Geohydrologic Framework, Ground-Water Hydrology, and Water Use in the Gasconade River Basin upstream from Jerome, Missouri, including the Fort Leonard Wood Military Reservation

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Abstract

The Ozark aquifer is the principal source of ground water in the Gasconade River Basin upstream from Jerome, Missouri (herein referred to as the upper Gasconade River Basin), including the Fort Leonard Wood Military Reservation (FLWMR). The Ozark aquifer is composed of, in order of increasing age, the Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite. Sedimentary strata are nearly horizontal, except along folds and collapse zones where dips can be steep. The basin is cut by numerous faults, most of which trend generally northwest-southeast. The Jefferson City Dolomite and the Cotter Dolomite generally yield little water to wells. Wells completed in the Roubidoux Formation and Gasconade Dolomite commonly yield from several tens to several hundred gallons per minute of water. The Eminence Dolomite may form a weak hydrologic barrier to vertical ground-water flow between the overlying Gasconade Dolomite and the underlying Potosi Dolomite. The Potosi Dolomite is the most permeable formation in the Ozark aquifer. Wells completed in the Potosi Dolomite may yield from several hundred to 1,000 gallons per minute of water.

Water-table contours indicate several areas of high permeability karst terrain in the upper Gasconade River Basin. Ground-water levels may be as deep as 300 feet below the land surface beneath upland areas where karst features are prevalent. Although the Jefferson City Dolomite and the Roubidoux Formation are the uppermost bedrock formations in the upland areas of the FLWMR, the water table generally is deep enough to occur in the underlying Gasconade Dolomite throughout most of the FLWMR. Discharge from springs [311 ft^3/s (cubic feet per second)] represented 56 percent of the August 1999 discharge of the Gasconade River at Jerome, Missouri (552 ft^3/s).

From 1993 through 1997, annual pumpage from all public water-supply wells in the upper Gasconade River Basin ranged from 1,820 Mgal [million gallons; an average daily rate of 4.99 Mgal/d (million gallons per day)] in 1993 to 2,030 Mgal (an average daily rate of 5.56 Mgal/d) in 1997. Including an estimated 4 Mgal/d from domestic wells, the average daily pumping rate for all wells is estimated to range from 8.99 Mgal/d in 1993 to 9.56 Mgal/d in 1997. During the same period, annual pumpage from the Big Piney River, which supplies most of the water used at the FLWMR, ranged from 1,136 Mgal (an average of 3.11 Mgal/d) in 1997 to 1,334 Mgal (an average of 3.65 Mgal/d) in 1995, and as a percentage of total water use in the upper Gasconade River Basin, ranged from about 24.5 percent in 1997 to about 28.8 percent in 1993.

INTRODUCTION

The Gasconade River Basin upstream from Jerome, Missouri, is the study area for this report, and hereinafter is referred to as the upper Gasconade River Basin (fig. 1). It encompasses 2,836 mi^2 (square miles) of predominately rural countryside in parts of eight counties in south-central Missouri. It is drained by the Gasconade River and its tributaries, including the Little Piney Creek, Big Piney River, Roubidoux Creek, and Osage Fork (fig. 1). The 64,000-acre Fort Leonard Wood Military Reservation (FLWMR) is a large federal facility predominantly in Pulaski County in the north-central part of the basin.

The FLWMR (fig. 2) has been a major combat-troop training area since 1940. The U.S. Army base contains a variety of weapons training facilities, including small-arms firing ranges, grenade ranges, artillery ranges, an Air National Guard cannon and strafing range, and areas for armored vehicle training. The FLWMR presently (2003) is in a period of growth in personnel and training facilities. A chemical warfare training school recently was transferred to the FLWMR. Construction activities at the FLWMR have increased substantially and are expected to continue. Past, present, and future operations at the FLWMR involve the use, storage, and disposal of chemicals and petroleum products. These chemicals and petroleum products are potential ground-water contaminants.

There is concern that these potential contaminants could migrate into the FLWMR public water-supply wells or domestic and public water-supply wells located adjacent to and downgradient from the FLWMR. The U.S. Geological Survey (USGS), in cooperation with the Directorate of Public Works, Environmental Division (DPW-ED), FLWMR, began a study in 1998 of the geohydrologic framework, ground-water hydrology, and water use in the upper Gasconade River Basin. The results of this study will improve the understanding of the contributing areas of recharge to water-supply wells at and in the vicinity of the FLWMR, and thereby help protect the quality of water supplied by the water-supply wells. Data presented in this report can be used in future studies of contributing areas of recharge to wells and in other ground-water assessments of the upper Gasconade River Basin. Contributing areas of recharge refers to the source area (recharge area) of ground water pumped from wells.

The FLWMR receives most of its water supply from a surface-water intake in the Big Piney River (fig. 2) along the eastern boundary of the military reservation. A large part of the water in the Big Piney River comes from springs that discharge into the river. Ground-water level data collected during this study can help determine sources of water to the Big Piney River, and areas of spring recharge within the Big Piney River Basin upstream from the surface-water intake.

Purpose and Scope

The purpose of this report is to describe the geohydrologic framework, ground-water hydrology, and water use in the upper Gasconade River Basin (study area; fig. 1). The three major components of this report reflect the major tasks of the study: (1) to describe and map the geohydrologic units at the FLWMR and upper Gasconade River Basin, particularly the structure of several geologic formations; (2) to measure and map ground-water levels in the FLWMR and upper Gasconade River Basin; and (3) to compile water-use data, particularly pumpage data for public water-supply wells in the upper Gasconade River Basin. Ground-water levels measured in spring 1998; stream and spring discharge measurements made in September 1995, September 1998, and August 1999; and water-use data compiled for 1993–98 are presented in this report.

The study area is much larger than the FLWMR area and includes areas south of the FLWMR that potentially supply water to the FLWMR (fig. 1). Well-log and water-use data were compiled and ground-water levels were measured in the study area and in a 6-mi (mile) wide band surrounding the study area. Data were collected in the surrounding area to provide additional control to geologic and hydrologic contours near the study boundary and to define regional hydrologic boundaries.

Description of Study Area

Most of the study area (fig. 1) is located within the Salem Plateau of the Ozarks Plateaus physiographic province (Fenneman, 1938). The Salem Plateau is a large area of uplifted Cambrian- and Ordovician-age sedimentary strata in southern Missouri and northern Arkansas. It consists of an upland plain along a major southwesterly trending topographic divide, and more rugged topography north and south of the divide where stream erosion has been more exten-

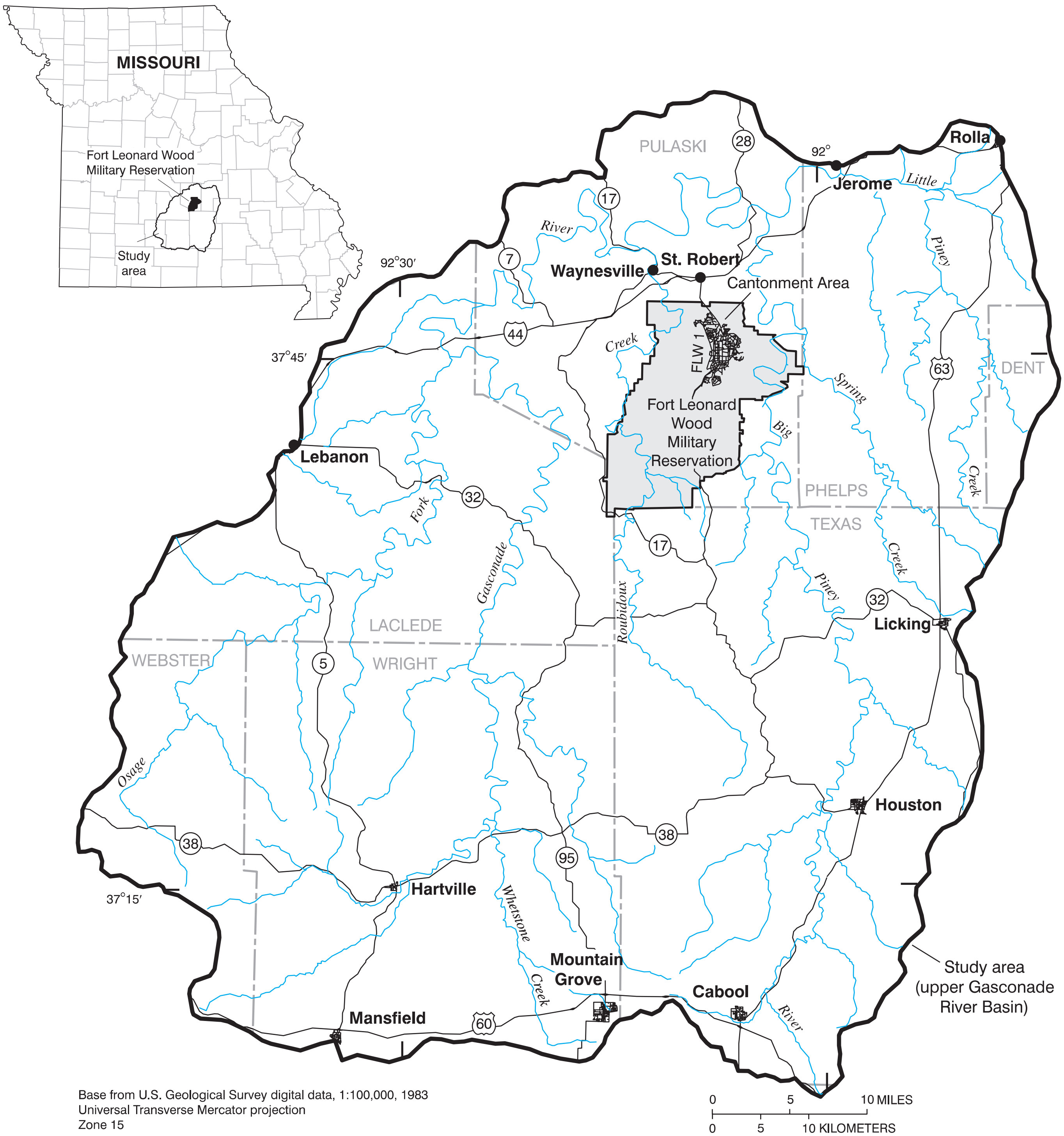
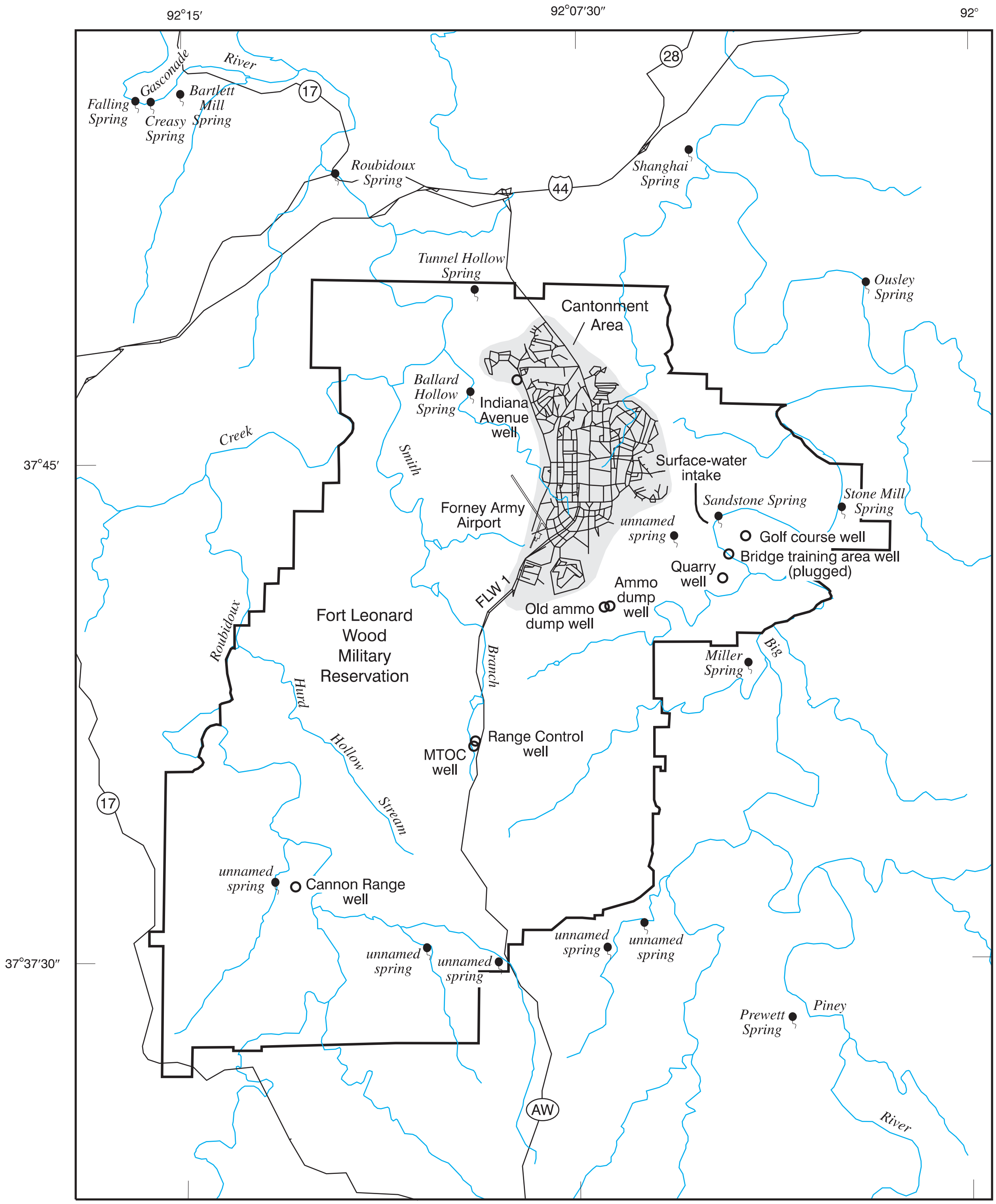


Figure 1. Location of the study area, streams, selected towns, major highways, county boundaries, and the Fort Leonard Wood Military Reservation boundary.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

0 2.5 5.0 MILES
0 2.5 5.0 KILOMETERS

Figure 2. Streams, springs, public water-supply wells, and surface-water intake in and near the Fort Leonard Wood Military Reservation.

sive. The extreme southwestern part of the study area is in the Springfield Plateau of the Ozark Plateaus physiographic province (Fenneman, 1938), which is underlain by uplifted Mississippian-age sedimentary strata. The southern part of the study area is characterized by gently rolling upland hills covered with forest and pasture. The northern and central parts of the study area are heavily forested areas where stream incision by the northerly to northeasterly flowing Gasconade River and its tributaries (fig. 1) has resulted in narrow, steep-walled stream valleys separating erosional remnants of the upland plain. Most of the FLWMR is located on a broad upland ridge between the northerly flowing Big Piney River to the east and the northerly flowing Roubidoux Creek to the west (fig. 2). The upland ridge is further dissected by tributaries to these streams.

The study area has a humid, temperate climate with warm, humid summers and cool, wet winters. The long-term monthly average temperature from a weather station at the Forney Army Airport at the FLWMR ranges from 31.8 ^{o}F (degrees Fahrenheit) in January to 76.8 ^{o}F in July (National Oceanic and Atmospheric Administration, 2000). The average annual precipitation recorded at the weather station is approximately 42 in. (inches; National Oceanic and Atmospheric Administration, 2000).

The largest town in the basin is Rolla (fig. 1), which had a population of 16,367 in 2000 (U.S. Census Bureau, 2000). Other towns along or near the western, southern, and eastern upland boundaries of the basin drainage divide and along the Interstate 44 corridor that passes through the northern part of the basin and their populations in 2000 include Lebanon (12,155), Mountain Grove (4,574), Waynesville (3,507), St. Robert (2,760), Cabool (2,168), Houston (1,992), Licking (1,471), Mansfield (1,349), Hartville (no population figure), and Jerome (no population figure; fig. 1; U.S. Census Bureau, 2000). The number of military and civilian personnel at the FLWMR in 2000 was estimated at 13,666 (U.S. Census Bureau, 2000).

Most of the facilities of the FLWMR are concentrated in the cantonment area (fig. 2) in the north-central part of the base. This area contains classrooms, barracks, recreation and shopping facilities, and support units. The southern part of the base contains large tracts of land that are used for firing ranges, armored vehicle training, heavy equipment training, and landfills for waste disposal. The area west, south, and east of the FLWMR boundary contains large tracts of federally managed National Forest land predominantly covered with oak and hickory trees. Private land primarily is in fescue pasture to support livestock grazing. The towns of Waynesville and St. Robert and the areas around them are the most populated areas near the FLWMR.

Previous Investigations

The USGS developed a regional ground-water flow model for the Ozark Plateaus Aquifer System (Imes and Emmett, 1994) that covered parts of Missouri, Arkansas, Oklahoma, and Kansas, and included the study area. Regional structure-contour, isopach, potentiometric, and water-quality maps of geohydrologic units were prepared in support of the model. The three-dimensional finite difference model was used to simulate pre-development regional ground-water flow. Because of the large size of the model area and computer resource limitations at the time the model was developed (1981 to 1986), model cells were 14 miles square; therefore, the model grid is too coarse to be a useful tool to assess the ground-water flow at the FLWMR.

An assessment of facilities at the FLWMR that contained toxic or hazardous materials having the potential to migrate beyond the boundaries of the FLWMR was conducted by the U.S. Army Environmental Hygiene Agency (USAEHA) in 1982 (Environmental Science and Engineering, 1982). The report identified the presence of leachate seeps at several solid-waste landfills and concluded that disposal practices at one landfill in the central part of the FLWMR were in violation of State of Missouri solid-waste regulations. Large dichlorodiphenyltrichloroethane (DDT) concentrations were detected in soils near an abandoned pesticide storage building.

During follow-up investigations in 1987 and 1988, the USAEHA drilled 17 shallow monitoring wells in unconsolidated residuum near several large landfills to assess the movement of leachate into ground water beneath the landfills (U.S. Army Environmental Hygiene Agency, 1988). None of the drilled wells penetrated the water table, which was approximately 100 to 150 ft (feet) below the bottom of the deepest monitoring well, and only three wells contained sufficient water to sample (perched water that had drained into the wells). Based on water samples collected from these monitoring wells and one leachate sample, the report concluded that ground water was not affected by the landfills.

Additional monitoring wells were subsequently drilled to supplement the first set of monitoring wells. These wells also were dry except where perched water collected. The report on this phase of work concluded that deeper monitoring wells were needed to determine if hazardous constituents have been released from these sites (U.S. Army Environmental Hygiene Agency, 1990).

The final Resource Conservation and Recovery Act (RCRA) Facility Assessment Report (PRC Environmental Management, Inc., 1992) for the FLWMR summarized data for 54 solid-waste management units (SWMUs). The report concluded that because of the lack of data and the potential for environmental contamination by several landfills and other facilities, further investigations were advisable. No monitoring well installation or water sampling was conducted during the study.

