CONTRIBUTED REPORT CR-10-C

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SEDONA SINKHOLES AND GROUNDWATER FLOW: THE GEOLOGIC HISTORY OF THEIR EVOLUTION

COCONINO AND YAVAPAI COUNTIES, ARIZONA

Paul A. Lindberg

May 2010

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ABSTRACT

Seven sinkholes surround the city of Sedona in Coconino and Yavapai Counties, Arizona. They occur in surface bedrock of Permian age Esplanade Sandstone, Hermit formation, and Schnebly Hill Sandstone, but the causative source is from the collapse of subsurface water-filled caves in Mississippian Redwall Limestone that underlies those formations. The original Mississippian-age Redwall karst surface has undergone two additional phases of dissolution enlargement in later geologic time. The first occurred after the Laramide uplift of the Mogollon Highlands when northeast flowing streams penetrated the exposed Redwall Limestone erosion surface, and the second took place following the generation of the Verde graben ~10 million years ago when regional drainage reversal took place. Pre-graben Miocene basalt lava flows that overlie eroded Paleozoic strata are present on either side of, and faulted within, the Verde graben closed depression. Post-graben erosion generated the Mogollon Rim escarpment in the northern portion of the Verde Valley and allowed surface streams to erode the broad Dry Creek and Margs Draw valleys. Oak Creek fault, and the erosion of its canyon, is much younger than the faulting that generated the Verde graben. Over time water flow through the Sedona area evolved from surface flow to dominantly groundwater flow, mainly due to leakage through abundant northwest-southeast oriented rock joints and permeable fault zones into underlying cavernous Redwall Limestone. USGS oxygen isotope studies show that water recharge entering the northeastern part of the Upper Verde watershed, and passing beneath the greater Sedona area, originated high on the Colorado Plateau above 6900 feet before discharging at a rate of ~15 millions of gallons per day at artesian springs in the Page Springs area to the southwest of Sedona. Dissolution caves in the underlying Redwall Limestone have now enlarged to the point where their sandstone roof rocks have collapsed into limestone caves over the past several thousand years. Devils Kitchen sinkhole has historic records of collapse in the 1880s, 1989 and 1995, and it will continue to collapse in future years. Six additional sinkholes are in various stages of collapse from modern time and possibly to the end of the last Ice Age. While the danger of future collapse is probably minimal to humans, unregulated septic leakage into hidden sinkhole breccias within the town limits could contaminate groundwater being tapped for municipal use or the contamination of the Page Springs outflow. The report contains geologic maps, cross sections, photographs and individual features of the sinkholes as of the end of 2009.

Key Words: Redwall Limestone, Laramide Orogeny, Mogollon Highlands, exotic gravels, Miocene basalts, Verde graben, drainage reversal, limestone dissolution, groundwater, modified karst topography, rock joints, double age of faulting, sinkhole genesis, groundwater contamination

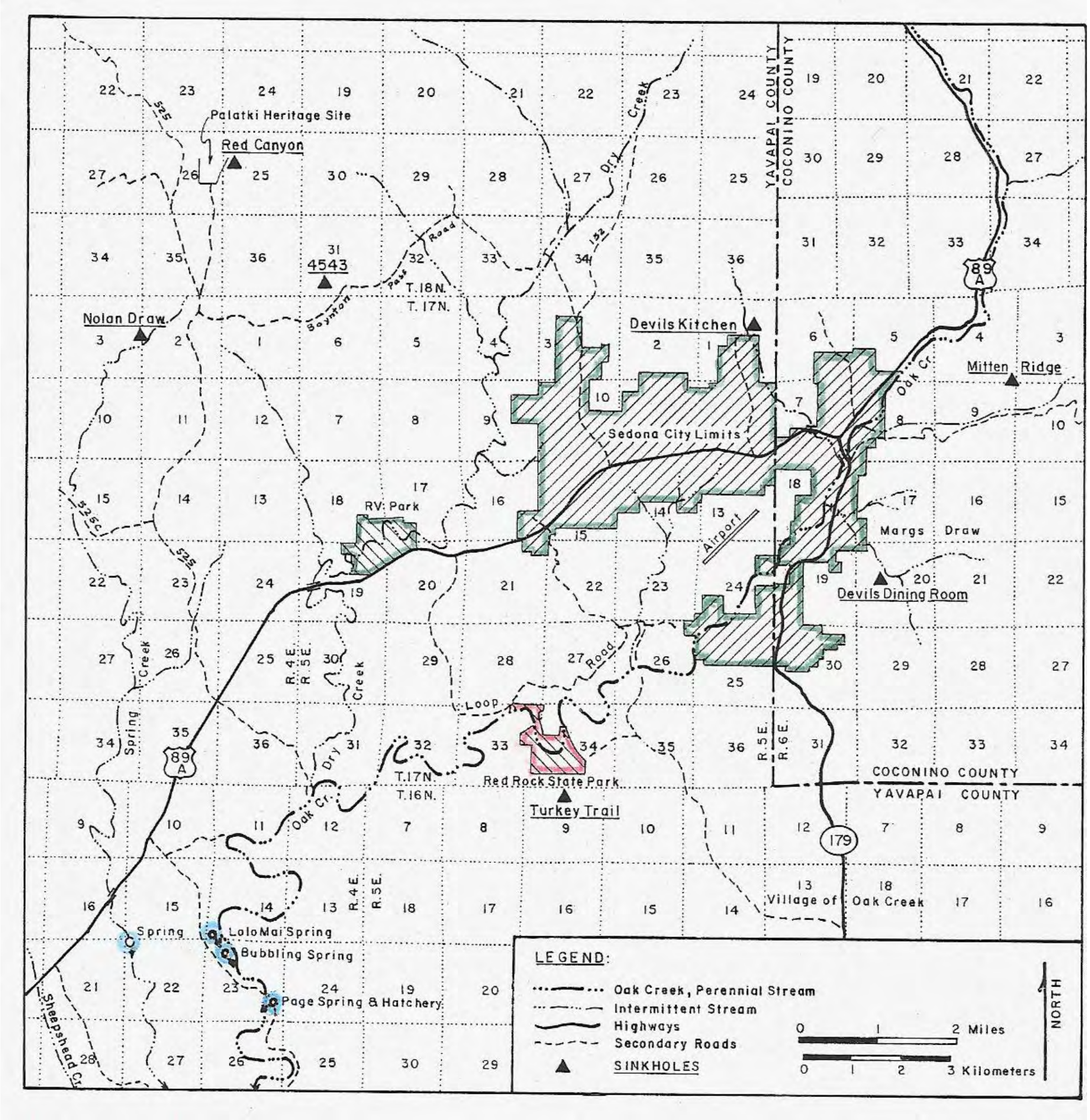


Figure 1. Location map of Sedona sinkholes. The seven known sinkholes are described in the text in clockwise order, starting with the Devils Kitchen sinkhole just north of the city limits in Yavapai County. Red Canyon sinkhole is by far the largest of the collapse features and the miniscule 4543 feature is probably in its formative stages of collapse.

PURPOSE OF REPORT

At least seven sinkholes surround the city limits of Sedona, Arizona (fig. 1). They occur at bedrock locations but additional sites may remain hidden beneath alluvial cover, especially near streambeds and dry washes. Despite their recognition as local curiosities, there has been no dedicated geologic study as to why these sinkholes have formed or their relationship to subsurface groundwater flow. The purpose of this report, therefore, is to clarify that relationship and describe their features. In order to understand the geological framework within which the sinkholes have formed, it is necessary to present a synopsis of the region's complex geologic history. Included in this report are maps, cross sections and photographs showing the status of sinkholes as of late 2009 along with a model for their genesis. Sinkholes can present collapse hazards and the potential for groundwater contamination, so they are not trivial features of the landscape. It is hoped that this information will allow the public and administrative authorities to become better acquainted with these local phenomena.

RESULTS OF INVESTIGATION

This study provides the following information:

a) Historic records of Devils Kitchen sinkhole collapse from 1880s to 1995.
b) A synopsis of regional and local geologic factors that have affected groundwater flow and sinkhole development.
c) Method of sinkhole investigation.
d) A description of each of the sinkholes with geologic maps, sections and photos.
e) A model for groundwater evolution through Sedona over the past ~10 million years.
f) Estimates as to the size of the Redwall Limestone cave system underlying Sedona.
g) Prediction of sinkhole hazards and potential groundwater contamination.

LOCAL PHYSIOGRAPHIC SETTING

In 1988 Sedona was incorporated as a community that straddles county boundaries. The original part of town, referred to as Uptown Sedona, is located in Coconino County and West Sedona is located in Yavapai County (fig. 1). The town lies at the base of the Mogollon Rim erosional escarpment at an elevation of ~4300-4500 feet (~1310-1370 m). To the north and east are competent flat-lying, cliff-forming Paleozoic sedimentary rocks capped by Miocene basalt lava flows. The broad bench upon which most of Sedona's infrastructure is built was formed by erosion of relatively incompetent Permian age Hermit formation, a somewhat shaly siltstone/sandstone (fig. 2). Over time, and exposed to the elements, Hermit formation decrepitates and is more susceptible to erosion than the more resistant rocks in the cliffs above town. Headward erosion into the Colorado Plateau from the eastern fault scarps of the Verde graben has created the serrated Mogollon Rim erosional escarpment only within the past 10 million years. Below the erosional bench are competent sedimentary rocks of Lower Paleozoic age, including Esplanade Sandstone and the Redwall Limestone that lies completely hidden several hundred feet under the surface of Sedona (fig. 2). Beneath the Redwall lies Devonian-age Martin Dolomite, a less soluble carbonate rock, identical to outcrops exposed in fault blocks above and below the town of Jerome across the Verde Valley to the southwest.

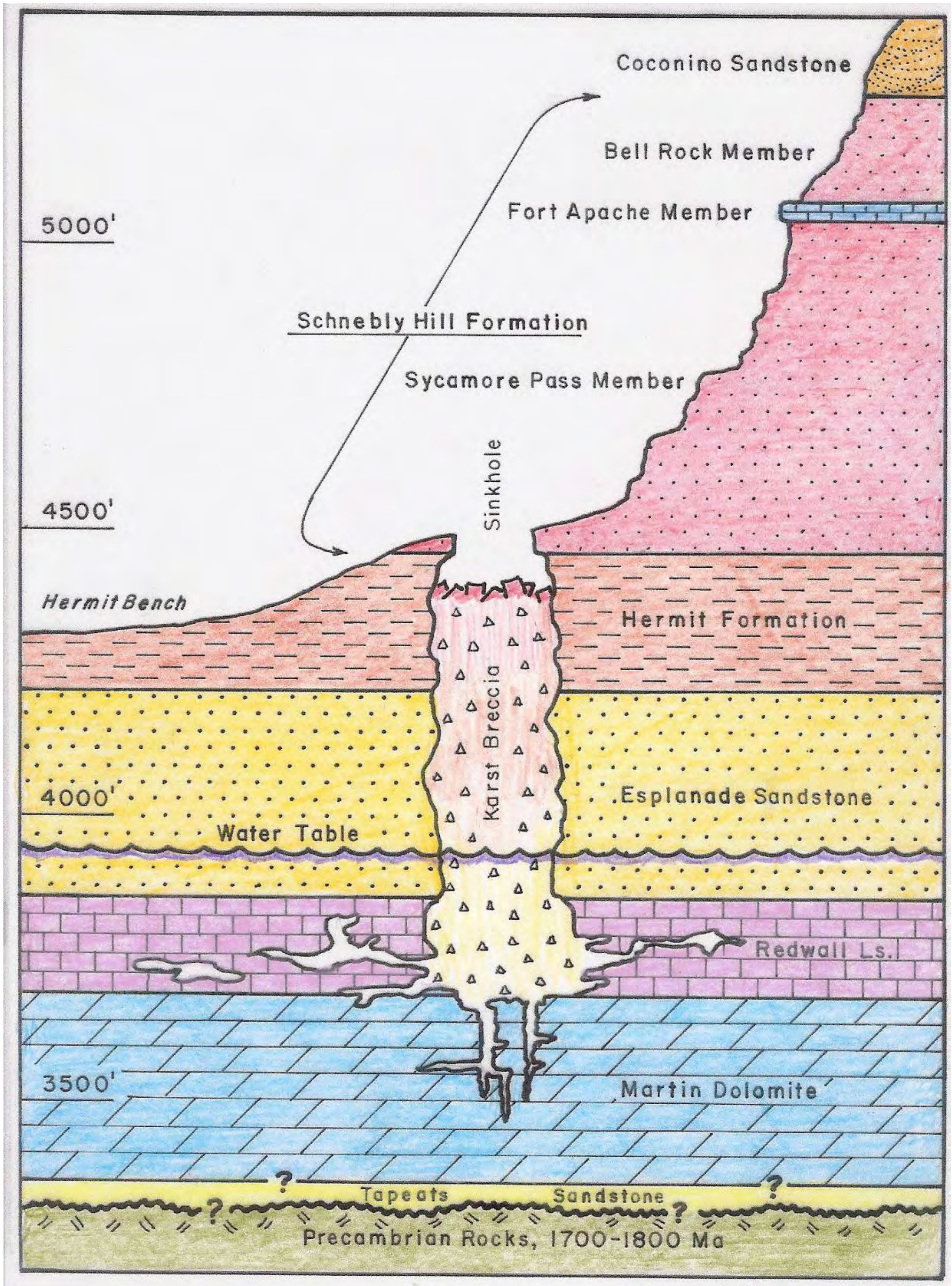


Figure 2. Section showing genesis of a Devils Kitchen type sinkhole. Stratigraphy for the Sedona area is shown in this section. The broad erosional bench that has been cut into the Hermit formation at left is the main platform upon which Sedona's infrastructure is built.

At further depth below Sedona are lower Paleozoic sedimentary strata that unconformably overlie crystalline Precambrian basement rocks, similar to exposures at Jerome and Prescott to the southwest and the depths of the Grand Canyon to the north. This entire succession of rocks, ranging in age from 1800 to 250 million years ago (Ma), extends to the north-northwest for ~100 miles (~160 km) beneath the Colorado Plateau where the strata are again exposed in the walls of Grand Canyon.

Verde Valley lies to the immediate southwest of Sedona. It is not a typical valley that was cut by stream erosion. It is a rift valley called a graben (pronounced “grah–bin”). The graben was formed by basin and range crustal extension that had migrated eastward into the Sedona area approximately 10 Ma (fig. 9c). Hickey and House Mountain basalt lava flows, found on either side of the Verde Valley, are pre-graben in age and are found at many different elevations within graben fault blocks (Lindberg, 1983 & 1986). Those lava flows were not deposited inside an older, river-carved Verde Valley as some have proposed (Ranney, 1988, 1989 & 1993) but have been faulted into their present position.

Post-graben basalt lavas, on the other hand, of the “Ramp” type that underlie Interstate-17 from Flagstaff to Camp Verde and Hackberry volcanic rocks further south, have been deposited within the partially eroded graben margins (Elston and Young, 1991; Holm and Cloud, 1990; Holm, 2001). The Verde graben was once a closed drainage depression that is now filled with unconsolidated Verde lake beds and gravels to depths in excess of 2000 feet (>610 m) (fig. 9d). Further west is the Mingus/Woodchute Mountain horst, a high standing remnant of the Colorado Plateau that was left behind as the Chino graben to the west and the Verde graben to the east dropped many thousands of feet during basin and range crustal extension ~10 Ma (fig. 9c; DeWitt, et al., 2008). Only in the last few million years has the Verde River established a drainage that connects surface water flow from the Chino graben into the Verde graben. Today the Verde River flows south and in the last few million years has eroded the graben margins, post-Miocene volcanic rocks and uppermost layers of the thick Verde lake beds. The terrane lying between the present margin of the relatively stable Colorado Plateau and the fully broken up basin and range terrane to the west has been classified as a “Transition Zone” because it contains elements of both terranes (Pierce, 1985).

HISTORIC ACTIVITY AT DEVILS KITCHEN SINKHOLE

Devils Kitchen is the most active of the Sedona area sinkholes but it is not the largest. Located just north of the Sedona city limits, Devils Kitchen is a popular tourist attraction that is readily accessed by hiking trails and a jeep road (fig. 3). The single historic reference as to its origin is included in a compendium of recorded oral histories made by early pioneer families in the Sedona area (Those Early Days, 1968). That book contains a secondhand account by pioneer Albert E. Thompson who said “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 to see the new hole in the ground”. Weathered bedrock in the southeastern corner of Devils Kitchen suggests that a small opening probably existed prior to the reported “early 1880s” cave-in.

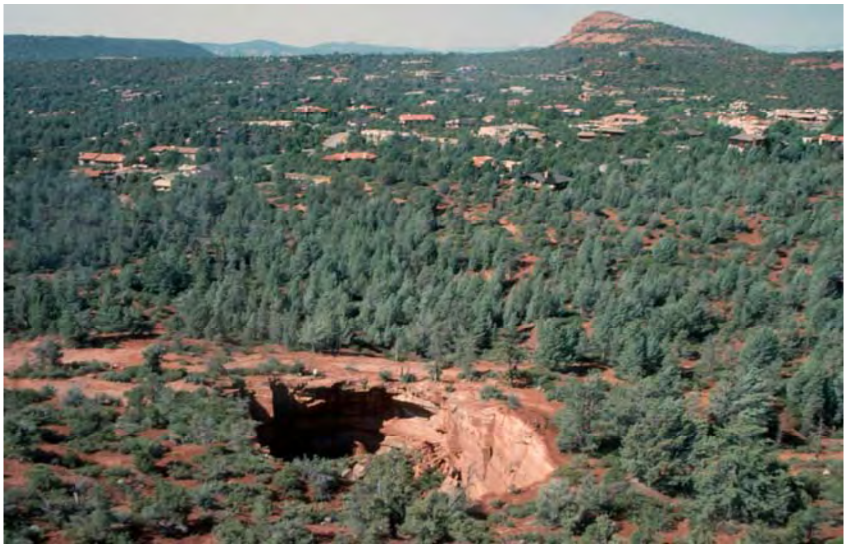


Figure 3. Devils Kitchen sinkhole viewed to southwest toward West Sedona. Note the person at the south end for scale. Photo taken in 1990.

Figure 4. Photo of Devils Kitchen sinkhole, October 1983. In 1989 this northern wall will collapse and the sinkhole would expand substantially. Note tree roots on north face, indicating that rock falls had taken place within previous decades.

Pioneer Albert Thompson went on to record, “All of the old timers agree that Devils’ Kitchen is west of *[Uptown]* Sedona up Soldiers Wash. I do not know who gave it the name of Devils’ Kitchen, but it was much later than the cave-in. Devils’ Dining Room is on the east side of Oak Creek not far from the Broken Arrow subdivision. Joe Lay, an old-timer and Sedona Westerners member, told me it was named by Frank Owenby, the first person to patent a homestead in Sedona. It was likely after Devils’ Kitchen had been named that he named it, else he would not have given it the name of Devils’ Dining Room”.

In 1983 the Devils Kitchen sinkhole was 90 feet (27 m) wide by an estimated 110 feet (~34 m) in a north-south direction (fig. 4). The northern wall still had a few tree roots hanging from it and patches of white caliche on joint faces, indicating that pre-1983 rockfalls had occurred within the decade or two before that time. In 1989 the northern portion of Devils Kitchen collapsed and was heard and felt by local residents who lived within Sedona city limits as close as 1000 feet (~300 m) away. One resident whose house was located ~2500 feet (~760 m) to the southwest of the collapse area heard what she first thought was a dynamite blast, but the noise and vibration lasted for perhaps a full minute before tapering off (Nancy Bihler, personal communication). As a result of the 1989 collapse the Devils Kitchen sinkhole had become substantially larger (fig. 5).

By the summer of 1990 the U.S. Forest Service was concerned for public safety and requested that the owners of Red Rock Jeep tours commission a geological study of the site to be made by a professional geologist. Up to that time jeeps regularly stopped directly over the deeply undercut southern edge of the sinkhole. The writer was contacted and he prepared a gratis report that was given to the jeep tour owners and U.S. Forest Service (Lindberg, 1990). That report contains a detailed geologic map, cross sections, an assessment of the enlarged sinkhole, and a prediction of future collapse hazard.

In the fall of 1995 a piece of the northern face fell off and landed behind the large rotated block shown in the 1990 study (fig. 6). Photographs taken in 1983, 1990, and after 1995, show the progression of collapse activity over a 12 year period (figs. 4-6). More recently, rock fall noise has been reported to the U.S. Forest Service but late 2009 examination by the writer has failed to reveal any major changes.

The 1990 study discovered severely fractured bedrock surrounding the southwestern corner of the sinkhole. One particular rock fracture on the west side has been widening over the past several decades and will eventually fail catastrophically (fig. 15). A re-write of the 1990 study has appeared as an on-line article of Arizona Geology, a publication of the Arizona Geological Survey (Lindberg, 2009). Recent newspaper articles also describe present day conditions at the Devils Kitchen sinkhole (Ayers, 2010; Maresh, 2010).

Figure 5. Devils Kitchen after the 1989 collapse. This 1990 photo shows the white coating of caliche on the north and east faces that was left behind on rock joint faces after the collapse. Note the figure at the top end of the sinkhole for scale.

Figure 6. Devils Kitchen sinkhole after 1995 rock fall. This 2009 photograph shows the large sandstone block at the north end of the sinkhole that rotated forward during the 1989 collapse. Another piece of the northern joint face just above it fell off the cliff in 1995 and landed behind the big slab (compare with fig. 5). In the twenty year interval since the 1989 collapse, weakly acidic rainwater has dissolved most of the thin white coating of caliche ($CaCO_3$) on the near vertical joint face. Geologic plan map (fig. 13) and cross sections (fig. 14) show the rock fall locations. Note the bell-shaped, downward enlarging rock fractures in the northwestern corner of the sinkhole. Arcuate fractures such as this are localized around sinkhole sites and have been superimposed upon the arrow-straight and nearly vertical northwest-trending rock joints.

LOCAL AND REGIONAL GEOLOGIC FRAMEWORK

Sedona Area Stratigraphy

The following list shows the stratigraphic succession of rock formations found along the Mogollon Rim near Sedona and adjacent Verde Valley (figs. 2 & 7). Age of rock units and geologic events are estimated in millions of years ago (Ma). Rock formation thicknesses are estimated and those affected by sinkhole collapse are denoted with an asterisk (*). Nomenclature is modified from published sources (Blakey, 1990).

