Surface and Subsurface Water Flow in the Sedona Region of Arizona

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Physiographic Setting:

Sedona, Arizona is located beneath the colorful sedimentary rock cliffs of the Mogollon Rim that forms the serrated erosional margin of the Colorado Plateau. The town is situated at the boundary of two major physiographic provinces of Western United States. The high standing Colorado Plateau rises abruptly to the northeast above town level. To the southwest lies the Basin and Range physiographic province. Verde Valley and Mingus Mountain are the first of a series of paired basin and range structural depressions and elevated highlands that extend westward for hundreds of miles into California. The area near the boundary of these two distinctive physiographic provinces contains numerous fault zones, none of which are believed to be active in recent geologic time. Within 20 miles (32 km) of Sedona a wide variety of rock types and ages are exposed. Crystalline Precambrian rocks exposed at Jerome are ~1,750 million years old and impervious to significant water transfer. In sharp contrast, the sinkholes and collapse breccias in the Sedona area have developed in historic time in Paleozoic rocks. Limestone solution caves and locally porous aquifers exist in local subsurface rocks. Figure 1 shows the spatial relationship of physiographic features in this unique landscape.

Relationship of Hydrology to Geological Features:

Surface and subsurface water flow is dictated by geological conditions that exist within any drainage system. In most regions of the country surface water flows very fast relative to the passage of groundwater through the underlying rocks. For example, the great volume of water that the Mississippi River discharges into the Gulf of Mexico exceeds the amount of groundwater flowing into the gulf by many orders of magnitude. Along the Mogollon Rim a completely different set of conditions is present. Rainfall and snowmelt recharges the hydrologic system for ~2500 feet (~760 m) above the town. Oak Creek collects water from flash runoff and numerous springs along its southwestward course into the Verde Valley. Down slope from Sedona large point discharges of groundwater occur at Page Springs, Spring Creek, and Montezuma Well. More than 17 million gallons of water per day are passing through a complex network of solution caves and watercourses that lie well below the ground surface in the Sedona area. These water conduits are inferred geologically but are not readily obvious from surface observations. What flows below ground level constitutes a substantial portion of the overall water transport that eventually reaches the confluence of Oak Creek and the Verde River.

Geology and Stratigraphy of the Mogollon Rim Area:

The imposing and colorful cliffs of the Mogollon Rim near Sedona are composed of Paleozoic age (550-250 million years old; Ma) sedimentary rocks that are relatively similar to the rock strata found in the upper half of the Grand Canyon that lies about a hundred miles to the north-northwest. The cliffs above town level are mainly composed of sandstone and limestone belonging to the latter part of Paleozoic age. Figure 2 shows a schematic stratigraphic section of the rocks exposed in the Sedona area (1).

