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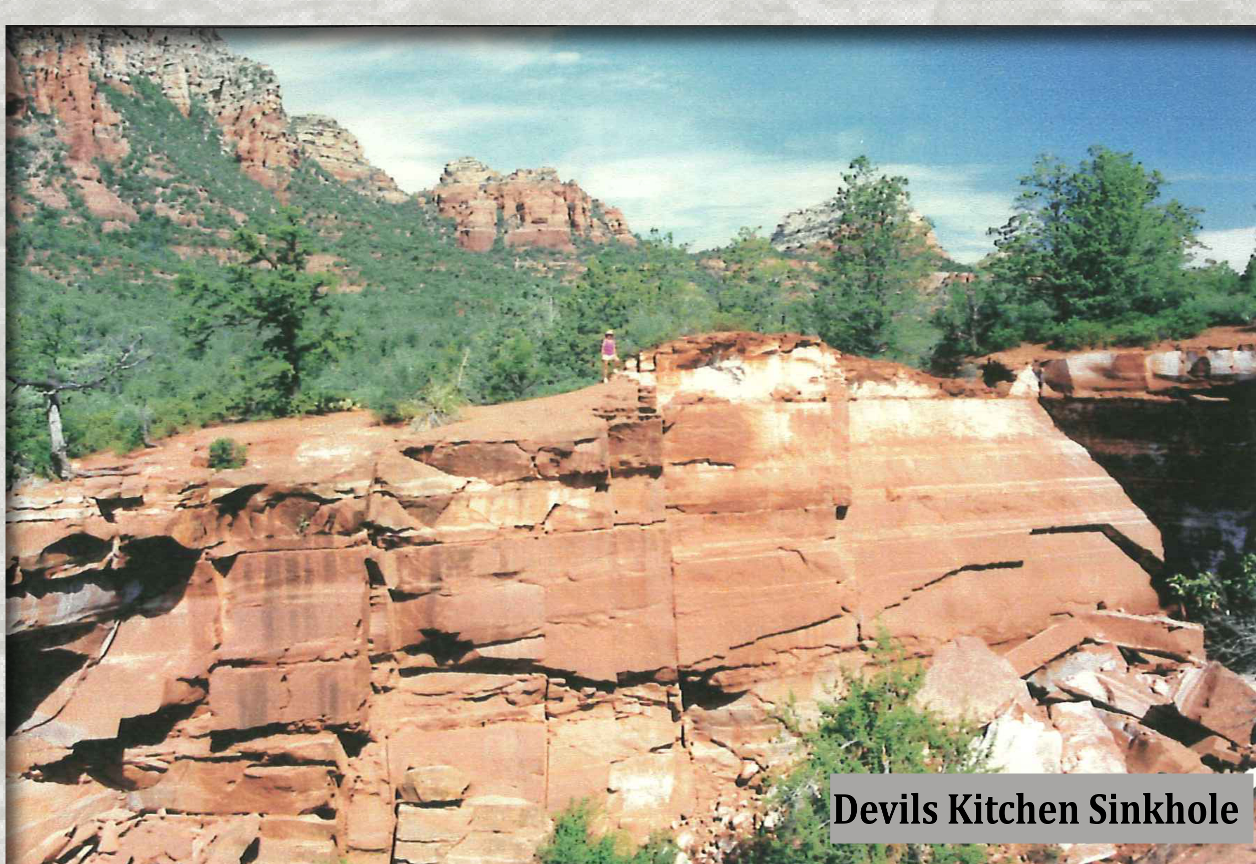

GEOLOGIC REPORT OF THE DEVILS KITCHEN SINKHOLE

Paul A. Lindberg

February 2010

Geologic Report of the Devils Kitchen Sinkhole

Section 1, Township 17 N, Range 5 E
Sedona, Yavapai County, Arizona

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Arizona Geological Survey Contributed Report Series

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BACKGROUND

At the request of the U.S. Forest Service to Red Rock Jeep Tours of Sedona a geologic report on the condition of the Devils Kitchen sinkhole was required for the safe continuation of Jeep visits to the site (Fig. 1). Mark Avery of the jeep company contacted me to study the site and write up my findings. The study of sinkholes in the Sedona area has been of interest to the writer for some time and the present study is hoped to shed some light on these fascinating geologic features. This report is offered as a public contribution at the cost of publication and without fee.

HISTORIC PERSPECTIVE

A description of the Devils Kitchen collapse is presented by Albert E. Thompson (Those Early Days, 1968, Sedona Westerners, p. 60). "My parents were living in Sedona in the early 1880s and heard the crash when the spot caved in. Mother said the dust from the cave-in filled the air all day and the sun looked like it was shining through heavy smoke. Her brother, Jim James, was the first one to see the new hole in the ground".

The current examination of the sinkhole (as of September 27, 1990) suggests that the southernmost wall of the collapse area may have pre-dated the supposed cave-in of the entire area. The reason for saying this is that there is surface evidence that rounded outcrops and a patina of manganese [oxide] suggests that an opening in that area may have been small but open for several hundred years. This weathering is in sharp contrast to the recent collapse (latter half of 1989) of the entire northern wall of the sinkhole. The edges of the new breaks are very angular and the surface soil has not yet begun to slough off.

A massive collapse of the northern portion (one third?) of the sinkhole added very large breccia blocks to the sinkhole collapse rubble. The largest of these blocks rotated outward toward the center of the rubble pile and was detached along three bounding walls from its caprock.

Figure 1. Aerial photograph showing Devils Kitchen Sinkhole situated north of Sedona, Arizona. Note the pervasive north west trending joint system. Inset map shows the approximate location of the study area.

GENERAL STATEMENT ABOUT SINKHOLES

There are several possible reasons for the development of sinkholes but the most common, by far, is from the collapse of caves in limestone bedrock by the agency of weakly acidic groundwater and the [dis]solution of the mineral calcite. Small amounts of dissolved carbon dioxide in rainwater provide weakly acidic groundwater which slowly dissolves limestone along fractures. Over long periods of geologic time these slow rates of [dis]solution are capable of making gigantic underground caverns. During the formation of a cave the slowly enlarging chambers are formed below the water table and may form important groundwater aquifers. If a cave is finally unroofed by erosion or the groundwater [table] lowers below the cave floor, then, and only then, will the cave be termed "dry" and be able to form secondary stalagmites and stalactites. The Karst region of Yugoslavia lent its name to "karst topography" that is common in many parts of the world where limestone is the dominant surface rock type. In such a topography there are collapse areas of large subterranean caves, internal drainage below ground level, and poor soil development. Caves which form in such regions may become so large that the overlying rocks collapse into the openings. Sinkholes formed in this fashion may collapse with great speed. Or they may slowly collapse upward until the opening is filled with broken rubble. Broken rock occupies a greater volume than solid rock and may contain up to 35% open spaces between breccia blocks.

THE DEVILS KITCHEN SINKHOLE

Unlike typical karst topography the outcrops in the immediate vicinity of the Devils Kitchen sinkhole contains no limestone. The walls of the collapse area contain massive [Schnebly Hill] sandstone in the upper walls and a much weaker [Hermit Formation] shaly siltstone in the undercut lowest portions of the sinkhole walls. This sinkhole, as well as the similar Devils Dining Room to the south of Sedona (Fig. 1), is formed as the result of deep-seated collapse of Redwall Limestone caves at depth.

