USGS Geologic Mapping and Karst Research in Ozark National Scenic Riverways, Missouri, USA

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Introduction

Ozark National Scenic Riverways (ONSR), a unit of the national park system, was created in 1964 to protect 134 miles of the Current River and its major tributary, the Jacks Fork, that are located in south-central Missouri (Figure 1). The park includes numerous large karst springs, including Big Spring, which is the largest spring in the national park system by flow volume. The National Park Service (NPS) administers a narrow, nearly continuous corridor of land adjacent to the two rivers. Base flow for the rivers is chiefly supplied by groundwater that has traveled through the karst landscape from as far as 38 miles away (Imes and Frederick 2002). The watershed is vulnerable to pollution, but the area remains largely rural with few industries. The springs and rivers provide habitat for numerous aquatic species as well as recreational resources for floaters, fishermen, and campers. ONSR is a major cave park with hundreds of known caves and diverse in-cave resources.

The geology of ONSR comprises a Mesoproterozoic (~1.4 giga-annum) basement of intrusive and extrusive igneous rocks discomformably overlain by relatively flat-lying Cambrian and Lower Ordovician (~500– to 470–mega-annum) sedimentary rocks, on which various surficial and residual sedimentary units are superposed. The basement rocks, chiefly granite and rhyolite, are exposed as erosional remnant hills in an uplifted area near the central part of the park area (Figure 2). The Paleozoic sedimentary rocks are chiefly dolomite that contain interlayerings of quartz sandstone and chert. The bedrock is cut by chiefly vertical strike-slip faults of the Ouachita Orogeny to the south. The entire exposed Paleozoic section is pervasively karstified.

Geologic issues at ONSR

The US Geological Survey (USGS) conducted geologic mapping in ONSR area for two

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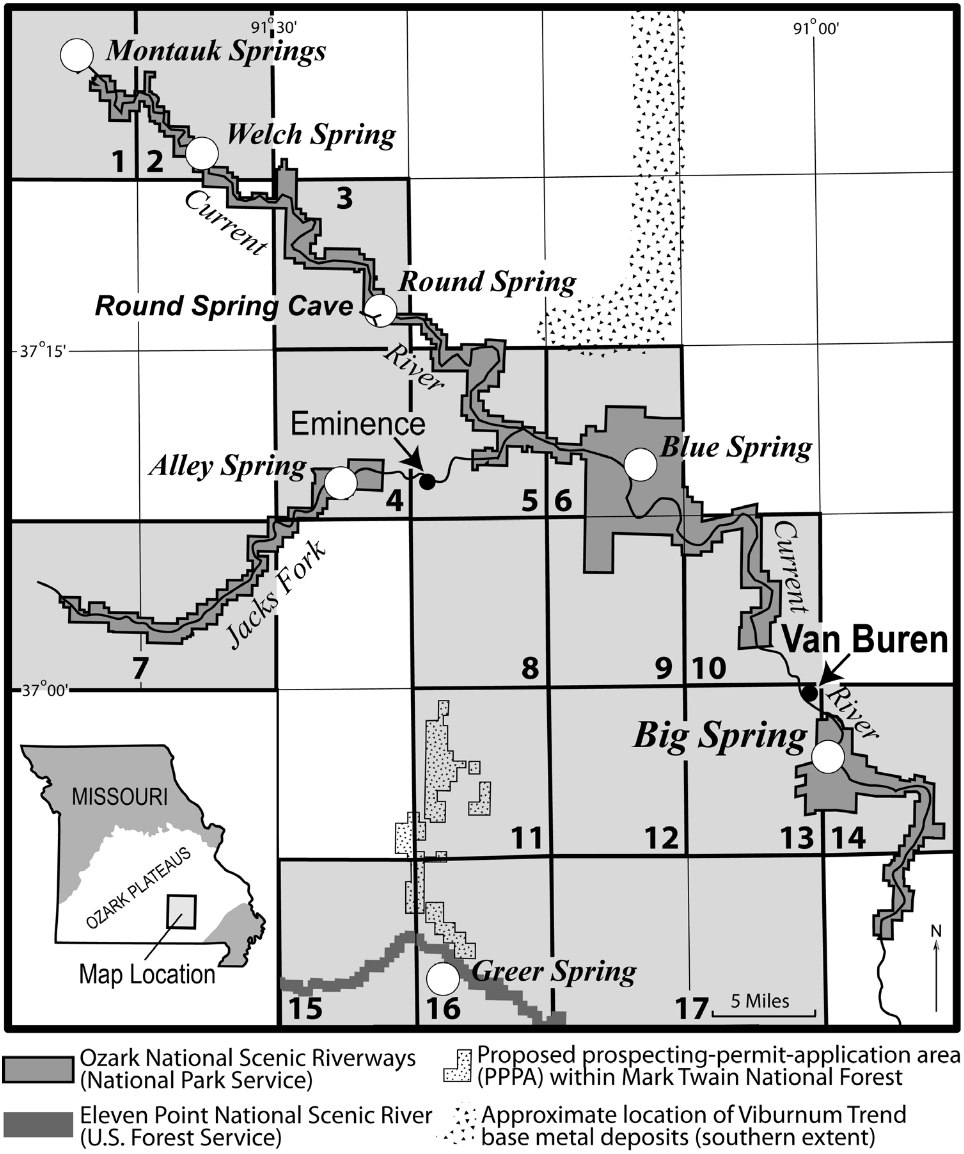


