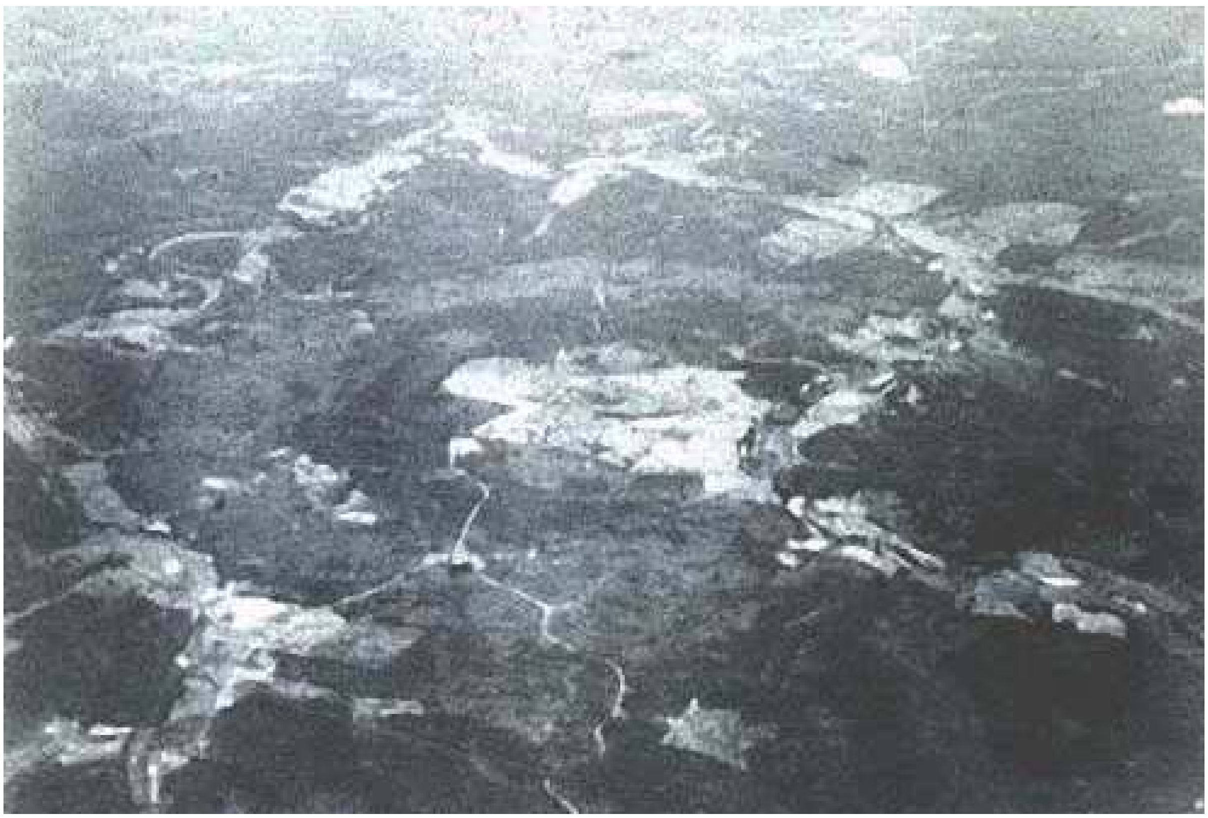
Association of Missouri Geologists Field Trip Guidebook



51st Annual Meeting

Rolla, Missouri
October 1-2, 2004

MISSOURI DEPARTMENT OF NATURAL RESOURCES
Geological Survey and Resource Assessment Division

ASSOCIATION OF MISSOURI GEOLOGISTS

Cover Photo: *Aerial photograph of the Crooked Creek ring structure looking northwest. Image from the Planetary and Space Science Centre, Earth Impact Database, University of New Brunswick.*

ASSOCIATION OF MISSOURI GEOLOGISTS

51ST ANNUAL MEETING
OCTOBER 1-2, 2004
ROLLA, MISSOURI

GUIDEBOOK TO FIELD TRIPS:

Geohydrology of the Fort Leonard Wood Military Reservation, Pulaski County, Missouri

Geology of the Crooked Creek Ring Structure, Crawford County, Missouri

2004

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Rolla, Missouri

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ASSOCIATION OF
MISSOURI GEOLOGISTS

51ST ANNUAL MEETING AND FIELD TRIPS

OCTOBER 1-2, 2004
ROLLA, MISSOURI

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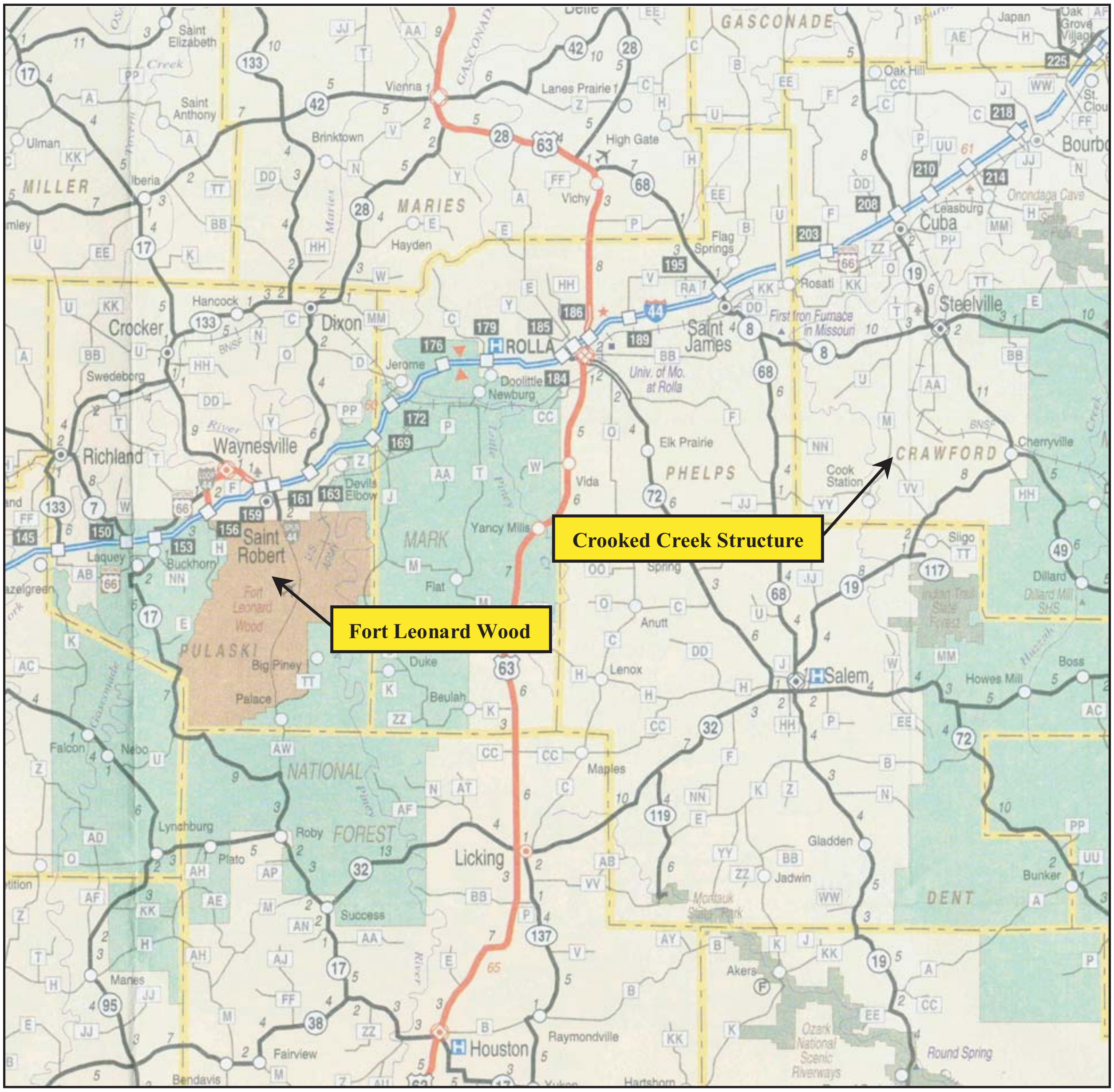
Association of Missouri Geologists
2004

Field Trip I:
Geohydrology of the Fort Leonard Wood Military Reservation, Pulaski County, Missouri

Douglas N. Mugel and **John G. Schumacher**
United States Geological Survey, Rolla, Missouri

AREA HIGHWAY MAP SHOWING FIELD TRIP LOCATIONS



GEOHYDROLOGY OF THE FORT LEONARD WOOD MILITARY RESERVATION

The Fort Leonard Wood Military Reservation (FLWMR) is located in south-central Missouri, almost entirely within Pulaski County, approximately 130 mi (miles) southwest of St. Louis. The approximately 61,000-acre FLWMR opened during 1941 for the training of combat troops during World War II. The FLWMR was deactivated in 1946 at the end of the war, but was re-opened during 1956 as a combat troop training center and engineering school.

Many facilities are concentrated in the north-central part of the FLWMR. This area contains classrooms, barracks, recreation and shopping facilities, and support units. The remainder of the FLWMR contains large tracts of land set aside for small-arms firing ranges, grenade ranges, artillery ranges, training areas for armored vehicle night maneuvers, an Air National Guard cannon and strafing range, and heavy equipment training areas. During 1995, as part of the Base Realignment and Closure Commission (BRAC), the U.S. Army initiated the relocation of the U.S. Army Chemical and Military Police Schools from Fort McClellan, Alabama, to FLWMR.

During 1980, the U.S. Department of Defense (DOD) initiated a comprehensive Installation Restoration Program (IRP) to assess and control the migration of environmental contaminants that may have resulted from past operations or disposal practices at DOD facilities. In 1994, the FLWMR Directorate of Public Works, Environmental Division (DPWED), requested support from the U.S. Geological Survey (USGS) in a regional geohydrologic and water-quality assessment and investigation of selected landfills and other potential contaminant sources at the FLWMR. The results of the study were reported in Imes and others (1996), which also incorporated the results of a separate USGS study (Harrison and others, 1996) to map the geology of the FLWMR, focusing on bedrock fractures and faults. From 1995 to 1998, geohydrologic and water-quality assessments were conducted by the USGS at 12 potential contaminant sites at the FLWMR (Schumacher and Imes, 2000). Since then, USGS work has continued with detailed investigations at several sites at the FLWMR, including the installation and sampling of a number of monitoring wells.

