Stratigraphy and Vertical Hydraulic Conductivity of the St. Francois Confining Unit in the Viburnum Trend and Evaluation of the Unit in the Viburnum Trend and Exploration Areas, Southeastern Missouri

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Abstract

The confining ability of the St. Francois confining unit (Derby-Doerun Dolomite and Davis Formation) was evaluated in ten townships (T. 31–35 N. and R. 01–02 W.) along the Viburnum Trend of southeastern Missouri. Vertical hydraulic conductivity data were compared to similar data collected during two previous studies 20 miles south of the Viburnum Trend, in two lead-zinc exploration areas that may be a southern extension of the Viburnum Trend. The surficial Ozark aquifer is the primary source of water for domestic and public-water supplies and major springs in southern Missouri. The St. Francois confining unit lies beneath the Ozark aquifer and impedes the movement of water between the Ozark aquifer and the underlying St. Francois aquifer (composed of the Bonneterre Formation and Lamotte Sandstone). The Bonneterre Formation is the primary host formation for lead-zinc ore deposits of the Viburnum Trend and potential host formation in the exploration areas.

For most of the more than 40 years the mines have been in operation along the Viburnum Trend, about 27 million gallons per day were being pumped from the St. Francois aquifer for mine dewatering. Previous studies conducted along the Viburnum Trend have concluded that no large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity. Because of similar geology, stratigraphy, and depositional environment between the Viburnum Trend and the exploration areas, the Viburnum Trend may be used as a pertinent, full-scale model to study and assess how mining may affect the exploration areas.

Along the Viburnum Trend, the St. Francois confining unit is a complex series of dolostones, limestones, and shales that generally is 230 to 280 feet thick with a net shale thickness ranging from less than 25 to greater than 100 feet with the thickness increasing toward the west. Vertical hydraulic conductivity values determined from laboratory permeability tests were used to represent the St. Francois confining unit along the Viburnum Trend. The Derby-Doerun Dolomite and Davis Formation are statistically similar, but the Davis Formation would be the more hydraulically restrictive medium. The shale and carbonate values were statistically different. The median vertical hydraulic conductivity value for the shale samples was 62 times less than the carbonate samples. Consequently, the net shale thickness of the confining unit along the Viburnum Trend significantly affects the effective vertical hydraulic conductivity. As the percent of shale increases in a given horizon, the vertical hydraulic conductivity decreases.

The range of effective vertical hydraulic conductivity for the confining unit in the Viburnum Trend was estimated to be a minimum of 2 x 10^{-13} ft/s (foot per second) and a maximum of 3 x 10^{-12} ft/s. These vertical hydraulic conductivity

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values are considered small and verify conclusions of previous studies that the confining unit effectively impedes the flow of ground water between the Ozark aquifer and the St. Francois aquifer along the Viburnum Trend.

Previously-collected vertical hydraulic conductivity data for the two exploration areas from two earlier studies were combined with the data collected along the Viburnum Trend. The nonparametric Kruskal-Wallis statistical test shows the vertical hydraulic conductivity of the St. Francois confining unit along the Viburnum Trend, and west and east exploration areas are statistically different. The vertical hydraulic conductivity values generally are the largest in the Viburnum Trend and are smallest in the west exploration area. The statistical differences in these values do not appear to be attributed strictly to either the Derby-Doerun Dolomite or Davis Formation, but instead they are caused by the differences in the carbonate vertical hydraulic conductivity values at the three locations.

The calculated effective vertical hydraulic conductivity range for the St. Francois confining unit at each location is: 2×10^{-13} to 3×10^{-12} ft/s for the Viburnum Trend; 3×10^{-14} (minimum reporting level) to 1×10^{-12} ft/s for the west exploration area; and 3×10^{-13} to 2×10^{-12} ft/s for the east exploration area. Based on the calculated vertical hydraulic conductivity ranges, the St. Francois confining unit is considered ‘tight’ at all locations. However, in relation to each other, the west exploration area is the tightest, and the most conductive area is the Viburnum Trend. No apparent large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity in the Viburnum Trend. Therefore, using similar mining practices as those along the Viburnum Trend, no large cones of depression in the Ozark aquifer would be expected in the exploration areas, unless preferred-path secondary permeability has developed along faults or fractures or resulted from exploration activities.

INTRODUCTION

Initial ore production from the first Viburnum area mine began in the 1960’s. Lead is the primary element extracted, but substantial amounts of zinc, copper, and silver also are mined. Other major ore bodies were discovered by 1964 along a 30-mi (mile) linear zone that is now referred to as the Viburnum Trend (Wharton, 1979; fig. 1). By 1970, two new smelters and five new mine-mill complexes were in operation. From the early 1970’s into the early 1990’s, lead and zinc production from the Viburnum Trend reached then record highs. Throughout the late 1970’s, the area was the largest lead producing area in the world, accounting for more than 15 percent of the total recorded world output.

The Bonneterre Formation of Upper Cambrian age is the primary host formation for the lead-zinc ore deposits of the Viburnum Trend, and together with the underlying Lamotte Sandstone forms the carbonate rock (dolostone and limestone) and sandstone St. Francois aquifer (figs. 2 and 3). The formation ranges from about 400 ft (feet) below land surface in the northern part of the Viburnum Trend to about 1,000 ft below land surface in the southern part (fig. 3). The St. Francois confining unit overlies the St. Francois aquifer and consists of dense carbonate and shale of the Derby-Doerun Dolomite and Davis Formation. The confining unit is considered the barrier that confined ascending ore-forming hydrothermal solutions to the Bonneterre Formation. Formations of Upper Cambrian and Lower Ordovician age consisting of the Potosi Dolomite to the Roubidoux Formation are exposed at land surface along the Viburnum Trend and overlie the St. Francois confining unit. These rocks form the Ozark aquifer, the primary source of water for private and public-water supplies and major springs in southern Missouri. The geologic names used in this report follow the nomenclature used by the Missouri Department of Natural Resources, Geological Survey and Resource Assessment Division (GSRAD), formerly known as the Division of Geology and Land Survey.

Mine dewatering before ore extraction is part of normal mine operation. Twenty-six million gallons of water per day were pumped from the St. Francois aquifer in 1971 (Warner and others, 1974) and in 1999 the total pumpage was slightly larger at 27 million gallons per day (Denis Murphy, The Doe Run Company, written commun., 2000). These withdrawal rates from the St. Francois aquifer are typical for the Viburnum Trend and have been occurring for most of the more than 40

years the mines have been in operation. Previous studies conducted along the Viburnum Trend to assess the effects of mine dewatering in the St. Francois aquifer on water levels in the surficial Ozark aquifer have concluded that no large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity. However, some localized leakage of water from the Ozark aquifer into the St. Francois aquifer probably is occurring at mine shafts, ventholes, and inadequately plugged exploration drill holes. Therefore, small areas of drawdown may exist (Warner and others, 1974; Miller and Vandike, 1997; Kleeschulte, 2001).