Figure 1. Map showing the location of Ozark National Scenic Riverways (ONSR) and geologic maps (gray rectangles) published by USGS from 1998 to 2013. Numbers on rectangles correspond to entries on Table 1. See reference section for full citations. The ONSR headquarters is located in the town of Van Buren. Base metal (lead–zinc) deposits occur in the subsurface of the Viburnum Trend and in parts of the previously proposed prospecting–permit application area of Mark Twain National Forest.

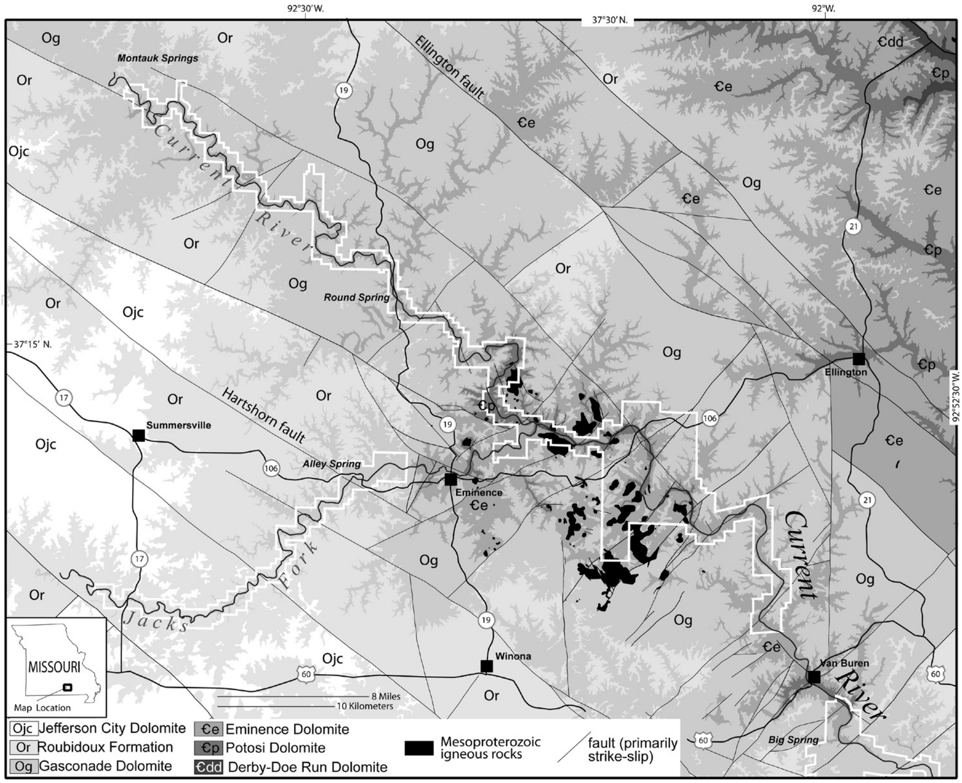


Figure 2. Generalized geologic map of ONSR park area. The ONSR boundaries are indicated by the white lines. Note that the park extends an additional 7.2 miles beyond the south border of this map. Map modified from Lowell et al. (2010).

primary reasons. First, to provide mapping to an NPS-mandated geologic inventory of the park; and second, to provide a detailed regional geohydrologic framework in support of ongoing multidisciplinary studies in an effort to determine the potential for migration of groundwater contaminants into ONSR from a proposed subsurface base-metal exploration site located on US Forest Service land near the park (Figure 1).

USGS mapping in ONSR

Geologic mapping is a valuable investment in earth science research, as it is multidisciplinary, exploratory, and results in expanded research insights years after the initial ground traverses are made. The bedrock geology of an area comprises the basal part of the earth's "critical zone" and knowledge of it is integral to all other ground-based natural science studies. The critical zone is defined as "the external terrestrial layer extending from the limits of vegetation down to and including the zone of groundwater. This zone sustains most terrestrial life on the planet" (Brantley et al. 2006). Prior to USGS mapping, the only geologic map data available for ONSR was a 1:62,500-scale map covering part of the park area by Josiah Bridge (1930), and reconnaissance maps by the Missouri Department of Natural Resources, Division of Geology and Land Survey. None of the previous mapping was in digital form.

USGS, in partnership with NPS and other federal and state agencies, conducted geologic mapping in the vicinity of ONSR from 1996 to 2013. Detailed geologic maps by USGS were completed in nineteen 7.5-minute quadrangles (See Figure 1 and Table 1).

A seamless 1:24,000-scale digital compilation map, planned for publication in 2014, will complete geologic coverage of ONSR, thereby enabling NPS to achieve its inventory goal under the geologic resource evaluation initiative. All of these maps are GIS-based and the data are available via the Internet. A 1:100,000-scale geologic map for the combined area of the West Plains and Spring Valley, Missouri (1:100,000 sheets, and adjacent areas) is in preparation and will be released for publication in 2014. This area, approximately 4,300 mi2 (11,116 km2), encompasses most of the drainage basins for the Current River, the Jacks Fork, and the Eleven Point River to the south of ONSR.

