Geologic Resource Evaluation Scoping Summary
Montezuma Castle National Monument, Arizona

Geologic Resources Division
National Park Service
U.S. Department of the Interior

The goal of the Geologic Resource Evaluation (GRE) Program is to provide each "natural area" park with a digital geologic map and accompanying geologic resource evaluation report. As a means of obtaining this goal, the NPS Geologic Resources Division (GRD), which administers the inventory, coordinates scoping meetings that bring together park staff and local geologic experts. The scoping process includes an evaluation of the adequacy of existing geologic maps and a discussion of park-specific geologic management issues. When possible, a site visit with local experts is also part of the scoping process. Outcomes are a scoping summary (this report), and ultimately a digital geologic map and geologic resource evaluation report. Along with the completed digital map, this scoping summary will serve as the starting point for compiling the final GRE report for Montezuma Castle National Monument.

Table 1. Scoping Session Participants

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The National Park Service held a GRE scoping meeting at Dead Horse State Park near Cottonwood, Arizona, for Montezuma Castle National Monument on Wednesday, May 10, 2006. On the evening of May 9, 2006, Andy Hubbard (Sonoran Desert Network), Laurie Wirt (U.S. Geological Survey–Denver), and GRE staff participated in an informal field trip to Montezuma Well. In addition, after the scoping meeting on May 10, John Schroeder (Montezuma Castle and Tuzigoot national monuments) led participants on a field trip to the fossil-mammal track site and alcoves at Montezuma Castle National Monument.

Discussion during the meeting addressed geologic mapping coverage and needs, distinctive geologic processes and features, resource management issues related to these features and processes, and potential monitoring and research needs. Melanie Ransmeier (NPS Geologic Resources Division) facilitated the discussion of map coverage, and Lisa Norby (NPS Geologic Resources Division) led the discussion of geologic processes and features. Participants at the meeting included NPS staff from Montezuma Castle and

Tuzigoot national monuments, the Geologic Resources Division, Sonoran Desert Network, and Southern Arizona Office, as well as cooperators from the U.S. Geological Survey (USGS), Arizona Geological Survey, Northern Arizona University, and Colorado State University (table 1).

Status of Scoping and Products

As of May 2006, the NPS Geologic Resources Division had completed the scoping process for 169 of 270 "natural resource" parks. Staff and partners of the GRE Program have completed digital maps for 69 parks. These compiled geologic maps are available for download from the NR-GIS Metadata and Data Store at http://science.nature.nps.gov/nrdata. The U.S. Geological Survey, various state geological surveys, and investigators at academic institutions are in the process of preparing mapping products for 49 additional parks. Writers have completed 22 GRE reports with 60 additional reports in progress.

Park and Geologic Setting

Montezuma Castle National Monument was proclaimed under the authority of the Antiquities Act on December 8, 1906, to protect 12th- and 13th-century Sinagua culture cliff dwellings and artifacts, and surrounding areas. It was subsequently enlarged in 1937 and again in 1959 to protect and preserve the remaining remnants of the pre-Columbian Sinagua culture in the Verde Valley. Montezuma Castle—a five-story, 20-room cliff dwelling nestled into a limestone recess high above Beaver Creek—served as a "high-rise apartment building" for prehistoric Sinagua Indians over 600 years ago. It is one of the best preserved cliff dwellings in North America. A boundary adjustment to protect fossil mammal tracks adjacent to the monument was made in 1978. Boundary changes to the monument also occurred in 1947, and a 2003 legislative boundary expansion of 157 acres is pending.

The monument consists of two distinct units: the Castle unit, containing one of the best examples of a Sinagua culture dwelling and surrounding landscape, and the Well unit, containing Montezuma Well. The Well unit was established by an Act of Congress and added to Montezuma Castle National Monument in 1943. In addition to preserving a unique spring-fed pond in the bottom of a limestone sinkhole, the Well unit hosts the prehistoric Sinagua culture and historical Apache culture. Montezuma Well is a constant source of water in the desert environment, providing 1.4 million gallons of water a day. Spanish explorers may have visited the well as they entered the Verde Valley in the late 16th century. The well received its name from Anglo pioneers who noted the similarity of the cliff dwellings located under the rim to the structures seen in Mexico attributed to the Aztecs. The northern edge of the well area was mined during the 1950s for travertine, which resembles marble when the rock is cut and polished.