Fletcher (1974) states that faults along the Viburnum Trend can be grouped into three systems: the Palmer Fault system to the north, which includes the Conway Fault; the Black Fault in the east central part; and the Ellington Fault to the south (fig. 1). The Palmer Fault system forms the northern boundary of the Viburnum Trend and is a group of normal faults. McCracken (1971) describes the fault system as being 45 mi long consisting of one or more parallel faults cutting rocks from the Roubidoux Formation to the Precambrian basement rock. McCracken states the faults are all normal and high-angle with a maximum offset of 1,200 ft on the east side of the fault in Washington County, and offsets decreasing westward to 200 ft in Crawford County. Fletcher interpreted the stratigraphy so offsets did not exceed 150 ft. The Conway Fault was interpreted by Fletcher (1974) to be a left lateral wrench fault with a minor offset. The Black Fault has a displacement of 300 ft and brings the Potosi Dolomite (Ozark aquifer) in contact with the Bonneterre Formation (McCracken, 1971). The fault may extend northwest to connect with (or be cut off by) the Palmer Fault system. The Ellington Fault was interpreted by Fletcher (1974) as a normal fault, with the southern side being downthrown with a maximum offset that does not exceed 50 ft. Pratt (1982) shows a more detailed map than Fletcher (1974) of the faults along the Viburnum Trend; however, for the purposes of this report, a generalized overview of the major faults is sufficient without the multiplicity of minor displacement faults. Based on conversations with several mine geologists who have worked in the Viburnum Trend, they state that based on their experiences, permeability does not increase around the faults. Instead, the confining unit (Davis Formation in particular) is a vertical barrier to ground-water flow and the faults serve as lateral barriers.

From the 1960's to the end of the 1990's, lead and zinc exploration occurred in two exploration areas in the Doniphan/Eleven Point Ranger District of the Mark Twain National Forest (fig. 1). These exploration areas are 20 mi south of the Viburnum Trend, and a possible southern extension of the Trend. The exploration peaked in the late 1970's and early 1980's, resulting in several hundred exploration holes being drilled in the National Forest. The exploration areas lie within a larger region of well-developed karst terrain with an extensive network of solution-enlarged fractures ranging from small channels to large conduits. The two largest springs in Missouri (Big Spring and Greer Spring, fig. 1) are in this area, and discharge from these springs helps sustain flow in two nationally designated streams; the Current River (Ozark National Scenic Riverway) and the Eleven Point River (Eleven Point Wild and Scenic River). The potential for lead-zinc mining in this environmentally sensitive and federally designated scenic area has concerned the Forest Service and the Bureau of Land Management (BLM) in regard to possible effects that mining may have on the water resources of the area. The concerns include but are not limited to the effects that mine dewatering in the St. Francois aquifer may have upon water resources of the surficial Ozark aquifer.

As a result of these concerns, two previous studies (Kleeschulte and Seeger, 2000, 2001) assessed the confining ability of the St. Francois confining unit in the west exploration area and the adjacent property toward Big Spring, referred to in this report as the east exploration area (fig. 1). These studies described the depositional environment and stratigraphy, and quantified the vertical hydraulic conductivity of 94 rock core samples collected from 28 boreholes in the confining unit. Both studies conclude that the vertical hydraulic conductivity of the confining unit is small. The confining unit effectively impedes ground-water flow between the Ozark and St. Francois aquifers, unless preferred-path secondary permeability has developed along faults and fractures that extend through the confining unit.

Mining has been occurring in the Viburnum Trend for more than 40 years with no appreciable drawdown being observed in the Ozark aquifer. Because of the similarity in geology, stratigraphy, and depositional environment between the Viburnum Trend and the exploration areas in the Doniphan/Eleven Point Ranger District of the Mark Twain National Forest, the Viburnum Trend may be used as a pertinent, full-scale model to study and assess how mining may affect aquifers in the exploration areas. To address these needs, the confining ability of the St. Francois confining unit along the Viburnum Trend was quantified and compared with the results from the exploration areas to evaluate potential mine dewatering effects in the exploration areas.

Purpose and Scope

This report describes the stratigraphy and vertical hydraulic conductivity of the St. Francois confining unit in a 400 mi^2 (square mile) study area of 10 townships (T. 31–35 N. and R. 01–02 W.; fig. 1) along the Viburnum Trend in Crawford, Iron, Washington, Dent, Reynolds, and Shannon Counties of southeastern Missouri. The vertical hydraulic conductivity data for the study area also was evaluated by comparing it to the vertical hydraulic conductivity data collected in the west and east exploration areas by Kleeschulte and Seeger (2000, 2001). This was accomplished by evaluating borehole core log data and examining available rock core samples. These stratigraphic data were used to prepare maps that depict the altitude of the top of the Derby-Doerun Dolomite and Davis Formation of the St. Francois confining unit, and the Bonneterre Formation (base of the Davis Formation) of the St. Francois aquifer. Maps showing the total thickness and net shale thickness (cumulative shale thicknesses) of the confining unit also were drawn. Forty rock core samples from the St. Francois confining unit and the St. Francois aquifer were collected and sent for laboratory permeability and porosity determination as part of this study. The vertical hydraulic conductivity of the rock core samples was calculated from the laboratory permeability values. These data were added to an existing vertical hydraulic conductivity and porosity data base for the St. Francois confining unit and St. Francois aquifer created from rock core samples analyzed from the exploration areas and the Viburnum Trend.

Exploration Borehole Data

Several thousand exploration holes have been drilled along the Viburnum Trend to delineate ore bodies. The BLM, GSRAD, and The Doe Run Company have copies of many of the core logs from the various mining companies that have explored or mined in the area. The BLM receives copies of core logs from exploration holes drilled on Federal lands, the GSRAD acquired donated copies of logs from several mining companies, and The Doe Run Company owns and operates the active mines in the Viburnum Trend and received core logs from predecessor mining companies. Much of the core log data used in this report came from the public-access core log files at the GSRAD. However, even with these log data, no core log data were available for several areas. Because the Viburnum Trend is an active mining area, the core logs on file at the BLM are classified as confidential and unavailable for viewing. A request was made and granted by The Doe Run Company for permission to examine the core log information for holes located in selected areas where no data were publicly available. Consequently, additional core logs were available for restricted use during the study described in this report.

The core logs provided general site information such as location and land-surface altitude of the borehole, total depth of the borehole, and depths to the top of formations. In some cases, the logs provided detailed lithologic descriptions for the interval from the base of the Potosi Dolomite into the Lamotte Sandstone or Precambrian basement, typically an interval from 500 to 600 ft. The core logs and available core samples that were examined as part of this study were the primary source of the stratigraphic data contained in this report. The analyzed rock core samples were obtained from The Doe Run Company and the GSRAD.

Borehole locations reported on the core logs were defined to the nearest quarter-quarter-quarter section or as distance from the north/south and east/west section line. Land-surface altitudes were typically determined at the time of drilling using altimeters or topographic maps; however, occasionally the site was surveyed and altitudes were reported to the nearest foot. The reported altitudes were verified during this study using U.S. Geological Survey 7.5-minute topographic maps that generally had contour intervals of 20 ft; therefore, the land-surface altitudes are accurate to about 10 ft (one-half the contour interval). In a few instances, the reported land-surface altitudes on the core logs did not agree with the land surface shown on the topographic maps for the given location. When this situation occurred, the altitude shown on the topographic map at the borehole location was used.

In this report, the locations of exploration boreholes (tables 1 and 2, at the back of this report) are shown by latitude and longitude coordinates and by the local well number, which follows the General Land Office coordinate system (fig. 4). According to this system, the first three sets of numbers representing a borehole location designate township, range, and section. The letters that follow indicate quarter section, quarter-quarter section, and quarter-quarter-quarter section. The quarter sections are represented by letters A, B, C, and D in counterclockwise order, starting in the northeastern quadrant. Occasionally, the borehole location was described as being in the center of a particular quarter section or in the northern, southern, eastern, or western one-half of a quarter section. In these cases, abbreviations (Cr for center; N2, S2, E2, or W2 for northern, southern, eastern, or western one-half of a quarter section) were used to convey this meaning.

Considerable interpretation was necessary to identify stratigraphic boundaries in some of the core logs and core samples because of variable stratigraphic nomenclature applied by the different mining companies and the different criteria for assigning the contacts between these formations. The conformable and transitional contacts that exist between all the formations from the Potosi Dolomite to the Bonneterre Formations also make it difficult to distinguish the contacts between formations. This may account for some of the irregularity shown on structure maps in this report.