Most of the FLWMR is located on a broad ridge between the northerly flowing Big Piney River to the east and the northerly flowing Roubidoux Creek to the west (fig. 1). Early Ordovician-age dolostones and sandstones form the bedrock surface throughout the FLWMR. Sedimentary strata are nearly horizontal with dips of 1.5 degrees or less, except along folds and collapse zones where dips can be steep. Stream incision of these nearly horizontal strata has produced a dendritic pattern on the geologic map of the FLWMR (fig. 1).

The oldest geologic formation to crop out at the FLWMR is the Canadian Series Ordovician-age Gasconade Dolomite. It underlies the major streams and their tributaries (figs. 1, 2) and is exposed as bluffs along the Big Piney River and Roubidoux Creek valleys. The pre-erosion thickness of the Gasconade Dolomite is between 200 and 300 ft (feet) at the FLWMR (Mugel and Imes, 2003). The Gasconade Dolomite primarily is a cherty dolostone and is divisible into informal upper and lower units based on chert content and a basal sandstone unit called the Gunter Sandstone Member (Thompson, 1991). A stromatolitic chert horizon that generally is 10 to 15 ft thick and 30 to 50 ft below the top of the formation separates the upper and lower units at the FLWMR (Harrison and others, 1996). The lower Gasconade Dolomite generally is medium to thin bedded, medium to finely crystalline dolostone and may have greater than 50 percent chert by volume, whereas the upper Gasconade Dolomite is massive, medium to finely crystalline dolostone and may contain small amounts of chert and sandstone stringers. The upper part of the Gasconade Dolomite contains intraformational breccia horizons as much as 4 ft thick that may

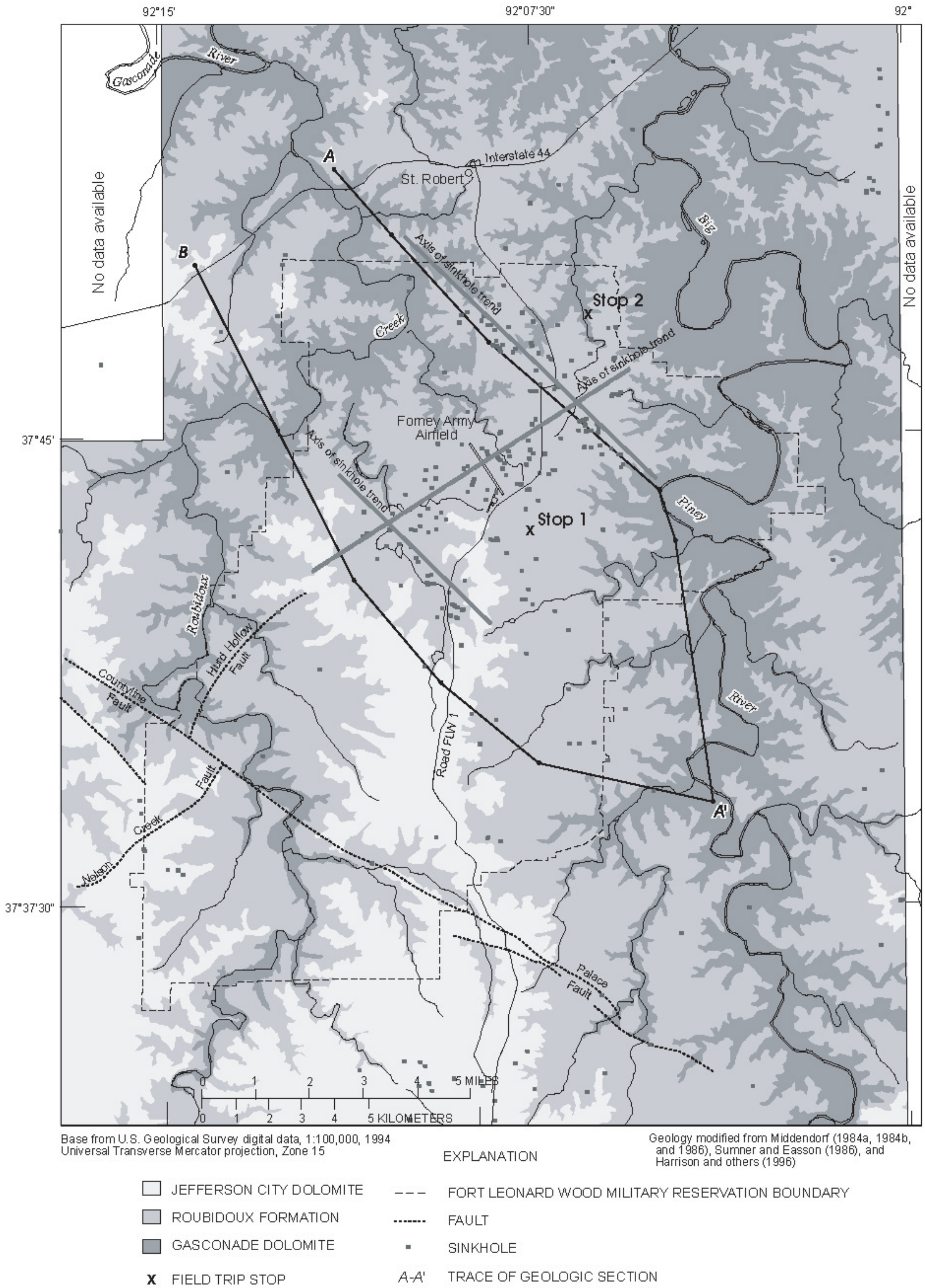


Figure 1. Bedrock geologic formations at the Fort Leonard Wood Military Reservation and vicinity, and indications of faults and sinkholes (modified from Schumacher and Imes, 2000).

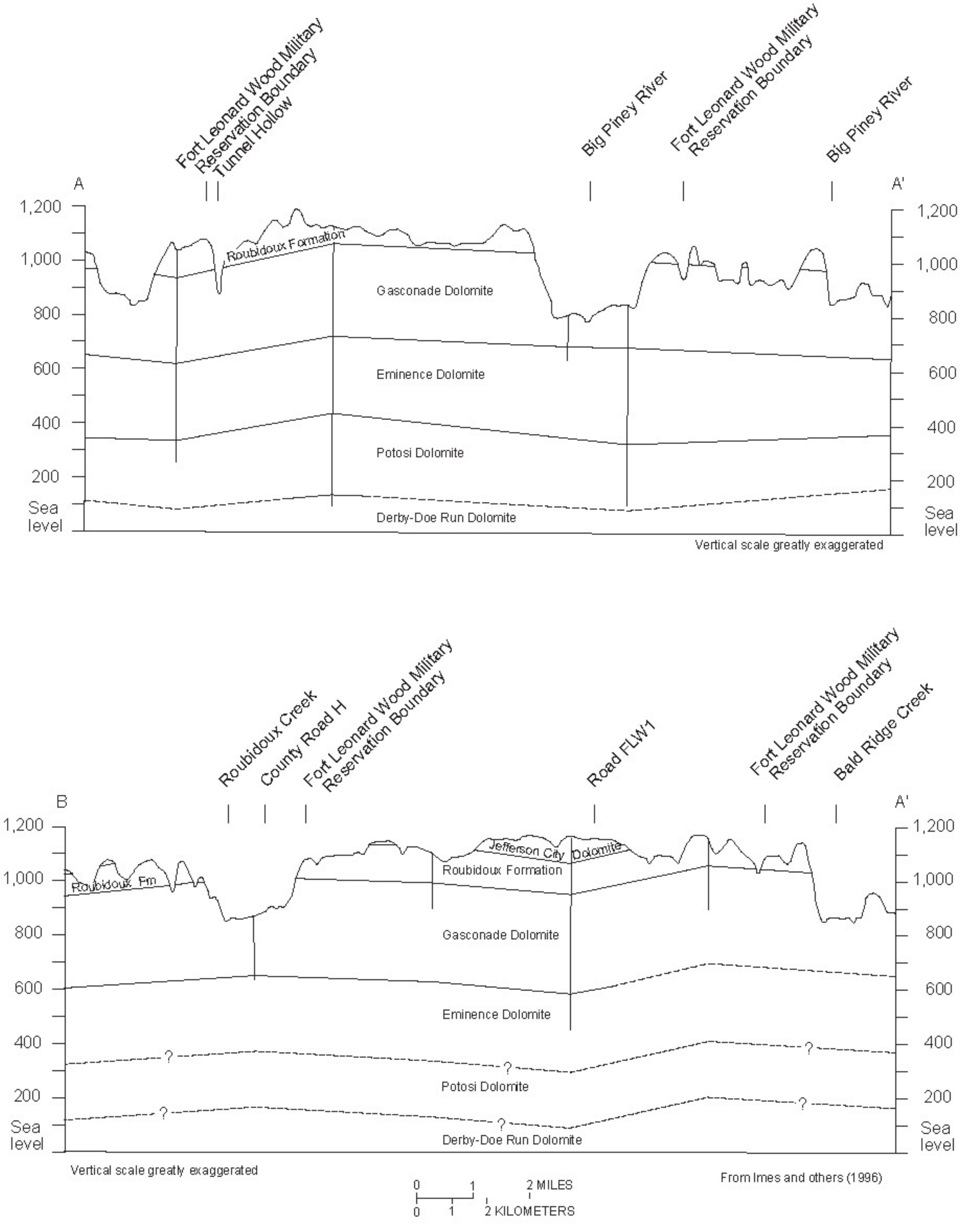


Figure 2. Generalized geologic sections trending northwest to southeast across the Fort Leonard Wood Military Reservation (the traces of sections A-A' and B-A' are shown in Fig. 1).

be indicative of larger permeability zones that are capable of transmitting large quantities of water (Imes and others, 1996). Most caves and larger springs at the FLWMR and vicinity occur in the upper part of the Gasconade Dolomite.

The Canadian Series Ordovician-age Roubidoux Formation overlies the Gasconade Dolomite. The Roubidoux Formation crops out across most of the upland areas and hillsides in the western, northern, and eastern parts of the FLWMR (figs. 1, 2). The pre-erosion thickness of the Roubidoux Formation ranges from less than to somewhat more than 200 ft throughout the FLWMR (Mugel and Imes, 2003). The lithology of the Roubidoux Formation ranges from dolostone to cherty dolostone to sandy dolostone to sandstone. The amount of sandstone ranges from about 10 to 25 percent throughout most of the FLWMR (Harbaugh, 1983; Thompson, 1991). Harrison and others (1996) noted substantial dissolution of the more dolomitic parts of the lower Roubidoux Formation, resulting in the subsequent collapse of the overlying, more sandstone-rich beds. This intense dissolution of the lower part of the formation is expressed as a pattern of narrow steep-sided folds in the overlying sandstone units. Most sinkholes occurring in upland areas of the FLWMR are formed in the Roubidoux Formation (fig. 1). The Canadian Series Ordovician-age Jefferson City Dolomite overlies the Roubidoux Formation, and is the youngest formation at the FLWMR (fig. 2). It crops out extensively in upland areas in the southern part of the FLWMR (fig. 1). The Jefferson City Dolomite is a medium to finely crystalline dolostone and argillaceous dolostone with chert, and may contain lenses of orthoquartzite, conglomerate and shale. A massive bed of gray, finely crystalline argillaceous dolostone informally referred to as the Quarry Ledge by Thompson (1991), because of its resistance to erosion, occurs about 30 ft above the base of the formation throughout the FLWMR (Harrison and others, 1996).

