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A MOVING MYSTERY

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Along the southeastern edge of California's Salton Sea, there are several areas that contain geothermal mud pots and mud volcanoes—geological features that may change shape, but never location. In 2016, a large, muddy CO_2 -driven mud spring in Imperial County, California, developed—and in a completely unexpected way, began moving southwest. By early 2018, the mud spring threatened local infrastructure, including a railroad, a pipeline, and a state highway.

Mud pots and mud volcanoes are common in geothermal areas of the world. They form when upward-moving gases (primarily carbon dioxide [CO_2]) produced below the water table entrain water and carry it to the surface, usually through sediment. If the sediment load is low and the muddy water is inviscid (nonviscous), mud pots form; however, if the mud is viscous enough to support itself, mud volcanoes form. In both cases, water is brought to the surface by the rising CO_2 and not by hydrostatic pressure as is the case with artesian springs.

The Salton Sea geothermal field, in Southern California, is in the Salton Trough, which is an active tectonic pull-apart basin formed by three right-lateral transform faults in Southern California and northern Baja, Mexico-San Andreas, Imperial, and Cerro Prieto. The area is seismically active and experiences frequent earthquakes and earthquake swarms.

The trough, much of which is below sea level, is filled to depths of thousands of feet with sediments from the Colorado River that have been deposited on basement rock over the last 5 million years. Mineralogically, the sediment is mostly very fine-grained quartz with a small amount of clay minerals; the submicron particles exhibit claylike plastic properties-slippery mud when wet and hard earth when dry. Rocks or boulders in the sediment are rare except near the Salton Buttes. The trough has experienced periods of natural and human-induced flooding from, respectively, Lake Cahuilla and the Salton Sea.

Carbon dioxide is the most common gas that seeps out of the soil, but hydrogen sulfide (H_2S), ammonia, and methane can also be found in the area. Carbon dioxide is widely distributed in the trough, going largely unnoticed except where CO_2 bubbles are apparent in surface water. The origin of the CO_2 has not been definitively identified; it could be a hydrothermal alteration of carbonates to diagenetic greenschist facies or plutonic CO_2 from the shallow magma body that produces the high geothermal gradients.

While mud pots and mud volcanoes can change shape as more fluid rises to the surface-or as precipitation and wind erode them-their locations remain unchanged. However, in 2016, a moving mud spring developed-adjacent

A moving mud spring developed in 2016 in Imperial County, California, that threatened railroad tracks and other local infrastructure. (David K. Lynch)

to an existing mud spring-on private land that threatened local infrastructure: railroad tracks (owned by Union Pacific Railroad), a petroleum pipeline, fiber-optic cables, and California State Route 111. The mud spring's behavior indicated that it would continue to move, eventually reaching and going beyond the railroad tracks. As a result, Union Pacific's attempted mitigation of this situation was forced by the circumstances to become an accommodation.

Location maps of mud spring (David K. Lynch)

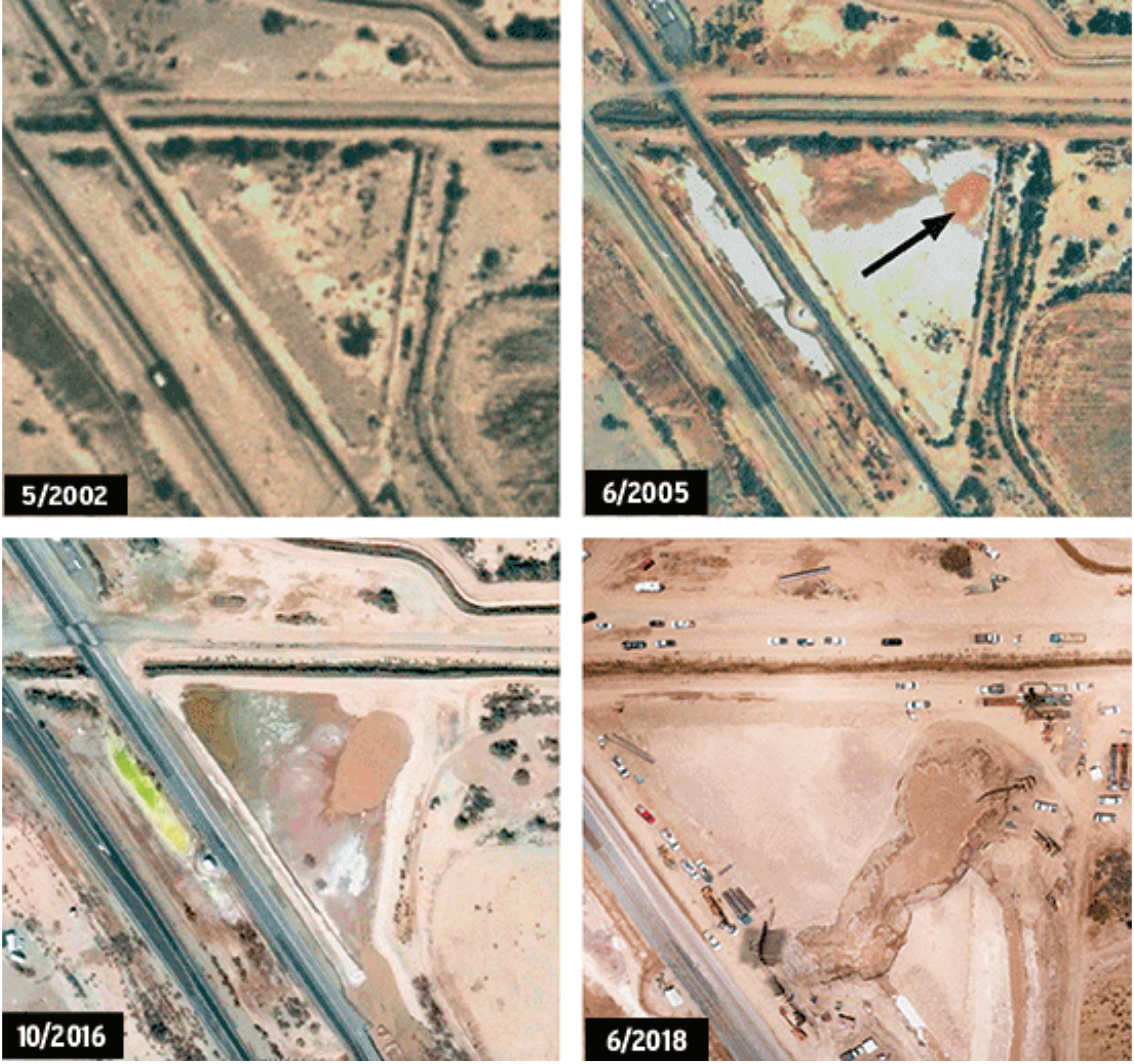
The origins of this mud spring is as murky as its water. The owner of the property on which the original mud spring appeared-near the southeast corner of Route 111 and Gillespie Road in Imperial County, California (see the map above)-reported that it had been present there for decades, growing to approximately 80 ft wide in the early 2000s. Google Earth images over time showed what appeared to be a large pond by 2005; it was subsequently labeled W9 (See the image labeled 6/2005, below.). It is one of about 30 seeps, mud pots, and other hydrologic structures defining a northwest-striking lineament known as the Wister Fault, which is probably a southeast extension or abandoned strand of the San Andreas Fault.

