Big Spring and Recharge Area
and the Possibility of Lead Mining

BY QUINTA SCOTT

Big Spring boils up beneath caves, old outlets in a wall of Eminence Dolomite. It delivers 286,000,000 gallons of water a day to a short spring branch, which carries it east to the Current River. However, Big Spring draws its water from the Eleven Point River watershed to the west in Shannon, Oregon, and Carter counties, Missouri. Its recharge area fans out to the eastern edge of Howell County near Fanton, close to 39.5 miles away. Within the watershed Hurricane Creek, a losing stream and tributary to the Eleven Point, contributes all its water to Big Spring in eight losing sections.[1]

In 1983 USX, formerly U.S. Steel Corp., and Amax Exploration, Inc., applied to the U.S. Forest Service for an exploratory permit to drill for lead in the Hurricane Creek watershed. Through a series of mergers and acquisitions, the application ended up in the hands of the Doe Run Corporation. It raised several issues. Geologists with the U.S. Geological Survey and its Missouri counterpart realized they had no idea how lead mining would affect a watershed in a karst landscape. They lacked the basic knowledge of the Hurricane Creek landscape beyond Thomas J. Aley's 1975 study. Their available geological maps dated back to 1930, when Josiah Bridge completed his study of the *Geology of the Eminence and Cardareva Quadrangles*.

Over the next 15 years, geologists brought Bridge's maps up to date. Their work recognized the Ozark National Scenic Riverways as a geology-based national park. They took their studies beyond the Big

Opposite and above – Big Spring, Carter County.

Hurricane Creek at Missouri Route19.

By 1975, Aley had proven that sinkholes and losing streams give access to the aquifer to deliver the water that pours through the karstic Big Spring recharge area. However, hydrogeologists had yet to define the aquifer's structure. The U.S. Geological Survey studied the structure of the Ozark and St. Francois aquifers and their confining unit over the next two decades. Aley's work helped the process along.

This is the second article, published in *The Confluence*, on the springs that feed the Ozark National Scenic Riverways, the Current and Jacks Fork rivers. The first article covers Aley's work in the 1960s and early 1970s tracing the subterranean conduits that lie under the riverways and the Eleven Point River watershed. On the surface, Hurricane

Creek is a tributary of the Eleven Point River, but it is a classic Ozark losing stream. Rain falls on the creek and disappears within a day or two into a subterranean system that delivers water to Big Spring, a tributary to the Current River. When Aley dropped dye into the middle fork of the Eleven Point at Fanchon–another losing stream–it showed up at Big Spring, 39.5 miles away.

This article covers the decades-long response to Doe Run's desire to mine lead in the Hurricane Creek watershed. It set off a wave of research by the U.S. Forest Service, to whom the company made its application; the National Park Service, the owner of the Ozark National Scenic Riverways; the U.S. and Missouri Geological Surveys; and the Missouri Department of Conservation, which covered the whole of the Current River watershed.

While lead mining in Missouri began in 1710 at Mine la Motte, near Fredericktown, it prospered in the Old Lead Belt in Washington County along the Big River throughout the eighteenth and nineteenth centuries. By the middle of the twentieth century mining companies had exhausted the supply of lead and turned their attention to the Viburnum Trend in the Black River watershed. In the late 1970s and early 1980s, the lead-mining industry looked at declining deposits in the Viburnum Trend, turned its eye to public lands in the Mark Twain National Forest, and sought a permit to begin exploratory drilling for lead and zinc in the karst landscape west of Big Spring and directly north of Greer Spring.

In the 1970s and 1980s, Doe Run and other mining companies made more than 300 test borings in the Hurricane Creek watershed to see if lead could be found in the Mark Twain Forest and, if so, where and how far down.

Environmentalists looked at the application to mine lead in the Mark Twain National Forest, objected, and held up the application for eight years. After the Forest Service and the Bureau of Land Management granted the permit in 1991 and as drilling began in late 1992, Roger Pryor of the Missouri Coalition for the Environment protested: "My basic fault with the whole thing is not so much the drilling of these holes. We're opposed to mining in those areas. We believe the drilling permit is the first step toward mining." Missouri's new attorney general, Jay Nixon, elected in 1992, also opposed mining in the National Forest and echoed Pryor's comment: "Mining inevitably follows successful

Doe Run Mine #29, in the Viburnum Trend on Indian Creek in the Courtois Watershed

Site Near Drill Hole 84-40 in the Doe Run Exploration Area of the Mark Twain National Forest, Oregon County

exploration." Arkansas–whose governor, Bill Clinton, had just been elected president–also planned to appeal the permit. Pryor feared that Clinton would not be inaugurated soon enough to withdraw the permit.[2]

Once granted in 1991, the permit allowed the company to drill twenty holes, eight inches in diameter, at two sites, drill holes 84–40 and 801–148. The following November, the company's drilling crew laid out "diapers," black plastic tarps to prevent grease seeping off the drill from oozing into the soil, on a one-acre site that had been clear-cut several years earlier. Doe Run stopped exploratory drilling in 1993 when the price of lead fell, but it did not give up its permit until October 1998. It did so in the face of opposition from Bruce Babbitt, Secretary of the U.S. Department of the Interior, owner of the Ozark National Scenic Riverways, who told the company, "Mining is a valuable industry, and mining jobs are good jobs, but mining should not be allowed to threaten very special places like Yellowstone and the Ozark National Scenic Riverways." Nor, he added, would he guarantee that Interior would allow mining should Doe Run exploratory efforts be successful. And, maybe, Interior would not compensate the company for its exploratory costs. With that, Doe Run gave up its permit.[3]

That was not the end of it. In July 1999, Attorney General Nixon asked Secretary Babbitt to withdraw 400,000 acres in the Mark Twain National Forest from drilling. Within three weeks, Sen. Christopher "Kit" Bond (R-MO) attached an amendment to Interior's spending bill to ban the agency from banning lead mining in the forest until 2001. After Senate Republicans withdrew Bond's amendment, he came back in September and added $250,000 for research into the environmental and economic impacts of drilling in the region. At the same time, he added a provision to ban Doe Run from exploratory drilling until 2001. The bill passed in November 1999.[4]