Faults occur in the subsurface at the FLWMR and surrounding areas. The dominant trend of the faults is northwest-southeast, with a smaller number of faults trending in other directions, particularly northeast-southwest. Three nearly vertical faults (Countyline Fault, Nelson Creek Fault, and Hurd Hollow Fault) with vertical displacements of less than 100 ft have been identified in the southern and western parts of the FLWMR (fig. 1).

The permeability of geologic formations that underlie the FLWMR has been greatly increased by dolostone dissolution. Evidence of the magnitude of dissolution is shown by the numerous, irregular, small folds with steep attitudes and the numerous sinkholes that have been created in the Roubidoux Formation by collapse of overburden into solution-enlarged cavities. Karst features commonly are well developed at the FLWMR, and numerous caves, springs, and more than 220 sinkholes have been identified at the FLWMR (fig. 1; Schumacher and Imes, 2000). Many of the sinkholes located in the north-central part of the FLWMR are distributed along a 1-mi-wide linear trend oriented northeast to southwest (fig. 1; Imes and others, 1996). Two narrower bands of sinkholes with major axes oriented northwest to southeast also have been noted (fig. 1; Imes and others, 1996).

Groundwater supplies at the FLWMR and vicinity are from wells that are completed in the Ozark aquifer, the middle aquifer of the Ozark Plateaus aquifer system (Imes and Emmett, 1994). Across southern Missouri, the Ozark aquifer is used extensively for domestic and public water supply. Although the Ozark aquifer includes the Jefferson City Dolomite, this formation generally is unsaturated at the FLWMR, and the regional water table generally occurs within the lower Roubidoux Formation or upper Gasconade Dolomite. The Roubidoux Formation and Gasconade Dolomite are productive water-bearing strata with well yields ranging from several tens to several hundreds of gallons per minute (Melton, 1976). Unlike most of the municipalities in southern Missouri, which generally obtain their water from groundwater sources, the FLWMR obtains nearly all of its drinking water from a pumping station on the Big Piney River. A large capacity public water supply well (Indiana Avenue well) is in the northern part of the FLWMR, but supplies less than 3 percent of the water use at the FLWMR (Mugel and Imes, 2003). Several small capacity (less than a few tens of gallons per minute) wells supply drinking water to training facilities that are scattered across the FLWMR.

Depth to the water table at the FLWMR is variable and generally ranges from about 130 to 300 ft or more in upland areas to less than 25 ft in the Big Piney River or Roubidoux Creek valleys. A north-trending groundwater divide occurs at the FLWMR with groundwater generally flowing away from the uplands along the axis of this divide east toward the Big Piney River or west toward Roubidoux Creek (fig. 3).

Groundwater flow patterns at the FLWMR are the result of a complex combination of diffuse flow through porous residual material and bedrock and conduit flow through solution-enlarged openings along bedding planes and interconnected fractures. Fracture sets exhibiting solution activity have a pronounced northeast orientation (Imes and others, 1996). Conduit flow may have developed in some of these fractures. However, about 98 percent of all observed fractures have narrow [less than 0.5 in. (inch)] apertures and show no evidence of secondary mineralization (Harrison and others, 1996). These observations, combined with evidence of extensive dissolution of interbedded dolostone in the lower part of the Roubidoux Formation and the fact that nearly 45 percent of all observed Gasconade Dolomite exposures show evidence of bedding-plane-controlled caves, solution cavities, or vugs, lead to the conclusion that much of the water discharged at large springs is transported along high-permeability pathways within solution-enlarged bedding planes rather than fractures (Imes and others, 1996).

The presence of karst features can substantially alter the movement of groundwater from flow patterns commonly associated with rocks of more uniform permeability. Although groundwater flow in the aquifer is controlled in a general way by regional topography, flow in solution-enlarged openings commonly is independent of topography. For example, in the central part of the FLWMR the groundwater divide (fig. 3) is as much as 2 mi west of the topographic divide. Groundwater that normally would have flowed westward to Roubidoux Creek has been captured by a zone of large secondary permeability and redirected eastward toward the Big Piney River.

A number of dye-trace tests have been conducted at the FLWMR to determine spring catchment areas (Harvey, 1980; Rory McCarthy, Fort Leonard Wood Military Reservation, written commun., 1995; Imes and others, 1996; Schumacher and Imes, 2000). Dye that was injected into sinkholes or losing stream segments at the FLWMR emerged at one of four known perennial springs—Miller Spring, Roubidoux Spring, Shanghai Spring, or Sandstone Spring (fig. 4). Travel times obtained from successful dye-trace tests at the FLWMR indicate that groundwater can flow from recharge areas at FLWMR to vicinity springs within a matter of days.

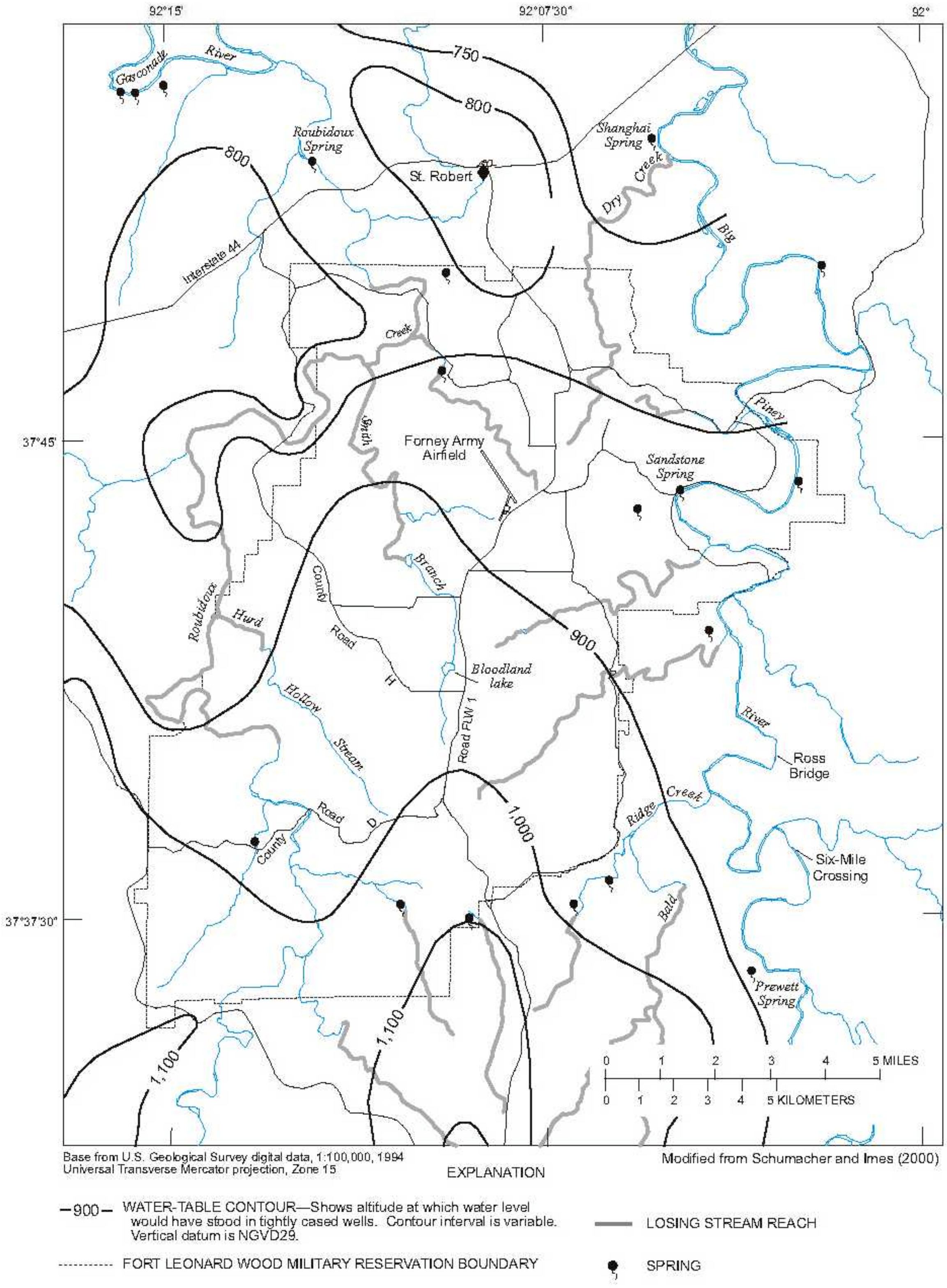


Figure 3. Fort Leonard Wood Military Reservation surface drainage features, location of springs, and the altitude of the regional water table measured in August and October, 1995.