Part of the Central Highlands of Arizona, Montezuma Castle National Monument is situated in the Verde Valley. In addition to being a "water province," the Central Highlands is a transition zone between two physiographic provinces: the Basin and Range to the south and west and the Colorado Plateau to the north and east. Tilted fault blocks that form long, asymmetrical ranges or mountains and broad, intervening basins characterize the Basin and Range. The Colorado Plateau is a high, undeformed area. A distinctive feature of the Central Highlands is the Mogollon Rim, which extends more than 200 miles from the White Mountains in eastern Arizona to the headwaters of the Verde River on the western side of the state. Elevation exceeds 7,000 feet along the Mogollon Rim, just 20 miles north of the monument.

The major geologic components of the Verde Valley are the (1) basin sediments; (2) lacustrine, swamp, and playa deposits of the Verde Formation; and (3) uplifted Paleozoic sedimentary rocks. The ancestral and present-day Verde River deposited the basin sediments, which consist primarily of semi-consolidated alluvium and igneous rocks such as dikes and basalts. Also included in this category are the Quaternary river sediments, which form a rather shallow veneer in only part of the basin. The uplifted Paleozoic sedimentary rocks occur along the margins of the valley and are exposed along the Mogollon Rim (table 2). Included in this third category is the Paleozoic Supai Group, which is the regional aquifer to the east and northeast of the monument. Rocks of the Supai Group are underlain by the Redwall limestone, which is known to have caves and rubble zones. Overlying these rocks are the Verde Formation (7–9 million years old) and basalts, such as the 15-million-year-old Hickey basalt and the 5-million-year-old Rim basalt. The Verde Formation is a freshwater limestone that contains some halite, clay beds, and volcanic ash that is interbedded with the basalt flows. It was deposited in an environment consisting alternately of a large swamp, shallow lake, and playa. Lava flows and tectonic activity periodically obstructed this swamp-lake-playa system, shifting from an open to closed basin.

By about 2 million years ago, the Verde Valley was filled with sediment. The ancestral Verde River initially flowed over the limestone and then began to erode it. Hence, rivers began to drive landscape evolution, ultimately forming the present landscape. Large floods occurred in 1891, 1906, 1920, 1938, 1978, 1980, 1993, and 1995, all of which helped to incise the river. Moreover, the 1993 flood had a strong impact on the current channel form (P. Pearthree, Arizona Geological Survey, written communication, June 7, 2006). In addition to eroding the Verde Formation via downcutting, the Verde River and its tributaries produced terraces, meanders, and the present floodplain. Alluvial fans were deposited along the edges of the valley. A series of three groups of alluvial fans are evidence of past landscapes within the Verde Valley, with the highest fans preserving the most ancient landscapes.

Table 2. Geologic Settings of the Verde Valley

Period	Events	Representative Rocks	Setting
Neogene (25 Ma–present)	Canyon cutting and valley erosion Basin sedimentation Faulting Volcanism	Rim basalts Verde Formation Hickey basalts	Modern landscape Swamp and shallow lake Volcanoes
Paleogene (35–65 Ma)	Regional mountain building and plateau uplift Tectonic forces produce folding and faulting (e.g., monoclines) Sediment shed from uplifted areas	Local conglomerate above Mogollon Rim	Phoenix is an alpine city. Cottonwood River is at 10,000 feet in elevation.
Mesozoic (65–250 Ma)	Deposition of marine and continental sediments Erosion	Not well represented in Verde Valley; some rocks in Sycamore Canyon (e.g., Moenkopi and Chinle)	
Paleozoic (250–525 Ma)	Marine and continental sedimentation Eolian deposits Numerous periods of erosion produce unconformities	Flat-lying sedimentary rocks in canyon walls (e.g., Tapeats sandstone; Martin [fossiliferous], Moenkopi, and Chinle Formations; Supai Group)	Arid river valley Inland sea
Long period of erosion			
Proterozoic (>1.6 Ga)	Sedimentation Volcanism Mountain building	Crystalline basement (i.e., schist and related metamorphic rocks) Yavapai Supergroup Prescott Granite	Island arcs