USGS geologic research in ONSR

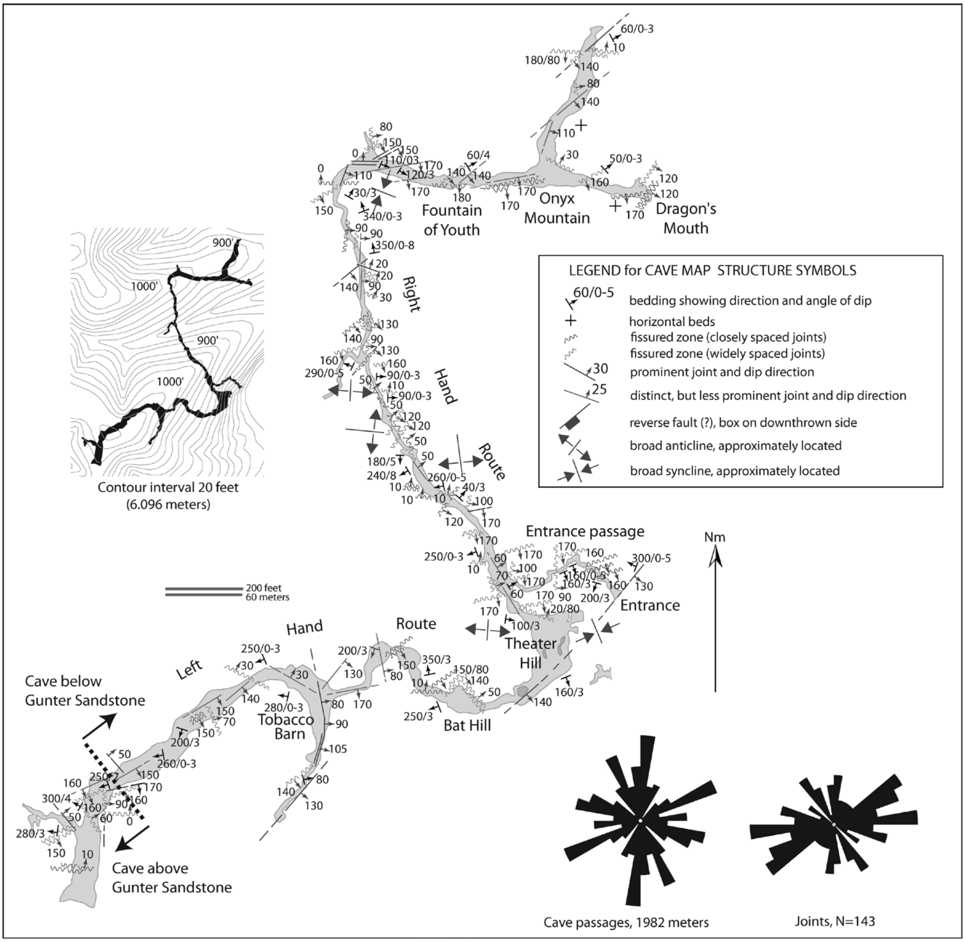
In addition to completing geologic maps of park areas, USGS scientists have produced numerous reports and made many presentations on various geologic and cave research

Table 1. List of quadrangle maps completed in ONSR and vicinity by USGS. See reference section for full citations. Numbers correspond to quadrangle locations in Figure 1.

Figure 1 number	Quadrangle(s)	Author(s)	Year of publication or status
1	Montauk	Weary	In production, estimated 2014
2	Cedargrove	Weary	2008a
3	Round Spring	Orndorff and Weary	2009
4	Alley Spring	Weary and Orndorff	2012
5	Eminence	Orndorff et al.	1999
6	Powder Mill Ferry	McDowell et al.	2000
7	Jam Up Cave and Pine Crest	Weary et al.	2013
8	Winona	Orndorff and Harrison	2001
9	Stegall Mountain	Harrison et al.	2002
10	Van Buren North	Weary and Weems	2004
11	Low Wassie	Weems	2002
12	Fremont	Orndorff	2003
13	Van Buren South	Weary and Schindler	2004
14	Big Spring	Weary and McDowell	2006
15	Piedmont Hollow	Weary	2008b
16	Greer	McDowell	1998
17	Wilderness and Handy	Harrison and McDowell	2003

topics. One of the prime research topics was to characterize karst features in ONSR and interpret their importance to both the present and past geohydrologic framework of the area. Locations of sinkholes, caves, and springs, some previously unknown, were recorded during the course of the geologic mapping. Cave locations have not been published following the rules and guidance of the Federal Cave Resources Protection Act, but other karst features are included in the GIS data published with each quadrangle map. From 1996 through 1999, various aspects of cave geology were studied by USGS in cooperation with Stanka Sebela of the Slovenian Karst Research Institute. Sebela is an expert on the role of small-scale geologic structures (faults, fractures, bedding orientation, etc.) as controls on cave passage formation. See Figure 3 for an example from this research.

Figure 3. Map of structural features mapped in Round Spring Cave, ONSR (from Sebela et al. 1999). Rose diagrams show orientations of cave passage segments and orientations of joints measured in the cave.