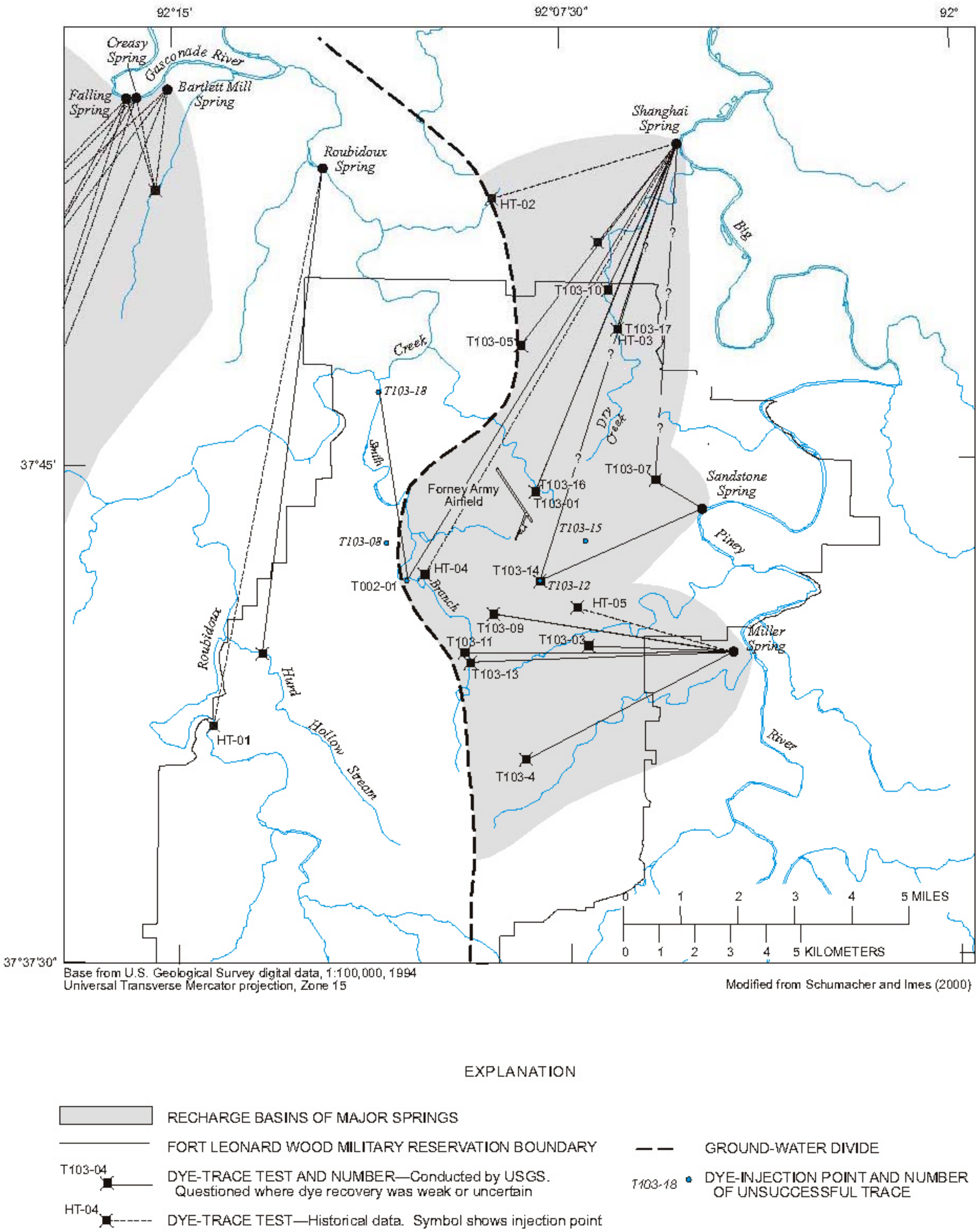


Figure 4. Recharge basins of major springs, regional groundwater divide, and injection and recovery points for dye-trace tests in and near the Fort Leonard Wood Military Reservation and vicinity.

Field Trip Stop 1: Monitoring well MW-308A (fig. 1)

The USGS has installed several monitoring wells near three landfills (landfills 3A, 3B, and 3C) in the approximately central part of the FLWMR. Monitoring well MW-308A was installed in 2004 as an open-hole well (open borehole below steel casing, without a well screen, riser, or sand pack) in a dry cave approximately 140 ft above the water table. A few feet from MW-308A is monitoring well MW-308, which was completed in 2001 at 280 ft deep. The depth-to-water is approximately 255 ft below land surface in MW-308.

The USGS routinely videotapes boreholes using a down-hole camera to locate areas of seepage and to observe the condition of the borehole before completing the monitoring well. Because MW-308A was left as an open-hole well, this field trip stop will allow visitors to view the borehole using a television monitor attached to a down-hole camera. About 40 ft of vuggy Roubidoux Formation is present below the steel casing. The borehole then intersects the upper part of a cave that mostly is filled by a debris pile of mud and rock. The cave is located near the Roubidoux Formation/Gasconade Dolomite contact, probably at the bottom of the Roubidoux Formation.

Field Trip Stop 2: Dry Creek (fig. 1)

Dry Creek is a losing stream whose flow is to the north through the northern part of the FLWMR. Streamflow is lost to the subsurface through two swallow holes that can be observed in the streambed of Dry Creek at this field trip stop. These swallow holes are part of a cave system that also can be observed in the bluff above the streambed. This bluff is chert with dolostone of the lower Gasconade Dolomite; well preserved stromatolites can be observed both in the bluff and in the streambed. As a result of the lost streamflow, vegetation grows in the streambed downstream from the second swallow hole, whereas the streambed is more barren upstream from the swallow hole.

A dye trace was conducted at this location (T103-17; fig. 4) in 1997 as part of an assessment of storm-event discharge and water quality at Shanghai Spring 2.8 mi north-northeast of the swallow hole. The peak dye concentration at Shanghai Spring occurred 86.4 hours after dye placement, indicating a rate of travel of 0.77 mi/day (Schumacher and Imes, 2000).

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Association of Missouri Geologists
2004

Field Trip II: Geology of the Crooked Creek Ring Structure, Crawford County, Missouri

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GEOLOGY OF THE CROOKED CREEK RING STRUCTURE

Geographic Location

The Crooked Creek ring structure is located in southwestern Crawford County, Missouri, USA. It occurs in the northeast portion of the Cook Station 7.5' minute quadrangle, extending eastward into the adjoining Cherryville 7.5 minute quadrangle. The center of the structure is located at Center, NE1/4, SW1/4, SW1/4, Section 17, T.36 N. R.4 W. (91.39485 degrees west longitude, 37.83496 degrees north latitude).

Regional Geologic Setting

The Crooked Creek structure is a localized occurrence of intensely disturbed early Paleozoic strata situated on the western flank of the Ozark dome at a location about 80 km (50 mi) WNW of the St. Francois Mountains (Middendorf, 2003). The west-trending, down-to-the-north Palmer fault terminates on the east end of the structure. The south-southeast-trending, down-to-the-east Cuba fault may or may not extend to and terminate on the north end of the structure. Normal regional dip for strata in the area is about 2.8 m/km (15 ft/mi)(Hendrix, 1954).

The Crooked Creek structure is in line with seven other localized structural disturbances that occur from southern Illinois to eastern Kansas (Snyder and Gerdemann, 1965). From east to west the disturbances are Hicks dome, Avon, Furnace Creek, Crooked Creek, Hazelgreen, Decaturville, Weaubleau, and Rose dome. This line of structures defines what has been called the "38th parallel lineament" because it closely approximates the 38th parallel line of latitude (Heyl, 1972).

Previous Field Trips

To date, three published field trips have been conducted in the Crooked Creek structure: Snyder and others (1964) for the <u>Eleventh Annual Field Trip of the Association of Missouri Geologists</u>; Snyder and others (1965) for the <u>1965 Annual Meeting of the Geological Society of America</u>; and Kisvarsanyi and Hebrank (1982) for a <u>Field Trip to the St. Francois Mountains and the Historic Bonne Terre Mine</u>.

Discovery

The Crooked Creek structure was first recognized by assistants of the Missouri Bureau of Geology and Mines while engaged in reconnaissance fieldwork in Crawford County during 1910 (Hughes, 1911). Their interests were focused primarily on the possibility of the structure hosting economic ore deposits.

Geologic Maps

Hughes (1911, 1912) produced the first geologic map of the Crooked Creek structure (fig. 1). The map depicts a concentrically-ringed, 1.25-mile-diameter, circular outcropping of Cambrian strata conspicuously situated in Ordovician strata. The map resembles a target, replete with bull's-eye. Hughes' map constitutes the central uplift portion of the structure as later mapped by Hendriks (1954).

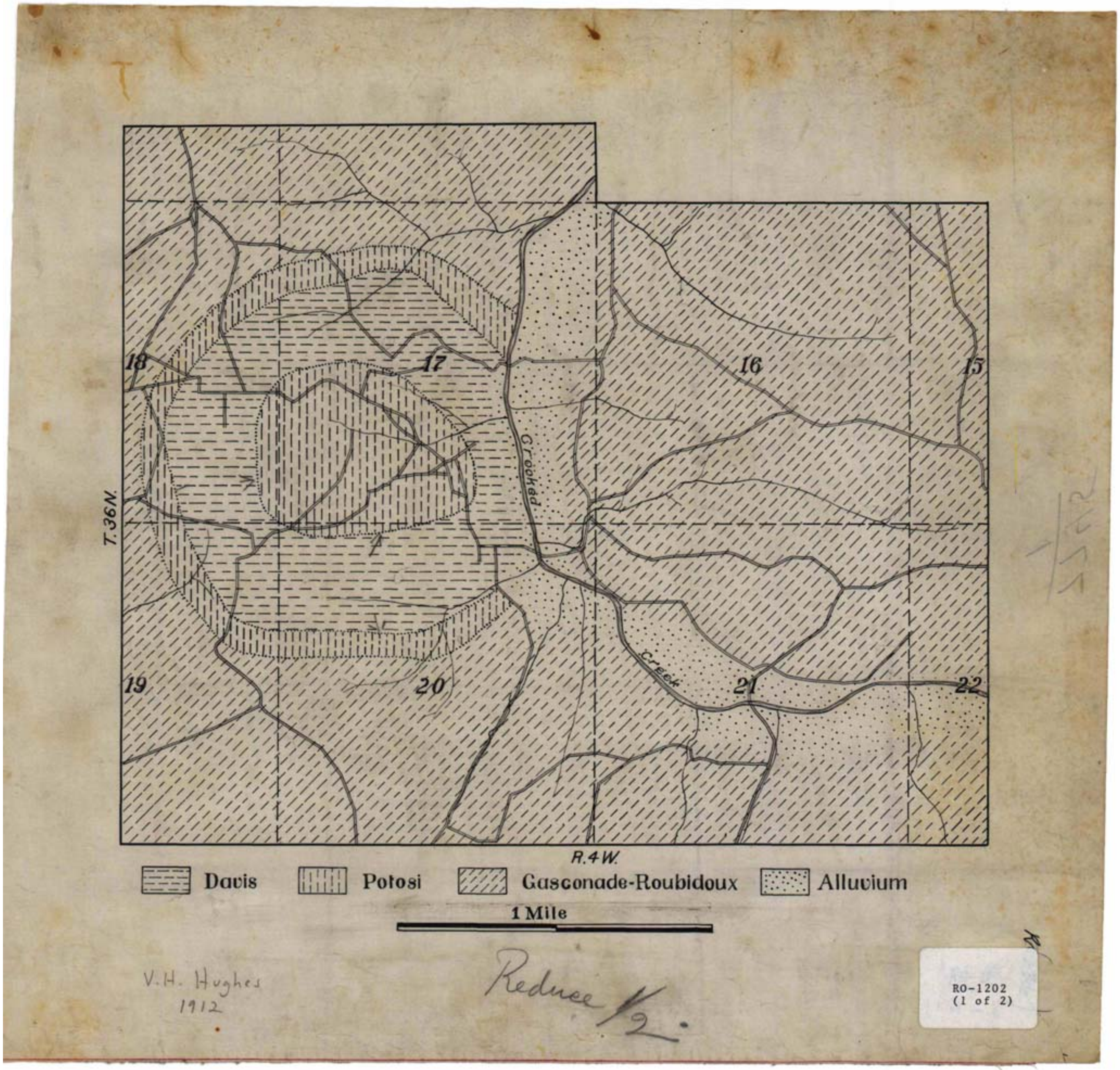

Figure 1. The first geologic map of the Crooked Creek structure (from Hughes, 1911, 1912).

