbayan (1996).
Mt. St. Helens, Washington (1980)	9.4	Volcanic eruption	United Nations (1996).

[1]Evaluation of magnitude is based on volume of source landslide. Depositional volume is a minimum because of potential additional erosional contribution from channel.

[2]The trigger of this event was extremely complex involving landslide-induced flooding of a small lake and subsequent stream channel erosion (Glancy and Bell, 2000). The volume cited is that part deposited on the fan.

[3]The volume represents the total deposition from debris flows onto about six fans.

[4]Volume represents total of lahar deposition within drainages of Mt. Pinatubo within first two months following major eruption. Typhoon Yunya during the eruption and subsequent typhoons and monsoons continued to generate flows with voluminous sediment deposits on fans for the next several years, so this figure represents only the initial debris flow volume from Typhoon Yunya.

DEBRIS-FLOW AND FLOODING DEPOSITS IN COASTAL VENEZUELA ASSOCIATED WITH THE STORM OF DECEMBER 14–16, 1999

By
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