Geohydrologic Units

Delineation of geohydrologic units is based on hydraulic properties and the hydrologic relation of each unit to adjacent geohydrologic units at a regional scale. The terms aquifer and confining unit, as defined regionally, may not adequately describe the hydraulic properties of a sequence of rocks locally because of the variation in water-yielding capability of the same rock sequence from one area to another. Although this report is concerned with the St. Francois confining unit, the geohydrologic units from the Precambrian basement through the surficial aquifer will be briefly discussed so that the entire geologic framework of the area can be described and the relation of one unit to another shown.

The lowermost geohydrologic unit in the study area is the Basement confining unit of Precambrian age (figs. 2 and 3), which is predominantly granite and rhyolite. Imes (1989) states that this confining unit is virtually impermeable. In areas where extensive faulting and fracturing has occurred, Imes reports the Basement confining unit can yield small quantities of water. In areas where the unit crops out, well yields are less than 10 gallons per minute. The surface of the Basement confining unit can be highly irregular. Isolated Precambrian basement knobs mapped in the subsurface of the study area and adjacent property by Fletcher (1974) indicate these knobs may extend 600 to 1,000 ft above the surrounding basement rock.

The St. Francois aquifer (Imes, 1990a) overlies the Basement confining unit and consists of the Lamotte Sandstone and the Bonneterre Formation (figs. 2 and 3). In areas of southeastern Missouri near the St. Francois Mountains (about 10 mi east of the study area; fig. 1) where the St. Francois aquifer is close to land surface, the aquifer yields adequate supplies of water for domestic and small capacity public-supply wells. The thickness of the St. Francois aquifer can vary considerably because of the irregular surface of the underlying basement rocks.

The Davis Formation and the Derby-Doerun Dolomite form the St. Francois confining unit (Imes, 1990b) that overlies the St. Francois aquifer (figs. 2 and 3). Imes and Emmett (1994) state in their regional study of the Ozark Plateaus aquifer system that substantial secondary porosity and permeability have not developed regionally in the St. Francois confining unit. The fine-grained nature of the formations indicates they have minimal permeability, even in areas containing little or no shale. Regionally, the physical and hydraulic characteristics of the unit generally impede the movement of ground water between the overlying Ozark aquifer and the underlying St. Francois aquifer (Imes and Emmett, 1994). This report will attempt to verify and quantify the general statement made by Imes and Emmett that the confining unit impedes the movement of ground water between aquifers locally along the Viburnum Trend.

The Ozark aquifer (Imes, 1990c) is the uppermost geohydrologic unit in the study area and consists of rocks from the base of the Potosi Dolomite to the top of the Roubidoux Formation (figs. 2 and 3). This predominantly carbonate aquifer is dolostone with some sandstone, and is the most widely used aquifer in southern Missouri. In the study area, ground water in the aquifer normally occurs under water-table conditions.

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STRATIGRAPHY

The entire Upper Cambrian Series, of which the St. Francois confining unit is a part, represents a series of transgressions and regressions by ancient seas. The repeated advancing and subsequent retreat of the sea over land areas created a complex series of dolostones, limestones, shales, sandstones, and siltstones. The stratigraphic sequence is controlled, in large part, by pre-Upper Cambrian faulting and erosion of the igneous Precambrian basement, and by faulting during the deposition of Upper Cambrian sediments. Rift-related faulting created a series of mountains and basins; erosion of Precambrian basement knobs provided detrital material for alluvial fan deposits and fluvial braided streams (lowermost Upper Cambrian). A transgression with continued deposition of clastic material led to the accumulation of the marine Lamotte Sandstone. Inundation and development of an intrashelf basin (lowermost Bonneterre Formation) followed; deposition of fan deltas was still active during the earliest stages (Lamotte Sandstone-Bonneterre Formation transition). Intrashelf basin development was followed by a cycle of regression and transgression. The shelf eventually filled with detrital material to form a ramp (Sullivan Siltstone member) from the land areas to the depositional basins, but was again inundated during Whetstone Creek member deposition (fig. 2). The Davis Formation-Whetstone Creek member contact indicates abrupt intrashelf basin development, followed by repeated shallowing and flooding, leading to the deposition of the rest of the Upper Cambrian section (Derby-Doerun Dolomite, Potosi Dolomite, and Eminence Dolomite; Palmer, 1989, 1991). Periods of epigenetic dolomitization of paleokarsted limestones developed whiterock horizons. “Whiterock” is a term that originated in the southeast Missouri lead district to describe coarse-crystalline white, light gray, or light brown dolostones that are the product of epigenetic dolomitization of reddened-paleokarsted limestones. Whiterock generally does not have apparent preserved primary depositional fabrics; however, occasional ghost textures are suggestive of deposition in an extremely shallow platform interior (Howe, 1968). Carbonate rocks are described in this section using the Dunham classification system (Dunham, 1962).

The St. Francois confining unit is a complex series of dolostones, limestones, and shales. Usually, the shale content of a geohydrologic unit is the primary indicator of the confining unit effectiveness as a flow barrier. As the shale content of a unit increases, the hydraulic conductivity of the unit decreases, inhibiting the flow of water through the unit. Because of this, the net shale thickness of the Derby-Doerun Dolomite and the Davis Formation was determined for this report at boreholes where either detailed lithologic descriptions were provided or where core samples were available for inspection. The detailed descriptions typically divided the cored section into small intervals in which the lithology had similar characteristics. The rock was described as to color, texture, grain size, physical features (stromatolites, staining, and vugs), and percent of each rock type (shale, dolostone, and limestone). The net shale thickness was calculated by multiplying the reported percent shale in an interval by the thickness of the described interval. The net shale thicknesses of all the intervals were summed to determine the total net shale thickness for the rock core. If borehole core samples from the St. Francois confining unit were available for inspection, these samples were relogged for net shale thickness determination.

There were 315 borehole logs (fig. 5, tables 1 and 2) used to describe the stratigraphy for this study. Of this total, 175 boreholes are in the study area (table 1); the remainder are on adjacent property and are considered supplemental stratigraphic data (table 2) used to refine contours near the study area boundaries. Faults shown on the structure maps were modified from Fletcher (1974). Of the available core logs in the study area, 173 logs contained stratigraphic information for the St. Francois confining unit. The altitudes used in defining the geologic formation tops were determined by subtracting the depth of the formation top reported on the core log from the recorded land-surface altitude. The lithologic summaries that are presented in this section are necessarily brief and focused on lithologic properties that potentially affect vertical hydraulic conductivity.

Davis Formation

The Davis Formation is the basal part of large-scale shallowing-upward sequences. Horizontal burrows are indicative of slow periodic deposition in a marine subtidal setting during early stages of shelf flooding. Intraclast conglomerate beds can be interpreted as storm-generated mass-flow deposits that presumably moved down slopes of a few degrees or less. The intrashelf basin facies tends to thin towards the geographic center of the deeper depositional basins where shale is more abundant. An increase in the volume of carbonate beds indicates proximity to the intrashelf basin edge. Oolites in some carbonate layers are likely grain flows (Palmer, 1989, 1991).

The Davis Formation is an intrashelf basin facies consisting of shales interbedded with shaly limestones, clean limestones, and local dolostones, with both shale- and carbonate-dominant sequences. In the basal to lower parts of some Davis Formation sections, shales are interbedded with thin glauconitic fine-grained quartzose sandstones. Shales generally are light to dark green, with some gray to dark gray beds. The entire formation contains as much as 47 percent or greater shale content. Carbonate-filled burrows comprise the only carbonate in some shale layers. Davis Formation carbonates primarily are tan to gray dolomitic mudstone and packstone, or grainstone. They are fine to medium grained and fine to medium crystalline. The carbonates contain pellets, fossil fragments, oolites, glauconite, and few stromatolites. Occasional intraclast conglomerates are noted and scattered arkosic or porphyry conglomeratic layers are present.