Figure 2 shows a stratigraphic cross section of the rock strata in the vicinity of the Devils Kitchen sinkhole. The stratigraphic subdivisions have been derived from various recent sources and are believed to be accurate enough for the purposes of this report.

The schematic cross section shows that the top portion of the Devils Kitchen sinkhole is at an approximate elevation of 4510 feet above sea level. Rocks at this position belong to the upper part of the Hermit formation (*) which is made up of bedded sandstone, siltstone, and shale. These strata were formerly classified as part of the "Supai Sandstone" (i.e., the "Red Rocks") but recent reclassification has restricted "Supai" to the massive sandstone beginning at about 210 feet below the collar of the sinkhole. The massive Supai [Esplanade] Sandstone is approximately 430 feet thick and rests conformably on top of Redwall limestone which is approximately 180 feet thick. Below the Redwall is a thick layer of [Devonian] Martin Dolomite and [Cambrian] Tapeats Sandstone. The crystalline Precambrian basement lies approximately 1350 feet below the collar of the Devils Kitchen sinkhole.

(*) More recent correlation work shows that the bedrock lip of the Devils Kitchen sinkhole is situated in Schnebly Hill Sandstone and its contact with underlying Hermit formation lies about 40-60 feet below the sinkhole lip. The softer shaly sediments under the eastern wall of the sinkhole, as seen in Cross Section B-B', is now defined as the uppermost part of the Hermit formation that forms the prominent undercut situated 40 feet below the sinkhole rim. In addition, there are new refinements of elevations and rock formation thicknesses.)

Above the sinkhole are the imposing cliff-forming sandstone strata of the [Schnebly] Hill formation. About 520 feet above the sinkhole is a thin rock strata known as the Fort Apache Limestone. This is the same thin limestone bed that forms the "Merry-Go-Round" off the Schnebly Hill Road and the "deck" of Steamboat Rock. The limestone marker bed provides a good datum for measuring the stratigraphic sections in the Sedona area. The Fort Apache Limestone above and the hidden Redwall limestone below were formed in shallow seas during times of local crustal sinking below sea level. The entire intervening "Red Rock" succession (Schnebly Hill [Sandstone], Hermit formation, and Supai Sandstone) were all [deposited] close to sea level and sometimes within inter-tidal areas. The whole rock succession from Redwall Limestone to the Fort Apache Limestone ranges in age from approximately 350 to 285 million years old. During that interval this portion of the Earth's crust lay close to the Equator with deposition of terrestrial and marine sediments close to the edge of warm, tropical oceans. Continental drift since that time has shifted this part of the crust northward to its present latitude.

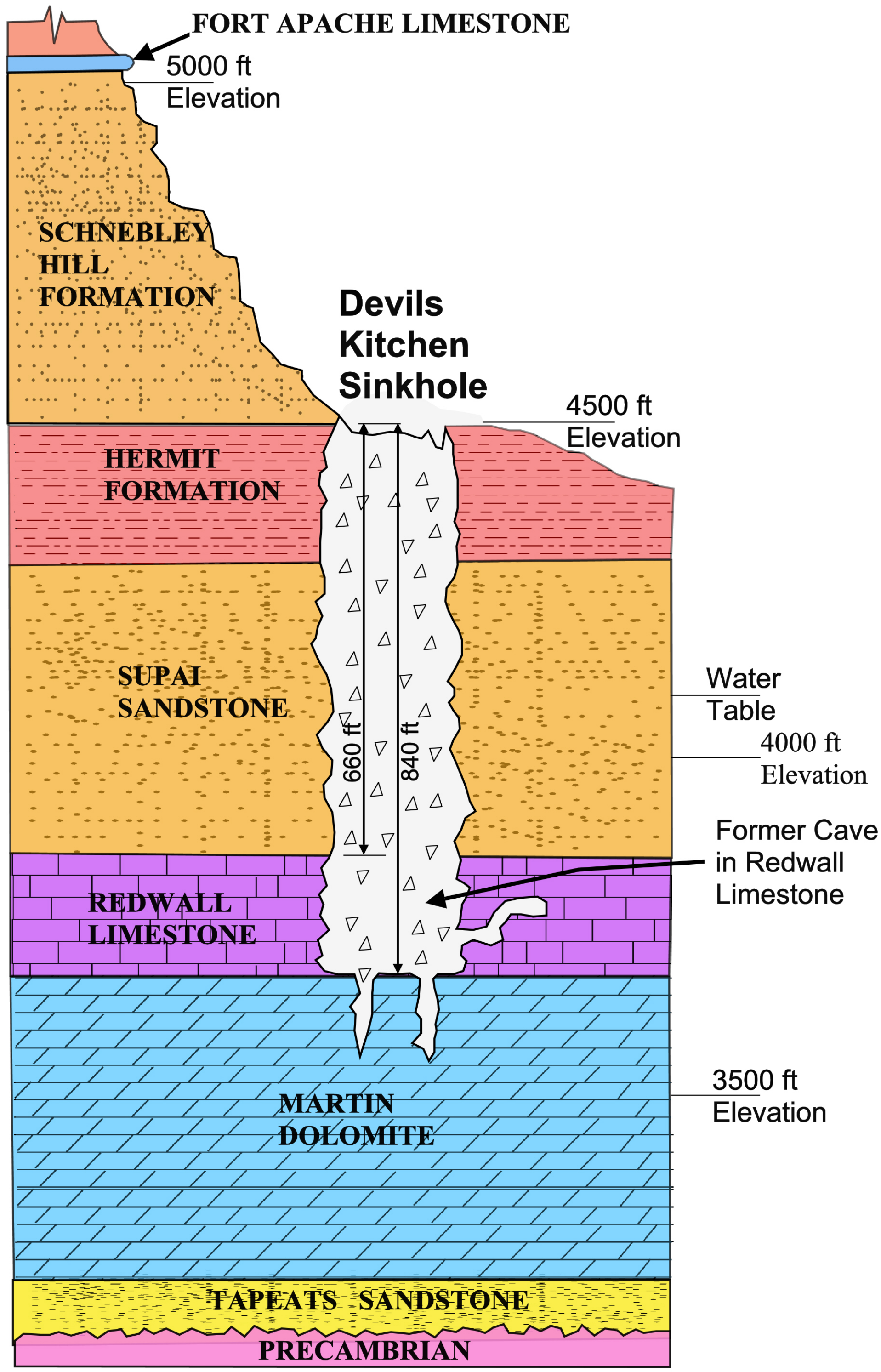


Figure 2. Schematic cross section of rock strata in vicinity of Devils Kitchen sinkhole. The elevations and geologic formation contacts may vary by small amounts due to interpretational differences. A solution cave with the Redwall Limestone (approximately 200 feet in diameter and 180 feet high) collapsed due to lack of roof support. Over a period of time the caprock caved in and finally broke through to the surface (1880s?).

The rock strata of the Colorado Plateau and Sedona region were not uplifted to their present elevations until about 75 million years ago during the Laramide Orogeny. All of the present-day landscape, including the retreating cliff rims, canyons, and butte development took place only within the past 10 million years.

