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1998, pp. 61-69. https://doi.org/10.56577/FFC-49.61

in:

Las Cruces Country II, Mack, G. H.; Austin, G. S.; Barker, J. M.; [eds.], New Mexico Geological Society 49 th Annual Fall Field Conference Guidebook, 325 p. https://doi.org/10.56577/FFC-49

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THE AGUIRRE SPRING DEBRIS FLOW OF AUGUST 14, 1991

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Abstract—A meso-scale convective storm in the White Sands-Aguirre Spring area during the late evening and early morning hours of August 13–14, 1991, initiated a major flow event in the basin of Anvil Creek, a long, narrow watershed that heads just below the Needles on the east side of the Organ Mountains. Field evidence indicates that the flow in its upper reaches was confined to the north branch of Anvil Creek where the channel was greatly modified and enlarged, producing a chute-like bed of polished bedrock. At the lower end of the bedrock channel, the flow followed the natural bend of the north branch to the north-northeast, depositing a viscous lobe of boulders encased in a matrix of gravelly grus. A subsequent flow failed to negotiate the turn, instead surging ahead to enlarge a breach in a narrow divide between the north branch and south branch of Anvil Creek. Cross-sectional measurements of the active channel of Anvil Creek upstream of the breach produce estimated peak water discharges that are unrealistically high for such a small basin. In addition, there is no evidence for major flood discharges on the valley floor downstream of the lobe. The lobe that plugs the floor of the former north branch of Anvil Creek rafted large boulders and relatively unscarred trees, plus inundated the bases of many large shrubs and trees, in most cases without any damage. Downstream of the breach along the active channel of the south branch, the flow built marginal rock levees, often with the largest boulders on top instead of on the bottom, a feature diagnostic of a slow-moving, viscous flow. The inescapable conclusion is that the event of August 14, 1991, was not a simple water flood, but rather a localized debris flow.

INTRODUCTION

Anvil Creek drains a small, narrow watershed on the eastern flanks of the Organ Mountains of southern New Mexico, approximately 12 mi east of Las Cruces. The creek has north and south branches whose confluence is a short distance upslope from a Bureau of Land Management (BLM) campground and picnic facility. This BLM facility, known as the Aguirre Spring Recreation Area, attracts approximately 100,000 visitors annually, many of whom hike the trails along Anvil Creek.

During the late evening and early morning hours of August 13–14, 1991, during a particularly intense cluster of convective thunderstorms (Ellison, unpubl., 1992), several campers in the upper Aguirre Spring campground were forced from their tent by runoff from a nearby hillslope. The campers took refuge at a BLM trailer house until daybreak, then discovered that their exit along the one-way loop road between the upper and lower campgrounds was blocked by an accumulation of massive boulders and debris (Fig. 1). A reconnaissance by BLM personnel revealed that a major flow event had heavily scoured the banks and bed of Anvil Creek, built rock levees both upstream and downstream of the loop road, and inflicted serious damage to the lower campground area (Fig. 2). The south branch of Anvil Creek contributed mostly boulders, whereas the north branch contributed water that splayed sand and gravel across the road.

FIGURE 1. Loop road through the Aguirre Spring Recreation Area as it appeared in middle September, 1991, one month after the major flow event. The sand, gravel, and vegetation debris in the foreground are associated with the now largely abandoned north branch of Anvil Creek. The boulder accumulation in the background is associated with the south branch or major active channel of Anvil Creek.

DESCRIPTION OF STUDY AREA

Topography

Anvil Creek and its major tributaries originate at an elevation of approximately 8000 ft just below and to the east of the northern extent of the Organ Needles. From there to the loop road through the Aguirre Spring Recreation Area, Anvil Creek is about 1.25 mi long and drains an area of 0.515 mi^2. The entire drainage basin consists of steep to moderately steep, northeast-facing, mountainous terrain into which is incised a well-developed parallel drainage pattern.

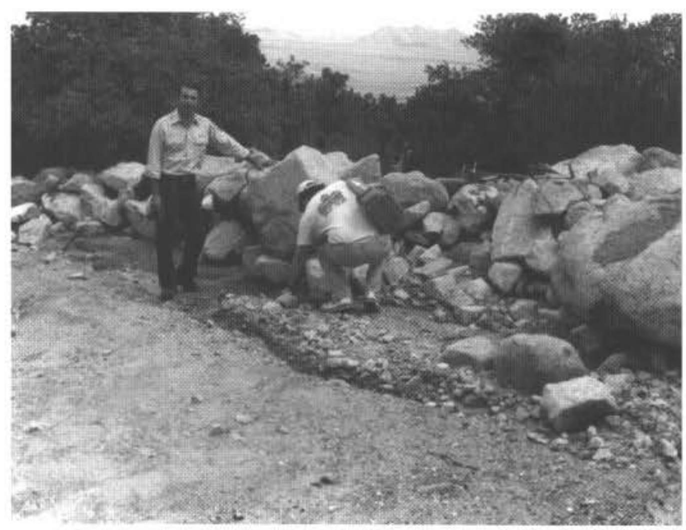

FIGURE 2. Marginal rock levee that formed between the channel and an interior road within the lower campground. Between the two people a precariously balanced tabular rock is standing on end. The direction of flow was from right to left.

In its upper reaches, Anvil Creek displays an open or chute-like channel developed in bedrock. In its middle reaches, the creek has established a bedrock channel inset below valley walls comprised of older alluvial fans. In its lower reach just above the loop road, Anvil Creek exits from its narrow bedrock channel and displays an alluvial channel of sand, gravel and boulders. Channel slope ranges from 8° on the lower channel to more than 20° on the upper reaches.