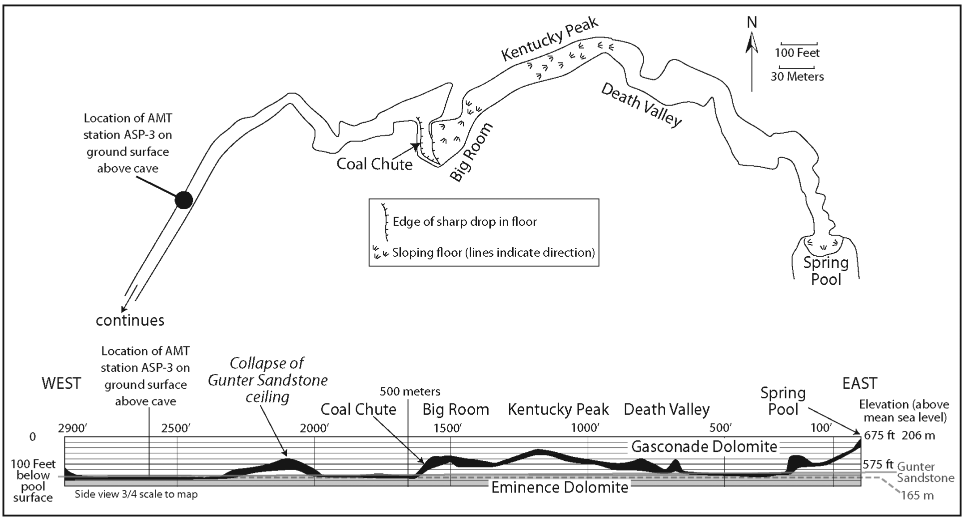


Seventy-nine caves in or near ONSR were studied to understand the geologic controls on the development of groundwater conduits along the southeastern margin of the Ozark Plateaus. Geologic mapping of 19 of these caves provides information on the stratigraphy, cave passage orientation and morphology, and fracture attributes (Sebela et al. 1999; Orndorff et al. 2006). Most of the cave base maps were obtained from the Missouri Speleological Survey. A few of the caves were mapped by USGS scientists in cooperation with personnel from the Cave Research Foundation (CRF), particularly Bob Osburn of St. Louis, Missouri.

USGS cooperation with the Ozark Cave Diving Alliance (OCDA) facilitated NPS permitting the OCDA to dive and map the underwater cave feeding Alley Spring, the third largest spring in ONSR (Figure 4). Geologic observations made by the divers verified assumptions about the stratigraphic control of the geometry of the conduit. Video recordings of the dives have been a valuable outreach tool for the park.

Knowledge of the geometry of the Alley Spring conduit (cave) led to a successful proposal for a FY2009 USGS geology venture capital fund award titled "Three-dimensional geophysical prospecting for a major spring conduit in the Ozark karst system using audio-magnetotelluric (AMT) soundings and ground penetrating radar: A proof of concept study." AMT field data collected over a 2-week period in the vicinity of Alley Spring were processed and analyzed by Herbert A. Pierce of USGS. Use of ground-penetrating radar is inappropriate for the geologic setting and was not attempted. The results of the study were integrated with

Figure 4. Map and profile of Alley Spring Cave, simplified from a map produced by the Ozark Cave Diving Alliance (2005). Geologic interpretation by D. Weary (USGS), based on surface geologic mapping, observations by OCDA divers, video footage, and analogy to geologic control seen in air-filled caves in the region. Discussions of this figure may be found in Weary and Pierce (2009) and Lowell et al. (2010).



the detailed geologic information, acquired through mapping, and the synthesis reported in Weary and Pierce (2009) and discussed in detail in Lowell et al. (2010).

Early in the project, USGS mappers utilized conodont biostratigraphy as a tool to aid in verification and correlation of stratigraphic units in ONSR. Conodonts are nearly microscopic phosphatic parts of the oral apparatus of extinct primitive chordates that lived during a period about 500–200 million years ago. Conodonts were ubiquitous in warm and temperate seas during the Paleozoic through early Mesozoic and are one the most useful fossils for biostratigraphic research in sedimentary rocks of this age.