Montezuma Castle National Monument is situated on the eroded Verde Formation. The park setting is composed of the Beaver Creek and Wet Beaver Creek floodplains, relict terraces, and an old meander belt. Montezuma Well is at least 55 feet deep and provides a steady supply of water to its outlet. Flow varies between 1 to 3 cubic feet per second, showing both long- and short-term variability. On an annual basis, peak flow is during the spring and summer; flow is lowest during the fall and early winter. The past six years of drought conditions does not appear to have substantially impacted discharge, though there could be a “lag effect” (Laurie Wirt, USGS-Denver, presentation, May 10, 2006).

In many ways, Montezuma Well is an enigma. It is a flowing sinkhole in the desert, and was undoubtedly a source of wonder as well as sustenance for prehistoric people. Early written accounts of the well speculate that it was either a meteor impact crater or a collapsed volcanic cinder cone; however, geologists today are largely in agreement that it is a limestone sinkhole. Nevertheless, many other questions remain unanswered:

- What is the source of groundwater to Montezuma Well?
- Why is the sinkhole located on top of a hill or mound?
- How deep is it? What is the nature of the soft bottom?
- Is Montezuma Well somehow related to nearby Soda Springs?
- What effects have the unique chemistry had on the biota—past and present?

Laurie Wirt (USGS-Denver) is beginning to form a hypothesis and gather data to answer these questions (see Langenheim and others, 2005). In particular, she hypothesizes that buried basalts within the Verde Formation short circuit the “plumbing system” between the recharge areas north of the Mogollon Rim and the well. Thus, a deep source within the regional Paleozoic aquifer (i.e., Supai Formation) may not be the driving force for Montezuma Well, as scientists have theorized (e.g., Konieczki and Leake, 1997). Environmental isotopes and chemistry of water and rock samples will be used to trace the source(s) of water emerging in Montezuma Well. For example, high levels of strontium-87 would indicate a flow path through the 5-million-year-old ramp basalts, whereas low levels would indicate a sedimentary source such as the Supai Formation (regional aquifer).

In a written communication on June 23, 2006, Laurie Wirt (USGS-Denver) clarified the following: The basalts are not continuous between the Mogollon Rim and Montezuma Well and therefore either the Coconino or Supai Formations probably supply water to the basalts along the flow path. Some water might also be recharged along Wet Beaver Creek. DeWitt now indicates that flow could be emerging along a growth fault. The real issue is that the plumbing in the vicinity of Montezuma Well is probably shallower than previously thought, and the location of the sinkhole may be driven by both the fault and the relatively high permeability of the basalts. (This is slightly different than what Wirt presented on May 10, 2006.)

Geologic Maps for Montezuma Castle National Monument and Montezuma Well

During the scoping session on May 10, 2006, Melanie Ransmeier (NPS Geologic Resources Division) showed some of the main features of the NPS GRE Geology-GIS Geodatabase Data Model—the digital geologic map model used by the GRE Program. This model reproduces all aspects of a paper map, including notes, legend, and cross sections, with the added benefit of being GIS compatible. Staff members digitize maps or convert digital data using ESRI ArcMap software. Digital data are provided in each of the following three formats: geodatabase, shapefile, and coverage. Layer files (legends), FGDC-compliant metadata, and a Windows HelpFile that captures ancillary map data, are also part of the final dataset.