Surface water and moisture also appeared west of W9 on either side of the railroad tracks and adjacent to the highway in 2005. By 2017, much of the soil in the parking lot of the Wister unit of the Imperial Wildlife Area, which is located west of Route 111, also showed areas of surface moisture along west-southwest-trending lineaments. These moist areas were thought to be water that was related to W9, and their west-southwest orientation suggested cross faults through which water could rise to the surface (see the image labeled 7/31/2018).

From 2005 to 2016, water from W9 flowed south and west and came within 60 ft of the railroad tracks. In 2014, the Imperial Irrigation District cut a trench on the northeast side of W9's caldera to redirect the water away from the tracks. This measure proved ineffective; water continued to flow south and west, coming even closer to the tracks. A second attempt was made to redirect the water, this time south and west toward the Salton Sea, but did not result in any noticeable change in the flow.

In mid-2016, an ambient-temperature, CO_2-driven mud spring appeared that partially overlapped W9. Gas sampling confirmed the presence of CO_2 with minor levels of H2S. The mud spring, labeled W9a, began to move southwest toward the Union Pacific railroad tracks and Route 111 at a rate of about 16 ft per month. This new spring was less than 1 mi northeast of the Wister Fault, moving perpendicular to it, as though along a cross fault.

In May 2018, Union Pacific hired Seattle-based Shannon & Wilson Inc. to manage the site and mitigate the threat. By this time W9a had carved out a large basin nearly 11 ft deep that was filled with muddy water. After acoustic imaging studies were carried out, Union Pacific authorized the dumping of riprap into W9a to "plug" it.



The time series from Google Earth shows the appearance of W9 and the first detection of the moving mud spring (in 2016) as a southwestern elongation in W9. (images adapted from Google Earth by David K. Lynch)

However, this did not work because most of the rock sank into the mud and vanished below the surface (see the image labeled 7/31/2018).

In May and June, a 140 ft long sheet pile wall was constructed and inserted to a refusal depth of 75 ft to stop or slow W9a's southwesterly movement and to maintain the integrity of the sediment between the sheet piles and the railroad tracks. Not long after the wall was installed, the mud spring changed direction and began moving more westerly (see the image labeled 8/26/2018).

As it advanced westward, W9a fluidized the sediment and grew to an approximately 24,000 sq ft basin about 11 ft deep. Water sampling revealed that the sediment-to-water ratio was 0.051 by volume. The sediment particles in the water were on average less than a micron in diameter. Moving in a fairly straight line, the mud spring remained a discrete, point-like structure and did not develop into a linear trench-like source as might be expected.

W9 and W9a split, with W9a carving out a large basin that was filled with muddy water. (David K. Lynch)

Also in June, a well was drilled northeast of W9's location and about 350 ft from W9a with the hope that drilling would decompress the aquifer that was powering the spring. When the drill reached a depth of 326 ft below grade, there was a blowout. Mud, CO_2, and water shot from the well to a height of about 100 ft. The blowout gradually subsided after a few hours, although the well produced water for many days afterward. No discernible effect on W9a was detected after the blowout.