Geology

The monoliths known as the Organ Needles are described by Seager as remnants of the Organ batholith, produced by the "exfoliation of a massive but jointed crystalline rock" (Seager, 1981, p. 14). The Organ Needles Quartz Monzonite, mapped by Seager as unit Tmo, has an estimated age of 32.8 Ma, its date inferred as slightly older than the Sugarloaf Peak Quartz Monzonite. The rock texture is even-grained and coarse. Fresh specimens are typically gray, whereas weathered samples are buff, brown or red. The Sugarloaf Peak Quartz Monzonite (map unit Tmps) is exposed along the middle course of Anvil Creek and consists of both monzonite and granite. The rock is coarse grained and typically gray to pink-gray.

The third map unit in the study area is the piedmont slope facies of the Camp Rice Formation (Qcrp). These moderately cemented fanglomerates consist of sandstone to poorly indurated gravelly alluvium and "form the highest, extensively preserved surfaces on the upper and middle piedmont slopes..." (Seager, 1981, p. 80). Seager (1981) also noted that the upper reaches of these fan remnants had car-sized or larger boulders set in matrices comprised of smaller boulders, coarse sand and mud; attributable he suggests, to high viscosity mudflows. C. B. Hunt assumed that these deposits were formed under periglacial conditions (Seager, 1981). Seager, however, concluded that these deposits form in the modern environment as well.

Climate

The Organ Mountains provide a zone of semiarid climate within the surrounding and much drier Chihuahuan Desert. At the highest elevations of 6000–8870 ft, the mean annual temperature is 51°F and mean annual precipitation is 16 in.; in the lower elevations of 4800–6000 ft, the mean annual temperature is 62° F and the average annual precipitation is 11 in. (Soil Survey of Doña Ana County Area New Mexico, 1980). There is a marked proclivity in the higher terrain toward high-intensity convective thunderstorms, particularly during the July through September rainy season. Of particular significance are the storms described as Mesoscale Convective Systems (MCS) (Ellison, unpubl., 1992). Ellison argues that surface heating alone is not sufficient to produce the deep and intense convection of a MCS. Instead, the general unstable conditions of the late summer–early fall monsoon season are enhanced by "backdoor" surface cold fronts that move into the White Sands area from western Texas and eastern New Mexico. According to Ellison (1992) such a backdoor front supplemented the prevailing atmospheric conditions that initiated the violent meteorological response on the night and early morning hours of August 13–14, 1991.

Antecedent moisture

Weather data from White Sands Missile Range (elevation 4016 ft) for 1950–1991 and one year of unofficial rain gauge data from Aguirre Spring (elevation 5500 ft) reveal that antecedent moisture likely played a major role in events leading up to the August 13–14, 1991, debris flow. The mean annual precipitation at White Sands for the period 1950–1990 was 11.43 in.; for 1991, the figure was 18.26 in., the second wettest year on record. August at White Sands averages 2.18 in. of rain, but August of 1991 received 4.26 in. The second greatest two-month rainfall at White Sands is 7.38 in. for July–August, 1991, exceeded only by the 10.31 in. received in July–August, 1988. The storm of August 13–14, 1991, brought 1.25 in. of rain to White Sands between 11:30 p.m. and 6:00 a.m. Aguirre Spring recorded 3.75 in. from the same storm, and it is conceivable that portions of the upper watershed of Anvil Creek received substantially more rainfall from greater orographic influences. The total annual rainfall at Aguirre Spring for 1991 was 29.7 in., or about 63% more than at White Sands.

THE BREACH

The breach is a relatively wide swath cut through a narrow divide that formerly separated the two branches of Anvil Creek (Fig. 3). Where it is intact adjacent to the breach, the divide consists of older debris-flow material. Within the breach, the north branch of Anvil Creek has developed a small incised channel and a major knickpoint. Based on field evidence and air photos of September 1991, one might mistakenly assume that the lobe came down the north branch and plugged the channel, with the rest of the flow diverted eastward across the divide to form the breach. This, however, is not the case. The breach is already present on 1980 air photos. In fact, the breach also appears on the earliest air photos of the area taken in 1936, although the feature is somewhat difficult to discern. Therefore, the breach was initially formed by an older, but probably historical, flow event. Interestingly, there is a huge rock levee deposited on the outside bend of the active channel of Anvil Creek immediately downstream of the breach. Although much of the deposit was carried or modified by the 1991 flow event, resting on top of the levee is a boulder 7.5 x 7.9 x 11.0 ft estimated at 37.8 tons (Fig. 4). Thin, discontinuous patches of lichens preserved on the top and downstream side of the boulder suggest this rock was in situ in 1991, while at the same time, woody stems protruding from the upstream base of the boulder indicate at least local transport of the rock in 1991. The size and position of the boulder argue for a debris flow rather than running water as the process that greatly enlarged the breach in 1991.

THE LOBE

The debris flow widened out as it issued from the lower end of the bedrock channel. As it did so, part of the flow was diverted to the north, following the floor of the long-abandoned north branch of Anvil Creek. At one point, the flow gained almost enough depth and momentum to override the western divide of the north branch. The viscous mass flowed about 150 ft downslope in a northerly direction. Its width was restricted on the west by a steep bank of older and well-vegetated debris-flow deposits; along its eastern margin, the flow was intercepted and restricted by a line of oak trees growing on the floor of the north branch. The flow dumped approximately 29,000 ft^3 of round to subangular boulders in a matrix of gravelly to pebbly grus-like material. The largest of its boulders, located 125 ft downslope along the western margin of the lobe, measures 3 x 6 x 10 ft and is estimated at 10.5 tons. Many more large boulders were pushed to the eastern margin of the flow, nearly engulfing the line of oak trees.

The deposit appears to have little depth along its western margin where it merges with the adjacent hillslope. However, the lobe thickens eastward—on the outside of the bend—and reaches a maximum known depth of 8 ft along the line of trees. The lobe narrows downslope and has a terminus that is 29 ft wide and 4 ft deep.

FIGURE 3. Air photo of the Aguirre Spring Recreation Area taken one month after the debris flow of August 13–14, 1991. Numbers 1 and 3–6 are adjacent to the north branch of Anvil Creek. Numbers 9–11 are along the south branch of Anvil Creek.