Hendriks (1954) produced two geologic maps, which, to present-day, are regarded as the most authoritative geologic maps of the Crooked Creek structure. The maps are at two different scales. The 1:9,600-scale map depicts in detail the central uplift portion of the structure. The 1:62,500-scale map shows the entire structure, though in a generalized manner because the structure occupies only a small portion of the Steelville 15-minute quadrangle. Figure 2 represents a GIS compilation of these two maps.

Stratigraphy

Sedimentary strata of the upper Cambrian, lower Ordovician, and Carboniferous crop out in the Crooked Creek structure. Holocene alluvium occurs in present-day stream valleys. The stratigraphic succession, as adapted from Hendriks (1949, 1954), is outlined below.

Neogene System
Holocene Series
Alluvium—quartz sand and chert pebbles and cobbles.
Unconformity
Carboniferous System
Pennsylvanian Subsystem
Quartz sandstone, fireclay, and coal filling depressions in underlying Cambrian-Ordovician strata.
Mississippian Subsystem
Hendricks (1949) found the bryozoan *Fenestella* in a piece of residual chert.
Unconformity
Ordovician System
Ibexian Series
Jefferson City Dolomite—thin- to thick-bedded, light gray to buff, argillaceous, cherty, fine-crystalline dolomite (cotton-rock) with persistent medium- to massive-bedded, gray dolomite containing quartz roses (Quarry Ledge).
Roubidoux Formation—quartz sandstone and dolomite; cherty.
Gasconade Dolomite—well bedded, medium-crystalline, light gray dolomite: very cherty; Gunter Sandstone Member at base comprising quartz sandstone and sandy dolomite.
Cambrian System
Upper Series
Eminence Dolomite—massive to bedded, coarse-crystalline, very light gray dolomite; cherty.
Potosi Dolomite—massive, poorly-bedded, fine- to medium-crystalline, light to dark brown dolomite; abundant quartz druze; petroliferous odor on fresh breaks, non-cherty. Hosts shatter cones in central uplift.
Derby-Doerun Dolomite—thick-bedded, sandy, buff-gray dolomite; non-cherty.
Davis Formation—interbedded limestone and dolomitic limestone, green to brown shale, slabby siltstone to fine-grained sandstone, edgewise to pebble limestone conglomerate; glauconitic, especially in lower part; non-cherty.
Bonneterre Dolomite—massive, gray-brown, coarse-crystalline dolomite; non-cherty.
Lamotte Sandstone—yellowish to white, friable quartz sandstone containing rounded granules and small pebbles of quartz; exposed only as float material in the central uplift.
Unconformity
Precambrian Eonothem
Presumably igneous and/or metamorphic rocks occur in the subsurface beneath the Crooked Creek structure, though no boreholes have been drilled sufficiently deep within the structure proper to encounter them or in the region immediately surrounding the structure.

Structural Geology

Geologic mapping by Hendriks (1954) (fig. 2) depicts the Crooked Creek structure as comprising two main structural elements: a central uplift and a synclinal ring graben that encircles the central uplift. The central uplift is fault-bound and roughly circular, ranging from 2.3 km (1.4 mi) to 3.0 km (1.9 mi) in diameter. The central uplift is further characterized as comprising a central basin that is circumscribed by a ring anticline. A long, narrow, dogleg horst is shown cutting across the middle of the basin. Strata ranging from Lamotte Sandstone upwards stratigraphically to Gasconade Dolomite crop out in the central uplift. The oldest rocks, Bonneterre Dolomite and Lamotte Sandstone, occur at the surface along the axial trace of the ring anticline. Potosi Dolomite crops out in the center of the basin and forms the bull's-eye of the structure. One small outcrop of Eminence Dolomite and scattered Lamotte Sandstone float occur in the basin. The rocks in the central uplift are variously displaced upwards 150 to 300 m (500 to 1000 ft) from what is considered normal elevation for them in the area (Snyder and Gerdemann, 1965).

The synclinal ring graben tapers northward. Its overall shape and orientation is that of a teardrop appearing to fall southward. Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite crop out in the graben. The Jefferson City is displaced downwards by about 76 m (250 ft) from what is considered normal elevation for it in the area (Snyder and Gerdemann, 1965). Sandstone, fireclay, and coal strata of probable Carboniferous age also occur in the graben, but the outcrop pattern of these strata has not been systematically mapped. Written descriptions by Hendriks (1954) and the locations of coal mines and clay pits and the one drill hole that penetrated these deposits provide the only clues for locating outcrops of these Carboniferous strata in the ring graben.

The fault-bound outer perimeter of the graben defines the outer limits of the Crooked Creek structure, which, according to the small-scale map by Hendriks (1954), measures 5.6 km (3.5 mi) from west to east and 7.2 km (4.5 mi) from north to south. Strata beyond this limit are generally considered to be unaffected by the events that created the structure. However, Nickerson (2002), using three-dimensional GIS visualization, concluded that the entire Crooked Creek structure is considerably larger, ranging from 9 to 10 km in diameter.

Several mineral exploration holes were drilled in the central uplift between 1910 and 1926. The cuttings, cores, and descriptive logs of these boreholes are on file at the Geological Survey and Resource Assessment Division, Rolla, Missouri. The descriptive logs indicate complex structuring in the subsurface. Log number 2668, for example, shows the Eminence and Potosi dolomites repeated five times to a total drill depth of 864 ft. This subsurface data led Snyder and Gerdemann (1965) to conclude that "...the structure at depth is far more complex than is suggested by the simple ring pattern of formation outcrop." In other words, the geologic maps by Hendriks (1954) that depict orderly structuring may represent gross oversimplifications. Perhaps the lithologic contents of the Crooked Creek structure constitute a megabreccia that is upthrown in the central uplift and down-dropped in the ring graben.

Topographic Expression

The Crooked Creek structure is discernable on the shaded relief map shown in Fig. 3. The central basin appears as nonforested, depressed, low-relief terrain that slopes eastward towards Crooked Creek. The remainder of the structure appears as arcuate, forested, higher elevation, and higher relief terrain.

Age of Structuring

Hendriks (1954) stated as follows concerning the date of origin of the Crooked Creek structure: "The residual sandstone boulders of Pennsylvanian age lie with equal distribution over the entire struc-

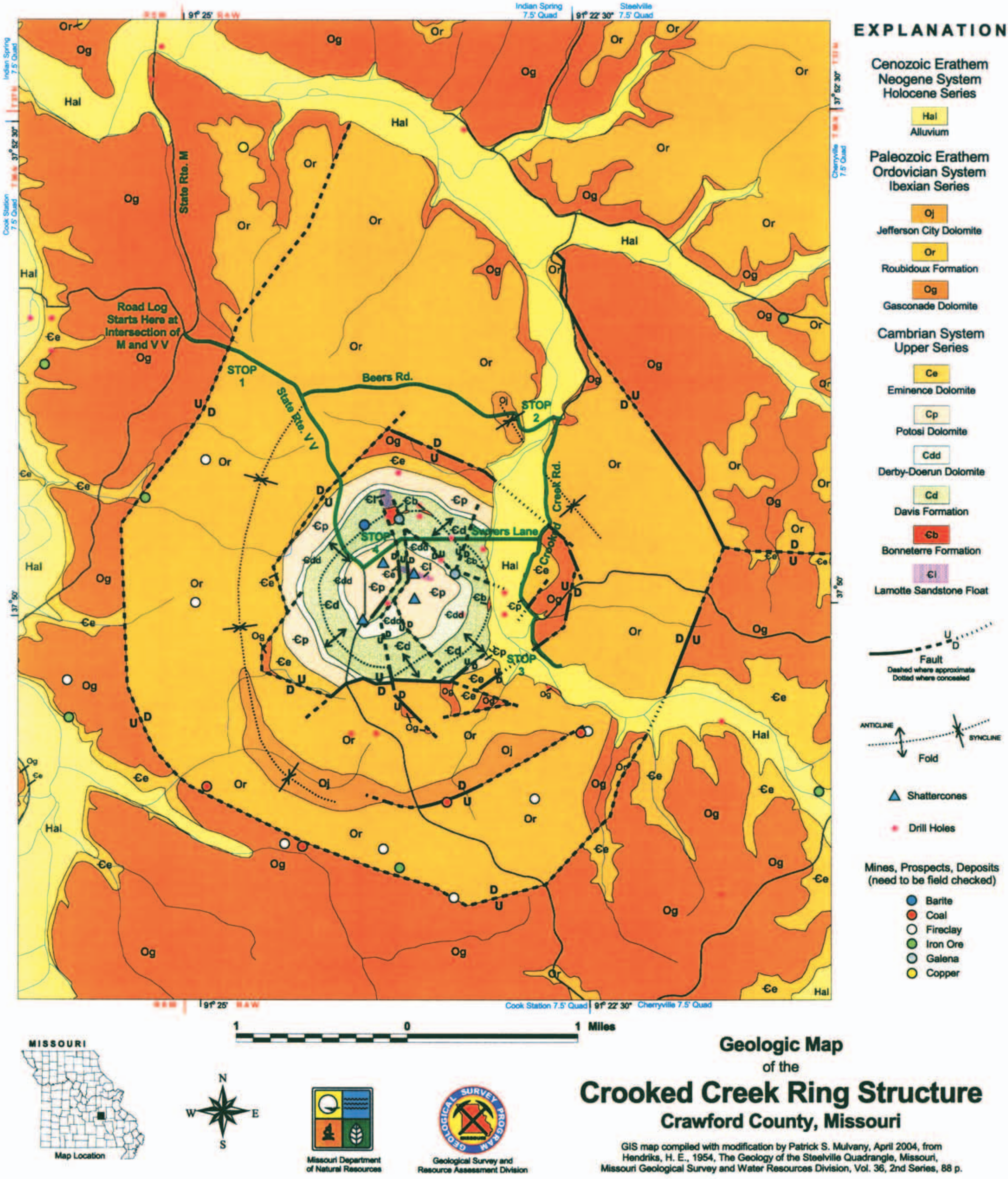

Figure 2. Geologic map of the Crooked Creek structure showing field trip route.

