mined by small-scale structure, we expect little relationship of this profile to the measurements made at northern latitudes. Little was found, except for the area between 120° and 140°W, which was dark to radar at both latitudes.

G. S. DOWNS
R. M. GOLDSTEIN
R. R. GREEN
G. A. MORRIS
*Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103*

**References and Notes**

1. R. M. Goldstein and W. F. Gillmore, *Science* **141**, 1171 (1963); R. M. Goldstein, *ibid.* **150**, 1715 (1965).
2. G. H. Pettengill, C. C. Counselman, L. P. Rainville, I. I. Shapiro, *Astron. J.* **74**, 461 (1969); R. M. Goldstein, W. G. Melbourne, G. A. Morris, G. S. Downs, D. A. O'Handley, *Radio Sci.* **5**, 475 (1970); A. E. E. Rogers, M. E. Ash, C. C. Counselman, I. I. Shapiro, G. H. Pettengill, *ibid.*, p. 465.
3. The original of the Mars chart was prepared by C. A. Cross and M. E. Davies of the Rand Corporation, under contract to the National Aeronautics and Space Administration.
4. This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory under NASA contract NAS 7-100.

12 October 1971

## Cave Development during a Catastrophic Storm in the Great Valley of Virginia

Abstract. *Observations made before and after a catastrophic storm support the conclusion that caves receiving storm recharge may be significantly developed in the vadose zone by the processes of mass transfer. These processes are greatly accelerated during times of major floods. Evidence indicates that in ancient times floods of similar magnitude have occurred.*

We present here observations which indicate that storm runoff is an important factor in the development of caves in the vadose zone. The effects of a single high-magnitude storm and evidence of similar events in the past are reported.

On 17 August 1969, Hurricane Camille, a relatively small but extremely intense storm, blew into the United States along the coast of Mississippi. The damage it produced, its extremely low barometric pressure (901 mb), and its high surface wind velocities [172+ miles per hour (275+ km per hour)] may have gained it the title of "this century's greatest hurricane" (*1*). On the evening of 18 August Camille left northeastern Mississippi as a tropical depression (winds less than 38 miles per hour) and arched northeastward through Tennessee and Kentucky; it grazed the southern edge of West Virginia and moved into Virginia.

Camille's cyclonic circulation fed the storm into the northeast-trending Great Valley system where it encountered a relatively warm mass of moist maritime air, the orographic effect produced by the Blue Ridge Mountains, and the influence of a cold front approaching from the north (*2*). At several locations in Virginia 25 to 28 inches (63.5 to 71 cm) of rainfall in 8 hours were recorded, and in one instance 31 inches in a similar time interval was reported. The maximum rainfall has a return period "well in excess of 1000 years" (*3*); the peak discharge of many streams in the storm area has a comparable return period. New high-water marks were established for many of the streams in the James, Potomac, Rappahannock, and York river basins (*4*).

Cataclysmic changes were not confined to the surface, for much of the Great Valley contains karst topography with substantial subterranean drainage. Figure 1 shows a collapse feature which formed during the Camille storm near Lexington, Virginia.

Prior to the storm, we were studying the hydrology of a stream located in Cave Springs Cave, about 1 mile northwest of Lexington, Virginia, in a karst terrain underlain by the New Market and Lincolnshire formations. The stream flows through approximately 2000 feet (610 m) of the cave's passageways and occupies entrenched meanders along some reaches. It enters and leaves the cave through joints enlarged by solution, eventually reappearing at the surface a short distance away whereupon it flows into the Maury River.

Before the storm, the stream had a maximum depth of 2 to 3 feet, had an average depth of less than a foot, and carried a load consisting predominantly of mud containing some well-rounded chert pebbles. The stream load consisted of the typical insoluble residue to be expected from the limestone bedrock. Apparently the feeding joint system would not permit coarser alluvium access to the cave. Like many of the caves in the region, Cave Springs Cave is decorated with those kinds of speleothemic features that commonly adorn limestone caverns. These features testify to the supersaturation of waters with respect to calcium carbonate during at least part of the cave's history. The walls of the cave along the stream exhibited smooth, subdued, polygonal scallops (*5*). These features, which in the past have been interpreted as evidence of mechanical erosion (*6*), have in recent years been attributed to mass transfer on a molecular scale, that is, solution (*5*, *7*). Most of the scallops were masked by a patina of mud ranging in color

Fig. 1. Dolina or sinkhole which formed near Lexington, Virginia, during the Camille storm. [Courtesy of E. W. Spencer, Department of Geology, Washington and Lee University, Lexington, Virginia]