<u>Cenozoic Era</u>

Quaternary alluvium, Pleistocene Epoch, 0-2.6 Ma, Variable thickness of unconsolidated alluvium (silt, sand, gravel)

Verde Lake Beds, 2.6-10 Ma during Neogene Period; Verde graben fill composed of thousands of feet of gravel, sand, silt, brackish water limestone, gypsum and salt

Post-Verde graben basalt lava flows and rhyolitic pyroclastics, Late Miocene to Pliocene Epoch of Neogene Period, 5.5-8 Ma; Contemporaneous with Verde Lake beds; Includes “Ramp basalts” and, further south, Hackberry bimodal volcanic rocks

------ *Verde graben formed by basin and range crustal extension ~10 Ma*

Pre-Verde graben basalt lava flows and dikes, Miocene Epoch of Neogene Period, 10-15 Ma; Includes Hickey basalt and House Mountain volcanic rocks

Rim Gravels/Beavertail Gravels, >12.8 Ma, Neogene and Paleogene Periods; Stream-borne conglomerate eroded from Precambrian and Paleozoic Mogollon Highland terrane to the southwest of Sedona; Contains Precambrian to Paleozoic rock clasts

------ *Unconformity*

------ *Laramide Uplift ~65-70 Ma raises Sedona/Jerome area rocks to current elevation*

------ *Unconformity*

<u>Paleozoic Era</u>

Kaibab Limestone, Permian Period, 251-299 Ma, >100 ft (>30 m)

Toroweap Formation & Coconino Sandstone, Dominated by dune sand, grading into limey beds near top of Toroweap; Permian Period, ~1000 feet (~300 m)

Sycamore Pass Member, Schnebly Hill formation, Permian Period, ~200 ft (~58 m)

Ft. Apache Member, Schnebly Hill fm. limestone, Permian Period, ~10 ft (~3 m)

***Bell Rock Member, Schnebly Hill formation**, Permian Period, ~600 ft (~180 m)

***Hermit formation**, Pennsylvanian/Permian Period, ~250 ft (~60 m)

***Esplanade Sandstone**, Pennsylvanian Period, ~290-318 Ma, ~350 feet (105 m)

***Redwall Limestone**, Mississippian Period, 318-359 Ma, ~200 ft (~60 m); Upper surface exposed to subaerial weathering and karst dissolution at end of period

***Martin Dolomite**, Devonian Period, 359-416 Ma, ~400 ft (~120 m)

------*Disconformity*

Chino Valley Marl, Cambrian Period, ~500 Ma, 22 feet thick (6.7 m) at Jerome

Tapeats Sandstone, Cambrian Period, ~525 Ma, Zero to ~100 feet thick (0-~30 m)

------*“Great Unconformity” of John Wesley Powell*

<u>Precambrian Eon</u>

Mesoproterozoic Era, Volcanic-dominated metamorphic “basement rocks”; Includes volcanogenic massive sulfide ore deposits of Yavapai County and granitic rocks.

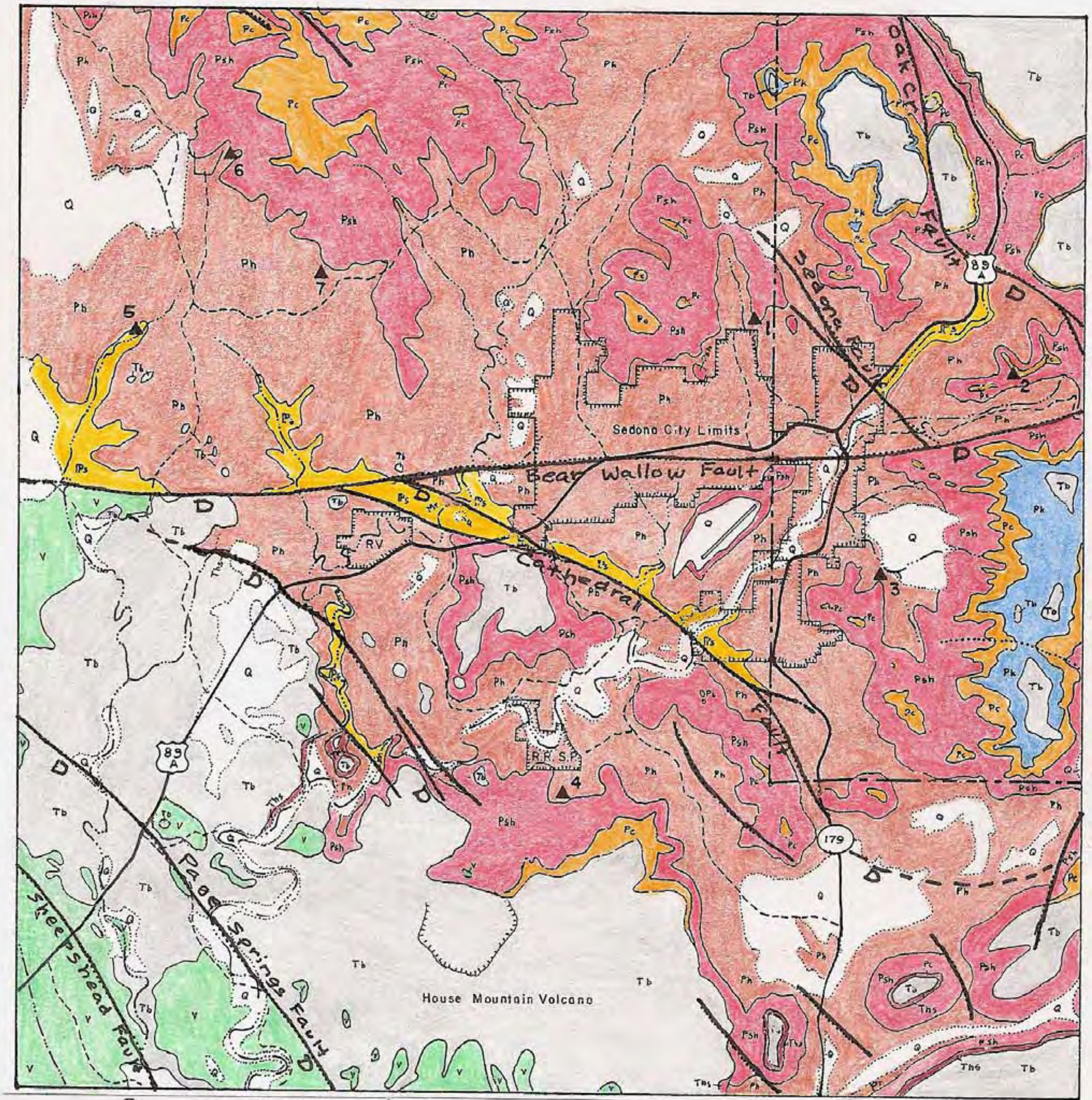


Figure7, Geologic Map of Sedona, Arizona Showing Sinkholes

Sinkholes ▲
1 Devils Kitchen
2 Mitten Ridge
3 Devils Dining Room
4 Turkey Trail
5 Nolan Draw
6 Red Canyon
7 4543

Q	Alluvium
V	Verde Lake Beds
Tb	Miocene Basalt
Tbs	Beavertail and Rim Gravels
Pk	Kaibab Limestone, Permian
Pc	Coconino-Toroweap Formations, Permian
Psh	Schnebly Hill Sandstone, Permian
Ph	Hermit Formation, Permian
IPs	Esplanade Sandstone, Penn.-Permian
Mr	Redwall Limestone, Mississippian

—D— Faults

0 1 2 Miles
0 1 2 3 Kilometers

P.A.L. January 2010

Sedona Area Geology

A recent geologic map of the Prescott National Forest and Upper Verde River watershed has been compiled by the USGS at a scale of 1:100,000 (DeWitt, et al., 2008). The map consolidates geologic mapping across the area and includes the Sedona area with contribution from a variety of sources (Levings, 1980, Levings and Owen-Joyce, 1980; Ranney, 1988; etc.). Figure 7 shows the major geologic features, stratigraphic units and major faults in the Sedona area that affect groundwater flow and sinkhole genesis. Many of the faults have experienced two distinct ages of oppositely-directed offsets.

Geologic Events Affecting Groundwater Flow and Sinkhole Genesis

A complete geologic history of the Sedona portion of the Verde watershed is too complex to be presented in this current synopsis. Based on the writer's experience and investigations since 1971, a more complete interpretation of the evolution of the Jerome-Verde Valley-Sedona-Mogollon Rim area is being drafted for future publication. What follows has been condensed to show the salient needs of this current paper.

This present geologic synthesis differs from that proposed by some investigators (Pierce, et al., 1979; Nations, et al., 1981; Pierce, 1984). The major difference of interpretation hinges on the timing and hydrological significance of when and how the Verde Valley was formed. From 1972 to 1976 the writer supervised an Anaconda Company mineral exploration drilling and geologic mapping of the western margin of the Verde Valley that demonstrated conclusive evidence that the Verde Valley was formed as a rift valley, or graben, about 10 Ma and not formed as a river-eroded valley into which Miocene basalt flows were deposited (fig. 8). Based on abundant drilling records and detailed structural mapping, the writer presented a model for the genesis of the Verde graben, the timing of two stages of Miocene mafic volcanism, and the effects of two ages of faulting on both sides of the rift valley that formed the modern Verde Valley that we know today (Lindberg, 1983, 1986a). An independent interpretation still maintains that 10-15 Ma House Mountain volcanic rocks on the eastern side of Verde Valley were emplaced within an older river-eroded Verde Valley (Ranney, 1988).

Figure 8 of this report shows a structural cross section of the central portion of the Verde graben that shows the evidence that the valley was formed by the faulting of the complete rock succession that existed ~10 Ma. The same graben fault evidence is found in the Sedona area. Further explanation of Figure 8 is presented under the title: **Basalt Lavas, Generation of Verde Graben, and Formation of the Mogollon Rim**.

Mississippian Karst Development and Subsequent Burial of Redwall Limestone

During the Mississippian Period Redwall Limestone was deposited in shallow tropical waters by accumulation of vast numbers of marine shells composed of calcium carbonate ($CaCO_3$). Following its deposition, ~350 Ma, sea level fell and exposed the upper surface of the limestone to terrestrial weathering. Grand Canyon provides the type section for observing the topmost layers of limestone that were affected (Beus and Martin, 1999; Beus and Morales, 2003a). Subaerial weathering of the limestone created a karst topography containing abundant solution caves, collapse breccias, and depressions that were later filled by Surprise Canyon formation (Billingsley and Beus, 1999).

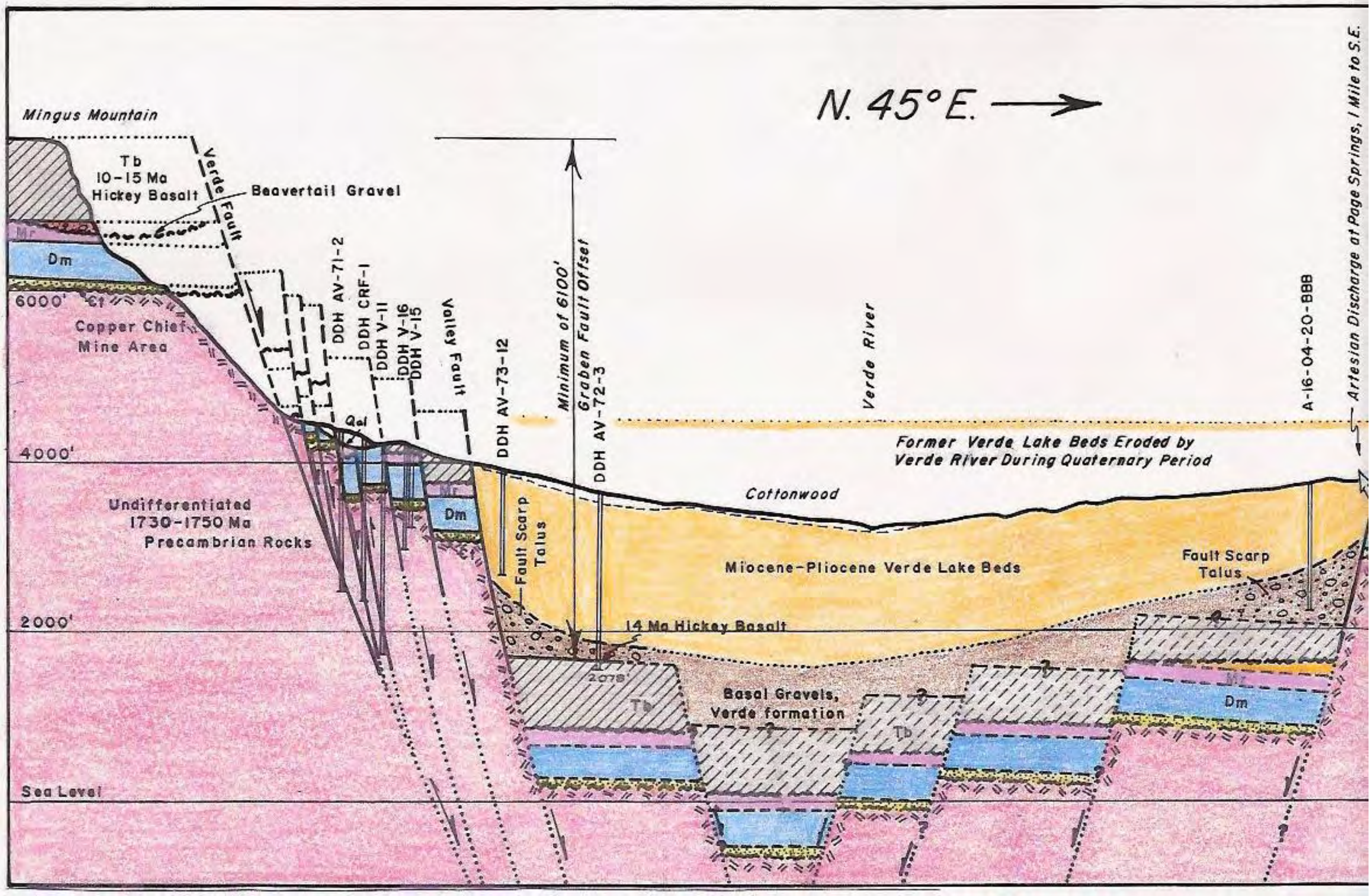
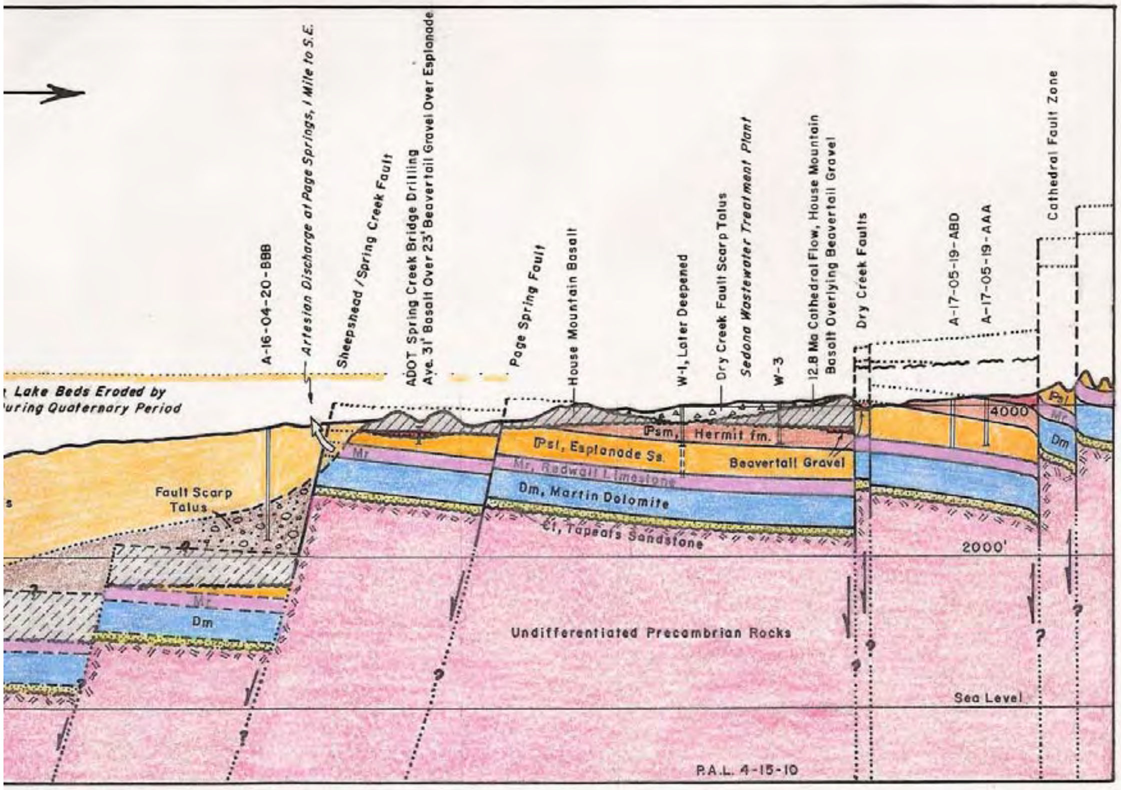


Figure 8. Structural section of Verde graben.

View is to the northwest with coverage from the Copper Chief mine area south of Jerome to the Dry Creek Bridge area on Highway 89A to the southwest of Sedona. Undifferentiated Precambrian basement rocks are shown in pink. On the western margin of the Verde Valley detailed surface mapping and seven 1973 and older mineral exploration drill holes show that the Verde fault system has dropped the western margin of the graben by a minimum of 6100 feet (1860 m). Even deeper displacement is projected further into the valley based on gravity surveys. Hickey Basalt was penetrated in Hole AV-73-12 and has been recently age dated at 14 Ma (Ed Dewitt, USGS, personal communication).

Similar graben faults and drill hole information on the Sedona margin of the Verde graben to the northeast show similar displacement. The Bear Wallow, Dry Creek, Page Springs and Sheepshead faults offset 12.8 Ma Cathedral basalt of House Mountain-age, including underlying Beavertail Gravels and all older stratigraphy. Mapping and drill hole evidence shows conclusive proof that the Verde graben is a closed structural basin and not a river-carved valley. The Mogollon Rim escarpment was formed by retreat into the Colorado Plateau from erosion of the Dry Creek and nearby graben fault scarps.

Miocene-Pliocene Verde formation gravels and lake beds fill the Verde graben. During the Quaternary Period the Verde River developed as a south flowing river that has eroded the topmost layers of the Verde formation to its present elevation.



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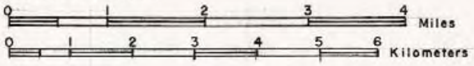

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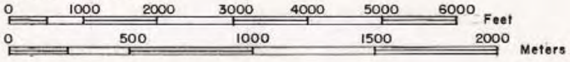

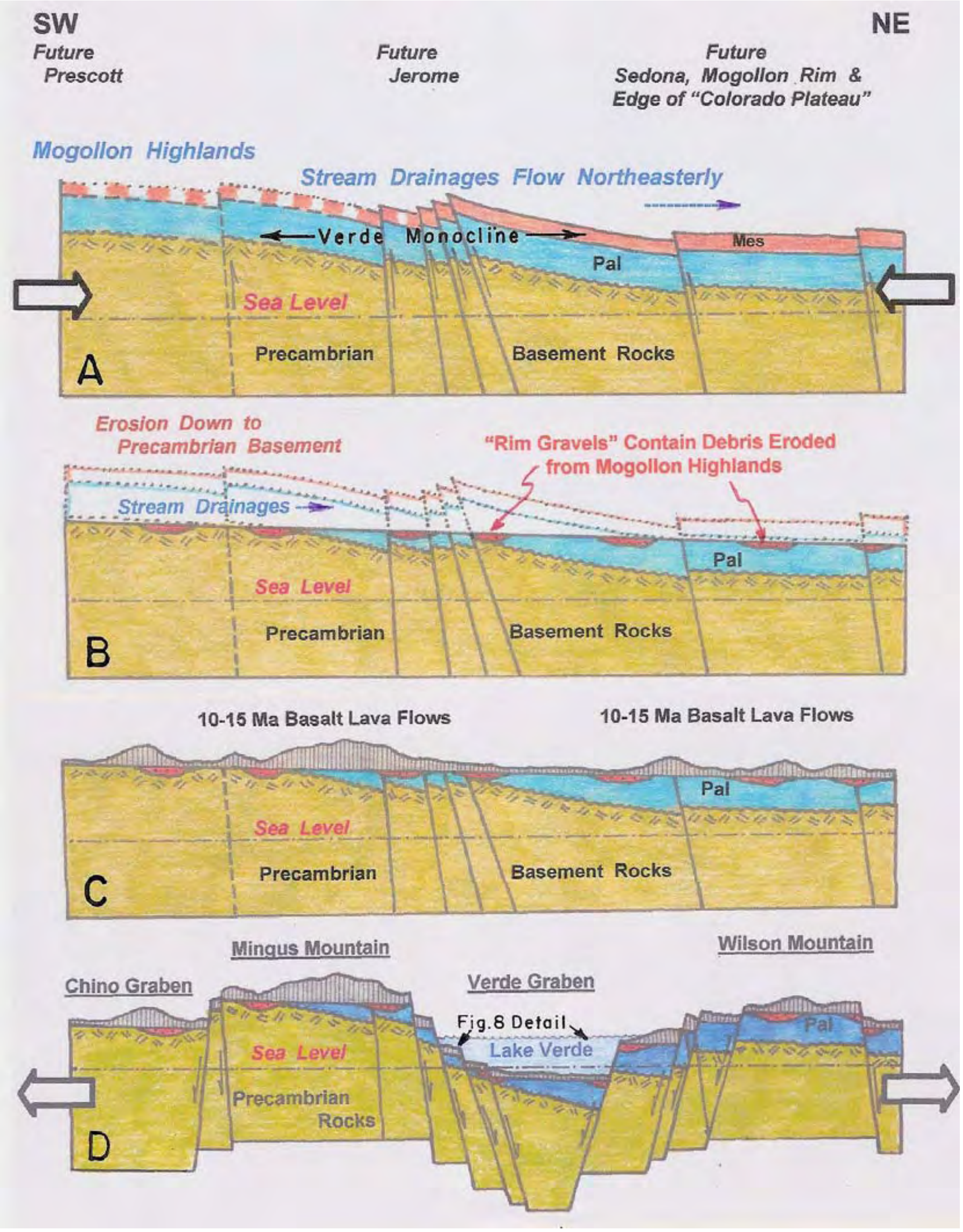

Figure 9. Cross sections, Mingus Mountain to Oak Creek Canyon showing evolution of Verde graben. **A,** Laramide uplift generates the Mogollon Highlands accompanied by high-angle faults formed under compression. Drainage is to northeast across the Verde monocline at future site of Verde Valley. **B,** Erosion truncates Paleozoic sediments across the Verde monocline and leaves Beavertail and Rim Gravels behind. Northeast flowing groundwater enhances Redwall Limestone dissolution. **C,** 10-15 Ma Hickey Basalt and House Mountain Basalt buries exotic gravels. **D,** Basin and range crustal extension creates Verde graben and creates regional drainage reversal ~10 Ma. Water now flows into the closed depression from all sides. (Sketch sections from unpublished Lindberg 1980s-2000s research.)