After the National Parks Conservation Association declared the Ozark National Scenic Riverways an endangered national park, Bond added $750,000 to a new Interior appropriation for additional funding to study the effects of drilling, bringing the total to $1 million. The money would go to the U.S. Geological Survey, which would lead twelve other government agencies, experts from the mining companies, the University of Missouri at Rolla, and Tom Aley's Ozark Underground Laboratory. The bill passed.[5]

Understanding the Aquifers

In his 1975 report on the Big Spring recharge area, Aley wrestled with two concepts of an aquifer: the water-holding capacity of individual rock formations or that of the entire geological column. In the 1960s when Aley did his research, hydrogeologists still depended on well records that identified individual rock formations as individual aquifers. Early in the study, Aley referred to the importance of the Gunter Formation as an aquifer. Later in the report, he described the storage capacity of the "entire spring system," that is, water stored in soil on the uplands and on hillsides, in solution-widened joints in bedrock, and in bedrock itself, particularly in sandstone. In short, he described the aquifer as it would be defined five years later, using figures from his dye traces in the recharge area.[6]

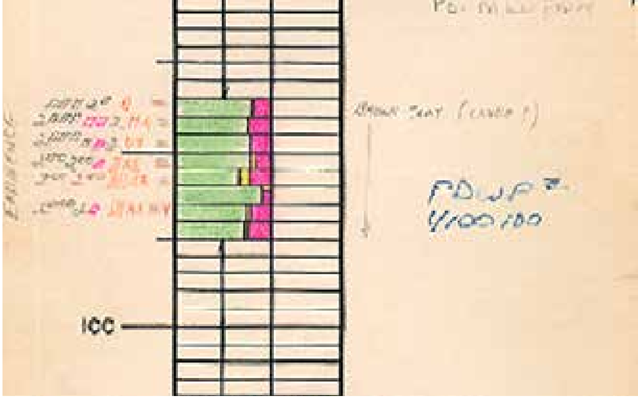
In the wake of a severe nationwide drought in 1977, Congress mandated the Regional Aquifer-System Analysis, "a systematic effort to study a number of the nation's most important aquifer systems," the following year. In 1981, the U.S. Geological Survey published its plan of research for the Central Midwest Regional Aquifer System, including a study of the aquifers in southern Missouri, which was scheduled for completion in 1986. However, geologists had been studying aquifers since the 1920s.[7]

In his 1921 survey of Missouri's water resources, Henry Claus Beckman referred to the large underground storage-capacity of the springs feeding the Current, the Jacks Fork, and the Eleven Point rivers. Josiah Bridge's 1930 study noted that Eminence Dolomite is highly soluble along bedding planes, creating underground conduits capable of storing large quantities of water that come to the surface in springs.

Springs, according to Bridge, supplied domestic water in the 1920s. The town of Eminence pumped its water from a small spring, set on a hill above the village. Bridge also noted that the water table in porous rock runs deep, and water flows through a system of underground drainage. While shallow wells went dry in the summer, wells drilled deep into bedrock yielded water from Gunter Sandstone through all seasons.[9]

Mark Twain National Forest: McCormack Lake Recreation Area in the Hurricane Creek watershed

Montauk Spring: According to the *U. S. Geological Survey*, "a spring is the result of an aquifer being filled to the point that the water overflows to the land surface. They range in size from intermittent seeps, which flow only after much rain, to huge pools flowing hundreds of gallons daily."[8]



Well records or drill logs tell geologists where water and minerals can be found under the landscape. In 1977, Amax Exploration drilled a mineral test well in the Hurricane Creek watershed. (Image: Record from the Missouri Department of Natural Resources, Geologic Well Logs of Missouri, Shannon County Well Log, 025627)

In 1967, at the behest of senators Stuart Symington and Edward V. Long of Missouri, Edward J. Harvey of the U.S. Geological Survey and Dale L. Fuller and Robert D. Knight of the Missouri Geological Survey detailed which rock formations yielded the most groundwater. Based on well records, they found that five principal water-bearing formations in the Ozarks yielded the most water: Lamotte Sandstone, Potosi and Eminence dolomites, the Gunter Member of the Gasconade Formation, the Roubidoux Formation, and St. Peter Sandstone. They labeled each as an individual aquifer.

Of the five, researchers listed Potosi Dolomite as the most productive aquifer, capable of yielding as much as 500 gallons per minute. The large storage capacity of Potosi and Eminence dolomites feeds the springs of the Current and Black river valleys, with a yield of as much as 90,000 gallons a minute from the largest springs. Openings and fractures in the upper hundred feet of Eminence Dolomite are capable of delivering moderate quantities of water for small industry and towns. Wells in Gunter Sandstone yield as little as forty gallons a minute or as much as a thousand, depending on the locations of the wells. Finally, farmers drilling shallow wells draw water from the Roubidoux Formation at the rate of 15 to 20 gallons a minute.

Below the Potosi Formation, Lamotte Sandstone yields small amounts of water from wells on the northern and eastern edges of the St. Francois Mountains in towns like Bismarck and Farmington. Larger yields could be obtained west of the mountains. While the Bonneterre Formation, where lead is found, yields adequate supplies for domestic use, very little is to be had from the shale of the Davis and Derby-Doe-Run formations, but the authors give no explanation as to why.[10]

In 1972, Harvey returned to the study of aquifers under the Ozark plateaus. At the time, the Environmental Protection Agency was considering designating the region as a sole-source aquifer. The U.S. Geological Survey published Harvey's report in late 1980. While he understood from his earlier research that wells drilled in Potosi Dolomite produce the largest quantities of water in the Ozark plateaus, he concluded that the size and thickness of the Potosi Formation does not explain the "three-dimensional flow of water through the entire body of dolomite" land surface to the base of the Potosi. To understand the extent of the aquifer, he looked at 1,000 feet or more of dolomites and sandstones, which extend past the Potosi to Derby-Doe Run Dolomite and the Davis Formation.[11]

To illustrate his point, he consulted the work of Thomas Aley and Laszlo Jakucs, a Hungarian geologist. Aley, while still at work on his study of the Big Spring recharge area, sent Harvey the results of traces he made between various losing streams and sinkholes in the Big Spring recharge area, noting the formation in which he dropped the trace and the formation from which he retrieved it. Hence, when Aley dropped a trace in Jam Up Creek, a losing stream in the Jefferson City-Cotter Formation, water carried the dye down through the Gasconade Formation and Gunter Sandstone to emerge from Big Spring in the Eminence Formation.[12]

