BEFORE THE OKLAHOMA DEPARTMENT OF MINES

IN RE: Permit Application of Arbuckle Aggregates to mine limestone, dolomite, shale, sand, gravel, clay and soil.	)))	Permit No. 2361 Date: January 14, 2011

CITIZENS FOR THE PROTECTION OF THE ARBUCKLE SIMPSON AQUIFER'S BRIEF IN OPPOSITION OF ARBUCKLE AGGREGATES' PERMIT APPLICATION

Citizens for the Protection of the Arbuckle Simpson Aquifer (hereinafter "CPASA") and its members hereby submit this brief in opposition to Oklahoma Department of Mines Permit Application No. 2361 filed by Arbuckle Aggregates, LLC, as captioned above. CPASA is a grassroots citizens' organization dedicated to protecting and preserving the Arbuckle Simpson Aquifer and all the springs and streams dependent on the Aquifer by preventing the waste, pollution and/or transfer of the Aquifer's invaluable water resources.

The Arbuckle Simpson Aquifer (hereinafter "ASA") is a fractured-karst aquifer that encompasses over 850 square kilometers in south-central Oklahoma and is the primary drinking water resource for the region. *See* Attachment 1, Professor Roger A. Young, Analysis of Seismic Reflection Data From The Hunton Anticline, The Oklahoma Water Resources Board (2009); *see also* Attachment 2, Jason R. Faith, et al., Three-Dimensional Geologic Model of the Arbuckle-Simpson Aquifer, South-Central Oklahoma, U.S. Geological Survey Open-File Report 2010-1123. Approximately 39,000 people in Ada, Sulphur, and surrounding communities depend on the ASA as their principal drinking water source. *See* Attachment 3, The Oklahoma Water Resources Board, The Arbuckle-Simpson Hydrology Study: Management and Protection of an Oklahoma Water Resource (2003). Additionally, the ASA provides water in the form of springs and streams to various national and state parks such as the Chickasaw National Recreation Area, which boasts over 3.3 million visitors each year. *Id*. The U.S. Environmental Protection Agency (hereinafter "EPA") has designated portions of the ASA as a sole source aquifer, which is an aquifer that provides at least 50 percent of the drinking water consumed in the overlying area and to which no feasible alternative source of potable water exists.[1] *See* Safe Drinking Water Act of 1974, 42 U.S.C. § 300 et seq., § 1424(e). Moreover, the Oklahoma Legislature, by statute, designated the entire ASA as a Sensitive Sole Source Aquifer. 82 O.S. § 1020.9A; *See also* OAC 785:30-1-2.

The Oklahoma Department of Mines (hereinafter "DOM") regulates non-coal surface mining and reclamation operations and is responsible for protecting Oklahoma's natural resources from mining activities. OAC 460:10-104. Specifically, it is the duty of the DOM to

> provide for the reclamation and conservation of land subjected to surface disturbance by mining and thereby to preserve natural resources, to encourage the productive use of such lands after mining, to aid in the protection of wildlife and aquatic resources, to encourage the planting of trees, grasses and other vegetation, to establish recreational, home and industrial sites, to protect and perpetuate the taxable value of property, to aid in the prevention of erosion, landslides, floods and the pollution of waters and air, to protect the natural beauty and aesthetic values in the affected areas of this state, and to protect and promote the health, safety and general welfare of the people of this state.

45 O.S. § 722 (emphasis added).

The permit application filed by Arbuckle Aggregates, if granted, would illegally impair the State's natural resources, harm wildlife and aquatic organisms, drastically decrease surrounding property values, pollute water systems, degrade air quality, disturb the regions naturally-occurring scenic value, and endanger the health and safety of local citizens. In addition, Arbuckle Aggregates' permit application is administratively incomplete. Because of

[1] Since 1974 when the Sole Source Aquifer program was authorized, the EPA has designated less than 100 Sole Source Aquifers. Region 6 of the EPA, to which Oklahoma belongs, has six sole source aquifers: the Arbuckle-Simpson in Oklahoma, the Chicot Aquifer System in Louisiana, the Edwards Aquifer I and II in Texas, the Espanola Basin Aquifer System in New Mexico, and the Southern Hills Aquifer System in Louisiana.

these substantive and administrative deficiencies, the DOM must deny Arbuckle Aggregates' permit application.

I. Granting Arbuckle Aggregates' Permit Application Would Cause Irreparable Damage to the Environment and Would Destroy the Region's Natural Resources.