MAPPING OF THE DEVILS KITCHEN SINKHOLE

Figure 3 shows a plan map of the Devils Kitchen sinkhole area on a scale of 1 inch equals 40 feet. Three steel pins were placed at points A, B, and Q and they were driven flush to the ground. They may provide future reference points for

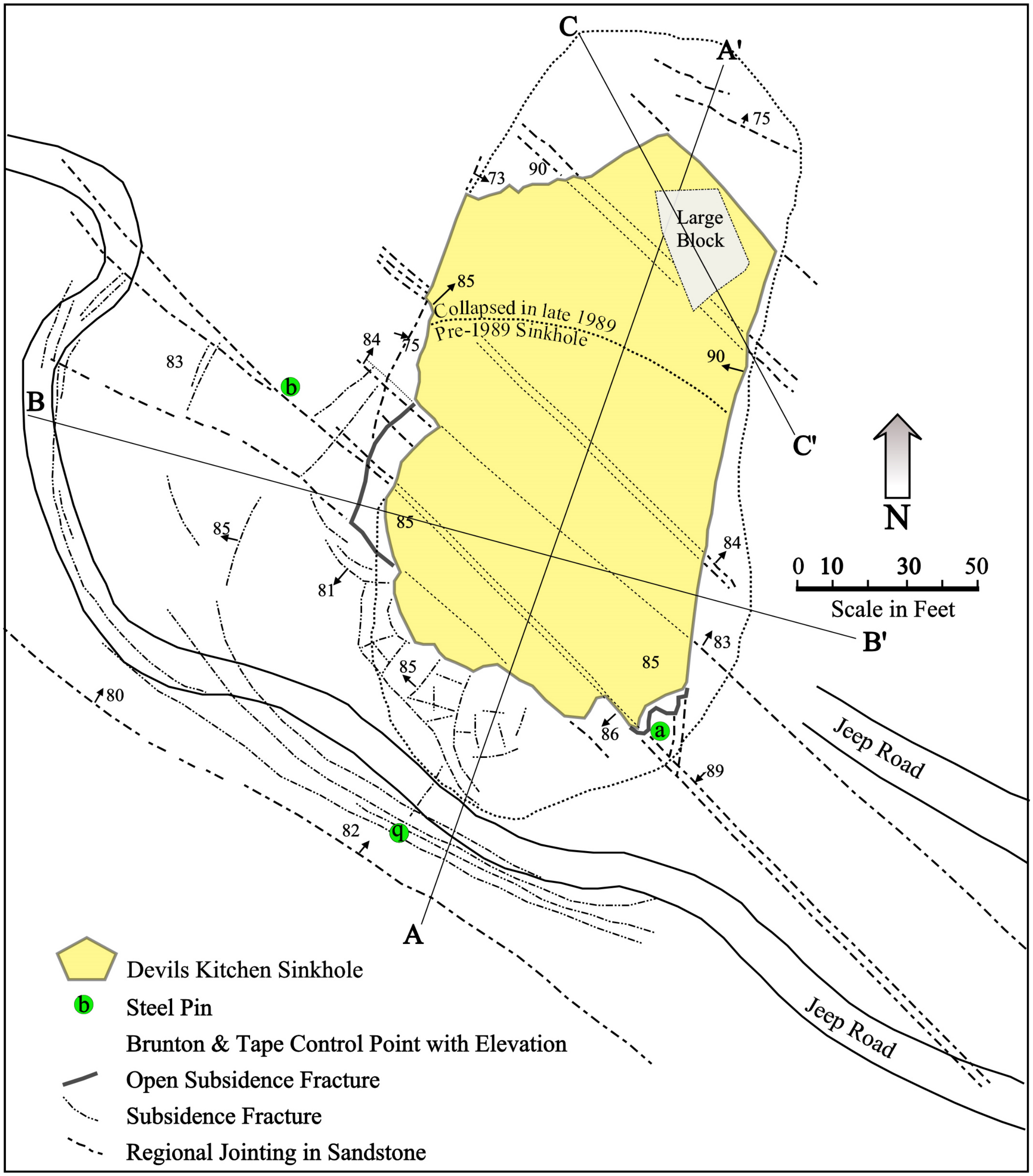


Figure 3. Devils Kitchen sinkhole plan map: Sec. 1, T17N, R5E, Yavapai County, Arizona. Outcrops of Hermit Formation are cut by steep NW-trending joints. Locally a weak and subordinate set of NNE-trending joints also help control sinkhole subsidence. The sinkhole is a surface expression of an upward-migrating breccia column overlying a large collapsed cave opening in the Redwall Limestone, the top of which is estimated to be 660 feet below the edge of the sinkhole. Arcuate subsidence fractures dominate the SW sinkhole corner.

additional measurements. Map surveying was done by [tripod-mounted] Brunton compass and measuring tape with point A as the master control. An arbitrary datum of zero [foot] elevation was assigned to this point and measurements are recorded for either above or below this reference. Extrapolating from the topographic map suggests that point A is about 4510 feet above sea level.

Figures 4, 5, and 6 show selected longitudinal and cross sections across various azimuths over the sinkhole to best illustrate key geologic features. Section A-A' (Fig. 4) shows the long axis of the sinkhole and demonstrates many of the salient features of the upper portion of a sinkhole. Note the arcuate fractures beneath the overhanging south wall (left side). As a column of rock collapses upward its roof is composed of arcuate shells of rock that slab inward into the