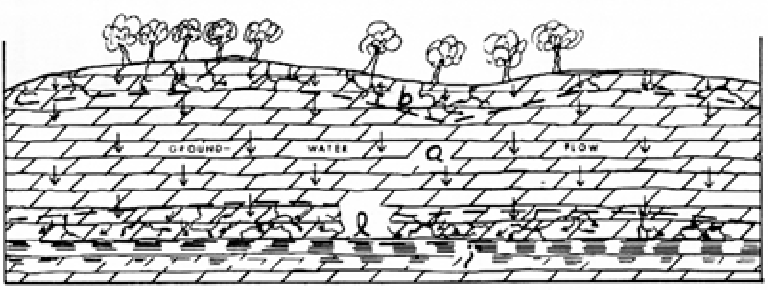
Based on Aley's work, Harvey noted that water enters the underground system through upland infiltration, sinkholes, and losing streams. Once it sinks into the underground system, water flows in three dimensions across descending rock formations through "cavernous connections" that reach down as much as 1,500 feet from the surface. Harvey estimated that Ozark Aquifer holds 100 to 500 cubic miles of water in underground conduits. Like Aley, Harvey concluded that sinkholes and losing streams could feed pollution into the underground system through accidental spills or the purposeful dumping of toxic substances.

Jakucs proposed that shale in the Davis Formation prevented water from seeping below Potosi Dolomite and into the Bonneterre Formation. It acted as a barrier between two aquifers. He provided visualization of the process in his 1977 book, *Morphogenetics of Karst Regions*. It was the same process that Aley had outlined in the Big Spring recharge study. Water enters the underground system through the infiltration of the soil in the uplands and through sinkholes and losing streams (see page 40, lower left). Once it sinks into the underground system, water filters down along

Jam Up Creek

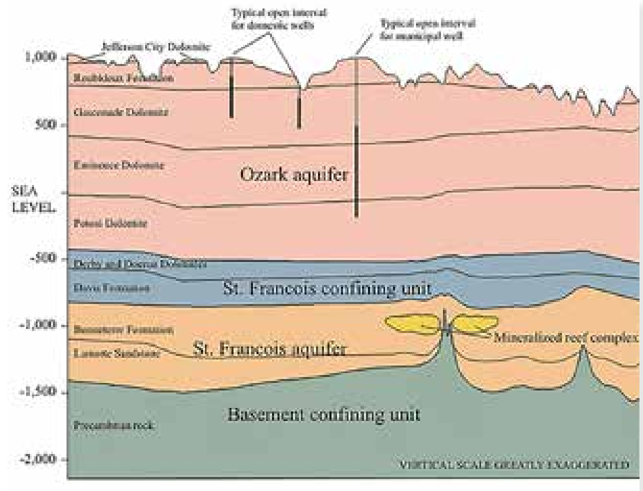
vertical joints through a thousand feet of rocks (a). The underground flow of water under high pressure dissolves dolomite and creates conduits that run as much as a thousand feet below the surface (wiggly lines). Jakucs departed from Aley by noting that at bottom, shale in the Davis Formation (dashed lines) limits the permeability of the aquifer.[13]

Jeffrey L. Imes and L. F. Emmett completed their study of the Ozark plateaus' aquifers in 1994. The aquifer system covers Missouri south of the Missouri River before bleeding into northwestern Arkansas, northeastern Oklahoma, and the southeastern corner of Kansas. The system in Missouri includes the impermeable Precambrian rocks at the base of Missouri's geological column, the St. Francois Aquifer at bottom, the St. Francois Confining Unit, the Ozark Aquifer under the Salem Plateau, the Ozark Confining Unit, the Springfield Plateau aquifer in Mississippian formations, Chouteau Limestone in Southeastern Missouri, and Northview Shale in the Springfield Plateau.



C. GROUND-WATER FLOW SYSTEM

Harvey provided Laszlo Jakucs' 1977 illustration of his concept of Davis Shale (dashed lines) as the confining unit between aquifers. *(Image: Edward J. Harvey, "Ground Water in the Springfield-Salem Plateaus of Southern Missouri and Northern Arkansas")*



The 1994 Imes and Emmett Study of the Ozark Aquifer and Aley's Response to the Doe Run Application generalized Geohydrologic Section Of Ozark and St. Francois Aquifers across Lead Exploration Area, Including Probable Location of Lead in the Mineralized Reef Complex.[14]

The thickness of the St. Francois Aquifer is about 300 feet in southern Missouri. The thickness of the St. Francois Confining Unit in the Salem Plateau ranges from 0 to 400 feet. While the thickness of the Ozark Aquifer is about 1,500 feet at the Missouri-Arkansas border, it ranges from 800 to 3,000 feet thick overall. Mississippian rocks confine the Ozark Aquifer in the Springfield Plateau.[15]

Thomas Aley first weighed in on lead mining in the Big Spring Recharge Area in 1987, when he and Catherine Aley published their work on the recharge areas of the Current River springs. In their update of the Big Spring Recharge Area, they noted that its hydrological complexity mitigated lead mining.[16]

Two years later, Aley examined the drafts and the accompanying maps that would go into the Imes and Emmett report. He noted that the Davis and Doe-Run formations in the targeted mining area just north of the confluence of Hurricane Creek and the Eleven Point River are 200 to 300 feet thick, thinner than in other places. He also remarked that it is only 20 percent shale and that the remaining dolostones in the formations are semipermeable. From this, Aley questioned whether the St. Francois Confining Unit in the target area was capable of retarding leakage of the Ozark Aquifer into the St. Francois Aquifer below, should mining happen.[17]