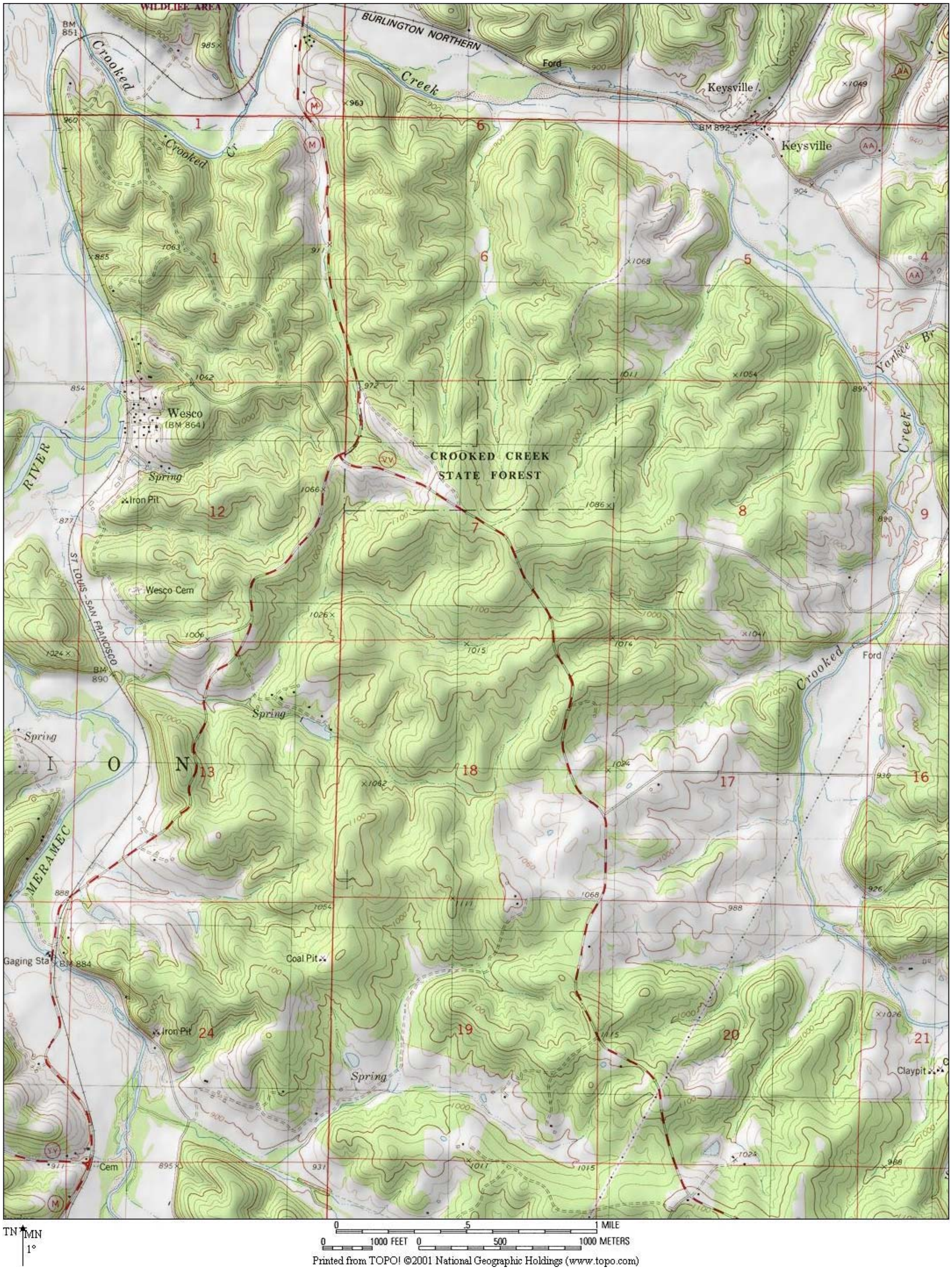

Figure 3. Shaded relief map of the Cook Station 7.5-minute quadrangle showing the Crooked Creek structure in the southeast quadrant of the map.

ture. There is also an outcrop of Pennsylvanian sandstone in place, lying horizontally, and with angular unconformity, upon dipping Eminence dolomite. These occurrences indicate the origin of the structure after the deposition of the Jefferson City and prior to Desmoinesian time."

On this subject, Snyder and Gerdemann (1965) stated, "This structure cannot be closely dated. The youngest formation involved is the Jefferson City. Younger Ordovician beds and up to 400 feet of Mississippian may once have covered the area but were removed by erosion prior to Pennsylvanian time. Scattered blocks of sandstone, believed by Hendriks (oral communication) to be Pennsylvanian in age, occur within the disturbed area but apparently were not involved in the deformation. Presumably, the structure is post-Jefferson City—pre-Pennsylvanian in age."

Luczaj (1998) concluded that the Crooked Creek structural event occurred from Ordovician to Cenozoic if caused by igneous activity, or it occurred from Ordovician to pre-Pennsylvanian if caused by meteorite impact

It does appear *a priori* to conclude anything about the nature of the contact between Carboniferous strata and underlying lower Ordovician strata in the Crooked Creek structure because the Carboniferous strata have not been mapped. Detailed mapping of Carboniferous strata and detailed examinations of its basal contact are needed to reveal the true stratigraphic relationship. Interestingly, log number 23379 of a well drilled in 1965 in the south part of the ring graben (next to the "Or" symbol in Figure 2) describes Pennsylvanian sandstone and shale down to total depth of 210 ft. The section contains what is described as a one-foot-thick cannaloid coal. A remark on the log states, "Filled sink."

Breccias

Hendriks (1954) pointed out, "The Derby-Doerun and Potosi formations in the basin are extensively fractured and brecciated, and in places they are so thoroughly pulverized that no trace of bedding remains." Kiilsgaard, Heyl, and Brock (1962) recognized "shatter breccias" and "intrusive breccias" as occurring in the central uplift. They characterized one kind of shatter breccia as consisting "...of rocks of the same lithology fractured in diverse directions, but without rotation of the multisized undisplaced fragments." They described a second kind of shatter breccia "…in which angular and subangular fragments of the same lithology have been dislodged and rotated so that all trace of bedding is obliterated."

The author and colleagues at the Survey have observed cobbles and boulders of chert breccia float on the forest floor along both sides of Beers Road, which courses across the ring graben in the north part of the structure. Also observed are similar chert breccias that occur in fault zones bounding the central uplift.

Shatter Cones

Hendriks (1949, 1954) was the first to recognize shatter cones in the Crooked Creek structure (fig. 4). The Crooked Creek shatter cones received subsequent address from Dietz (1959, 1960, 1968), Amstutz (1965a, 1965b) and Kiilsgaard, Heyl, and Brock (1962). Shatter cones at Crooked Creek are known to occur only in the central basin and are apparently restricted to Potosi Dolomite.

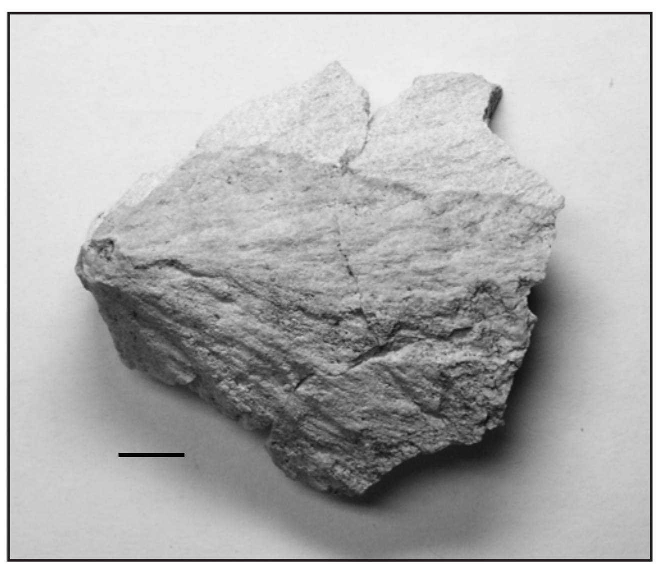

Figure 4. Shatter cone in Potosi Dolomite from central basin of Crooked Creek structure. Black scale bar represents 1 cm. Photo by P.S. Mulvany.

Shocked Quartz

Dietz and Lambert (1980) reported shock features in quartz granules in Lamotte Sandstone float from the central uplift area of the Crooked Creek structure. They stated, "All grains reveal a strong undulose extinction and are highly fractured—the fractures often radiating from contact points. Some grains are broken and collapsed into former voids presenting a breccia texture. Definite decorated planar elements [decorated planar deformation features (PDFs)] in quartz *are* locally present, but only among those which are in point-point contact. The planar elements [PDFs] show one of four different orientation sets. The most abundant are parallel to the (1013) and the (1012) crystallographic planets [sic for planes] of quartz. Rather remarkably, the quartz grains with planar elements are unfractured possibly due to the low porosity of the immediate environment."

Origin of Structure

Hendriks (1949, 1954), after considering and rejecting salt dome intrusion, igneous intrusion, and subterranean explosion causes of the Crooked Creek structure, settled on the meteorite impact mode of origin. Meteorite impact origin was subsequently supported by Dietz (1959, 1960, 1968), Hendriks (1965), Dietz and Lambert (1980), Rampino and Volk (1996), French (1998), Kenkmann (2001), Norton (2002), and Nickerson (2002). French (1998) considers shatter cones and PDFs as "...unique shock-metamorphic features that provide definite evidence for meteorite impact origin."

Fox, Allen, and Heinrich (1954), Kiilsgaard, Heyl, and Brock (1962), Snyder and Gerdemann (1965), Heyl (1972, 1983), and Luczaj (1998) favored the cryptovolcanic or cryptoexplosion modes of origin for the Crooked Creek structure. Mr. Gerdemann (personal communication September 2, 2004) now believes that the Crooked Creek structure was caused by meteorite impact. Amstutz (1965a) postulated that the Crooked Creek structure "…can only be explained by a long lasting, slow, diapiric process, with very many different periods of folding and faulting."

The Crooked Creek structure is probably a complex meteorite impact structure (fig. 5 and fig. 6) that has been deeply eroded. Complex impact structures are characterized by a central uplift surrounded by a ring graben. They contain shatter cones, shocked quartz, breccia dikes, faults, and fractured rock. Depending on the degree to which the Crooked Creek structure has been eroded, fallback materials such as devitrified melt, devitrified suevite breccia and lithic breccia may or may not be present. The chert breccias on the tops of hills along Beers Road are possible candidates for lithic breccia.