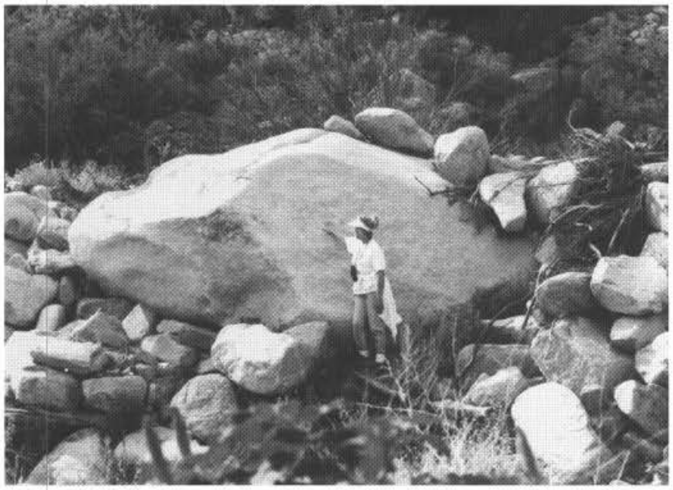

FIGURE 4. The largest boulder along the lower active channel of Anvil Creek. It is positioned on top of a major rock levee and probably moved a short distance during the 1991 flow event. View is to the south just downstream of the breach. Direction of flow is from right to left.

The head of the lobe

The head of the lobe that has been truncated at the breach has a relatively flat surface comprised predominantly of: (1) boulders less than 20 in. in diameter and (2) a nearly level fill of gravelly grus-like material between the boulders. The thickness of the lobe at its head is estimated to be about 4 ft based on exposed broken tree trunks and a change in soil and sediment characteristics between the lobe above and the old valley floor below (Fig. 5). There is some tendency of the smaller boulders toward imbrication, with a steep plane that dips upslope.

The width at the head of the lobe is 81 ft. The surface of the western-most 50 ft is flat, with only an occasional small boulder protruding above a nearly level fill of sand and gravel. There is an abrupt change in the composition and topography of the lobe eastward from the 50-ft location. Here the boulders are considerably larger. Their long axes range from 0.5–10 ft, and they provide a micro-relief of 1–2 ft. The majority of the larger boulders range from 2.5–5.5 ft; they are light gray, unweathered, and free of lichens, all of which indicate they were transported and deposited by the 1991 flow event. It is not certain, however, if the 10-ft boulder was actually moved in the same flow that formed the lobe, or if it is part of another deposit.

The eastern margin of the lobe

Coarse boulders dominate everywhere along the eastern margin of the lobe. They are largely free of sand and gravel fills and provide a micro-relief of 3–6 ft (Fig. 6). A few remain precariously balanced one atop the other and present a clear hazard to hikers who might venture off the Pine Tree Trail, a mere 40–75 ft to the west.

The steep eastern margin of the flow follows the trend of a series of well-established oak trees. It is believed that these trees became established along an inner channel of the old valley floor sometime after the north branch of Anvil Creek was abandoned. Of the 13 oak trees, only three were damaged or destroyed by the debris flow. The rest are intact and thriving despite the fact that they may be up to halfway surrounded by large boulders that range from 2–4 ft on the long axis. Shrubs, too, survived the inundation by the debris flow. Near the terminus of the lobe, a 15-stem shrub has been buried to a depth of 26 in. by boulders that range up to 25 in. on the long axis. The largest stem is 2.5 in. in diameter, yet the debris managed to bend only a few of the stems, while in contrast, the majority continue to stand upright. The relationship of the boulders to the vegetation and the fact that very little vegetation was damaged argue convincingly for a debris flow, because a water flow would have damaged all the trees and shrubs in its path. Further, these relationships confirm that the movement and deposition along the margin of the flow was exceedingly slow.

The middle of the lobe

At mid-lobe, the width of the zone of coarse boulders increases. Here the largest of the many boulders range from 6–10 ft on the long axis, with a dominant range of 8–10 ft. At this point, the larger boulders completely cover the surface of the lobe. Their dominant 8–10 ft size range is, most likely, a reflection of the joint pattern and joint density of the rocks farther upstream.

Several rafted tree-trunk segments lie atop the boulders in this area. The distribution of these tree trunks corresponds with the largest of the boulders. They are situated atop the boulders, transverse to the flow, and have 85–90% of their bark intact. These con-

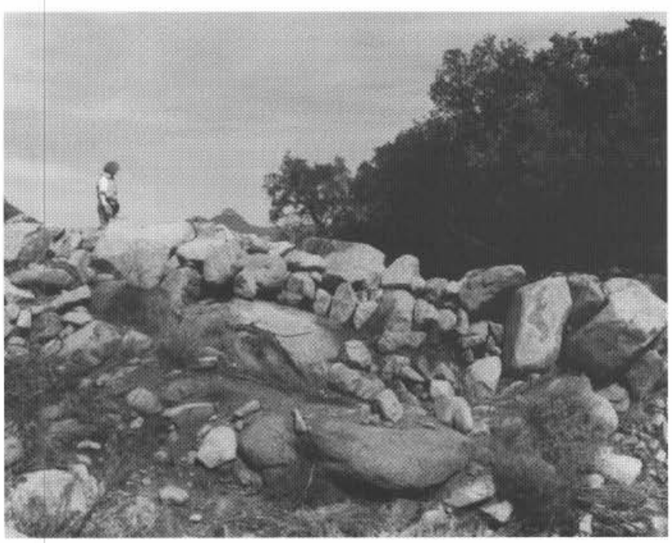

FIGURE 5. Cross section at the head of the lobe. Modern deposits approximately 4 ft thick overlie older and darker deposits. Note the coarsening of the boulders to the right or outside bend of the north branch of Anvil Creek. The breached divide was part of the wooded ridge to the far right.