Outcrops of the same Redwall Limestone karst features and time-stratigraphic equivalent of Surprise Canyon formation are also found in the Jerome and Clarkdale areas west of Sedona. Those locations show that Redwall Limestone karst is widespread throughout northern Arizona. The same Redwall karst features are also evident in water wells that penetrate the Sedona subsurface.

During the following Pennsylvanian/Permian Period, low gradient terrestrial river systems not far above sea level deposited iron oxide-stained Supai formation sand and silt onto the Redwall Limestone karst surface. Fine-grained Supai sediment filtered into the abundant dissolution cavities and open caves in the underlying limestone. Today, outcrops of the karstic Redwall Limestone can be observed in the Grand Canyon, Jerome, Clarkdale and upper Verde River areas. Its distinctive pinkish color is due to Permian silt infiltration into the dissolution voids in limestone collapse breccia. Un-dissolved Redwall Limestone, by contrast, is grey in color.

Not all the solution cavities and cave openings in Redwall Limestone were filled after burial by Supai silt infiltration. The topmost portion of Redwall Limestone remained riddled with unfilled solution cavities that would be reactivated in later geologic time and become the nucleus for the evolution of modern groundwater passageways that eventually grew into extensive cave systems at Grand Canyon and beneath Sedona.

Laramide Uplift, Faulting, Erosion, and Deposition of Exotic Gravels

A second phase of Redwall Limestone dissolution is inferred to have taken place during the latter part of a prolonged period of erosion that followed the Laramide orogeny. Beginning 65-70 Ma, a large area of central Arizona was uplifted several miles during the formation of the Mogollon Highlands that stretched from northwest of Prescott to beyond Payson to the southeast (Blakey and Ranney, 2008). As a result, the Prescott-Payson area was uplifted several thousand feet higher than the present day elevation of Flagstaff on the Colorado Plateau. Regional drainage from the highlands has long been recognized by geologists with stream flow directed to the northeast over a period of many millions of years. A segment of that Laramide uplift includes the Verde monocline, as defined in this paper, whose faulted remnants are preserved in outcrop from the west side of Sedona to the southern end of Mingus Mountain (figs. 9 & 10). The Verde monocline strikes northwest-southeast and dips at a low angle to the northeast and is now disrupted into multiple fault blocks located throughout the northern Verde Valley area (fig. 9d).

Compressive forces associated with the Laramide orogeny generated numerous high-angle reverse faults in the Jerome, Sedona, Oak Creek and Grand Canyon areas (fig. 9a; Beus and Morales, 2003b; Lindberg, 1983, 1986a, 1986b, 1989). In Sedona and Oak Creek Canyon the Bear Wallow, Cathedral and Oak Creek faults show evidence of Laramide-age high-angle reverse offsets. Outcrops adjacent to those faults display sharply upturned sedimentary strata as a result of compressive forces (fig. 11). By 14-15 million years ago the Phanerozoic sedimentary rocks that once capped the Mogollon Highlands in the Prescott region had been eroded away, exposing Precambrian basement rocks. Stream erosion removed the Paleozoic sedimentary formations across the Verde monocline and left behind a wedge-shaped segment of Paleozoic age sedimentary rocks between the future sites of Mingus Mountain and Sedona (figs. 9a & 9b).

Figure 10. View of faulted remnant of Verde monocline. The Highway 89A roadcut near Sedona High School exposes tilted beds close to the Esplanade-Hermit formation contact. Exposed Precambrian and Phanerozoic rocks on Mingus Mountain and Jerome are visible to the southwest across the Verde Valley.

Figure 11. Folded Schnebly Hill Sandstone in Oak Creek Canyon. At creek level below the Halfway Picnic area, a Laramide-age compressional fold has forced the east side up along the ancestral high-angle reverse phase of the Oak Creek fault.

During the Neogene Period Redwall Limestone was exposed in a broad northwest-southeast erosional window cut into the tilted Paleozoic sedimentary succession within the Verde monocline (fig. 9b). Surface water would have been able to enter the Redwall Limestone karstic topography and flow downslope to the northeast into the depths of the Colorado Plateau for many millions of years. Mississippian-age solution cavities in the limestone would have been subjected to enhanced dissolution and new groundwater channelways would have been created along a northeast-directed subsurface flow path. In future time, after the Verde graben had formed ~10 Ma and regional drainage reversals had developed across the region, those northeast oriented limestone channels would have allowed future groundwater to pass beneath the Sedona area in a reversed southwestern flow direction toward an artesian outlet in the Page Springs area (see figs. 38-40).

The surface of the relatively subdued and deeply eroded post-Laramide peneplane contains numerous sinuous braided river channels that were cut into truncated Paleozoic strata by northeast flowing rivers (fig. 9b). From the Jerome area to the top of the Colorado Plateau on the east side of Oak Creek Canyon the base of the channels cuts into progressively younger Paleozoic strata (figs. 9b & 9c). Contained within those various channels are exotic conglomerates, variously classified as Beavertail and Rim Gravels, that contain Precambrian and lower Paleozoic pebbles and boulders derived from a provenance well to the southwest. In the Jerome area Precambrian granite cobbles contained within the succession of 10-15 Ma Hickey Basalt lava flows were intersected in one of the drill holes. That shows evidence that streams were still flowing to the northeast by about 12-13 Ma. All vestiges of Laramide age fault scarps had been eroded away by 12-15 Ma and no Mogollon Rim would have existed at that time.

Exotic gravels, especially those deposited during the Neogene Period, have been variously described as “Tertiary gravels of the Hickey formation” at Jerome (Anderson and Creasey, 1958), “distant gravel” (Holm, 2001), “Beavertail Gravel” (Peirce, et al., 1979) and other assorted “Rim Gravels” (fig. 9b). This paper considers that Beavertail Gravels, found throughout the northern portion of the Verde Valley area, are the time-stratigraphic equivalent of Rim Gravels found on the present day surface of the Colorado Plateau, and not clasts derived from an “ancestral Mogollon Rim” to the east (fig. 9).

At Beavertail Butte, located south of Village of Oak Creek, 14.3 Ma House Mountain basalt lies directly on Beavertail Gravel that contains an abundance of Redwall Limestone and Precambrian clasts that were derived from a source area to the southwest (Lindberg, 2006). Beneath that conglomerate is an older gravel member that contains locally derived angular clasts of Kaibab Limestone and Coconino Sandstone. Some investigators have used this as evidence that the debris came from an “ancestral Mogollon Rim” escarpment to the east (Ranney, 1993; Holm, et. a., 1998). The writer’s investigation concludes that the deeper gravel was derived from the eroded flank of the Verde monocline lying to the west, and not from a hypothetical ancestral Mogollon Rim lying to the east (figs. 9b-9d). Exposures of Beavertail and Rim Gravels are preserved in outcrop and drill holes over an elevation range of 4200 feet (1280 m) in post-10 Ma fault blocks on both sides of the Verde graben, and are presumed to exist even deeper in the core of the rift valley. Those conglomerates should not be confused with younger gravels that formed within the Verde Valley in post-Verde graben time.

Basalt Lavas, Generation of Verde Graben, and Formation of Mogollon Rim

Hickey Basalt lava was erupted from numerous vents in the Mingus Mountain, Jerome, and Clarkdale area from 10-15 Ma and they buried the “Tertiary gravels” of Anderson and Creasey (McKee and Anderson, 1971). Identical Miocene House Mountain basalt flows on the northeastern side of the Verde Valley overlie Beavertail Gravels that are nearly identical to time-stratigraphic equivalents of Rim Gravels found on the east side of Oak Creek Canyon. Miocene basalt flows on both sides of the Verde Valley are pre-Verde graben in age and should not be confused with post-graben basalt flows that were deposited within the partially eroded valley well after the graben had been formed (Lindberg, 1983 & 1986; Holm, et al., 1998; Holm, 2001).

House Mountain volcanic rocks, and its numerous satellitic volcanic vents and dikes in the Sedona and Margs Draw areas, began erupting basaltic lavas onto the post-Laramide peneplane on what is today the western side of the Verde Valley. Potassium-argon (K/Ar) age dates of House Mountain basalt lava flows reveal that the flows erupted between 12.0 and 14.5 Ma (Ranney, 1988; Lindberg, 2006). An enlarged 12.8 Ma mafic dike that cuts through Cathedral Rock is believed to be the source of the identical composition and age as the graben-faulted 12.8 Ma Cathedral basalt flow that underlies the Sedona Wastewater treatment Plant west of Sedona (fig. 12). Another mafic dike that cuts through the south wall of Devils Kitchen sinkhole has a K/Ar age date of 12.0 Ma, indicating that sinkhole development took place sometime after the dike had been intruded (fig. 23; Lindberg, 2006). At many locations in the Sedona area House Mountain basalt lava overlies Beavertail Gravel that contains a large component of Redwall Limestone and Precambrian cobbles that were derived from the southwest (figs 9a & 9b).

As shown in Figure 8, drill hole AV-72-3 on the western margin of the Verde graben demonstrated that a minimum of 6100 feet (1860 m) of fault offset had taken place relative to the stratigraphic counterparts on the summit and flanks of the Mingus Mountain horst to the west (fig. 9d). Recent re-sampling of un-weathered drill core from that hole by the writer and Ed DeWitt (USGS) revealed an age of 14 Ma for the Hickey Basalt intersected at the bottom of the hole. Gravity data shows that the deepest part of the graben lies even further to the east, roughly under the present day course of the Verde River by Cottonwood (Smith, 1984), supporting the graben model. Miocene lava flows found on either side of the valley have been faulted into their present elevation positions and were not deposited within an already eroded river valley as earlier postulated (Pierce, et al., 1979, Nations, et a., 1981, and Ranney, 1988).

Figure 9 contains four structural cross sections across the northern Verde Valley that shows the postulated evolution of the Verde graben. The section is oriented to the northeast from Mingus Mountain to Oak Creek Canyon and passes across the Verde Valley sub-parallel to Highway 89A and through the Sedona Wastewater Treatment Plant (Lindberg, unpublished 1980s-2000s research). The Verde graben has offset the entire stratigraphic section on both sides of the Verde Valley (fig. 9d). The basalt covered surface at the Sedona Wastewater Treatment Plant is considered herein to be a floundered segment of the Colorado Plateau, equivalent in time and age to the Miocene lava caps on the surface of the Colorado Plateau to the northeast and the surface of Mingus Mountain to the west (Lindberg, 1983, 1986).

On the eastern side of the Verde Valley the Spring Creek/Sheepshead faults, vital for allowing Page Springs artesian flow to vent from subsurface Redwall Limestone solution cave openings to the surface, has a graben displacement in excess of 1500 feet (460 m) (fig. 9d). One strand of the Dry Creek fault zone is exposed in a Highway 89A roadcut west of Sedona. A 400 foot (120 m) graben fault offset places 12.8 Ma House Mountain-age Cathedral basalt lava against Permian Esplanade Sandstone with its Beavertail Gravel caprock (fig. 12). Further east, several reactivated normal stage strands of the Cathedral and Bear Wallow faults add substantial amounts of graben fault displacement. The Sedona fault on the east side of Uptown Sedona marks the northeast limit of the Verde graben. Collectively, the exposed faults on the eastern margin of the Verde graben display large fault normal offsets, many of which were reactivated reverse faults (fig. 9d).

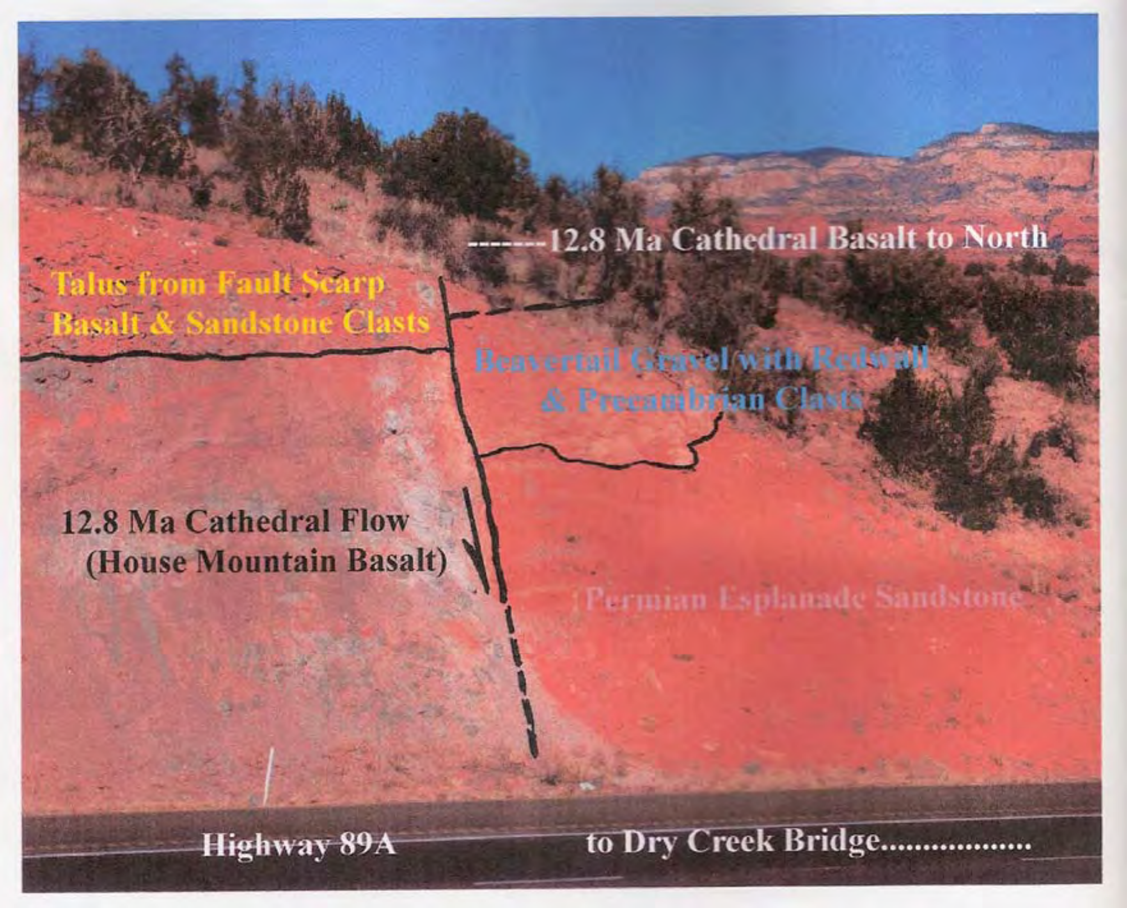

Figure 12. Highway 89A roadcut through Dry Creek fault. West of Dry Creek Bridge the Dry Creek fault displaces 12.8 Ma Cathedral Basalt lava and underlying rock strata against Permian age Esplanade Sandstone. Beavertail Gravels that unconformably overlie the sandstone contain an abundance of Redwall Limestone and Precambrian rock clasts that were derived from the southwest (from the left) with stream flow going to the right. Fault displacement is about 400 feet down to the southwest as part of a family of graben faults. The fault scarp talus at upper left is post-graben faulting in age and shows debris eroded to the left from a former fault scarp to the right. This outcrop shows dramatic evidence that a drainage reversal had taken place after the graben had been developed.

Drainage Reversal, Erosion of Verde Graben and Post-Graben Volcanic Activity

Following the formation of the Verde and Chino grabens about 10 Ma, major drainage reversals took place (McKee and McKee, 1972; Lindberg 1986, 2008). Surface streams across this part of Arizona no longer flowed toward the northeast but now flowed into the closed depressions from all sides of the fault bounded Chino and Verde grabens.

Gravels eroded from the bounding fault scarps were the first to accumulate inside the deep and closed depression. Later on, chemical deposition of calcium carbonate, gypsum and halite evaporite beds was intermixed with clastic sediments and deposited into the lake basin as it slowly filled with debris. Impure limestone, deposited in brackish water, and travertine deposits dominate the upper and central portions of Verde lake beds. Post-graben basalt lavas were erupted onto the partially eroded graben margins and deposited as interlayers within Verde Lake beds. Examples can be found in Sycamore Canyon, along the “Ramp” lava flows that underlie Interstate 17 entering Verde Valley from Flagstaff, and other lava flows younger than ~8 Ma (Holm, 2001).

Deposition of Hackberry volcanic rocks to the south of Camp Verde are post-graben in age and were deposited inside the graben, partially blocking drainage to the south. However, they were not the cause of a lava dam that created “Lake Verde”. Only in the last few million years has modern erosion established a drainage connecting the Chino graben to the Verde graben. That enabled the Verde River to erode the upper layers of Verde lake beds and eventually flow south out of the Verde Valley.

Headward erosion into the Colorado Plateau of the Verde graben fault scarps in the past 10 million years created the Mogollon Rim that we see today in the Sedona area of the Verde watershed. Erosion also created the Hermit erosional bench upon which the city of Sedona now occupies. Surface water sculpted the now serrated margin of the Mogollon Rim escarpment but over time water transport evolved into one that was dominated by subsurface groundwater flow that helped to enlarge the underlying Redwall limestone caves, ultimately leading to sinkhole collapse.

Anomalous Post-Graben Valley Erosion

One of the remarkable features of the Sedona landscape is the presence of two large and broad stream-cut valleys, now completely dry, that only host intermittent stream flow and cause minimal erosion today. Dry Creek Valley to the north of Sedona and Margs Draw to the east are valleys that once hosted a substantial flow of surface water in order to account for the headward erosion into the Mogollon Rim escarpment following the formation of the Verde graben. Surface water infiltration through abundant northwest-oriented bedrock joints and leakage into fault planes with two ages of offset partially explains the decrease of the once active waterways. But that alone cannot account for the now dry valleys. Before the modern normal phase of Oak Creek fault dropped the plateau surface down on the east side a few million years ago, the plateau surface hosted perennial streams that once flowed across the plateau edge and cut deeply into the Mogollon Rim escarpment, thereby eroding Dry Creek and Margs Draw valleys. This would account for the large volume of rock removed and deposited into the Verde graben. Once the modern phase of Oak Creek faulting took place, however, surface flow was again disrupted and streams entering Dry Creek and Margs Draw were cut off.

REGIONAL FRACTURE PATTERNS

Faults

Laramide-age faults and abundant rock joints throughout the area played a major role in determining the latest phase of surface water infiltration into subsurface rocks. Those fractures greatly enhanced Redwall Limestone dissolution and the ultimate development of modern Sedona sinkholes, especially along reactivated fault planes.

The oldest faults and rock joints affecting Paleozoic sedimentary rocks in the Sedona area were formed during the Laramide orogeny that began ~70 Ma. That tectonic event raised the entire rock succession to the southwest of Sedona by more than 2 miles (>3.2 km) to elevations higher than today's Colorado Plateau surface. The Mogollon Highlands to the southwest formed the backbone of that uplift. During that time crustal rocks were subjected to compression that generated monoclinal folds and high-angle reverse fault offsets (fig. 9a). On the Jerome side of the Verde Valley the ancestral phase of the Warrior, Verde, Bessie, Valley and many un-named faults in the Clarkdale cement plant area experienced high-angle reverse faulting in which the east side of the fault blocks were typically raised higher than the west (Lindberg, 1986b). Near Sedona the ancestral phase of the Cathedral, Bear Wallow and Oak Creek faults also experienced major high-angle offsets on their southwestern and eastern sides during the uplift (fig. 9a). Effects of Laramide age faulting can be seen in the Sedona and Oak Creek area where sedimentary strata have been sharply upturned adjacent to a compressional fault. Examples can be found just west of the Sedona Post Office along the ancestral Bear Wallow fault, a half mile north of Grasshopper Point on Highway 89A along the ancestral Oak Creek fault plane, and at the Halfway picnic site at stream level in Oak Creek Canyon (fig. 11).

The prolonged period of northeast-directed stream erosion that followed the Laramide uplift removed the up-on-the-east compressional fault scarps of the ancestral phase of numerous faults throughout the Verde Valley region. Along the ancestral Oak Creek fault scarp erosion removed the Kaibab Limestone and uppermost Coconino Sandstone from the eastern side of the fault block before Rim Gravels and Miocene basalts were deposited onto the deeply eroded surface. In the last few million years the fault was reactivated to form the down-to-the-east normal offset that we see today (Holm and Cloud, 1990). Even though the modern phase of Oak Creek fault has a displacement of ~900 feet (~275 m) down to the east, the net offset of the planed-off underlying sedimentary strata only amounts to 300-400 feet (90-120 m) of down-to-the-east displacement.

Reactivated faults often closely follow the original fault plane, but with movement in the opposite direction. In some cases faults with opposite senses of movement will result in a net zero offset, such as along the trace of the Verde fault several miles north of Jerome. Bear Wallow and Cathedral faults in West Sedona show similar characteristics.

North-south and east-west structural zones of weakness in exposed Precambrian basement rocks at Jerome to the southwest of Sedona are well documented (Anderson and Creasey, 1958). Similar Precambrian basement rock structural features may also exist beneath the Paleozoic rock succession in Sedona. Those ancient lines of weakness may have influenced the orientation of the east-west Bear Wallow fault that passes through West Sedona and the north-south orientation of Oak Creek fault.

Rock Joints

All of the larger sinkholes in the Sedona area are associated with northwest-southeast oriented rock joints (figs. 13 and beyond). Joint patterns have also greatly influenced the weathering of the modern landscape and the generation of Sedona's spectacular scenery. Joints are particularly evident in bedrock exposures of Schnebly Hill Sandstone. The joints were developed during brittle rock deformation that accompanied the formation of the Verde monocline in Laramide time (fig. 9a). Rock joints have played an important role for subsurface limestone dissolution by creating thousands of narrow drainage channels for surface water infiltration to descend through subsurface porous sandstone and into cavernous limestone. As discussed in the sections that follow, joint orientations have played an important role in determining the major alignments of modern subsurface cave systems that are associated with sinkhole collapse.

In bare sandstone outcrop, rock joints are typically very tight and show no offset, either vertically or horizontally. Some of the sinkholes, such as Devils Kitchen, also display subordinate north-northeast oriented joints that had a strong influence on the shape of the east and west sinkhole boundaries (fig. 13).

Several of the northwest-southeast joints throughout the Sedona area were later intruded by Miocene House Mountain-age mafic dikes that emanated from numerous satellitic vent sites surrounding the main volcanic center. The Devils Dining Room sinkhole has 12.0 Ma mafic dikes cutting through the collapse feature that obviously pre-date the formation and subsequent collapse of a subsurface Redwall Limestone cave opening (Lindberg, 2006). That evidence reinforces the timing of drainage reversal and activation of groundwater flow that followed the formation of the Verde graben ~10 Ma.