In late June, Union Pacific decided to drain the basin of W9a-pumping out and disposing nearly 5 million cu ft of water-to reduce hydrostatic pressure on the sheet piles and reduce water diffusion through the sediment toward the tracks, activities that enabled workers to better monitor W9a's behavior. The basin had a flat bottom 10-15 ft deep, although slightly deeper at the mud spring. Draining the basin obliterated W9, but its original CO_2 sources remained evident: dozens of small, bubbling mud pots and mud volcanoes at the bottom of the basin at the northeast end. Pumping of W9a continued, with the discharge being somewhat variable but averaging 40,000 gal. per day.

As a precaution, Union Pacific constructed a shoofly (detour track) west of the existing railroad tracks in July. Owing to surface moisture and scattered standing water with alkaline deposits, a 500 ft long section of soil was first dewatered and stabilized using engineering lime down to a depth of 2 ft along the planned path. In addition, Union Pacific constructed an elevated railroad bed followed by the deposition of ballast and the laying of the tracks. The plan was to use the shoofly temporarily if the mud spring began to undermine the existing tracks. Consideration was also given to building a bridge over any failed tracks if necessary.

A 140 ft long sheet pile wall was constructed to slow W9a's southwesterly movement. (David K. Lynch)

By mid-July, W9a had moved to within 40 ft of the railroad tracks, reaching the sheet piles. Bubbling water began to erode the sediment and expose the east side of the piles. The sediment on the west side remained in place and continued to support the eastern railroad track. At this time W9a remained more or less fixed immediately adjacent to the east side of the sheet piles. This location was the only conduit through which pressure could be relieved. As was discovered later, the spring was carving out a hollow in the sediment west of the sheet piles.

In August, Union Pacific authorized the drilling of two additional decompression wells east of the tracks. Well B-2 was 100 ft north-northwest of the mud spring (now hard against the sheet piles), and well B-3 was 100 ft southeast of the mud spring. B-2 was advanced to a depth of 800 ft, encountering predominantly dense-to-plastic clays with interbeds of fine-to-medium sand and silt. No significant water-bearing zones were found. One zone of high-pressure CO_2 gas was encountered at a depth of roughly 550 ft, and this was sealed off with steel casing when the hole was drilled deeper.

Well B-3 was drilled to 405 ft, revealing similar dense-to-plastic clays with interbeds of fine-to-medium sand and silt. Workers encountered a high-pressure CO_2 gas zone near a depth of 400 ft that stopped the drilling for several days. Upon resumption of drilling, B-3 vented CO_2 gas continuously when the wellhead valve was open. When it was shut, CO_2 pressure built up to 140 psi after several days. Whether the valve was open or closed, there was no noticeable effect on the mud spring.

By mid-August, W9a's behavior changed dramatically. For three weeks, the spring cycled between the sudden onset of a violent, splashing outburst and a gradual lessening of activity, which would leave the spring nearly quiescent for several minutes, except for minor flow and isolated bubbles. Eventually the outbursts became imperceptible, and by early September the spring resumed its constant flow. By then, many of the sheet piles had become exposed to depths of 22 ft, which was the average water level maintained by pumping.


9/20/2018


10/5/2018

An approximately 60 ft wide and 25 ft deep sinkhole suddenly emerged west of the sheet piles, extending to the ballast shoulder on Main 1 track. (David K. Lynch)

The gas and water pumped from W9a were measured daily. Carbon dioxide levels at the ground level above the mud spring surface near the spring were almost always within safe levels, rarely (and temporarily) rising enough to be of concern. Hydrogen sulfide levels were always within safe limits. A gas monitor was lowered along the sheet piles to about 2 ft above the spring. The CO_2 was off the scale and dangerously high at 10,000 ppm. Oxygen was 2.4 percent, H_2S was 61.7 ppm, and there was no sulfur dioxide (SO_2).

During August and September W9a remained fixed relative to the sheet piles but continued to erode the sediment pool's periphery east of the sheet piles until the sinkhole walls were exposed vertically. Bouguer microgravity measurements revealed an area of reduced gravitation, suggesting that a cavity was forming just west of the sheet piles. On October 3, work crews heard gurgling coming from a surface crack that opened up immediately west of the sheet piles. Jets of muddy water were also seen squirting to the east.

The next morning a shallow, 3 ft wide, bubbling mud puddle was observed about 3 ft west of the sheet pile-an ominous sign. At this time the mud spring was at the bottom of a 25 ft deep caldera immediately east of the sheet piles, as it had been for several months. At 1:15 p.m., author Travis Deane witnessed the loud, violent formation of a roughly 150,000 cu ft sinkhole, this time just west of the sheet piles (see the image labeled 10/5/2018).

Deane approached the mud spring from the northeast to make last-minute observations before a daily 1:30 p.m. telecom meeting with the railroad and the rest of the team. Suddenly he saw jets of dust shoot 5 ft into the air immediately west of the sheet piles. The jets stopped after about 15 seconds followed by loud rattling of the sheet piles. Deane ran to the north end of the sheet piles and witnessed an explosive release of gas and dust on the west side of the sheet piles. After the dust had settled (literally), he found that the ground had collapsed to form a roughly 60 ft wide, 25 ft deep sinkhole. This new crater extended from the sheet piles to the ballast shoulder on Main 1 track, threatening a line of stationary railroad cars parked there. The sloping sides of the new sinkhole continued to cave into the bubbling mud spring below. Deane could now see that in less than five minutes, the mud spring had "hopped" about 60 ft southwest, under the sheet piles to its new location at the bottom of the new sinkhole.