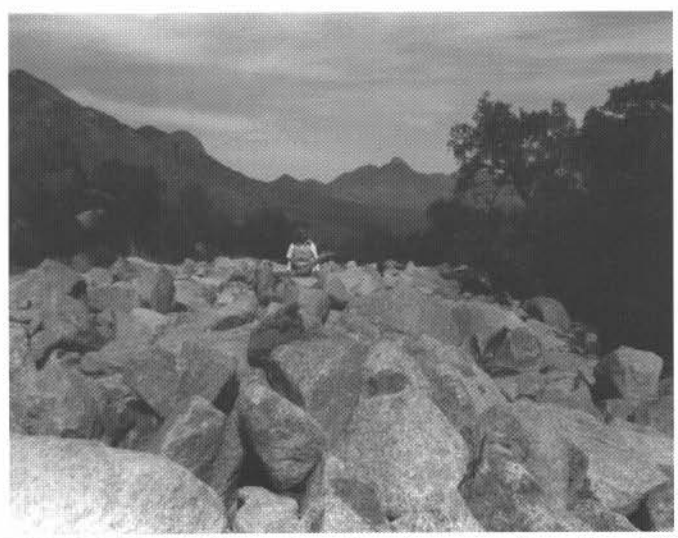

FIGURE 6. View looking north or downslope across the surface of the lobe. Large, clean, subangular boulders terminate abruptly to the right where the line of oak trees along the remnant valley floor of the north branch of Anvil Creek restricted the flow.

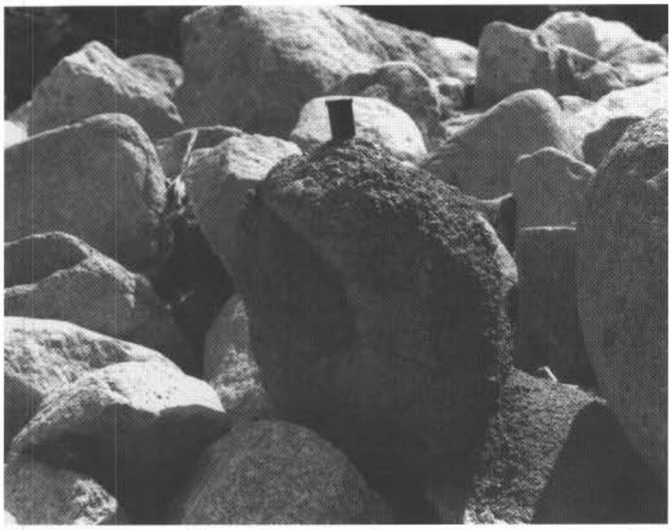

FIGURE 7. Thoroughly weathered corestone resting on top of large fresh boulders of mid-lobe region. Granular disintegration began almost immediately after the corestone was exposed at the surface. No trace of the corestone was found in 1996. Film canister for scale.

ditions lend support to the conclusion that deposition took place by way of a laminar, viscous debris flow rather than as the result of a turbulent, non-viscous flood flow.

A small, 1.5-ft diameter, chemically and concentrically weathered marginal corestone was centrally located and balanced atop and among the largest of the fresh, angular boulders (Fig. 7). This corestone attests not only to the mechanics of a debris flow, but also to the weathering and erosional processes which transformed the rock itself (Durgin, 1977). This altered rock would qualify, according to Durgin (1977), as a 60% chemically weathered corestone, the second stage in the erosional evolution of a granitic terrain. Corestones can range from 15–85% weathered material before breaking down to a third stage called decomposed granitoid or grus. In the decomposed granitoid stage, the mass is very friable due to its 85–100% alteration. There was no trace of the corestone at Aguirre Spring in 1996, an indication of the rate of granular disintegration once the corestone was deposited and exposed on the surface of the lobe.

If, as Durgin (1977) proposes, debris-flow movement is related to the decomposed granitoid stage, then this small but very important piece of evidence argues convincingly for a debris flow as opposed to a water flood. This corestone, marginal to a decomposed granitoid, must have been rafted in a viscous, laminar flow, because a turbulent flood and the very large rocks with which the corestone was found, would have crushed such a small and friable mass. This evidence, combined with the evidence at the head of the lobe for a proportionally higher amount of decomposed granitoid, suggests that large amounts of grus were initially deposited as part of the lobe. Later, however, some of the grus was winnowed out by surface runoff and redeposited downstream ahead of the lobe.

The terminus of the lobe and beyond

At the distal end or the nose of the lobe, one small shrub with 10 major stems ranging from 1.5–3.0 in. in diameter was a very effective agent in creating a boulder jam; yet the shrub is intact and alive in spite of the fact that it is 80% encircled by several boulders having a long axis of 3–4 ft. A transition zone of boulders and finer sediment extends 38 ft downstream from the terminus of the lobe. About 30% of the zone is covered by large, scattered, unweathered boulders that average 5 ft on the long axis. The rest of this zone is