Use of Maps, Aerial Photos and Satellite Images to Observe Faults and Joints

Topographic maps and Google Earth™ satellite images of Paleozoic sedimentary strata near Sedona reveal abundant linear fracture patterns that are especially pronounced in Schnebly Hill Sandstone strata. The Google Earth™ images, in particular, display a myriad of fractures throughout bedrock exposures in the Sedona area. Northwest-southeast regional joints dominate the fracture pattern but there is also a subordinate set of joints oriented in a north-northeast to south-southwest direction.

To the northwest of Sedona there are prominent joints exposed in the western wall of the Red Canyon sinkhole that have an average orientation of N.65ºW. Examination of joint patterns from Google Earth™ images that straddle the sinkhole also reveals the presence of Schnebly Hill Sandstone joints that vary from N.60ºW to N.80ºW, and they are not always regularly spaced (fig. 31). The satellite image clearly shows areas where joints are more widely spaced, thereby creating unbroken, high-standing massive buttes like the one immediately to the west of the Palatki Heritage site. Water wells drilled into massive blocks such as those would have little chance of encountering subsurface water. Intersecting joint patterns are considered to be important locations for the modern reactivation of Mississippian-age and later Redwall Limestone solution cavities that ultimately evolved into areas with increased ground-water flow, cave enlargement, and ultimate sinkhole collapse.

Further examination of topographic maps, satellite images, and aerial photographs may reveal additional sinkholes in the Sedona area. Future water wells sited along closely spaced northwest-southeast fractures will have a far better chance of success than holes drilled into massive, un-fractured sandstone bedrock. It is hoped that an educated public and governmental agencies will be better able to deal with these natural phenomena. What lies out of sight should be appreciated for what they represent.

INVESTIGATION OF SEDONA AREA SINKHOLES

Knowledge of Sinkhole Locations

Over the past 38 years the writer has learned about sinkhole locations from long time residents, members of the Sedona Westerners hiking club, and from U.S. Forest Service Sedona District rangers. Devils Kitchen and Devils Dining Room sinkholes are well known to the general public and are regularly visited sites, but other sites are less well known. The miniscule 4543 sinkhole was brought to the writer's attention by a forest service ranger who recognized that air would escape through small rock surface openings when atmospheric pressure changed rapidly. That particular site may be an example of what the initial stage of a future sinkhole collapse might look like. It would be an ideal candidate for future geophysical study. Mitten Ridge sinkhole was shown to the writer by Dr. Stan Beus, geology professor emeritus from Northern Arizona University, but this unusual hole, located behind a massive sandstone cliff wall, was recognized some years ago as the "Cave" (Norm Herkenham, personal communication). Additional information from some of the sites was provided by two members of the Independent Cave Resource Specialists who examined some of the sinkholes during bat surveys conducted within the Sedona Ranger District (Backman and Serface, 1995).

Method of Investigating Sinkholes

The surface geology of each sinkhole was mapped in detail with the use of a tripod-mounted Brunton compass and slope- and elevation-corrected tape measurements. Where possible, sinkholes were mapped underground by means of rappelling or by entering through an access point. The interior of the Devils Kitchen sinkhole, however, was measured by triangulation from surface survey points. During a survey of bat populations on February 4, 2002, the writer accompanied Lee Luedeker (Ranger, Arizona Game and Fish Dept.) and Janie Agyagos (Wildlife Biologist, U.S. Forest Service) and rappelled into the Devils Dining Room sinkhole in order to map the geology of the interior. Later on, similar mapping was conducted by rappelling into the Turkey Trail sinkhole with the same team. Elevations for each sinkhole were extrapolated from existing topographic maps with an estimated elevation accuracy of ~5 feet (~1.5 m). Once field mapping was completed, plan maps and cross sections were drafted for this current report. Appropriate longitudinal and cross sections have been oriented to best illustrate the salient features of each sinkhole.

Features Common to Most Sinkholes

Sinkholes occur in sandstone bedrock, often close to the contact between cliff-forming Schnebly Hill Sandstone and less competent Hermit formation lying beneath it. Those sandstone formations contain negligible amounts of soluble carbonate minerals but sometimes do contain irregular lenses of intraformational conglomerates with limestone clasts. Overall, the sandstones are incapable of creating large underground solution cavities responsible for the collapse of surface rocks in the Sedona area. Interior floors of sinkholes contain coarse sandstone breccia that has dropped below the lip of the collapse. All interior surfaces of sinkholes are well-drained and dry. Their breccia columns are presumed to extend all the way to the bottom of a collapsed cave below the water table in subsurface Redwall Limestone. Sinkholes have surface openings that enlarge downward, thus creating a bell-shaped withdrawal of downward collapsing karst breccia.

Bare tree roots, knife-sharp rock edges, and a coating of white caliche on freshly exposed rock fractures are all indicators of relatively recent sinkhole activity. Freshly broken rock ledges are in sharp contrast with much older features where weathering has rounded off sandstone ledges, bare tree roots are absent, and soil has been eroded away from the bedrock opening. Over several decades or centuries of time, weathering can significantly modify exposed sinkhole margins. The northern wall of Devils Kitchen sinkhole provides a good example of how surface features change over time. When the northern third of the sinkhole collapsed in late 1989, a large, northwest-trending joint surface in Schnebly Hill Sandstone was exposed. The perfectly smooth, steeply dipping joint face was covered by a thin pure white coating of caliche (calcium carbonate) that concealed the otherwise red sandstone color. The effect was so conspicuous that when the writer made a stop in 1991 at the Airport Mesa viewing area, 2.3 miles (3.7 km) away from the sinkhole, a tourist was heard to remark “what is that big white building doing out there in the wilderness.” It was explained to her that it was not a building but a film of freshly exposed caliche on the far side of a recently collapsed sinkhole that had caved-in more than a year before. Within 20 years, rainwater, which is weakly acidic due to dissolved carbon dioxide, has dissolved away most of the white caliche and the reddish color of the Schnebly Hill Sandstone now shows through (figs. 4-6).

Another distinctive characteristic of sinkholes is found at Devils Kitchen where localized arcuate fractures indicate significant bedrock strain release. Local arcuate fractures have been superimposed on older regional rock joints that are straight as an arrow, indicating that the ground has been stressed to the point where rock breakage has taken place but bedrock has not yet collapsed. The southwestern corner of the Devils Kitchen sinkhole contains scores of arcuate fractures, many of which display dips that point away from the sinkhole opening, thus indicating that a bell-shaped downward withdrawal is already underway beneath the broken surface (figs. 3-6, 14 & 17).

Possible Concealed sinkholes

Known sinkholes in the Sedona area occur at sandstone bedrock sites that are located above active stream courses. The Red Canyon sinkhole is an example of one that exhibits both well-exposed rock outcrop to the west and a completely hidden alluvium-covered eastern margin (fig. 34). Its western edge displays a dramatic 100 foot high (30 m) sandstone cliff but its eastern rock edge drops below ground surface and is completely concealed by coarse stream-borne alluvium derived from erosion of the Mogollon Rim cliffs. Not too many centuries in the past water flowed down Red Canyon and bypassed the sinkhole but in more recent years a flash flood had created a natural levee that now allows all of the surface flow from Red Canyon to flow directly into the sinkhole where it quickly drains into subsurface passageways (fig. 33). This sinkhole presents an excellent example of how an active water course can obliterate the visual presence of a sinkhole and allow surface runoff to rapidly drain into a subsurface aquifer. Completely hidden, alluvium-filled sinkholes in a suburban area would have the ability to short circuit contaminated surface water to drain directly into the subsurface aquifer, thus creating a potentially dangerous situation.

Further study would be required to determine if and where such concealed sinkholes exist, particularly those within the Sedona city limits. The potential problem of septic discharge into hidden sinkholes is discussed later in this report.

KARST TERMINOLOGY

The term **karst** is defined as: “A type of topography that is formed on limestone, gypsum, and other rocks, primarily by dissolution, and that is characterized by sinkholes, caves, and underground drainage” (Glossary of Geology, 4th edition). Its type locality is the Karst district of northwestern Yugoslavia where karst features are abundant in limestone outcrop. In general usage the term karst applies to surface exposures of carbonate rocks and their underground drainage system that have undergone severe dissolution and volume loss. **Karst hydrology** is defined: “a) The drainage phenomena of karstified limestone, dolomite and other slowly soluble rocks, and b) The surface and groundwater hydraulics in karst drainage systems”. **Karst Breccia** is defined: “collapse breccia or solution breccia”.

While dissolution of subsurface Redwall Limestone and the deeper Martin Dolomite beneath the Sedona area may not be considered as classic karst terrane, in its literal definition, the area does contain geologic features that are associated with typical karst development. Sedona sinkholes have been formed by the cave-in of extensive subsurface limestone solution caves that have allowed for the development of vertically oriented collapse breccia pipes that have broken through overlying sandstone to the modern rock surface. For purposes of this paper, the writer prefers to call these locally formed collapse breccias and the development of sinkholes as a type of **modified karst** topography.

SEDONA SINKHOLES (Arranged clockwise around Sedona)

Devils Kitchen Sinkhole; Type Example for the Sedona Area

Yavapai County; NE¼ Section 1, T.17N.-R.5E., Wilson Mountain 1:24,000 Quadrangle
34º 53’ 11” N, 111º 46’ 57” W
Bedrock at lip of sinkhole: Schnebly Hill Sandstone
Bedrock at lower undercut, south and east side: Hermit formation
Average bearing of dominant joints: N.49ºW.
Bearing of subordinate joints: N.09-16ºE.
Dimension of surface opening: 90 x 150 ft (27 x 46 m)
Area of rock surface opening: 13,650 sq ft (1,270 sq m)
Dimension of underground opening: ~100 x ~225 ft (~30 x ~69 m)
Area of underground opening: ~22,160 sq ft (~2,060 sq m)
Depth below rim to top of collapse breccia: 35-70 ft (11-21 m)
Date of final mapping: November 24, 2009; Photographs 1983 to January 2010

Devils Kitchen sinkhole is the best known and most active of the Sedona area collapse features but it is not the largest (figs. 1-6 & 13-18). That distinction goes to the Red Canyon sinkhole located seven miles to the west-northwest.

Devils Kitchen is easily accessed by the Soldier Pass hiking trail and visited daily by jeep tours. Before the northern third of the steep walled sinkhole collapsed in 1989, the surface opening was estimated to be 90 feet wide (27 m) and ~100 feet long (~30 m) in a north-south direction (fig. 4). Bedrock at the sinkhole is competent basal Schnebly Hill Sandstone with collapse rubble laying 35-70 ft (11-21 m) below the abrupt rock lip. Several trees and shrubs had grown on the coarse rubble floor inside the southern end of the sinkhole by the early 1970s. Uranium prospecting in the 1950s might have accounted for two small cribbed “shafts” in the rubble floor of the sinkhole in a futile attempt to penetrate the coarse rubble in the floor of Devils Kitchen sinkhole (fig. 13). Between the time of the reported collapse in the “early 1880s” and 1989, some small rock falls must have occurred at the site. Evidence for that activity was the presence of bare tree roots and remnant white caliche coatings on the northern rock face that were still visible in 1983 (fig. 4). The greatest degree of sandstone weathering and “rounding” of rock edges occurs in the extreme southeastern corner of the sinkhole where a small surface opening may have existed prior to the early 1880s collapse.

During the mapping of the sinkhole for the jeep franchise and the U.S. Forest Service in 1990, the writer recorded the typical northwest- and north-northeast trending near vertical joints that define the sinkhole boundary. Field checks were also made in late November 2009 and January 2010 that refined the earlier drawn geologic map and sections of Devils Kitchen (figs. 13 & 14). The 1990 study discovered the existence of superimposed localized arcuate fractures that dip outwardly from the sinkhole, thus creating a downward widening, bell-shaped collapse feature around the southwestern corner of the sinkhole (Lindberg, 1990). That feature indicated that bedrock in the entire southwestern corner of the sinkhole has already been broken by withdrawal of support from below, but the ground has not yet collapsed.

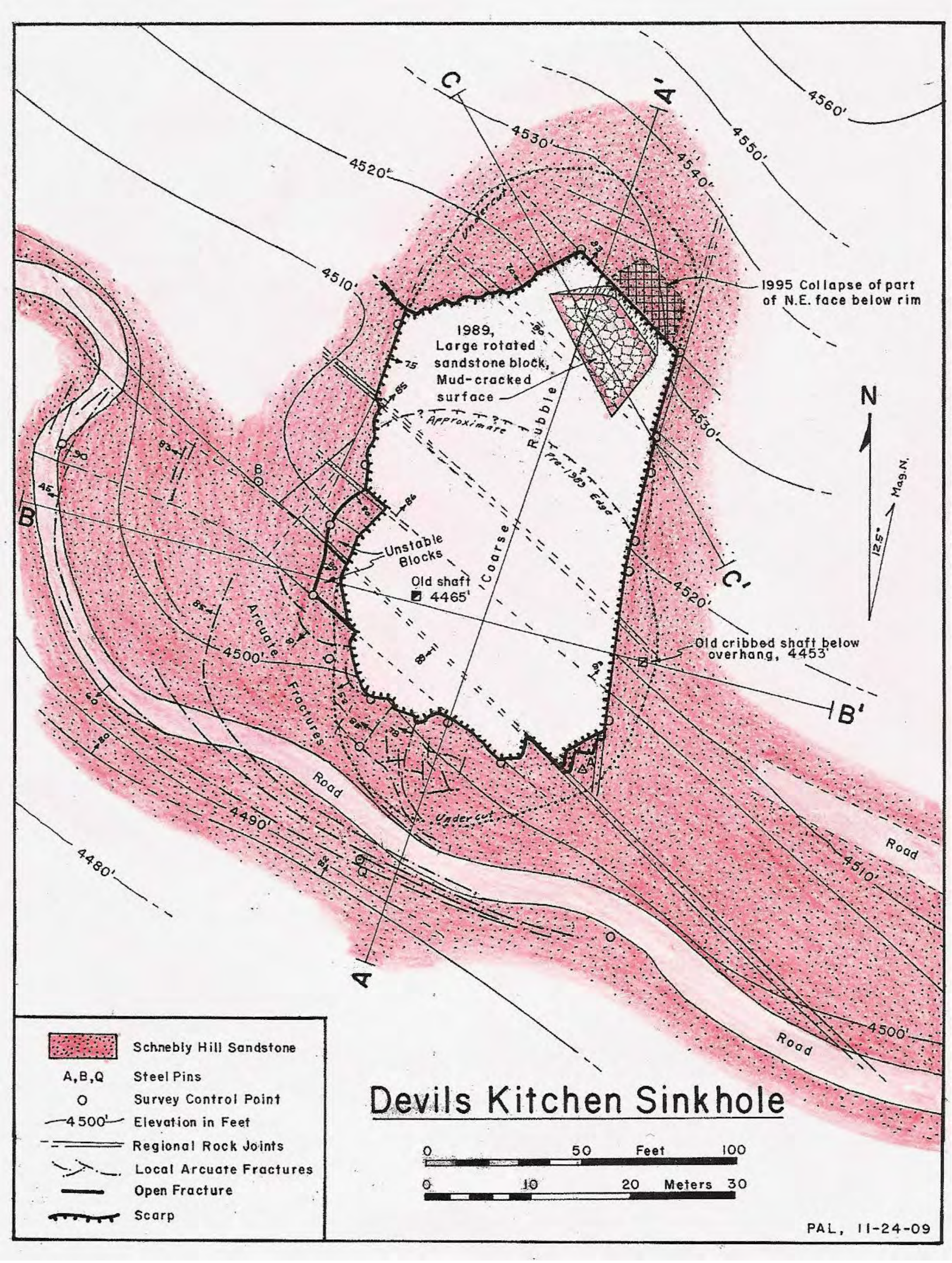

Figure 13, Geologic map of Devils Kitchen sinkhole as of 2009. In 1989 the northern third caved in and in 1995 a large chunk (cross-hatched) fell out of the north face. Joints trend NW-SE but superimposed arcuate fractures in the SW corner indicate broken rock.

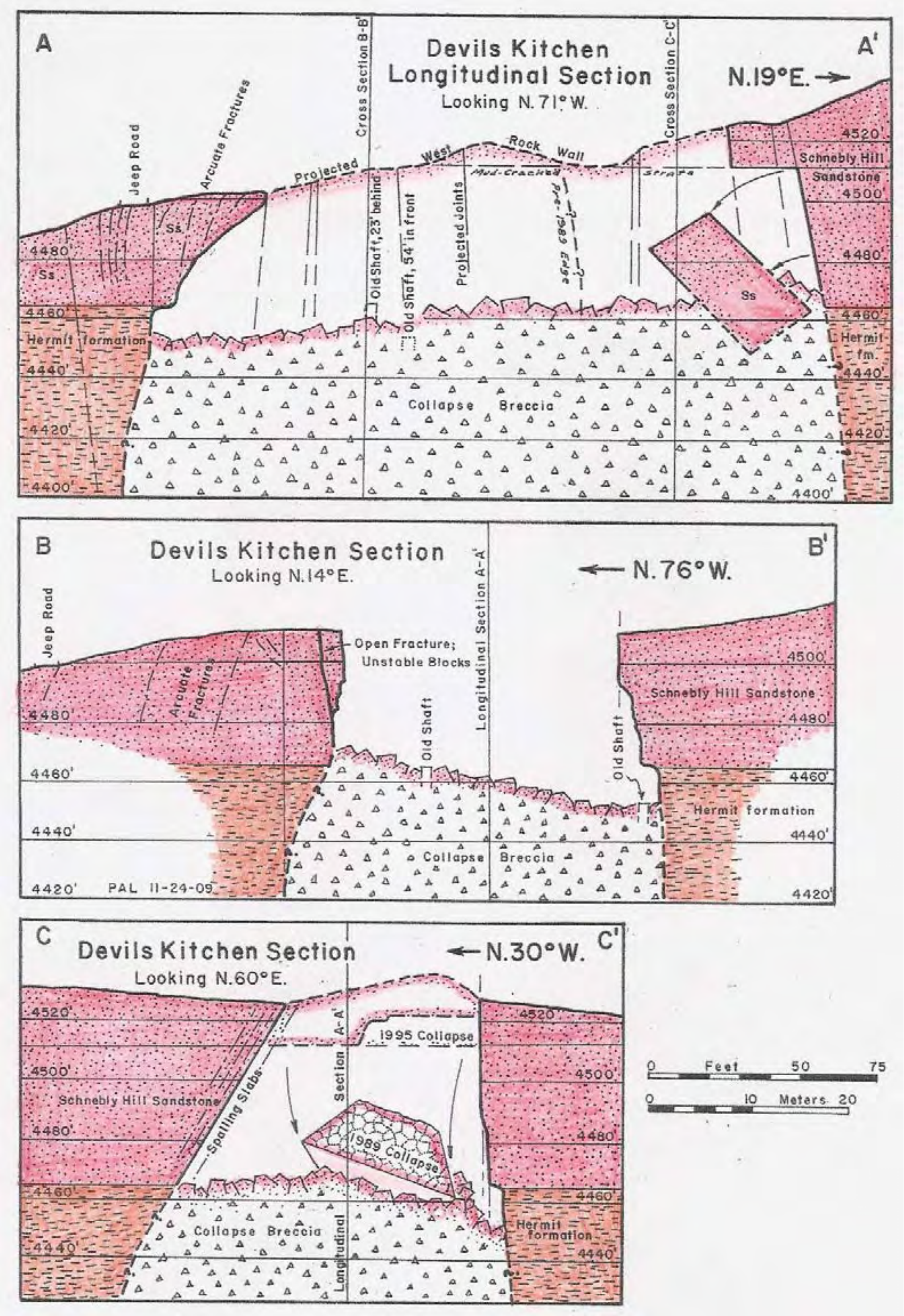

Figure 14. Sections through Devils Kitchen sinkhole. **A,** Longitudinal section viewed in the direction of regional rock joints. Note how the breccia-filled collapse opening enlarges downward. **B** & **C,** Cross sections that also show the downward widening collapse, especially within the underlying Hermit formation.

One open fracture, in particular, has been enlarging over the years (fig. 15). In the early 1970s the north-south crack was visually estimated at ~2 inches (~5 cm) wide, but as of November 23, 2009 the opening measures 7-9 inches (18-23 cm) in the southern block and 11.5 inches (29 cm) in the companion northern block. Frost heaving and rock wedging are currently widening this fracture toward the breaking point. When failure does occur at this location, the "horizontal arch" formed by two large sandstone blocks are predicted to unload much of the southwestern corner of the sinkhole and generate a larger collapse (figs. 13 & 18). Arcuate fractures extend outward from the corner for at least 90 feet (27 m) and over the next several centuries the sinkhole is expected to enlarge substantially toward the west and southwest.

Figure 15. Open fracture in west edge of Devils Kitchen sinkhole. This fracture has been widening over the past several decades. What was once a 2 inch (5 cm) break is now 7-9 inches wide (18-23 cm). Frost heaving and rock wedging will ultimately cause this piece, and another similar block to the north, to break loose and "unload" the southwestern corner of the sinkhole in a future collapse. The entire outcrop to the southwest of this fracture has already been broken with arcuate fractures.

Figure 16. Devils Kitchen sinkhole in September 2008. Note the fresh, angular rock breaks and vestige of white caliche that marks the pre-1989 boundary of the sinkhole.

Figure 17. Example of arcuate fractures in bedrock. Rock fractures such as this are only found in areas where subsurface collapse has already broken the surface outcrop. These fractures occur at the south end of Devils Kitchen sinkhole. Note how the arcuate fractures have been superimposed on the straight regional joints. Clipboard shows scale.