Arbuckle Aggregates' permit application poses serious threats to the environment, including but not limited to devastation of the regional geologic and water resources, reduction of air quality and interference with wildlife habitats. By statute, the DOM is required to protect these resources, including water resources. *See* 45 O.S. § 722 (stating that the DOM is to "aid in the protection of wildlife and aquatic resources. . . [and] to protect the natural beauty and aesthetic values in the affected areas of this state"). Granting Arbuckle Aggregates' permit application would be contrary to the DOM's duties for the following reasons:

A. Mining in a Karst Geologic Formation is Especially Damaging to the Environment due to Karst's Unique Physical Composition.

The ASA is comprised of karst, which is "a type of topography that is formed on limestone, gypsum, and other rocks by dissolution that is characterized by sinkholes, caves, and underground drainage regions." *See* Attachment 4, William H. Langer, Potential Environmental Impacts of Quarrying Stone in Karst—A Literature Review, p. 1, U.S. Geological Survey Open-File Report OF-01-0484, (hereinafter "Potential Environmental Impact of Quarrying Stone in Karst"). Human activities, such as mining and quarrying, have widespread negative effects on karst environments, ranging from sedimentation of caves, deterioration of water quality, destruction of landforms, collapse of sinkholes and depletion of springs. *Id*. at Figure 2.

Further, mining in karst structures alters delicate parts of the natural system thereby creating "cascading environmental impacts." *Id*. at 8. Cascading impacts are triggered by an engineering activity (such as removing rock), which changes the natural system. The natural system responds to this change, which in turn causes another impact, which then causes yet another response by the system, and so on. *Id.* These cascading impacts "may be severe and affect areas well beyond the limits of the aggregate operation." *Id*.

A karst environment can be impacted in many ways by mining. Geomorphic impacts are a function of various factors, such as the size of the quarry, the total number of quarries and the location of the quarries. *Id*. It is known that "[g]reat numbers of quarries in a karst region amplifies the geomorphic impact." *Id*. Indeed, it is thought that the environmental disturbance created by numerous smaller quarries exceeds the disturbance created by one large quarry. *Id*.

In 2008, the Oklahoma Department of Mines reported production from 15 separate mines in Johnston County alone. *See* Attachment 5, Oklahoma Department of Mines, 2008 Reported Production. Many of these quarries are within the ASA. The environmental devastation created by such a high volume of mines, compounded by their close proximity to each other, is visible. Evidence of these impacts will be presented by CPASA at a formal hearing. The volatile nature of karst environments has not been lost on other State agencies. The Oklahoma Department of Transportation denied Arbuckle Aggregates its request to tunnel under Highway 7 because of concerns with "slumping, settling and rock integrity." *See* Arbuckle Aggregates Permit Application No. 2361.

Great caution must be taken before granting another mining permit over the ASA—especially because cascading impacts in karst systems "may manifest themselves some time after mining activities have begun and continue well after mining has ceased." *See* Attachment 4 at 8. Moreover, no studies have been conducted regarding the cumulative effect that the area mines are having on the ASA.

The Department of Mines cannot legally grant Arbuckle Aggregates' permit application because Arbuckle Aggregates failed to present evidence sufficient to satisfy the Department of Mines' obligation to protect the environment and natural resources in the area. Unless and until Arbuckle Aggregates establishes that removing vast quantities of rock from a sensitive karst geologic structure will have no adverse impacts on the surrounding region, it's application must be denied.

B. Arbuckle Aggregates' Proposed Mining Operation will cause Irreparable Injury to the Region's Water Resources.

1. **Arbuckle Aggregates' proposed mine would impermissibly pollute the ASA.**

Karst water is extremely susceptible to pollution due to its low self-purification capabilities. *See* Attachment 4 at 14. Moreover, removing the protective vegetative and soil cover of the ASA that acts as a barrier between contaminants and the underground basin may cause severe pollution to the underlying groundwater. In addition, the porous nature of karst allows mass quantities of silt, waste, fuel and oil utilized in everyday mining operations to pollute rivers and underground bodies of water both within and far beyond the boundaries of the quarry. *Id*. at 15.