Beginning in 1994, the USGS conducted a regional geohydrologic and water-quality assessment of the FLWMR, and preliminary geohydrologic and water-quality assessments of 12 SWMUs located on the FLWMR. The regional assessment was designed to characterize the geohydrologic framework of the FLWMR and to provide the background hydrochemical data needed to conduct and interpret more detailed investigations of contaminant distribution and movement near individual SWMUs. As part of this study, potentiometric surface maps were prepared to determine ground-water flow directions near the FLWMR. Ground-water discharge was measured indirectly by stream seepage-run discharge measurements and directly at several large springs. Ground-water, surface-water, or streambed samples were collected from wells and streams in the immediate vicinity of the FLWMR to define background chemical concentrations in water at the FLWMR. Dye-tracing techniques were used to map the recharge areas of springs that receive water from fractures and conduits in the extensive karst terrain beneath the FLWMR. The results of the regional geohydrologic and water-quality assessment were published in Imes and others (1996). A significant discovery of this investigation was the detection of tetrachloroethene (PCE) at Shanghai Spring (fig. 2) about 2.5 mi northeast of the FLWMR.

The regional geohydrologic assessment of the FLWMR included a comprehensive geologic mapping program of the FLWMR and immediate surrounding areas to determine the density and properties of bedrock fractures and their effect on ground-water flow (Harrison and others, 1996). Most of the observed fractures do not show evidence of solution activity, but those that do have a pronounced northeast orientation (Harrison and others, 1996), and conduit flow may have developed in some of these fractures (Imes and others, 1996). Most of the water discharged at large springs probably is transported along high-permeability pathways within solution-enlarged bedding planes rather than fractures (Imes and others, 1996). Nonetheless, hydrologic control by fractures is indicated by the distribution of some karst features at the FLWMR (Imes and others, 1996). During the mapping of fractures, geologic contacts that differed from those shown on existing geologic maps published by the Missouri Department of Natural Resources (MDNR), Geological Survey and Resource Assessment Division (GSRAD; formerly known as the Missouri Division of Geology and Land Survey) were noted, and a revised bedrock geologic map at 1:24,000 scale was produced (Harrison and others, 1996). A short summary document describing the complex karst terrain and associated ground-water flow system at the FLWMR and results of additional dye-trace tests not reported in Imes and others (1996) were reported by Kleeschulte and Imes (1997).

Results of the preliminary geohydrologic and water-quality assessments at 12 SWMUs are reported in Schumacher and Imes (2000). Assessments were made for six landfills, two open burn/open detonation areas for the disposal of unexploded ordnance, a former pesticide mixing and storage building, an ammunition container storage area, an abandoned fire training area, and the site of a former laundry and dry-cleaning facility. These assessments were focused on the immediate vicinity of each SWMU and areas where ground or surface water can readily migrate from the site. Samples collected for chemical analysis from the SWMUs included leachate, soil, soil gas, ground water, surface water, and sediment from streambeds and dry washes. Monitoring wells were installed at one landfill to assess the effect of this facility on ground water. Results of these assessments indicated that contaminants were being released to soil, surface water, streambed sediment, or ground water from several facilities. Analyses of water samples from monitoring wells indicated the release of contaminants to the regional water table. Samples from wells monitoring perched water in the overburden and shallow bedrock contained larger than background concentrations of many inorganic constituents. Water samples from Sandstone Spring (fig. 2) contained larger than background concentrations of sodium, chloride, and total nitrite plus nitrate, possibly a result of contaminant releases from three landfills located in or near the recharge area of the spring. The assessment also confirmed the release of pesticides from the former pesticide mixing and storage building to nearby soils and stream sediments. Soils at the former laundry and dry-cleaning facility were contaminated with large concentrations of PCE and trichloroethene (TCE). The site is suspected to be the source of the PCE detected at Shanghai Spring during the regional assessment. A geohydrologic and water-quality assessment also was conducted at Shanghai Spring. Concentrations of PCE in Shanghai Spring increased during and immediately following runoff events, indicating that infiltrating rainfall or runoff entering the unsaturated zone quickly mobilizes PCE.

GEOHYDROLOGIC FRAMEWORK

The USGS defines geohydrologic units on the basis of hydrologic properties. Geohydrologic units are composed of sequences of stratigraphic units and are classed as aquifers, aquifer systems, confining units, and confining systems. Generally, aquifers and aquifer systems are considered capable of providing a water supply, and confining units and confining systems are not.

Regional geohydrologic units in the study area are, in order of increasing depth: the Springfield Plateau aquifer, Ozark confining unit, Ozark aquifer, St. Francois confining unit, St. Francois aquifer, and Basement confining unit (fig. 3). The Springfield Plateau aquifer and Ozark confining unit are composed of Mississippian-age rocks that occur primarily in the extreme

TIME-STRATIGRAPHIC UNIT			ROCK-STRATIGRAPHIC UNIT	REGIONAL GEOHYDROLOGIC UNIT
ERA	SYSTEM	SERIES		
PALEOZOIC	MISSISSIPPIAN	Osagean	Burlington Limestone Elsey Formation Pierson Limestone	Springfield Plateau aquifer
		Kinderhookian	Chouteau Group Northview Formation Compton Limestone Bachelor Formation	Ozark confining unit
	ORDOVICIAN	Canadian	Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite	Ozark aquifer
	CAMBRIAN	Upper	Eminence Dolomite Potosi Dolomite	
			Elvins Group Derby-Doe Run Dolomite Davis Formation	St. Francois confining unit
			Bonneterre Formation Lamotte Sandstone	St. Francois aquifer
PRECAMBRIAN			Precambrian igneous and metamorphic rocks	Basement confining unit

Figure 3. Hydrostratigraphic column of geologic units for the study area (modified from Imes, 1990a; stratigraphic nomenclature follows that of the Missouri Geological Survey and Resource Assessment Division, formerly known as the Missouri Division of Geology and Land Survey).

southwestern part of the study area and are, therefore, not hydrologically significant in the study area. The Ozark aquifer is the principal source of ground water in the study area and is the focus of this report. It ranges from less than 700 ft thick in the northern part of the study area to more than 1,500 ft thick in the southern part of the study area (Imes, 1990b). The Ozark aquifer is composed of, in order of increasing age: the Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite (stratigraphic nomenclature for all geologic formation names in this report follows that of the Missouri Geological Survey and Resource Assessment Division, formerly known as the Missouri Division of Geology and Land Survey; fig. 3). The underlying St. Francois confining unit is composed of the Derby-Doe Run Dolomite and the Davis Formation (fig. 3). The St. Francois confining unit impedes the vertical movement of ground water, and only a small fraction of the ground-water recharge in the study area likely penetrates below the confining unit. Water wells in the area are open only to formations above the St. Francois confining unit or terminate in the upper part of the Derby-Doe Run Dolomite. The underlying St. Francois aquifer is composed of the Bonneterre Formation and the Lamotte Sandstone (fig. 3). The St. Francois aquifer is an important aquifer in some parts of Missouri, but because ground water is readily available from the shallower Ozark Aquifer, it is not an important aquifer in the study area. The Basement confining unit, which is composed of Precambrian-age igneous and metamorphic rocks, underlies the St. Francois aquifer (fig. 3).

The geologic data and a substantial part of the hydrologic data used for this report were compiled from existing databases. Data from approximately 2,900 geologic logs were collected from the GSRAD geologic well log database. These logs generally contain geologic descriptions of formations encountered during the drilling of domestic and public water-supply wells and also may contain construction data (for example, well depth and casing depth), water-level data, and specific-capacity data. Also, approximately 4,100 well records were collected from the GSRAD well permit database. These records contain well-construction and water-level data for permitted wells constructed since 1987. Also, approximately 200 records were collected from the MDNR, Public Drinking Water Program. These records contain ownership data for public water-supply wells and also may contain well-construction, water-level, and specific-capacity data. Some of these records duplicate those collected from the GSRAD geologic well log database. In addition to data collected from Missouri state agencies, approximately 600 records were extracted from the USGS Ground Water Site Inventory (GWSI) database. Depending on the original source of the data, these records may contain geologic, well-construction, water-level, and specific-capacity data. Some of these records duplicate data collected from Missouri state agencies.

Latitude and longitude coordinates for well locations were converted to Universal Transverse Mercator (UTM) coordinates for use in a Geographic Information System (GIS) database. Because most well records did not have latitude and longitude coordinates, a computer program was developed to first convert land net (Section-Township-Range) descriptions to approximate latitude and longitude coordinates for these wells. Base maps of the study area were compiled from existing 1:100,000 scale USGS digital maps. These maps included streams attributed by stream basin and size, topographic contours attributed with altitude, spring locations, roads, county boundaries, township boundaries, and topographic quadrangle boundaries.

Bedrock Geology

A bedrock geologic map of the study area showing the geologic formations and major faults present at the bedrock surface was prepared from a GIS database constructed by combining digital versions of published and unpublished 7 1/2- and 15-minute quadrangle geologic maps prepared by the GSRAD (Easson, 1984a, 1984b; Easson and Sumner, 1984a, 1984b, 1984c; Middendorf, 1984a, 1984b, 1984c, 1984d, 1984e, 1984f, 1984g, 1984h, 1984i; Middendorf and McFarland, 1984; Sumner, 1984; Sumner and Easson, 1984; Sumner and Middendorf, 1984; Thomson, 1982a, 1982b; Thomson and others, 1982). Additional data from geologic maps prepared by the USGS and GSRAD as part of the Conterminous United States Mineral Assessment Program (CUSMAP; Middendorf, 1985; Middendorf and others, 1991; Pratt and others, 1992) and from geologic mapping of the FLWMR by the USGS (Harrison and others, 1996) also were included. During the process of combining separate databases, contacts and faults at quadrangle boundaries were joined, conflicts at boundaries were resolved, and minor faults and some other structural features were deleted.

Except for Mississippian-age rocks in the extreme southwest part of the study area and two isolated erosional outliers, Early Ordovician-age dolostones and sandstones (fig. 3) form the bedrock surface throughout the study area (fig. 4). Residuum and colluvium form a mantle over the bedrock throughout most of the study area. Alluvial deposits occur along streams. Sedimentary strata are nearly horizontal, 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 study area (fig. 4), with younger strata underlying the uplands and older strata exposed along streams. The study area is cut by numerous faults, some of which are pronounced enough to be shown on the geologic map. Most of these faults trend generally northwest-southeast. Vertical throw is more than 100 ft in places along the Macks Creek-Smittle Fault in the southwestern part of the study area (fig. 4). A detailed discussion of faulting at the FLWMR is contained in Harrison and others (1996). Another structural feature of interest in the study area is the Fort Leonard Wood Anticline (Middendorf, 1985) that trends generally north-south through the northern part of the FLWMR (fig. 4).

Stratigraphy and Geologic Structure

A series of generalized geologic maps were constructed to help describe the geologic framework of the Ozark aquifer in the study area. Generalized maps were made showing the altitude of the top of the Derby-Doe Run Dolomite, Potosi Dolomite, Eminence Dolomite, Gasconade Dolomite, and Roubidoux Formation. These maps were constructed by plotting and contouring top-of-formation altitude data from the GSRAD geologic well log records. Some of the top-of-formation data from these records are lower than the actual top-of-formation altitude because the log begins within the formation, and other top-of-formation data are lower than the pre-erosional top-of-formation altitude where the well is located in the outcrop area of the formation. These data represent minimum altitudes and were used in some places to determine the general location of contours. Also, approximate top-of-formation altitude data points were generated where well data were sparse by digitally superimposing geologic contacts on land surface topographic contours. The locations of faults, along which offset of top-of-formation altitude contours occur, were copied from the bedrock geologic map that was prepared as part of this study. The contours are approximately located out of necessity where data points are sparse and to show general trends without showing all the minor variations in top-of-formation altitudes where data points are dense. The top-of-formation maps were used to construct generalized thickness maps of the Potosi Dolomite, Eminence Dolomite, Gasconade Dolomite, and Roubidoux Formation. Generalized thickness maps were constructed using a combination of measured formation thicknesses from well-log data and formation thicknesses estimated by digitally interpolating each top-of-formation altitude map and subtracting the interpolated data from subjacent top-of-formation maps.

The oldest Paleozoic-age formation in the study area is the Upper Cambrian-age Lamotte Sandstone (fig. 3), which is a clean quartzose sandstone. It is overlain by the Upper Cambrian-age Bonneterre Formation (fig. 3), which is predominantly dolostone. Overlying the Bonneterre Formation is the Upper Cambrian-age Davis Formation (fig. 3), which is shale with interbedded limestone or dolostone. The Davis Formation and the overlying Derby-Doe Run Dolomite compose the Elvins Group (fig. 3).

The generalized map of the altitude of the top of the Derby-Doe Run Dolomite, which also is the base of the Ozark aquifer, is shown in figure 5. It is based on few data points because water-supply wells do not normally penetrate as deep as the top of the Derby-Doe Run Dolomite. Some of the structure contours are drawn to approximate the trend of contours on maps of overlying formations where more data are available. The top of the Derby-Doe Run Dolomite is highest along a ridge that trends generally east-west through the center of the study area. The axis of this ridge is offset to the northwest along the Macks Creek-Smittle Fault (fig. 4), with more than 100 ft of vertical displacement. The Fort Leonard Wood Anticline trending north-south through the FLWMR (fig. 4) is shown by contours that wrap around the anticlinal axis.

The Upper Cambrian-age Potosi Dolomite overlies the Derby-Doe Run Dolomite (fig. 3). The Potosi Dolomite is not exposed in the study area, and is the deepest formation of hydrologic significance to water-supply wells at the FLWMR. The Potosi Dolomite is a

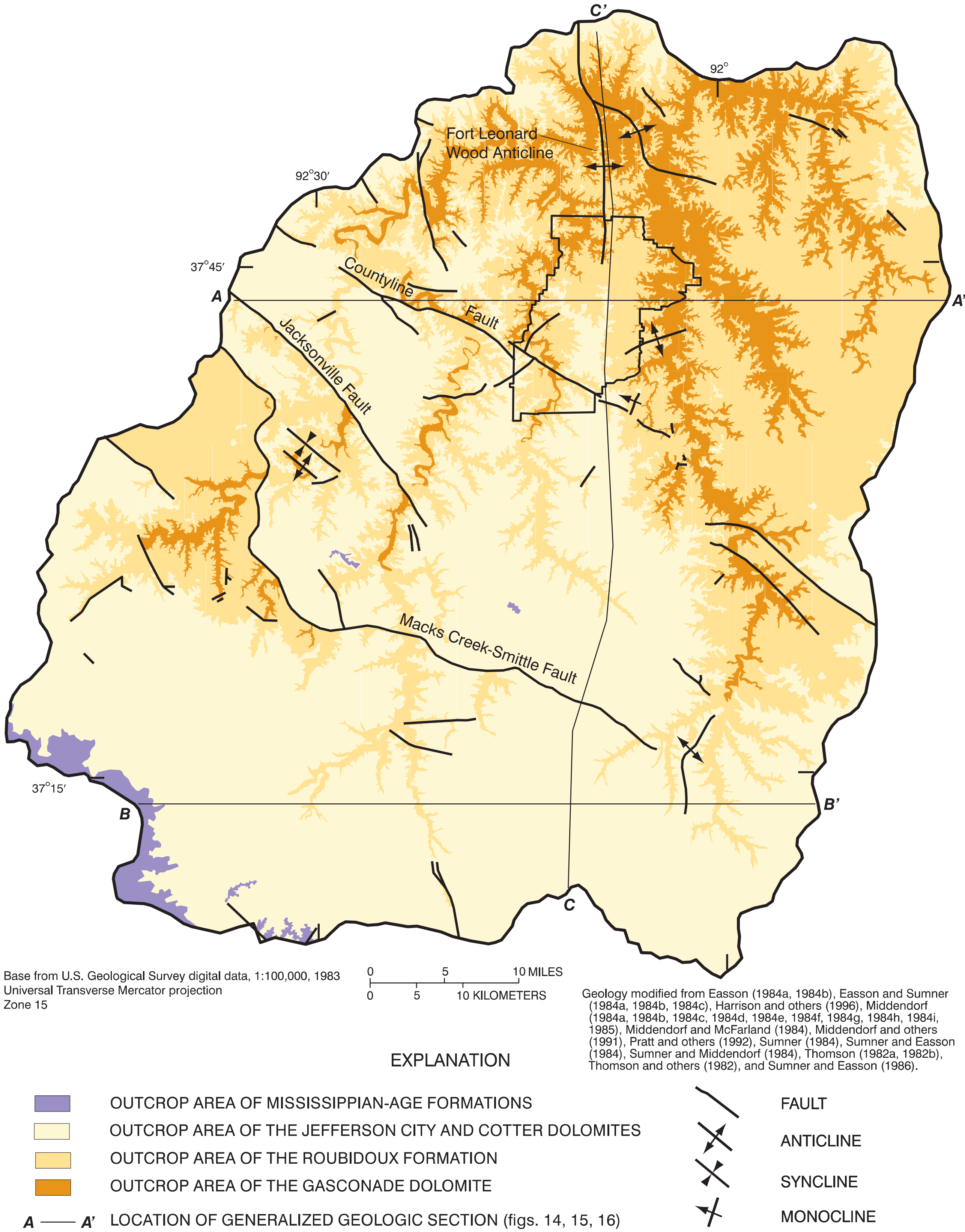


Figure 4. Bedrock geology of the study area showing location of generalized geologic sections.

massive bedded, vuggy dolostone with quartz druse that is associated with chert (Thompson, 1995). The large porosity and permeability of the formation causes it to be a good source of water to wells, and it is utilized by many public water-supply wells in the study area. The Potosi Dolomite is between 200 and 400 ft thick throughout most of the study area, thins to less than 200 ft thick in the southwestern part of the study area and in a few small isolated areas, and is more than 400 ft thick in two small areas in the northern and western part of the study area (fig. 6). The pattern of the structure contours for the top of the Potosi Dolomite (fig. 7) is similar to the pattern of the structure contours for the top of the Derby-Doe Run Dolomite (fig. 5) because the Derby-Doe Run structure contours were modeled after the Potosi Dolomite structure contours to a large extent. Similar to the structure contours for the top of the Derby-Doe Run Dolomite, the structure contours are generalized for the top of the Potosi Dolomite because they are based on few data points. In some places the top of the Potosi Dolomite structure contours are drawn to approximate the trend of contours on maps of overlying formations where more data are available. The top of the Potosi Dolomite is highest along a ridge that trends generally east-west through the center of the study area in approximately the same position as a corresponding ridge on the top of the Derby-Doe Run Dolomite. This ridge also is offset to the northwest along the Macks Creek-Smittle Fault (fig. 4). The Fort Leonard Wood Anticline (fig. 4) also is shown by the wrapping of contours of the top of the Potosi Dolomite around the anticlinal axis.