The impactor that formed the Crooked Creek structure was probably either an iron or a stony meteoroid. Of the two, iron is more likely because irons are stronger and tougher than stones and, therefore, better able to withstand the rigors of penetrating Earth's atmosphere without fragmenting catastrophically before hitting the ground (Norton, 2002). Assuming the impactor was an iron meteoroid of ideal spherical shape, assuming the impact velocity was 15 km/s, assuming the angle of impact was vertical, and assuming the crater diameter was 9 to 10 km (inferred from Nickerson, 2002), Figure 7 can be used to estimate the impactor's diameter at 250 m, with a mass of 6.5×10^{10} kg. Using the kinetic energy equation ($E = 0.5mv^2$, where m = mass and v = velocity (French, 1998; Norton, 2002)), the energy released upon impact was about 7.4×10^{18} Joules, which equates to 1,800 megatons. This enormous release of energy and the formation of the Crooked Creek structure occurred in mere seconds. The resulting complex crater, with its breccia and melt fill, had a depth of about 500 m, based on a 1:17 depth-to-diameter ratio (Norton, 2002). The crater was subsequently eroded. Whether any portions of the crater and its fallback contents still exist today is not known.

Rampino and Volk (1996) and Rampino (1997) theorize that the individual structures along the 38th parallel lineament are the result of a single serial impact event, similar to the serial impact of the fragmented Comet Shoemaker-Levy 9 into Jupiter during 1994.

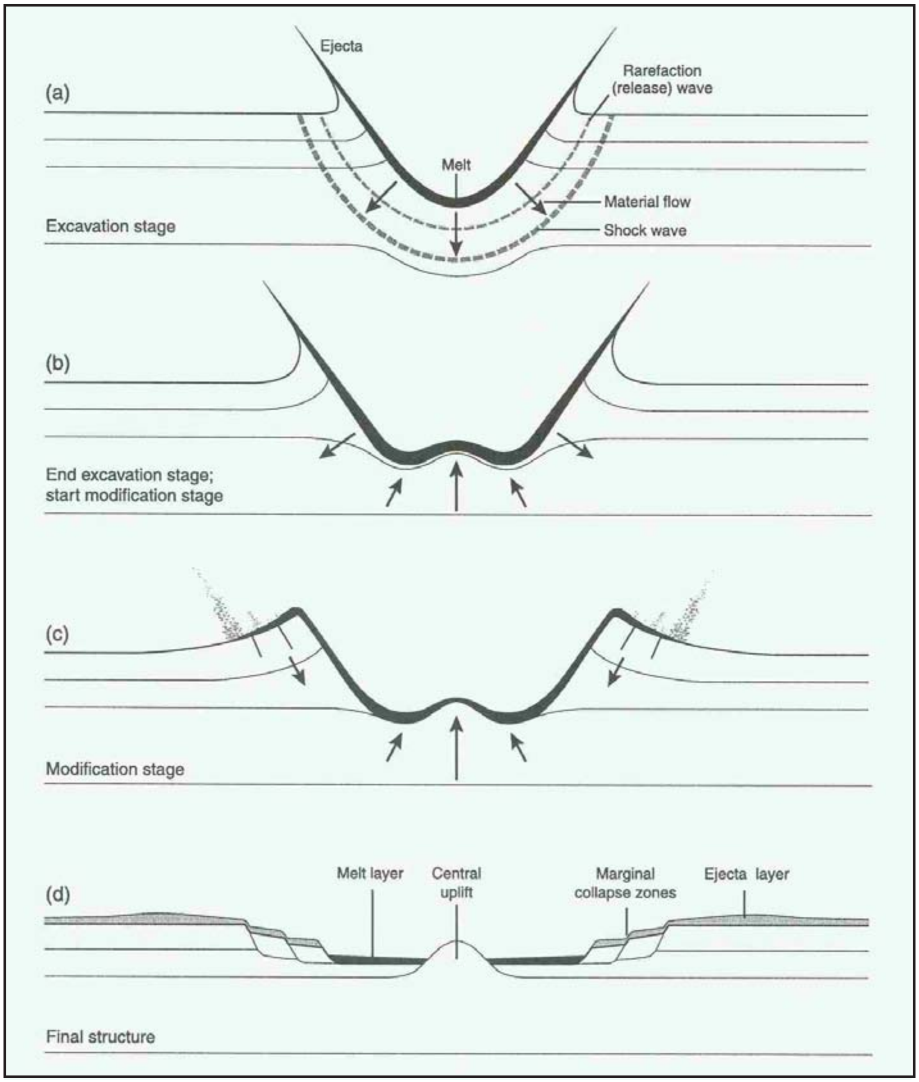

Figure 5. Creation of complex crater by meteorite impact (from French, 1998).

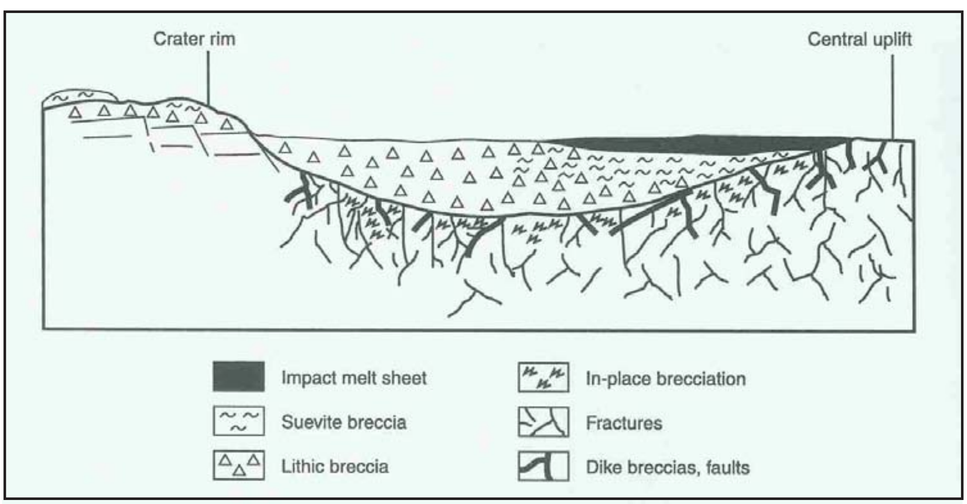

Figure 6. Cross section of complex meteorite crater showing distribution of fill facies (from French, 1998).

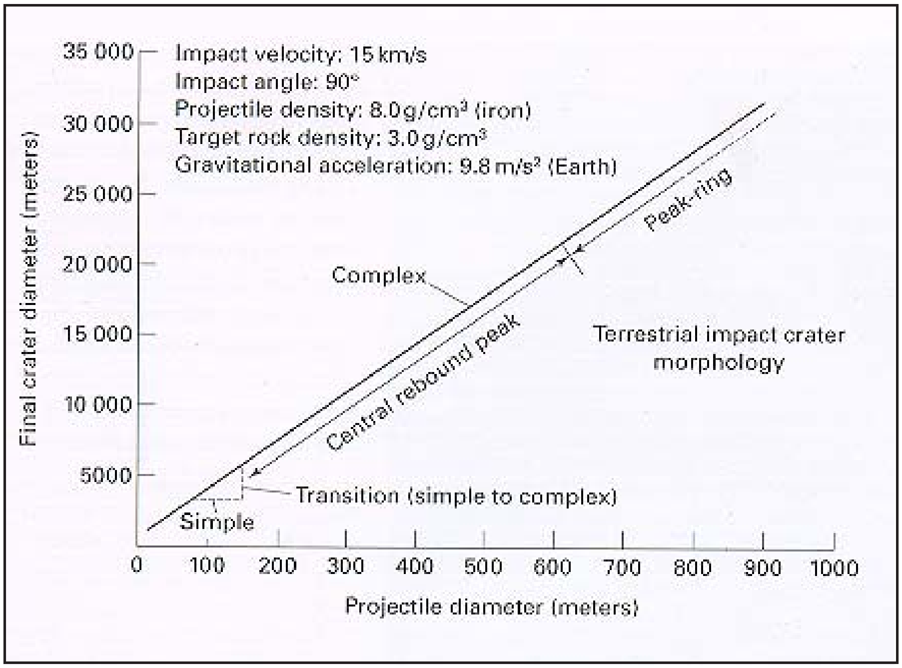

Figure 7. Chart relating diameter of crater to diameter of spherical iron impactor (from Norton, 2002).

Mineral Resources

Galena mineralization has been reported at two locations in the central uplift (fig. 2). A mined barite deposit occurs on the axis of the ring anticline. Mined deposits of fireclay and coal occur in the western and southern portions of the ring graben. Several deposits of iron ore have been mined in and around the structure. The fireclay, coal, and iron ore deposits are generally considered to be of the filled sink variety (Hendriks, 1954). One instance of copper mineralization was reported outside the north edge of the structure.

ROAD LOG

0.0 mi. Road log starts at the intersection of State Route M and State Route VV. Yellowish orange residuum exposed on southeast and northeast corners of intersection contains chert derived from complete weathering of Gasconade Dolomite. The chert is in part stromatolitic and drusy. Drive east on State Route VV.

0.4 mi. **STOP 1.** Turn right off of road and into spacious parking area. Gather around group leader in parking area for overview of the Crooked Creek structure. Then walk across road to other side. As you walk along the road downhill to the northwest, note the succession of rock exposures as described below.

A. Orange to tan, massive-bedded, fractured, fine-grained quartz sandstone. It appears to be Roubidoux Formation.
B. Grayish red purple fireclay with white mottling occurs in the bar ditch.
C. Slickensided, fractured, massive, orange to tan, fine-grained quartz sandstone of the Roubidoux Formation.

D. White chert breccia, which represents the fault that defines the outer limit of the Crooked Creek structure.
E. Stromatolitic and druzy chert residuum of weathered Gasconade Dolomite.

0.6-0.8 mi. Exposures of Roubidoux Formation quartz sandstone on left side of road.

0.8 mi. Intersection of State Route VV and Beers Road. Turn left onto Beers Road and drive east. Fireclay, quartz sandstone, and chert breccia are exposed at this intersection.

0.8-2.0 mi. Cobbles and boulders of Roubidoux Formation and chert breccia can be seen in the woods and fields on both sides of road, especially during winter months.

1.2 mi. Orange to tan, massive, fine-grained quartz sandstone is exposed along north side of man-made pond on right side of road. It is probably Roubidoux Formation. Boulders of chert breccia (some oolitic) rest on the sandstone.

2.1 mi. Mr. Bob West residence on left. Road turns sharply right and descends into valley of Crooked Creek. Bench of southwest-dipping, thick-bedded, dark gray-weathered Jefferson City Dolomite is exposed on inside of turn. It resembles Quarry Ledge.