Rock samples for conodont analysis were collected, as needed, under annual sampling permits issued by NPS. USGS geologists were highly cognizant of the need to make as little impact as possible on park resources, so samples were kept as small as practical and collected from inconspicuous locations. These samples also contributed data to ongoing studies on the stratigraphic history of Lower Paleozoic strata in the Ozarks region. Two research topics of particular interest are: (1) the nature of the unconformable contact between the Eminence Dolomite and the overlying Gasconade Dolomite, which corresponds to the Cambrian–Ordovician boundary, and (2) the age of the Gasconade Dolomite to Roubidoux Formation transition interval (Repetski et al. 1998, 2000a, 2000b; Miller et al., in press). Macrofossil abundance is sparse, and when present they are commonly poorly preserved due to the pervasive recrystallization of the rocks in ONSR; therefore they were not specifically studied by USGS.

Uses for USGS data in ONSR

Beginning in 1996, USGS geologic data were being used by Missouri Department of Conservation (MDC) as the foundation of the ecological classification system within the park watershed. An ecological classification system is a physical and biological framework that allows managers to identify, map, and describe land characteristics at scales suitable for natural resources planning and management. Geologic data are one of the important layers used in producing these maps and USGS cooperated closely with MDC and others by providing timely geologic map data as particular areas were being mapped. These products are used for vegetative community mapping, modeling, and management; invasive species control; and species management and protection, among other uses.

Geologic education and outreach

Since 1996, USGS geologists have been *ad hoc* consultants for ONSR in support of multidisciplinary studies, proposals, land management issues, and geologic educational outreach. USGS geologists have been asked to review or comment on various geologic interpretive displays produced for the park. On two occasions USGS karst experts accompanied groups of seasonal cave guides assigned to Round Spring Cave to discuss and educate them on the various aspects of the geology and speleology of the cave. This knowledge is used to enhance the information provided by NPS guides in public tours of the cave. USGS geologists also have led formal field trips in the project area in conjunction with professional geological society conferences (e.g., Lowell et al. 2010).

Direct and indirect support for USGS mapping activities

The majority of the funding for geological mapping and research in ONSR came from the USGS National Cooperative Geologic Mapping Program (NCGMP), with additional funding provided by the NPS Geologic Resources Division (GRD). Other significant contributions included Congressional line-item funds via the US Forest Service to support studies related to potential base metal mining in the area. ONSR has also contributed valuable field support to USGS researchers via vehicle loans, vehicle parking, subsidized lodging, and canoe shuttles for river work. Federal investment in this project leveraged additional geologic mapping in ONSR by the Missouri Geological Survey. ONSR natural resource specialists have also coordinated informal information exchange between USGS geologists and other scientists working in the park.

Comments on and recommendations for USGS and NPS collaboration

Over the duration of the approximately 16-year mapping project, it became apparent to USGS that there was value in involving several different mappers. Each geologist possessed a particular set of knowledge and interests beyond his or her core competencies as mappers. This diversity enriched and compounded the scope of geologic inquiry and interpretation.

Cooperation between USGS geologists and ONSR staff has been an ongoing success because of the consistent funding support between similarly aligned programs within each bureau. The presence of a NCGMP-supported project in the park area encouraged interdisciplinary networking that leveraged other research activities. Communication and coordination between NPS and USGS personnel has been successful due to the enthusiasm and personal commitments by the individuals involved to the research.

After the GRD geologic inventory is completed, and NCGMP-sponsored activity has moved elsewhere, it would be valuable to have a mechanism in place to encourage and support continued USGS research and outreach in the national parks. This would encourage topical research and USGS geologists could author or contribute to interpretive materials and publications for parks they have worked in. Both agencies have invested time, money, and significant parts of the careers of their staff in park geologic research. Formal ongoing relationships between USGS researchers and the parks would facilitate extended use of the geologic expertise gained and encourage delivery of better outreach and education products to the American public.