The Upper Cambrian-age Eminence Dolomite overlies the Potosi Dolomite (fig. 3). The Eminence Dolomite is conformable with the underlying Potosi Dolomite and also is not exposed in the study area. The Eminence Dolomite is a massive bedded dolostone with small amounts of chert and quartz druse (Thompson, 1995) and is less vuggy than the underlying Potosi Dolomite or the overlying Gasconade Dolomite. The Eminence Dolomite is 200 to 400 ft thick throughout most of the study area, with a few isolated areas where the thickness is less than 200 ft (fig. 8). One of the areas where it is thickest (greater than 300 ft) is in the southwestern part of the study area. This area corresponds with the area where the Potosi Dolomite is thinnest (fig. 6). The map of the altitude of the top of the Eminence Dolomite (fig. 9) is controlled by a few more data points than the maps for the top of the Derby-Doe Run Dolomite and the Potosi Dolomite, but data points are still sparse, and structure contours are generalized and, in some places, follow trends of contours on maps of overlying formations where data are more available. The top of the Eminence Dolomite is highest along the same east-west trending ridge shown by the top of the Derby-Doe Run Dolomite and the top of the Potosi Dolomite. The east-west ridge also is offset to the northwest by the Macks Creek-Smittle Fault (fig. 4). Wrapping of contours around the axis of the Fort Leonard Wood Anticline (fig. 4) also is apparent.

The Canadian Series Ordovician-age Gasconade Dolomite overlies the Eminence Dolomite (fig. 3). It is the oldest formation to crop out in the study area and forms the bedrock surface along the major streams and their tributaries (fig. 4). 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 (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 (Thompson, 1991). The upper part of the Gasconade Dolomite may be more permeable than the lower part at the FLWMR. Evidence for this includes the presence of permeable intraformational breccia horizons in the upper Gasconade Dolomite at the FLWMR and the fact that most caves and large springs in and around the FLWMR are in the upper Gasconade Dolomite (Harrison and others, 1996). The thickness of the Gasconade Dolomite in the study area is shown in figure 10. The thickness is not shown where the Gasconade Dolomite has been eroded and forms the bedrock surface (fig. 4). The pre-erosional thickness of the Gasconade Dolomite generally decreases from greater than 400 ft in the southwestern part of the study area to less than 300 ft in the northeastern part of the study area. The map showing the altitude of the top of the Gasconade Dolomite (fig. 11) is somewhat more complex than corresponding maps for deeper formations because more wells penetrate the Gasconade Dolomite, providing more data points. The structure contours in figure 11 are drawn through areas where the Gasconade Dolomite is the bedrock formation and are, therefore, approximations of the pre-erosional surface of the Gasconade Dolomite in these areas. The generally east-west ridge that is observed on other top-of-formation maps also is observed on this map, but with somewhat more detail. The Fort Leonard Wood Anticline at and north of the FLWMR (fig. 4) also is shown by the contours on figure 11.

The Canadian Series Ordovician-age Roubidoux Formation overlies the Gasconade Dolomite (fig. 3). It forms the bedrock surface throughout a large part of the study area, including a large part of the FLWMR (fig. 4). The Roubidoux Formation crops out in upland areas and hillsides in the northern part of the study area and along stream bottoms in parts of the southern part of the study area. The lithology of the Roubidoux Formation ranges from dolostone to cherty dolostone to sandy dolostone to sandstone. The amount of sandstone ranges throughout the study area from less than 5 percent west of the FLWMR to more than 40 percent in the southern part of the study area and is about 10 to 25 percent throughout most of the FLWMR (Harbaugh, 1983; Thompson, 1991). Solution effects in the Roubidoux Formation at the FLWMR can be pervasive in the interbedded dolostones in the lower part of the formation (Imes and others, 1996; Harrison and others, 1996). Although bedding normally is nearly horizontal, numerous irregular small folds occur in sandstone beds at the FLWMR and are interpreted to be the result of collapse in response to dissolution of interbedded or underlying dolostone (Harrison and others, 1996). Most of the observed sinkholes in the upland areas of the FLWMR are formed in the Roubidoux Formation (Imes and others, 1996). The thickness of the Roubidoux Formation in the study area is shown on figure 12. The thickness of the Roubidoux Formation is not shown where it has been eroded and forms the bedrock surface. The pre-erosional thickness of the Roubidoux Formation ranges from 100 to 200 ft throughout a large part of the study area, is less than 100 ft in isolated patches, and is more than 200 ft in places in the southern part of the study area. Contours of the altitude of the top of the Roubidoux Formation (fig. 13) are drawn through areas where the Roubidoux Formation or the Gasconade Dolomite forms the bedrock surface and are, therefore, approximations of the pre-erosional surface of the Roubidoux Formation in these areas. Contours are more detailed than corresponding contours for the Gasconade Dolomite (fig. 11) in the southern part of the study area because more wells penetrate the shallower Roubidoux Formation, but are more generalized in the northern part of the study area where they approximate the pre-erosional surface of the Roubidoux Formation. The generally east-west trending ridge that is observed on other top-of-formation maps also is observed at the top of the Roubidoux Formation (fig. 13). One significant difference is that this ridge also trends to the southwest in the southwestern part of the study area. The contours that define the Fort Leonard Wood Anticline at and north of the FLWMR (fig. 4) are pre-erosional and were drawn to approximate the trend of contours of the top of the underlying Gasconade Dolomite.

The Canadian Series Ordovician-age Jefferson City Dolomite and Cotter Dolomite overlie the Roubidoux Formation (fig. 3). These two formations are conformable and are sometimes difficult to distinguish (Thompson, 1995). They are grouped together on the geologic map of the study area (fig. 4) where they underlie the upland areas in the approximately southern two-thirds of the study area and in a few upland areas in the northern one-third of the study area. Most of the outcrop area is underlain by the Jefferson City Dolomite, with the Cotter Dolomite being the bedrock formation in the southern and southwestern part of the study area (Thompson, 1991) along the regional topographic ridge. The Jefferson City Dolomite is the youngest formation at the FLWMR and underlies the central upland ridge that trends north-south through the FLWMR (Imes and others, 1996). 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 (Thompson, 1991). The Cotter Dolomite is medium to thin bedded, medium to finely crystalline cherty and non-cherty dolostone (Thompson, 1991). The combined thickness of the Jefferson City and Cotter Dolomites ranges from 0 to more than 400 ft, with the thickest sections in the southern and southwestern parts of the study area where both formations are present.

Kinderhookian and Osagean Series Mississippian-age rocks of the Springfield Plateau form the bedrock surface in the extreme southwestern part of the study area and at two small areas in the central part of the study area (fig. 4). These rocks are sandstone of the Bachelor Formation; limestone of the Compton Limestone; shale and siltstone of the Northview Formation; limestone, dolostone, and chert of the Pierson Limestone; limestone and chert of the Elsey Formation; and cherty limestone of the Burlington Limestone (fig. 3;

Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

EXPLANATION

— 200 — STRUCTURE CONTOUR—Shows altitude of the top of the Derby-Doe Run Dolomite. Contour interval is 100 feet. Vertical datum is NGVD 29

DATA POINT—Black points are the top of the Derby-Doe Run Dolomite; red points are below the top of the Derby-Doe Run Dolomite

FAULT

ANTICLINE

SYNCLINE

MONOCLINE

Figure 5. Altitude of the top of the Derby-Doe Run Dolomite in the study area.

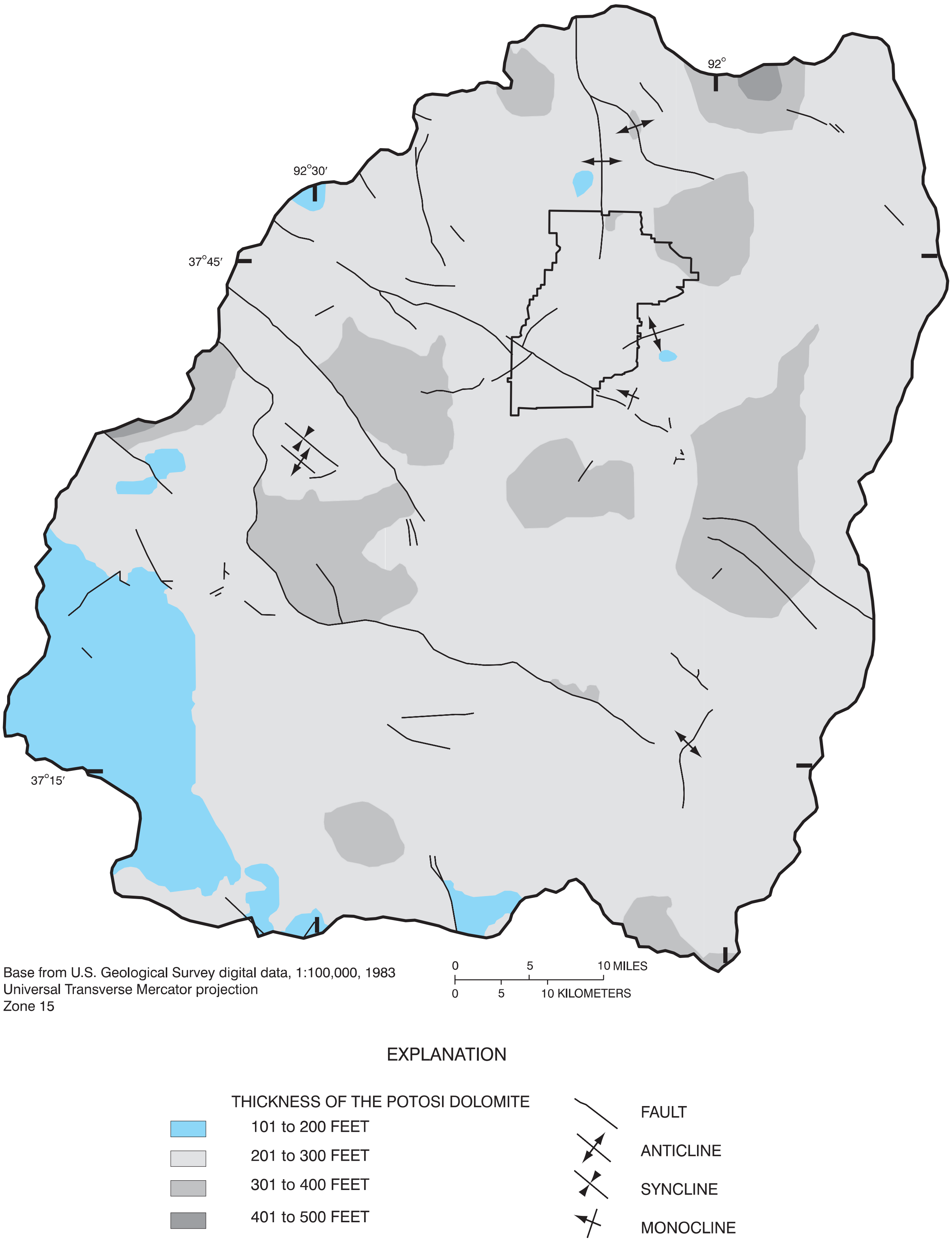


Figure 6. Thickness of the Potosi Dolomite in the study area.

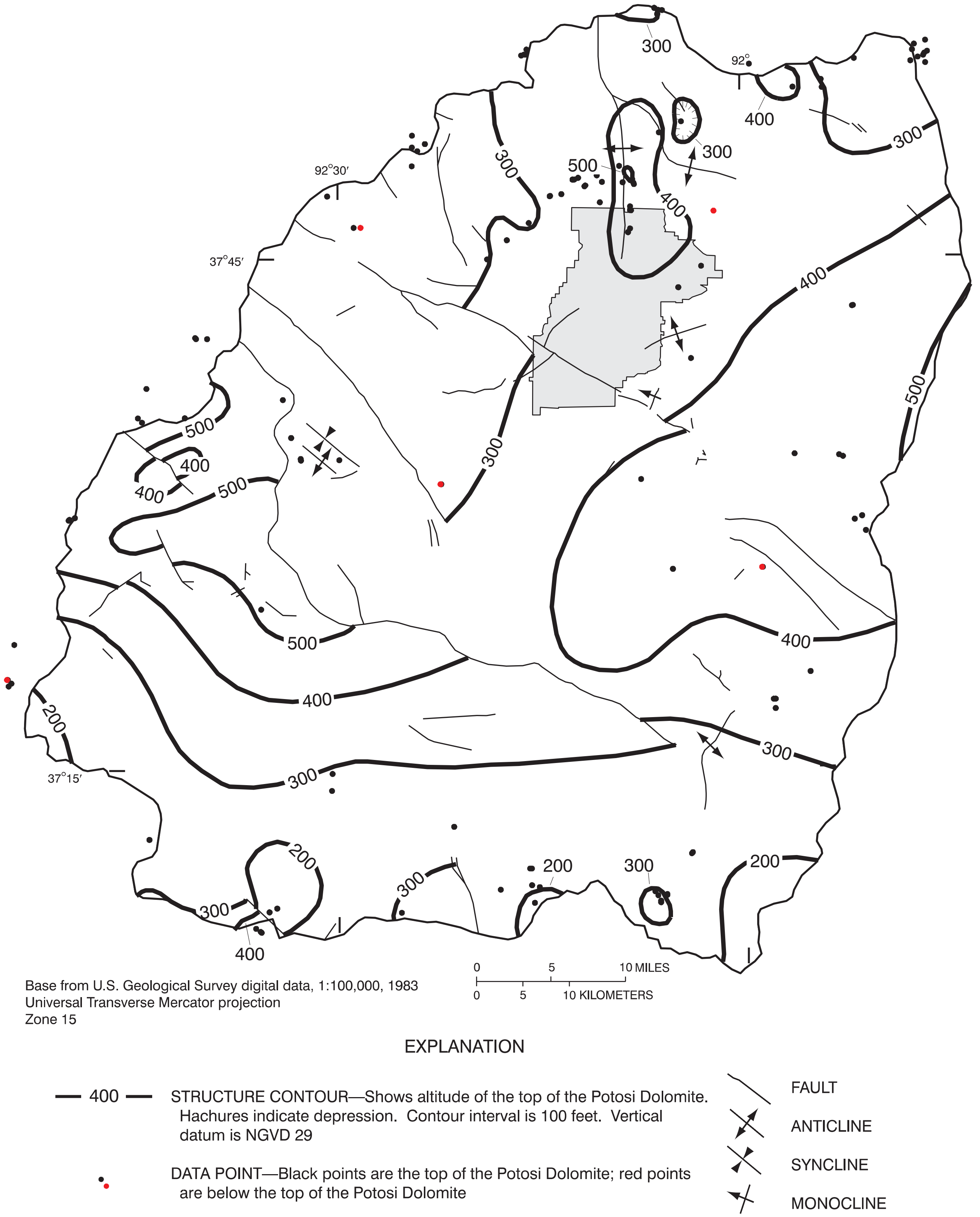


Figure 7. Altitude of the top of the Potosi Dolomite in the study area.

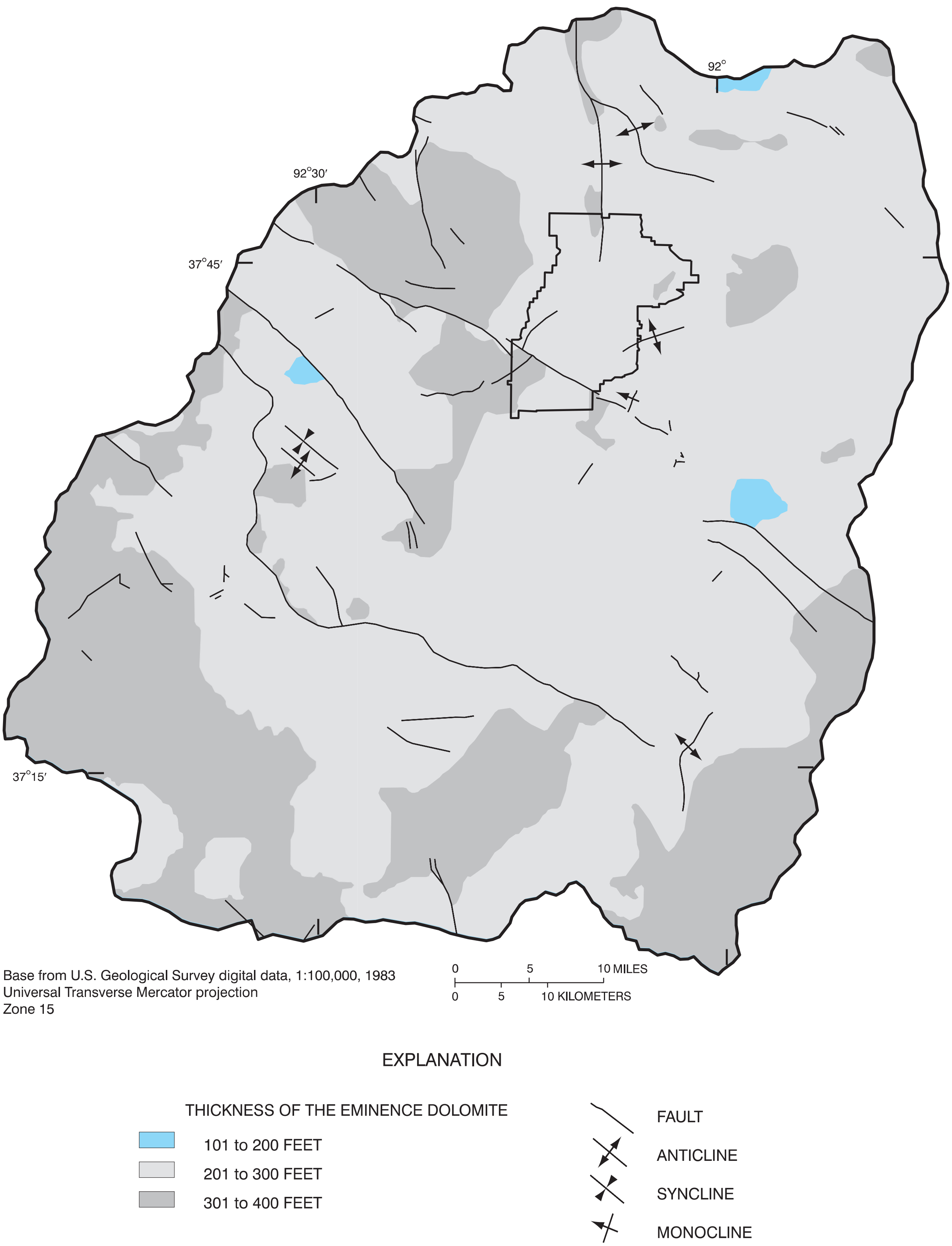


Figure 8. Thickness of the Eminence Dolomite in the study area.