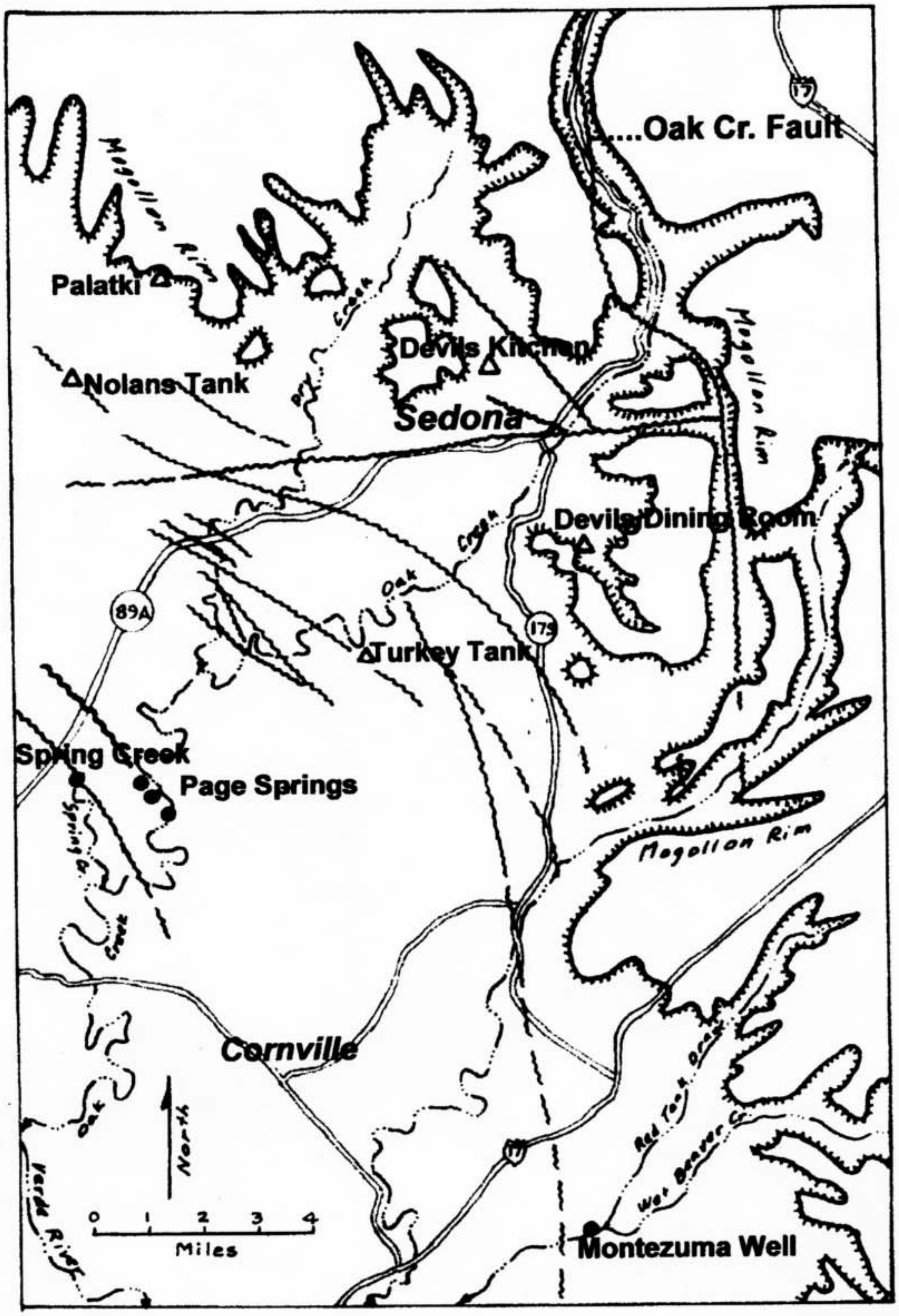

Figure 1. Location map of the Sedona area showing major towns, roads, drainages and other physiographic features. Faults are shown as wiggly lines; Sinkholes are open triangles; Springs are black circles.