He listed the possible sources of contamination

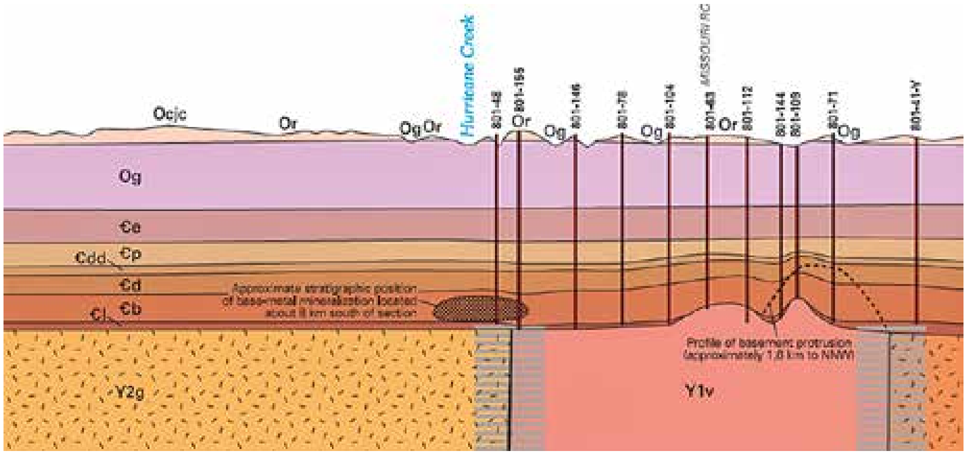
Clearwater Lake

to the watershed. Lead mining could damage the aquifer above and below the surface of the watershed. Mine drainage could direct heavy metals into streams and the underground system. So could the leaching of mine tailings. The failure of tailings dams could empty ponds into clear streams and muddy them. He gave the example of a 1977 tailings pond dam break in the wake of a spring storm that polluted Logan Creek clear to Clearwater Lake, 40 miles away. Finally, processed ore wastes can leach into streams. Should such contamination get into sinkholes or losing streams, the subterranean flow of water through conduits would feed it into local wells, Big Spring, and the smaller springs in the Hurricane Creek Watershed. He recommended against mining in the Hurricane Creek Watershed.[18]

Imes and Emmett noted in their report that Missourians draw approximately 200 million gallons of water a day from the Ozark Plateaus aquifer for domestic, industrial, and agricultural consumption. Yet, there was no evidence that the system was being depleted. However, dewatering the Bonneterre Formation in the Viburnum Trend draws 26 million gallons a day from the St. Francois Aquifer at a point where the Ozark Aquifer is very thin.[19]

Hydrogeologists continued their work on the aquifers after the publication of the 1994 report. They used mining company logs of boreholes and some well logs to determine the thickness of the St. Francois Aquifer and its confining unit. The logs, some more than 2,500 feet deep and made in the Hurricane Creek watershed, helped determine whether Davis shale impeded movement of water between the two aquifers. In 2000, they published a report that concluded that, barring faults or fractures in the confining unit that could open conduits between the two aquifers, Derby-Doerun Formation would stop the Ozark aquifer from leaking into the St. Francois. In 1999, geologists made a similar study in the Viburnum Trend and came to a similar conclusion.[21]

In 2005, hydrogeologists from the USGS sunk a monitoring well near boreholes 80-48 and 84-40, the location of Doe Run's exploratory drilling sites. They drilled down through Davis shale 2,098 feet to the Bonneterre Formation where lead can be found. Previous studies found that samples taken from drill hole 80–148 were found to contain 11 percent lead and 2.9 percent zinc; those from drill hole 84–40 were found to contain 35.9 percent lead and 12.2



Location of a cluster of boreholes in the hurricane Creek Watershed. Doe Run's actual exploratory sites were five miles south of Drill Hole 801-48, which reaches down to a mineralized reef complex in the Bonne Terre Formation.[2]

percent zinc. These amounts are comparable to mines in Viburnum Trend and offer great potential should the sites ever be mined. The two are located within a half-mile of each other. Once they sunk their well through the St. Francois Confining Unit, researchers could determine the rise or fall of the St. Francois and Ozark aquifers within the confines of the well. They could also measure the character of the water in both aquifers.[22]

As they drilled, they encountered bedding planes, caves, mudstone, and shale. Between 500 and 1,440 feet, large quantities of water flowed out of the well at the rate of more than 500 gallons per minute. In measuring the flow of the well, hydrogeologists found that the St. Francois aquifer rose above its confining unit an average of 13.4 feet during the fall and winter, when water levels in the Ozark aquifer dropped. During the summer, March to August, when rain recharged the Ozark Aquifer, the reverse was true. Water rose an average of 53.84 feet higher than the St. Francois Aquifer. When examining water quality, the researchers found large quantities of sodium, chloride, and sulfate and trace quantities of lithium and boron in the St. Francois, but no lead, because lead is not soluble in water. The Aquifer was low in water containing traces of calcium-magnesium-bicarbonate. However, the Ozark Aquifer was high in such water, as much as 250 milligrams per liter, derived from dissolved rock formations.

Done, the hydrogeologists capped the well. Should mining ever happen in its vicinity, they would have a means of monitoring changes in water quality in the aquifers, particularly the Ozark, which serves as the major source of domestic and industrial water in southern Missouri.[23]

Just as Doe Run started drilling its exploratory holes in the Mark Twain National Forest, lead contamination of the Big River from chat pile–piles of mining waste–in the Old Lead Belt to its confluence with the Meramec River came to light. It alerted geologists with both the U.S. and Missouri Geological Surveys to the need to learn more about the possibility of lead contamination in the karst terrain of the Hurricane Creek Watershed.[24]

Geologists needed to learn if lead and other metals from mining could leach into the karst landscape of the riverways drainage area. They started with a study of lead contamination in the New Lead Belt, the Viburnum Trend. Shaped like a hockey stick, the Viburnum Trend stretches from the Huzzah and Courtois creeks in Crawford and Washington counties, south through Reynolds County, and ends at the Reynolds/Shannon County line. Mining began on Indian Creek, a tributary of the Courtois, at the northern end of the hockey stick in the 1960s. Mining companies moved south through Dent County into Reynolds, opening new mines as old mines played out. Researchers took samplings of lead and other minerals in streambeds in Viburnum Trend, the Ozark National Scenic Riverways, and the Eleven Point River, including its tributary Hurricane Creek (A18 on the map on pagee 44).

A study conducted between 2002 and 2005 found tailings ponds to be the source of lead contamination

Lead Contamination in the Old and New Lead Belts. A Bonne Terre mine chat pile rises over a Bonne Terre Cemetery. It lies close to the banks of the Big River in Washington County.