As noted above, the ASA is a sole source aquifer on which tens of thousands of people rely for drinking water. If the ASA becomes polluted, the welfare of these individuals is jeopardized because, as acknowledged by the EPA, there are no reasonably feasible alternative water supply sources. Although Arbuckle Aggregates' proposed mine overlays a relatively small portion of the ASA, the effects of its pollution will be felt by the entire region. There is no known method to completely—or even mostly—prevent mining pollutants from entering the hydrologic cycle. Arbuckle Aggregates' permit application must be denied because of the risk of pollution to both surface and ground water, not only because it will cause irreversible damage to the region's environment, but also because 39,000 Oklahoma citizens would lose their only drinking water source.

2. Arbuckle Aggregates' proposed mine would interfere with the natural flow of surface and groundwater.

Mining and quarrying activities alter the hydrologic patterns of the surrounding areas. Groundwater and surface water are very much interrelated and interdependent—a fact that Oklahoma law acknowledges—meaning that the depletion of groundwater will also affect surface water flow. *See Jacobs v. Smith*, 2006 OK 34, ¶ 12, 148 P.3d 842. Thus, any effect Arbuckle Aggregates has on groundwater levels may impermissibly interfere with previously granted and valid surface water rights. Flow paths of both surface and groundwater may abruptly change direction due to quarrying. These changes in natural flows pose serious threats to surrounding communities, businesses, individuals, and recreational areas that depend on the ASA for water.

The DOM has not conducted any studies on the disruption mining causes to the flow of surface and ground water. Moreover, the DOM has not studied the cumulative impact the various mines have on the natural flow of the ASA and its springs. Unless and until such time as it is shown by verified scientific data that Arbuckle Aggregates' proposed mine would have no significant negative impact on the surrounding area, either alone or as part of the bevy of mines over the ASA, the DOM is statutorily obligated to deny Arbuckle Aggregates' permit.

Pursuant to Oklahoma statute, no water may be taken from a sensitive sole source aquifer, such as the ASA, if it would "reduce the natural flow of water from springs or streams emanating from said basin or subbasin." 82 O.S. § 1020.9A(B)(2). The statute does not distinguish between regulated and unregulated water—thus, *any* action interfering substantially with the natural flow of springs and streams within the ASA is prohibited. Mines currently enjoy an exemption from the obligation to obtain a permit to divert or use water in their pits. Yet this exemption does not allow Arbuckle Aggregates to "reduce the natural flow of water from springs or streams emanating from said basin or subbasin." Arbuckle Aggregates' operation would be immediately adjacent to streams and springs within the ASA, and one significant spring is located within the company's planned mining area. CPASA stands ready to provide expert testimony that mining in such close proximity to those springs and streams will substantially and negatively interfere with the natural flow of those water bodies in violation of SB288. The DOM must follow the statutory mandate set forth by the state legislature by denying Arbuckle Aggregates' permit.

Moreover, special protections are afforded to High Quality Waters, as designated by the Oklahoma Water Resources Board ("OWRB"), which are waters that "possess existing water quality which exceeds those levels necessary to support propagation of fisheries, shellfishes, wildlife, and recreation in and on the water." OAC 785:45-3-2(b). The headwaters of Pennington Creek, which is a High Quality Water, originate less than one-half mile from Arbuckle Aggregates' proposed mining site. Arbuckle Aggregates' operation is not within Pennington Creek's surface watershed; however, CPASA will present expert testimony that Arbuckle Aggregates' site is within Pennington Creek's *sub*surface watershed. The DOM cannot allow Arbuckle Aggregates to begin operations without first ascertaining the underground hydrological relationship between the headwaters of the High Quality Waters of Pennington Creek and the proposed mining activity, and the impact that mining within a High Quality Water will have on the legal regime applicable to the permit application.

The natural flows of springs and streams within the ASA are statutorily protected. Unless and until scientific studies prove that no damage will occur from Arbuckle Aggregates' mining activities to the springs and streams emanating from the ASA, the DOM cannot legally grant Arbuckle Aggregates' permit.

3. **Granting Arbuckle Aggregates' application would impermissibly change the physical and chemical characteristics of the ASA's hydrologic system.**

Wildlife and aquatic animals depend on the ASA for nourishment, shelter and reproduction. Even the slightest change in the composition of the ASA's water quality, quantity and geomorphology will erase entire species of organisms from the immediate area. Moreover, changes to the composition of the hydrologic system may render the water undrinkable, in which case nearly 40,000 Oklahoma citizens would not only be without potable water but would have no feasible alternative from which to obtain suitable drinking water.