With W9a exposed west of the sheet piles, its true location was pinpointed at 20 ft southwest of the sheet piles. Based on previous location measurements, the mud spring appeared to be moving at an average rate of about 110 ft per year.

Riprap was used to buttress the sheet piles on the west side, and the mud spring basin on the east side was backfilled with sediment. Soon, individual piles began to sink into the mud and tilt westward into the sinkhole; therefore, more riprap was placed into the sinkhole against the sheet piles. Later that month, the sinkhole was excavated to the southwest to monitor the spring's movement and help predict its path (left).

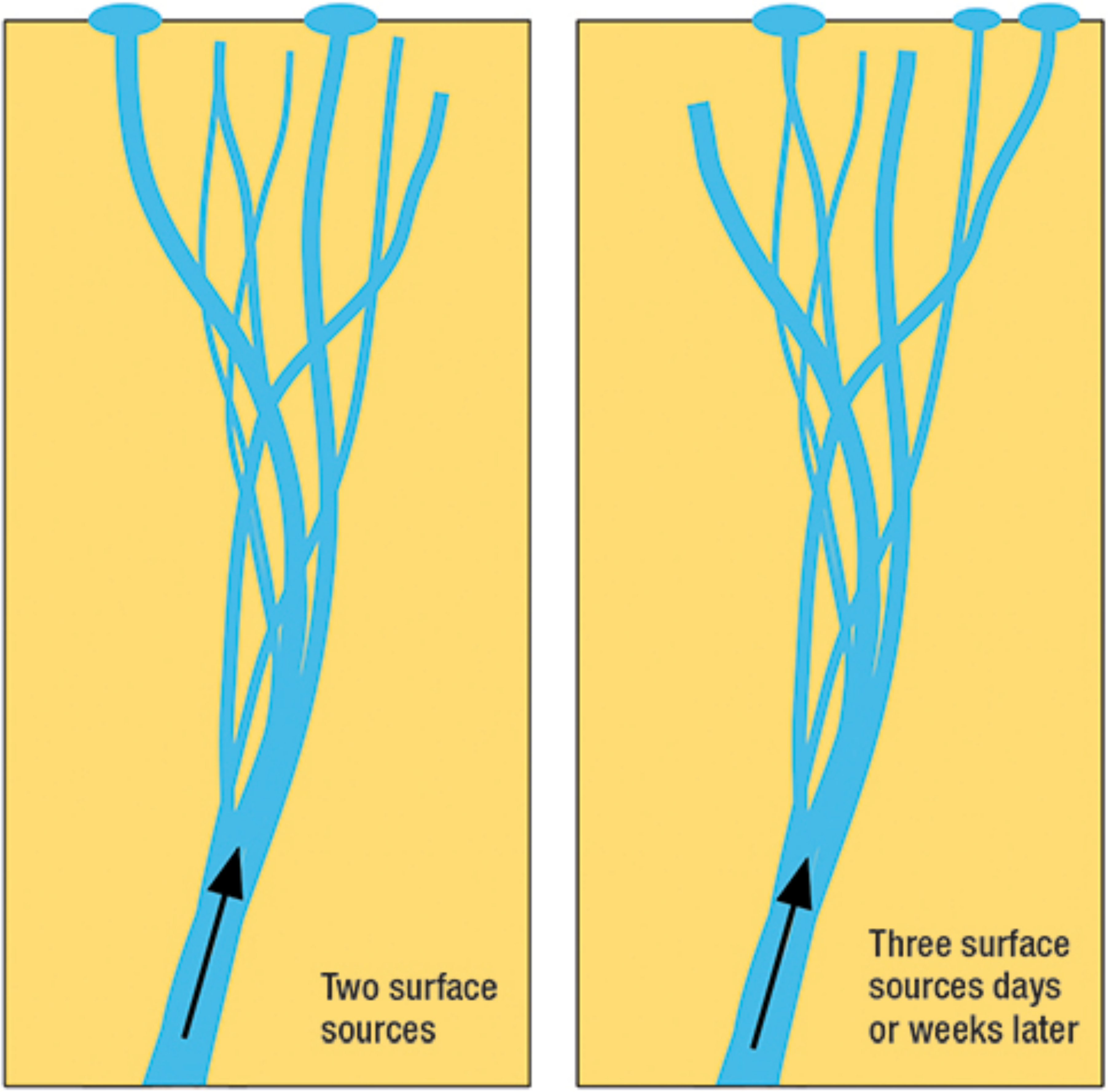
By mid-October, work crews had refilled the basin with sediment because of the danger that the steep sides posed and the high levels of CO_2 that were being emitted. Refilling the basin allowed Union Pacific to build a second shoofly east of the mud spring so that there were two operational tracks again.

In late October, work crews drilled two boreholes west of the west shoofly for Houston-based Kinder Morgan, an energy infrastructure company, whose petroleum/gasoline pipeline was now only 150 ft from the spring. Both

Work crews partially filled the sinkhole with riprap west of the sheet piles to ensure that the sediment supporting the east shoofly did not move. A west shoofly was built so that there were two railroad tracks in operation again. (David K. Lynch)

boreholes reached depths of 100 ft and produced very wet mud up to depths of about 5 ft, which was probably because of residual moisture from when W9a first appeared. Below 5 ft, only interbedded dry sediment and sand were encountered.