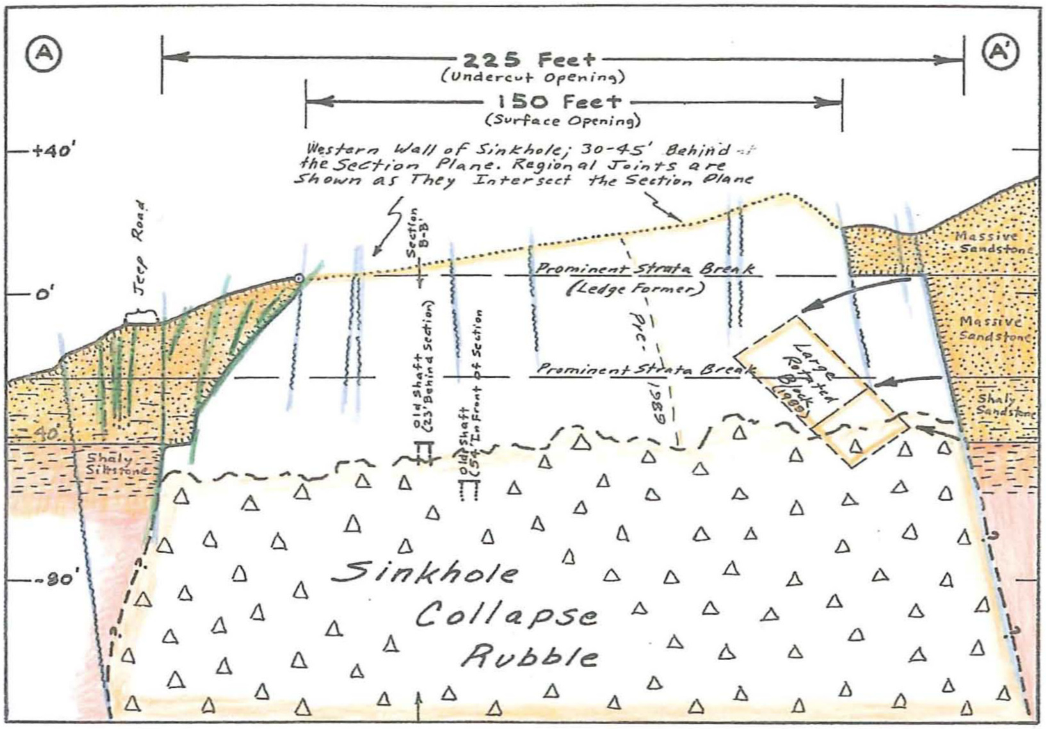


Figure 4. Longitudinal section through axis of Devils Kitchen sinkhole. The scale of the section is about 1”=40 feet and views toward the NNW. The overhanging left edge (south) contains three-dimensional arch-like subsidence features marking the oldest portion of the sinkhole. The right edge (north) contains large rubble blocks that collapsed during the latter half of 1989. The sinkhole was reported to have collapsed “in the early 1880s” but may have been pre-dated by a small opening toward the left edge.

breccia column (see Fig. 8). What this illustrates on surface is a "holing through" of the upward migrating collapsing column that has been blind until it breaks through to the surface. There may be many more such collapse areas around Sedona but until it breaches the surface it is not yet a "sinkhole".

RECENT ROCK COLLAPSE

During the last portion of 1989 there were major increases in the size of the Devils Kitchen sinkhole. While there are no precise measurements to go by it seems probable that the original sinkhole was about 2/3 the size as the [new] opening. Analysis of historic photographs would be necessary to quantify that figure. Nevertheless, a substantial collapse occurred during 1989, more [than] a century after the initial collapse. Virtually all of the new collapse took place on the north wall (Fig. 4 and 6). A gigantic block was rotated outward into the opening but measurements show that it did not drop to a lower elevation.

If the sinkhole is viewed today, the new fractures are very evident when compared to the older south wall which exhibits well-rounded cliff edges and a surface weathering patina. The recent collapse has made a highly unstable north wall to the sinkhole and is severely undercut as shown in the sections. Figure 6, in particular, illustrates how the "scaling" or

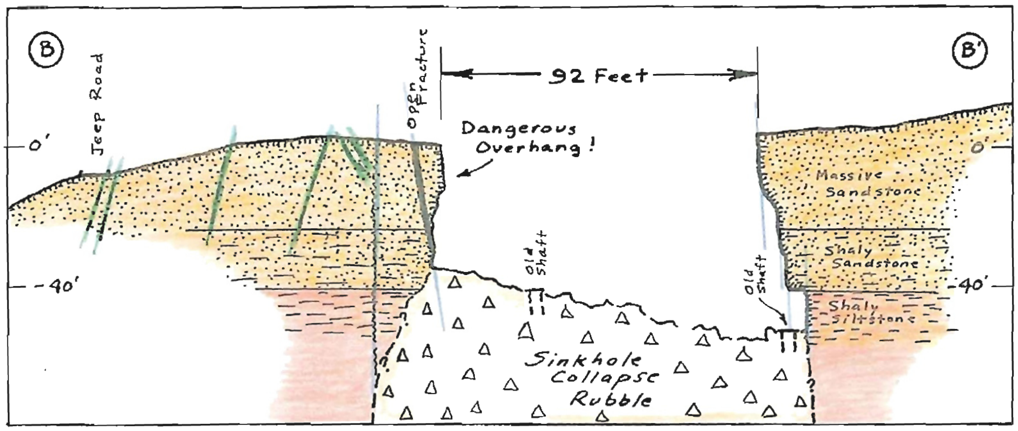


Figure 5. Cross-section through south-central portion of Devils Kitchen sinkhole. The scale of the section is about 1"= 40 feet and views toward the NNE. A large detached block on the left edge (west) is in imminent danger of falling and exhibits 5-inch openings in surface fractures. Attempts to sink shafts in the floor of the sinkhole by “old-timers” indicates how little they understood of the process that formed the cave-in. Collapse breccia may extend for 800 feet below the sinkhole floor.

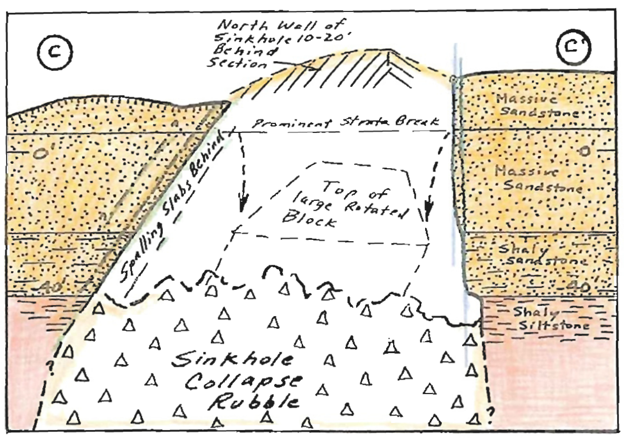


Figure 6. Cross-section through northern portion of the Devils Kitchen sinkhole. The scale of the section is 1" = 40 feet and views toward the NE. The left edge (NW wall) is strongly undercut by NW-dipping subsidence fractures. The large block of rock which collapsed during 1989 fell southward and rotated into the plane of the section. The right edge of the sinkhole (east wall) is controlled by a NNE-trending and steep-dipping joint set. The upper wall of the sinkhole is dominated by massive sandstone that is being “sapped” from below by a soft shaly siltstone strata.

"slabbing" process works. As support is removed from below by continued settling of the breccia column, the upper sinkhole walls have insufficient strength to hold the weight of overlying rock strata. The collapsing rock tries to form an arch over the zone of subsidence and Figure 6 shows part of one of those arches. This area should continue to spall off over the near future.

GEOMORPHIC FEATURES CONTROLLING SINKHOLE DEVELOPMENT

The Devils Kitchen and Devils Dining Room sinkholes share the same controls that led to their formation. Both are situated on NW-trending joints traversing the entire Sedona area. These joints are regional in scope and may have been originally formed during the Laramide Orogeny when the [Earth’s] crust was warped and uplifted to its present elevation. The joints, subtle as they may appear, show no amount of offset but were effective over the last 75 million years