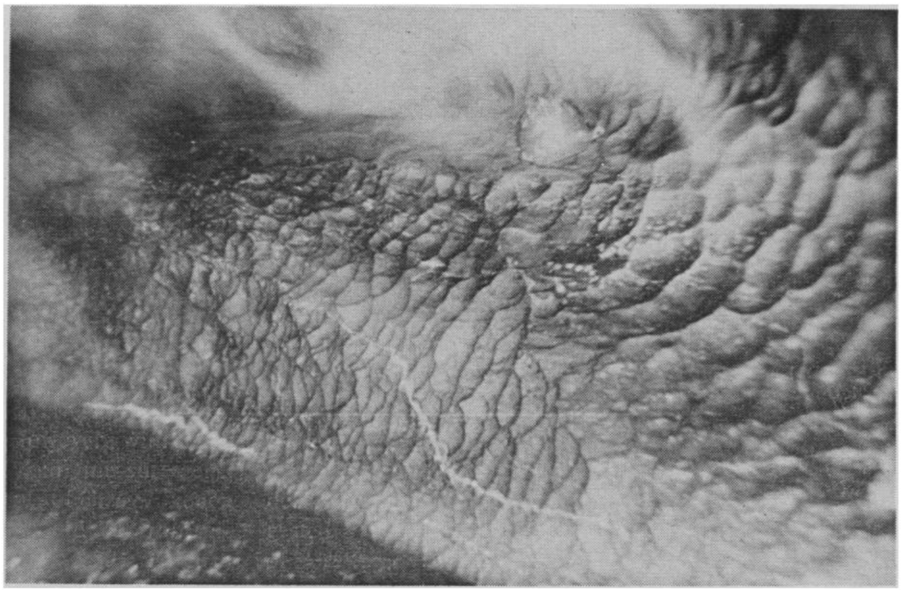

Fig. 2. Scallops on the wall of Cave Springs Cave. The hard hat rests near the boundary between the older, smoother scallops and the fresh, angular scallops produced during the storm. The stream bed is gravelly.

from rust to chocolate brown and, in some instances, by the weathering rind of the rock (Fig. 2).

We have no direct measurements of streamflow during the storm because our hydrologic equipment was completely swamped and rendered inoperative. Removal of patina, in some places accompanied by the establishment of fresh-appearing scallops, indicates that the stream depth exceeded 10 feet. The fresh scallops, undoubtedly a redevelopment of preexisting features, have angular margins, expose unweathered bedrock, and are pitted, particularly near constrictions in the channel. The character of the stream bed changed during the storm, for alluvium remaining in the stream bed after the storm was predominantly angular to subangular sand and gravel-sized clasts. Limestone was a major constituent of the alluvium after the storm. At one location a terrace deposit approximately 5 feet thick and some 25 feet wide by 45 feet long was deposited. The upper surface of the terrace is located 6 feet above the present stream, is composed of sand and gravel, and is capped by a 6-inch bed of well-sorted, medium- to fine-grain sand. Discharge in the cave had remained abnormally high through October 1970, the time of our last visit. Apparently the increased discharge of the storm flushed out or enlarged the feeding joint system, or both, and also permitted the passage of the coarse alluvium. In their present state, the feeders allow a higher base flow.

