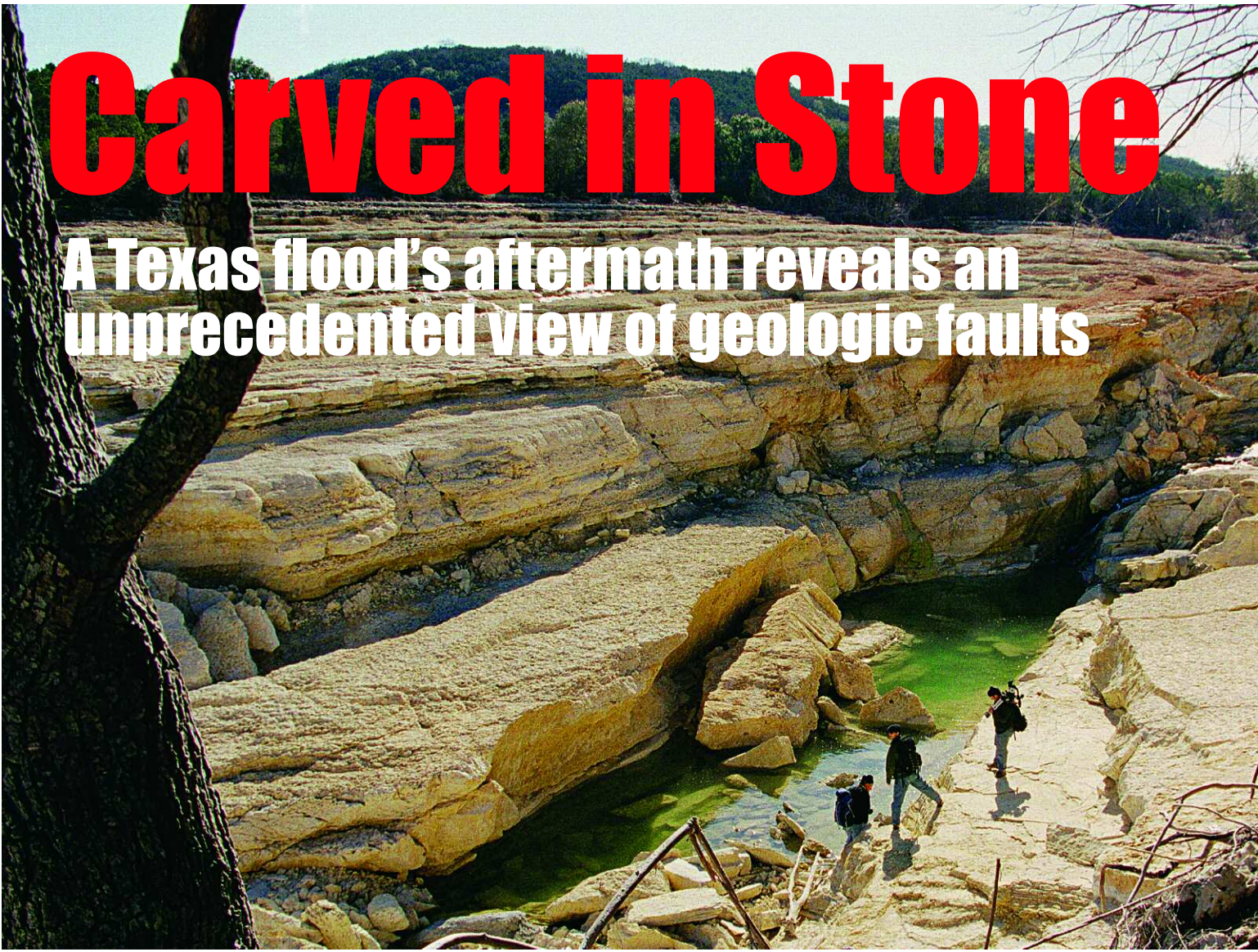


Carved in Stone

A Texas flood's aftermath reveals an unprecedented view of geologic faults



By David A. Ferrill, Ph.D. and Alan P. Morris, Ph.D.