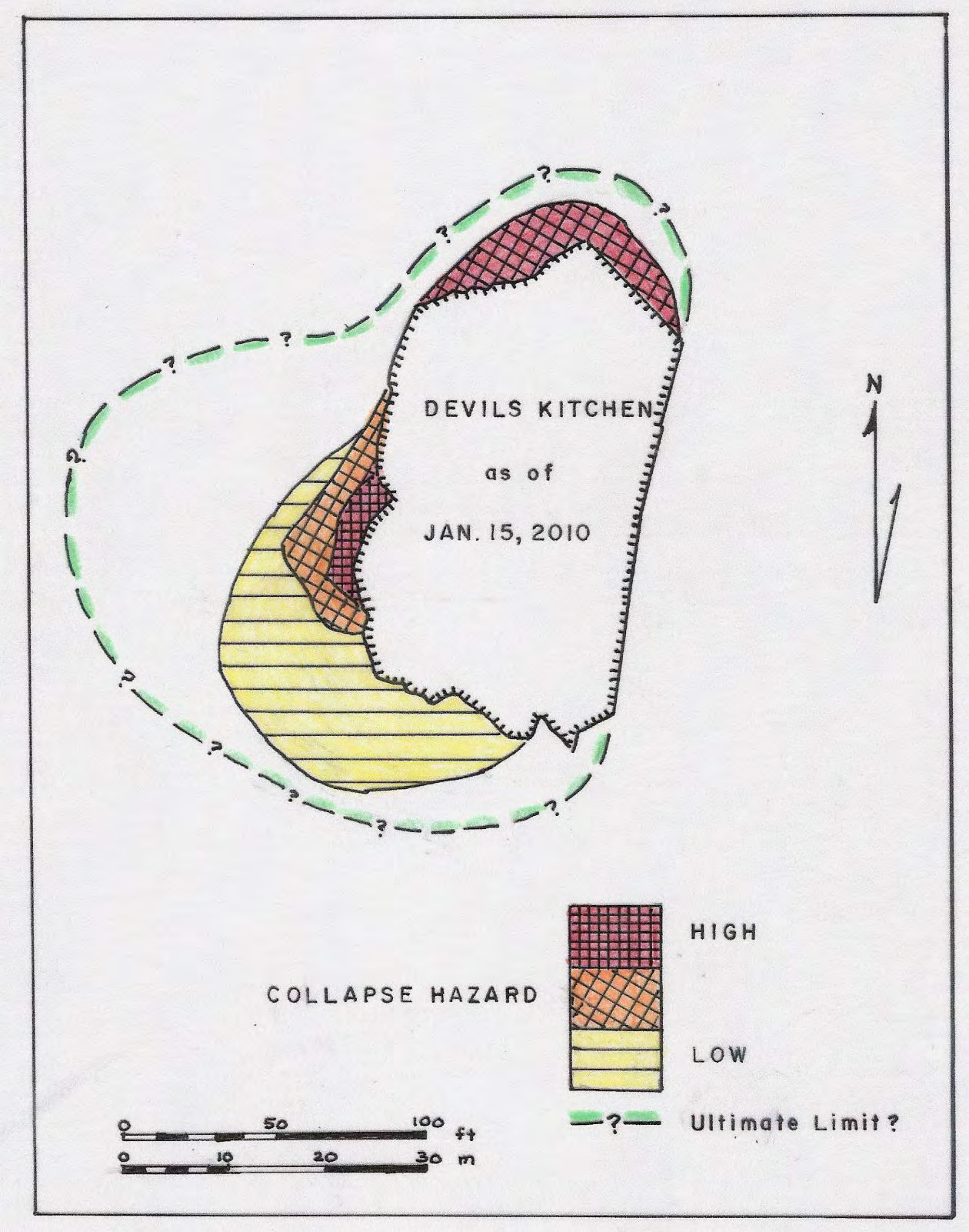

Figure 18. Predicted collapse hazard at Devils Kitchen sinkhole. Based on existing map information and past historic rock falls, the above map shows where additional collapse is likely to occur in future years.

Mitten Ridge Sinkhole

Coconino County; SE corner, Section 4, T.17N.-R.6E., Munds Park 1:24,000 Quadrangle
34º 52’ 37” N, 111º 43’ 35” W (approximate)
Bedrock at sinkhole: Schnebly Hill Sandstone
Oval shaped sinkhole behind cliff face: 18 x 24 ft (5.5 x 7.3 m)
Area of opening, including partially collapsed entryway: 406 sq ft (38 sq m)
Maximum height of inside room: 9 ft (2.7 m)
Date of mapping and photographs: October 3, 2009

Mitten Ridge (derived from a German word for middle) is an east-west ridge situated midway between the Midgley Bridge area of lower Oak Creek Canyon and Bear Wallow Canyon. The well hidden sinkhole is located at the base of a steep and massive cliff located to the northeast of a prominent saddle on Mitten Ridge (fig. 1, 19-21). Access to the site is made via the Schnebly Hill Road and on the Cow Pies Trail to the north and then west to the saddle. Mitten Ridge is an unusual sinkhole because of the great height at which it is exposed above a presumed deep-seated Redwall Limestone cave collapse. Inside its opening, located behind a sheer sandstone cliff face, the sandstone bedrock contains abundant sub-vertical stress fractures that are spaced about 2-3 inches (5-7.5 cm) apart. No other Sedona sinkhole contains these unusual vertical fractures. While the interior walls of the 18 by 24 foot (5.5 by 7.3 m) room are completely fractured, the flat roof is composed of massive, unbroken Schnebly Hill Sandstone. A sharply defined horizontal parting plane separates the massive sandstone from underlying fractured rock. This small sinkhole collapse feature is estimated to occur ~1100 feet (~335 m) above the top of the Redwall Limestone cave that is assumed to be responsible for the collapse, making this the tallest known karst breccia column in the Sedona area.

Norm Herkenham, a long time resident of Sedona, says the site has been known to local hikers as “The Cave” (personal communication 2009). A flattened rock-lined bench to the immediate north of the sinkhole opening clearly shows a prehistoric platform at the cliff base and the roof of the cave has fire-blackened soot, indicating prehistoric occupancy. The site was brought to the writer’s attention by Dr. Stanley Beus, professor emeritus from Northern Arizona University in Flagstaff who believed it may be a sinkhole. Subsequent study of the site convinced the writer that it is a most unusual one.

On October 3, 2009 the site was mapped in detail. Since prehistoric occupancy, and apparently in post-occupation time, several large sandstone blocks have spalled off from the overhanging cliff face above the opening to the sinkhole. That has partially blocked the present narrow crawl space entry into the room. *Large and unstable cliff blocks lying directly above the entrance are precariously perched and could fall at any time!*

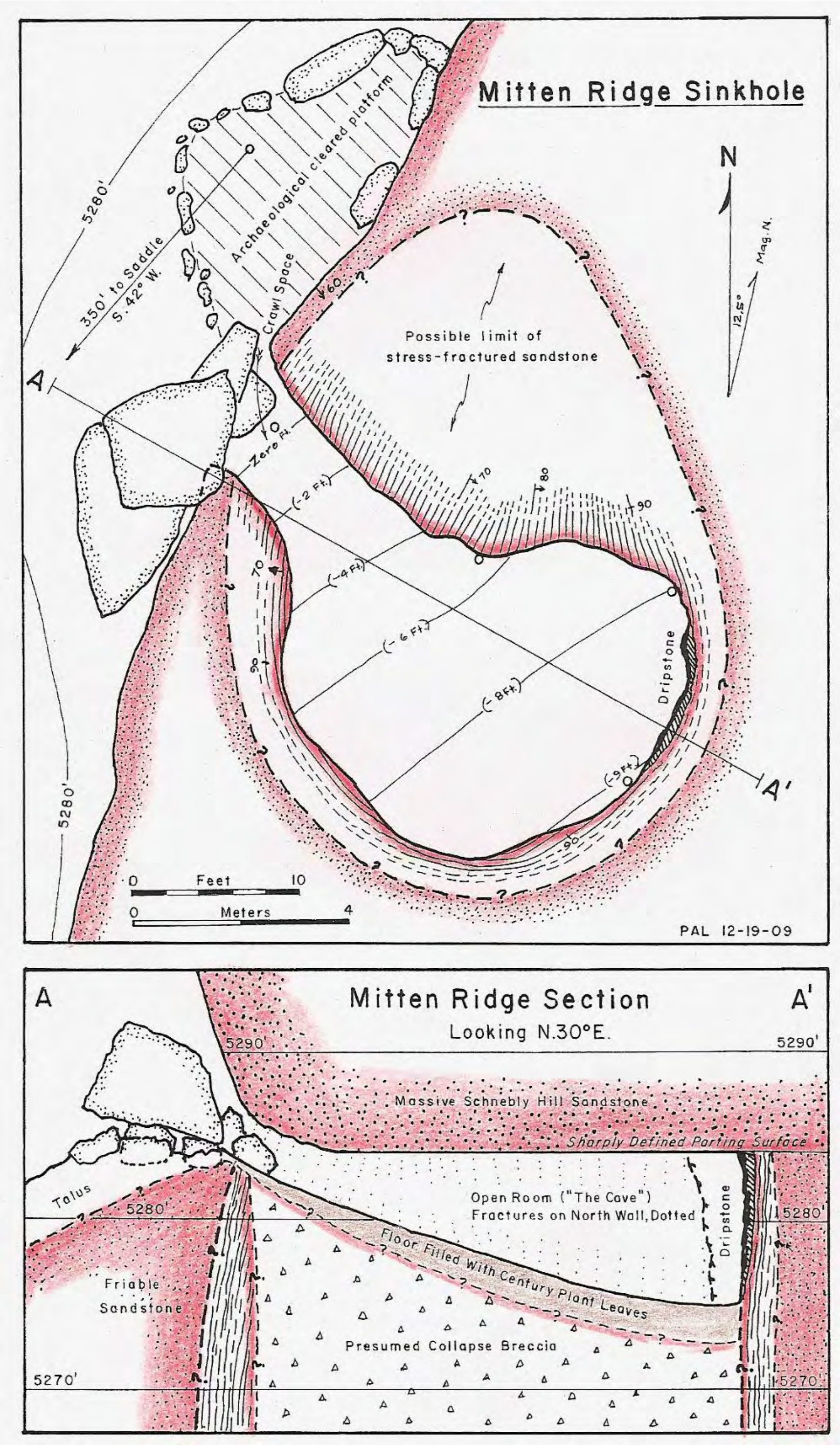

Figure 19. Map and section through Mitten Ridge sinkhole. This unusual sinkhole contains abundant narrow, steeply oriented stress fractures within the collapsed area but is capped by massive, unbroken Schnebly Hill Sandstone. Known as the “Cave” by long time residents, this small site was once occupied in prehistoric time.

Figure 20. Entrance to Mitten Ridge sinkhole. Small prehistoric clearing lies to north of crawl space into the “Cave”. Note fractured and unstable cliff rocks above opening.

Figure 21. Interior of Mitten Ridge sinkhole. The walls show abundant, closely spaced stress fractures in Schnebly Hill Sandstone that widen downward. Massive sandstone caprock appears to be unbroken, indicating that this is the extreme top of a column of collapse breccia. Note the black soot from prehistoric occupancy on the ceiling.

Devils Dining Room Sinkhole

Coconino County; NW¼ Section 20, T.17N.-R.6E., Sedona 1:24,000 Quadrangle
34º 50’ 25” N, 111º 45’ 19” W
Bedrock at lip of sinkhole: Near the top of Hermit formation
Bearing of dominant joints and basalt dike: N.78ºW.
Area of rock surface opening: 600 sq ft (55 sq m)
Area of underground opening: 3,720 sq ft (345 sq m)
Maximum depth below rim to deepest collapse breccia: 80 ft (24 m)
Date of underground mapping: February 4, 2002
Date of surface mapping: February 15, 2002 and field checked December 15, 2009

Devils Dining Room sinkhole is located just off the Broken Arrow trail and jeep road to the southeast of Sedona (fig. 1 & 22-23). With the aid of Lee Luedeker (Ranger, Arizona Game and Fish Dept.) and Janie Agyagos (Wildlife Biologist, U.S. Forest Service), who were investigating bat populations, the writer rappelled into the sinkhole on February 4, 2002 to map its interior and retrieve a fresh mafic dike sample for age dating. A relatively small surface opening, roughly 27 feet in diameter (~8 m) opens up below to a chamber that is 45 feet wide (14 m) by 90 foot long (27 m) with the long axis being sub-parallel to the N.64ºW joint direction. Devils Dining Room is unique in that it exposes two en echelon basalt dikes that cut through the south wall of the collapse feature. A fresh sample of the main 10 inch wide (25 cm) dike collected underground revealed a K-Ar House Mountain-age date of 12.0 Ma (Lindberg, 2006). That date implies that modern sinkhole formation took place sometime after the dikes had been emplaced, and in agreement with the drainage reversal that accompanied the formation of the Verde graben ~10 Ma (Lindberg, 1983 & 1986).

The en echelon dikes exposed within the sinkhole reveals features about stress conditions in the earth’s crust prior to sinkhole development. Another N.65ºW trending basalt dike is exposed along the trail to the west of the sinkhole and that links up with a 1500 foot (460 m) long dike exposure that cuts through Battlement Mesa to the northwest. Collectively, these en echelon dikes have a net trend of N75ºW, indicating that the basalt dikes have been intruded into joints that display left-lateral strain release at the time of emplacement 12 Ma. Inside the sinkhole the main 10 inch wide (25 cm) dike thins to 3 inches wide (7.6 cm) at the southeastern corner of the sinkhole as an en echelon companion dike of 7 inches wide to the north takes over. These are part of a family of numerous House Mountain-age feeder dikes found throughout the Sedona area that vented thin lava flows that once covered the entire area.

Devils Dining Room sinkhole is situated near the top of the Hermit formation where overlying Schnebly Hill Sandstone has been eroded away. When viewed from inside the opening, it becomes clear that a large block on the northern side of the hole had been dropped and rotated with a 15º dip to the north (Cross Section B-B’ in fig. 22). The rotated block appears to have dropped several tens of feet during an older collapse event, but soil and weathered sandstone obscures its exact surface boundary. Also evident in the underground opening is a narrow vertical crack that extends downward for a considerable distance as a block rotated inward (fig. 22, B-B’).

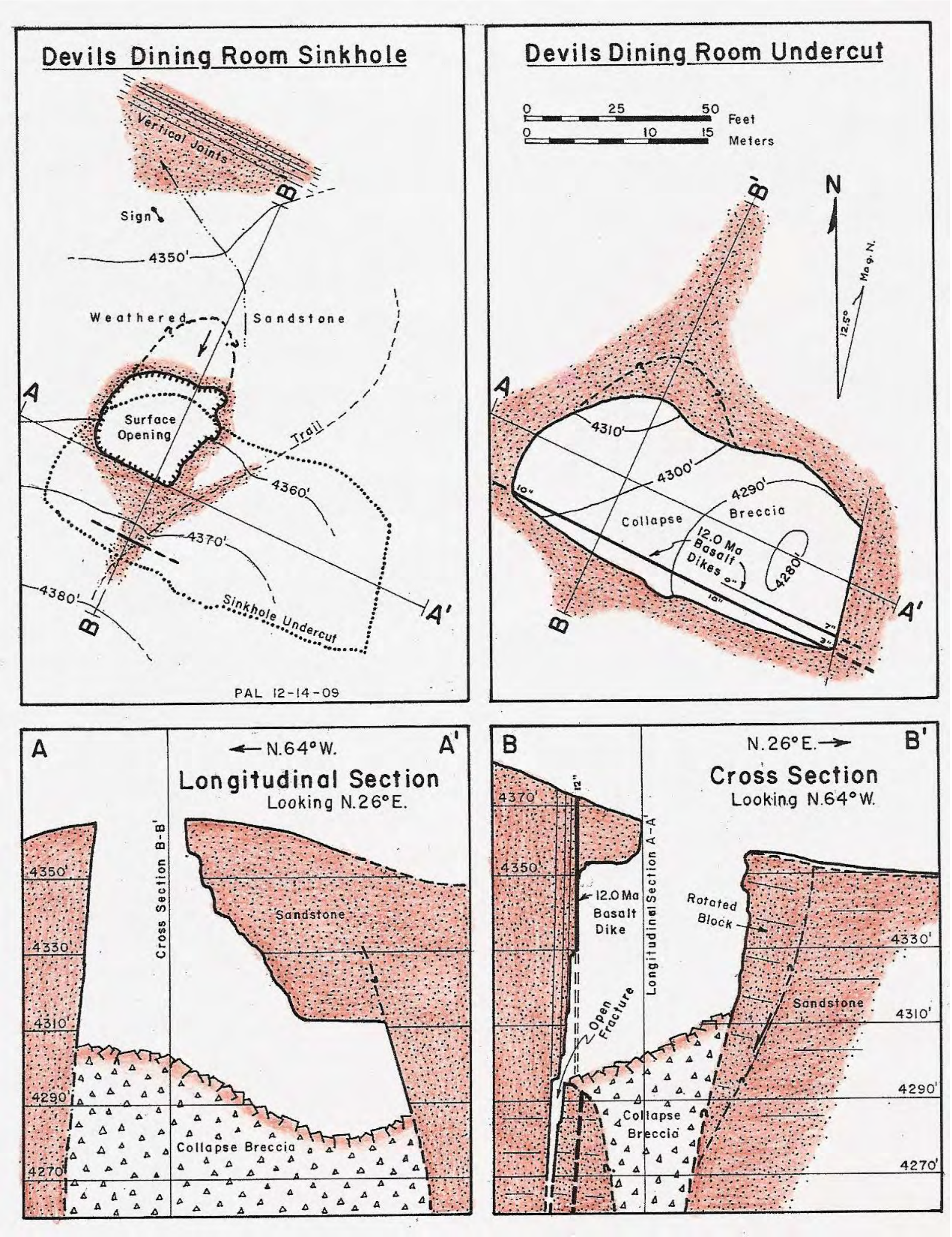

Figure 22. Map and sections through Devils Dining Room sinkhole. The undercut portion of the sinkhole is substantially bigger than the surface opening and is elongated sub-parallel to regional rock joints (Section A-A'). Section B-B' shows the 12.0 Ma basalt dike that cuts bedrock in the direction of regional rock joints. The dike had to have been intruded before sinkhole development. The north wall shows evidence of an old collapse.

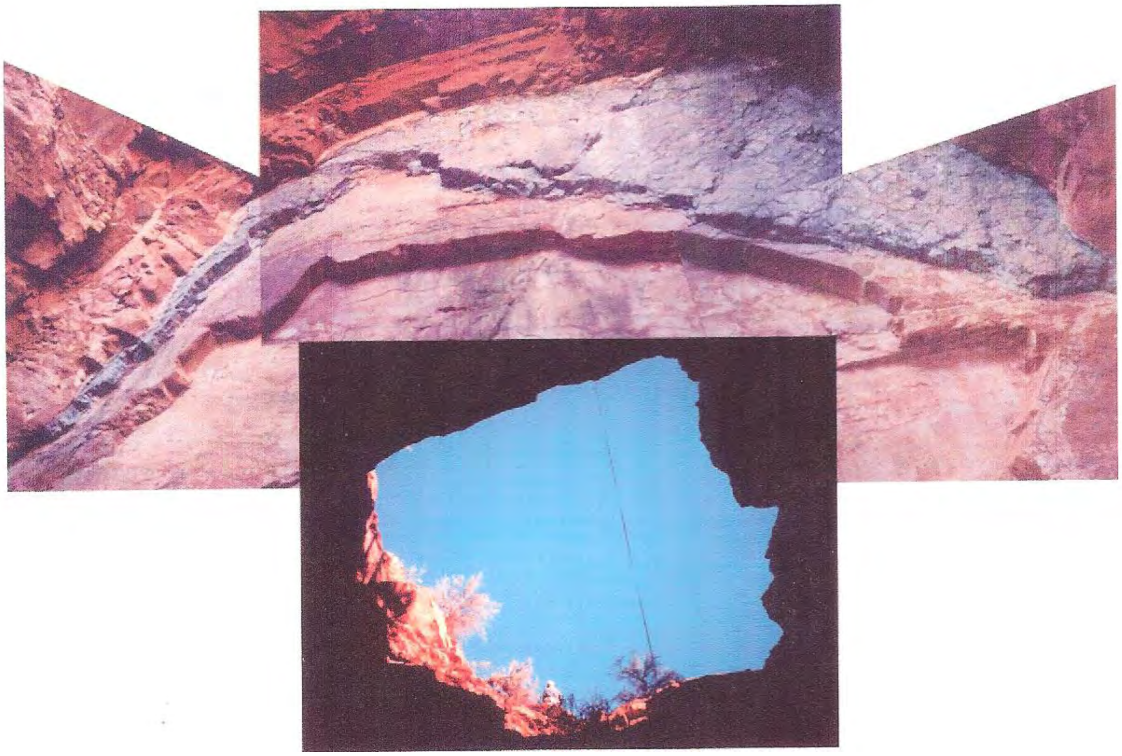

Figure 23. Interior views of Devils Dining Room sinkhole. The composite photo shows a vertical 12.0 Ma House Mountain-age basalt dike that has been intruded into the plane of a regional N.64ºW. rock joint. Bedrock is believed to be the topmost portion of the Hermit formation. Since the sinkhole must have collapsed into a large Redwall Limestone cave at depth, the origin of the subsurface dissolution cavity must be younger than the time of dike emplacement. That agrees with the timing of drainage reversal and development of modern groundwater flow beneath the Sedona area following the formation of the Verde graben 10 Ma.

Turkey Trail Sinkhole

Yavapai County; NW¼ of NW¼, Section 9, T.16N.-R.5E., Sedona 1:24,000 Quadrangle
34º 48’ 10” N, 111º 49’ 26” W
Bedrock at surface of sinkhole: Hermit formation
Bearing of dominant joints: N.43ºW.
Area of rock opening into the underground opening: 45 sq ft (4 sq m)
Area of underground opening: 1,840 sq ft (170 sq m)
Maximum depth below rim to bottom of collapse breccia: 75 ft (23 m)
Date of underground mapping: March 6, 2002
Date of surface mapping: March 6, 2002 and field checked September 30, 2009

Turkey Trail sinkhole was entered on March 6, 2002 by rappelling into the opening with Lee Luedeker (Ranger, Arizona Game and Fish Dept.) and Janie Agyagos (Wildlife Biologist, U.S. Forest Service). While they investigated bat populations, the writer mapped the interior. Surface mapping followed the underground examination and was field checked and refined on September 30, 2009 (figs. 1 & 24-26).

Figure 24. Surface view of Turkey Trail sinkhole. View is to the southeast in the direction of regional rock joints. A small 5 by 10 foot rock opening deeper down leads into the larger underground opening. Most surface water in this area is shunted around the surface opening. Brunton compass tripod and clipboard show scale.

This may be one of the older sinkholes in the area. Weathered sandstone outcrop is exposed at the top of a shallow, oval-shaped crater about 30 by 55 feet across (9 by 17 m) that lies above the sinkhole's smaller bedrock entrance. The small rock opening leading into the underground chamber is only about 5 by 10 feet (1.5 by 3 m) but it widens below into an opening that is 25 by 85 feet (7.6 by 26 m). The long axis of the lower chamber is oriented in the direction of prominent northwest-trending joints. Minor northeast-trending joints are seen on surface and underground. An unusual feature of this sinkhole is the presence of calcium carbonate dripstone in the extreme western corner of the undercut. The source of calcium-rich water responsible for dripstone deposition is uncertain, since local bedrock is composed of carbonate-deficient sandstone (fig. 25). Fort Apache limestone strata, occurring higher up in the stratigraphy and to the southeast of the sinkhole, may have provided the calcium from groundwater evaporation.

Figure 25. Dripstone inside Turkey Trail sinkhole. Photo taken by Janie Agyagos, US Forest Service.