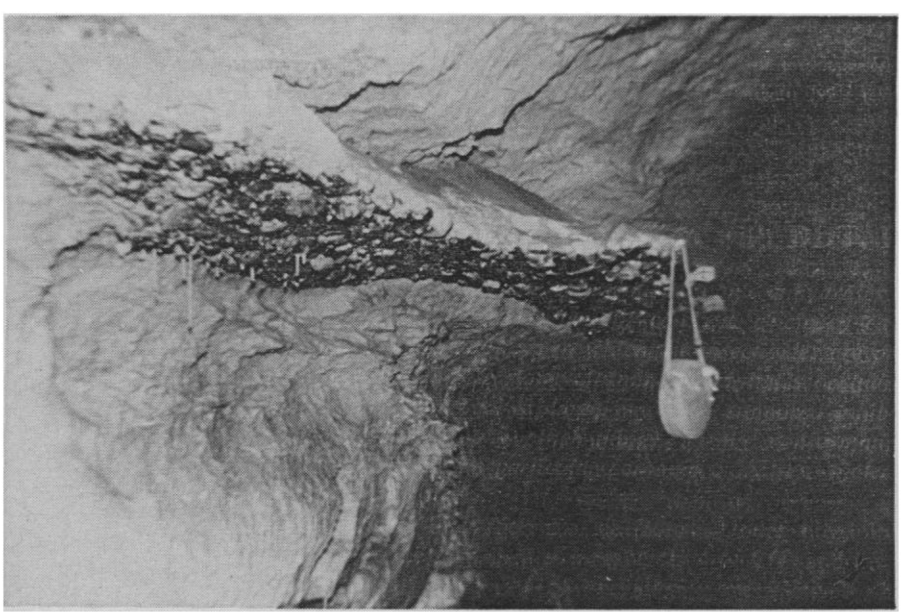

Fig. 3. The canteen hangs from one of many terrace-like deposits of conglomerate in Cave Springs Cave. The conglomerate is composed chiefly of subangular limestone and chert clasts.

During the flood, the processes of mass transfer were accelerated. Molecular mass transfer (solution) was increased by the higher flow velocity (probably in excess of 10 feet per second at peak discharge) and the expanded wetted perimeter of the stream. Macromolecular mass transfer (mechanical erosion) was greatly accelerated. Evorsion due to the high flow velocity and corrasion resulting from the suspended load are indicated by pits and potholes in and near the stream bed.

We view cave development at Cave Springs Cave in terms of cooperation between the processes of mass transfer. Solution, probably near the water table and influenced by joints, initially determined the location and general shape of the cave system. It produced the first avenues for flowing water. Like most accessible caves, Cave Springs Cave is now in the vadose zone where water is commonly saturated or supersaturated with respect to calcium carbonate (*8*). The wide variation in seasonal surface water temperatures suggests that there may be seasonal solution in the cave at present. Because streamflow has access to the cave, macromolecular mass transfer can play an important role in the further development of the cave. Corrasion and evorsion not only serve to enlarge the cave but also promote solution by exposing fresh rock and removing the impermeable patina. In this regard, one cataclysmic storm, such as the Camille storm, may accomplish more work than many centuries of more typical erosion.

Evidence which indicates that Cave Springs Cave has experienced floods in ancient times similar to that produced by the Camille storm includes scallops high on the walls of the cave, potholes near and above the present stream level, and terrace-like deposits of conglomerate very similar in composition and texture to the alluvium that was produced after the storm of 1969 (Fig. 3). The effects of these floods have survived the intervening periods of more normal erosion. Although we do not presume that the mode of cave development described here is universally applicable, we do believe that similar conditions may be recognized in other limestone caves which receive storm water recharge.

D. O. DOEHRING
*Department of Geology, University of Massachusetts, Amherst 01002*

R. C. VIERBUCHEN
*Department of Geology, Washington and Lee University, Lexington, Virginia 24450*

**References and Notes**

1. R. M. DeAngelis, *Weatherwise* **22**, 173 (1969).
2. H. J. Thompson, *ibid.*, p. 181.
3. R. M. DeAngelis and E. R. Nelson, *Climatol. Data Nat. Sum.* **20**, 8 (1969).
4. J. D. Camp and E. M. Miller, "Flood of August 1969 in Virginia" (U.S. Geological Survey open file report, Washington, D.C. 1970).
5. R. L. Curl, *Trans. Cave Res. Group Gt. Brit.* **7**, 121 (1966).
6. J. H. Maxson and I. Campbell, *J. Geol.* **43**, 729 (1935).
7. J. R. L. Allen, *Sediment. Geol.* **5**, 167 (1971).
8. J. Thrailkill, *Bull. Geol. Soc. Amer.* **79**, 19 (1968).
9. We thank A. N. Palmer and I. Karcz for their many helpful comments.

1 June 1971; revised 14 September 1971

## Nonspreading Crustal Blocks at the Mid-Atlantic Ridge

Abstract. *Transverse ridges consisting of protrusions into crustal fractures of ultramafic bodies derived from the upper mantle exist at the intersection of the Mid-Atlantic Ridge with equatorial fracture zones. Shallow-water limestones containing detrital grains of quartz, microcline, and orthoclase 1 millimeter in diameter were found on the summit of one such transverse ultramafic body at the Vema Fracture Zone; these findings are explained on the assumption that the limestones were deposited within a narrow, shallow proto-Atlantic and were left behind during the further opening of the Atlantic. Transverse ultramafic bodies from the offset zones of the Mid-Atlantic Ridge behave as nonspreading blocks plastered between spreading crustal plates.*