On July 5, 2002, after 35 inches of rain had fallen in eight days on the Guadalupe River drainage basin in Central Texas, Canyon Lake reached its highest level since the lake began to fill in 1964. The spillway, notched into a ridge line as an emergency outlet for lake water near Canyon Dam, flowed for the first time.

The 2002 flood channeled more than seven feet of water, at 70,000 cubic feet per second, over the 1,247-foot (380-meter) wide spillway and into a narrow valley vegetated with juniper and oak forest. The raging torrent incised the valley floor, removing thousands of cubic yards of soil, weathered bedrock and limestone blocks. The excavated material was transported to the confluence of the spillway and the Guadalupe River below the dam, where much of it was deposited. This deposition of eroded material created a natural dam that caused extensive and costly damage to a

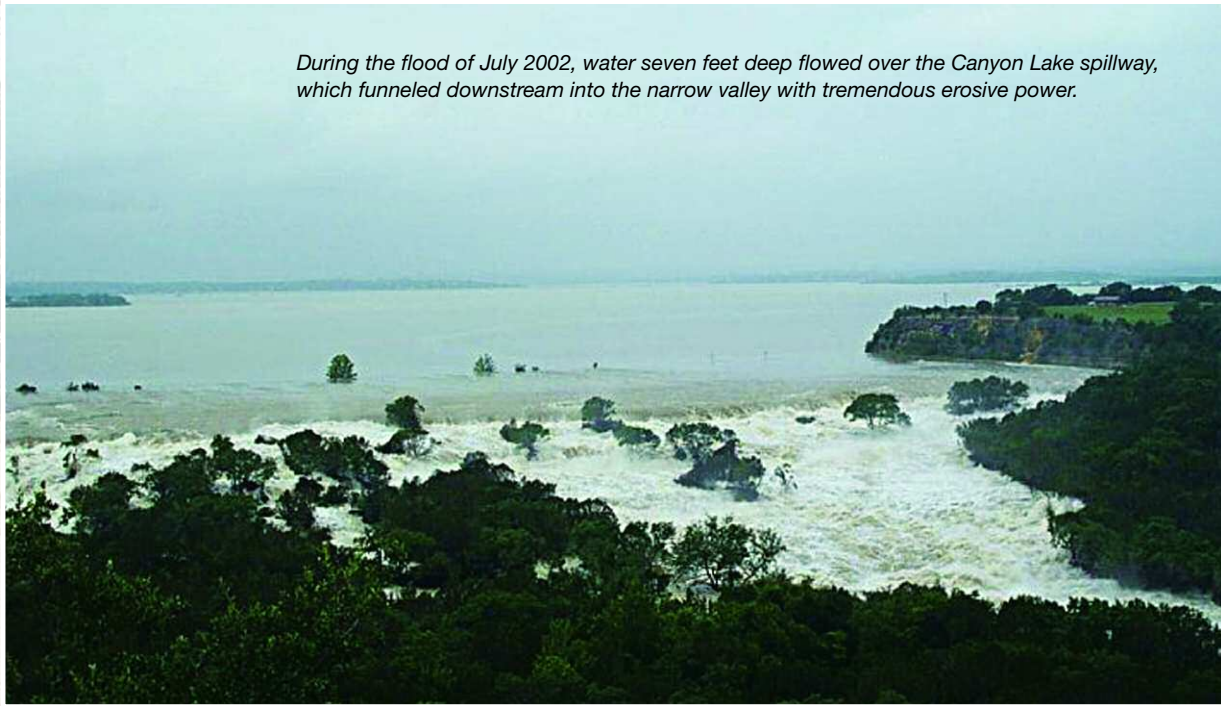
hydroelectric plant at Canyon Dam when floodwater backed up and entered the power plant. Farther downstream, the flood caused loss of life and considerable damage to private homes and lands.

For geologists, however, the receding floodwaters revealed a pristine gorge containing rocks that had not been exposed for more than 65 million years since the Cretaceous period, when the sedimentary strata were deposited as carbonate sand, shells of marine animals and mud. The unanticipated scientific and public benefits from the flood-created Canyon Lake Gorge are now being realized through studies under way at Southwest Research Institute (SwRI). In cooperation with the U.S. Army Corps of Engineers and the Guadalupe-Blanco River Authority, and with financial assistance from sources including the Edwards Aquifer Authority, the Corps of Engineers and SwRI internal funds, two research projects have been completed and two more are ongoing.