2.2 mi. Driving across contact between Jefferson City Dolomite and underlying Roubidoux Formation. The contact can be discerned in the bar ditch.

2.4 mi. STOP 2. Drive across low-water crossing that spans Crooked Creek and park vehicles alongside the road on the east side of the creek.

Brecciated, northwest-dipping, cherty dolomite that Hendriks (1954) mapped as Gasconade Dolomite is exposed on northeast side of low-water crossing. On September 4, 2004, Ms. Shannon Dulin, student, University of Oklahoma, Ms. Ivy Graham, student, Oklahoma State University, and Dr. Kevin Evans, Southwest Missouri State University, drilled cores from this exposure for use in a paleomagnetism study to determine time of origin of the Crooked Creek structure. Apparently the heat generated by meteorite impact can reset the magnetic field in rock.

As one looks to the northwest across the valley, Roubidoux Formation can be seen dipping to the northeast. Confusingly, the direction of dip is away from the axial trace of the northwest-trending syncline that Hendriks (1954) delineated at a location about 500 ft to the southwest of Bob West's house. As Snyder and Gerdemann (1965) suggested, the Crooked Creek structure is probably more complicated than depicted on Hendriks' maps. It may well be that the Crooked Creek structure is best characterized as comprising chaotic megabreccia that can be divided into two main types: megabreccia of the central uplift that contains the oldest rocks and megabreccia of the ring graben that contains the youngest rocks.

The original concrete low-water crossing, which had been in existence for many decades, was removed and replaced with a new one made of poured concrete during August and September 2004. On September 4, when only the west one-half of the crossing had been replaced, Mr. Ted Craig found fresh looking, angular cobbles and boulders of red granite on the downstream side of the new concrete segment. Further searching revealed pieces of granite imbedded in the undersides of ripped up slabs of the concrete driving surface of the old crossing. The granite is most probably part of the fill that was used in building the old low-water crossing.

Also, on September 4, Mr. George Davis found strophomenid brachiopods in a large boulder of friable quartz sandstone situated on the southeast side of the crossing. The author, who was also present, collected several specimens and identified them as *Orthotetes keokuk* (Hall), a determination later corroborated by Dr. A. C. Spreng, University of Missouri-Rolla. *O. keokuk* is a Mississippian-Osagean brachiopod. The origin of the sandstone boulder is not known. It could be from the Crooked Creek structure, or it could have been hauled in from an outside location. This is the second reported occurrence of Mississippian-age fossils within the confines of the Crooked Creek structure. Hendriks (1949) reported finding the bryozoan *Fenestella* in a piece of residual chert. To date, there are no reports of Pennsylvanian-age invertebrate fossils having been found within the confines of the Crooked Creek structure.

2.5 mi. T-intersection of Beers Road with Crooked Creek Road. Turn right and proceed south on Crooked Creek Road.

2.7-3.0 mi. Roubidoux Formation sandstone crops out in the power line right-of-way and on the wooded hillside to the left.

3.2 mi. T-intersection with Swyers Lane. Maintain southerly course on Crooked Creek Road. Note the broad valley of Crooked Creek on the right.

3.3-3.4 mi. Light gray to tan, medium- to coarse-crystalline dolomite crops out on left side of road. It contains lenticular vugs and some glauconite. Hendriks (1954) mapped this as Eminence Dolomite.

3.5 mi. Medium- to light-gray, fine-crystalline dolomite crops out on left side of road. Hendriks (1954) mapped this as Potosi Dolomite.

3.6 mi. Chertified and cavernous-weathered breccia is exposed prominently on the once burned hillside to the left. This breccia constitutes a wide, southwest-trending fault zone located near the perimeter of the central uplift.

3.7 mi. Road curves to left and meets with CC4 250 at T-intersection. Turn right onto CC4 250 and proceed south.

3.8-3.9 mi STOP 3. The fault zone transition from the central uplift to the ring graben is exposed along the hillside on the east side of the road. From north to south for about 500 ft along the hillside, rocks are encountered in the following order: 1) relatively flat-lying Gasconade Dolomite of the central uplift, 2) crumbly, bleached chert breccia that is fault zone gouge, 3) chert breccia containing blocks of Gasconade Dolomite and Roubidoux sandstone that is also fault zone gouge, and 4) towering exposures of very steeply dipping to vertical to possibly overturned Roubidoux quartz sandstone intermixed with coarse breccia and crumbly chert breccia representing down-dropped, drag-folded and mega-brecciated Roubidoux. The relatively rock-free slots between the towering sheets of Roubidoux strata are probably the result of preferential weathering of breccia lenses. There is some cavernous weathering.

4.1 mi. Residence of Mr. and Mrs. Williard West. Turn vehicles around in area in front of carport.

4.1-4.9 mi. Retrace route back to Swyers Lane. Turn left and proceed west on Swyers Lane.

5.2 mi. Low-water crossing through Crooked Creek.

5.5 mi. Depending on road conditions, greenish, silty and calcareous Davis Formation can sometimes be seen in the bar ditches.

5.8 mi. STOP 4. Park vehicles alongside road. Residence of Jim West is situated atop knoll on the left.

Walk one-quarter mile north to view the Metcalf lead diggings, exposures of Bonneterre Dolomite, and Lamotte Sandstone float. This location is in the vicinity of the axial trace of the ring anticline. The Metcalf diggings are a random array of circular pits in residual red clay of weathered Bonneterre Dolomite. About 65 tons of lead was reportedly mined from these pits in the 1860s (Hendriks, 1954). Lead mineralization, however, has not been found in the nearby exposures of Bonneterre Dolomite. Pieces of Lamotte Sandstone float occur scattered throughout the area. The sandstone contains conspicuous, rounded, granule-sized to small pebble-sized quartz clasts. Dietz and Lambert (1980) reported decorated PDFs in Lamotte sandstone collected at an unspecified location in the central uplift.

Walk back to road and then walk one-quarter mile south to the intermittent stream that drains eastward into Crooked Creek. This location is in the basin of the central uplift. The rocks exposed here were beneath ground zero of the meteorite impact. Shatter cones occur in isolated exposures of Potosi Dolomite. The drusy quartz that is so characteristic of some parts of the Potosi is fragmented and distributed randomly through the dolomite matrix. This rock was completely disrupted and relithified. An exposure of the horst containing green, near-vertical-dipping shale of the Davis Formation can be seen in the creek. Float pieces of Lamotte Sandstone occur along the course of the streambed. Hendriks (1954) mapped a small outcrop of Eminence Dolomite near the center of the basin.

6.0 mi. T-intersection with State Route VV. Turn right and proceed north on VV.

6.8 mi. Shallow road cut through ridge top exposes Roubidoux Formation quartz sandstone and chert breccia. A piece of slickensided sandstone was found and collected here on May 13, 2004, by the author.

7.2 mi. End Road Log. T-intersection with Beers Road.

Remarks and Comments

Geologic mapping of the Crooked Creek structure in greater detail is needed; however, such mapping may be very difficult to accomplish because of the paucity of rock exposures. The structure begs to be mapped in detail in three dimensions, but the number of drill holes needed to accomplish this task seemingly would be many, at a cost that would be prohibitive.

The timing of the Crooked Creek structural event requires further study. It must be determined with certainty whether structuring occurred before or after deposition of Carboniferous strata. Ostensibly, detailed studies of the stratigraphic relationship between Carboniferous and Ordovician strata are in order. Studies that address the presence or absence of shocked quartz and the high-pressure mineral phases coesite, stishovite, and diamond in Carboniferous rocks would provide important information on timing. Lastly, the age of the Carboniferous strata needs to be determined with greater accuracy, and this perhaps can be accomplished through palynological studies.

Additional studies of the Cambrian and Ordovician rocks are likewise needed to further test the meteorite impact hypothesis. The occurrence of PDFs in quartz probably should be revisited and verified. Other studies could be directed towards finding high-pressure mineral phases in these rocks. Polymict breccias need to be identified and analyzed for siderophile-element anomalies, including iridium content and osmium isotopes.

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Association of Missouri Geologists
2004

Appendix:
Newly Found Mastodon (Mammoth) East of Kansas City and Its Relation to the Pleistocene Glacial Boundary

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NEWLY FOUND MASTODON (MAMMOTH) EAST OF KANSAS CITY AND ITS RELATION TO THE PLEISTOCENE GLACIAL BOUNDARY

During July 2004, a deep, ongoing excavation for a small lake 1.3 miles south of the Highway I-70 exit to the town of Grain Valley, Missouri (24 miles east of Kansas City), exposed a group of large bones. Based on the presence of fragments of a tusk and thick leg bone, these were identified by Larry Martin[1] as part of a mastodon and assigned a general age of about 50,000 years. Subsequent exploration found a few associated horse and deer bones. All of these faunal remains were enclosed in the lowest 3 feet of a gray clay that is underlain by 2 feet of coarse, angular chert gravel that rests on limestone bedrock. Overlying the bones, approximately 50 feet of clay extends, apparently uninterrupted, to the top of a broad ridge. This presented an immediate problem of interpretation. For clay to be deposited, an environment of very quiet water is required; currents will remove such fine particles. The site is located on the western side of the valley of Sni-A-Bar Creek about 20 miles from its confluence with the Missouri River. No evidence has been found of any obstruction and impoundment on the creek or the nearby river during the last 50,000 years.

The enigma has perhaps been solved by the last-minute discovery of a tooth that clearly came from a mammoth, not a mastodon. Furthermore, the width of the constituent dental plates very strongly indicates relatively great antiquity. This may be the remains of the most ancient mammoth yet recorded; Larry Martin now speaks of a possible age near one million years. That makes possible a reasonable explanation for the thick clay deposit. It has long been known that the Early Pleistocene ice sheet advanced southward from Canada to a terminal zone a few miles south of the present Missouri River. This glacier would have blocked every local creek valley that had preglacial drainage toward the north. There would have been formed a series of impounded lakes, each of which could have captured fine-grained rock flour washing off the ice. Primitive mammoths undoubtedly wandered through the adjacent tundra; some would have died there and scattered bones could have been preserved.

Some of the microscopic grains in the clay may contain iron. During deposition these would have become oriented according to the Earth’s magnetic field then existing. If the remnant magnetism is normal; i.e., like that existing today, then the clay was probably deposited less than 780,000 years ago. However, if the magnetism is reversed, a greater age of deposition is indicated. It is therefore possible that laboratory analysis of the clay that encloses the bones will demonstrate a greater age for the sediment and, by implication, an age of continental glaciation greater than is currently proposed. This would also indicate the approximate antiquity of the Missouri River here, as well as major tributaries such as the Kansas River. This would present implications pertinent to the current debate regarding the validity of the Kansan and Nebraskan glaciations and their several subdivisions.

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