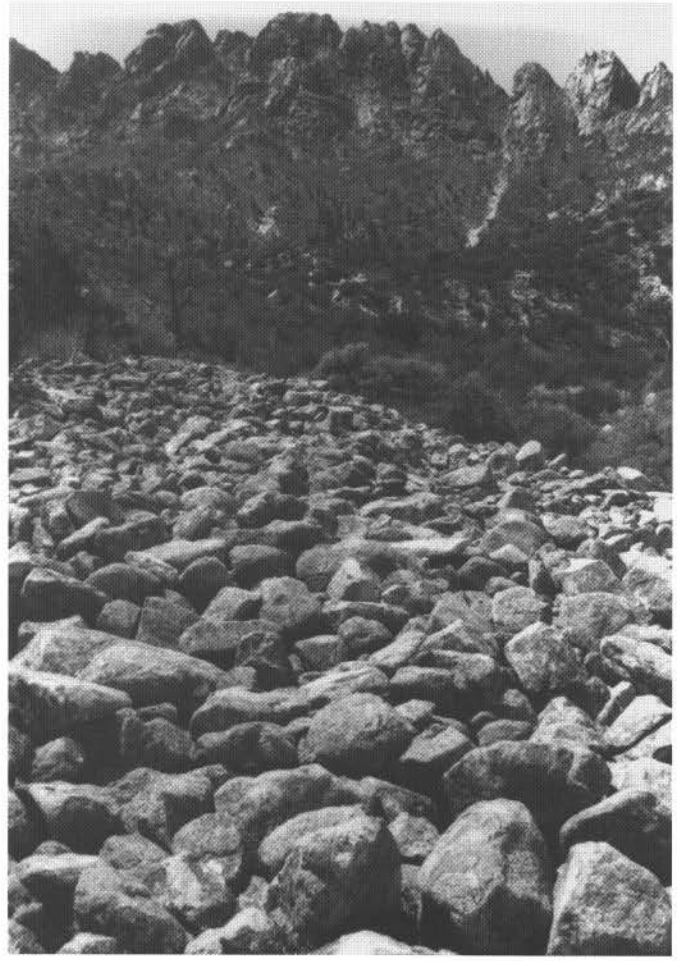

FIGURE 8. Relict debris-flow deposit preserved on the divide between the two branches of Anvil Creek. The stain and size of the rocks suggest in situ fracturing through frost action. The view is upslope, with the scarred bedrock channel of the north branch of Anvil Creek clearly visible just below the Organ Needles.

covered by a mix of old and recent sediment resting on top of an older debris-flow deposit. Some, if not most, of the recent sediment was derived from the flushing of sand and gravel fill from the margins of the lobe. However, the maximum water discharge during or immediately after the deposition of the lobe was not great. On the contrary, high water marks that are clearly preserved on the old valley floor ahead of the lobe indicate a maximum water depth of 3 ft. Extending another 72 ft down valley is a zone where the evidence for water discharges is much greater. Here, the valley floor is covered by a mixture of recent fluvial deposits and reworked, older debris-flow material However, as in the case in the transitional zone above, the water depth never exceeded 3 ft during the 1991 event. The average maximum depth of water on the valley floor was 25 in.

THE REMNANT VALLEY FLOOR

Between the east valley wall of the north branch of Anvil Creek and the eastern margin of the lobe is a preserved stable remnant of the old valley floor. It shows very little evidence of runoff in recent times and definitely no major runoff in association with the deposition of the lobe. The floor is devoid of an active, definable channel. Instead, there are numerous small rivulet-like features (poorly defined rills). Dark-stained, lichen-covered boulders provide a micro-relief of 2–3 ft. Several of these older boulders are at least as large as the largest boulders associated with the 1991 lobe deposit.

FIGURE 9. View upstream along the main stem of the active channel. The chute-like appearance of the channel and the polished bedrock floor suggest recent grinding by a viscous flow.

The remnant valley floor downstream of the transitional zones is also very stable. Numerous small channels carry local runoff between the many trees and shrubs that anchor the valley floor. This is true even in areas of moderately steep slope. There is at least one very well preserved, older rock levee along the eastern margin of this reach of the remnant valley floor. It contains one 10-ft high, 13-ft long, and 10-ft wide boulder estimated at 74.4 tons. The boulder has several detached blocks that indicate that, upon deposition, the original boulder was considerably larger. This boulder and others in the levee are marginal to one of the most conspicuous features in the study area—an unusually large, steeply sloping accumulation of pinkish-red boulders on the divide between the two branches of Anvil Creek (Fig. 8). The deposit contains thousands of small, lichen-covered boulders that probably represent an ancient debris-flow deposit. If true, then this boulder field, now perched 15–30 ft above the modern drainage lines, represents local relief inversion on an old valley floor. A conspicuous difference between the modern and ancient debris flows is the dominant size of the boulders at the surface. Field evidence suggests the boulders of the older debris-flow deposits have been shattered or fractured in situ, probably as a result of frost action.

THE WEDGE EFFECT OF THE LOBE IN THE NORTH CHANNEL

The lobe, flowing as a viscous mass, initially followed the floor of the abandoned north branch of Anvil Creek. Although the valley floor is quite steep, the flow came to rest because it became constricted between a valley wall on the west and a well-defined line of oak trees on the east. The oak trees trend diagonally away from the east valley wall and encroach and constrict the valley floor. The resistance of the lobe deposit caused subsequent flows to reroute to the east, through the breach, into the active south channel of Anvil Creek. The floor of the north branch is now permanently plugged or sealed by the lobe, and barring the occurrence of an even larger and catastrophic debris flow, the north branch should no longer pose an immediate threat to the BLM campground and recreation area downstream. This is especially true for water floods that are no longer able to turn out of the incised active channel and into the north branch.

The protection that the lobe itself provides against subsequent debris flows in the north branch is less certain. This is because the central and upper reaches of Anvil Creek basin are mantled by a substantial regolith that occupies moderately steep slopes. These slopes have been scarred deeply in many places, exposing weathering fronts, corestones, and reworked older debris flows. More importantly, however, these unconsolidated materials are often overlain by debris-flow levees containing car-sized and larger boulders. It is not unreasonable to suggest that should these slopes in the central and upper reaches fail again, ultimately causing another debris flow, the lobe in the north branch could be remobilized.

CHARACTERISTICS OF THE ACTIVE CHANNEL

There are several forks to the north branch of Anvil Creek. Only one produced the flow event that impacted the Aguirre Spring Recreation Area. This fork, herein referred to as the active channel, is a scar in the landscape that can be seen from a distance of several miles. On aerial photographs, the active channel appears mostly light gray and is readily distinguished from the dark background of soil and vegetation.

The head of the active channel

The active channel begins as a set of first order tributaries near the divide along the upper, central portion of Anvil Creek basin. These two small channels form an Y-junction at an elevation of approximately 7400 ft. Their confluence has developed at a water gap or notch eroded through two rock columns developed in unit Tmo. It is from this junction downstream that the effects of the 1991 flow event are most pronounced.