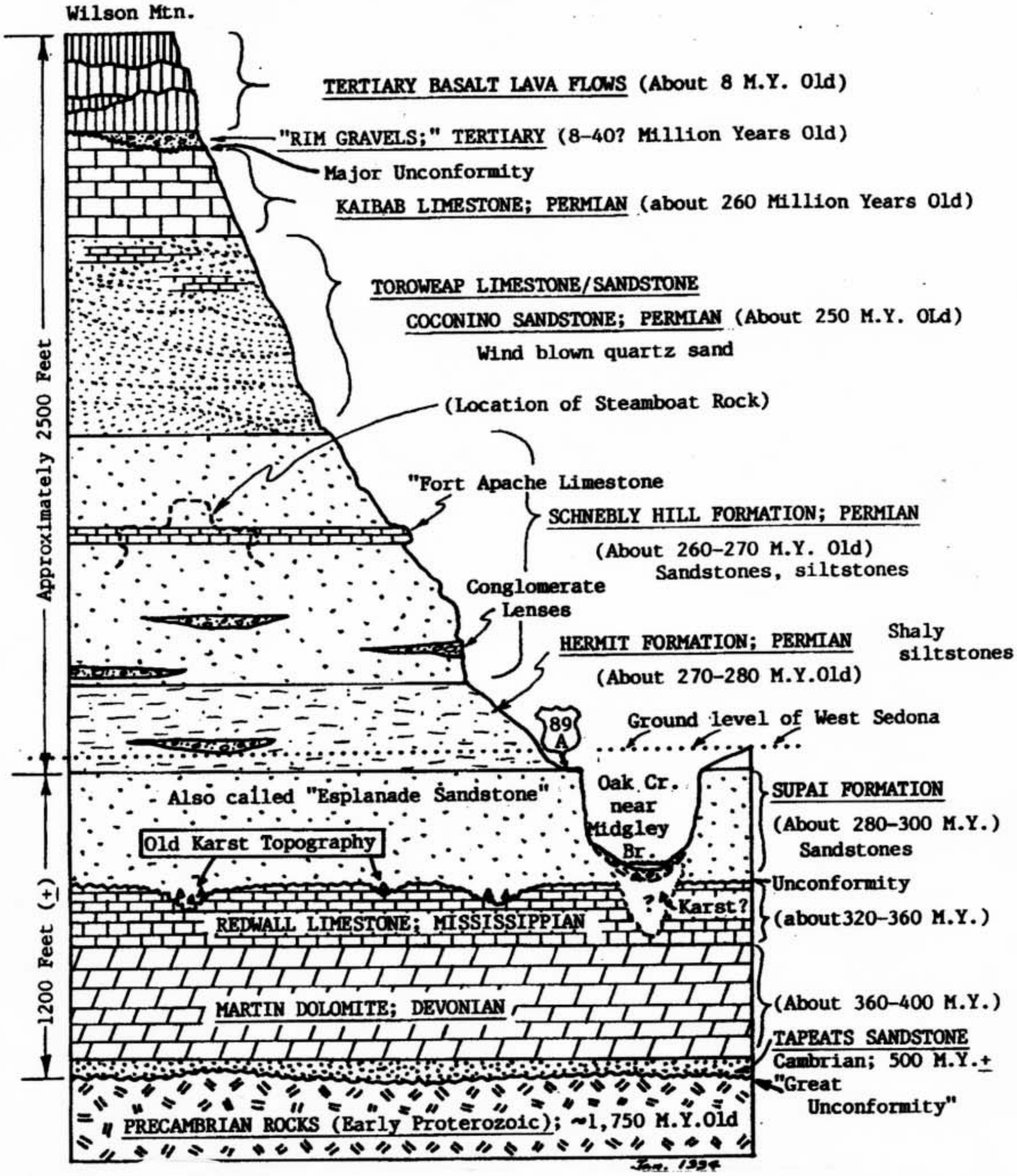

Figure 2. Schematic stratigraphic section of rocks in the Sedona area. This representation shows the rocks exposed near the Midgley Bridge on Highway 89A adjacent to Wilson Mountain (1). The rock strata below the level of Oak Creek are projected into the section from drill hole data and surface mapping from the Jerome area. Note the difference between the "cliff-forming" and "slope-forming" rocks in the stylized geologic section. Cliff-forming rocks stand relatively tall, whereas the softer Hermit formation rocks contain just enough clay to decompose much faster and make an erosional bench. The flat bench upon which the town of Sedona is built is underlain almost exclusively by the slope-forming Hermit formation.

Kaibab Limestone of the Permian Period (~230-250 Ma) caps the top of the Mogollon Rim cliffs. This limestone was deposited in a warm and shallow tropical sea prior to the breakup of the Pangea Supercontinent. Moving down from the plateau, just as groundwater would percolate, thick layers of cream-colored Coconino Sandstone and red-colored Schnebly Hill Sandstone lie beneath the Kaibab Limestone. And further below at town level is the red-colored shaly siltstone of the Hermit formation. This softer rock layer forms the erosional bench upon which the residences of West Sedona and Uptown Sedona are built. Less than 200 feet (<60 m) below ground level is the top of the massive Esplanade Sandstone. The Esplanade is not exposed in Sedona itself but is exposed just east of town on the uplifted side of the Sedona fault at Midgley Bridge on Highway 89A (see Figure 2). Some Sedona water wells extract water from fractured and porous Esplanade Sandstone. The important carbonate aquifers lie beneath the Esplanade Sandstone. The Redwall Limestone of Mississippian age is composed of calcium carbonate ($CaCO_3$) that is relatively water soluble. The underlying Martin Dolomite of Devonian age is made up of less soluble dolomite ($CaMgCO_3$). Five known sinkholes in the area show evidence of recent collapse. Drill hole records reveal that an extensive cave system exists below the water table within the two carbonate rock formations. Subsurface solution caves have now grown large enough to collapse in modern time!

Local Faults:

Figure 1 shows the major faults that offset the sedimentary rock layers in the Sedona area. These inactive faults should not to be classified as "earthquake faults" that present a seismic hazard. Groundwater will move laterally as well as vertically along the plane of faults such as these that contain broken and permeable rock debris. Faults also permit groundwater transfer across permeable beds that are offset to different levels.