Arbuckle Aggregates' mining operations, including pit dewatering and wetland eradication, will have significant, negative effects on the water table including, but not limited to, the alteration of the physical and chemical makeup of a hydrologic system, fluctuations in the pH of the water, increased water temperatures, and changes in the physical makeup.

Unfortunately for the individuals, wildlife and aquatic animals in the ASA region, the environmental devastation will not be limited to the actual mining area, but rather will manifest itself throughout the various reaches of the ASA. Because the DOM is responsible for protecting the State's wildlife and aquatic resources and promoting the health, safety and general welfare of the people of Oklahoma, Arbuckle Aggregates' mining application must be denied.

4. **Arbuckle Aggregates' application must be denied because it has not obtained—or even attempted to obtain—necessary permits under the Clean Water Act.**

The Clean Water Act ("CWA") serves as the cornerstone for surface water quality protection in the US. Its foundational purpose is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." 33 U.S.C. § 1251. In light of this overarching theme, the statute employs a mixture of regulatory and nonregulatory tools to minimize and eliminate pollution to waters of the United States.

The heart of the CWA, however, is found in Section 301, which establishes the default rule that without a permit "the discharge of any pollutant by any person shall be unlawful." 33 U.S.C. § 1301. Two of the basic permitting provisions are found in Sections 402 and 404 of the CWA. Section 402 of the CWA prohibits point-source discharges while Section 404 of the CWA focuses mainly on the dredging and filling of wetlands. Arbuckle Aggregates' entire business revolves around the production of rock, sand and gravel—all of which are identified by the CWA as pollutants. 33 U.S.C. § 1362(6). Any discharge of such a pollutant, even if unintentional, requires a Section 402 permit under the CWA. Likewise, the process of removing vast portions of the mining area will unavoidably include the dredging and filling of wetlands within the area. Such action necessitates a Section 404 permit.

The acreage identified in Arbuckle Aggregates' permit application includes a blend of leased and fee land totaling approximately 2,000 acres spanning across sections of Johnston County and Murray County. Although the actual mining will be conducted on approximately 500 acres, the expansive acreage included in the proposed operation is necessary to supply Arbuckle Aggregates with sufficient water for its mining activities.

Surface water use permits have also been submitted by Arbuckle Aggregates to the OWRB. Currently, Arbuckle Aggregates' proposal requires water be diverted from a small spring and piped to its quarry. The pipeline originates in a small pond surrounded by designated wetland areas and bisects Mill Creek and certain other unnamed tributaries of Mill Creek. The proposed pipeline route will cause unavoidable destruction and degradation of numerous wetlands, as well as discharging pollutants from a point source into waters of the United States.

Furthermore, Arbuckle Aggregates' stated Area of Use encompasses numerous designated wetlands—all of which will be wholly demolished by the mining process. The stockpile area in which Arbuckle Aggregates will store its crushed rock is immediately adjacent to designated wetlands. Any rock, stone, gravel, dirt or sand that encroaches upon the wetlands is a point source discharge.

Section 404

Four (4) basic requirements must be met before a Section 404 permit is necessary. First, the area in question must be a wetland. Second, the water or wetland in question must be a water of the U.S.—in other words, the wetland must be a jurisdictional wetland in order for the CWA protections to apply. Third, the activity must be considered a dredging and filling activity. Finally, the activity must not be exempt under Section 404(f). Here, all four requirements are met. Thus, Arbuckle Aggregates must obtain a Section 404 permit before constructing its pipeline or preparing its Area of Use.

Numerous Wetlands are Encompassed within Arbuckle Aggregates' Proposed Construction and Mining Sites. Arbuckle Aggregates plans to build a pipeline that bisects Mill Creek and several unnamed tributaries of Mill Creek—all of which are classified as wetlands. Additionally, Arbuckle Aggregates intends to completely demolish a large designated wetland area, which unfortunately lies within its proposed mining area. Arbuckle plans to discharge its crushed rock into wetland areas, and its operations will constitute a redistribution of material within a wetland. All of Arbuckle Aggregates activities require a permit under CWA § 404.

A wetland is an area "inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." 33 C.F.R. § 328.3(b). The definition identifies three key features of wetlands: (1) hydrology—either surface or ground water; (2) wetland-dependent vegetation; and (3) soil types associated with water-saturated conditions. Although all three characteristics often present, it is not required that a wetland possess all three features.