EXPLANATION

— 600 — STRUCTURE CONTOUR—Shows altitude of the top of the Eminence Dolomite—Hachures indicate depression. Contour interval is 100 feet. Vertical datum is NGVD 29

DATA POINT—Black points are the top of the Eminence Dolomite; red points are below the top of the Eminence Dolomite

FAULT

ANTICLINE

SYNCLINE

MONOCLINE

Figure 9. Altitude of the top of the Eminence Dolomite in the study area.

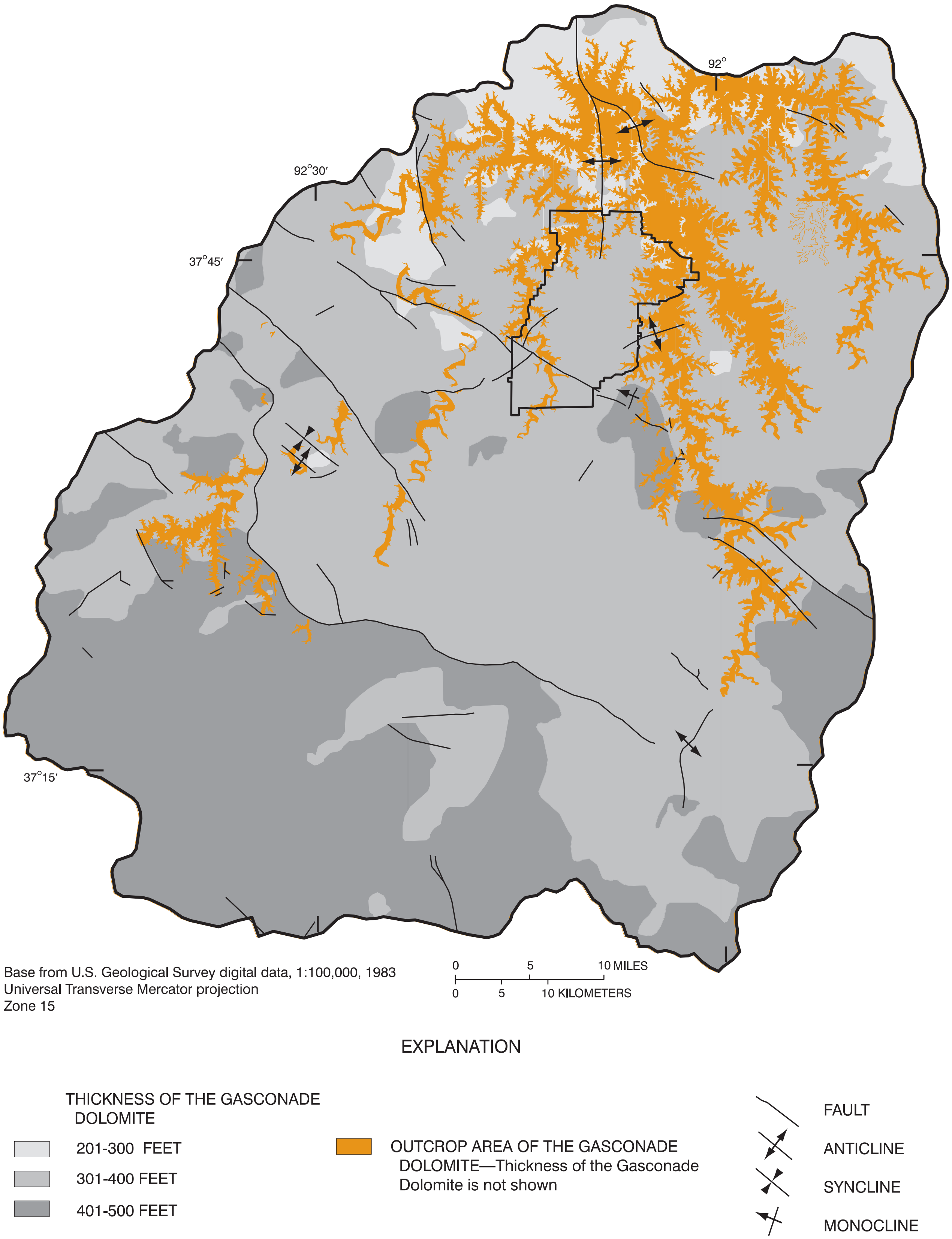
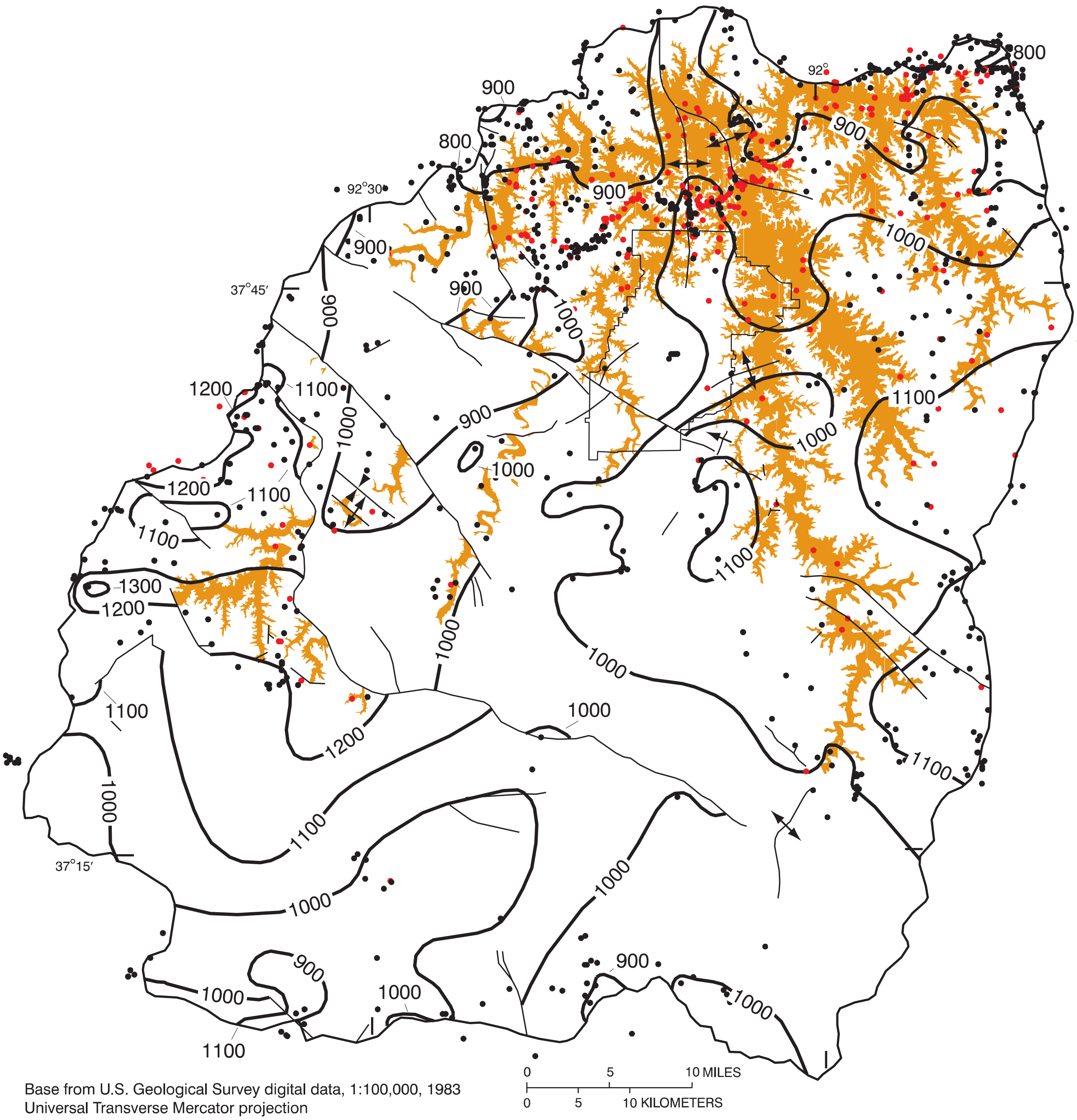


Figure 10. Thickness of the Gasconade Dolomite in the study area.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

EXPLANATION

OUTCROP AREA OF THE GASCONADE DOLOMITE

1000 — STRUCTURE CONTOUR—Shows altitude of the top of the Gasconade Dolomite. Contours in outcrop area of the Gasconade Dolomite represent the estimated pre-erosional surface. Contour Interval is 100 feet. Vertical datum is NGVD 29

DATA POINT—Black points are the top of the Gasconade Dolomite; red points are below the top of the Gasconade Dolomite

FAULT

ANTICLINE

SYNCLINE

MONOCLINE

Figure 11. Altitude of the top of the Gasconade Dolomite in the study area.

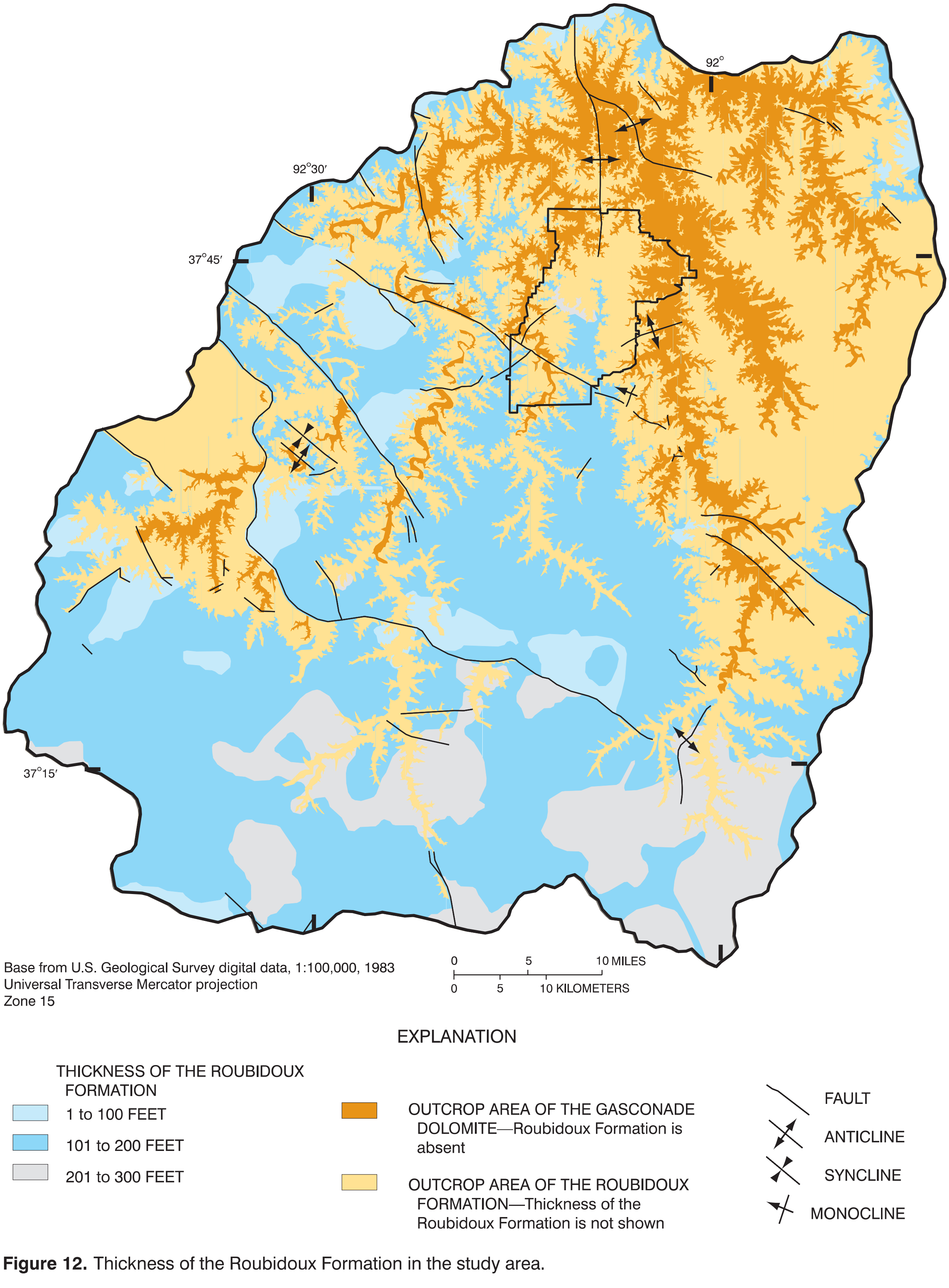
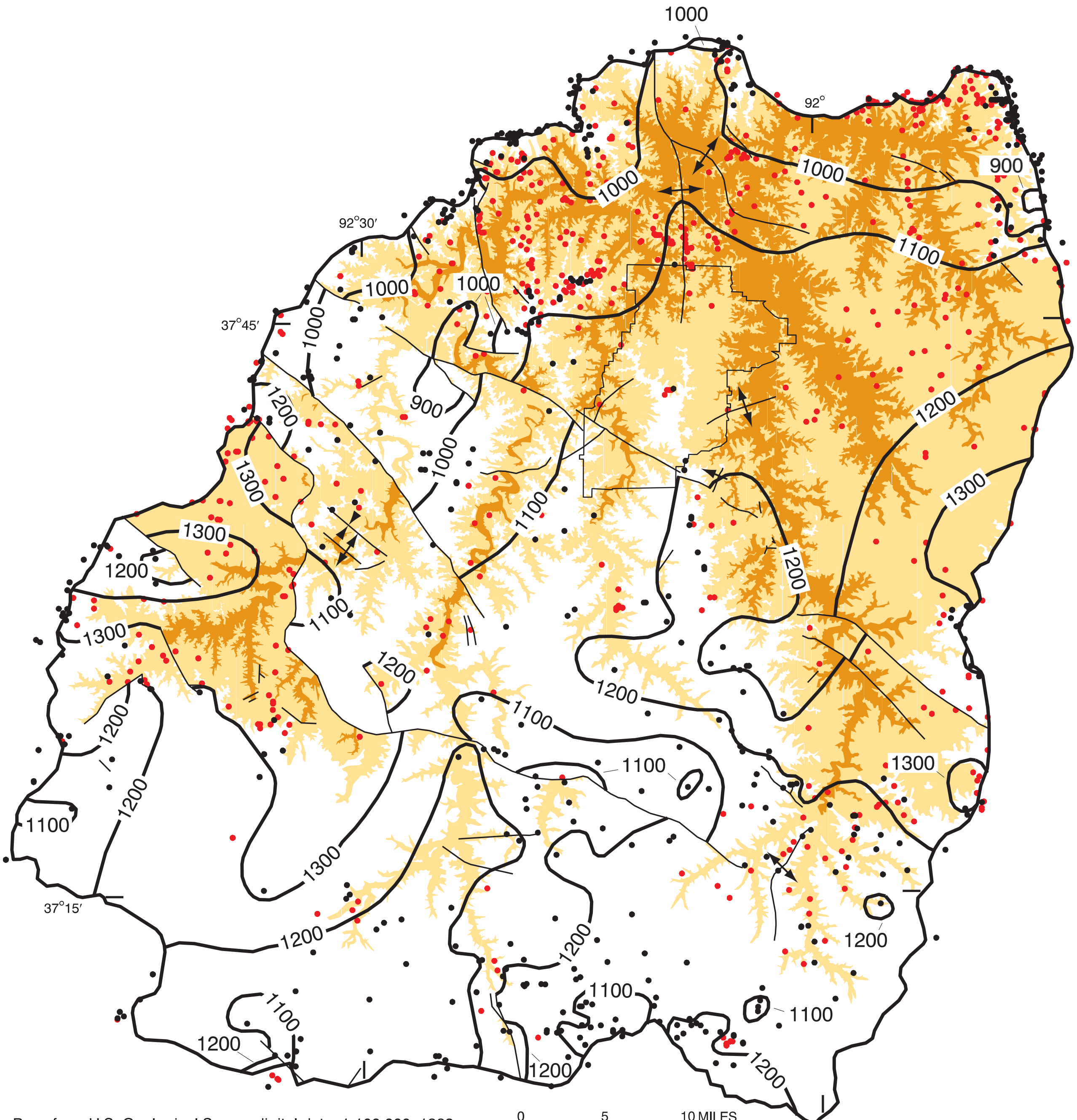


Figure 12. Thickness of the Roubidoux Formation in the study area.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

OUTCROP AREA OF THE ROUBIDOUX FORMATION

OUTCROP AREA OF THE GASCONADE DOLOMITE

—1000— STRUCTURE CONTOUR—Shows altitude of the top of the Roubidoux Formation. Contours in outcrop areas of the Roubidoux Formation and the Gasconade Dolomite represent the estimated pre-erosional surface. Contour interval is 100 feet. Vertical datum is NGVD 29

DATA POINT—Black points are the top of the Roubidoux Formation; red points are below the top of the Roubidoux Formation

FAULT

ANTICLINE

SYNCLINE

MONOCLINE

Figure 13. Altitude of the top of the Roubidoux Formation in the study area.

Thomson, 1986). The maximum thickness of Mississippian-age rocks in the study area probably is less than 150 ft.

Two east-west trending geologic sections (figs. 14, 15) and one south-north trending geologic section (fig. 16) were constructed using top-of-formation and thickness maps, and show in a third dimension the structure and relative thicknesses of formations. The geologic sections generally show more local relief on the upper formation contacts than contacts for the lower formations, in part because more data are available for these formations and because erosion has removed or partially removed the upper formations. The substantial topographic relief along some streams also is shown in the geologic sections.

In the northern part of the study area (fig. 14), the thicknesses of the Potosi and Eminence Dolomites are fairly uniform at about 250 to 300 ft each. The Gasconade Dolomite ranges from a little more than 200 ft to a little more than 400 ft because of the more irregular formation top and because in places part of the formation has been removed by erosion. The Roubidoux Formation, Jefferson City Dolomite, and Cotter Dolomite are present only in some places because they have been removed by erosion over much of the northern part of the study area.

In the southern part of the study area (fig. 15), the Potosi Dolomite thins to the west and is somewhat thinner (generally about 200 to 250 ft thick) than the Eminence Dolomite (about 300 ft thick). The thickness of the Gasconade Dolomite is fairly uniform at about 400 ft. The thickness of the overlying Roubidoux Formation is fairly uniform at about 200 ft except where it has been eroded along streams. The Jefferson City Dolomite and Cotter Dolomite are present across most of the southern part of the study area (fig. 15), but are thicker at ridges and thinner or absent at valleys.