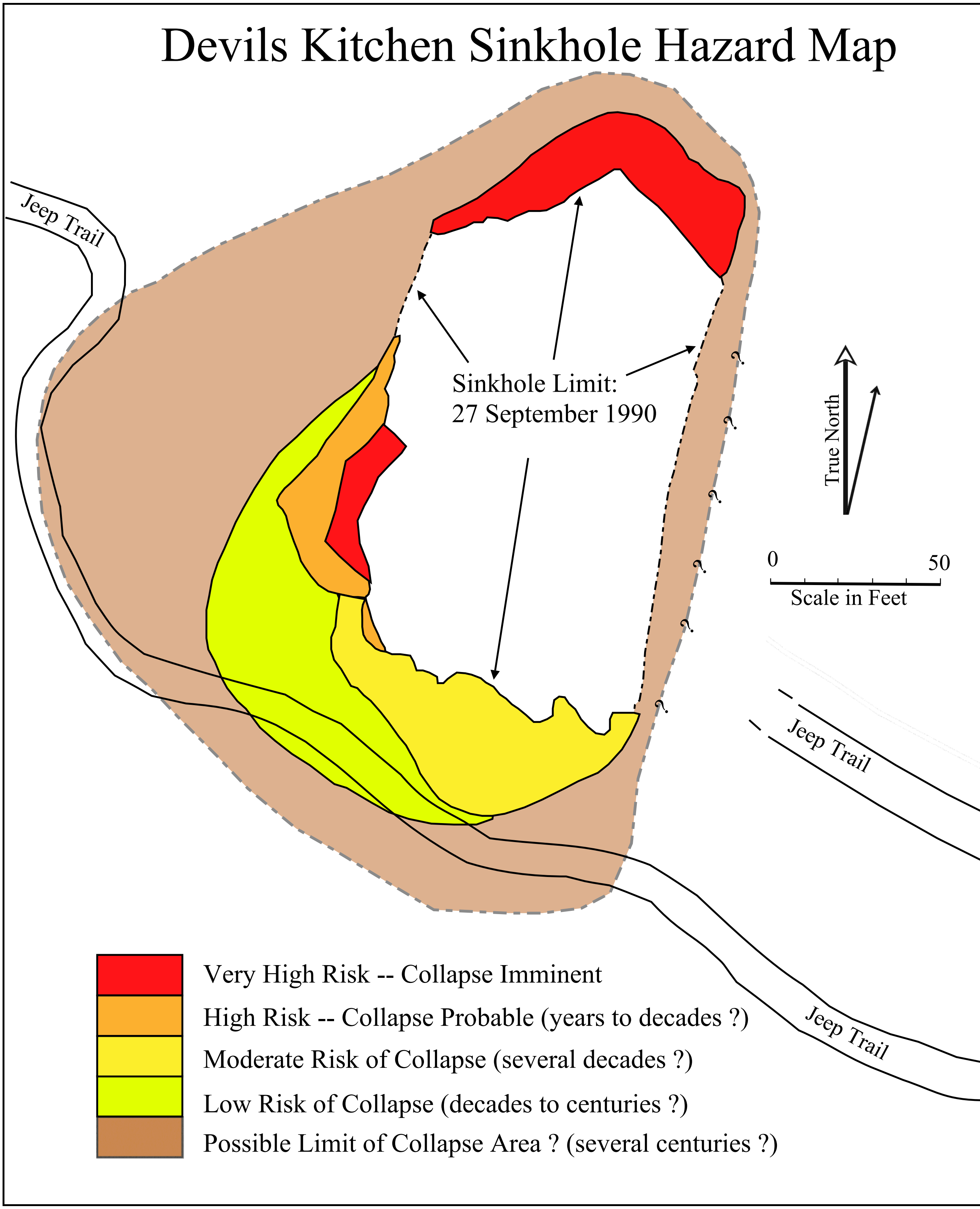


Figure 7. An attempt to quantify future collapse hazards at the Devils Kitchen sinkhole. The nature of sinkhole collapses is such that little accurate prediction can be made because of the inherent instability of the unseen deep-seated conditions that cause their formation. Nevertheless, certain features appear to be obvious and prudent precautions should be entertained because of these possible dangers. This sinkhole appears to be enlarging into a more circular plan outline with time.

by channeling groundwater to depth through these cracks in the upper crustal rocks. As groundwater seeped downward along the joints they passed through thick sandstone strata that contained little or no carbonate minerals. After passing through the sandstone the groundwater finally encountered the very pure Redwall Limestone and solution cavities began to form. (Editor's note: Initial karstification of the Redwall Limestone probably dates to the Mississippian.) This process has probably been continuous over the past 75 million years [but] has been particularly intensive during the past 10 million years as groundwater transport rates increased. The end product was the development of abundant caves within the Redwall Limestone and it was this strata that provides most of the municipal water for Sedona. Water wells in the vicinity have encountered solution cavities in the Redwall and the interconnection of the many small and large caverns provide one of the best aquifers in the world. At the present time rain and snowfall on the Colorado Plateau above the Mogollon Rim provides the aquifer recharge in the porous Redwall limestone. This water passes beneath the Sedona region from the Mogollon Rim toward the Verde Valley in a southwesterly direction. The slow water movement can be likened to that flowing through a saturated sponge that is inclined at a very low angle toward the southwest. The former cave [opening] that once lay below the Devils Kitchen sinkhole had grown so large by groundwater [dis]solution of the limestone that it finally collapsed into the sinkhole we see today.

There is no way of knowing how many caverns there are below the ground surface but water wells indicate that they are very abundant, indeed. Experience from other parts of the world show that caves commonly line up along fracture zones and often develop into large vertical chimney-like features at the intersection of two or more fractures. Examination of the Devils Kitchen map shows that there are prominent NW-trending joint sets and a subordinate NNE-trending set of joints. It is probable that where these joints project downward to the Redwall Limestone a large cavern had developed at this site. Upward stoping, or caving, took place until the upward advancing collapse [breccia] column finally broke through to the [ground] surface as shown schematically in Figure 2.

Figure 8 illustrates how this process of upward-stoping took place. It is highly unlikely that the entire column of rock fell at one time, although it probably did advance by catastrophic pulses. If a collapse of this magnitude took place below the ground surface in a "blind" collapse zone it may be capable of generating an audible "bump" on the surface in much the same manner as that experienced from a large underground mine blast. Such reports should not be taken as frivolous in nature, but be regarded with some concern. While highly unlikely, such events may provide advanced warning [as] to future sinkhole development.

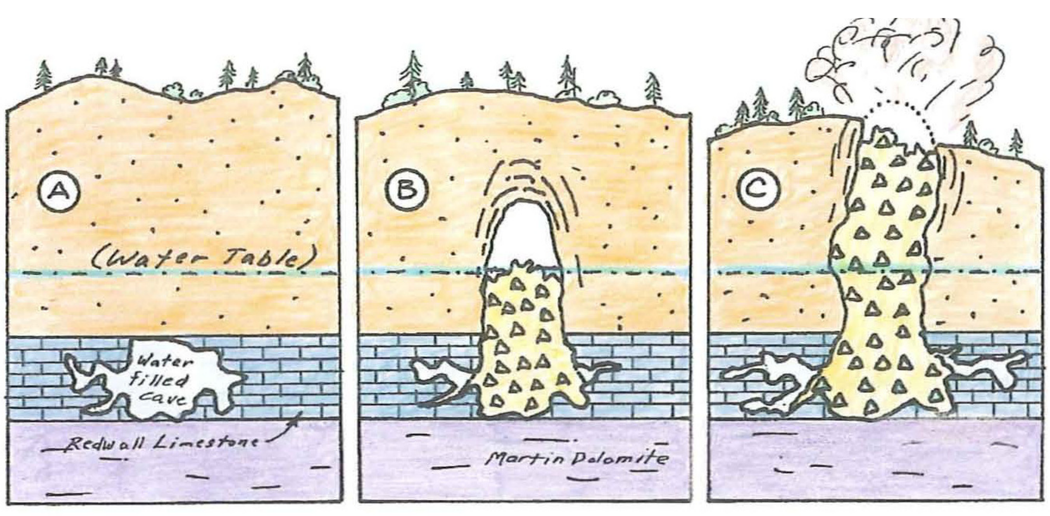


Figure 8. Schematic cross-sections illustrating how a sinkhole may develop. Part A shows a limestone cave beneath a cover of sandstone, much the same as seen at the Devils Kitchen area. Part B shows that as the cave got too large to support the roof rocks it began to cave in the overlying strata. The broken rock which occupies the enlarging cavity is called breccia. Part C show how the upward-stoping collapse finally breaches through the surface.