Origin of Sinkholes:

Figure 1 also shows the location of known sinkholes. The Devils Kitchen sinkhole lies just north of a residential development in the Soldier Wash area of West Sedona. An early pioneer recounted: "*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.*"(2). In late 1989 the northern third of the sinkhole collapsed to form a surface opening of 92 x 150 feet (28 x 46 m) that enlarges downward to 105 x 225 feet (32 x 69 m). In 1990 the writer mapped the site and reported it in detail (3). Figure 3 shows a geologic map of the site and Figure 4 shows a longitudinal section through the long axis of the sinkhole. The sinkhole was formed by the collapse of a large water-filled Redwall Limestone solution cave that is estimated to lie ~700-850 feet (~215-260 m) below the ground surface. In order to account for this large a volume of downward-displaced broken rock rubble, the original cave opening prior to collapse may have exceeded 250 feet (>75 m) in diameter. All 5 known sinkholes in the Sedona area lie along prominent northwest-trending joints that allowed weakly acidic surface water to penetrate downward and dissolve limestone. Throughout geologic time rainwater has always contained dissolved atmospheric CO_2, making it acidic.

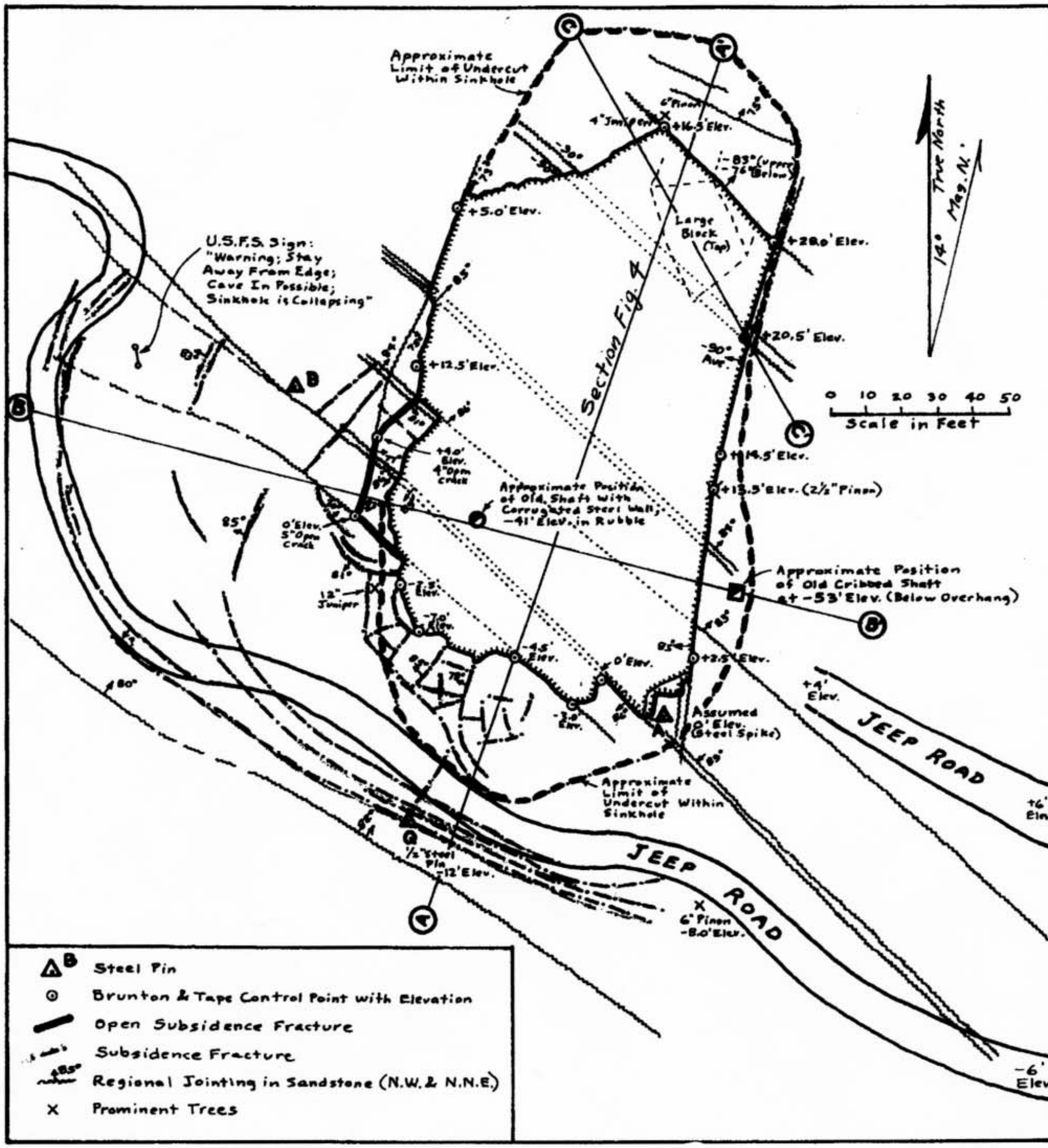

Figure 3. Geologic map of the Devils Kitchen sinkhole, West Sedona, Arizona. The dominant northwest-trending joints and subordinate north-northeast joints have allowed surface groundwater to penetrate downward to dissolve Redwall Limestone cave openings at depth. Collapse has taken place in historic time. Note the arcuate fractures in the southwest corner of the sinkhole where caving will be taking place in the near future.