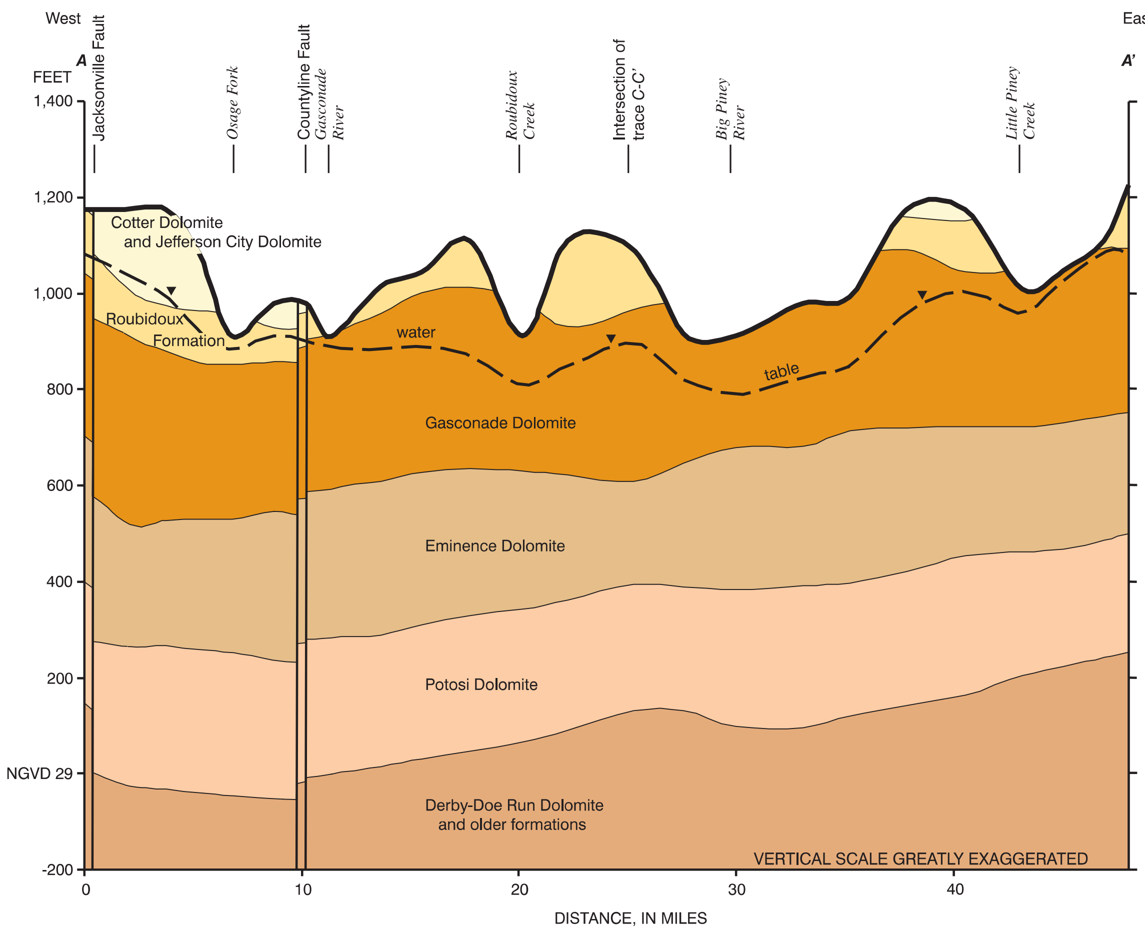


Figure 14. Generalized geologic section trending west-east across the northern part of the study area. The trace of the section is shown in figure 4.

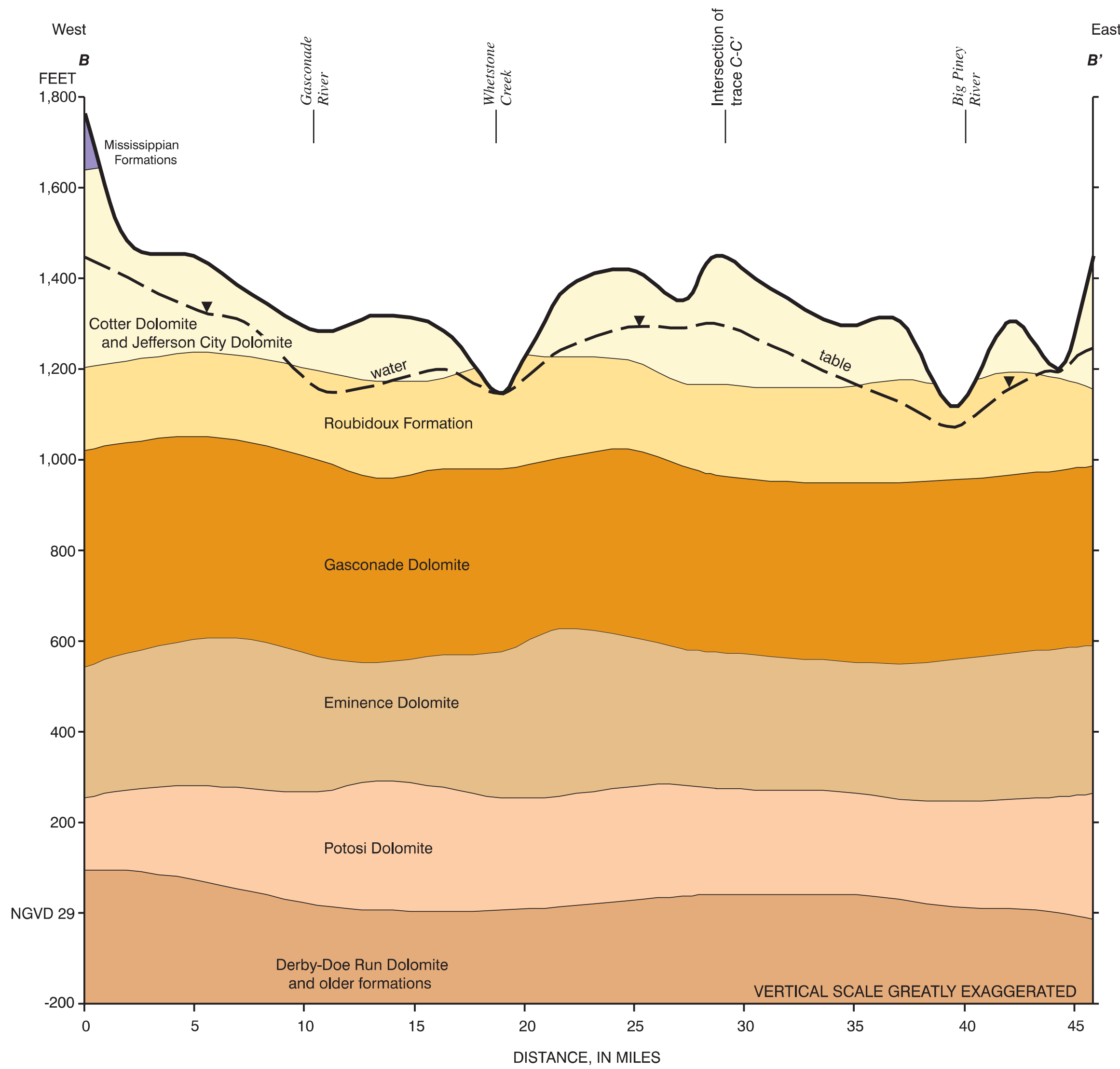


Figure 15. Generalized geologic section trending west-east across the southern part of the study area. The trace of the section is shown in figure 4.

The south-north trending geologic section (fig. 16) shows a broad structural high in the center of the section that is observed in the top-of-formation maps, and also shows another structural high in the northern part of the section. The thicknesses of the Eminence Dolomite and Potosi Dolomite do not vary much from south to north. The thickness of the Gasconade Dolomite generally decreases from about 400 ft in the south to about 300 ft in the north, but is much thinner where it has been eroded along the Gasconade River in the northern part of the study area. The thickness of the Roubidoux Formation ranges from 0 ft along the Gasconade River in the northern part of the study area to about 100 to 200 ft in most places in the central and southern parts of the study area where the entire formation is present. The Jefferson City Dolomite and Cotter Dolomite thin from more than 400 ft in the extreme south to 0 ft in most of the northern part of the study area.

GROUND-WATER HYDROLOGY

The geologic formations that compose the Ozark aquifer have different hydrologic properties. The Jefferson City Dolomite and Cotter Dolomite generally are less permeable than the stratigraphically lower rocks of the Ozark aquifer and yield little water to wells (Imes and Emmett, 1994). Wells completed in the Rou-

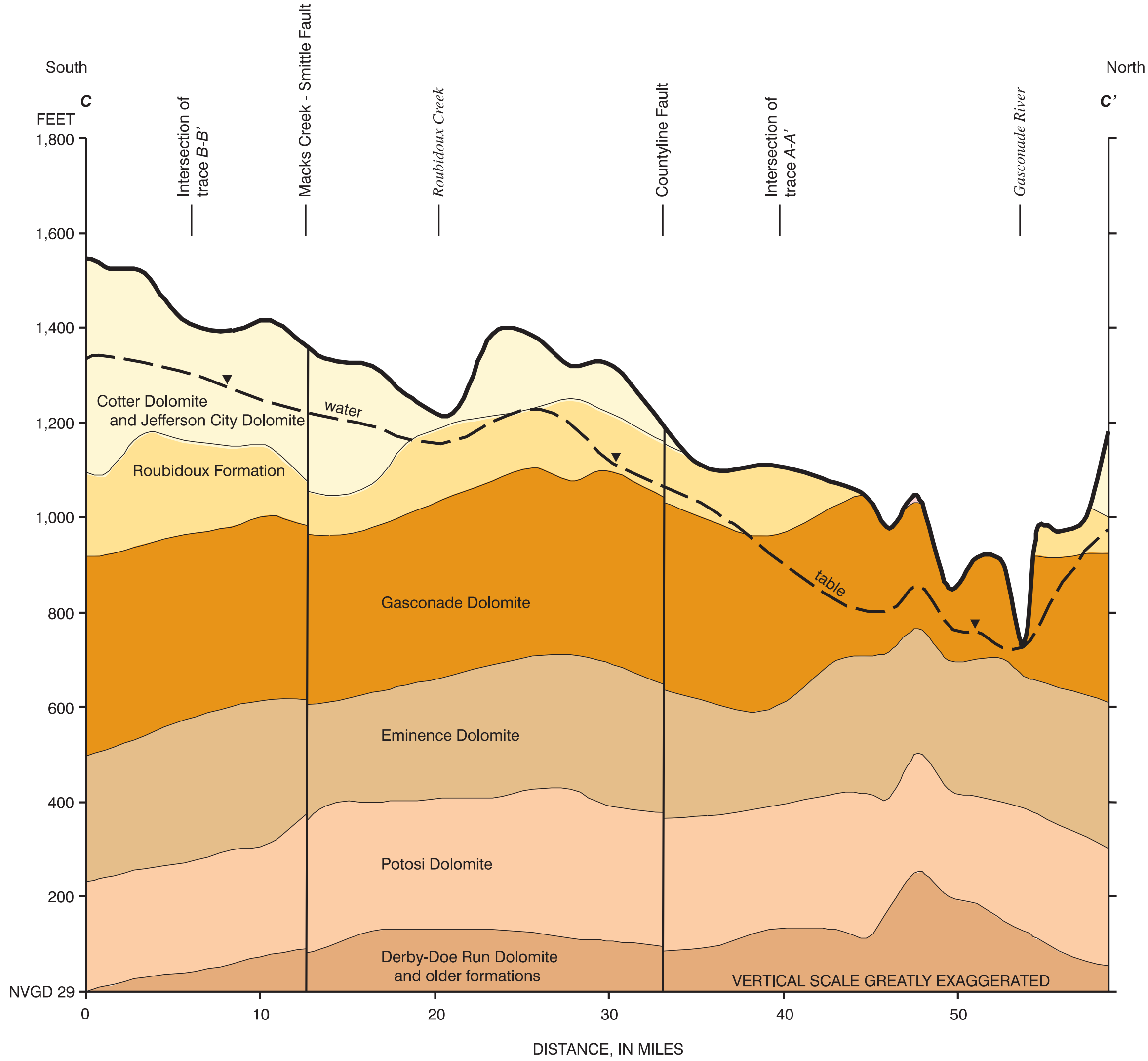


Figure 16. Generalized geologic section trending south-north across the central part of the study area. The trace of the section is shown in figure 4.

bidoux Formation and Gasconade Dolomite commonly yield from several tens to several hundred gallons per minute of water (Melton, 1976). Yields at the lower end of this range are suitable for domestic supplies, the primary use of ground water pumped from these formations. The Eminence Dolomite may form a weak hydrologic barrier to vertical ground-water flow between the overlying Gasconade Dolomite and the underlying Potosi Dolomite. The Potosi Dolomite is the most permeable formation in the Ozark aquifer. Wells completed in the Potosi Dolomite can yield from several hundred to 1,000 gal/min (gallons per minute) of water (Fuller and others, 1967; Imes and Emmett, 1994).

Domestic and Public Water-Supply Well Inventory

A well inventory was conducted in spring 1998. Depth to water was measured in 367 wells in the study area and in a 6-mi wide band surrounding the study area (table 1, at the back of this report). Wells in the GSRAD geologic well-log and well permit databases were targeted because it was preferable that well construction information be known for the wells that were measured. In areas where a targeted well was not available, the water level in another well was measured and construction information was obtained from the well owner, if it was known. Depth-to-water measurements in shallow wells open only to the uppermost saturated formation were preferred as representative water-table data. However, these ideal conditions were not encountered for many wells, because wells were commonly open to more than one formation or cased well below the water table.

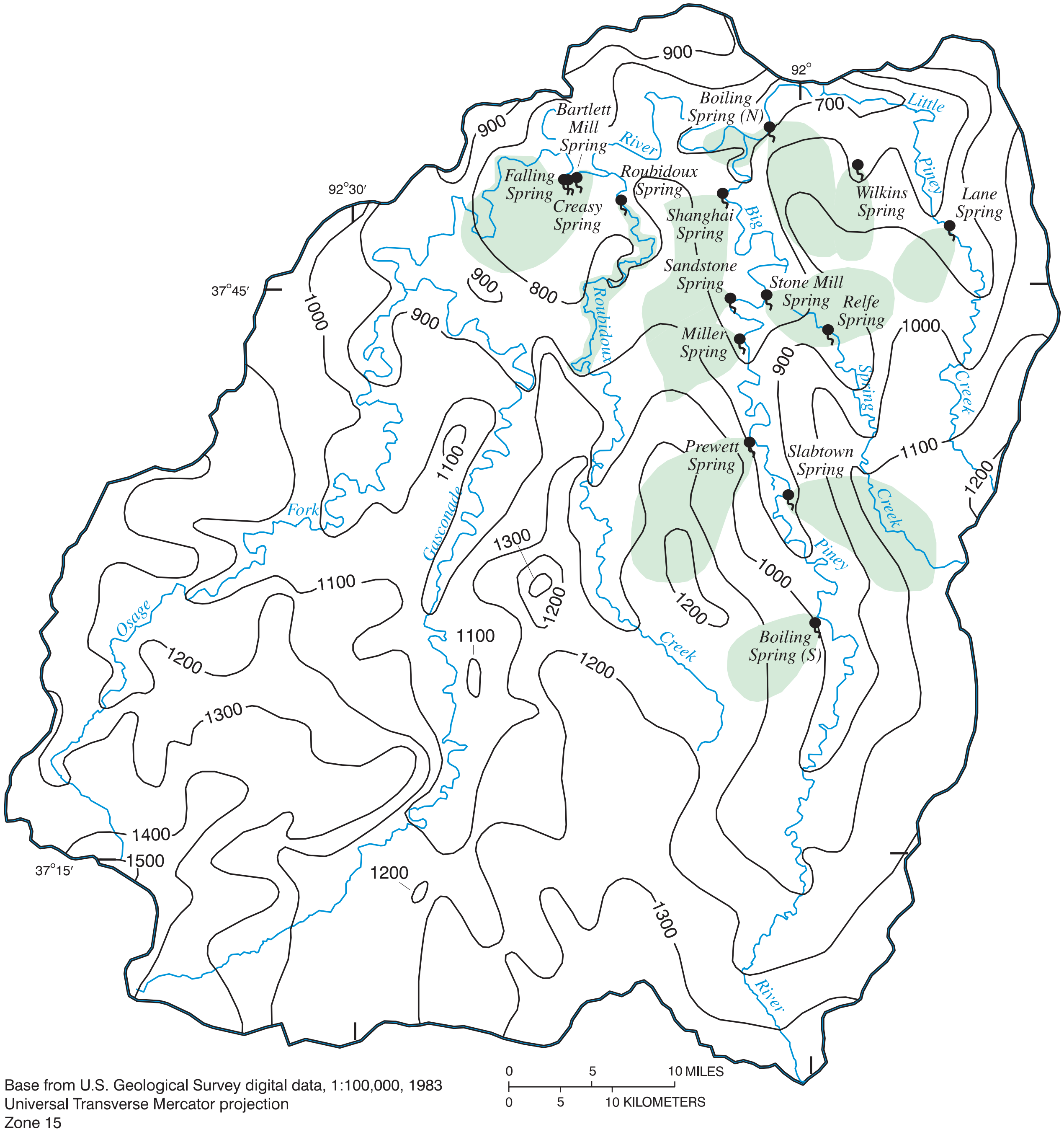
The procedure at each well consisted of measuring the static depth to water to the nearest 0.1 ft with an electric tape with the pump off. If the pump had been on recently, the water level was allowed to recover before taking a measurement. The land-surface altitude was estimated using contours on a 7 1/2-minute USGS topographic map; the land-surface altitude was accurate to one-half the contour interval of the topographic map, which was either 10 or 20 ft. The water-level depth from land surface was subtracted from the land-surface altitude to calculate the water-level altitude, after subtracting the height of the measuring point (usually the top of the well casing) above the land surface. An acoustic water-level instrument was used to measure the depth to water in some of the deeper wells, particularly public water-supply wells. Also, the specific conductance of the well water was measured for 62 of these wells (table 1).

Ground-Water Occurrence and Flow

A pre-development water-table map (fig. 17) shows the altitude of the water table (potentiometric surface) in the study area. The map was constructed using most of the water-level measurements made in 1998. Because water-level drawdown probably is minimal in domestic wells, these measurements were considered suitable for constructing the map. Some water levels were not used because they were measured in wells that did not fit this criterion. These included water levels in public water-supply wells that are open to a deeper part of the aquifer and may have drawdown because of the large pumpage from the wells, and water levels that appeared to be affected by pumpage in nearby wells. Some of the water-level measurements made in 1998 were in wells that were measured previously in 1994 and 1995 during a regional geohydrologic investigation of the FLWMR (Imes and others, 1996). Because the water-level changes from 1994 and 1995 to 1998 were small (less than 5 ft), measurements made in 1994 and 1995 in wells not measured in 1998 also were used to construct the pre-development water-table map. Historic water-level data from the GSRAD geologic well-log database also were used in a few places where more recent water-level data were lacking. The location of the onset of flow in small streams was available for several streams and was used as an indication of the altitude at which the streambed intersected the water table. Several dye-trace investigations, which demonstrate subsurface fracture, bedding-plane, and conduit flow from sinkholes and losing streams to springs, had been conducted previously (Imes and others, 1996). This information was used to position water-table contours in areas near large springs.