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References

Brantley, S.L., T.S. White, A.F. White, D. Sparks, D. Richter, K. Pregitzer, L. Derry, J. Chorover, O. Chadwick, R. April, S. Anderson, and R. Amundson. 2006. *Frontiers in Exploration of the Critical Zone*. Report of a workshop sponsored by the National Science Foundation, October 24–26, 2005, Newark, DE. Online at www.czen.org/files/czen/CZEN_Booklet.pdf.

Bridge, J. 1930. *Geology of the Eminence and Cardareva Quadrangles*. Missouri Bureau of Geology and Mines, 2d ser., v. 24. Jefferson City, MO: Botz Printing and Stationery Co.

Harrison, R.W., and R.C. McDowell. 2003. Geologic map of the Wilderness and Handy quadrangles, Oregon, Carter, and Ripley counties, Missouri. US Geological Survey Geologic Investigations Series Map I–2801, scale 1:24,000.

Harrison, R.W., R.C. Orndorff, and D.J. Weary. 2002. Geology of the Stegall Mountain 7.5-minute quadrangle, Shannon and Carter Counties, south-central Missouri. US Geological Survey Geologic Investigations Series Map I–2767, scale 1:24,000.

Imes, J.L., and B.S. Fredrick. 2002. Using dye-tracing and chemical analyses to determine effects of a wastewater discharge to Jam Up Creek on water quality of Big Spring, southeastern Missouri, 2001. USGS Fact Sheet 103-02.

Imes, J.L., and M.J. Kleeschulte. 1995. Seasonal ground-water level changes (1990–93) and flow patterns in the Fristoe Unit of the Mark Twain National Forest, southern Missouri. US Geological Survey Water-Resources Investigations Report 95–4096, 1 sheet.

Lowell, G.R., R.W. Harrison, D.J. Weary, R.C. Orndorff, J.E. Repetski, and H.A. Pierce. 2010. Rift-related volcanism and karst geohydrology of the southern Ozark dome. In *From Precambrian Rift Volcanoes to the Mississippian Shelf Margin: Geological Field Excursions in the Ozark Mountains*. K.R. Evans and J.S. Aber, eds. Field Guide 17. Boulder, CO: Geological Society of America, 99–158; doi: 10.1130/2010.0017(06).

McDowell, R.C. 1998. Geologic map of the Greer quadrangle, Oregon County, Missouri. US Geological Survey, Geologic Investigations Series Map I-2618, scale 1:24,000.

McDowell, R.C., and R.W. Harrison. 2000. Geologic map of the Powder Mill Ferry quadrangle, Shannon and Reynolds Counties, Missouri. US Geological Survey Geologic Investigations Series Map I–2722, scale 1:24,000.

Miller, J.F., K.R. Evans, V.E. Kurtz, and J.E. Repetski. In press. Biostratigraphy and sequence stratigraphy of the Cambrian strata in Missouri. In *Paleozoic Succession in Missouri: Part 1, Cambrian System*. T.L. Thompson and P. Mulvany, eds. Missouri Geological Survey Report of Investigations 70. Columbia: Missouri Department of Natural Resources, 13–24.

Orndorff, R.C. 2003. Geologic map of the Fremont quadrangle, Shannon, Carter, and Oregon counties, Missouri. US Geological Survey Geologic Investigations Series Map I–2775, scale 1:24,000.

Orndorff, R.C., and R.W. Harrison. 2001. Geologic map of the Winona quadrangle, Shannon County, Missouri. US Geological Survey Geologic Investigations Series Map I–2749, scale 1;24,000.

Orndorff, R.C., R.W. Harrison, and D.J. Weary. 1999. Geologic map of the Eminence quadrangle, Shannon County, Missouri. US Geological Survey Geologic Investigations Series Map I–2653, scale 1;24,000.

Orndorff, R.C., and D.J. Weary. 2009. Geologic map of the Round Spring quadrangle, Shannon County, Missouri. US Geological Survey Scientific Investigations Map 3073, scale 1:24,000.