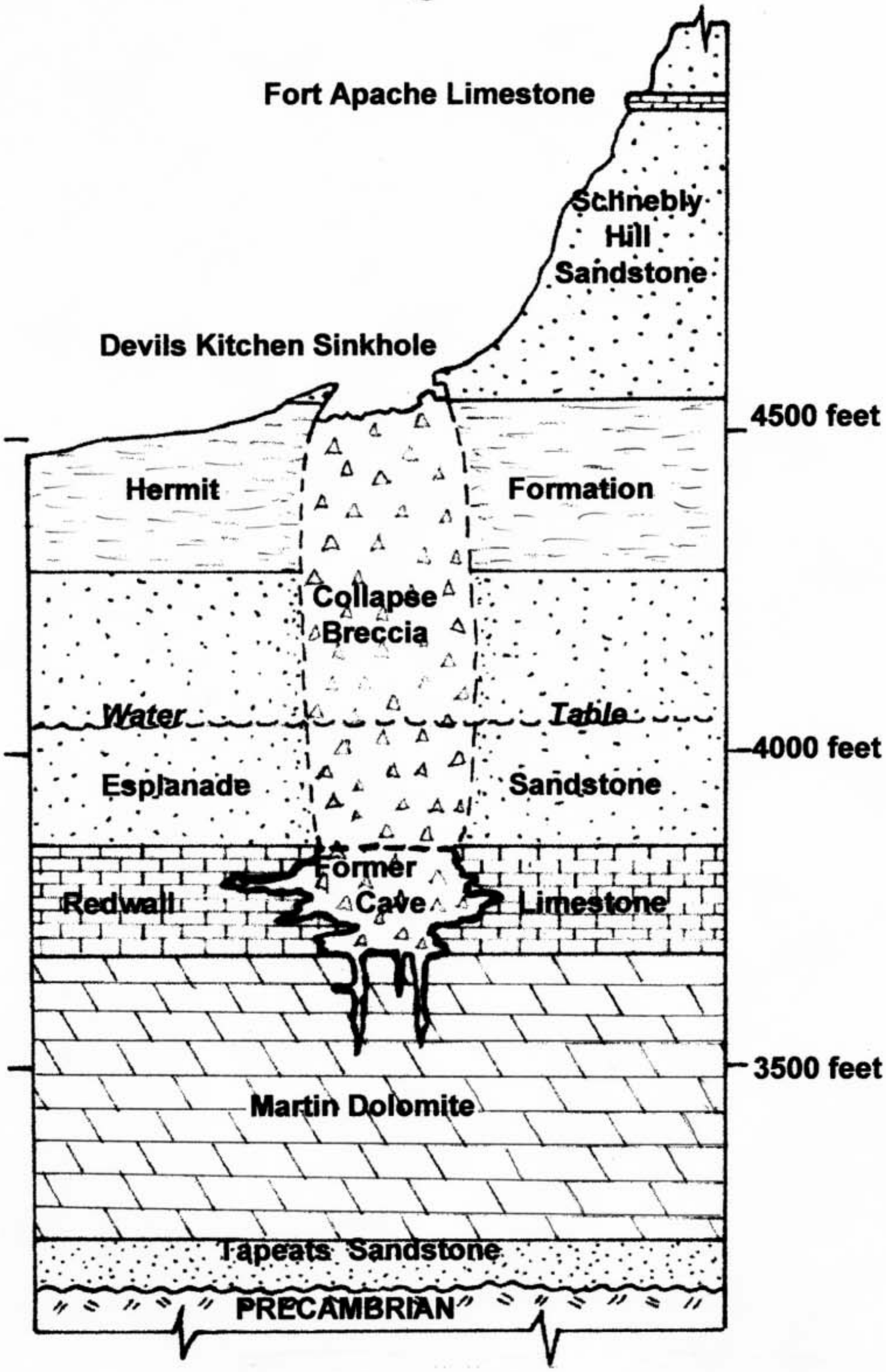

Figure 4. Longitudinal section through Devils Kitchen sinkhole. This section looks northwesterly along prominent regional joints that penetrate the Sedona region. Over the past several million years weakly acidic surface and groundwater has dissolved large solution caves in the Redwall Limestone lying deep beneath the present ground surface. When the cave openings became too large to support the roof rocks the caves collapsed. An upward migrating cylindrical column of broken rock filled the void. The sinkhole is breaching the surface in historic time.

Surface Water Runoff Through the Sedona Area:

Oak Creek maintains a water flow even during years of drought. The upper reaches of the creek are fed by several springs in Oak Creek Canyon. During most of the year its tributaries are dry but they can reach flood conditions during times of rapid snowmelt or summertime thunderstorm activity. Oak Creek picks up a substantial amount of water below the Page Springs area before joining the Verde River downstream.

Suspected Subsurface Water Flow Beneath the Sedona Area:

Figure 5 shows a schematic cross section oriented along an idealized transect running through the West Sedona area from the top of the Colorado Plateau to the Page Springs area. The rainfall and snowmelt that are added to the top of the plateau slowly percolate downward through the Paleozoic sedimentary layers. By the time water has dropped down to the elevation of Sedona, it reaches the less permeable Hermit formation that contains minor clay-rich shale beds. Most water probably passes downward through the Hermit formation and the underlying Esplanade Sandstone (part of the Supai group of rocks) along fault zones and numerous joint systems. The water table beneath West Sedona would lie within the Esplanade Sandstone; several hundred feet below the present day ground level. Water is suspected to collect into a complex interconnected system of solution cavities and open caves in the Redwall Limestone, well below the water table.