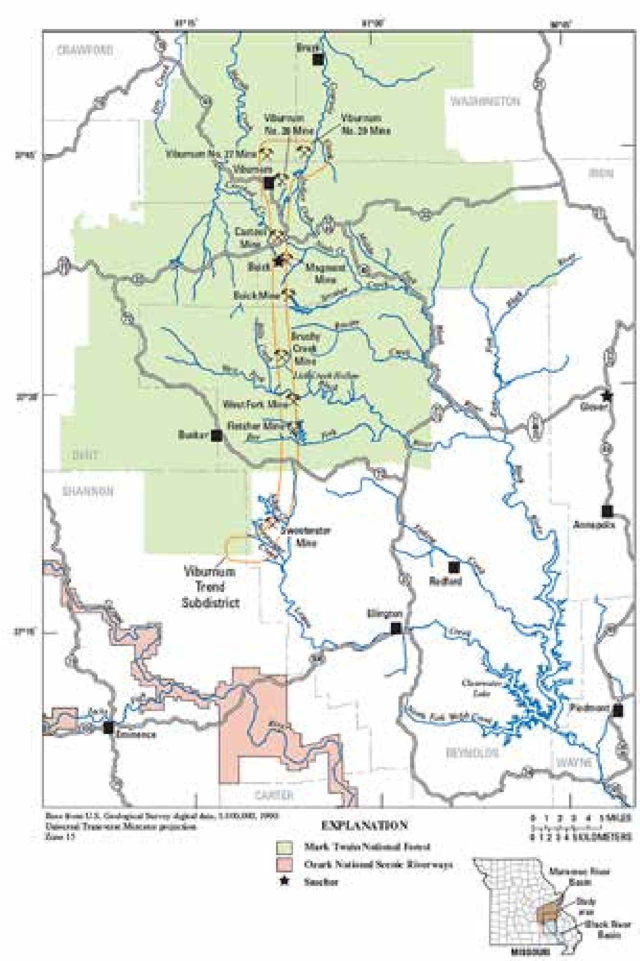
on the Black River Watershed. They found increased levels of lead, particularly after heavy rains in 2002, in the middle and west forks of the Black River, in Bee Fork, in Logan Creek near Ellington, and in Clearwater Lake.

In 1930, Josiah Bridge speculated, correctly, that Blue Spring drew its water from Logan Creek, but carried it to the Current River. Three different hydrogeologists performed dye traces between 1969 and 1984. Each confirmed Bridge's guess that Logan Creek delivered water to Blue Spring, with each result more detailed than the last. All traces were made within the vicinity of the tiny Church of Latter Day Saints, located northwest of Ellington.

The upper reaches of Logan Creek flow year 'round. Once the creek streams past the church, it disappears into its gravel bed. Only in the strongest storms does water fill its fifty-foot width and overflow onto its floodplain, which lies eight to twelve feet above its channel. Normally, the creek remains dry until it reaches its confluence with Dickens Valley.[26]

In October 1969, when upper Logan Creek was

Monitoring Well Installed Near the Doe Run Exploratory Drill Sites in the Mark Twain National Forest



The Viburnum Trend, its relationship to the Ozark National Scenic Riverways, Hurricane Creek, the Eleven Point River, and the proposed Doe Run Lead exploration site (in yellow) in the Mark Twain National Forest.[25]

Mark Twain National Forest: West Fork Black River, Sutton's Bluff Recreation Area

Logan Creek below the Church of Latter Day Saints

running a low 3.2 cubic feet per foot, G. L. Feder and J. M. Barks injected dye into the creek. Water and dye disappeared downstream, within a mile of the Mormon Church. They recovered their charcoal packets from Blue Spring. They also recovered a second packet from the creek near Ellington.[27]

James C. Maxwell took his research into Logan Creek a step further. He identified a series of caves and sinkholes into which water could vanish. Unless the flow in the upper creek was higher than normal, water seldom made it past a pair of elongated sinks, lined with coarse gravel, four to six feet wide, and no more than three feet deep.[28]

Thomas Aley and Catherine Aley conducted their traces of Logan Creek in 1984 and 1986. They first confirmed the work of Bridge, Feder, and Barks, and Maxwell. They injected the 1986 trace in Christian Hollow, which showed up in several places, including Blue Spring.[29]

The U.S. Geological Survey started taking water quality samples from Blue Spring as early as 1925. The agency started taking water quality samples of Logan Creek in the vicinity of the Mormon Church and below its confluence with Sweetwater Creek in 1965, three years after the Ozark Lead Mine Company drilled for lead at the Sweetwater Mine and three years before the company began producing lead in 1968.

Early samples of water taken from both Blue Spring and Logan Creek reflected that spring water is normally loaded with calcium plus magnesium and bicarbonate, derived from dissolved limestone and dolomite. Only after 1968 did increased levels of sodium, sulfate, and chloride from the St. Francois Aquifer appear in both places. Hydrogeologists attributed the rise to the Sweetwater Mine. They measured the Blue Spring results against water quality at Big Spring and Greer Spring to establish a baseline.

Logan Creek above the Church of Latter Day Saints

Changes at Blue Spring in light of seepage from the Sweetwater Mine could forecast similar water quality changes at Big and Greer springs, should mining take place in their recharge areas.[30]

The 1977 Sweetwater Mine tailings pile breach that released mine tailings into Adair Creek, a tributary of Logan Creek, also muddied Blue Spring. Because lead cannot be found dissolved in water, researchers sampled sediment in the bed of Logan Creek, Blue Spring Brook, and the Current River downstream of the spring and compared it to sediment samples from Big and Greer springs. Later they sampled the river at Van Buren, Big Spring, and two other areas. These samples established a base line for lead contamination in a non-mining area. Researchers found contamination in Blue Spring's spring branch in 2001. They found none in their samplings in 2002 or thereafter in spite of a heavy rain.[31]

Blue Spring Branch in Shannon County, a tributary to the Current River Watershed

Joshua Bridge published his geological map of the Current River Watershed in 1930. When Doe Run sought permission to explore for lead in the Big Spring recharge area, geologists realized they could not depend on Bridge's maps to understand the karst landscape that feeds Current River springs.