Besides the unprecedented exposure of parts of the Upper and Lower Glen Rose Formation, Canyon Lake Gorge reveals a nearly continuous, 2,625-foot (800-meter) long section of the Hidden Valley fault. This fault is a fracture zone along which rocks of the Glen Rose Formation slipped downward about 230 feet (70 meters) toward the Gulf of Mexico during the Tertiary geological time period, which followed the Cretaceous.

This Hidden Valley fault was not unknown to geologists before the 2002 flood. It had been mapped by the United States Geological Survey in 1952 and again, a decade later, as construction of Canyon Dam was under way. No one, however, had a clear view of the fault until the flood.

The Hidden Valley fault is typical of normal faults mapped throughout the Balcones fault system of South Central Texas. These faults most commonly drop rock strata down toward the Gulf of



During the flood of July 2002, water seven feet deep flowed over the Canyon Lake spillway, which funneled downstream into the narrow valley with tremendous erosive power.

Photo courtesy Comal County Engineer's Office



The flood of the Canyon Lake spillway scoured through the valley floor, incising a deep gorge in the Glen Rose Formation bedrock, leaving hints of the former valley floor with exposed root mats on the edges of the gorge. The locally deepest incision occurred where faulted and fractured rock adjacent to the Hidden Valley fault was stripped out along the valley floor.

Mexico, forming key components of the local groundwater flow pathways as well as the regional Trinity Aquifer system. In the oil industry, faults with displacement (slip) of 10 to 20 meters (33 to 66 feet) or more can be imaged with seismic reflection surveying. These faults are referred to as "seismic scale" faults. Faults with smaller displacements,

below the detection limit of seismic reflection data, are known as "subseismic." Seismic and subseismic faults are common in oil and gas reservoirs around Texas and throughout the world, including carbonate reservoirs that are similar to the Glen Rose Formation exposed in the Canyon Lake Gorge. Thus, the insights gained from studying the Hidden Valley fault could contribute to improved management of Texas' two most valuable fluids: water and oil.

Faults and Water

As part of the two projects jointly funded by the Edwards Aquifer Authority and the Corps of Engineers to analyze and characterize the structure of the Edwards and Trinity aquifers in northern Bexar County, Texas, SwRI researchers began studying the geologic structures and related hydrology of the Canyon Lake Gorge a few months after the flood. At the gorge they observed springs and seeps



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A large surface water pond, partially fed by a spring discharging from the Hidden Valley fault, rests on the up-thrown side of the Hidden Valley fault and the principal fault displacement zone itself. The pond is formed where layers that dip gently toward the fault were stripped off by erosion during the flood, leaving a depression now filled by the pond.

that discharge groundwater from fractures, faults and bedding planes in the Glen Rose Formation. A steady supply of surface water fed by these springs flows along and locally creates ponds on the surface trace of the Hidden Valley fault zone in several places. After cascading across two waterfalls separated by a pool, the water collects in a lower pool resting directly on the fault and then sinks into the valley floor along the fault trace. A short distance down the gorge, SwRI researchers observed that a five-meter-deep depression scoured out of the heavily fractured fault zone remains dry, except immediately after a storm when the depression will briefly collect water and then quickly drain over a couple of days. Still farther along, water steadily gushes from the exposed fault zone in the wall of the gorge and falls into a large pond resting on the fault. Taken together, these observations of the laid-bare Hidden Valley fault not only illustrate, but make possible a direct characterization of the complex hydrology of a typical fault in the upper Glen Rose Formation.

In fact, the Hidden Valley fault acts as both a barrier and a conduit for water. Where water is able to pond on the fault, it is apparent that the fault has low permeability. In other areas, where water sinks into the fault or flows out of the fault zone, it is clear that the fault serves as a conduit

for flow. Meanwhile, springs and seeps discharge groundwater along certain beds, in many cases localized along fractures. The combined effect amounts to a natural laboratory that provides definitive evidence of the complex barrier and conduit behavior of faults in the Upper Glen Rose Formation and Trinity Aquifer.