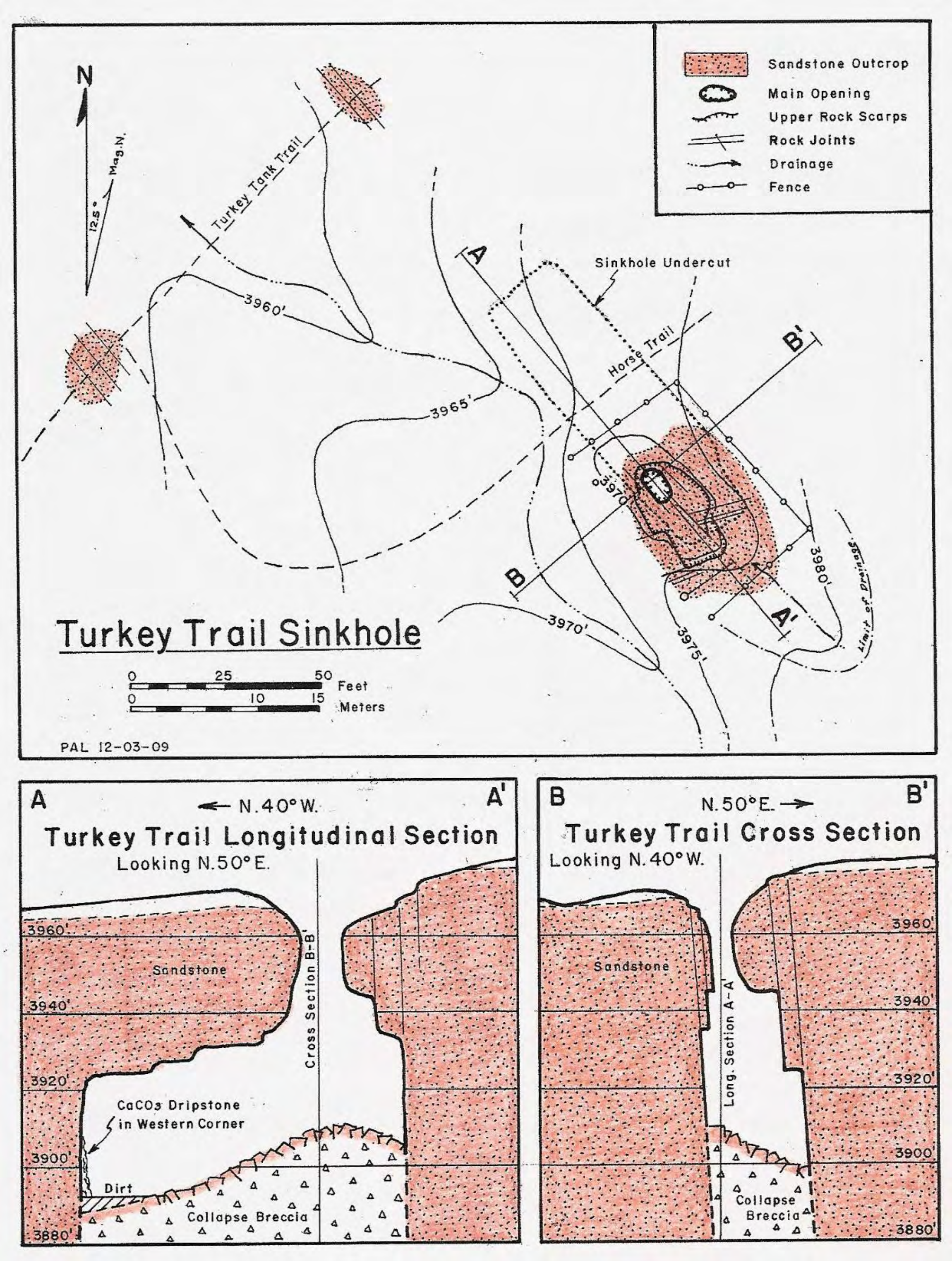

Figure 26. Map and sections through Turkey Trail sinkhole. This may be one of the older sinkholes in the Sedona area as suggested by the weathering of the surface outcrops.

Nolan Draw Sinkhole

Yavapai County; E.¼ corner, Section 3, T.17N.-R.4E., Loy Butte 1:24,000 Quadrangle
34º 53’ 01” N, 111º 55’ 11” W
Bedrock at lip of sinkhole: Topmost Esplanade Sandstone
Bearing of dominant joints: N.69-73ºW.
Date of final mapping: September 27, 2009
Area of rock surface opening: 1830 sq ft (170 sq m)
Area of underground opening: ~8410 sq ft (~780 sq m)
Maximum depth below rim to bottom of collapse breccia: 68 ft (21 m)

Nolan Draw sinkhole appears as a small closed 4400 foot contour on the Loy Butte 1:24,000 quadrangle (figs. 1 & 27-29). Robert Gillies, U.S. Forest Service Ranger, and the writer visited the site in the late 1990s to assess its potential as a site for disposing of treated waste water from the Sedona Wastewater Treatment Plant west of Sedona in an effort to recharge the Verde Valley aquifer. The dirt road that passed by the west side of the sinkhole has been blocked off by the forest service several years ago.

On September 28, 2009 the writer finished mapping the surface geology and inside features of the Nolan Draw sinkhole with a tripod-mounted Brunton compass and tape measurements. The surface opening is located a little over 300 feet (+90 m) to the west of the eastern un-surveyed ¼ corner of Section 3, T.17N.-R.4E. At least 8 rock joints, with an average bearing of N.70ºW., were mapped within the sinkhole. Dips of joints passing through the sinkhole range from -80º north to vertical. The maximum surface opening of the sinkhole in Esplanade Sandstone bedrock is 46 feet by 56 feet (14 by 17 m) and the irregularly shaped hole has an area of ~1830 square feet (~170 sq m). The undercut opening, however, has an area of ~8410 square feet (~2563 sq m). The collapsed area below ground surface expands well to the northeast and is 4.6 times larger than the surface opening (fig. 28-29). The dirt covered eastern floor of the sinkhole lies at a maximum depth of 68 feet (21 m) below its bedrock lip. While most Sedona sinkholes enlarge downward, the Nolan Draw sinkhole displays the most dramatic increase in the undercut enlargement. This illustrates another example of the bell-shaped downward enlargement of the karst breccia column overlying a Redwall Limestone cave at depth.

Bedrock at this site is believed to lie just below the Esplanade Sandstone-Hermit formation contact. Bedrock at the upper lip of the sinkhole is composed of an intraformational conglomerate that overlies massive sandstone. The conglomerate contains rounded limey clasts in a sandy matrix. Surface features of the Nolan Draw sinkhole appear to be relatively old, based on the presence of well rounded bedrock features, giving the site a degree of stability. On the northwestern end there are two 2 foot (0.6 m) diameter potholes that indicate that a significant amount of surface water once cascaded with sufficient enough force to carve potholes in sandstone to a depth of more than 2 feet (>0.6 m). Only fierce and highly focused summer thunderstorms of today could provide enough water to carve such features from such a limited drainage area to the northwest. Perhaps this surface feature might date back toward the end of the last Ice Age when precipitation was more abundant?

When viewed from inside the yawning cavity the sinkhole suggests a much younger appearance. As shown in the cross sections, there is a very large pile of coarse boulders that have collapsed into the uneven floor of the sinkhole, especially in the southwestern corner where angular blocks reach to within 15 feet (~4.5 m) of the rock lip. The northeastern floor of the sinkhole exhibits a nearly flat, water-laid, now dry mud-cracked surface. It is impossible to know just when this sinkhole came into existence, but the large dirt covered floor could well contain valuable post-Ice Age faunal and floral remains.

In the dry bedrock floor of Nolan Draw, 350 feet (105 m) to the east-northeast of the sinkhole, there is an area in solid sandstone outcrop where small open cavities occur below the bedrock surface. And a short distance further to the northeast there are a few arcuate cracks in bedrock. These features may be indicative of yet another collapse just beginning to break through to the surface to the east of the main sinkhole.

Figure 27. Surface view of Nolan Draw sinkhole. View is looking toward the east-southeast. Surface rocks are well rounded and appear to have been stable for many years.

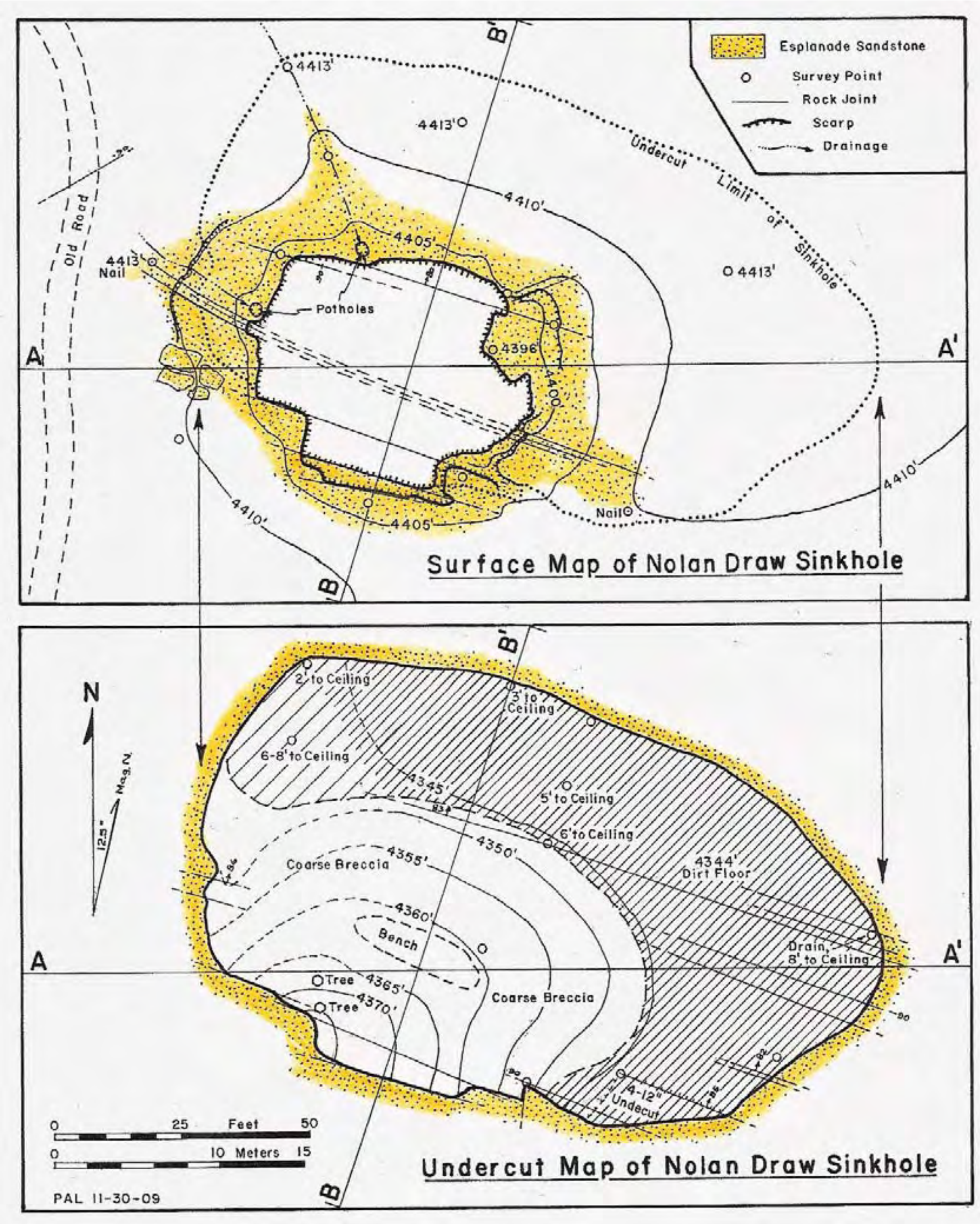

Figure 28. Surface and undercut maps of Nolan Draw sinkhole. At least eight rock joints help to control the collapse feature. Surface outcrop is quite rounded and the site appears to be relatively old, perhaps dating back to the Ice Age? Two water-formed potholes are present in the northwestern corner, suggesting that past climates were much wetter. The undercut area is 4.6 times larger than the surface opening with a large dirt floor extending to the northeast. The small human-formed bench inside the sinkhole probably dates from prehistoric time but has been enhanced by modern activity. The sinkhole drain is located at the extreme eastern end of the undercut and lies beneath an 8 foot sandstone roof.

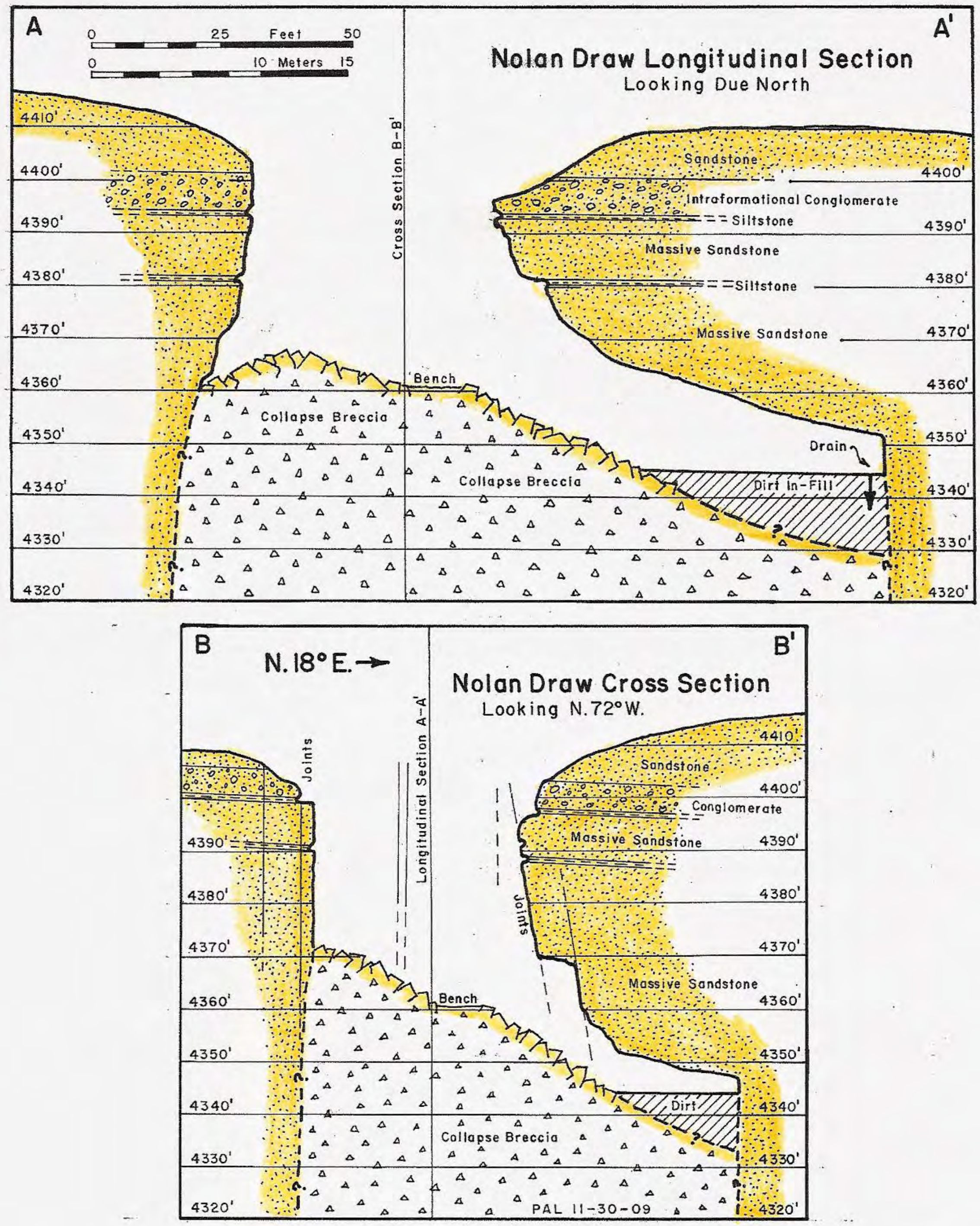

Figure 29. Sections through the Nolan Draw sinkhole. Northwest joints are prominent in Section B-B' and they clearly helped shape the collapse boundaries.

Red Canyon Sinkhole

Yavapai County; NW¼, Section 25, T.18N.-R.4E., Loy Butte 1:24,000 Quadrangle
34º 54’ 54” N, 111º 54’ 54” W
Bedrock at lip of sinkhole: Basal Schnebly Hill Sandstone
Average bearing of dominant joints: N.65ºW.
Date of final mapping and photographs: November 6, 2009
Estimated area of sinkhole; bedrock and alluvial cover: ~32,900 sq ft (~3,055 sq m)
Maximum depth below rim to collapse breccia: 103 feet (31 m)

Red Canyon sinkhole is by far the largest sinkhole in the Sedona area. It lies on the eastern side of a low bedrock ridge located east of the Palatki Heritage archaeological site (figs. 1, 30-35). The sinkhole contains a dozen or more prominent rock joints that have an average bearing of N.65ºW. They form part of a family of regional joints that are readily seen on Google Earth images (fig. 31).

The western and northern margins of the Red Canyon sinkhole are composed of bold Schnebly Hill Sandstone walls with a sheer drop of ~100 feet (~30 m) to the deepest part of the depression where surface water drains downward. Collapsed bedrock on the low southeastern side is masked by coarse alluvium washed in from Red Canyon to the northeast. The easternmost bedrock margin of the collapse feature, therefore, is somewhat uncertain. Figure 34 is a geologic map of the sinkhole and Figure 35 shows longitudinal and cross sections through the feature. Arizona walnut, hackberry and other trees grow in the dry floor of the sinkhole. Large, angular sandstone blocks fill the southwestern and northern floor of the sinkhole and a large area of loose soil and leaf litter occupies the flat base of the closed depression at an elevation of ~4742 feet (~1445 m). Underfoot, the floor of the depression sounds hollow in places when walking across its surface. A drainage sump at the base of the sinkhole lies directly in line with, and 98 feet (30 m) directly below, an 8 foot (2.4 m) wide zone of four prominent rock joints that cut through the northwestern cliff wall of the sinkhole (fig. 32). These joints are believed to be master fractures that make up a major control for sinkhole collapse.

The latest appearance of subsidence activity lies at the base of the northwest corner of the sinkhole beneath a prominent joint face. Large chaotic sandstone blocks and open spaces occur at that location. On November 5, 2009 dank air could be felt exiting from a hole in the coarse rock rubble, indicating that a sizeable opening exists below that point and above the presumed water table at depth. The rock ledge that was used to paint prehistoric pictographs (1300-1400 AD?) has collapsed by at least 15 feet (~4.5 m) since the anthropomorphic figures were drawn.

In 2001 the writer investigated the Red Canyon drainage that cuts through coarse alluvium and enters the eastern end of the sinkhole. The original course of stream bypassed the sinkhole, as indicated on the 1:24,000 Loy Butte topographic map. Examination of the gully cut into coarse alluvium revealed that a Red Canyon flash flood in the distant past had created a natural debris flow levee that is composed of coarse sandstone boulders. The levee is 40 feet wide at the base and ~6 feet high (12 by 1.8 m) and it changed the course of the drainage from its original channel into one that now empties directly into the sinkhole (fig. 34).

Red Canyon drainage area on the southwest flank of Bear Mountain is relatively small at ~0.4 square miles (~1.0 sq km). On March 12, 2001 the writer witnessed snowmelt flowing into the sinkhole, visually estimated at about 1 cubic foot per second (fig. 33). The water began to percolate into coarse alluvium before entering the main floor of the sinkhole where the remainder rapidly disappeared into a drain located at the extreme western end of the depression. Water dropped through the sump much like water exiting from a bathtub, complete with audible sounds of water cascading downward through subsurface boulders. That part of the sinkhole floor is unstable and porous. The original Red Canyon drainage bypassed the sinkhole and once flowed to the southwest onto the flat area south of the Palatki Heritage site. That gully appears to have not carried surface water for several centuries. It is quite possible that surface flow bypassed the sinkhole in prehistoric time when the Palatki ruin site was occupied (fig. 34).

The gravel-covered eastern side of the collapse area provides an excellent example of how a concealed sinkhole can swallow up surface water flow and hide the presence of a sizable breccia column leading directly into a subsurface aquifer. In the case of Red Canyon, it is fresh water that recharges the aquifer, and not septic waste. It is unknown if additional sinkholes exist to the east-southeast of Red Canyon or within the Palatki box canyon itself. Both alluvium covered flat areas are in alignment with Red Canyon sinkhole (fig. 31). Because of the alluvial covered southeastern side there is no way of knowing exactly how large Red Canyon sinkhole is. The surface area of the exposed rock and its projected eastern margin is estimated to be ~35,000 sq ft (~3250 sq m). That equates to the equivalent of a collapse with an average diameter of ~212 feet (65 m), making this the largest of the known Sedona area sinkholes.

Figure 30. View of Red Canyon sinkhole from the south. Intermittent Red Canyon drainage comes in from the right and over the past several centuries has flowed directly into the closed depression where it disappears into subsurface karst breccia.