Even before Doe Run gave up its exploration application, the U.S. Geological Survey had started mapping the karst landscape of the Current River Watershed. Funding for the mapping project came from the U.S Geological National Cooperative Geologic Mapping Program, created in 1992, with additional funds coming from the National Park Service Resources Division. The Missouri Geological Survey contributed additional mapping. The Ozark National Scenic Riverways subsidized the project with lodging, canoe shuttles for the river work, the loan of vehicles, and parking. Its natural resource specialists coordinated the exchange of data between geologists and other scientists working on the project.[35]

Between 1995 and 2001, geologists mapped the bedrock geology between Hurricane Creek, which feeds water to Big Spring and the Current River, with attention to the cracks, joints, and faults in the rock. They also documented bedding planes along which cave systems develop and groundwater flows.[36] In the larger Current River Watershed, geologists poured over field notes made by geologists with the Missouri Geological Survey. They drove most of the roads between the head of Spring Valley Creek on the west and Big Spring on the east to observe outcrops and floats, loose rocks not attached to outcrops. They examined drill hole and well logs to identify contacts between rock formations. Because they had difficulties identifying faults in the field, where vegetation and residuum covered rock exposures, well records helped them locate faults in the bedrock. Finally, they noted the locations of lead company drill holes, such as 801–148 and 84–40, on their maps.[37]

The project served three purposes. First, it provided a better understanding of how karst functions generally. Second, it provided a geological inventory of the Ozark National Scenic Riverways. Finally, it afforded the framework for future multidisciplinary studies geared to understanding the migration of groundwater contaminants released into the karstic landscape by underground exploration for lead and zinc. When geologists set about making detailed geologic and hydrogeologic studies of the region to understand how groundwater moves through karst terrain, they looked to the work of Josaih Bridge, Thomas Aley, and Jerry Vineyard.[38]

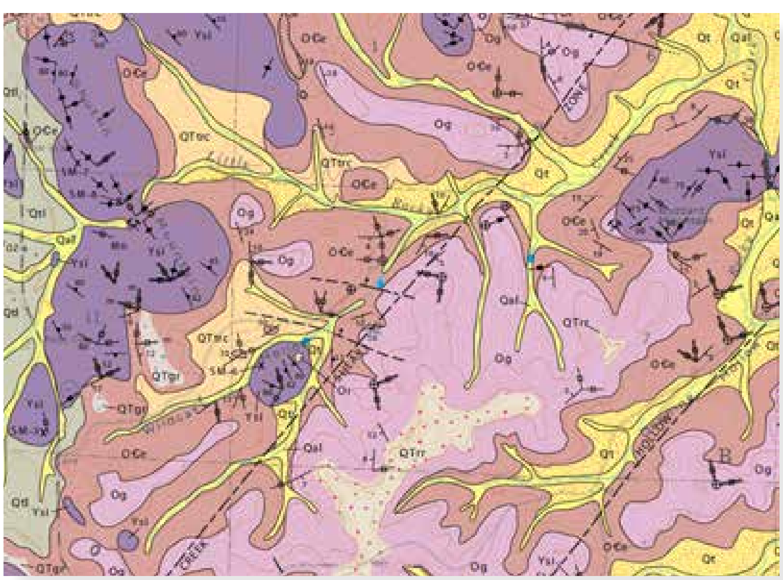
Bridge stated, "the large number of springs in the Eminence region implies a well developed system of subterranean drainage." The underground system stores so much water that the flow of streams in the region is constant. Floods are seldom, brief, happen only after very heavy rains, and are absorbed by losing streams soon after. He added a list of known losing streams that deliver water to local springs: Pike Creek at the town of Midco to Big Spring, ten miles away, and Blue Spring, which rises after heavy rains on upper Logan Creek.[39]

In 1958, Vineyard explored the idea that Devils Well and Wallace Well, located close to Cave Spring, were storage reservoirs for the spring. To prove their connection to the spring he dropped dye traces in both wells. Both failed. Later, he performed a successful trace from Wallace Well to the spring. Based on those results, he speculated that Devils Well was also connected to Cave Spring but was unable to perform the trace, proving it, until 1961. That trace demonstrated that a main conduit, located 120 to 130 feet below the water table, linked Devils Well and Wallace Well to Cave Spring.[40]

In June 2015, Vineyard guided a group from the Cave Research Foundation to Devils Well. He watched as his younger counterparts donned hard hats and wet suits, lowered four inflatable rafts, and rappelled 90 feet down to the lake. Hazy water spoiled their attempt to document aquatic life in the well.[41]

In his 1975 study of the Big Spring Recharge Area, Aley measured the amount of water disappearing underground in eight losing sections of Hurricane Creek, including Blowing Spring south of New Liberty. Blowing Spring contributes the only water flowing in the creek at the rate of 0.1 cubic feet per second. An estavalle, ten feet in diameter and downstream of the spring, swallows it up. However, given a heavy rain, the estavelle is also a resurgent, capable of spewing water at the rate of 24 cubic feet per second into the creek. It took ten days for dye injected into the estavelle to reach Big Spring.[42]

Geologists studied the role of sandstone in the development of sinkholes and conduits, the underground channels that speed water to springs. They relied on the work of the Cave Research Foundation, whose members had mapped hundreds of caves in the Current River Watershed, including caves found in the valley walls of streams and those accessed through sinkholes, like Devils Well.



Understanding the Karst Landscape of the Ozark National Scenic Riverways. This is a topographical section of the Updated Stegall Mountain Quad, 2002. It illustrates the Rhyolite of Shut-in Mountain (Ysi, purple); the upper Cambrian/Lower Ordivician rocks (OCe, beige) that lapped the sides of the mountain; residuum (QTgr, blue spots on light ground) eroded from the Gasconade Formation; the Gasconade Formation (Og, pink) above the OCe; residuum (QTrr, red spots on white ground) eroded from Roubidoux Formation, terrace-like landforms (QTrc, creamy yellow) of silt, clay, sand, and gravel commonly found adjacent to volcanic rocks; and Recent Terrace deposits (Qt, bright yellow) cobbles and peddles of chert and sandstone that lie above Alluvium (Qal, pale yellow), steam deposits.[34]

Devils Well, Photograph by Dan Lamping, Cave Research Foundation

Foundation maps provided an excellent opening into the structure of the system of conduits. Geologists also studied the work of the Ozark Cave Diving Alliance at Alley Spring, where divers had been exploring the conduits that supply the spring for 25 years.[43]