HAZARDS AT THE DEVILS KITCHEN SINKHOLE

The Devils Kitchen sinkhole was formed catastrophically and will continue to enlarge over geologic time. Man's brief occupancy of the area has been too short to fully appreciate the scope of these highly unpredictable developments. Figure 7 attempts to illustrate the potential risk areas at the sinkhole.

Certain edges of the Devils Kitchen sinkhole are at greater risk of collapse while others are deemed "relatively" safe. It should be emphasized, however, that no degree of certainty exists at this site. The area should be kept under investigation over time and safety precautions should be strictly adhered to. The present policy of driving jeeps on tours along the southern access road and viewing from the southwestern comer of the sinkhole is considered by the writer to be about as safe as any other human activity. The obvious danger point is in the extreme south wall where many people walk unknowingly onto a severe overhang. As long as this overhang is pinned-in by the rock buttresses on the west wall (marked in red and orange, the yellow area should remain somewhat locked in place. If the areas shown in red and orange collapse at some time in the near future, as here predicted, the entire situation should be re-evaluated.

CALCULATION OF THE SIZE OF THE COLLAPSED CAVE SYSTEM

A cursory examination of the surface map, longitudinal section and cross sections indicate that a subsurface column of breccia 200 feet in diameter would extend downward for 660 feet to the top of the former Redwall Limestone cave. From sinkhole surface to the top of the Redwall this would represent a cylinder of rock with a volume of 20,735,000 cubic feet. Assuming the entire Redwall Limestone strata was dissolved over its 180 foot height this would have allowed for a 200 foot diameter cave opening to have been present prior to the collapse. Since broken rock occupies a greater volume than solid rock (approximately 1.3 times as much volume) this means that as the collapse progressed [expanding] it probably came close to equilibrium at the present ground surface when about 27,000,000 cubic feet of breccia now occupy the old cave chamber [with] the column stretching up to the surface. These calculations show that the present sinkhole can be explained by collapse into a cave in the Redwall that was probably about 180 feet high and 200 feet in diameter. These hidden cave networks probably rival those known from the Mammoth Cave National Park of Kentucky.

RECOMMENDATIONS

Because of the very long periods of time between significant collapses at the Devils Kitchen sinkhole I see no reason to curtail visitations to the site. Additional warning signs should be erected in addition to that already present. In particular, a specific warning sign should be placed at the edge of the unstable block marked in red (dark cross-hatching) on the hazard map (Fig. 7). Also, warning signs on the west side and eastern ends of the north wall should warn hikers to stay back away from the edge.

The present study shows the sinkhole conditions at a specific point in time and this will serve as an important benchmark for future studies. I recommend that records be kept as to future cave-ins at the site by the U.S.F.S. personnel. This information would permit me, or future geologists, to add to the data base on what has occurred at the site over time. In addition, I will gladly take the time to show interested parties what can be observed at sinkhole sites and what the inherent dangers are at those places. I am planning to document the conditions at the Devils Dining Room as well in a future study.

The surface map (Fig. 3) shows a large number of arcuate fracture zones (shown in green) along the southwestern portion of the sinkhole. As indicated on the hazard map (Fig. 7) I believe that over a long enough period of time the sinkhole may expand in this direction. There is no way of ascertaining how long this might take. It could progress by incremental steps, it could collapse in a catastrophic mode, or it might remain much as it now is for several centuries. Monitoring of this area by visitors and professionals alike is necessary over [the] long term to see if any danger signs are developing. The key thing is to be aware of is expanding [or] new open fracture development. These may be warnings of imminent collapse.

Author's Note

The following document was originally typed and is now presented herein as a Microsoft Word Document that has been re-drafted in October 2009.

For purposes of clarification of grammatical errors and to help the dialogue read more clearly, the writer has added words in [brackets].

Since the time the original report was written in September 1990, several refinements have been made to rock formation terminology, thickness of rock formations, new mapping of additional sinkholes in the area, and other geological features in the greater Sedona area. A new document is currently being written that encompasses all seven of the known sinkholes and that document will include a more thorough study of sinkhole development and knowledge of its relationship to subsurface groundwater flow. It will bear the title of: The Sedona Sinkholes, Their Origin and Relationship to Groundwater Flow, Coconino and Yavapai Counties, Arizona.

In the following recast of the original text the writer has added some geological clarifications in a place where new information has come to light. Those clarifications are denoted with an asterisk (*) and with notes shown in italics.

Paul A. Lindberg (Consulting Geologist)
Arizona Registered Geologist Certificate #22226
American Institute of Professional Geologists, Certificate #6344
Sedona, Arizona
October 20, 2009