Between elevations 7400 and 6500 ft, the active channel is cut across Tmo and Tmps. This main stem begins as an open chute-like channel and becomes progressively incised in the downstream direction (Fig. 9). The bedrock exposed on the channel floor and walls is everywhere highly fractured by steeply-inclined joint sets. Above the bedrock in the valley walls is a deep regolith of grus, corestones, and boulders. The channel floor, by contrast, has been swept clean of almost all boulders and debris associated with the 1991 flow event. The most unusual feature of this entire reach is a large isolated boulder along the south margin of the channel. This boulder, estimated at several hundred tons, was overridden by the 1991 flow event but was not mobilized. Although it was scoured and cleaned on its upstream face and sides, its downstream side remains covered by lichens and an organic soil.

The active channel near Pine Tree Trail

The active channel intersects Qcrp at an elevation of 6550 ft. The Pine Tree Trail crosses the active channel from north to south near the head of unit Qcrp, at an elevation of 6525 ft (Fig. 10). Immediately downstream of the trail crossing, the active channel displays a prominent knickpoint. Flows from the bedrock channel above plunge into and undercut the older fan materials below, producing steep valley sidewalls of exposed gravelly grus and partially decomposed boulders. From here to the lower end of the bedrock channel near the breach, the active channel displays alternating reaches of bedrock (Tmps) and debris. It is clear that the 1991 flow event entrenched the active channel but not its tributaries. As a result, several knickpoints have developed at tributary junctions. Other knickpoints have developed due to differential erosion of the bedrock channel floor. At a point approximately 900 ft upstream of the lower end of the bedrock channel, a knickpoint has developed along a 6-ft high boulder dam. Also conspicuous along this reach are sharply defined marginal levees and in situ boulders that are considerably larger than those carried by the 1991 flow event. It is apparent that a great amount of fractured bedrock and unconsolidated older fan and debris-flow material remain in this middle portion of Anvil Creek basin.

Hydraulic characteristics of the active channel above the breach

Along the lower end of the bedrock channel and just above the breach, scour lines are clearly preserved on the channel walls. Therefore it is possible to measure the cross-sectional characteristics of the active channel and to make estimates of flow velocity and discharge (Benson and Dalrymple, 1967; Riggs, 1985). However, the results can be applied only to running water and not to a possible debris flow. Further, the calculations are based on a channel that is filled with water in the present cross-section, yet it is a certainty the cross sections were being modified as the 1991 flow event was in progress. Specifically, the modern cross-section is probably much larger than the cross-section associated with the momentary peak discharge of any single flow event. In order to ease the task of measurement and calculation, the minor irregularities of the cross-sections have been ignored. The hydraulic characteristics can be used to substantiate or refute the possibility that the 1991 flow event was a water flood.

The north branch of Anvil Creek in the vicinity of the breach drains approximately 0.3 mi^2, or 60% of the entire Anvil Creek basin upstream of the loop road. The estimated peak velocities at five cross sections immediately upstream of the breach range from 18.3–28.3 ft^3 per second . The estimated peak discharges range from 7374–19,252 ft^3 per second. This produces a peak water yield of 24,500–64,175 ft^3 per second per mi^2. It is not possible from a meteorological or hydrological standpoint to produce such great magnitudes of discharge and water yield from a basin the size of north Anvil Creek. According to the U.S. Soil Conservation Service (1984), the maximum discharge that could be produced in a basin of 200 acres (about 0.3 mi^2), under optimum conditions, is 390 cfs from a 4.0 in. thunderstorm and 1100 cfs from a 10.0 in. thunderstorm. Also, it is impossible for a natural channel with five closely-spaced cross sections to have such a great range in peak discharge from the same flow event. The only reasonable conclusion is that the active channel of Anvil Creek was significantly modified and enlarged while the 1991 flow event was in progress.

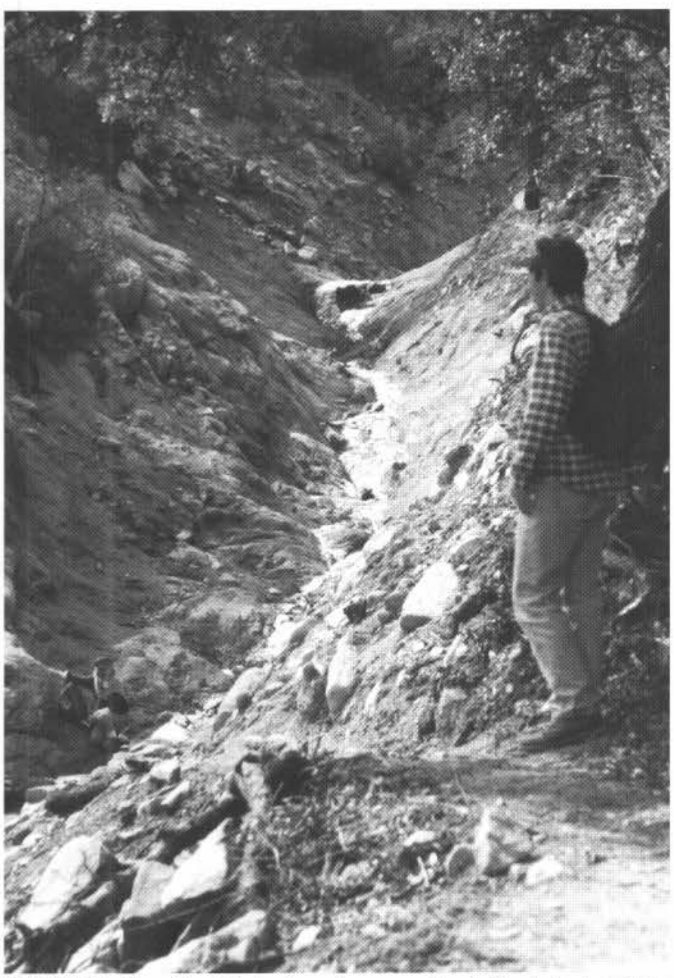

FIGURE 10. Pine Tree Trail where it crosses Anvil Creek, just upstream from a major knickpoint developed at the contact between bedrock and unconsolidated deposits. The thick regolith in this portion of Anvil Creek basin could serve as a source for future debris flows.