Over the next few months, a curious thing happened. After the collapse, two springs were evident. The main mud spring at the southeast end of the sinkhole and a tiny one to the northwest, the latter having appeared when the sinkhole formed. The main mud spring grew less active while the tiny spring on the northwest flank of the sinkhole expanded and became more active. By January, both springs were producing water at about the same rate, and by March, the northwest spring had become dominant. Such behavior had been seen before and was interpreted as the spring "hopping around." In this case, though, it was clear that there were two springs (at the surface) and that their water production varied inversely with each other.

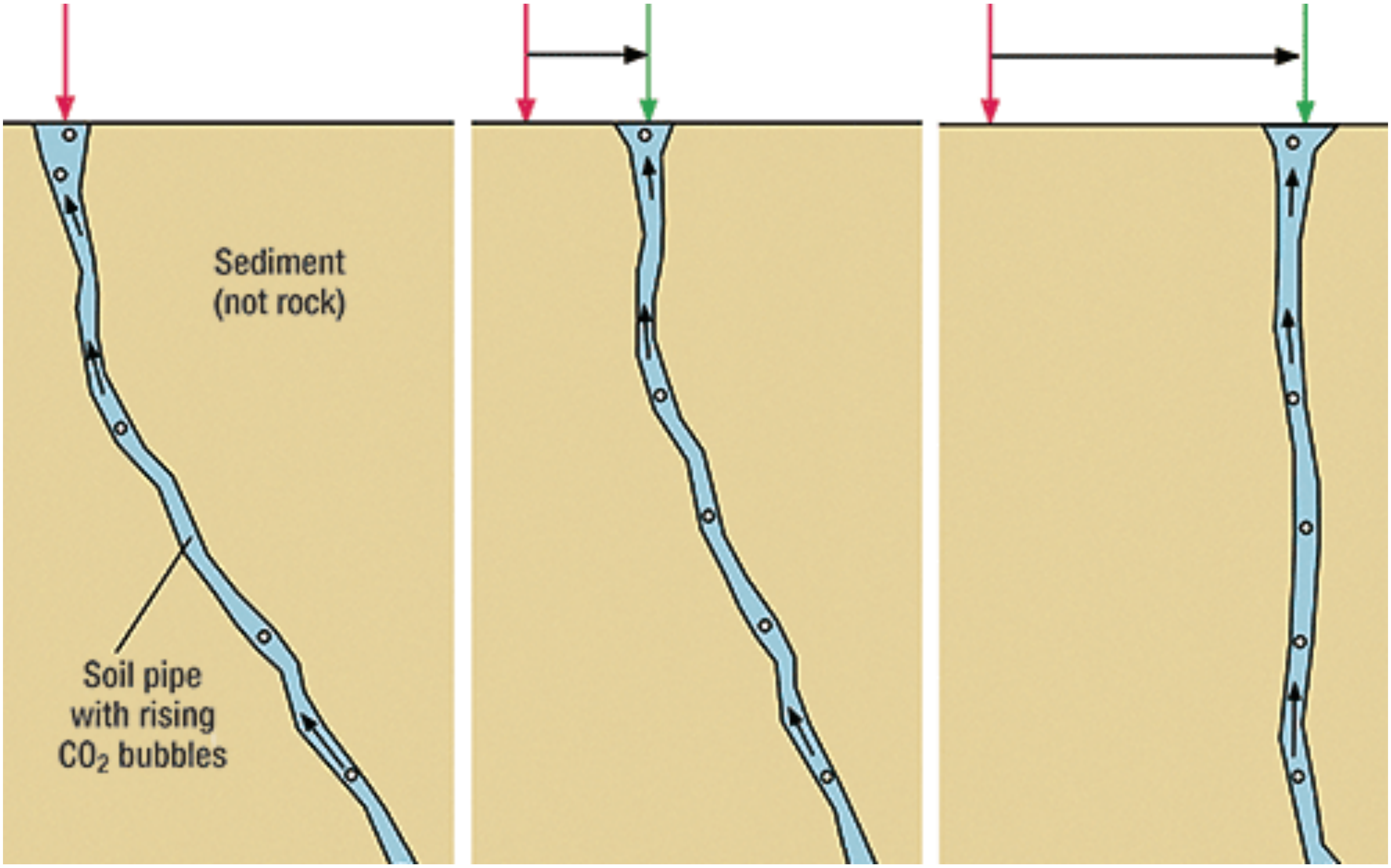


Hydra Model for Short-Term Motion (David K. Lynch)

W9A has shown two kinds of movement: a short-term motion (weeks to months) during which it appears to hop around by 10-20 ft, and a long-term southwesterly displacement of hundreds of feet over a period of years. Although the reason for the movement remains a mystery, the authors suggest two related mechanisms-related to subsurface sediment collapse-that could explain the movement and are consistent with the observed geology and hydrology in the area.

The short-term motion could be explained by a hydra-like structure, analogous to the flower structure found in faults. As water approaches the surface, it becomes progressively less constrained by hydrostatic pressure from the overlying sediment. Weak portions of the near-surface sediment allow the spring to split into many branches. Being in sediment that is being eroded by rising water and CO_2, there are occasional sediment collapses beneath the surface that block flow and create extra pressure locally. This causes the flow to push into or shift to another branch that reaches the surface. In this way, several surface springs may be present. As one wanes and another grows, the spring appears to hop around (see the image at left).