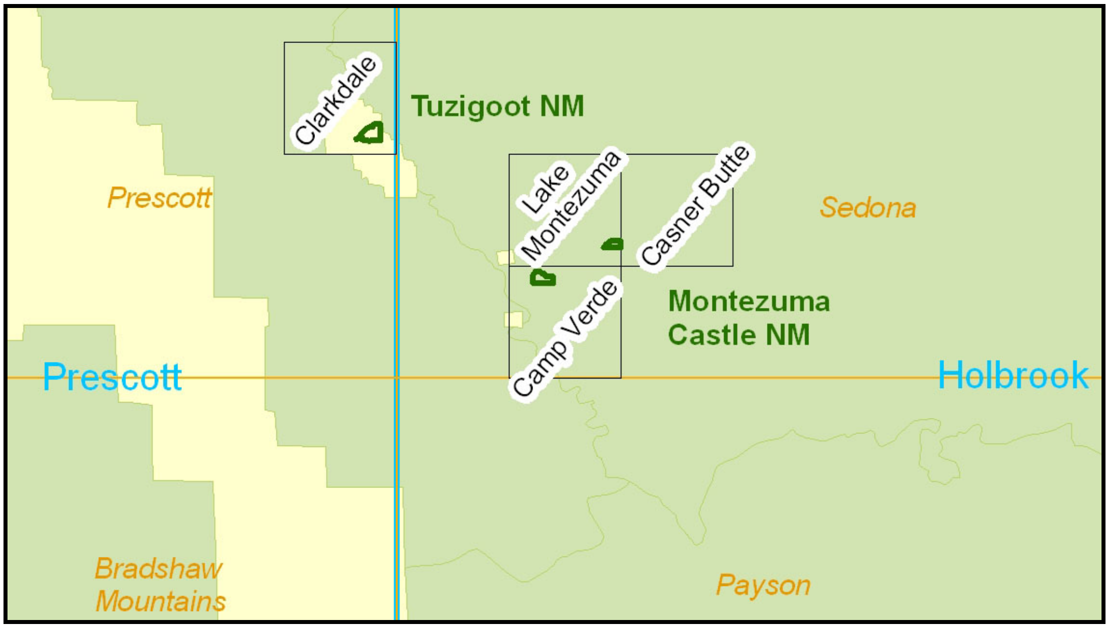

Figure 1. Quadrangles of Interest for Montezuma Castle National Monument, Arizona. The 7.5-minute quadrangles (scale 1:24,000) are labeled in black; names in yellow indicate 30-minute by 60-minute quadrangles (scale 1:100,000). Names in blue indicate 1-degree by 2-degree sheets (scale 1:250,000). Dark green outlines indicate the boundaries of the monument: the southern unit is Montezuma Castle, and the northern unit it Montezuma Well.

Parks in Inventory and Monitoring Networks have identified 7.5-minute “quadrangles of interest.” In general, digital geologic data from 7.5-minute quadrangles (scale 1:24,000) suit the purpose of geologic resource evaluations. The geologic features mapped at this scale are equivalent to the width of a one-lane road. Quadrangles of interest are used as a starting point for discussion in determining what the final digital geologic map for a park will include. A recent policy change for the GRE Program, however, excludes from potential digitizing any quadrangles that do not include a portion of the park. This summary attempts to outline an action plan that incorporates this new policy while providing a digital map useful for resource management.

Map coverage for Montezuma Castle National Monument consists of three quadrangles of interest (scale 1:24,000): Lake Montezuma, Casner Butte, and Camp Verde, which are situated on the Sedona 30' × 60' sheet (see fig. 1 and table 3). In 2005 GRE staff completed a digital map for the monument at the request of the NPS Water Resources Division–Water Rights Branch and Montezuma Castle National Monument. The following maps were incorporated into this dataset:

DeWitt, E., Langenheim, V.E., Force, E., Vance, K., and Lindberg, P.A., *with* a digital database by Hirschberg, D., Pinhassi, G., and Shock, N., 2006, Geologic map of the Prescott National Forest and headwaters of the Verde River, Yavapai and Coconino counties, Arizona [in press]: U.S. Geological Survey Miscellaneous Investigations Map I-[unpublished number], scale 1:100,000, two sheets.

Twenter, F.R., and Metzger, D.G., 1963, Geology and ground water in Verde Valley—the Mogollon Rim region, Arizona [out of print]: U.S. Geological Survey Bulletin 1177, scale 1:62,500.

Weir, G.W., Ulrich, G.E., and Nealey, L.D., 1989, Geologic map of the Sedona 30' × 60' quadrangle, Yavapai and Coconino counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1896, scale 1:100,000.