The core log data (tables 1 and 2) were used to draw the structural contour maps developed for the base (top of Bonneterre Formation; fig. 6) and top (fig. 7) of the Davis Formation. The Davis Formation base is coincident with the base of the St. Francois confining unit and the top of the Bonneterre Formation. The Davis Formation (and St. Francois confining unit) locally is absent in the St. Francois Mountains region, and no attempt was made to delineate where the confining unit is absent. The formation regionally tends to dip radially outward from the mountain area. Faults were considered when contouring the structural surface; however, because of few data in the area of the Conway Fault, the effect of the fault (fig. 1) is not noticeable on the altitude of the Davis Formation base. However, the Palmer Fault system shows an appreciable offset in several boreholes located in T. 35 N., R. 01 W. and T. 36 N., R. 01 E. (figs. 6 and 7), but the data did not indicate vertical offsets in T. 35 N., R. 02 W. A considerable offset to the base of the Davis Formation also is observed to the east of the Black Fault (fig. 6).

The altitude of the base of the Davis Formation (top of Bonneterre Formation; fig. 6) ranges from more than 900 ft above National Geodetic Vertical Datum of 1929 (NGVD 29) in the northeastern part of the study area to nearly 100 ft below NGVD 29 in the southwestern part. This map is based on 147 boreholes with Bonneterre Formation data (table 1). In the extreme northern part of the study area, the structure contours show the dip of the base of the Davis Formation is predominately to the west. The dip gradually changes to

the south in the central part of the area, and this trend continues through the southern extent of the area. Ninety-three data points located outside of the study area (table 2) were used to contour near the study area boundary.

Large knobs that occur on the Precambrian basement surface in the study area can also express themselves in the overlying strata. Mappable structural features that appear as subsurface ridges or highs can be seen at the base of the Davis Formation in T. 32 N. to T. 34 N. along the border between R. 01 W. and R. 02 W. and in T. 35 N., R. 01 W. (fig. 6). These features may be formed by differential subsidence between the thinner sediments on top of Precambrian knobs and ridges and the thicker sediments on the adjacent flanks (R.W. Harrison, U.S. Geological Survey, oral commun., 1996).

The altitude of the top of the Davis Formation (fig. 7) in the study area ranges from more than 900 ft above NGVD 29 in the northeastern part to less than 100 ft above NGVD 29 in the southern part. The altitudes are based on 159 borehole logs, which identified the depth of the top of the Davis Formation within the study area (table 1) and 83 supplemental logs on adjacent property (table 2). The dip of the formation top is similar to that for the base. In the northern part of the study area (T. 34–35 N.), the generally westward dip is masked by several structural highs that take the form of either isolated highs or ridges that correspond well with Precambrian knobs mapped deeper in the subsurface by Fletcher (1974). The dip gradually trends to the south in the central part of the study area. The effects of the Black Fault (fig. 1) on the structural contours are not as apparent at the top of the formation as at the base, except in the structural low adjacent to the fault shown in T. 33 N., R. 01 E. The offset of the formation top is apparent at localized areas along the Palmer Fault system and the Ellington Fault.

More localized features appear to be present on the structural map showing the top of the Davis Formation than on the formation base. These features are small, isolated highs or larger features such as ridges. Structural lows also appear at several locations with the deepest adjacent to the Black Fault.

Derby-Doerun Dolomite

The Derby-Doerun Dolomite represents a pair of carbonate ramp cycles that include ribbon rock carbonates (succession of thin layers of rocks with different composition) that grade up-section to sequences of thinner mudstone and thicker grainstone or packstone beds. Mudstone-grainstone sequences and local conglomerates support this depositional hypothesis. Stromatolite zones indicate isolated buildups within the section. Intraclast conglomerate beds (storm-generated mass-flow deposits) moved down slopes of only a few degrees. The basal shaly sequence represents a transition with the Davis Formation (Palmer, 1989, 1991).

The Derby-Doerun Dolomite in the study area is composed of light gray to gray or light tan to brown mudstones, grainstones, and mudstone-matrix stromatolite boundstones, with minor wackestones. Dolostones are fine to medium grained and fine to coarse crystalline. Whiterock and mottled beds are present. The dolostones contain fossil fragments and minor glauconite. Scattered thin black to dark gray and green shales are present. Shale content and thickness increase near the contact with the Davis Formation.

The altitude of the top of the Derby-Doerun Dolomite (fig. 8), which also is the top of the St. Francois confining unit, ranges from more than 1,000 ft above NGVD 29 in the northeastern part of the study area to about 200 ft above NGVD 29 in the southwestern part. These altitudes are based on 151 borehole logs in the study area with Derby-Doerun Dolomite data (table 1) and 90 supplemental borehole logs on adjacent property (table 2). The structure contours show a similar pattern as the contours for the top of the Davis Formation. Several large highs or ridges in the northern part of the study area (T. 34–35 N.) mask the general westward dip of the formation. The dip gradually trends to the south in the central part of the study area. One prominent difference between the top of the Derby-Doerun Dolomite and top of the Davis Formation is the absence of the structural low feature in T. 33 N., R. 01 E. (fig. 8), which appears to be filled by the Derby-Doerun Dolomite.

Thickness and Net Shale Thickness of the St. Francois Confining Unit

Based on logs from 123 boreholes that completely penetrate the St. Francois confining unit in the study area (table 1) and 49 supplemental logs in adjacent property (table 2), the thickness of the confining unit ranges from less than 200 to more than 350 ft in the study area (fig. 9). Local areas of thickening or thinning occur, but in general the unit is from 230 to 280 ft thick. The confining unit thickens in the western part of the

study area, especially in the area west of the Conway Fault.

The net shale thickness map (fig. 10) is for the rock sequence from the top of the Derby-Doerun Dolomite to the base of a persistent shale unit located at the base of the Whetstone Creek Member in the upper Bonneterre Formation. This shale unit is referred to locally as the False Davis (fig. 2). This method to determine the net shale thickness is consistent with that used to determine the net shale thickness reported by Kleeschulte and Seeger (2000, 2001). Fourteen net shale thickness values were calculated solely from detailed borehole core log descriptions (table 1) and 22 values were determined by relogging available core samples at the GSRAD McCracken Core Library. Based on the 36 data values, the net shale thickness ranges from less than 25 to greater than 100 ft, with the thickness increasing to the west. This increase is consistent with the current understanding of the geologic environment at the time these formations were deposited. The deeper part of the basin, west of the Viburnum Trend, would have been a low-energy setting that would have allowed the deposition of silts and clays and the formation of shale deposits.

VERTICAL HYDRAULIC CONDUCTIVITY

Shale typically has a smaller vertical hydraulic conductivity than carbonate rocks (Freeze and Cherry, 1979). By determining the thickness of the confining unit, estimating the net shale thickness of the confining unit, and measuring the vertical hydraulic conductivity of the various rock types present in the unit, the effective vertical hydraulic conductivity of the confining unit can be estimated. The permeability of rock core samples from the study area was measured in a laboratory and used to calculate the confining unit vertical hydraulic conductivity. Permeability measures the ease with which a porous medium (rock core) can transmit a liquid under a pressure gradient. It is a function of the medium alone and is not dependent on the fluid used or the force field causing the movement of the liquid (Lohman and others, 1972). Hydraulic conductivity is a measure of the ease with which a specific fluid can be transmitted through a porous medium, and is a function of the medium and of the density and viscosity of the fluid being transmitted.