To explain the long-term motion of the spring, consider a structure called a soil pipe, which is a tubular flow through sediment that is driven by gravity. While W9a is driven by buoyant CO_2 gas bubbles, internal erosion of the enclosing sediments would occur in both movement models, which could result in soil collapse (internal sapping) that blocks the flow and redirects it, thus moving the surface location of the spring. If the conduit through which water is brought to the surface is tilted, erosion would tend to remove sediment from the upper parts of the pipe and deposit it on the lower parts. This would lead to a gradual movement of the spring and would also maintain the spring as a discrete source. This model predicts that the spring would move toward a point on the surface directly above the deep source. When this location was reached, the spring would stop moving (see the Sapping Model, below right).



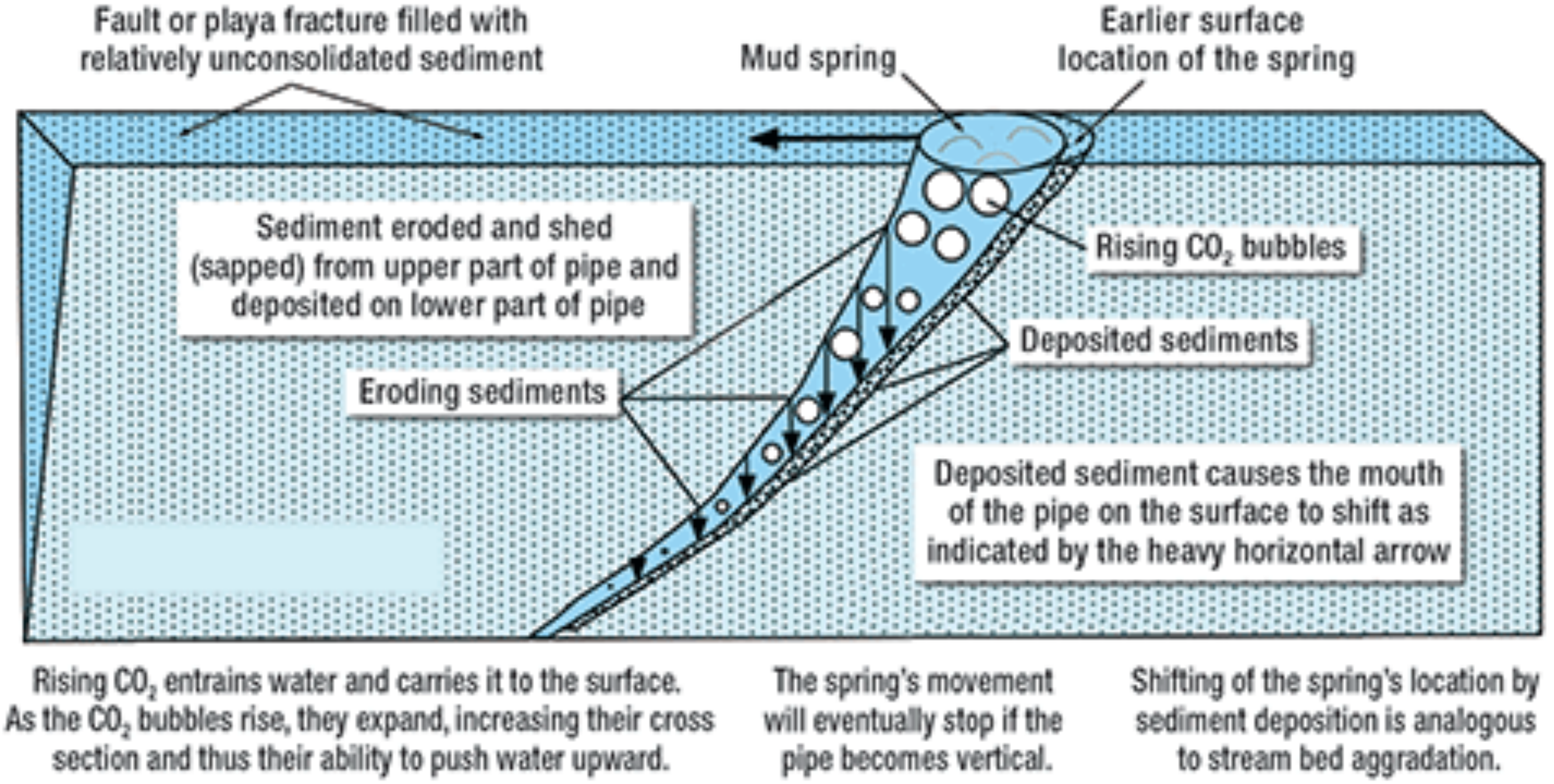
Sapping Model for Long-Term Motion (David K. Lynch)

For this mechanism to work, the sediment must fall to the bottom of the pipe rather than be carried upward by the water. This process is analogous to streambed aggradation; it places some conditions on how the soil collapses, the speed of the water, and sediment particle size. Erosion could occur because of the collapse of larger, more intact chunks of sediment. Otherwise, the small particles might be carried upward and away, perhaps later settling to the bottom when the flow slows.