Table 3. GRE Mapping Plan for Montezuma Castle National Monument

Quadrangles	GMAP[1]	Citation	Scale	Format	Assessment	GRE Action
Portions of Casner Butte, Lake Montezuma, and Camp Verde	1184	Twenter, F.R., and Metzger, D.G., 1963, Geology and ground water in Verde Valley—the Mogollon Rim region, Arizona [out of print]: U.S. Geological Survey Bulletin 1177, scale 1:62,500.	1:62,500	Paper	Several scoping participants recommended that this map not be used because more accurate geologic maps exist.	Do not use, though portions are already converted to GRE data model.
Casner Butte, Lake Montezuma, and Camp Verde	5615	DeWitt, E., Langenheim, V.E., Force, E., Vance, K., and Lindberg, P.A., *with* a digital database by Hirschberg, D., Pinhassi, G., and Shock, N., 2006, Geologic map of the Prescott National Forest and headwaters of the Verde River, Yavapai and Coconino counties, Arizona [in press]: U.S. Geological Survey Miscellaneous Investigations Map I-[unpublished number], scale 1:100,000, 2 sheets.	1:100,000	Unpublished—some pre-released data in digital format	Recommended for use by USGS and NAU participants. *Note*: Completion date for this map is unknown.	Portions already converted to GRE data model *Note*: This unpublished data may not be released to the public and will be superseded by the final map when published.
Portions of Casner Butte and Walker Mountain	1186	Weir, G.W., Ulrich, G.E., and Nealey, L.D., 1989, Geologic map of the Sedona 30' × 60' quadrangle, Yavapai and Coconino Counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1896, scale 1:100,000.	1:100,000	Digital	Several scoping participants recommended that this map not be used because more accurate geologic maps exist.	Do not use, though portions are already converted to GRE data model.
Camp Verde	74380	House, P.K., 1994, Surficial geology of the southern Verde Valley, Yavapai County, Arizona, Camp Verde 7.5' quadrangle [sheet 2 of 3]: Arizona Geological Survey Open-File Report OFR 94-23, scale 1:24,000.		Paper	Provides surficial geology for Castle unit. Use GMAP 5615 (Dewitt 2005) for bedrock, when completed.	Digitize this map.

[1]GMAP numbers are identification codes used in the GRE database.

The scoping process revealed the inadequacy of two of these maps: Twenter and Metzger (1963) and Weir and others (1989). Participants recommended that this data not be used for resource management. They suggested waiting for completion of the currently unpublished geologic map by Ed DeWitt and others (GMAP 5615). Participants consider House (1994), which provides surficial geology for the Camp Verde quadrangle, to be essential data for resource management. When the unpublished "Dewitt map" of the Prescott National Forest and vicinity (GMAP 5615) is finalized, it will provide the most up-to-date geologic compilation for this quadrangle. As of June 2006, the U.S. Geological Survey had completed technical reviews of the DeWitt map. The map currently resides with the Central Region Publications Group, and USGS management is attempting to expedite its publication (L. Wirt, USGS-Denver, written communication, June 23, 2006). Bedrock geology from the DeWitt map, when published will supersede geologic data already converted to the GRE data model.

Geologic Features, Processes, and Issues

The scoping session for Montezuma Castle National Monument provided the opportunity to capture a list of geologic features and processes in the monument, which will be further explained in the final GRE report. During the meeting, park staff identified to priorities related to geologic features and processes:

1. Disturbed lands, in particular upstream development
2. Hillslope processes, in particular rockfall hazards

Disturbed Lands

Development in Soda Springs, Arizona, could impact Montezuma Well. Participants reported that 200 homes could potentially be built near Montezuma Well. Ron Blakey (Northern Arizona University) mentioned that a common practice in Arizona is development in the floodplains, which changes the hydrological regime and causes catastrophic flooding downstream. In addition, urban development will require groundwater withdrawals, which could affect the base flow of Wet Beaver Creek and ultimately Montezuma Well. The Rim Rock Bottling Company is pumping groundwater near Montezuma Well, which is a concern for park resources. Laurie Wirt's (USGS-Denver) geohydrological study will check into this.