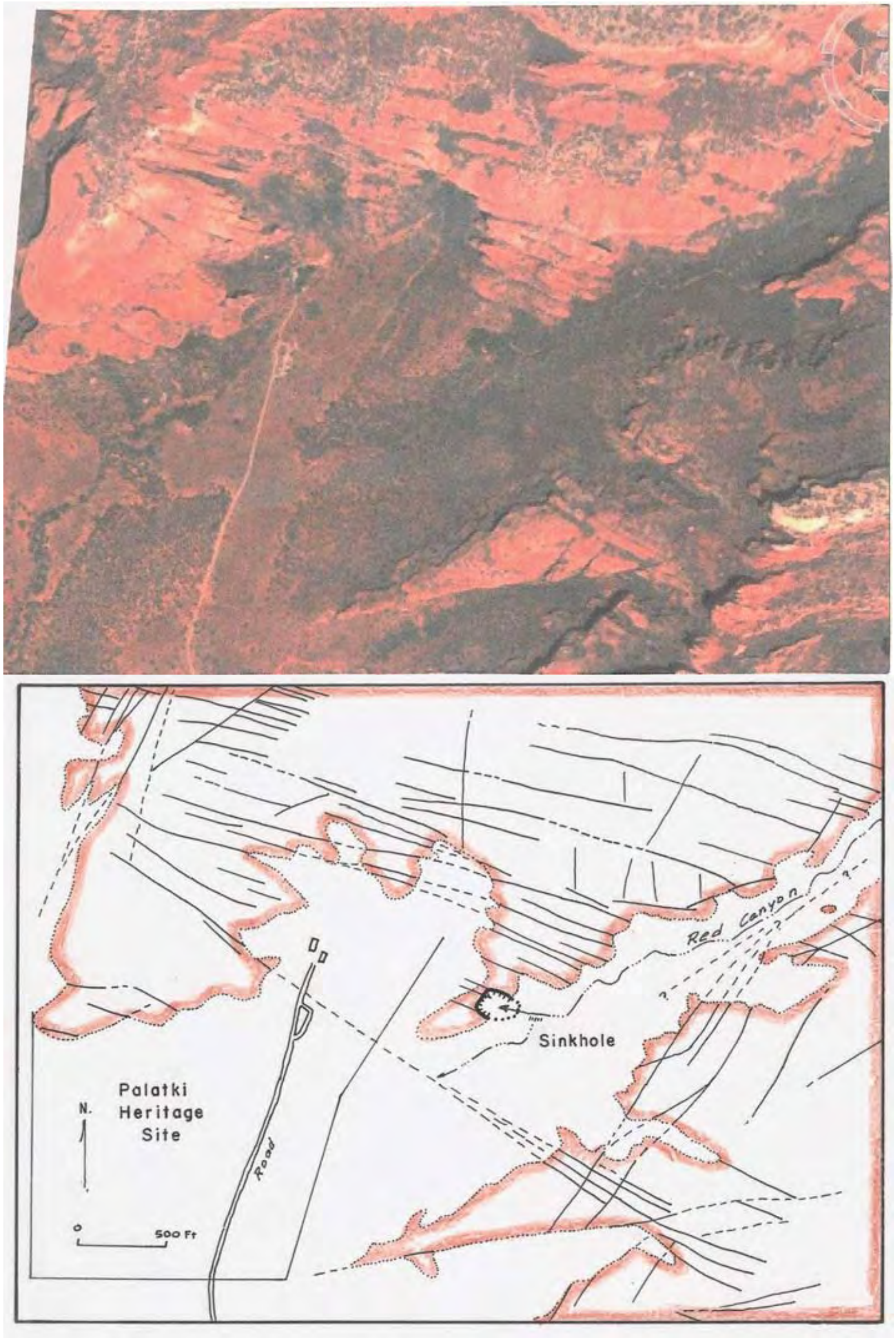

Figure 31. Google Earth™ image of Red Canyon rock joints. The satellite image above and the interpretation map below show major fracture systems in the area of Red Canyon sinkhole. Note the divergence of northwest-trending joints and their irregular spacing. Rock outcrop with multiple fractures tends to be more sculptured than the more massive buttes that host few fractures. Ground examination shows that many more joints are present than show up on the satellite images.

Figure 32. Northwest-trending joints on west wall of Red Canyon sinkhole. Drain is 98 feet (30 m) directly below these fractures.

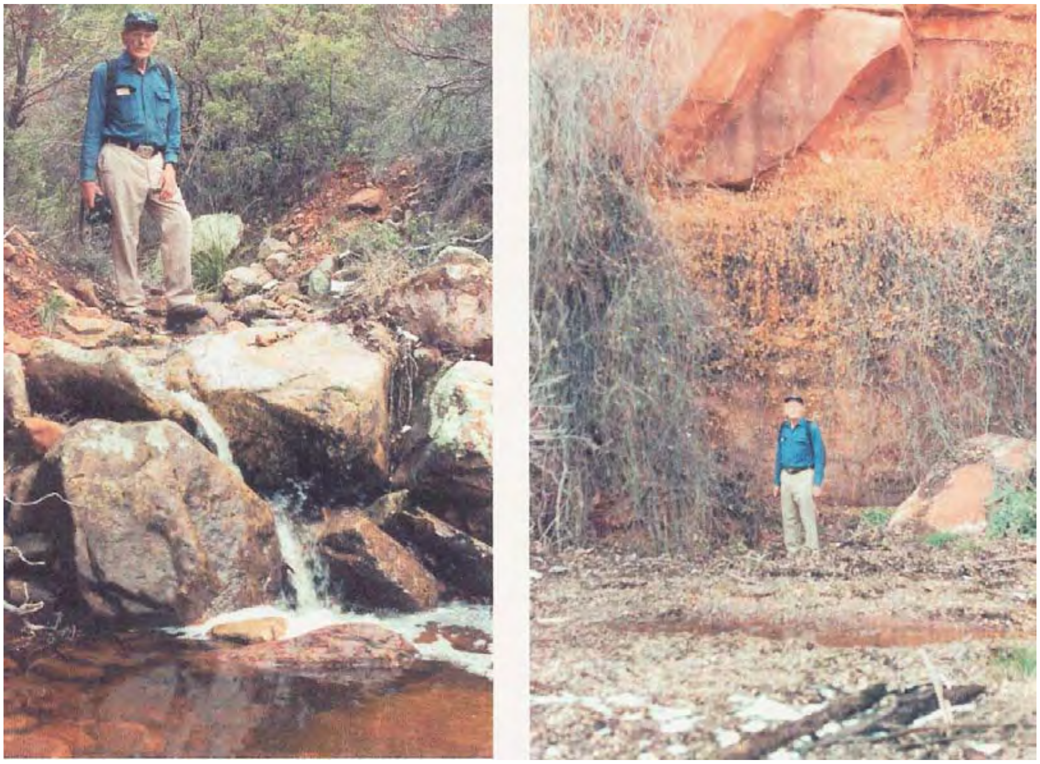

Figure 33. Snowmelt flowing into Red Canyon sinkhole. On March 12, 2001 a visual estimate of ~1 cubic foot per second of water flow was entering the sinkhole and rapidly draining at the far western side below the cliff shown in Figure 32.

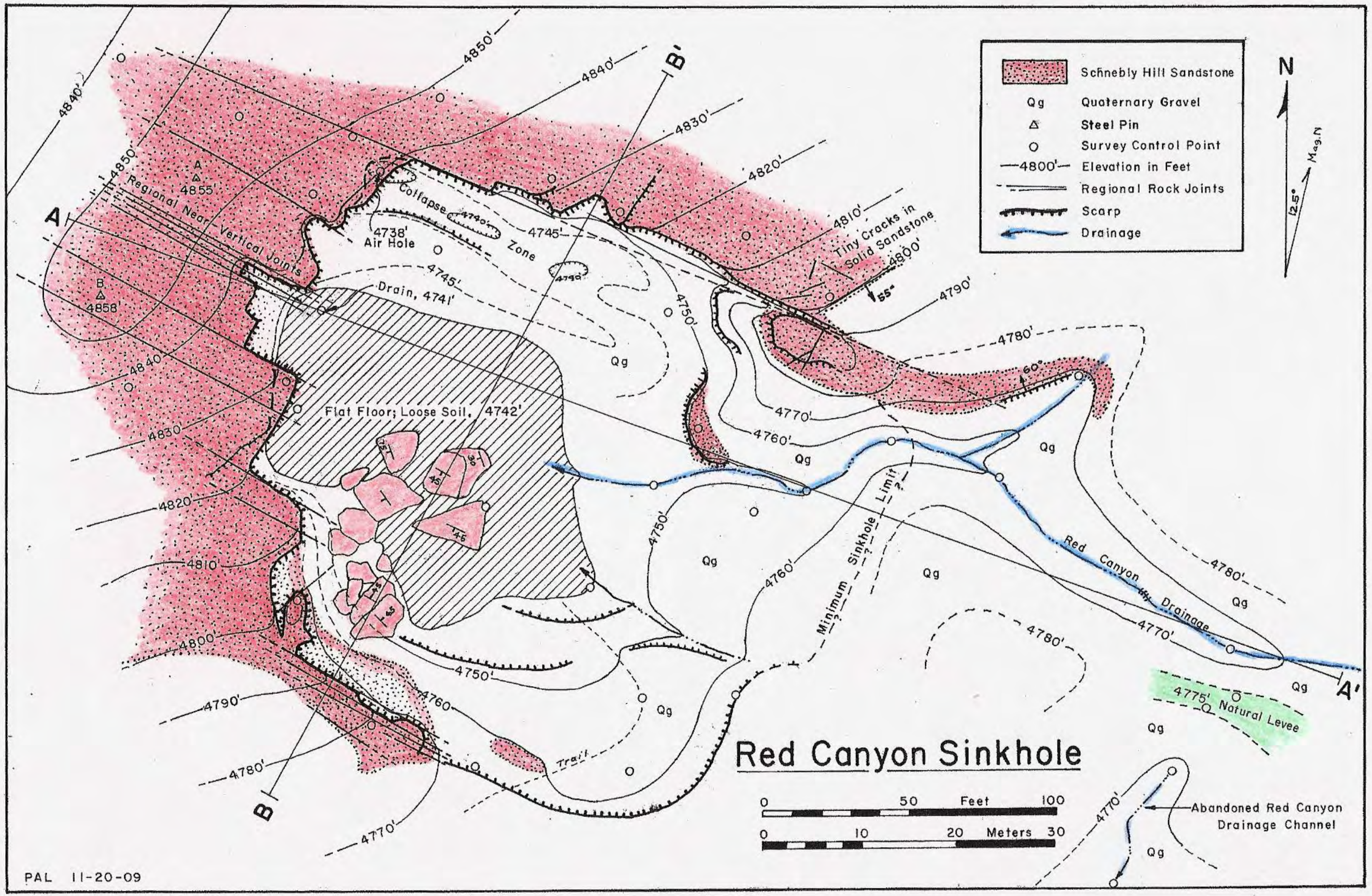

Figure 34. Geologic map of Red Canyon sinkhole. Bold outcrop cut by rock joints is shown in red. The flat dirt floor is shown cross hatched. The area in green is a naturally formed 5-6 foot high levee that diverts Red Canyon drainage directly into the sinkhole.

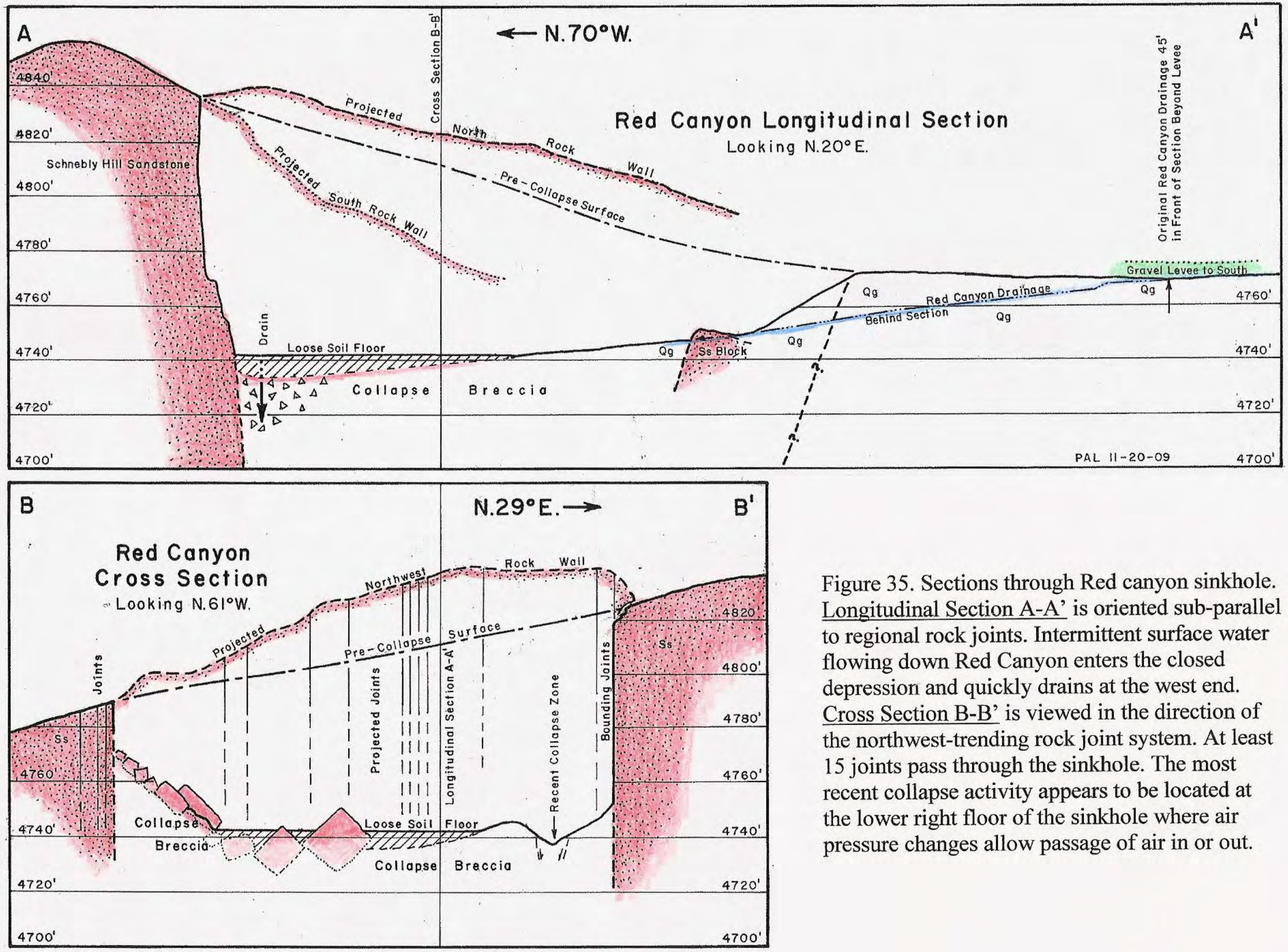

Figure 35. Sections through Red canyon sinkhole. Longitudinal Section A-A' is oriented sub-parallel to regional rock joints. Intermittent surface water flowing down Red Canyon enters the closed depression and quickly drains at the west end. Cross Section B-B' is viewed in the direction of the northwest-trending rock joint system. At least 15 joints pass through the sinkhole. The most recent collapse activity appears to be located at the lower right floor of the sinkhole where air pressure changes allow passage of air in or out.

4543 Sinkhole
Yavapai County; SW¼, Section 31, T.18N.-R.5E., Loy Butte 1:24,000 Quadrangle
34º 53’ 35” N, 111º 52:’ 43” W
Bedrock type at lip of sinkhole: Uppermost Hermit formation
Bearing of single observed joint: N.75ºW. (Weathered bedrock surrounds site)
Date of mapping: September 30, 2009
Small surface pit 13 feet in diameter by ~3 feet deep (4 m by ~1 m)
Surface area of pit: 133 sq ft (12 sq m)

In sharp contrast to Red Canyon, the 4543 sinkhole is the smallest in the Sedona area (fig. 36). The tentative name “4543” has been given by the writer to the feature because of its location near the 4543 foot elevation mark on the Loy Butte 1:24,000 quadrangle map. The site is next to a dirt road and the small pit has been partially degraded in past years by bulldozer in-fill and trash. Its cone-shaped depression is only 13 feet in diameter (4 m) and ~3 feet deep (~1 m). What makes this site a candidate for a fledgling sinkhole, however, is that a substantial amount of air will either exhaust or enter the subsurface through two small bedrock openings during periods of atmospheric pressure change. On December 10, 2001, after a period of 3-4 days of high pressure and a falling barometer, the writer observed a substantial amount of air rushing out of the rock openings. A similar outflow of air was witnessed by Sedona Westerners hikers on November 11, 2009. No attempt has yet been made to measure the amount of air movement in or out of the opening in an effort to calculate the volume of the subsurface void. Escaping air from the site was brought to the attention of the writer by U.S. Forest Service personnel. Weathered bedrock at the site is Hermit formation, not too far below its contact with the more massive cliff-forming Schnebly Hill Sandstone. One vertical joint along the northern pit edge has a bearing of N.75ºW. It is included in this report as a sinkhole that is probably in the formative stage of breaking through to the modern ground surface. Decrepitated bedrock and thin soil cover in the area that surrounds the sinkhole has prevented any detailed mapping of bedrock features thus far.

Figure 36. Photograph of 4543 sinkhole. Despite its small size, Air pressure changes allow air to exit or enter, indicating the presence of a large cavity below ground level.

Relative Size of the Known Sinkholes

Figure 37 is a map showing the relative size of all seven sinkholes plotted at the same scale. Surface and subsurface rock openings are shown for each of the sinkholes, along with the prominent rock joint bearings. Devils Kitchen, Devils Dining Room, Turkey Trail and Nolan Draw sinkholes all show a substantial enlargement at depth below the surface opening, with Nolan Draw having the largest undercut compared to its surface opening.

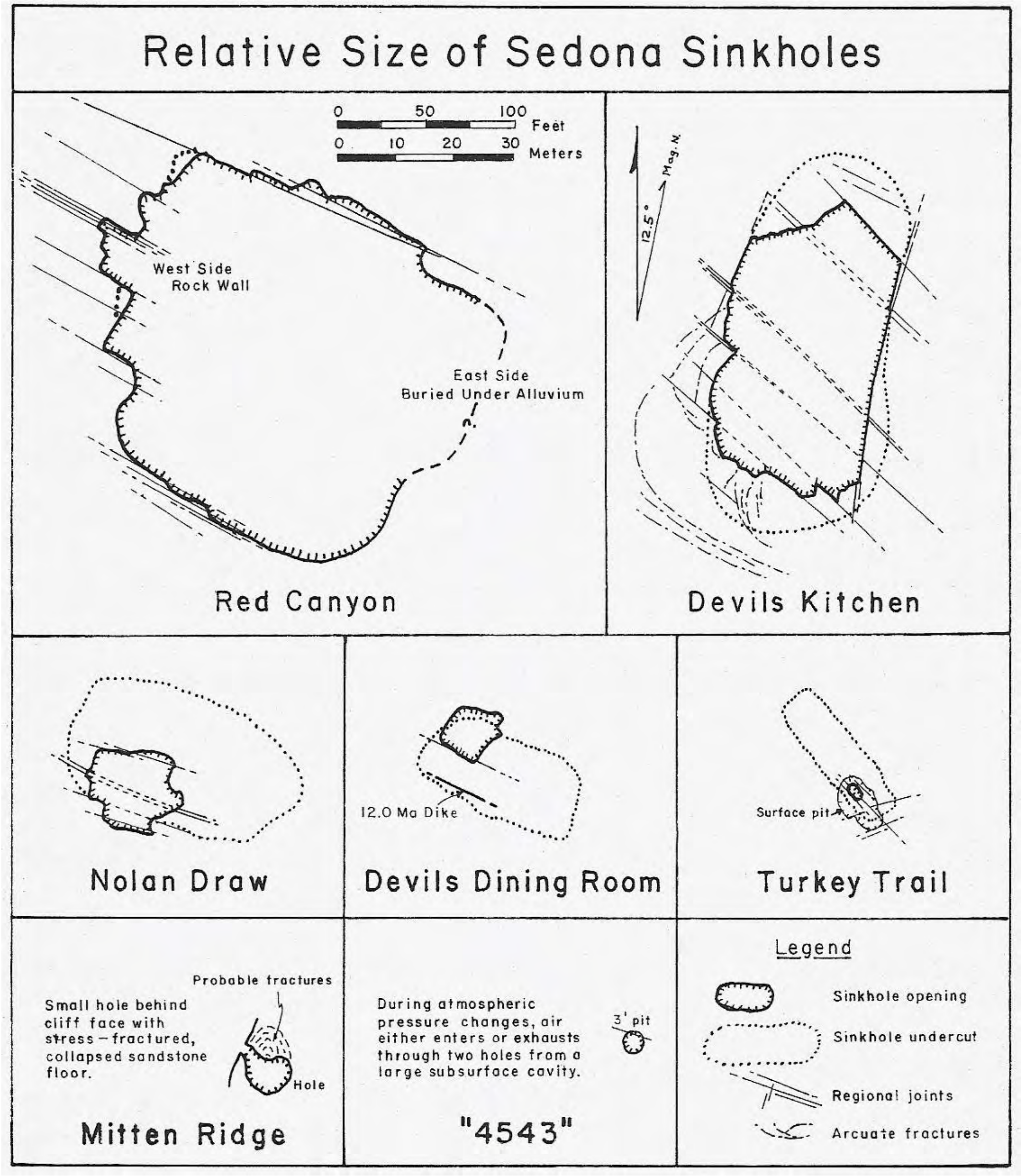

Figure 37. Relative size of Sedona sinkholes. Scale is the same for all sites.

Other Possible Sinkholes in the Sedona Area

Unconfirmed reports of local ground collapse, abnormally dry soil that might surround a collapse breccia, and/or air either entering or exiting from bedrock openings have yet to be investigated within the study area. Hopefully this current report will alert residents and hikers to be on the lookout for additional collapse features.

All but one of the sinkholes are located at surface elevations in the range of 3975 to 4840 feet (1210-1475 m), implying that they are located within eroded bedrock areas associated with the “Hermit bench” cited earlier. At those locations the rock surface is well above a Redwall Limestone cave system. Elevation differences also reflect the fault block within which the sinkhole is located. Mitten Ridge sinkhole, however, lies at an elevation of 5285 feet (1610 m), much higher than the others, and its opening lies not far below the Fort Apache Limestone member of the Schnebly Hill formation. Its small surface expression is at the extreme top of a collapse feature situated within a high bedrock ridge. If other collapse features are present under the Mogollon Rim cliff rocks to the north of Sedona, there may not have been enough erosion for them to have broken through to the present day ground surface. If other sinkholes are ever located it would help to demark the trajectories of hidden groundwater channels in the caves that underlie Sedona. Areas to the northeast of the Long Canyon trail north of Sedona show suspicious Google Earth images that warrant further investigation as potential sinkhole sites.

Estimated Size of Subsurface Redwall Limestone Caves

One can only speculate as to the size of Redwall Limestone caverns that lie beneath the Sedona ground surface. The following exercise attempts to quantify what happens when surface rocks collapse into an underground chamber. Because the exact dimensions of the entire system are unknown, these estimates should not be taken too literally.

Using Devils Kitchen sinkhole as a model, the following calculation has been made using the best available surface features. The undercut area of the sinkhole is estimated to be 22,160 square feet; equivalent to circle 168 feet in diameter. The distance from the original rock surface to the top of the Redwall Limestone cave opening is estimated to be ~600 feet (fig. 2). That means that a cylinder of rock 168 feet in diameter by 600 feet high once sat unbroken above a cave, equal to a volume of 13,301,970 cubic feet. When rock breaks it assumes a volume that is >15% larger than when it is not broken, making the volume of the collapse breccia approximately 15,297,265 cubic feet. After dropping into the cave opening the rock column would now be about 750 feet high from the bottom of a collapsed cave to the base of the rubble pile inside the sinkhole and have a volume of 16,625,350 cubic feet. The difference in volumes would account for the size of a cave opening, or 1,328,085 cubic feet before collapse. That would indicate that a former limestone cave approximately 100 feet high and 130 feet in diameter had collapsed.