The regional ground-water divide is approximately coincident with the surface-water divide of the upper Gasconade River Basin. Water levels along the ground-water divide decline from an altitude of about 1,500 ft in the southwest to less than 700 ft where the Gasconade River flows out of the northern part of study area (fig. 17). The lower altitude (less than 900 ft) of the ground-water divide in a small area in the northwestern part of the study area is indicative of the extensive karst development in the Dry Auglaise Creek valley (not shown; Harvey, 1980) about 2 mi northwest of the study area. Low water-table gradients along the right bank of the Gasconade River in the area between the mouths of Osage Fork and Roubidoux Creek also indicate high permeability karst terrain. The effect of karst on the water table also is evident along the left bank of the Big Piney River between Miller Spring and the mouth of the Big Piney River. Ground-water levels may be as deep as 300 ft below the land surface (table 1) beneath upland areas where karst features are prevalent.

A part of the precipitation that falls in upland areas of the Gasconade River Basin infiltrates into the soil and residuum overburden and percolates downward through the unsaturated zone to the ground-water system at the water table. This recharge is the primary mechanism by which ground water is replenished in the basin. In areas where substantial karst has developed, local recharge through losing streambeds may be a significant source of ground-water recharge. Once ground water reaches the water table, it flows under hydraulic gradient from areas of high potentiometric head to areas of low potentiometric head. Ground-water flow directions are perpendicular to the lines of equal water-level altitude, and can be inferred from the water-table map (fig. 17). Ground-water discharges to perennial reaches of streams, as shown by gradients inferred from the water-table contours adjacent to streams. Where conduit flow to springs exists, such as in the FLWMR



EXPLANATION

SPRING RECHARGE AREA

— 200 — PRE-DEVELOPMENT WATER-TABLE CONTOUR—Shows altitude of water table in spring 1998. Contour interval is 100 feet. Vertical datum is NGVD 29

Figure 17. Pre-development water-table surface of the Ozark aquifer and recharge areas of selected springs in the study area.

area (Imes and others, 1996), flow directions may depart locally from the generalized directions inferred from the contours on figure 17.

Generally, ground water flows downward in recharge areas to deeper parts of the Ozark aquifer, then laterally and upward at discharge areas. Vertical potentiometric head differences between upper and lower parts of the aquifer determine whether the vertical component of ground-water flow is upward or downward at any given location. A potentiometric map of the deeper part of the Ozark aquifer was not constructed because of insufficient water-level measurements in wells open primarily to the Potosi Dolomite. Deep wells in southern Missouri commonly are open to stratigraphically higher formations (especially the Roubidoux Formation and Gasconade Dolomite) in addition to the Potosi Dolomite. Water levels measured in these wells represent an average of the potentiometric head in the formations to which the wells are open and may not accurately represent the potentiometric head in the Potosi Dolomite.

Although a potentiometric map of the deeper part of the Ozark aquifer was not available, the vertical component of flow in the southern part of the study area can be inferred to be downward because this area is the regional recharge area for the Ozark aquifer. Further north, a downward vertical component of flow also is present along the main north-south topographic ridge at the FLWMR, as evidenced by the potentiometric head difference between two FLWMR wells known as the Range Control well and the Motor Transport Operator Course (MTOC) well (fig. 2). The Range Control well is 292 ft deep, cased to 82 ft, and is open to the middle part of the Gasconade Dolomite. The MTOC well is 692 ft deep, cased to 295 ft, and is open to the middle part of the Gasconade Dolomite as well as the Eminence Dolomite and the Potosi Dolomite. Two different sets of water-level measurements made in 1994 and 1995 indicate that the water level in the shallower Range Control well was 6 ft and 16 ft higher than the water level in the deeper MTOC well (Imes and others, 1996). Although the water level measured in the MTOC well represents an average of the potentiometric head over the open interval of the well rather than at a discrete point in the Potosi Dolomite, a higher potentiometric head in the upper part of the aquifer than the lower part of the aquifer is evident.

Further north in the FLWMR and east of the main north-south topographic ridge at the FLWMR, an upward vertical component of flow is present, as evidenced by the potentiometric head difference between two FLWMR wells known as the Old Ammo Dump well and the New Ammo Dump well (fig. 2). The Old Ammo Dump well was drilled into the top few feet of the Eminence Dolomite, and is about 400 ft deep (Imes and others, 1996). The New Ammo Dump well is 630 ft deep, cased to 488 ft, and is open to the middle and lower parts of the Eminence Dolomite and possibly the upper Potosi Dolomite. A set of water-level measurements made in 1995 show that the water level in the deeper New Ammo Dump well was about 8 ft higher than the water level in the shallower Old Ammo Dump well (Imes and other, 1996). The lower potentiometric head in the upper part of the aquifer may be a result of drainage of water to nearby springs (Imes and others, 1996).

Generally, the water table occurs within younger formations in the southern part of the study area and occurs within progressively older formations to the north as the younger formations become thinner and eventually become absent (figs. 16, 18). Where the water table occurs within a formation, the formation is only partially saturated. In the southern part of the study area, the water table occurs in the Jefferson City Dolomite and possibly in the Cotter Dolomite. To the north, the water table occurs in the Roubidoux Formation, and further north it occurs in the Gasconade Dolomite. Although the Jefferson City Dolomite and the Roubidoux Formation are the uppermost bedrock formations in the upland areas of the FLWMR, the water table generally is deep enough to occur in the underlying Gasconade Dolomite throughout most of the FLWMR. At one small location north of the FLWMR along the eastern flank of the Fort Leonard Wood Anticline, the water table occurs in the Eminence Dolomite.

The Jefferson City Dolomite and possibly the Cotter Dolomite are saturated where these formations crop out and are thick enough, generally in the southern part of the study area (figs. 16, 19). The saturated thickness of the Jefferson City and Cotter Dolomites is largest (locally more than 300 ft) in the extreme southwestern and south-central part of the study area (fig. 19). The saturated thickness of the formations generally decreases to zero to the north (figs. 16, 19) and along river valleys in the southern part of the study area, but increases in some places on the north side of the Macks Creek-Smittle Fault (fig. 4) where the formations are downthrown. The Jefferson City Dolomite normally is unsaturated at the FLWMR (fig. 18; Imes and others, 1996).

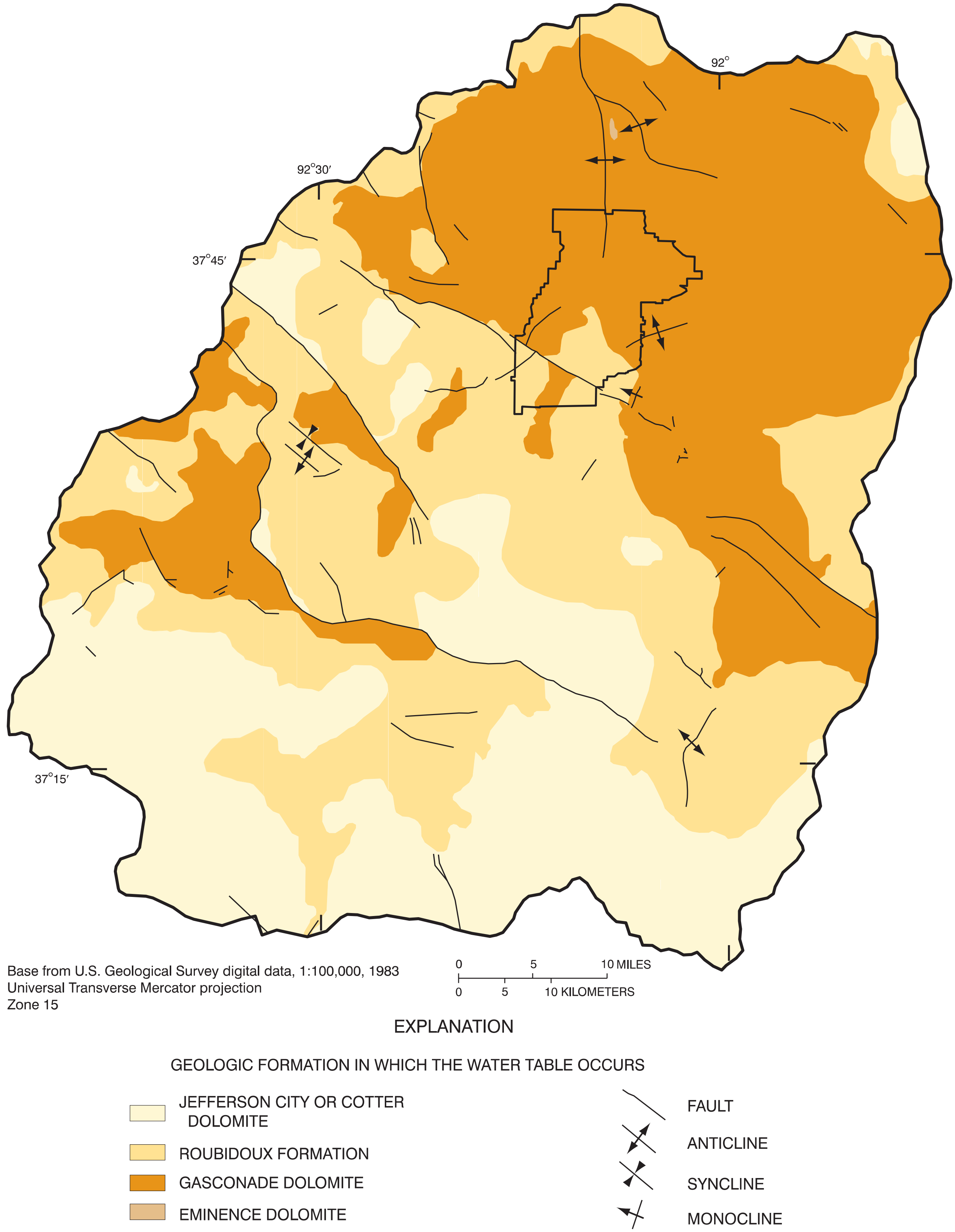
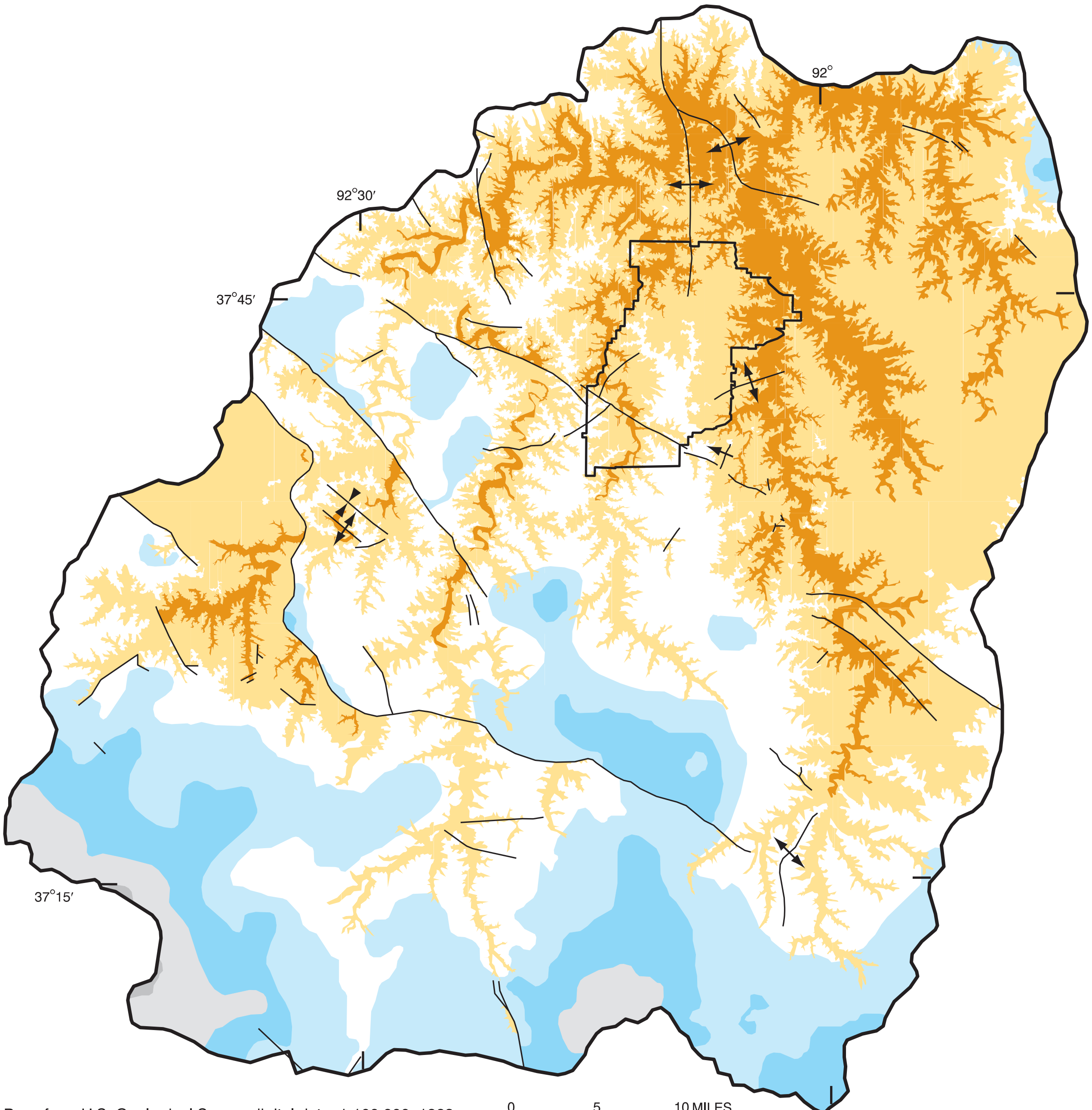


Figure 18. Area where the water table occurs within the indicated formation and where the formation is partially saturated in the study area, spring 1998.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

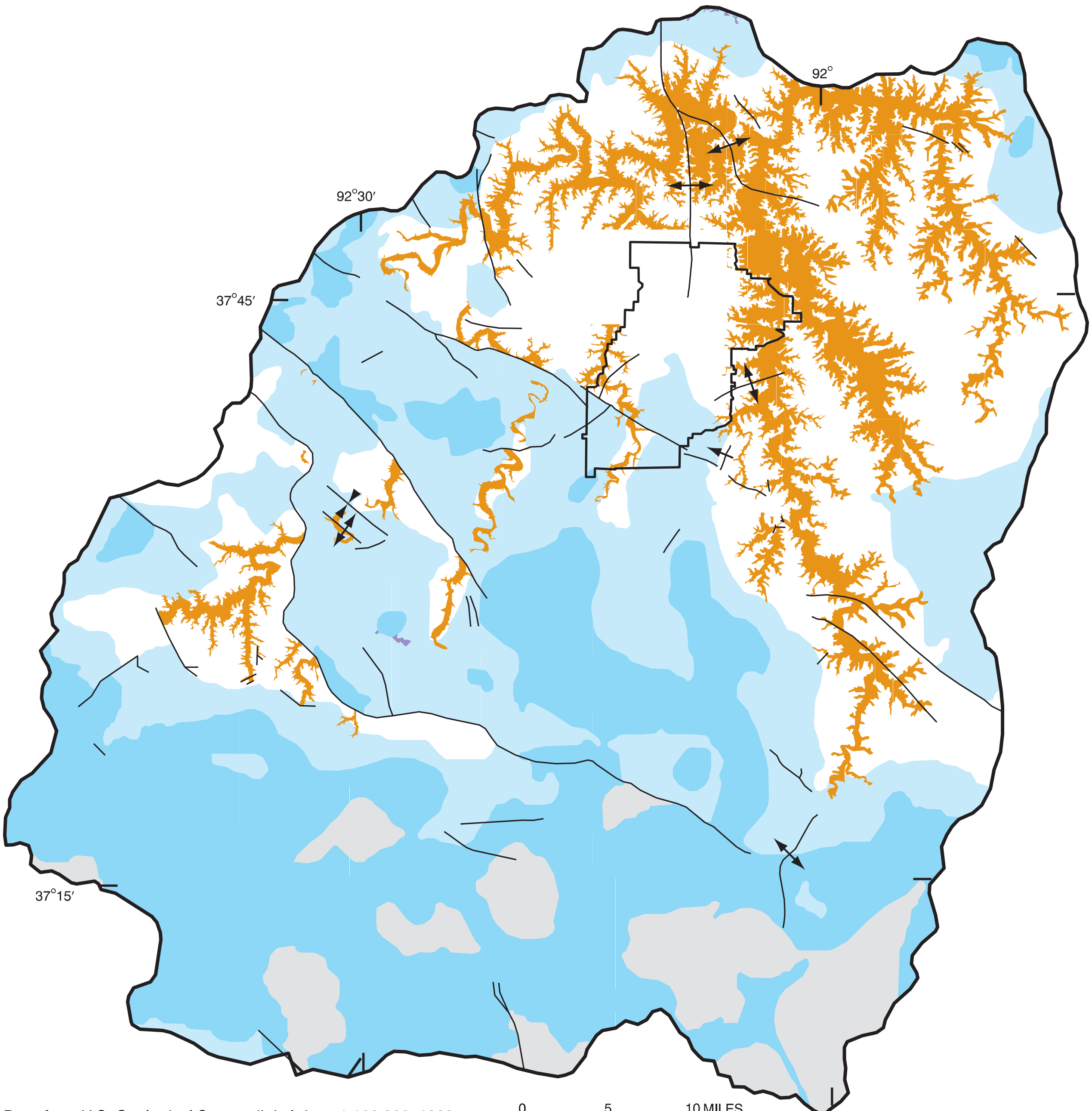
SATURATED THICKNESS OF THE JEFFERSON CITY AND COTTER DOLOMITES

- 0 FEET
- 1 to 100 FEET
- 101 to 200 FEET
- 201 to 300 FEET
- 301 to 400 FEET

- OUTCROP AREA OF THE ROUBIDOUX FORMATION
- OUTCROP AREA OF THE GASCONADE DOLOMITE

- FAULT
- ANTICLINE
- SYNCLINE
- MONOCLINE

Figure 19. Saturated thickness of the Jefferson City and Cotter Dolomites in the study area, spring 1998.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 15

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

SATURATED THICKNESS OF THE ROUBIDOUX FORMATION

- 0 FEET
- 1 to 100 FEET
- 101 to 200 FEET
- 201 to 300 FEET

OUTCROP AREA OF THE GASCONADE DOLOMITE

FAULT

ANTICLINE

SYNCLINE

MONOCLINE

Figure 20. Saturated thickness of the Roubidoux Formation in the study area, spring 1998.