Representing 250 ft of rock core with only 2 or 3 samples from each borehole has inherent deficiencies. Samples chosen for laboratory analysis are representative of typical formation lithologies in the sampled borehole. While fractures were not common in the available cores, they occasionally were observed. No rock core samples were sent to the laboratory for analysis that had observed fractures or were broken. This decision could skew the vertical hydraulic conductivity data set, but was necessary to ensure the samples would properly seal in the instrument used to measure permeability.

Methodology

Effective vertical permeability and porosity were determined in the laboratory from rock core samples using methods described by the American Petroleum Institute (1998). Vertical hydraulic conductivity and effective vertical hydraulic conductivity were calculated. Statistical techniques were used to compare vertical hydraulic conductivity among formations and rock types at three locations (Viburnum Trend, and the west and east exploration areas).

The laboratory simulated the in-situ conditions at the depth from which the core samples were collected. The permeability of a medium is inversely proportional to the net confining stresses to which the sample is subjected. A net confining stress [calculated using a pressure gradient of 0.758 pounds per square inch (psi) per foot depth] was applied to each core sample during the permeability analysis (Jim Seale, Core Laboratories, Inc., written commun., 1999). The fluid used during the permeability tests was water prepared to chemically imitate water from the city of Viburnum (fig. 1) public-water supply, which pumps water from an abandoned lead mine in the Bonneterre Formation. The vertical hydraulic conductivity of each sample was, in essence, directly measured because the laboratory water had similar density and viscosity properties as water that flows through the confining unit in the study area.

The core samples were prepared for analysis by cutting each sample to a right-angle cylinder (using air as the bit lubricant), extracting any precipitated salt with methanol, then oven drying the sample for 24 hours at a temperature of 240 degrees Fahrenheit. The bulk volumes of the samples were determined by fluid displacement (Archimedes' principle). Dry weights were recorded and the grain densities were calculated. Helium porosity (American Petroleum Institute, 1998) of the rock core at room conditions was obtained by

measuring grain volume using Boyle's Law (Jim Seale, written commun., 1999).

The core samples were evacuated and pressure saturated at 1,000 psi with the transmitted fluid. Saturations were verified gravimetrically upon removal from the saturation cell. The core samples were then placed in individual core holders, and the calculated net confining stress was applied. The differential flow pressure, time, and water volumes produced at room temperature were recorded. If the permeability was less than the minimum reporting level (1 x 10^{-9} darcy), the test ended after 48 hours. The effective vertical permeability of the rock core was calculated using the following equation (Jim Seale, written commun., 1999):

$$k = \frac{Q\mu L}{A(Pu - Pd)} , \qquad (1)$$

where k = effective permeability, in darcies (1 darcy = 9.87 x 10^{-9} centimeter squared);

Q = flow rate, in cubic centimeters per second;

μ = fluid viscosity, in centipoise (1 centipoise = 0.01 gram per centimeter-second);

L = core length, in centimeters;

A = core area, in square centimeters;

Pu = upgradient pressure, in atmospheres (1 atmosphere = 14.7 pounds per square inch); and

Pd = downgradient pressure, in atmospheres.

Hydraulic conductivity is related to permeability by (American Petroleum Institute, 1998):

$$K = \frac{k\rho g}{\mu} , \qquad (2)$$

where K = hydraulic conductivity, in centimeters per second;

k = effective permeability, in darcies;

ρ = mass density of the fluid, in grams per cubic centimeters;

g = acceleration of gravity, in centimeters per second squared; and

μ = fluid viscosity, in centipoise.

After substitution, the conversion of effective permeability in darcies to hydraulic conductivity in foot per second becomes:

$$K = (3.17) \times 10^{-5} k . \qquad (3)$$

The effective vertical hydraulic conductivity of the confining unit was calculated using the expression for two rock types in series having different vertical hydraulic conductivities:

$$\frac{d_t}{K_t} = \frac{d_1}{K_1} + \frac{d_2}{K_2} , \qquad (4)$$

where d_t = total thickness of the confining unit, in feet;

d_1, d_2 = thickness of rock type 1 and rock type 2, in feet;

K_t = effective vertical hydraulic conductivity of the confining unit, in foot per second; and

K_1, K_2 = vertical hydraulic conductivity of rock type 1 and rock type 2, in foot per second.

The computer software SYSTAT (SYSTAT Software Inc., 2002) was used for statistical hypothesis tests, summary statistics, and the preparation of boxplots. A level of significance (α-value) below 0.05 caused rejection of the null hypothesis that states the vertical hydraulic conductivity of the data sets being compared are equal. The "attained significance level" (p-value) is a probability value determined from the data (Helsel and Hirsch, 1995). It measures the "believability" of the null hypothesis. The larger the p-value, the more likely is the observed test statistic when the null hypothesis is true and the weaker the evidence to reject the null hypothesis. Boxplots using a logarithmic scale were used to graphically present the vertical hydraulic conductivity data.

Evaluation of the St. Francois Confining Unit along the Viburnum Trend

A total of 40 rock core samples from 18 spatially distributed boreholes were sent to the laboratory for vertical hydraulic conductivity and porosity determination for this report (fig. 5). Thirty-eight rock core samples were from 16 boreholes along the Viburnum Trend and the other two samples were duplicate Derby-Doerun Dolomite samples from the western exploration area analyzed during previous studies (Kleeschulte and Seeger, 2000, 2001). One of the 38 core samples from the Viburnum Trend also was a duplicate Derby-Doerun Dolomite sample that was analyzed by Kleeschulte and Seeger (2000). Data from the 3 duplicate samples were used for quality control and assurance.

Thirty-seven vertical hydraulic conductivity values (one core sample deteriorated in the saturation chamber before the vertical hydraulic conductivity could be determined) and 38 porosity values determined for this report were added to an existing data base for the St. Francois confining unit and St. Francois aquifer. This existing data base already included vertical hydraulic conductivity and porosity values from 94 rock core samples from 28 boreholes in the exploration areas (fig. 1; table 3, at the back of this report) and 24 rock core samples from 5 boreholes along the Viburnum Trend that were analyzed during previous studies (fig. 1; Kleeschulte and Seeger, 2000, 2001).

Combining the previously collected and new vertical hydraulic conductivity data changed the spatial distribution that was trying to be maintained. Nineteen of the 24 previously collected vertical hydraulic conductivity and porosity values from the Viburnum Trend (6 Derby-Doerun Dolomite and 13 Davis Formation values) and one duplicate Derby-Doerun Dolomite sample analyzed for this report were from boreholes in T. 31 N., R. 02 W. (fig. 1). This heavily biased the number of samples from this one township. To make the data set more spatially representative, the data from T. 31 N., R. 02 W. were combined, and only the median vertical hydraulic conductivity value for the Derby-Doerun Dolomite and the median vertical hydraulic conductivity value for the Davis Formation were used to represent the formations in that area. The same approach was used to represent the three lithologies that were present in that township. These samples are denoted by borehole identification in table 3 as "Generic F" (formation) or "Generic L" (lithology).

The modified vertical hydraulic conductivity data set used for the evaluation of the St. Francois confining unit and St. Francois aquifer (used for comparison purposes) along the Viburnum Trend in this report consisted of 46 values [17 Derby-Doerun Dolomite, 21 Davis Formation, 3 Bonneterre Formation, 2 generic formation (1 Derby-Doerun Dolomite and 1 Davis Formation), and 3 generic lithology (1 carbonate, 1 shale, and 1 carbonate and shale)]. The modified porosity data set for the Viburnum Trend consisted of 42 values (17 Derby-Doerun Dolomite, 22 Davis Formation, and 3 Bonneterre Formation). No generic formation or lithology values were included in the porosity data set.