The inverse production between the southeast and northwest springs in the sinkhole after October supports the hydra structure model. As the two springs varied, water production remained constant, which suggests an unchanging deep source whose gas and water find their way to the surface by any route possible. Water production is conserved, whether through a single spring or several.

Regarding the hydrology of the area, the authors believe that the water table-if such a concept makes sense in this situation-is patchy and inhomogeneous. This seems reasonable because there are two dry wells within 100 ft of W9a, which is producing 40,000 gal. of water per day. The explanation may be that the water source is not moving but the CO_2 source is, which is what is driving the mud spring's movement. If there is no major CO_2 source on either side of the spring, no water would be brought to the surface; therefore, the CO_2 emission would pass unnoticed.

It is also possible that W9a (or the CO_2 source) is moving along a northeast-striking fault. The spring's movement in a southwesterly direction is nearly perpendicular to the controlling faults in the area, mainly the San Andreas, as though moving along a cross fault. Cross faults are well known in the area, though none have been mapped at the W9a's location, primarily because the land surface has been heavily modified by agriculture and conservation efforts. Scarps and other tectonic structures have been erased, and there is nothing in the seismicity to suggest an active fault. The moist soil lineaments in the parking lot of the California Department of Fish and Wildlife west of Route 111 revealed an increase in near-surface water in the last few years. Their south-southwest trends could be indicative of cross-faulting by which water reaches the surface.



Conditions Near a Fault/Fracture in Sediment (David K. Lynch)

Another possibility is that the spring is moving along a playa fracture. These fissures are the result of desiccation cracking when a shallow lake dries up, in this case Lake Cahuilla. These fractures are usually linear and are large-scale analogs of mud cracks. Over time they fill with sediment that tends to be less hardened than the surrounding lake bed. Thus, upwelling water will tend to reach the surface through such a crack. (See the figures at left and below.)

Yet another fault geometry could also produce a southwest-moving spring. Instead of a cross fault striking northeast, suppose that it could be a shallow-dipping fault striking northwest and dipping southwest. Such a fault might be a growth fault, like one found in deltaic sediments. When rising water reaches the fault plane, it would be diverted along the fault in a southwest direction. Even though the water would encounter a planar fault, it would move upward at an angle along the fault following the steepest possible path, thereby carving out a soil pipe (see the figure at bottom).

As of this writing, Kinder Morgan has rerouted its pipeline around W9a and the former location of W9. If W9a's movement remains unchanged, it is expected to reach the western shoofly by the end of this year. The pipeline and fiber-optic cables will be affected by mid-2020, and Route 111 by 2021. However, exact predictions are impossible to make because this spring is a geological mystery, one that will remain a fascinating headache for years to come.