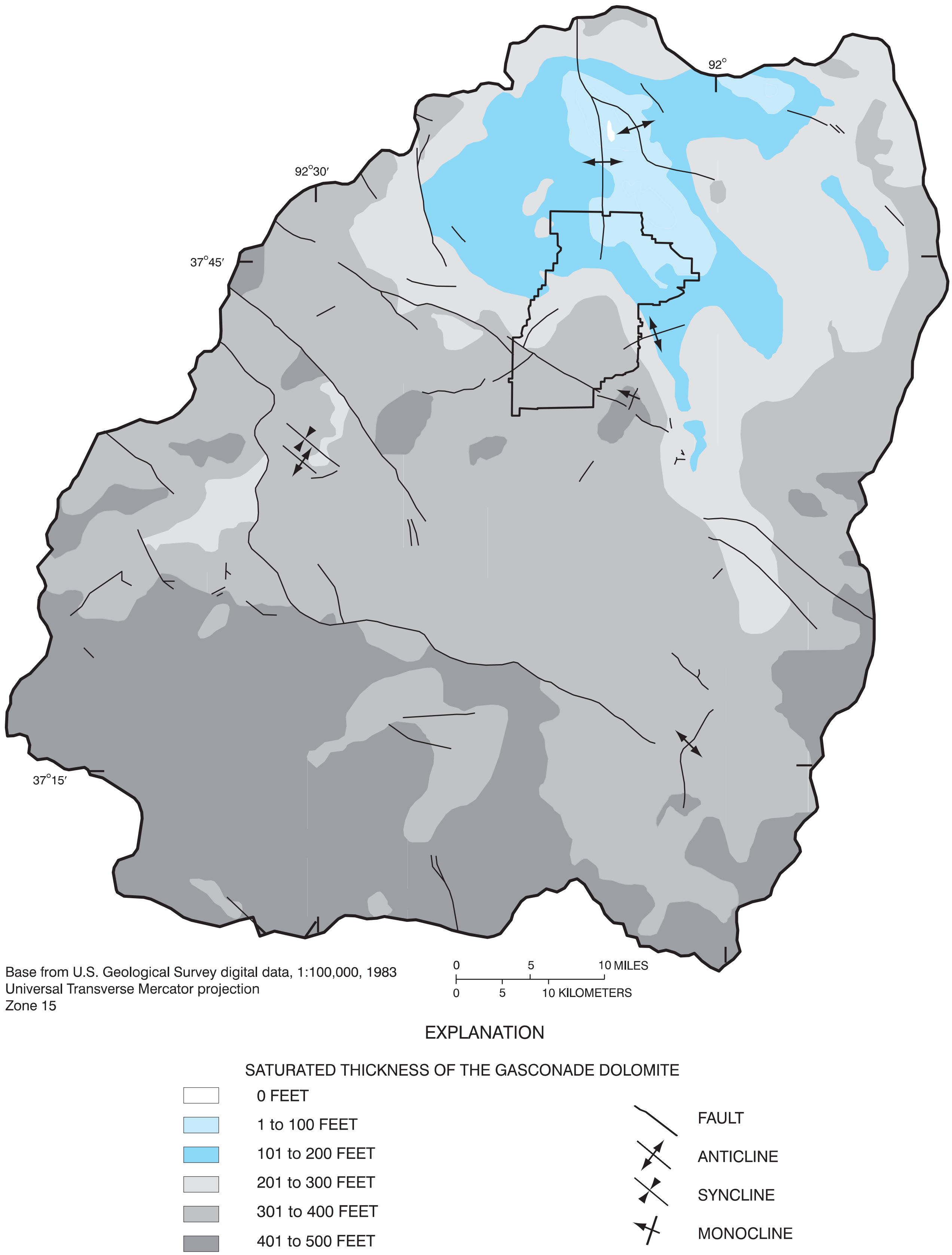


Figure 21. Saturated thickness of the Gasconade Dolomite in the study area, spring 1998.

The Roubidoux Formation is fully saturated throughout most of the southern one-third of the study area (figs. 16, 18) where its saturated thickness is larger than 200 ft in places (fig. 20). Its saturated thickness generally decreases to zero to the north (figs. 16, 20). In the central part of the study area, the lower part of the Roubidoux Formation is saturated beneath inter-valley ridges, but usually is unsaturated along stream valleys where ground-water levels are lower. The formation is unsaturated in most of the northeastern one-third of the study area. Although the formation is present beneath the inter-valley ridges in this area, the rocks are more permeable, ground-water discharge to springs is rapid, and the water table generally is low and occurs in the underlying Gasconade Dolomite.

The Gasconade Dolomite is fully saturated in most of the southern one-half of the study area (figs. 16, 18) where its saturated thickness is larger than 400 ft in places (fig. 21). It is partially saturated throughout the remainder of the area and its saturated thickness generally decreases to the north (fig. 21). The water table is in the underlying Eminence Dolomite in a small area in the north-central part of the study area (figs. 18, 21).

Ground-Water Discharge to Streams and Springs

One hundred and eleven discharge measurements or discharge estimates were made at 99 sites in September 1998 and August 1999 on the Gasconade River, Little Piney Creek, Big Piney River, Roubidoux Creek, Osage Fork, and their major tributaries and spring branches (table 2, at the back of this report). The specific conductance and temperature of the water were measured at most sites at the time discharge was measured. Discharge measurements were made during periods of low streamflow to quantify the exchange of ground and surface water. This exchange takes the form of gaining stream reaches where ground water enters streams by diffuse seepage through the streambed or from spring discharge, and losing stream reaches where surface water is lost to the ground-water system through the streambed.

Streamflow velocity was measured using either a standard AA or pygmy current meter, depending on stream velocity and depth. The methods used to make discharge measurements and the criteria used to determine the type of current meter applicable for the measuring section are described by Rantz and others (1982). The accuracy of the measurements was rated according to stream channel conditions and uniformity of flow using the following subjective scale: "good" indicates that the difference between the actual discharge and the measured discharge is less than 5 percent, "fair" is between 5 and 8 percent, and "poor" is greater than 8 percent. Discharge was estimated where shallow water depths or low-flow velocities prevented accurate current meter discharge measurements. The error at the sites where discharge was estimated may exceed 8 percent.

The planned series of discharge measurements made during low-flow conditions in September 1998 was suspended after a few days because rainfall and runoff were sufficient to cause streamflow to increase above low-flow conditions. Low-flow conditions were present again in August 1999, and discharge measurements were made on the stream reaches that were not measured in September 1998. Discharge measurements also were made at selected locations where measurements were made in September 1998 to correlate the two data sets. Discharge measurements also were made at selected springs by direct measurement of flow in the spring branch or by measuring upstream and downstream from the point where the spring branch discharged into a stream. Discharge data for springs that were not measured during September 1998 or August 1999 were estimated from low-flow or average discharge data published in Vineyard and Feder (1974). These data and discharge measurements (table 18 in Imes and others, 1996) made on the Big Piney River and Roubidoux Creek in September 1995 are presented in table 2.

A composite discharge was determined for streams and springs by scaling discharge measurements made in September 1995 and September 1998 to the measurements made in August 1999 (table 2; figs. 22, 23). The purpose of computing a composite discharge was to create a data set representative of one hydrologic condition, so that flow comparisons could be made across the basin. The scale factors were calculated as the ratio of an August 1999 measurement at the mouth of a stream and the appropriate September 1995 or September 1998 measurement at the same location. The Gasconade River scale factor was recomputed for the Gasconade River upstream of Osage Fork using the discharge values at site 17 (table 2). The composite discharge of the Gasconade River at Jerome was 552 ft^3/s (cubic feet per second), and discharges of main tributaries to the Gasconade River were 86.1 ft^3/s at the mouth of the Little Piney Creek, 246 ft^3/s at the mouth of the Big Piney River, 25.9 ft^3/s at the mouth of Roubidoux Creek, and 34.7 ft^3/s at the mouth of Osage Fork. Of the 552 ft^3/s discharged at Jerome, 393 ft^3/s were supplied by the four main tributaries of the Gasconade River and 159 ft^3/s were derived from the Gasconade River and its smaller tributaries.

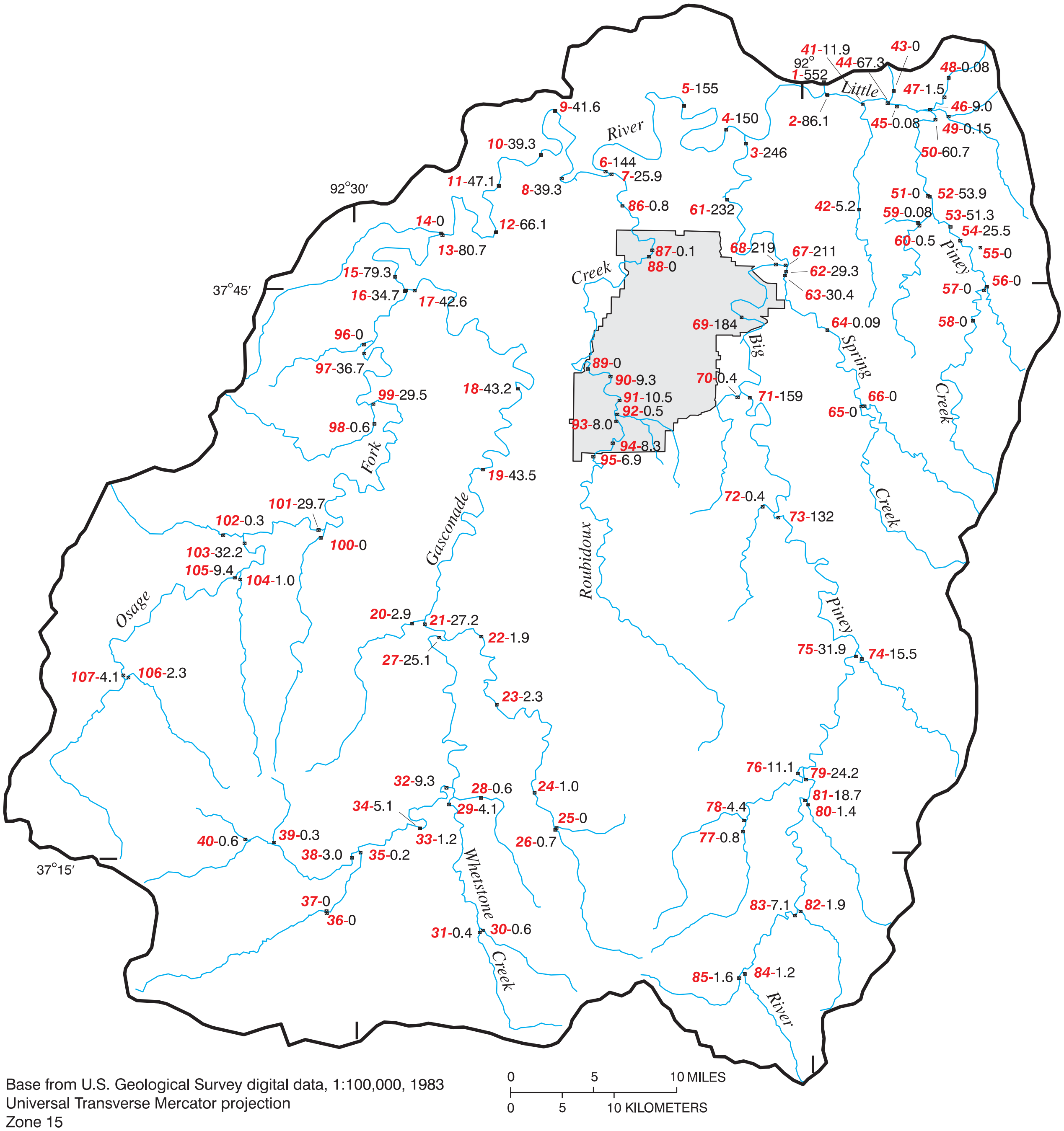
A substantial quantity of ground water in the study area discharges from springs. Springs are more numerous and larger in the northern part of the basin where the Gasconade Dolomite and Roubidoux Formations crop out (fig. 4) and karst terrain is more well developed. Discharge from springs represented 56 percent (311 ft^3/s) of the 552 ft^3/s total discharge from the upper Gasconade River Basin at Jerome. As a percentage of discharge at the mouth of the main tributaries of the Gasconade River, spring discharge represented 27 percent (23.3 ft^3/s) of the discharge of the Little Piney Creek, 54 percent (133 ft^3/s) of the discharge of the Big Piney River, 92 percent (23.8 ft^3/s) of the discharge of Roubidoux Creek, and 49 percent (17.1 ft^3/s) of the discharge of Osage Fork. Spring discharge also represented 72 percent (114 ft^3/s) of the 159 ft^3/s of discharge derived from the Gasconade River and its smaller tributaries.

Qualifications must be stated regarding the percentage of spring discharge that contributes to the discharge of Roubidoux Creek and of the Gasconade River and its smaller tributaries. Roubidoux Creek lost 9.3 ft^3/s (36 percent of the 25.9 ft^3/s flow at the mouth of Roubidoux Creek) of discharge to the ground-water flow system near Quesenberry Ford (table 2). This water returned to Roubidoux Creek 21 river miles downstream at Roubidoux Spring. The remainder of the ground-water discharge at Roubidoux Spring (16.6 ft^3/s) probably was from ground-water recharge in the immediate vicinity of the spring. Likewise, the Gasconade River lost 41.4 ft^3/s of discharge to the ground-water flow system between Highway 133 and Highway T (site 13 to site 10, fig. 22). The lost discharge reappears in Bartlett Mill Spring, Creasy Spring, and Falling Spring (fig. 23). These springs flow into the Gasconade River a short distance downstream from Collie Hollow (site 8, fig. 22). A series of discharge measurements were made on the Gasconade River during the extreme drought conditions of September 1953 (H.C. Bolon, U.S. Geological Survey, written commun., 1953). These measurements indicated that the Gasconade River lost 24.6 ft^3/s of discharge between Highway 133 (28.5 ft^3/s) and Highway T (called Lundstrum Ford Bridge; 3.9 ft^3/s). An appreciable volume of surface water was observed entering a sinkhole on the west side of the river near Cave Restaurant (site 11, fig. 22; called Ozark Springs Bridge). Stream discharge within the 0.75-mi reach of the Gasconade River below Collie Hollow reportedly increased from 4.3 to 69.8 ft^3/s, caused by discharge from Bartlett Mill Spring, Creasy Spring, Falling Spring, and discharge of ground water through the gravel streambed of the Gasconade River.

WATER USE FOR PUBLIC AND DOMESTIC SUPPLY

Well pumpage data were collected and compiled for public-water suppliers for the period from January 1993 through June 1998. Average daily pumping rates and annual pumpage for 80 public water-supply wells (owned by 30 public-water suppliers) in the study area and for 63 public water-supply wells (owned by 25 public-water suppliers) in a 6-mi wide band surrounding the study area (fig. 24) are presented in table 3, at the back of this report. Public water-supply wells in the study area are concentrated around the northern end of the FLWMR and are mostly associated with the towns of St. Robert and Waynesville (fig. 2), the Pulaski County Public Water-Supply District #1, or mobile home parks. Most of the remaining public water-supply wells are around towns along the boundary of the study area and are near the surface-water divide that defines the upper Gasconade River Basin.

Pumpage data for individual wells owned by public-water suppliers were collected directly from the suppliers and from the GSRAD, which compiles such data under their Water Resources Program. Where these data were not available, data published in the Missouri Census of Public Water Systems series (Missouri Department of Natural Resources, Division of Environmental Quality, 1991, 1996, 1997, 1998) were used. These publications contain annual consumption data for public water-supply wells on a system-wide basis, but not for individual wells. Average daily pumping rates and annual pumpage for individual wells were estimated from the published census data by interpolating the data between published intervals and, where necessary, prorating the data among the several wells of a public water-supply system. Data for surface-water pumpage by the FLWMR were supplied by the FLWMR Department of Public Works.



EXPLANATION

91-10.5 ▪ SITE NUMBER AND STREAM DISCHARGE VALUE, IN CUBIC FEET PER SECOND—Red numbers are site numbers; black numbers are composite discharge values (table 2)

Figure 22. Location of low-flow measurement sites and value of composite stream discharge.

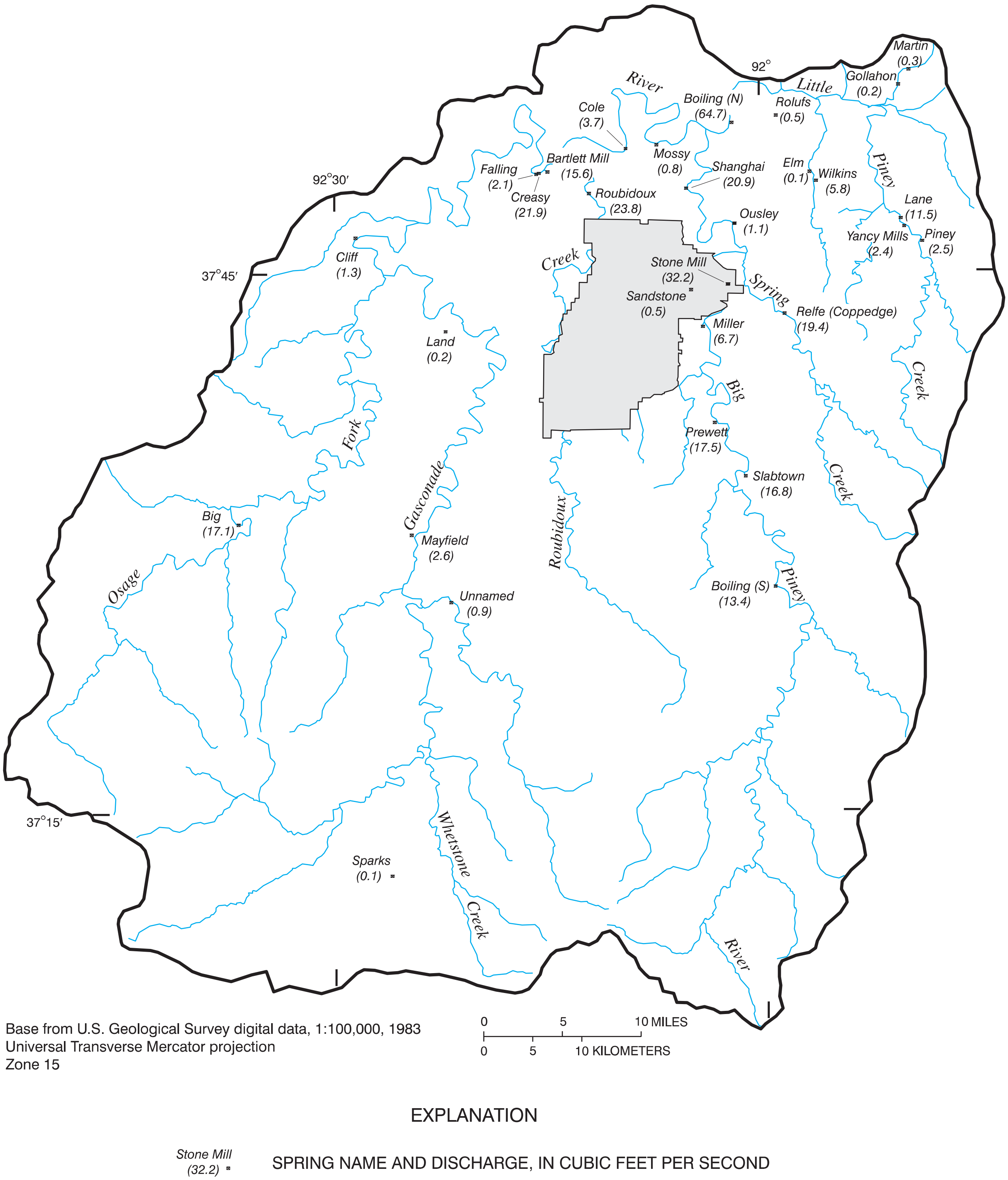


Figure 23. Location of selected springs in the study area and composite spring discharge values.