Sand and gravel used to be mined along Beaver Creek above Montezuma Castle National Monument; this operation is now closed. A local operator, B and B Materials, is currently mining gravel from the floodplain of Dry Beaver Creek. Participants suspect that this operation may be affecting water quality.

Grazing has been an issue for Montezuma Castle National Monument. It has caused loss of vegetation, soil erosion, soil compaction, and spread of noxious weeds. Although cattle grazed in the area as early as the 1850s, nearby ranches attest to 80 years of farming and raising livestock. Illegal gazing still occurs at the Castle unit with cows entering along the river. This causes damage to historic and prehistoric sites.

Hillslope Features and Processes

In addition to spalling in alcoves (see "Cave and Karst Features and Processes"), fragments of rocks fall from the cliff face onto the trail where visitors stop to view the alcoves and castle. Historically large pieces of rock have fallen, creating both a concern for visitor safety and for resource protection.

Rockfall along the trails at Montezuma Well is a concern. Meeting participants noted some huge boulders that have fallen in the past. In addition, rockfall deposits and other sediment could clog the outlet of the well, resulting in changes to the outlet location. Spalling from the roofs of the alcoves and cliff walls could impact rock shelters at Montezuma Well.

Cave and Karst Features and Processes

The archaeological sites at Montezuma Castle National Monument are located in caves (alcoves) in the Verde Formation, although not all the caves occur in this rock unit. The Redwall Formation is known to produce sinkholes and may also host caves. Caves at Montezuma Castle form and are enlarged via spalling of the rocks from the caves' ceiling and walls. Spalling is associated particularly with wet periods. Rocks have the potential to fall while staff and visitors are in the alcoves; hence, it is a safety concern for park managers. The alcove in which the castle was built is a large, very competent (not easily erodible) natural cave. Interesting research would study why this alcove is so large and competent compared to the other smaller caves near the monument. A possible hypothesis is that a depression above the castle pools water during large rainstorms, which could have facilitated erosion. Vandalism (historic) and animal activity are degrading archeological resources in the caves and alcoves at the monument.

In addition to the sinkhole at the Well unit, other cave resources include Swallet Cave and a number of alcoves that host rock shelters around the perimeter of the well. Swallet Cave is the outlet for Montezuma Well and leads to a prehistoric irrigation ditch along Wet Beaver Creek.

The potential for new sinkhole development exists at Montezuma Well. Participants noted surficial cracks near the oaks west of the well; however, this may be related to drought and dry, clayey soil.

Eolian (Windblown) Features and Processes

The sediment at the bottom of the well may be from eolian sand derived from the Paleozoic sedimentary rocks (Coconino or Supai). Laurie Wirt (USGS-Denver) will be analyzing this sediment as part of her geohydrologic study of Montezuma Well. A sand sample collected from nearby Soda Springs contains fragments of basalt minerals.

Fluvial Features and Processes

Beaver Creek is an intermittent stream with perennial reaches that flow through Montezuma Castle National Monument. During a flooding event in winter 2005, the creek damaged a historical 1930s gabion (levee-like structure) built by the Civilian Works Administration (CWA). This gabion is protecting infrastructure (i.e., picnic area and sidewalks) at the monument. Additionally, future flooding could threaten the water treatment facility (lagoons) and park housing. Dry Beaver Creek has flash floods during the summer months.

At Montezuma Well, Wet Beaver Creek, a perennial stream, could affect the irrigation canals and ditch gauging station. It could also scour vegetation during flood events. Cut slopes along the stream may fail, resulting in a safety hazard for visitors walking along the stream. Also, dissolution of limestone causes the location of the well's outlet to shift, which results in periodic flooding on the trail.

Geothermal Features and Processes

Verde Hot Springs is located in the vicinity of Montezuma Castle National Monument. It is the site of a former resort, which has not had paying customers since the 1930s. A concrete foundation, which encircles a number of pools, remains. According to various Web sites (i.e., http://www.fossilcreekaz.com/pages/verde.html and http://www.reith.ca/verde/), the hot springs is between 95°F and 104°F. In 1980 the U.S. Geological Survey published a map showing the areas with geothermal resources in the Verde Valley, which would undoubtedly be a good reference for park managers (Ross and Farrar, 1980).