The theory of sea-floor spreading implies that oceanic crust is continuously being produced at the axis of the Mid-Atlantic Ridge (MAR) and that it moves laterally at rates ranging from 1 to a few centimeters per year. Accordingly, only young material should be found at or close to the axial zone of the MAR. We present here results indicating that ancient, essentially nonspreading crustal blocks exist at the intersection of the MAR with fracture zones in the equatorial Atlantic. The axis of the MAR is offset laterally along these transverse fractures, as seen in the Atlantis, Vema, St. Paul, Romanche, Ascension, and other fracture zones (Fig. 1). The morphology of the Vema Fracture Zone is known in considerable detail (*1*); it is characterized by a deep valley running east-west and interrupting the axis of the MAR which is offset by about 300 km (Fig. 1). A steep and elongated transverse ridge can be observed bordering the valley on its southern side; this transverse ridge is considerably more elevated than the crestal zone of the MAR both north and south of the offset (Figs. 1 and 2); it abuts to the east against the displaced axial zone of the MAR; on the western side it continues and gradually flattens out beyond the zone of offset.

Extensive dredgings (*2, 3*) have established that the Vema transverse ridge is essentially an ultramafic body probably derived from the upper mantle by upward protrusion into a preexisting crustal fracture. Similar ultramafic transverse ridges exist at the intersection of the MAR with other fracture zones, as in the Romanche (*2*), Atlantis (*4*), and St. Paul fracture zones (*5*).

The crest of the Vema transverse ridge is capped by hard limestones and $MnO_2$ crusts. At one station on the very summit of the ridge (station P7003-5; 10°41′N, 44°18′W; 550 to 900 m below sea level) (see Figs. 1 and 2) we recovered a hard quartziferous limestone, which was studied by microscopic and x-ray diffraction methods. The limestone consists of abundant pelloids and ooids and of recrystallized fossils which include shallow-water (< 30 m) benthic foraminifera of the Miliolid group and gastropods and fragments of calcareous green algae of the Dasyclad group; the whole is in a fine calcitic matrix. The pelloids and ooids range in diameter from 0.2 to 0.8 mm. A common type of pelloid consists of clear calcite crystals surrounded by a dark micrite envelope; frequently, the core within the micrite envelope is empty; in other cases it consists of recrystallized calcite. Similar structures have been described in carbonate sediments deposited in shallow epicontinental basins, typically in the Bahama Banks (*6*). In addition, this limestone contains abundant angular grains of clear, monocrystalline quartz ranging in diameter from 0.2 to about 1 mm (Fig. 3); grains of microcline (Fig. 3) and orthoclase are also present. At the same site we recovered samples of a deeply pitted, selectively dissolved limestone with features suggesting subaerial weathering. Other suggestions of a past emersion of the Vema transverse ridge include our recovery at various sites on its crest of rounded pebbles of a strongly weathered basalt, and the aforementioned "micrite envelopes" with empty cores in the quartziferous limestone; identical types of "micrite envelopes" have been interpreted as due to selective dissolution under subaerial conditions (*6*).

At another site on the crest of the

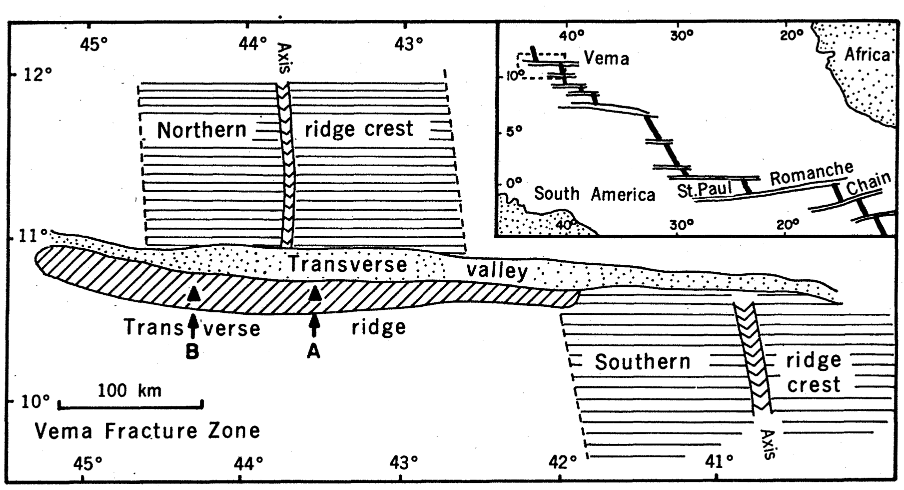


Fig. 1. Morphology of the Vema Fracture Zone, based on data of Van Andel *et al.* (*1*). Triangles indicate locations on the transverse ridge where the quartziferous limestone and the fossil shell were recovered. Arrows point to north-south profiles shown in Fig. 2.