Appendix I

Selected Images of Devils Kitchen Sinkhole

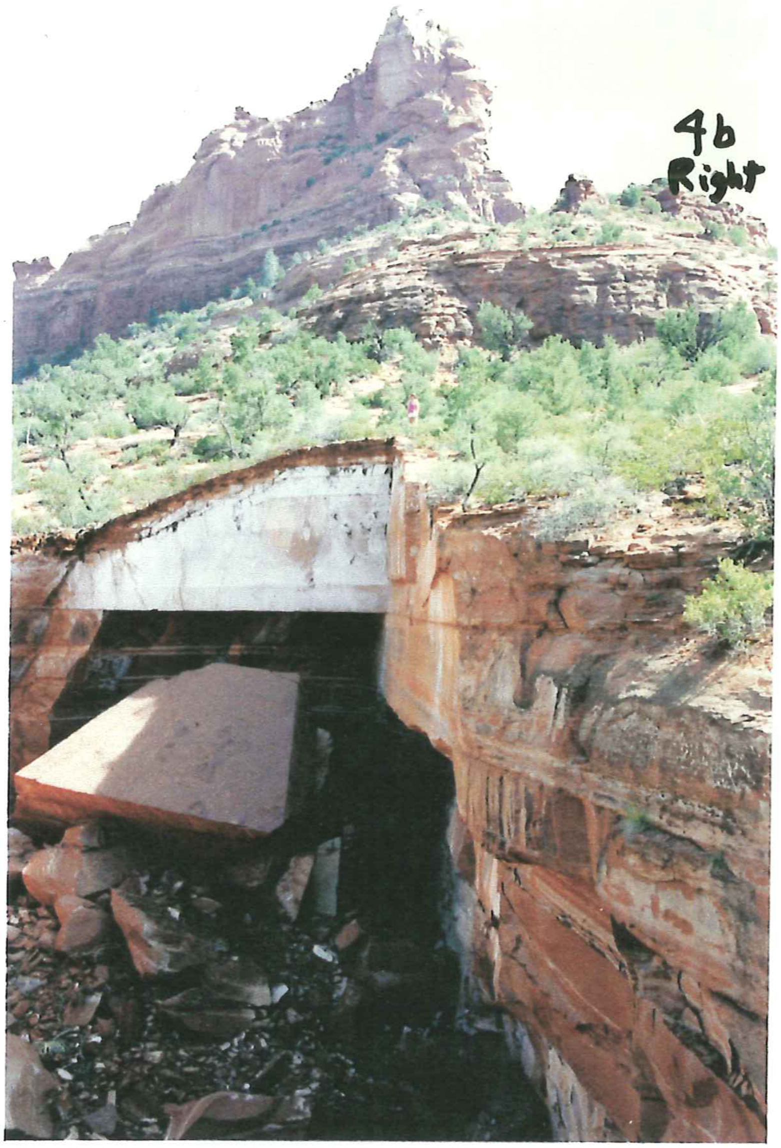


Photo #4; Looking to north-northeast along eastern edge of Devils Kitchen sinkhole. Lighter, caliche-coated NW and NNE joints show position of pre-late 1989 collapse of northern third of sinkhole. Note figure in photo at upper end of sinkhole.

Photo #1, above; View looking SSE into undercut southern edge of Devils Kitchen sinkhole.
Photo #5, below, View to north of late 1989 collapse rubble of Devils Kitchen. September 1990.

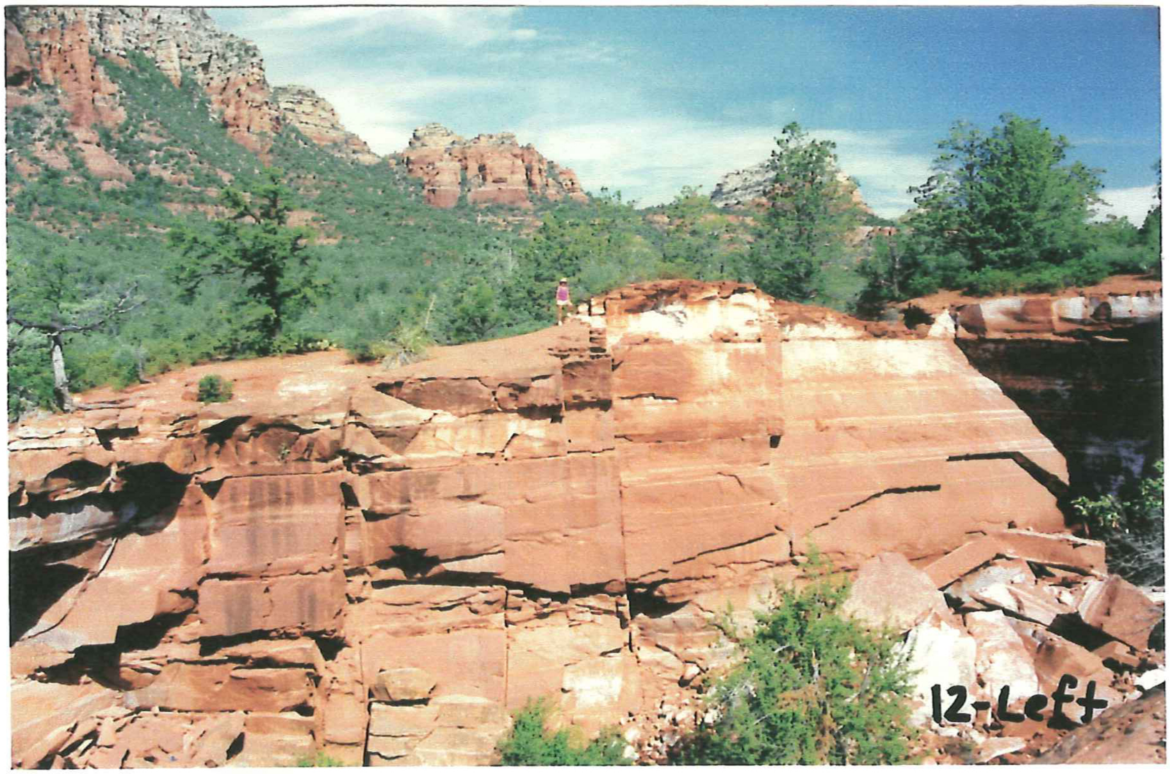
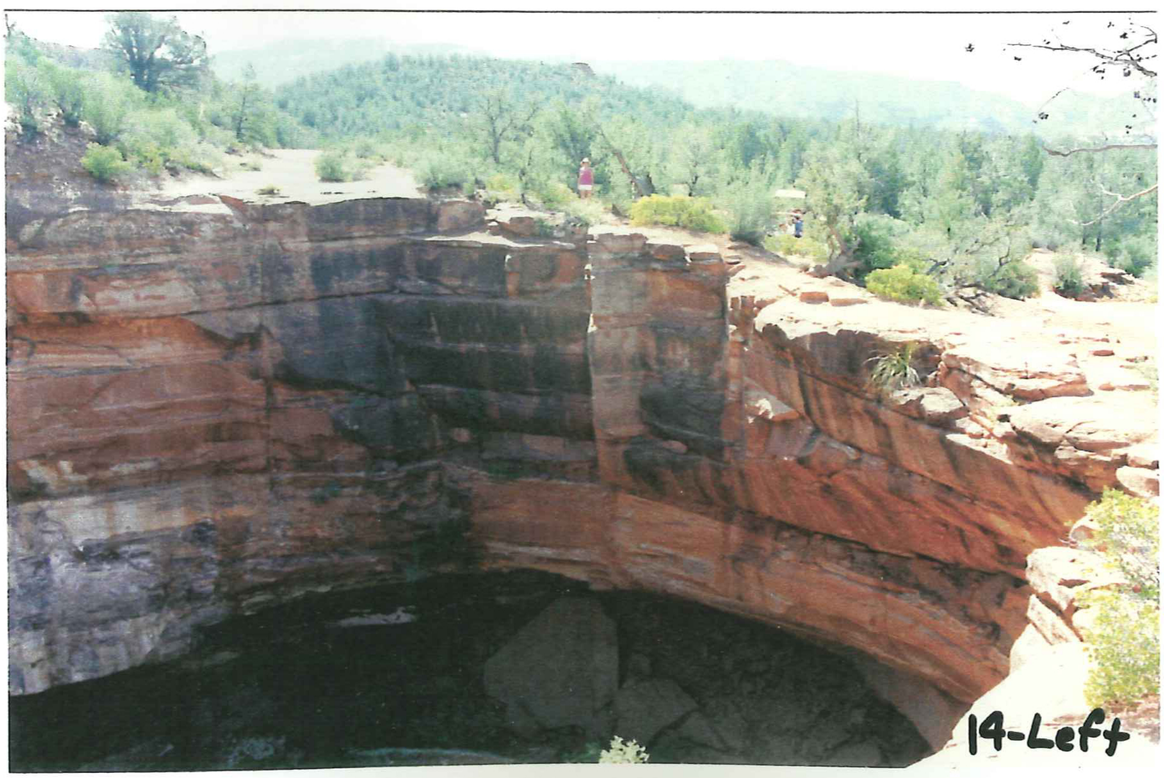


Photo #12, above; View to northwest across sinkhole showing regional vertical joints.
Photo #14, below; View of SE sinkhole corner showing Hermit formation undercut.