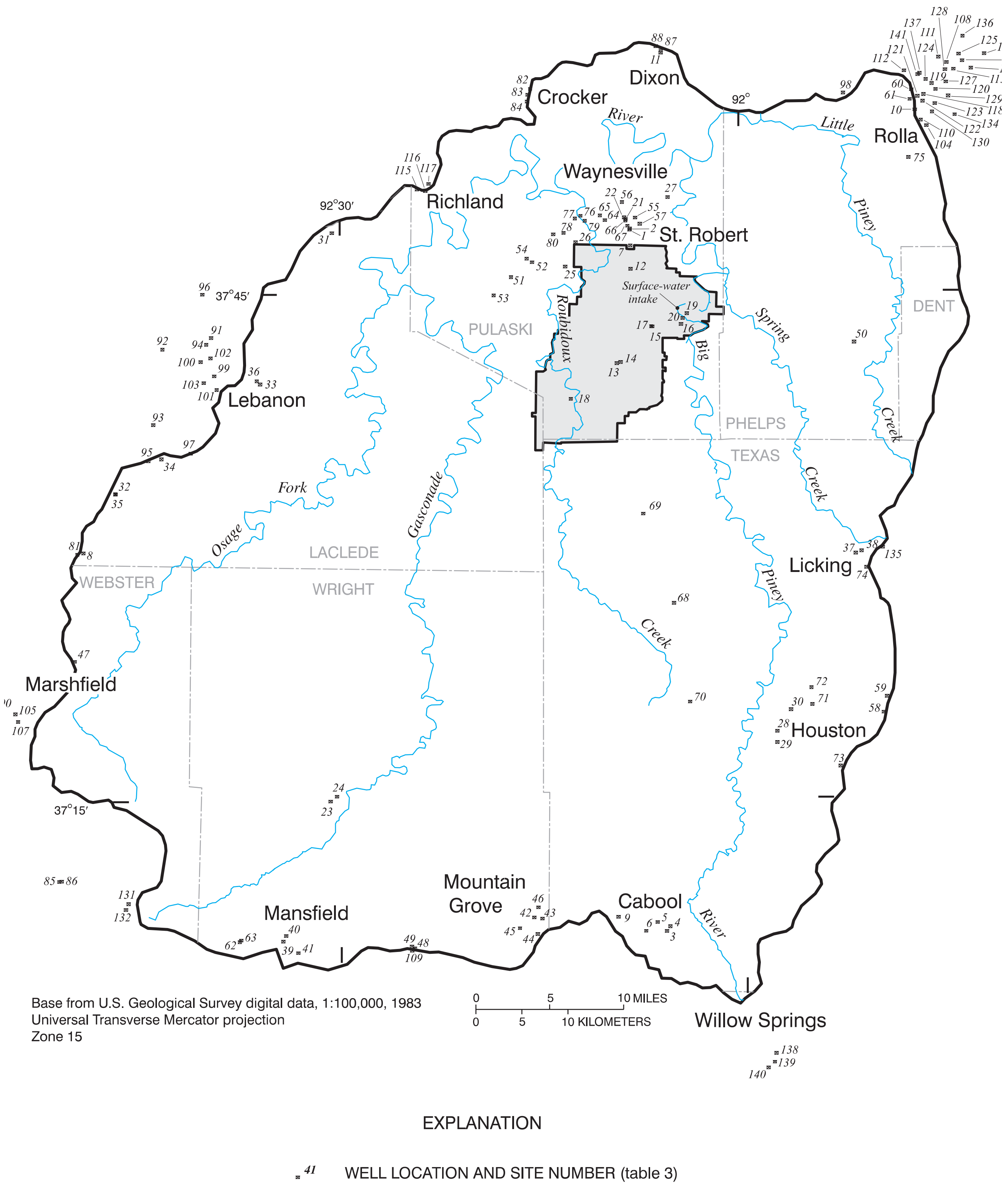


Figure 24. Location of public water-supply wells in the study area and in a 6-mile wide band surrounding the study area and the Fort Leonard Wood Military Reservation surface-water intake on the Big Piney River.

Except for water withdrawn from the Big Piney River for use at the FLWMR, all water used in the study area is ground water. Well pumpage, however, constitutes a much smaller amount of discharge from the ground-water system than discharge to streams. Average daily pumping rates ranged from 0 to 0.673 Mgal/d (million gallons per day) for individual public water-supply wells from January 1993 to June 1998 (table 3). Average daily pumping rates from all public water-supply wells in the study area during this period ranged from 4.73 (March 1998) to 6.29 Mgal/d (July 1997; table 3). Annual pumpage from all public water-supply wells in the study area from 1993 through 1997 (the latest year with full pumpage data) ranged from 1,820 Mgal (million gallons; an average daily rate of 4.99 Mgal/d) in 1993 to 2,030 Mgal (an average daily rate of 5.56 Mgal/d) in 1997 (table 3; fig. 25). The daily pumping rate from domestic wells in the study area is estimated at about 4 Mgal/d, based on an estimate of 40,000 people in the study area not served by public water-supply systems and an assumed water usage of 100 gal/d (gallons per day) per person. The average daily pumping rate for all wells in the study area from 1993 through 1997 is thus estimated to range from 8.99 Mgal/d in 1993 to 9.56 Mgal/d in 1997, much less than the 357 Mgal/d (552 ft^3/s) low-flow discharge measured for the Gasconade River at Jerome in August 1999. Annual pumpage from public water-supply wells in the 6-mi wide band surrounding the study area from 1993 through 1997 ranged from 1,580 Mgal (an average rate of 4.33 Mgal/d) in 1993 to 1,730 Mgal (an average rate of 4.74 Mgal/d) in 1996 and 1997 (table 3; fig. 25).

Most of the water used at the FLWMR is supplied from a pumping station on the Big Piney River. A smaller quantity of the water is supplied from eight (as of 1998) public water-supply wells at the FLWMR (fig. 2). Most of the ground water used at the FLWMR is pumped from the Indiana Avenue well, located at the western edge of the cantonment area (fig. 2). The seven other wells provide water to isolated small facilities and provide a much smaller quantity of water than the Indiana Avenue well. Pumpage records are not maintained for these wells. From 1993 through 1997, the Indiana Avenue well supplied from 1.6 percent (in 1994) to 2.9 percent (in 1997) of the total water use at the FLWMR. Annual pumpage from the Big Piney River during the same period ranged from 1,136 Mgal (an average of 3.11 Mgal/d) in 1997 to 1,334 Mgal (an average of 3.65 Mgal/d) in 1995 (table 4). Total water use in the study area ranged from a daily average of about 12.6 Mgal/d (9.12 Mgal/d ground water and 3.46 Mgal/d surface water) in 1994 to a daily average of about 12.8 Mgal/d (9.18 Mgal/d ground water and 3.65

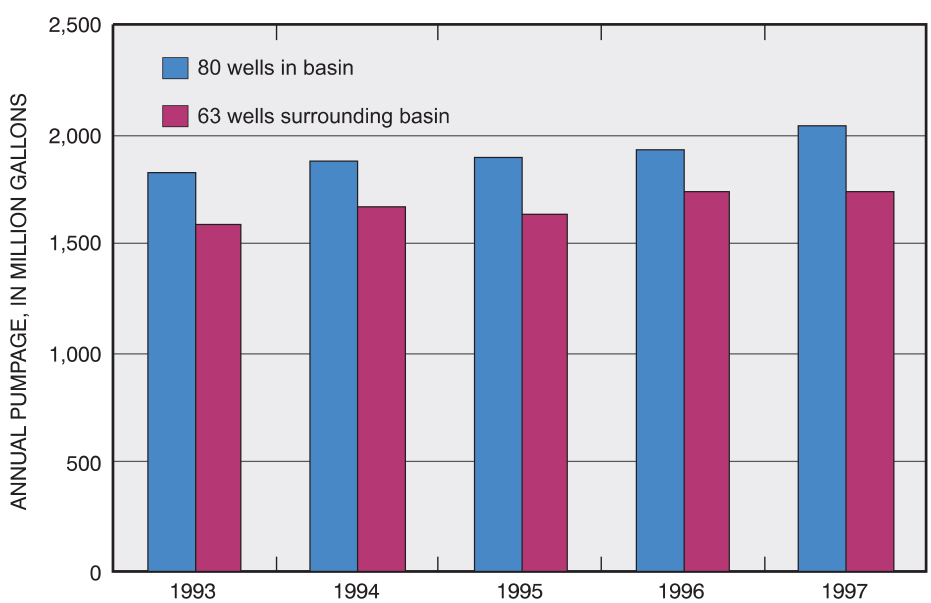


Figure 25. Annual pumpage for 80 public water-supply wells in the study area and 63 public water-supply wells in a 6-mile wide band surrounding the study area from 1993 through 1997.

Mgal/d surface water) in 1995 during the same period. Surface-water pumpage by the FLWMR as a percentage of total water use in the study area ranged from about 24.5 percent in 1997 to about 28.8 percent in 1993.

Table 4. Annual pumpage of water from the Big Piney River for public water use at the Fort Leonard Wood Military Reservation, 1993–1997

[MG, millions of gallons]

Annual pumpage (MG)				
1993	**1994**	**1995**	**1996**	**1997**
1,329	1,262	1,334	1,252	1,136

SUMMARY

The Gasconade River Basin upstream from Jerome, Missouri, is the study area for this report, and is referred to as the upper Gasconade River Basin. It encompasses 2,836 square miles of predominately rural countryside in south-central Missouri, and contains the 64,000-acre Fort Leonard Wood Military Reservation (FLWMR). There is concern that chemicals and petroleum products used and disposed of at the FLWMR could migrate into the FLWMR public water-supply wells or domestic and other public water-supply wells. The U.S. Geological Survey (USGS) in cooperation with the Directorate of Public Works, Environmental Division (DPW-ED), FLWMR, began a study in 1998 of the geohydrologic framework, ground-water hydrology, and water use in the upper Gasconade River Basin to improve the understanding of the contributing areas of recharge to water-supply wells at and in the vicinity of the FLWMR.

Regional geohydrologic units in the study area are, in order of increasing depth: the Springfield Plateau aquifer, Ozark confining unit, Ozark aquifer, St. Francois confining unit, St. Francois aquifer, and Basement confining unit. The Ozark aquifer is the principal source of ground water in the study area and is the focus of this report. The Ozark aquifer is composed of, in order of increasing age: the Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite. The underlying St. Francois confining unit is composed of the Derby-Doe Run Dolomite and the Davis Formation.

Early Ordovician-age dolostones and sandstones form the bedrock surface throughout most of the study area. Sedimentary strata are nearly horizontal, 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 study area, with younger strata underlying the uplands and older strata exposed along streams. The study area is cut by numerous faults, most of which trend generally northwest-southeast. The Fort Leonard Wood Anticline trends generally north-south through the northern part of the FLWMR.

The Upper Cambrian-age Potosi Dolomite is a massive bedded, vuggy dolostone with quartz druse that is associated with chert. The large porosity and permeability of the formation causes it to be a good source of water to wells, and it is utilized by many public water-supply wells in the study area. The Potosi Dolomite is between 200 and 400 ft (feet) thick throughout most of the study area. The Upper Cambrian-age Eminence Dolomite is a massive bedded dolostone with small amounts of chert and quartz druse and is less vuggy than the underlying Potosi Dolomite or the overlying Gasconade Dolomite. The Eminence Dolomite is 200 to 400 ft thick throughout most of the study area.

The Canadian Series Ordovician-age Gasconade Dolomite overlies the Eminence Dolomite. It is the oldest formation to crop out in the study area and forms the bedrock surface along the major streams and their tributaries. 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. The lower Gasconade Dolomite generally is medium to thin bedded and 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. Most caves and large springs in and around the FLWMR are in the upper Gasconade Dolomite. The pre-erosional thickness of the Gasconade Dolomite generally decreases from greater than 400 ft in the southwestern part of the study area to less than 300 ft in the northeastern part of the study area.

The Canadian Series Ordovician-age Roubidoux Formation overlies the Gasconade Dolomite. It forms the bedrock surface throughout a large part of the study area, including a large part of the FLWMR. The lithology of the Roubidoux Formation ranges from dolostone to cherty dolostone to sandy dolostone to sandstone. The amount of sandstone ranges throughout the study area from less than 5 percent west of the FLWMR to more than 40 percent in the southern part of the study area and is about 10 to 25 percent throughout most of the FLWMR. Although bedding normally is nearly horizontal, numerous irregular small folds occur in sandstone beds at the FLWMR and are interpreted to be the result of collapse in response to dissolution of interbedded or underlying dolostone. Most of the observed sinkholes in the upland areas of the FLWMR are formed in the Roubidoux Formation. The pre-erosional thickness of the Roubidoux Formation ranges from 100 to 200 ft throughout a large part of the study area.

The Canadian Series Ordovician-age Jefferson City Dolomite and Cotter Dolomite overlie the Roubidoux Formation. These two formations underlie the upland areas in the approximately southern two-thirds of the study area and in a few upland areas in the northern one-third of the study area. The Jefferson City Dolomite is the youngest formation at the FLWMR and underlies the central upland ridge that trends north-south through the FLWMR. 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. The Cotter Dolomite is medium to thin bedded medium to finely crystalline cherty and non-cherty dolostone. The combined thickness of the Jefferson City and Cotter Dolomites ranges from 0 to more than 400 ft.

The Jefferson City Dolomite and Cotter Dolomite generally are less permeable than the stratigraphically lower rocks of the Ozark aquifer and yield little water to wells. Wells completed in the Roubidoux Formation and Gasconade Dolomite commonly yield from several tens to several hundred gallons per minute of water. The Eminence Dolomite may form a weak hydrologic barrier to vertical ground-water flow between the overlying Gasconade Dolomite and the underlying Potosi Dolomite. The Potosi Dolomite is the most permeable formation in the Ozark aquifer and can yield from several hundred to 1,000 gallons per minute of water.

Low water-table gradients along the right bank of the Gasconade River in the area between the mouths of Osage Fork and Roubidoux Creek and along the left bank of the Big Piney River between Miller Spring and the mouth of the Big Piney River indicate high permeability karst terrain. Ground-water levels may be as deep as 300 ft below the land surface beneath upland areas where karst features are prevalent. Generally, the water table occurs in younger formations in the southern part of the study area, and occurs in progressively older formations to the north. The Jefferson City Dolomite and possibly the Cotter Dolomite are saturated in the southern part of the study area. The Roubidoux Formation is fully saturated throughout most of the southern one-third of the study area, and the Gasconade Dolomite is fully saturated in most of the southern one-half of the study area. Although the Jefferson City Dolomite and the Roubidoux Formation are the uppermost bedrock formations in the upland areas of the FLWMR, the water table generally is deep enough to occur in the underlying Gasconade Dolomite throughout most of the FLWMR.

A composite stream discharge was determined for streams by scaling discharge measurements made in September 1995 and September 1998 to measurements made in August 1999. The composite discharge of the Gasconade River at Jerome was 552 ft^3/s (cubic feet per second), and discharges of main tributaries to the Gasconade River were 86.1 ft^3/s at the mouth of the Little Piney Creek, 246 ft^3/s at the mouth of the Big Piney River, 25.9 ft^3/s at the mouth of Roubidoux Creek, and 34.7 ft^3/s at the mouth of Osage Fork. Of the 552 ft^3/s discharged at Jerome, 393 ft^3/s were supplied by the four main tributaries of the Gasconade River and 159 ft^3/s were derived from the Gasconade River and its smaller tributaries. Discharge from springs represented 56 percent (311 ft^3/s) of the 552 ft^3/s total discharge from the upper Gasconade River Basin at Jerome, 27 percent (23.3 ft^3/s) of the discharge of the Little Piney Creek, 54 percent (133 ft^3/s) of the discharge of the Big Piney River, 92 percent (23.8 ft^3/s) of the discharge of Roubidoux Creek, and 49 percent (17.1 ft^3/s) of the discharge of Osage Fork. Spring discharge also represented 72 percent (114 ft^3/s) of the 159 ft^3/s of discharge derived from the Gasconade River and its smaller tributaries.

Except for water withdrawn from the Big Piney River for use at the FLWMR, all water used in the study area is ground water. Annual pumpage from all public water-supply wells in the study area from 1993 through 1997 ranged from 1,820 Mgal [million gallons; an average daily rate of 4.99 Mgal/d (million gallons per day)] in 1993 to 2,030 Mgal (an average daily rate of 5.56 Mgal/d) in 1997. The daily pumping rate from domestic wells in the study area is estimated at about 4

Mgal/d. The average daily pumping rate for all wells in the study area from 1993 through 1997 is thus estimated to range from 8.99 Mgal/d in 1993 to 9.56 Mgal/d in 1997. Most of the water used at the FLWMR is supplied from a pumping station on the Big Piney River. A smaller quantity of water is supplied from eight (as of 1998) public water-supply wells at the FLWMR. Most of the ground water used at the FLWMR is pumped from the Indiana Avenue well. From 1993 through 1997, the Indiana Avenue well supplied from 1.6 percent (in 1994) to 2.9 percent (in 1997) of the total water use at the FLWMR. Annual pumpage from the Big Piney River during the same period ranged from 1,136 Mgal (an average of 3.11 Mgal/d) in 1997 to 1,334 Mgal (an average of 3.65 Mgal/d) in 1995. Total water use in the study area ranged from a daily average of about 12.6 Mgal/d (9.12 Mgal/d ground water and 3.46 Mgal/d surface water) in 1994 to a daily average of about 12.8 Mgal/d (9.18 Mgal/d ground water and 3.65 Mgal/d surface water) in 1995 during the same period. Surface-water pumpage by the FLWMR as a percentage of total water use in the study area ranged from about 24.5 percent in 1997 to about 28.8 percent in 1993.

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