Four censored values for the Davis Formation were in the modified Viburnum Trend data set. These data were collected by Kleeschulte and Seeger (2000) and had vertical hydraulic conductivity values less than the minimum reporting level of 3.17×10^{-14} ft/s (foot per second). None of the new vertical hydraulic conductivity values determined for this report and added to the existing St. Francois confining unit data set were less than the minimum reporting level.

A Lilliefors (two-tailed) test for normality (Iman and Conover, 1983) indicated the 40 vertical hydraulic conductivity values for the St. Francois confining unit formations along the Viburnum Trend in the modified data set (17 Derby-Doerun Dolomite, 21 Davis Formation, and 2 generic formation) were not normally distributed ($p = 0.000$). When a logarithmic transformation was applied, the data are considered normally distributed ($p = 0.070$); however, the strength of the evidence was marginal. Because the sample size was small (40 values) and the p-value of the transformed data was slightly greater than the preassigned α-value of 0.05, the nonparametric Kruskal-Wallis test (Helsel and Hirsch, 1995), was chosen to analyze the ranked data. When only two groups are used, the procedure reduces to the Mann-Whitney test (SYSTAT Software Inc., 2002).

Statistical comparisons of vertical hydraulic conductivity values of rock cores from the St. Francois confining unit grouped by formation (Derby-Doerun Dolomite and Davis Formation) show the data from the two formations are statistically similar (p-value = 0.073; table 4). The boxplot of the data (fig. 11A) shows that with the outliers, the data from the two formations span more than 5 orders of magnitude from 8.66×10^{-9} to 3.17×10^{-14} ft/s (tables 3 and 5). The interquartile range (see fig. 11 explanation) for the Derby-Doerun Dolomite (1.64×10^{-11} to 1.04×10^{-12} ft/s) spans slightly more than 1 order of magnitude, and the Davis Formation spans nearly 2 orders of magnitude (6.57×10^{-12} to 8.73×10^{-14} ft/s). The median vertical hydraulic conductivity value for Derby-Doerun Dolomite samples (3.27×10^{-12} ft/s) is similar to the median value for the Davis Formation samples (2.38×10^{-12} ft/s). Although statistics show the vertical hydraulic conductivity of the Derby-Doerun Dolomite and Davis Formation are considered similar, visually on the boxplots, the Davis Formation appears to be the more hydraulically restrictive medium (fig. 11A).

Three samples from the upper Bonneterre Formation (above the False Davis) also were plotted for comparison purposes (fig. 11A). The vertical hydraulic conductivity of these three samples are statistically similar to the those of the Derby-Doerun Dolomite (p-value = 0.615) and the Davis Formation (p-value =

Table 4. Summary of Kruskal-Wallis statistical test p-values

[DDR, Derby-Doerun Dolomite; DVS, Davis Formation; Carb, Carbonate sample; Both, Carbonate and shale sample; VT, Viburnum Trend; West, West exploration area; East, East exploration area]

Formation or Rock Type Comparisons	p-value
Viburnum Trend	
Formation	
DDR-DVS	0.073
Rock Type (all three rock types)	0.016
Carb-Shale	.012
Shale-Both	.032
Both-Carb	.118
Viburnum Trend, West and East Exploration Areas	
St. Francois confining unit (all three locations)	0.000
VT-West	.000
VT-East	.074
West-East	.012
Formation	
DDR (all three locations)	0.096
VT-West	.066
VT-East	.128
West-East	.212
DVS (all three locations)	0.034
VT-West	.018
VT-East	.420
West-East	.077
Rock Type	
Carbonate (all three locations)	0.001
VT-West	.001
VT-East	.019
West-East	.020
Shale (all three locations)	0.657
VT-West	.629
VT-East	.165
West-East	.668
Both (all three locations)	0.281
VT-West	.111
VT-East	.279
West-East	.766

0.094). This indicates that the confining ability of the upper Bonneterre Formation (above the False Davis) at the locations tested along the Viburnum Trend is comparable to the Derby-Doerun Dolomite and Davis Formation, even though regionally, the entire Bonneterre Formation is considered an aquifer. However, visually on the boxplots, the Davis Formation appears to have the lowest vertical hydraulic conductivity values compared to the Derby-Doerun Dolomite and upper Bonneterre Formation.

The ranked vertical hydraulic conductivity data from the St. Francois confining unit along the Viburnum Trend also was grouped by rock type (carbonate, shale, and samples containing both carbonate and shale). This data set contains 41 values; the two generic formation values were removed, and the three generic lithology values were added. Multiple comparisons were made to determine if the shale component of the confining unit was indeed more restrictive to flow than the carbonate component. The small shale sample size was caused in part by the age of the core samples. Older core samples become drier causing the shale to separate on small bedding planes (poker chipped) and become fragile. When removing samples from the core box, the shale tends to fall apart and is no longer coherent. A statistical comparison of the vertical hydraulic conductivity values using rock type as the grouping variable shows the three groups are different (p-value = 0.016; table 4). However, when the different rock types are paired and then compared, carbonate samples and samples containing both carbonate and shale shows a statistical similarity (p-value = 0.118). The other groupings, carbonate samples and shale samples (p-value = 0.012) and shale samples and samples containing both carbonate and shale (p-value = 0.032) are statistically different. The small shale sample set may have affected this relation.

The shale samples generally have the smallest vertical hydraulic conductivity and the carbonate samples have the largest (fig. 11B). Samples containing both shale and carbonate appear to have an intermediate value of both rock types indicating the affect that each component (carbonate or shale) has on the overall vertical hydraulic conductivity of the core sample. The variability of the interquartile range of samples containing both carbonate and shale is larger than either the carbonate or shale samples. This could be a result of the varying percentages of carbonate and shale in the samples with mixed lithology. The median vertical hydraulic conductivity of the shale samples (1.00×10^{-13} ft/s;

Table 5. Summary of vertical hydraulic conductivity values for the St. Francois confining unit along the Viburnum Trend

[ft/s, foot per second]

	Number of samples	Vertical hydraulic conductivity Minimum (ft/s)	Maximum (ft/s)	Median (ft/s)	Interquartile range (ft/s)
Formation					
Derby-Doerun Dolomite	18	1.27×10^{-13}	2.02×10^{-9}	3.27×10^{-12}	1.64×10^{-11} to 1.04×10^{-12}
Davis Formation	22	3.17×10^{-14}	8.66×10^{-9}	2.38×10^{-12}	6.57×10^{-12} to 8.73×10^{-14}
Rock type					
Carbonate	18	3.17×10^{-14}	8.66×10^{-9}	6.17×10^{-12}	2.06×10^{-11} to 1.04×10^{-12}
Shale	4	3.17×10^{-14}	7.26×10^{-13}	1.00×10^{-13}	2.76×10^{-13} to 6.37×10^{-14}
Carbonate and shale	19	3.17×10^{-14}	1.33×10^{-11}	4.56×10^{-12}	6.21×10^{-12} to 2.01×10^{-13}

table 5) was 62 times less than the carbonate samples (median value 6.17×10^{-12} ft/s) and 45 times less than carbonate and shale samples (4.56×10^{-12} ft/s). Because shale along the Viburnum Trend has the smallest vertical hydraulic conductivity of the three rock types, it would be the most restrictive medium to the flow of water in the confining unit. Consequently, the net shale thickness along the Viburnum Trend significantly affects the effective vertical hydraulic conductivity of the confining unit. As the percentage of shale increases in a given horizon, the vertical hydraulic conductivity decreases.