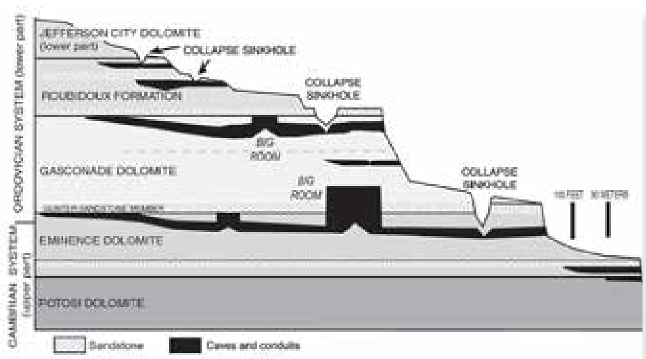
Geologists studied the role of sandstone in the development of sinkholes and conduits, the underground channels that speed water to springs. They relied on the work of the Cave Research Foundation, whose members had mapped hundreds of caves in the Current River Watershed, including caves found in the valley walls of streams and those accessed through sinkholes, like Devils Well. Foundation maps provided an excellent opening into the structure of the system of conduits. Geologists

Hurricane Creek: Blowing Spring Estavelle

also studied the work of the Ozark Cave Diving Alliance at Alley Spring, where divers had been exploring the conduits that supply the spring for 25 years.[43]

Sinkholes form in all formations—Jefferson City Dolomite on down through Potosi Dolomite—in the Salem Plateau. Most occur in the sandstone members of the Jefferson City and Roubidoux formations, which form the uplands. However, that they form in the Roubidoux Formation is misleading, because they develop when the uppermost part of Gasconade Dolomite underneath dissolves and collapses. Sandstone confines water moving under great pressure to the underlying dolomites, dissolving them and causing collapse. A sinkhole forms, its edge rimmed in sandstone. This happens where water runs under sandstone members in the Roubidoux Formation, causing sinkhole collapse in both

Alley Spring: Rise Pool

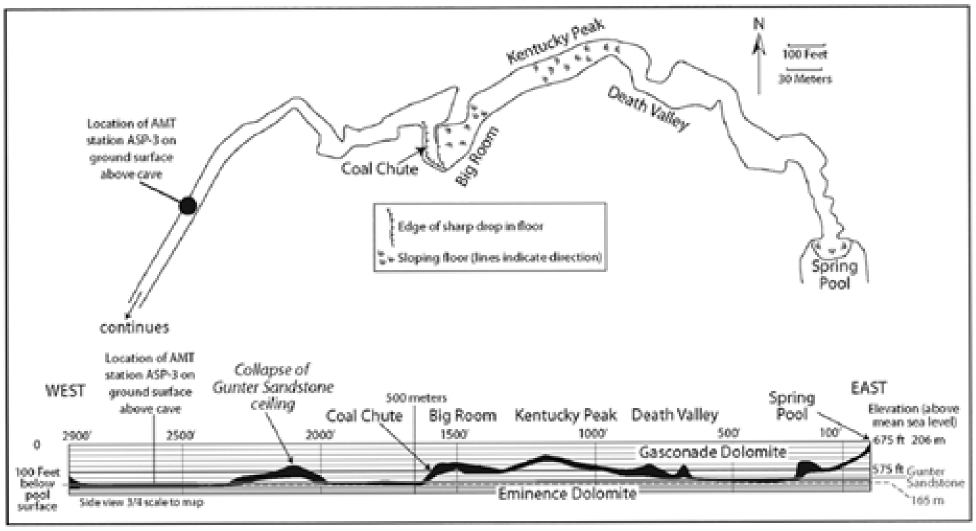


Model of How Sinkholes Form in the Formations in South-Central Missouri, Graphic by David Weary, U.S. Geological Survey.

underlying Roubidoux Dolomite and Gasconade Dolomite. This happens where water runs under a Gunter Sandstone Member of the Gasconade Formation, causing a sinkhole collapse in the underlying Eminence Dolomite. This happens where water runs under a sandstone member of the Eminence Formation, causing a sinkhole to form underneath.[44]

By 2005, divers had charted the geology of Alley Spring, where the average flow is 125 cubic feet per second or 81 million gallons a day. Water, flowing through the underground conduit or cave passage to Alley Spring, is confined to Eminence Dolomite under impermeable Gunter Sandstone. Here water, containing both sulfates and carbonates, mixes with and increases the dissolution of the Eminence Dolomite, enlarging the passage. High pressure within the confines of the cave passage—that is, hydraulic pressure—drives water along bedding planes in Eminence Dolomite. Water finally breaks through the confining sandstone where the Gunter Sandstone ceiling has collapsed. It is still under pressure and it still has a long way to travel to its rise in the spring pool. It rises and falls through Gasconade Dolomite, falls through the Coal Chute and into the Big Room, up across Kentucky Peak and down into Death Valley, and finally rises into the spring pool at a 25–degree angle.[45]

Finally, the geologists mapped out land use in the region that feeds the Current and Jacks Fork rivers: what is forested, open, cultivated, and urban. At the surface, different rock formations and their residuum, the soils derived from their erosion, support different ecosystems. In 1998, the Missouri Department of Conservation began developing the Missouri Ecological Classification System, identifying and

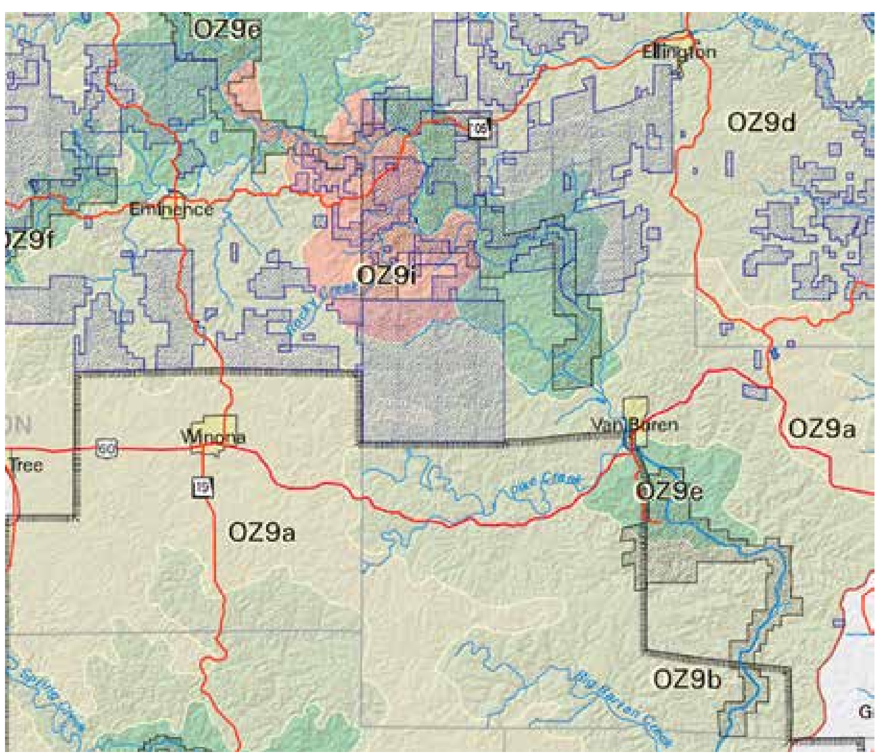


Cave Map and Profile of the Geology of Alley Spring, Drawn by David Weary, *U.S. Geological Survey*.