These observations and more detailed characterization of these conduit and barrier behaviors and their geologic and hydrologic causes help influence how groundwater is modeled. Because this fault is typical of thousands of miles of mapped faults in the Edwards and Trinity aquifers in the Balcones fault zone, the interplay among water and layering, faults and fractures in the Canyon Lake Gorge provides a remarkable opportunity to gain new insights into carbonate aquifer behavior. Those insights in turn could help hydrologists understand and predict the rate and direction of flow of groundwater within carbonate aquifers, thereby making possible a new generation of more accurate groundwater models.

Faults and Oil

Just as the Hidden Valley fault serves as an unprecedented natural laboratory to study carbonate aquifers, it also provides an analog for similar faults in carbonate petroleum reservoirs in Texas and around

the world. Most exciting about this field site is the quality of exposure, virtually devoid of vegetation and sedimentary cover and revealing the detailed faulting character of the carbonates, including the “seismic scale” Hidden Valley fault and also hundreds

of faults too small to image with seismic reflection data. Thus, this is an ideal laboratory to analyze subseismic faults, which are rarely characterized in detail but are widely recognized as important to reservoir quality and a key consideration in reservoir development planning.

SwRI investigations have produced important results that demonstrate the essential role of mechanical layering within carbonate rock sequences in controlling the deformation style and resulting fault zone architecture in layered limestone, dolomite, and shale sections. The Hidden Valley fault exposure in the Canyon Lake Gorge deforms the spectrum of clean carbonate sandstones (grainstones and packstones) and more mud-rich sedimentary beds (wackestone and mudstone), as well as clay shales. A detailed look at the deformation style below the fault in its footwall reveals a clear pattern of folding, with beds tilting downward toward the fault, along with small-scale faulting and thinning of beds, particularly where clay-rich shale beds are present. In some cases, bedding is steepened to the same dip as the fault, around 70 degrees. Where clay-rich shale beds are absent, thick limestone beds still tilt toward the fault, but their dip (inclination) is much more gentle—10 degrees or less.

Recognizing this opportunity to investigate in detail the subseismic- to seismic-scale faulting and the influence of

stratigraphy on how the rocks deformed, SwRI researchers worked with representatives from several major oil companies to develop a joint, industry-funded project to begin in late 2007. The multi-year project initially will focus on detailed characterization of the stratigraphy and structure of the Hidden Valley fault in the Canyon Lake Gorge. The project will include outcrop characterization and mapping, microstructural analysis at SwRI laboratories, drilling and coring, and subsurface characterization. This structural characterization work will culminate in a major report to the client companies at the end of the second year of the project. In later years, the project is expected to develop geomechanical characterization and modeling approaches to hone the oil industry's ability to predict rock deformation in reservoirs before drilling, and permeability characteristics of the fault zone and surrounding rock to help characterize such faults in reservoir models.

Future Directions

Through a memorandum of understanding with the Guadalupe-Blanco River Authority, the SwRI research team also is helping the river authority plan and prepare scientific materials to support developing a park that, when opened, will be used for public education and outreach. Scientists from SwRI are active members of the Science Advisory Team organized by the river authority to focus on scientific aspects of park planning, including identifying key geologic features to be showcased at overlooks as part of educational displays along a trail system among the bluffs overlooking the gorge. SwRI staff also will provide illustrations and explanatory text for displays, brochures and instructional materials for visitors to the gorge.

From the disastrous Canyon Lake flood of 2002, an opportunity was born to reap scientific rewards benefiting geologists, hydrologists, the international oil and gas industry and the public at large.

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Small displacement (“subseismic scale”) normal faults are abundant at Canyon Lake Gorge and, like this one, most commonly occur near the Hidden Valley fault. These small fault surfaces are marked by slickenlines formed during fault slip, providing clear indicators for the direction of slip on the fault.

The Hidden Valley fault dips steeply to the south-southeast. Layers on the up-thrown side of the fault are tilted gently to steeply in the same direction as the fault. Layers on the down-thrown side of the fault tend to be horizontal or dipping gently in the same direction as the fault.

Small displacement faults are abundant near the principal fault surface, and dip both in the same direction as, and opposite to, the principal fault.