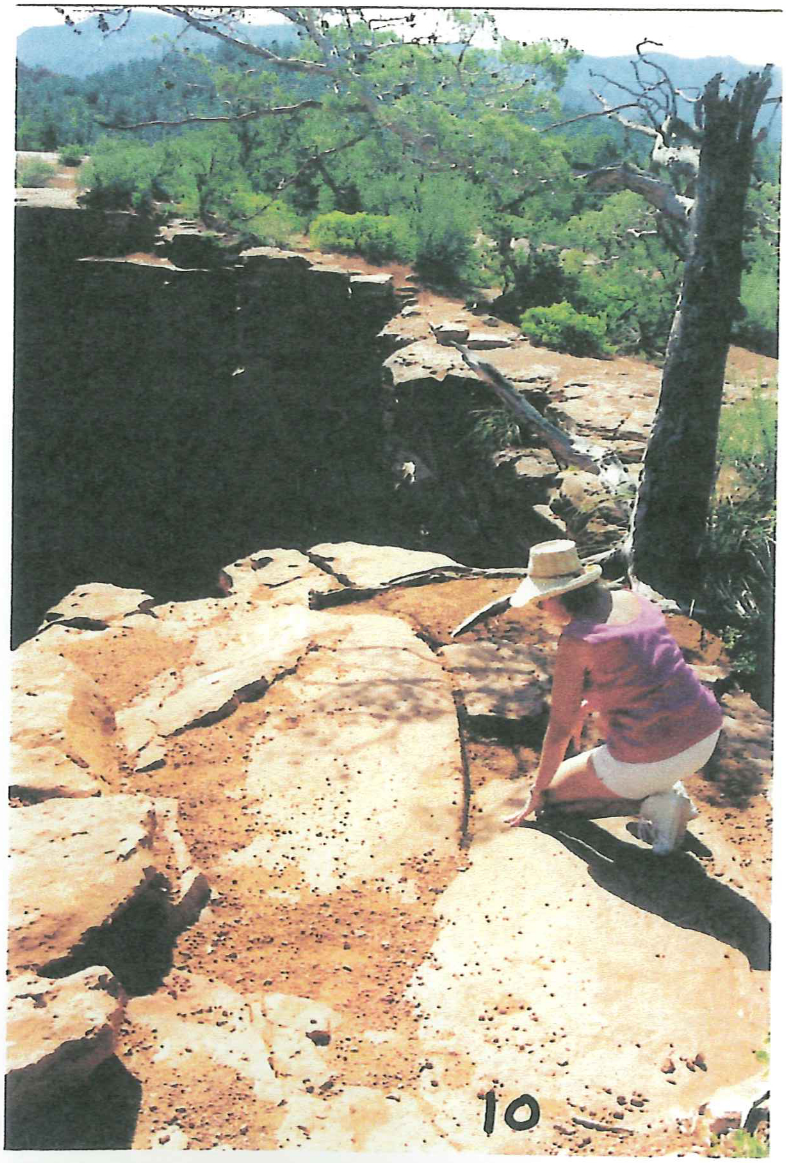


Photo #10; View across the south end of Devils Kitchen sinkhole from its southwestern corner. Localized arcuate fractures in that area dip outward from the sinkhole and they have been superimposed across the near vertical regional rock joint pattern. Several of these curving fractures near the SW corner indicate that the location has already been stressed and broken but not yet collapsed. Arcuate fractures show up on the geologic map as green lines (fig. 3). See Photo #8 on the next page to see where the above photo was taken.

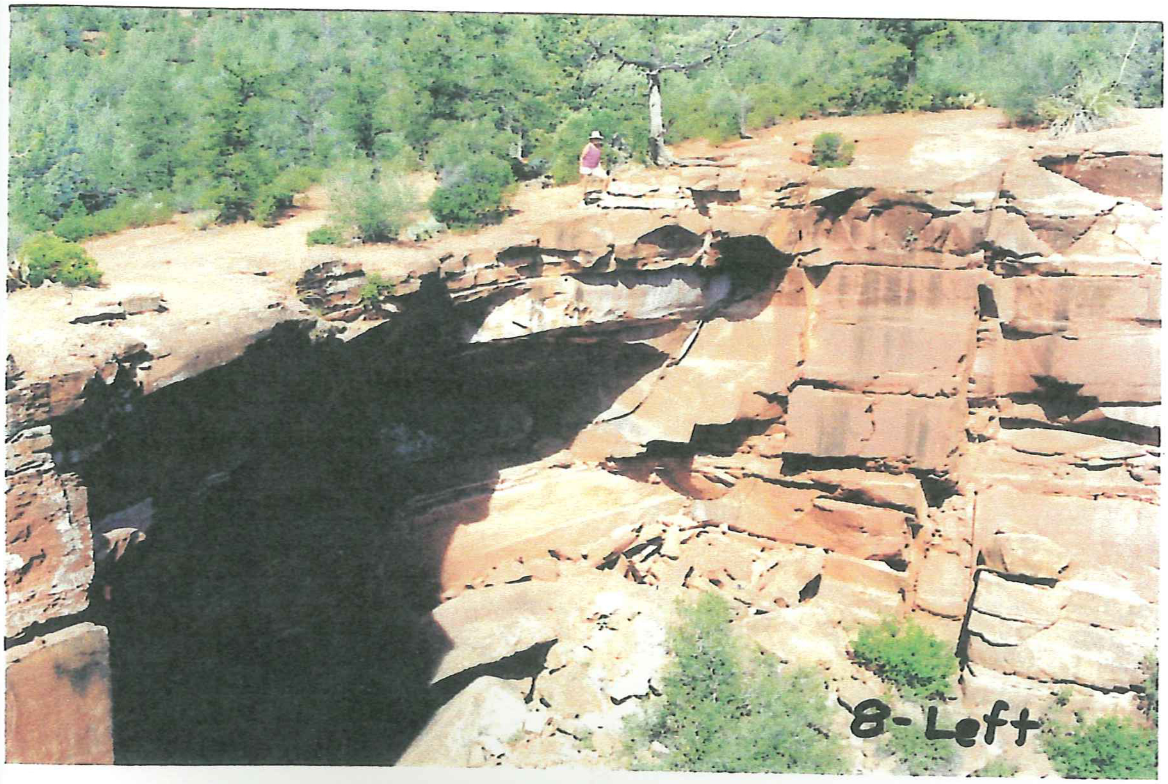


Photo #8; View toward the southwestern corner of Devils Kitchen sinkhole from the opposite wall. The juniper tree near the figure is the same tree as shown in Photo #10 on the previous page. Numerous arcuate rock fractures, open fractures that have been widening in that area in recent years, and a severe undercut indicate that this area is highly unstable and could collapse in the near future. As shown on the geologic map (fig. 3) and on the hazard map (fig. 7), the sinkhole is predicted to enlarge by stages of collapse that will increase the size of the opening toward the southwest. Future catastrophic collapse could reach as far as the jeep access road.