mapping the unique characteristics of vegetation, soils, topography, and geology of the varied regions across the state.

Using the system, resource managers can map discrete sites that have similar physical and biological characteristics and manage them for the vegetation and critters they support. With the help of field researchers from the U.S. Forest Service, the National Park Service, and the Nature Conservancy, the MDC field-tested various sites within the recharge regions of springs that feed the Current and Jacks Fork rivers, a region they call the Current

Landtype Associations of the Current River Hills, from *Atlas of Missouri Ecosystems:* OZ9a Current River Pine-Oak Woodland Dissected Plain; Oz9b Current River Oak-Pine Woodland Forest Hills; OZ 9d Black River Oak-Pine Woodland/Forest Hills; OZ9e Current River Oak Forest Breaks; OZ9f Jacks Fork River Oak-Pine Forest Breaks; OZ9g Eleven Point Oak-Pine Forest Breaks; OZ9i Eminence Igneous Glade/Oak Forest Knobs.



The Stegall Mountain Natural Area at Peck Ranch Conservation Area, Carter County. Southwest of the confluence of the Current and Jacks Fork rivers are the Eminence Igneous Glade/Oak Forest Knobs, one of the nine LTAs. Here, the crowns of rounded knobs of Precambrian rhyolite support igneous glades and woodland communities. Mixed-oak forests occupy the side slopes, where the soil is deeper.

Alley Spring Natural Area and the central part of the vast 39,245-acre Angeline Conservation Area lie within the Jacks Fork River Oak-Pine Forest Breaks LTA. The Jacks Fork River Oak-Pine Forest Breaks LTA and the Current River Oak Forest Breaks LTA surround the Igneous Knobs LTA. The two are similar, but drainages in the Current River Breaks cut slightly deeper than those in the Jacks Fork Uplands. Narrow ridges, falling to steep slopes, characterize both. Sinuous valleys, up to 250 feet deep, cut down through the Roubidoux Formation to the Upper Gasconade in the Jacks Forks Breaks, where an oak-pine forest anchors cherty soils, derived from both formations.

Peck Ranch Conservation Area: Shortleaf pine forest grows on an eroded bed of Roubidoux rocks, called residuum.

River Hills. Ecologists divided the Current River Hills, a subsection of the Salem Plateau, into nine Landtype Associations or LTAs–places with similar topography, geology, soils, and vegetation. The work culminated in 2002, with the publication of the *Atlas of Missouri Ecosystems*.

In 2006, collaborators from the MDC, the University of Missouri Department of Forestry, the U.S. Geological Survey, the National Park Service, and Nature Serve boiled down the ecosystems in the Current River Hills Subsection even more in an effort to map the vegetation communities in the Ozark National Scenic Riverways. Collaborators took the Eminence Igneous Glade/Oak Forest Knobs LTA and the surrounding Current River Oak Forest Breaks and the Jacks Fork River Oak-Pine Forest Breaks. They noted that when the Roubidoux Formation breaks down, it forms an acidic soil, conducive to shortleaf pine. When the Gasconade Formation breaks down, it forms a more neutral soil, conducive to oak and hickory on the northern and northeastern slopes of the hills. Where bedrock is close to the surface or exposed and the soil thin or non-existent, glades, surrounded by open woodlands, take up residence on southern and western slopes. Post oak and blackjack oak dominate the woodlands surrounding igneous glades, while oak and hickory grow on the slopes of igneous domes, where the soil is deeper.[46]

The collaborators used the Current River Hills as a model for developing other subsections across Missouri's ecologically diverse regions from the glaciated prairies in the north to the Ozark Highlands in the south, the Osage Plains in the west, and the Mississippi Lowlands in the extreme southeast.

The work to understand the karst landscape of the Ozark National Scenic Riverways continued under the 1998 National Parks Omnibus Management Act, requiring park managers to inventory the natural resources in their parks and to monitor long-term trends. In the Ozark National Scenic Riverways, scientists have studied invasive plants throughout the park, and especially in Powder Mill and the Big Spring Pines natural areas. They have developed a fire management plan, using prescribed fire to expand and maintain glades. When they turned to woodlands, they used fire to reduce shade-tolerant understory plants and open the tree canopy to sunlight. When setting fire to woodlands, fire managers had to understand how the timing of their fires in the late spring and early summer might impact the nesting

The Angeline Conservation Area extends east to the Current River Oak Forest Breaks LTA.

Big Spring Pines Natural Area

The Summerville Oak Savanna/Woodland Plain, pitted with sinkholes and laced with losing streams, delivers both water and contaminants to springs on the Jacks Fork and Current rivers. The landscape is a patchwork of pasture and oak forest and woodlands.

habitat of endangered species like the Indiana Bat and the Swainson's warbler.[47]

Finally, in 2009 geologists finished an investigation of the geohydrologic and landscape characteristics of the recharge areas of major springs that feed the Current and Jacks Fork rivers. Their work took them from Montauk Springs at the head of the Current River to Big Spring at the southern end of the national park. While the springs are found within limits of the Ozark National Scenic Riverways, most of their recharge areas are not. Starting with Thomas Aley's 1987 groundwater study of the Ozark National Scenic Riverways, geologists located sinkholes in the uplands that gathered water and delivered it to the underground system. Dye tracings told them which sinkhole delivered water to which spring and which losing streams delivered water to which springs. They identified the recharge areas where groundwater crossed under surface water divides. When they measured the water temperature of the Current River, they found it dropped downstream of the springs.

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