The cave system is suspected to shunt water in the subsurface toward the Verde Valley to the southwest until it ultimately breaks loose to the surface and flows as artesian water springs in the Page Springs area. Even though the springs breach the surface in Verde Lake beds the water comes from cave openings and point discharges from eroded and faulted subsurface termination of Redwall Limestone bedrock. This constant flow of underground water constitutes a major portion of the water transport passing through the Sedona area. The uniformity of water flow appears to be independent of recent drought conditions and probably taps deep-seated water reserves that lie well to the north of Sedona well into the Colorado Plateau.

Major Spring Discharges:

There are three major spring discharges lying to the southwest and south of Sedona (see Figure 1). By far the biggest discharge is in the Page Springs area several springs release in excess of 15,000,000 gallons per day at 68°F (>57,000,000 liters per day at 20°C). The second largest spring is at Montezuma Well where there is a constant discharge of ~1,585,000 gallons/day (6,000,000 liters/day) at 76°F (24.5°C). About a mile to the west-northwest of Page Springs is a relatively small spring discharge at Spring Creek. Altogether these springs constantly discharge >17,000,000 gallons of water per day (>64,000,000 liters/day) that originally passed beneath the Sedona area.

Travertine Domes at the Montezuma Well National Monument:

Montezuma Well is a spring that discharges a constant flow of water that is highly charged with dissolved calcium carbonate. It is located on a collapsed, spring-deposited travertine dome that has a central 325 foot (100 m) wide pond. The spring discharges water through the eroded southern edge of the travertine dome along Beaver Creek.