The water in Montezuma Well is about 5° warmer than expected, which could be evidence of a deep groundwater system. However, the water temperature of Montezuma Well is much more similar to Tavasci Marsh, in Tuzigoot National Monument, than Verde Hot Springs (L. Wirt, USGS-Denver, written communication, June 23, 2006). According to Laurie Wirt (USGS-Denver), many springs along the Verde River emerge from large faults or karst. These springs have the same water temperature of about 68°F (19°C). The largest one known to Wirt is at Page Springs, which is 6 miles east of Tavasci Marsh. At this location, fisheries are operated because the warm water encourages rapid fish growth. This temperature is a fairly common for some of the other carbonate springs along the Verde River, for example, Bubbling, Lolomai, and Turtle springs, which are upstream from Page Springs. Like Montezuma Well, the springs in the Verde Valley typically emerge through the Verde Formation, but probably come through the Paleozoic section below. The springs along Oak Creek also emerge just downgradient from a large mass of volcanic rocks, where there appears to be a fault. Hence, the geothermal system is rather complicated (L. Wirt, USGS-Denver, written communication, June 23, 2006).

Mineral Resources

Northwest of Montezuma Well on USDA Forest Service land is a small travertine quarry with semi-precious (gem-grade) onyx, known as "poor man's marble." The quarry used to be commercially mined for picture agate but is now only used by “rockhounds.” Park staff suspects that the deposit extends into the monument (i.e., John Schroeder has seen specimens in the monument); hence, the potential for illegal collection exists. Park staff needs to verify the location of the travertine deposit.

Paleontological Resources

Known paleontological resources occur in the Verde Formation in the monument. For example, investigators have identified Miocene and Pliocene fossils such as the camel, ancestors of the saber-toothed cat, and sloths (see Santucci and others, 1998; Hunt and others, 2005). Particularly noteworthy are gomphothere (Pliocene elephant) and camel tracks (see Brady and Seff, 1959; Schafer, 1971; McGeorge and Schur, 1994). Meeting participants visited this track site during a brief field trip as part of the scoping process.

The Redwall limestone in the vicinity of the monument may also be fossiliferous.

Seismic Features and Processes

No active faults are known to occur at Montezuma Castle National Monument. Hence, the Castle and Well units have low to moderate seismic potential. The closest fault is the Camp Verde fault zone, which runs along the base of the Black Hills. The active portion is 10–15 miles east of the monument. Other active faults in the area include the Big Chino fault northwest of the Verde Valley, the Cottonwood Basin fault in southeastern Verde Valley, and the Lake Mary fault southeast of Flagstaff, Arizona. The Flagstaff area has an earthquake potential of between 6.0 and 6.9 in magnitude, which would be felt at the monument. Historic earthquakes in the Verde Valley are documented as intensity VII (on the modified Mercalli scale), during which chimneys fell. Seismic vibrations from earthquakes and overflights may accelerate spalling and cause damage to archaeological resources.

Unique Geologic Features

Unique geologic features may include features mentioned in a park’s legislation, features of widespread geologic importance, geologic resources of interest to visitors, or geologic features worthy of interpretation. Also, type localities and age dates are considered unique geologic features. Montezuma Well is most assuredly unique: it is a single, isolated sinkhole, which according to Laurie Wirt (USGS-Denver) evokes a more compelling explanation than typical karstic processes. In addition, the geochemistry (Ismail, 1985) of the Verde Formation and the biology of the well are distinctive. For instance, no fish inhabit the well because of high dissolved carbon dioxide; the main aquatic species consist of unique amphipods and leeches (see http://www.nau.edu/biology/people/blinn.html) (L. Wirt, USGS-Denver, written communication, June 23, 2006).

In addition, students of Jayne Belnap (U.S. Geological Survey) have completed field work regarding lichens and soil crusts at Montezuma Castle National Monument. Because of the limestone, however, crusts are not widespread.

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