Orndorff, R.C., D.J. Weary, and R.W. Harrison. 2006. The role of sandstone in the development of an Ozark karst system, south-central Missouri, In *Perspectives on Karst Geomorphology, Hydrology, and Geochemistry: A Tribute Volume to Derek C. Ford and William B. White*. R.S. Harmon and C. Wicks, eds. Special Paper 404. Boulder, CO: Geological Society of America.

Ozark Cave Diving Alliance. 2005. Alley Spring, Shannon County, Missouri. (Cave map.)

Repetski, J.E., J.D. Loch, and R.L. Ethington. 1998. Conodonts and biostratigraphy of the Lower Ordovician Roubidoux Formation in and near the Ozarks National Scenic Riverways, southeastern Missouri. In *National Park Service Paleontological Research*. V.L. Santucci and L. McClelland, eds. Technical Report NPS/NRGRD/GRDTR-98/01, Washington, DC: NPS, 109–115.

Repetski, J.E., J.D. Loch, R.L. Ethington, and R.I. Dresbach. 2000a. A preliminary re-evaluation of the stratigraphy of the Roubidoux Formation of Missouri and correlative Lower Ordovician units in the southern Midcontinent. In *Platform Carbonates in the Southern Midcontinent, 1996 Symposium*. K.S. Johnson, ed. Circular 101. Norman: Oklahoma Geological Survey, 103–106.

Repetski, J.E., R.C. Orndorff, and D.J. Weary. 2000b. Conodont biostratigraphy of the Eminence Dolomite–Gasconade Dolomite contact interval in the Missouri Ozarks. *Geological Society of America, Abstracts with Programs* 32(3), A39–40.

Sebela, S., R.C. Orndorff, and D.J. Weary. 1999. Geological controls in the development of caves in the south-central Ozarks of Missouri, USA. *Acta Carsologica* 28(2): 273–291.

Weary, D.J. 2008a. Geologic map of the Cedargrove quadrangle, Dent and Shannon Counties, Missouri. US Geological Survey Scientific Investigations Map 2980, scale 1:24,000.

———. 2008b. Geologic map of the Piedmont Hollow quadrangle, Oregon County, Missouri. US Geological Survey Scientific Investigations Map, SIM-2979, scale 1:24,000.

Weary, D.J., and R.C. McDowell. 2006. Geologic map of the Big Spring quadrangle, Carter County, Missouri. US Geological Survey Scientific Investigations Map SIM-2804, scale 1:24,000.

Weary, D.J., and R.C. Orndorff. 2012. Geologic Map of the Alley Spring Quadrangle, Shannon County, Missouri. US Geological Survey Scientific Investigations Map 3161, scale 1:24,000.

Weary, D.J., R.C. Orndorff, and J.E. Repetski. 2013. Geologic Map of the Jam Up Cave and Pine Crest quadrangles, Shannon, Texas, and Howell counties, Missouri. US Geological Survey Scientific Investigations Map 3248, scale 1:24,000.

Weary, D.J., and H.A. Pierce. 2009. Prospecting for a major spring conduit in the Ozark karst system (Missouri, USA) using audio-magnetotelluric (AMT) soundings. In *Proceedings of the 15th International Congress of* Speleology, Kerrville, Texas, USA, July 19–26, 2009. W.B. White, ed. N.p.: International Union of Speleology, 1:457–460.

Weary, D.J., and J.S. Schindler. 2004. Geologic map of the Van Buren South quadrangle, Carter County, Missouri. US Geological Survey, Geologic Investigations Series Map I–2803, scale 1:24,000.

Weary, D.J., and R.E. Weems. 2004. Geologic map of the Van Buren North quadrangle, Shannon, Carter and Reynolds counties, Missouri. US Geological Survey Geologic Investigation Series Map I-2802, scale 1:24,000.

Weems, R.E. 2002. Geologic map of the Low Wassie quadrangle, Oregon and Shannon counties, Missouri. US Geological Survey Geologic Investigations Series Map I–2719, scale 1:24,000.

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