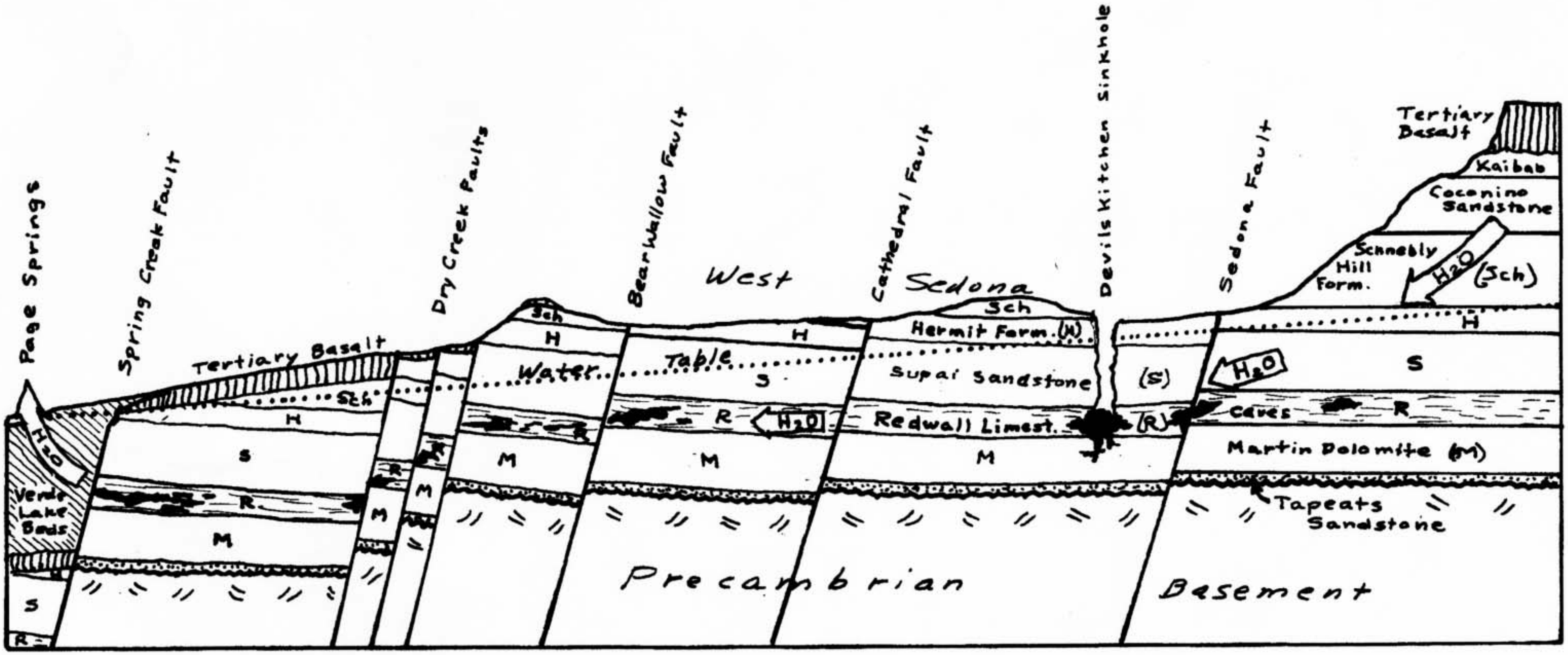

Figure 6. Schematic cross section through West Sedona from the Colorado Plateau to the Page Springs area showing suspected subsurface groundwater flow. This section is looking toward the northwest in the direction of prominent joint fractures that allowed surface-derived water to percolate downward and dissolve solution caves in the underlying Redwall Limestone. Water collects in the subsurface cave system and ultimately discharges to the southwest (left) in the Page Springs area.