Porosity values were available for 39 core samples from the St. Francois confining unit along the Viburnum Trend; no values were used for the generic samples. Porosity values range from a minimum of 0.25 to a maximum of 10.98 percent (fig. 11C; table 3). Lilliefors testing (Iman and Conover, 1983) shows the porosity values have a normal distribution (p-value = 0.238). Because the data were normally distributed and from two independent data groups, the two sample separate variance t-test was used to compare the porosity values of Derby-Doerun Dolomite and Davis Formation samples (Helsel and Hirsch, 1995). The test indicated no significant difference (p-value = 0.341) between the two groups. The porosity values of samples from the Davis Formation are more variable than the porosity values of the Derby-Doerun Dolomite samples, which is shown by the interquartile range of the Davis Formation samples having greater than twice the span of the Derby-Doerun Dolomite samples.

Using the two sample separate variance t-test (Helsel and Hirsch, 1995) for comparison of porosity values of the different rock types (fig. 11D), a statistical similarity exists between the porosity value of samples containing shale and samples containing both carbonate and shale (p-value = 0.079), but this relation is not as strong as the comparison between only carbonate and only shale samples (p-value = 0.432). Samples containing only carbonate and samples containing both carbonate and shale are statistically different (p-value = 0.003). The Spearman rank-order correlation (Helsel and Hirsch, 1995) shows a weak correlation between vertical hydraulic conductivity and porosity (r = 0.237).

The vertical hydraulic conductivity of carbonate and shale was statistically different in the St. Francois confining unit along the Viburnum Trend. The range of effective vertical hydraulic conductivity for the confining unit was estimated using minimum and maximum thickness values of the confining unit, total thickness of the carbonate and shale components in the confining unit, and appropriate minimum and maximum vertical hydraulic conductivity values for the carbonate and shale rock types. The St. Francois confining unit along the Viburnum Trend was estimated to have a minimum thickness of 230 ft (approximately the lower percentile) and a maximum thickness of 280 ft (approximately the upper percentile; table 1). A minimum and maximum net shale thickness of 20 and 100 ft, respectively, was also used (fig. 10; table 1). The upper and lower percentiles for carbonate and shale rock types were used to estimate the vertical hydraulic conductivities. The range of 2.06×10^{-11} to 1.04×10^{-12} ft/s was used for carbonate rocks and 2.76×10^{-13} to 6.37×10^{-14} ft/s was used for shale.

By using appropriate minimum and maximum values of confining unit thickness, net shale thickness, and vertical hydraulic conductivity, the range of effective vertical hydraulic conductivity for the St. Francois confining unit in the Viburnum Trend was estimated to be a minimum of 2×10^{-13} ft/s and a maximum of 3×10^{-12} ft/s (fig. 12A). These effective vertical hydraulic conductivity values are considered small and verify conclusions of previous studies (Warner and others, 1974; Miller and Vandike, 1997; Kleeschulte, 2001); the confining unit effectively impedes the flow of ground water between the Ozark aquifer and the St. Francois aquifer along the Viburnum Trend.

Evaluation of the St. Francois Confining Unit along the Viburnum Trend and Exploration Areas

Another objective of this report is to compare the vertical hydraulic conductivity of rock core samples from the St. Francois confining unit in the active mining area of the Viburnum Trend and in the exploration areas where future mining may occur. The west (T. 25–27 N., R. 03–04 W.) and east (T. 25–27 N., R. 01–02 W.) exploration areas both include six townships (fig. 1). For this analysis, previously collected vertical hydraulic conductivity data from two earlier studies (Kleeschulte and Seeger, 2000, 2001) were combined with the data collected along the Viburnum Trend for this report. The data sets are considered comparable because all the analyzed samples were chosen by the same people, using the same selection criteria, and were analyzed by the same laboratory using the same methods. Before combining the data sets, 27 vertical hydraulic conductivity data values from the west exploration area and 2 values from the east exploration area were censored to the minimum reporting level of 3.17×10^{-14} ft/s. A Lilliefors (two-tailed) test for normality (Iman and Conover, 1983) indicated the combined vertical hydraulic conductivity data were not normally distributed ($p = 0.000$), and attempts to transform the data into a normal distribution failed. This failure was caused in part by the numerous censored values being grouped at the lower end of the data set. Consequently, the nonparametric Kruskal-Wallis statistical test (Helsel and Hirsch, 1995) was chosen to test the null hypothesis that the vertical hydraulic conductivity of the St. Francois confining unit was similar along the Viburnum Trend and in the west and east exploration areas.

When the vertical hydraulic conductivity data were grouped by location, the St. Francois confining unit was statistically different in the three locations (p-value = 0.000; table 4). However, when the data in the three locations were analyzed in pairs, the Viburnum Trend and east exploration area showed a statistical similarity (p-value = 0.074). The other combinations, west and east exploration areas (p-value = 0.012) and the Viburnum Trend and west exploration area (p-value = 0.000), showed a statistical difference (fig. 12A). The vertical hydraulic conductivity values visually appear smaller in the west exploration area than at the other two locations.

Statistical analysis were used to determine if the vertical hydraulic conductivity differences between locations primarily were caused by variations in the geologic formations or rock type. Data from the confining unit were grouped by formation and then subgrouped by location. Analysis of Derby-Doerun Dolomite vertical hydraulic conductivity values (fig. 12B) show similarity at all three locations (p-value = 0.096; table 4). When comparing the Derby-Doerun Dolomite vertical hydraulic conductivity samples by location pairs, the strongest similarity was among the west and east exploration areas (p-value = 0.212), followed by the Viburnum Trend and east exploration area (p-value = 0.128), and then by the Viburnum Trend and the west exploration area (p-value = 0.066).

Statistical analysis of Davis Formation vertical hydraulic conductivity values (fig. 12B) grouped by location showed a statistical difference (p-value = 0.034; table 4). However, comparing location pairs show a strong similarity between samples from the Viburnum Trend and east exploration area (p-value = 0.420); followed by the west and east exploration areas (p-value = 0.077), but no similarity was shown between the Viburnum Trend and west exploration area (p-value = 0.018). The statistical results could be considered paradoxical because comparing the entire Davis Formation data set by location shows a statistical difference, but two of the three possible location pairs shows statistical similarity. Apparently, the differences between the Viburnum Trend and west exploration area is sufficient to cause the α-value for the data set to be less than 0.05. The median and interquartile range of the boxplots indicate the vertical hydraulic conductivity of the Derby-Doerun Dolomite and Davis Formation generally are largest in the Viburnum Trend area and smallest in the west exploration area.

Statistical comparisons of the vertical hydraulic conductivity values of the various rock types (carbonate, shale, and samples containing both carbonate and shale) grouped by location also were performed using the nonparametric Kruskal-Wallis statistical test (Helsel and Hirsch, 1995). When the carbonate values were considered and grouped by location, statistical analysis showed the three locations were statistically different (p-value = 0.001; table 4). The vertical hydraulic conductivity values of carbonate samples analyzed by location pairs showed no statistical similarities between any of the three locations (all the p-values were less than or equal to 0.020). Generally, the carbonate samples from the Viburnum Trend had the largest vertical hydraulic conductivity values and the west exploration area had the smallest (fig. 12C). The shale samples were statistically similar for all locations (p-value = 0.657). The small data sets for the Viburnum Trend and east exploration area plot within the interquartile range of the larger west exploration area data set. The largest statistical similarity for shale samples occurs when comparing the west and east exploration areas (p-value = 0.668), followed by the Viburnum Trend and west exploration area (p-value = 0.629), and the Viburnum Trend and east exploration area (p-value = 0.165). When the mixed lithology samples are considered and grouped by location, the statistical analysis showed a similarity between all locations (p-value = 0.281). The largest p-value occurs when comparing the west and east exploration areas (p-value = 0.766), followed by the Viburnum Trend and east exploration area (p-value = 0.279), and the Viburnum Trend and west exploration area (p-value = 0.111).

In summary, the vertical hydraulic conductivity values by formation and rock type generally are the largest in the Viburnum Trend and smallest in the west exploration area, and no statistical similarity exists between these two areas. The statistical differences in these values do not appear to be attributed strictly to either the Derby-Doerun Dolomite or Davis Formation, but instead they are caused by the differences in the carbonate vertical hydraulic conductivity values at the three locations (fig. 12C).