CONCLUSIONS

The evidence presented above and summarized below argues convincingly for a debris flow as opposed to a flood on the night and early morning hours of August 13–14, 1991. As Costa (1984), Costa (1988) and Williams and Costa (1988) suggest, several kinds of geomorphic and sedimentologic evidence remain behind following debris flows that can be used to delineate the type of flow. These diagnostic postevent features include: "(1) unsorted and unstratified deposits of gravel, sand, and fines; (2) marginal levees of coarse clasts, the largest of which may be at the top of the levees; (3) terminal, steep-fronted lobes of debris bordering the channel or flow path; and (4) unusually large boulders, transported at the margins of flows, which may have done little or no damage to vegetation..." (Williams and Costa, 1988, p. 67).

Poorly sorted and unstratified deposits of gravel, sand, and fines are common throughout the study area. This applies not only to the materials laid down by the 1991 flow event, but also to the deposits associated with paleoflows in and around Anvil Creek basin. Those deposits that are sorted and stratified are the exception rather than the rule, and occur in rather isolated patches along the bedrock channel floor, as well as in strands or almost terrace-like deposits along the active lower channel downstream of the breach. These localized sorted and stratified deposits appear in all cases to be associated with water runoff in the study area in late summer/early fall of 1991 and are subsequent to the flow event of August 14.

Marginal levees form when "Lateral areas of the flow mass are pushed to the sides and sheared from it as the rigid plug passes through the middle of the flow..." (Costa, 1984, p. 292). Furthermore, debris-flow levees often display a reverse grading, with the largest clasts or boulders at the top (Costa, 1988). There are three areas along Anvil Creek where marginal levees with coarse clasts at the top were present immediately after the 1991 flow event: (1) along the lower active channel immediately downstream of the breach (Fig. 11), (2) on the loop road where the active channel was temporarily diverted to the east and a long curved levee was deposited on the margin or outside bend of the flow route, and (3) along the margins of the active channel within the lower campground. Much of the evidence for the levees was removed by construction in the period 1992–1995.

Terminal lobes develop when a debris flow stops and the "strength of the material or concentrations of coarse clasts at the margins of the flow allow the formation of steep fronts and sides, creating terminal lobes of finite thickness on sloping ground" (Costa, 1984, p. 292). The terminal lobe that plugs the valley floor of the north branch of Anvil Creek is the single most convincing piece of evidence for a debris flow rather than a water flood. The distinction between the two flow events is especially important for mapping geomorphic hazards and for recommending mitigating

FIGURE 11. Marginal rock levee along the west bank of the lower active channel of Anvil Creek, approximately midway between the breach and the loop road. Although the large tree was rafted a considerable distance, its bark and branches survived mostly intact.

procedures. The evidence from the lobe could probably stand alone as the basis for an argument for a debris flow, but when combined with other field evidence, the argument is even more compelling. For example, the above-defined marginal levees and terminal lobes, as Costa (1984) suggests, can be, should be, and are, differentiated from those features created by water and mud floods called "boulders berms" (Stewart and LaMarche, 1967) or "boulder jams" (Krumbein, 1942). Thus, in the case of Anvil Creek, both the terminal lobe and marginal levees lead to the inescapable conclusion that the 1991 event was a debris flow.

The character of the active channel of Anvil Creek eliminates the 1991 flow event as a simple water flood. On the contrary, the upper reaches of the channel are developed in resistant rock that has been deeply scoured and highly polished, more reminiscent of flows of great viscosity such as alpine glaciers and debris flows. In addition, the active channel of Anvil Creek upstream of the breach has an enormous cross section and discharge capacity that would be impossible to fill from a single meteorological event. Furthermore, there is no evidence downvalley of the lobe or from the adjacent drainages that a major flood event occurred in 1991. It is not surprising that in 1991 BLM personnel surveyed the damage to the campground area and then exclaimed, "We can't figure out where all the water went."

Vegetation evidence

The evidence along Anvil Creek for "little or no damage to vegetation, except burial, at the edges of the flow..." (Costa, 1988, p. 118) lends additional support to Costa's diagnostic criteria for a debris flow. In many documented instances, small trees and shrubs on the slopes and at the margins of the flow have debris piled to their uppermost branches; while at the same time, the tree or branch survives. Costa (1984, p. 297) addresses this issue when he argues, "Trees engulfed by debris-flow levees can have rocks with diameters as large as 0.5 m packed around them" while at the same time having little or no bark removed (Fig. 12). Costa (1984, p. 297) suggests that this type of damage not only demonstrates the low velocity at the edge of the flow, but is also indicative of the type of event; because, he says, "Damage would have been much greater if the large boulders had been transported by a turbulent water flood." Additionally, there are some very large uprooted trees along Anvil Creek, bark intact, situated atop the debris; these trees, as can be evidenced by their largely unaltered form, have very obviously been rafted from above on top of the boulders rather than carried as part of a flood deposit. Finally, there is an abundance of small vegetation dispersed throughout the rocks and boulders which, after close inspection, reveals a coating of the "dried, gravelly, mud..." Costa (1988, p. 118) describes. Thus, in this case, as well as the others, the evidence argues overwhelmingly for a debris-flow event rather than a flood.

The combined geomorphic, hydrologic, sedimentologic, and vegetation evidence all support the conclusion that the flow event at Aguirre Spring in August of 1991 was not a simple water flood; it was a localized debris flow that was initiated in the north branch of Anvil Creek. Though significant or even catastrophic at the time of the event, the Aguirre Spring debris flow is but one relatively minor episode in a long sequence of similar events that has produced the landscape at Aguirre Spring.