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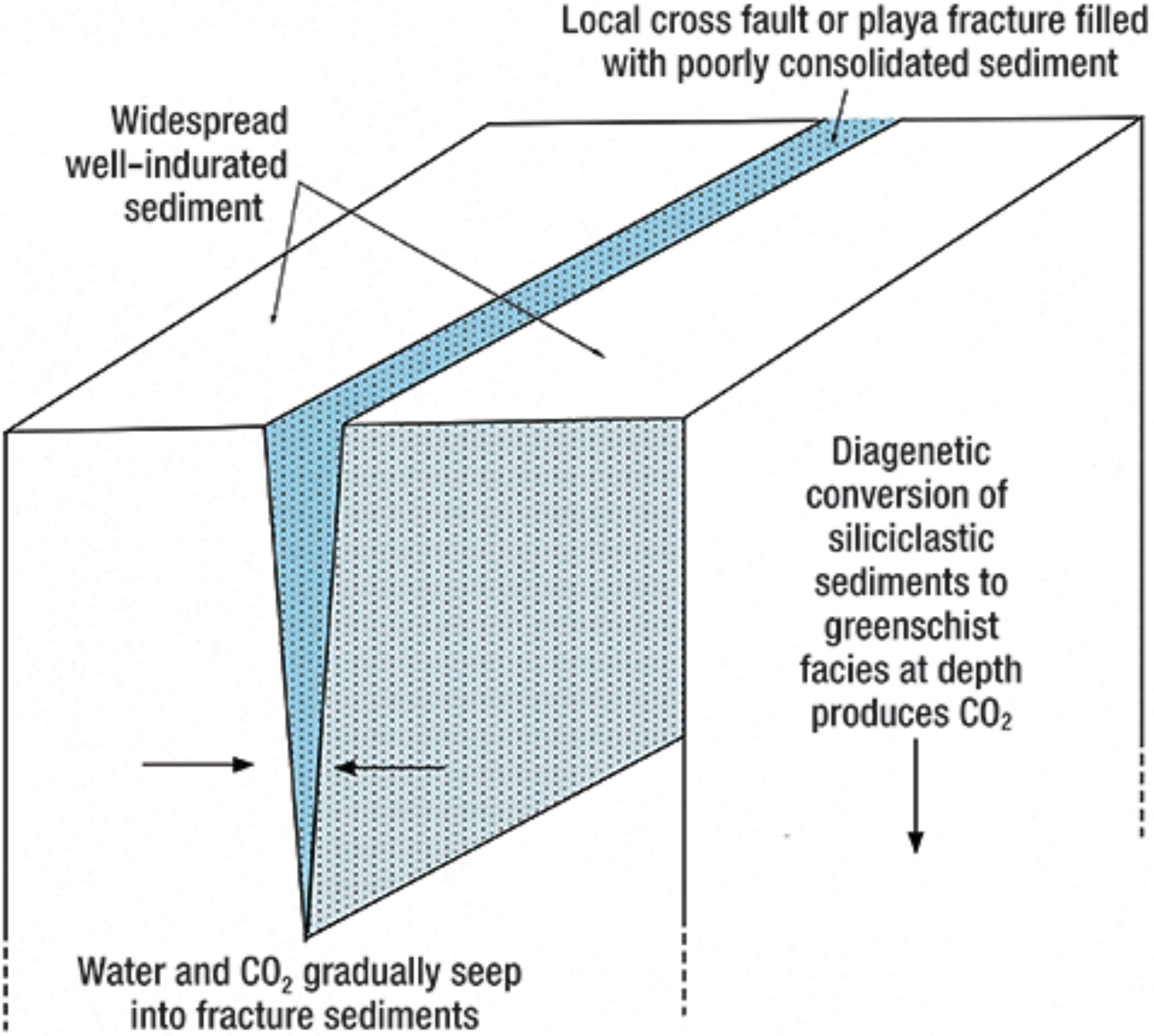
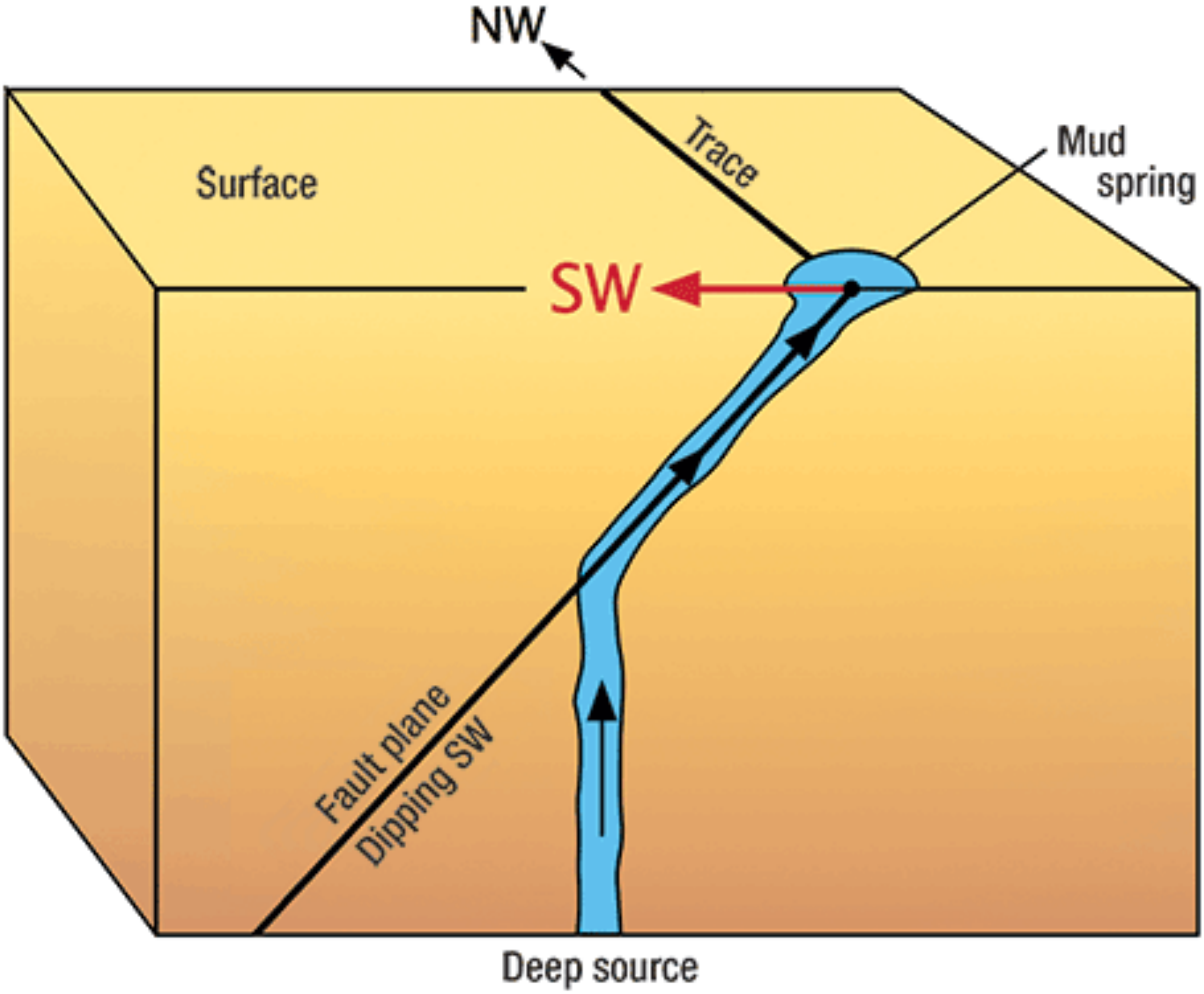


Spring Motion Due to Subsurface Sapping (David K. Lynch)



Long-Term Spring Motion in Northwest-Striking, Southwest-Dipping Fault (David K. Lynch)