The calculated effective vertical hydraulic conductivity range for the St. Francois confining unit at each location is: 2×10^{-13} to 3×10^{-12} ft/s for the Viburnum Trend; 3×10^{-14} (minimum reporting level) to 1×10^{-12} ft/s for the west exploration area (Kleeschulte and Seeger, 2000); and 3×10^{-13} to 2×10^{-12} ft/s for the east exploration area (Kleeschulte and Seeger, 2001; fig. 12A). Based on the calculated vertical hydraulic conductivity ranges, the St. Francois confining unit is considered 'tight' at all locations, but in relation to each other, the unit in the west exploration area is the tightest, and the unit in the Viburnum Trend is the most conductive. Active mining has been occurring along the Viburnum Trend with no apparent large cones of depression developing in the potentiometric surface of the Ozark aquifer as a result of mining activity. Therefore, using similar mining practices as those along the Viburnum Trend, no large cones of depression in the Ozark aquifer would be expected in the exploration areas, in particular the west exploration area, unless preferred-path secondary permeability has developed along faults or fractures or resulted from exploration activities.

SUMMARY AND CONCLUSIONS

The confining ability of the St. Francois confining unit (Derby-Doerun Dolomite and Davis Formation) was evaluated in 10 townships (T. 31–35 N. and R. 01–02 W.) along the Viburnum Trend of southeastern Missouri by describing the stratigraphy and calculating the vertical hydraulic conductivity of core samples from laboratory measured vertical permeability. These vertical hydraulic conductivity data were compared to the vertical hydraulic conductivity data collected during two previous studies 20 miles south of the Viburnum Trend in two lead-zinc exploration areas which may be a southern extension of the Viburnum Trend. Geologic formations from the base of the Potosi Dolomite to the top of the Roubidoux Formation form the surficial Ozark aquifer, the primary source of water for domestic and public-water supplies and major springs in southern Missouri. The St. Francois confining unit lies beneath the Ozark aquifer and impedes the movement of water between the overlying Ozark aquifer and the underlying St. Francois aquifer (composed of the Bonneterre Formation and Lamotte Sandstone). The Bonneterre Formation is the primary host formation for lead-zinc ore deposits of the Viburnum Trend and potential host formation in the exploration areas. For most of the more than 40 years the mines have been in operation along the Viburnum Trend, about 27 million gallons per day have been pumped from the St. Francois aquifer for mine dewatering. Previous studies conducted along the Viburnum Trend to assess the effects of mine dewatering in the St. Francois aquifer on water levels in the surficial Ozark aquifer have concluded that no large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity.

Because of the similarity in geology, stratigraphy, and depositional environment between the Viburnum Trend and the exploration areas, the Viburnum Trend may be used as a pertinent, full-scale model to study and assess how mining may affect the exploration areas. The confining ability of the St. Francois confining unit along the Viburnum Trend and in the exploration areas are compared to evaluate potential mine dewatering effects in the exploration areas.

The St. Francois confining unit is a complex series of dolostones, limestones, and shales. Borehole log data describe the unit as generally being 230 to 280 feet thick along the Viburnum Trend. The confining unit thickens in the western part of the study area, especially in the area west of the Conway Fault. The formations of the confining unit regionally tend to dip radially outward from the St. Francois Mountains area. In the northern part of the study area, the dip of the formations may be masked by underlying Precambrian structural highs (knobs), but generally is westward. The dip then gradually trends to the south in the central part of the study area. Based on 36 data values, the net shale thickness ranges from less than 25 to greater than 100 feet in the study area with the thickness increasing toward the west.

Vertical hydraulic conductivity values determined from laboratory permeability tests were used to represent the confining ability of the St. Francois confining unit along the Viburnum Trend. The data were not normally distributed and the nonparametric Kruskal-Wallis test was chosen to test the null hypothesis that the vertical hydraulic conductivity of the data sets being compared are equal. Statistical tests show the values for the Derby-Doerun Dolomite and Davis Formation are similar and boxplots of the data show the Davis Formation would be the more hydraulically restrictive medium. Multiple comparisons on the vertical hydraulic conductivity data from the St. Francois confining unit along the Viburnum Trend grouped by rock type (carbonate, shale, and samples containing both carbonate and shale) showed samples with only shale and only carbonate were statistically different, as were the shale samples and samples containing both carbonate and shale. Shale samples generally have the smallest vertical hydraulic conductivity and the carbonate samples have the largest. Only considering the median values of these data groups, the vertical hydraulic conductivity of the shale samples [1.00×10^{-13} ft/s (foot per second)] was 62 times less than the carbonate samples (median value 6.17×10^{-12} ft/s) and 45 times less than carbonate and shale samples (4.56×10^{-12} ft/s), making shale a more restrictive medium to the flow of water in the confining unit. Consequently, the net shale thickness of the confining unit along the Viburnum Trend significantly affects the effective vertical hydraulic conductivity. As the percentage of shale increases in a given horizon, the vertical hydraulic conductivity decreases.

By using appropriate minimum and maximum values of confining unit thickness, net shale thickness, and vertical hydraulic conductivity, the range of effective vertical hydraulic conductivity for the confining unit in the Viburnum Trend was estimated to be a minimum of 2×10^{-13} ft/s and a maximum of 3×10^{-12} ft/s. These vertical hydraulic conductivity values are considered small and verify conclusions of previous studies that the confining unit effectively impedes the flow of ground water between the Ozark aquifer and the St. Francois aquifer along the Viburnum Trend.

Another objective of this report is to compare the vertical hydraulic conductivity of rock core samples from the St. Francois confining unit in the active mining area of the Viburnum Trend and the exploration area where future mining may occur. The exploration area was divided into west (T. 25–27 N., R. 03–04 W.) and east (T. 25–27 N., R. 01–02 W.) areas. Previously collected vertical hydraulic conductivity data from two earlier studies were combined with the data collected along the Viburnum Trend for this report. The combined vertical hydraulic conductivity data set was not normally distributed and attempts to transform the data into a normal distribution failed. Consequently, the nonparametric Kruskal-Wallis statistical test was chosen to test the null hypothesis that the vertical hydraulic conductivity of the St. Francois confining unit was similar along the Viburnum Trend and in the west and east exploration areas.

A comparison of the vertical hydraulic conductivities of rock core samples from the St. Francois confining unit shows the Viburnum Trend and west and east exploration areas are statistically different. The vertical hydraulic conductivity values generally are the largest in the Viburnum Trend and are smallest in the west exploration area. The statistical differences in these values do not appear to be attributed strictly to either the Derby-Doerun Dolomite or Davis Formation, but instead they are caused by the differences in the carbonate vertical hydraulic conductivity values at the three locations.

The calculated effective vertical hydraulic conductivity range for the St. Francois confining unit at each location is: 2 x 10^{-13} to 3 x 10^{-12} ft/s for the Viburnum Trend; 3 x 10^{-14} (minimum reporting level) to 1 x 10^{-12} ft/s for the west exploration area; and 3 x 10^{-13} to 2 x 10^{-12} ft/s for the east exploration area. Based on the calculated vertical hydraulic conductivity ranges, the St. Francois confining unit is considered 'tight' at all locations, but in relation to each other, the unit in the west exploration area is the tightest, and the unit in the Viburnum Trend is most conductive area. No apparent large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity along the Viburnum Trend. Therefore, using similar mining practices as those along the Viburnum Trend, no large cones of depression in the Ozark aquifer would be expected in the exploration areas, unless preferred-path secondary permeability has developed along faults or fractures or resulted from exploration activities.

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