ACKNOWLEDGMENTS

The following individuals assisted with field work on this project: Julie Eggerton, Larry Hahn, Wayland Mueller, Albert J. Peters, and Tony Trejo. Terence W. Huck, Jr., kindly provided climatic data for White Sands. Special thanks to the following readers and reviewers of the manuscript: H. Curtis Monger, Albert J. Peters, and William R. Seager. Thanks also to the many BLM employees who assisted on several phases of this project.

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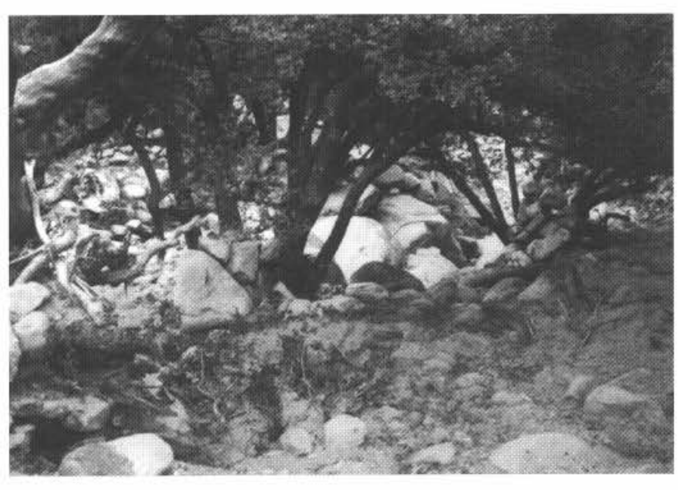

FIGURE 12. Oak trees in the lower campground engulfed by, but not damaged by, boulders of the 1991 debris flow deposit. The direction of flow was from right to left.

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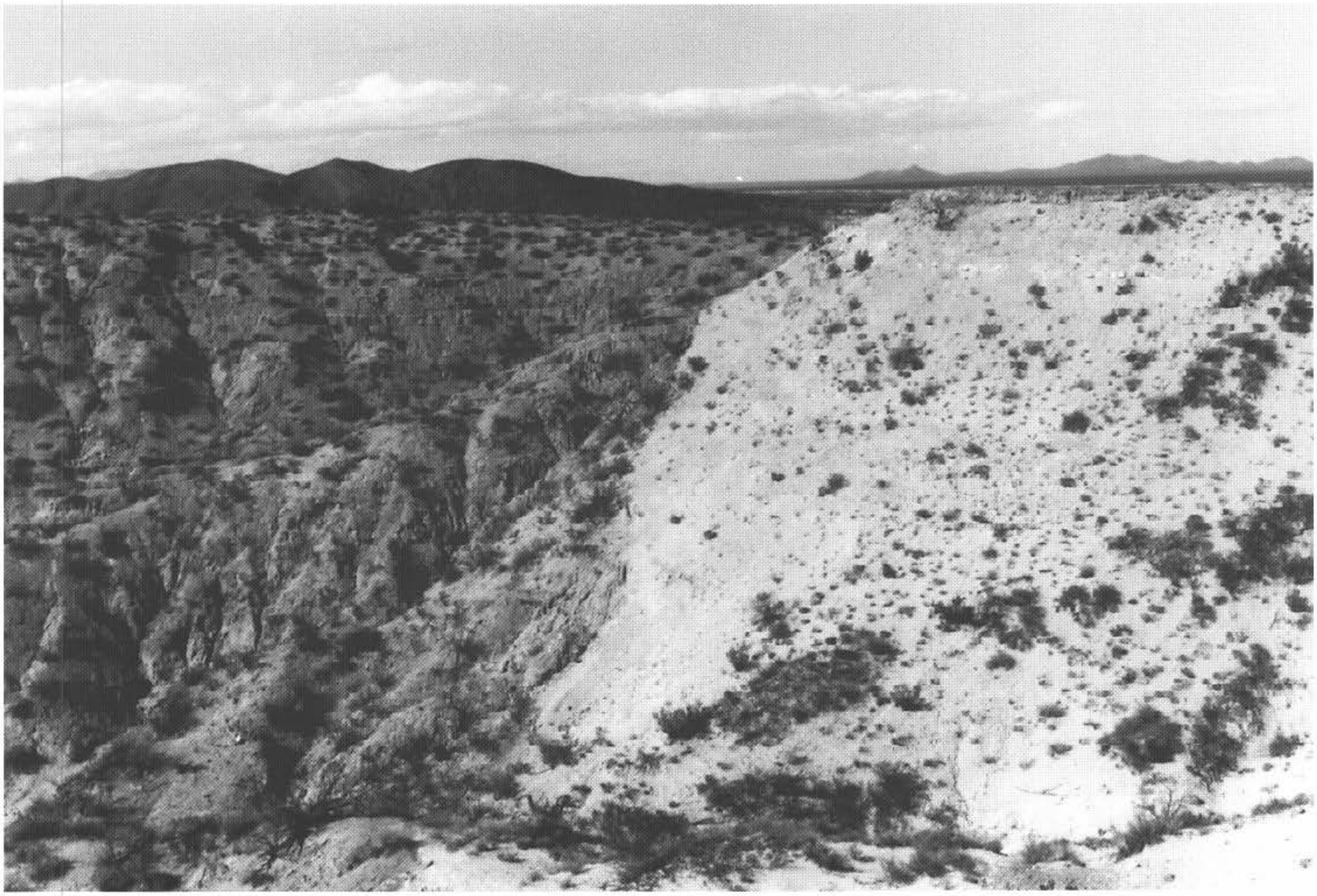

View looking north of the East Tonuco fault of Seager et al. (1971) south of San Diego Mountain. Perspective makes the fault appear to dip to the west (left), but it actually dips approximately 80° to the east (right). The fault offsets the Plio–Pleistocene Camp Rice Formation, placing axial-fluvial sediment on the hanging wall (right side). The East Tonuco fault probably connects southward with the Jornada fault, the main border fault of the Doña Ana Mountains. Photograph by Greg Mack.