While this estimate is speculative, it is considered to be conservative in the light of the large fractured surface to the southwest of Devils Kitchen sinkhole that indicates the sinkhole may ultimately double in size (see fig. 18). All in all, the surface evidence and groundwater throughput beneath Sedona provides a strong argument for the existence of a large cave network lying beneath the water table in the greater Sedona area. They may even rival the formative stage of a Mammoth Cave style system in Kentucky.

Age of Sinkholes

As yet there is no exact way of determining sinkhole ages, except in the case of eye witness accounts. Devils Kitchen sinkhole has been active between the 1880s and 1995 and is expected to enlarge in the near future and the site needs to be monitored. Turkey Trail sinkhole appears to be relatively old based on its surface features. It has an eroded funnel-shaped pit in weathered sandstone bedrock that narrows to a bedrock opening that measures only 5 by 10 feet (1.5 by 3 m). However, the sinkhole widens substantially underground to 25 by 85 feet (7.6 by 26 m). The westernmost interior corner of the sinkhole displays an unusual amount of calcium carbonate dripstone that covers sandstone bedrock (fig. 25). Similar dripstone was found in the Mitten Ridge sinkhole (fig. 19). Carbonate buildup in those openings is similar to limestone cave deposits that must have taken many thousands of years to develop.

Perhaps future paleontological research of Pleistocene faunal and floral remains may shed light on the age of some of the sites. Nolan Draw sinkhole would be an excellent candidate such a study. That site displays well rounded sandstone surface features that belie the large undercut opening that appears to be younger than the surface outcrops would suggest. The northwestern lip of Nolan Draw sinkhole also contains two potholes in sandstone bedrock that must have been formed by moderately strong surface water flow, possibly dating back to the waning stage of the Ice Age when precipitation was probably much greater. In short, it appears that the timing of the Sedona area sinkhole collapses has been quite variable over a period of several thousand years.

GROUNDWATER FLOW AND SINKHOLE RELATIONSHIP

U.S.G.S. Oxygen Isotopes and Sedona Water Recharge

Surface flow of water in Oak Creek and other stream drainages in the Sedona area is entirely independent of subsurface groundwater flow. Groundwater pumped from Sedona wells originates from Federal lands high on the Colorado Plateau.

Recent U.S. Geological Survey studies of oxygen isotopes have been made for groundwater reaching the Sedona area (Bryson, et al., 2007). The study reveals that in the Middle Verde watershed groundwater recharge comes from precipitation originating at elevations greater than 6900 feet (2100 m). That means that recharge for groundwater that ultimately passes beneath the Sedona area sub-basin of the Verde watershed extends up to the western flank of the San Francisco Peaks. In addition, isotope values for groundwater indicate that about 95% of that recharge comes from winter precipitation. An area of at least 700 square miles (1810 km^2) provides a static flow of ~15 millions of gallons per day of water that passes beneath the Sedona area before coalescing and discharging from several artesian springs in the Page Springs area (Lindberg, 2008).

Sinkholes Develop Over Major Groundwater Channelways

A modification of Figure 1 shows two hypothetical groundwater channelways that pass beneath the greater Sedona area (fig. 38). Until proven otherwise, it appears that sinkholes have been developing directly over caves in the subsurface Redwall limestone that have enlarged in modern time to the point of collapse.

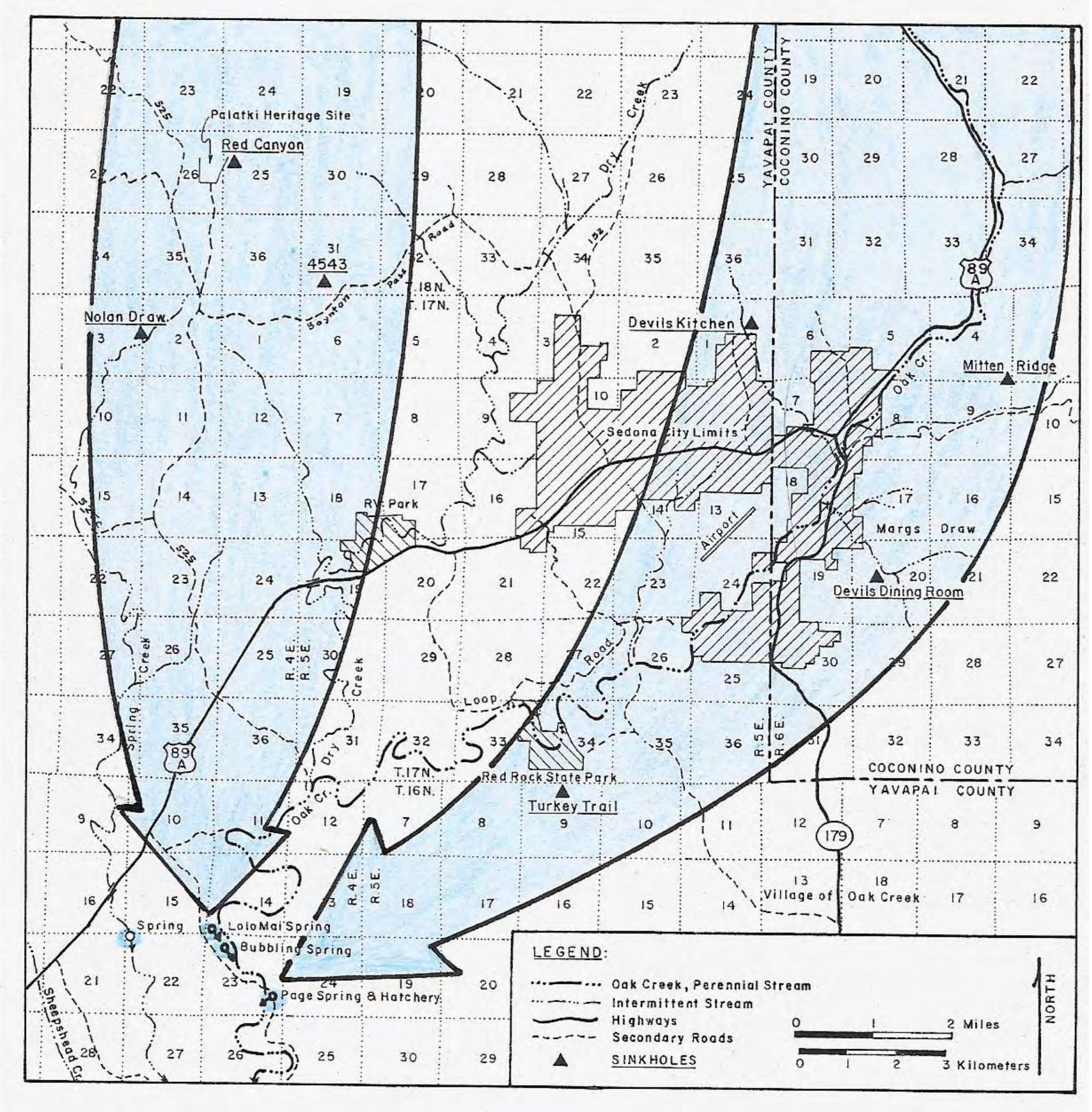

Figure 38. Hypothetical groundwater flow beneath the Sedona area. On the eastern side of Sedona the Devils Kitchen, Mitten Ridge, Devils Dining Room and Turkey Trail sinkholes are believed to overlie a major groundwater flow path through subsurface Redwall Limestone caves. Another possible flow path to the west would underlie the Red Canyon, 4543 and Nolan Draw sinkholes. It should be noted that these flow paths are entirely independent of Oak Creek or other surface flows. Coalesced groundwater first discharges below ground level where open Redwall cave openings intersect the plane of the Page Spring fault before rising to the surface as artesian flow (see figs. 8 & 39).

In the eastern part of Sedona the Devils Kitchen, Mitten Ridge, Devils Dining Room and Turkey Trail sinkholes are believed to overlie one set of inter-connected subsurface groundwater flow channels that lead to the Page Springs discharge area. To the west of town the Nolan Draw, Red Canyon and 4543 sinkholes are believed to overlie a separate subsurface flow channel that coalesces with the former before discharging as artesian springs in the Spring Creek and Page Springs area (figs. 8 & 38-40). It should be stressed that these groundwater flow paths are probably very complex in detail with many twists and turns before discharging as artesian flow.

Because a major component of sinkhole collapse is their preferential alignment along prominent northwest-oriented rock joints, a major part of the subsurface cave system must be oriented in that direction. The postulated northeast to southwest solution channels that may connect the water-filled caves to an overall southwest direction of flow down-gradient toward the Verde Valley, is believed to have formed during the post-Laramide erosional time period (see **Laramide Uplift, Erosion, and Deposition of Exotic Gravels**). Other suspected pathway inter-connections include the near east-west Bear Wallow fault through West Sedona, the north-south Oak Creek faults and various other Verde graben fault planes that have experienced more than one stage of offset.

Local oral presentations of Sedona area groundwater flow and sinkhole development have been made by the writer over the past decade. One of the diagrams presented in those talks is a schematic cross section showing water passage from the plateau recharge to its discharge in the Page Springs area (fig. 39). In addition to the recent AIPG/AHS symposium on water resources (Lindberg, 2008), illustrated talks on ground-water flow and sinkhole development have been presented to the Verde Watershed Symposium, the Northern Arizona Watershed Field School, and the University of Arizona Master Watershed Program (Lindberg 2001, 2002a & 2002b).

Page Springs Artesian Discharge of Groundwater

Page Springs Area Artesian Springs (Page Springs 1:24,000 Quad)

Lolomai Springs, SW cor. Section 14, T.16N., R.4E.
Bubbling Springs, NW ¼ Section 23, T.16N., R.4E.
Page Springs, SE ¼ Section 23, T. 16N., R. 4E.
Spring Creek Ranch, SW corner, Section 15, T.16N., R.4E.

An estimated 15 million gallons a day of groundwater flow discharges from four artesian springs in the greater Page Springs area. Lolo Mai Spring at the RV resort (private land), Bubbling Spring (fig. 40) and Page Spring (state lands) add a significant amount of water to Oak Creek and the Verde River further downstream. An additional small artesian flow occurs at the Spring Creek ranch to the northwest (figs. 1 & 38-40).

Artesian springs in the Page Springs area discharge at the 3500-3520 foot (1067-1073 m) elevation. However, the water first exits from open Redwall cave openings at the interface with the Page Spring-Spring Creek-Sheepshead fault planes several hundred feet below ground level before rising to the surface as artesian flow (figs. 8 &. That puts a straight line drop in the hydrologic gradient of ~450 feet (137 m) in 9.2 miles (14.8 km) between the Devils Kitchen sinkhole and the Page Springs discharge point, or a drop of ~50 feet per mile (9.3 m/km).

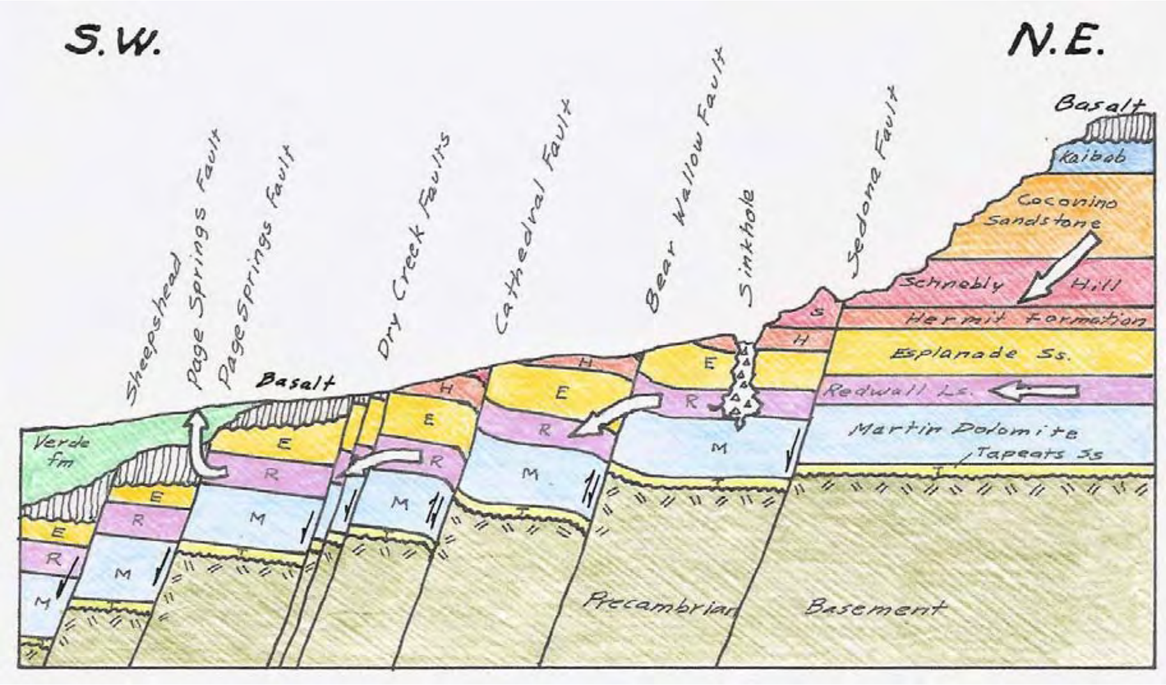

Figure 39. Schematic cross section through Sedona showing groundwater flow. This section shows how precipitation from the Colorado Plateau recharge area generates groundwater that passes beneath Sedona en route to the Page Springs discharge area (white arrows). Much of the flow passes through cavernous Redwall Limestone (lavender color) before exiting to surface from plane faults in the Page Springs area. Reactivated Laramide age faults, like Bear Wallow, Cathedral, and other staircase-like Verde graben faults, displace Paleozoic strata in numerous fault blocks, thus aiding to groundwater flow. Sinkholes have developed directly over water-filled Redwall Limestone caves.

Figure 40. Bubbling Spring artesian flow upstream from Page Springs. This water flows into the native fish ponds at the Page Springs fish hatchery a short distance away.

Evolution of Groundwater Flow in the Sedona Area

Reactivation of Laramide-age high-angle reverse faults as normal faults later in time has occurred on the Cathedral, Bear Wallow, Oak Creek and other faults in the Sedona area. Increased rock breakage along fault planes has allowed for greater groundwater permeability in modern time. Oak Creek Canyon is still too youthful to have evolved into one that is dominated by subsurface flow. Where Oak Creek makes an abrupt turn at Grasshopper Point and enters Sedona it displays an interesting feature. At static low water flow, typical of most months of the year, surface flow measurements by the Arizona Department of Environmental Quality (ADEQ) have measured more water flowing in Oak Creek as it enters Sedona than is measured a short distance upstream at Grasshopper Point. Several decades ago ADEQ personnel were perplexed as to why this was happening as several members of the Keep Sedona Beautiful organization watched the measurements being taken. If solution cavities exist in subsurface Redwall Limestone lying just below the stream surface beneath Midgley Bridge, flow through a subsurface cave could easily explain the additional water entering Sedona. Groundwater could be venting from a subsurface cave system where it intersects the plane of the Sedona fault and adding to the flow of surface water. Rocks in Uptown Sedona have dropped by ~200 feet (~60 m) relative to those within the Wilson Mountain horst. The Sedona fault marks the easternmost normal fault offset at the margin of the Verde graben.

As described in an earlier section (**Anomalous Post-Graben Valley Erosion**) the older Dry Creek and Margs Draw valleys are now dry but once had to have had substantial flows of surface water in order for so much material to have been removed by erosion. Not only have their original streams been beheaded following the offset of the modern down-to-the-east normal phase of the relatively young Oak Creek fault, their surface rocks are riddled by an abundance of rock joints and fault planes that allow present day surface water to percolate downward into a network of groundwater channels. Combined with the ever growing size of the subsurface Redwall dissolution cavities and open caves, emanating a source far to the north under the plateau, surface water flow has evolved into one that is dominated by subsurface groundwater flow since the time of drainage reversal following the formation of the Verde graben 10 Ma.

SINKHOLES AND GROUNDWATER CONTAMINATION HAZARD

As described in earlier sections, Devils Kitchen sinkhole poses a future collapse hazard to humans that could come without warning. Of greater importance, however, is the potential hazard posed by short-circuiting of septic waste directly into a subsurface Redwall Limestone cave system through a concealed sinkhole. Their karst breccia columns would allow septic waste water to drain directly and rapidly into the subsurface aquifer system thereby causing immediate contamination. Anomalously rapid drainage (standard ”perk test”) at a potential building site could be an indicator that a concealed karst breccia exits in that area and serious aquifer contamination is a possibility. While no sinkholes have yet been discovered within town limits, their hidden presence should not be ignored by community planners. Sinkholes do exist in close proximity. The sure way to eliminate that form of groundwater contamination is to have the entire community connected to a fully completed sewer system and wastewater treatment plant.

SINKHOLE ENTRAPMENT OF PLEISTOCENE MEGAFAUNA

Sinkholes in other parts of the world are known as ideal entrapment sites for prehistoric animals, especially those associated prior to the extinction of Pleistocene mega-fauna at the end of the last Ice Age about 10-11,000 years ago. Whether or not any of the Sedona area sinkholes are old enough to have trapped the now-extinct Pleistocene fauna remains to be seen. Excavation of the floors of some of the older sinkholes, such as Nolan Draw, could prove to be of interest to both archaeologists and paleontologists.

SYNOPSIS

Modern Sedona sinkholes have formed by collapse of large subsurface cave openings in Redwall Limestone beneath the water table in the greater Sedona, Arizona area. The location of sinkholes is believed to overlie collapsed Redwall Limestone caverns that carry groundwater from a recharge area high on the Colorado Plateau to its ultimate discharge in the Page Springs area about 9 miles (14.5 km) to the southwest of Sedona. Sinkhole collapse has probably been going on over several thousand years but the Devils Kitchen sinkhole is still enlarging in historic time. While the risk of sinkhole collapse to humans is probably quite small, the possibility of groundwater contamination through hidden sinkholes and its karst breccia presents a much greater hazard.

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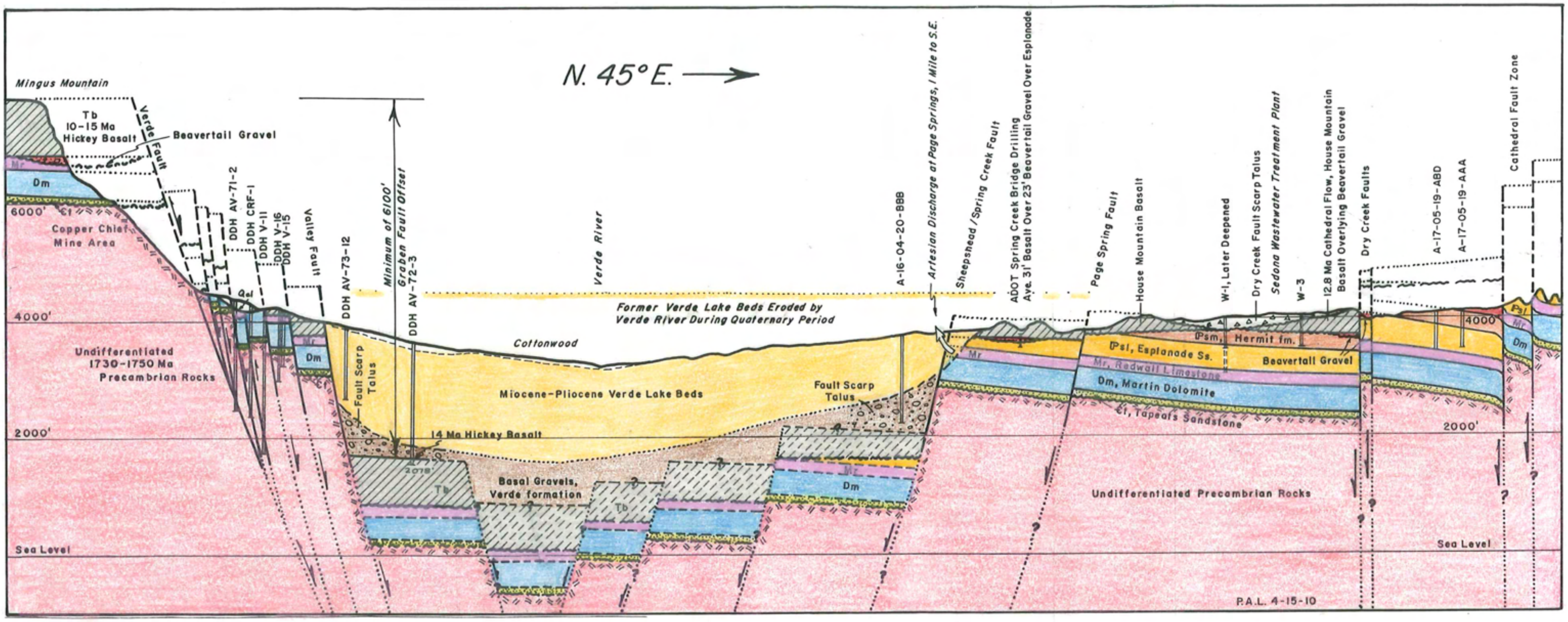

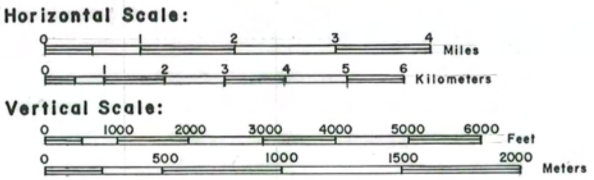

Figure 8. Structural section of Verde graben.

View is to the northwest with coverage from the Copper Chief mine area south of Jerome to the Dry Creek Bridge area on Highway 89A to the southwest of Sedona. Undifferentiated Precambrian basement rocks are shown in pink. On the western margin of the Verde Valley detailed surface mapping and seven 1973 and older mineral exploration drill holes show that the Verde fault system has dropped the western margin of the graben by a minimum of 6100 feet (1860 m). Even deeper displacement is projected further into the valley based on gravity surveys. Hickey Basalt was penetrated in Hole AV-73-12 and has been recently age dated at 14 Ma (Ed Dewitt, USGS, personal communication).

Similar graben faults and drill hole information on the Sedona margin of the Verde graben to the northeast show similar displacement. The Bear Wallow, Dry Creek, Page Springs and Sheepshead faults offset 12.8 Ma Cathedral basalt of House Mountain-age, including underlying Beavertail Gravels and all older stratigraphy. Mapping and drill hole evidence shows conclusive proof that the Verde graben is a closed structural basin and not a river-carved valley. The Mogollon Rim escarpment was formed by retreat into the Colorado Plateau from erosion of the Dry Creek and nearby graben fault scarps.

Miocene-Pliocene Verde formation gravels and lake beds fill the Verde graben. During the Quaternary Period the Verde River developed as a south flowing river that has eroded the topmost layers of the Verde formation to its present elevation.