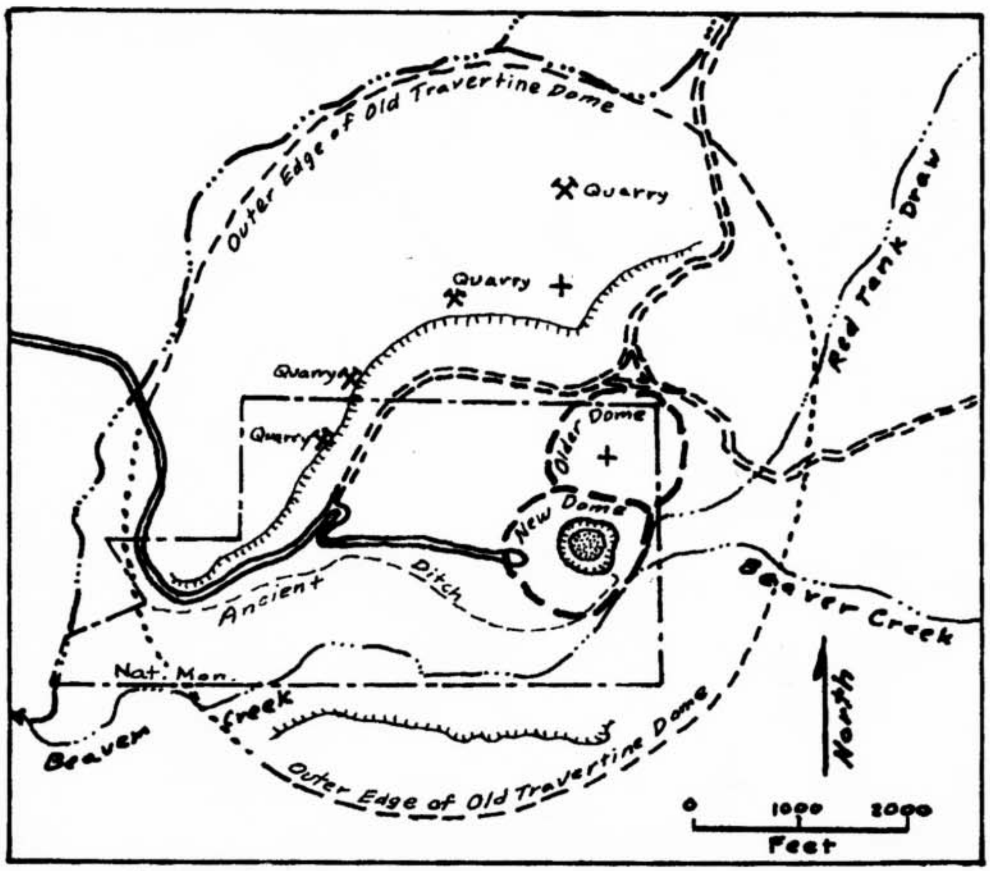

Figure 7. Modern and ancient spring-deposited travertine domes in the Montezuma Well area. Springs have been active in the area for a long period of time. The oldest travertine dome has been deeply eroded by an meander of the ancestral Beaver Creek and may be as much as two million (?) years old (4). A number of small quarries for crystalline spar calcite ("onyx") are present on the northern, outward sloping, hard upper carapace of the oldest and largest of the travertine domes.

A series of springs in the Montezuma Well area have been depositing travertine domes for possibly 2 million years (4). The spring water contains large quantities of dissolved calcium carbonate that has been derived from actively forming solution caves in limestone beds that lie up-gradient from the discharge point. The sheer volume of calcium carbonate in the travertine deposits and adjacent Verde Lake beds indicates that huge cave systems must exist in the cliffs to the north. As the spring releases mineral-charged water at ground level its contained carbon dioxide gas is released and the water is no longer acidic and calcium carbonate is deposited as travertine domes. Prehistoric Sinagua indians utilized the water for irrigating agricultural fields located west of the spring outlet. One of these prehistoric irrigation ditches has been excavated within the monument. The walls of the ditch are case-hardened with a thick layer of travertine that had been built up with many years of use.

As shown in Figure 6 the present day discharge site of the spring is centered on a 1500 foot (460 m) diameter travertine dome that merges with an older, similar sized dome located about 900 feet (~275 m) to the north-northeast. These domes are relatively small in comparison to an older, deeply eroded, and higher travertine dome that is ~7,000 feet (~2130 m) in diameter. That dome is centered ~2400 feet (~730 m) to the north of Montezuma Well and has been quarried on its northern flank for crystalline "onyx" spar calcite. The entire central part of the oldest dome has been eroded away by a meander of Beaver Creek during the past million years or so. A prehistoric pithouse has been excavated on the old flood plain of that ancient meander that cuts into the dome's core area. An accurate means of dating the oldest of the travertine domes may one day allow us to tell just how long the Montezuma Well springs have been operating. It is possible that they have been discharging spring water in this area for the past two million years.

Conclusions:

Oak Creek flows down Oak Creek Canyon and through the eastern part of the Sedona area along a perennial stream course. At times of heavy runoff many of the tributary drainages can contribute substantial but short-lived flows of water. But what is hidden from view is much more important from the standpoint of a dependable water supply. Figure 5 shows the suspected course of water that passes beneath town level and below the water table. Water wells extract the town's water supply from subsurface sandstone and limestone aquifers. Much of the water that is pumped from several locations is suspected to accumulate at the wells through abundant rock fractures and solution cavities. A significant amount of water continually flows below town level before emerging down slope to the southwest at locations like Page Springs.

References:

1. Jan. 1994, Lindberg, P.A., Schematic stratigraphic column, Sedona area: Proccedings of Our Common Ground Forum, Red Rock State Park, Sedona, Arizona.
2. 1968, Those Early Days: Published by Sedona Westerners, p. 60.
3. Sept. 28, 1990, Lindberg, P.A., Geologic report on the Devils Kitchen Sinkhole: Prepared for Red Rock Jeep Tours of Sedona and U.S. Forest Service, 15 p.
4. Personal comm; Field study made with Ed DeWitt of the U.S.G.S., April 14, 2002.