Arbuckle Aggregate's proposed pipeline is to originate in a freshwater pond which has previously been designated as a wetland. Moreover, a freshwater forested/shrub wetland has been identified immediately adjacent to the pond. Arbuckle Aggregates has been careful to avoid expansive areas of designated wetlands, however, smaller wetland areas are present throughout the region. As stated above, wetlands are not required to be "wet" on a continuous basis—indeed, playa lakes and prairie potholes are wetlands despite being dry a majority of the year. Numerous areas exist within the proposed construction and mining area that are wetlands based on the hydrology, vegetation and/or soil saturation.

Furthermore, a designated wetland is located squarely within the area Arbuckle Aggregates has identified as its Area of Use. Arbuckle Aggregates' proposed mine interferes with previously identified wetlands, making it insincere to assert that no wetlands exist within the planned operational area. *See* Attachment 7.

Mill Creek and its Unnamed Tributaries are Waters of the United States and Thus under the Jurisdiction of the CWA. The Clean Water Act applies only to "navigable waters" which are defined as "waters of the United States." 33 U.S.C. § 1362(7). Wetlands can also be considered waters of the United States. Generally, there are six instances in which wetlands are protected under the CWA. These instances are listed below:

1. The wetland crosses state lines;
2. The wetland is a traditional navigable water;[2]
3. The wetland is adjacent to traditional navigable waters;
4. The wetland, either alone or in combination with similarly situated lands in the region, significantly affect the chemical integrity, the physical integrity, or the biological integrity of any traditional navigable waters;
5. The wetland is adjacent to, and has a continuous surface connection with, a relatively permanent, standing or continuously flowing body of waters that is connected to a traditional navigable water; or
6. The destruction or degradation of the wetland affects interstate or foreign commerce.

The wetlands that will be affected by Arbuckle Aggregates fall under the latter three categories. Mill Creek is a relatively permanent or continuously flowing body of water that is connected to the traditional navigable waters of the Washita River. Thus, Mill Creek is classified as a wetland under the fifth category—it is adjacent to and has a continuous surface connection with a traditional navigable water—and as such is protected by the CWA.

The numerous unnamed tributaries to Mill Creek are also classified as wetlands under approachs four-six, above. These tributaries, both alone and in concert, significantly affect the chemical, physical, and biological integrity of the Washita River, a part of which is a navigable river in fact. Scientific data proves that even the slightest change in the Arbuckle Simpson Aquifer has disastrous effects on the chemical and physical composition of springs and streams in the entire area and severely threatens the very existence of the complex biological communities that rely solely on the aquifer. Here, the unnamed tributaries are simply the surface presentation of underground springs and streams emanating from the Arbuckle Simpson Aquifer. The degradation or destruction of these unnamed tributaries will negatively affect the chemical,

---

[2] A traditional navigable water is one that is currently used, or was used in the past, or is susceptible to use in the future, in interstate or foreign commerce.

physical, and biological integrity of a traditional navigable water, and, as such, is considered a wetland covered under the CWA.

Furthermore, these wetlands are or could be used by interstate or foreign travelers for recreational or other purposes, making the destruction of such wetlands a matter affecting interstate and foreign commerce. Because of the impacts on interstate and foreign commerce, the wetlands in question are protected by the CWA.

Construction of a pipeline and mining in a wetland requires dredge and fill activities requiring a section 404 permit. The installation of a pipeline that crosses Mill Creek and several unnamed tributaries will, by necessity, involve dredge and fill activities. Dredged material is "material that is excavated or dredged from waters of the United States." 33 C.F.R. § 323.2(c). Discharging dredged material means "any addition of dredged material into, including redeposit of dredged material other than incidental fallback within, the waters of the United States." 33 C.F.R. § 323.2(d)(1). Dirt and other material will undoubtedly be removed from the path of the pipeline in order for water to flow more efficiently through the pipe.

Installation of a pipeline requires dirt, sand, and fill materials to stabilize and secure the metal pipelines being inserted. The Army Corps of Engineers states that the term discharge of fill material generally includes "the building of any structure, infrastructure, or impoundment requiring rock, sand, dirt, or other material for its construction." 33 C.F.R. §323.2(f). Thus, Arbuckle Aggregates can either use the dredged material to secure the pipeline construction—in which case it would be a discharge of dredged material into waters of the United States—or use other material to secure the infrastructure—in which case it would be a discharge of fill material into waters of the United States. Either way, a Section 404 permit is necessary.

Arbuckle Aggregates also intends to mine in and around a designated wetland, which lies within its Area of Use. In light of the extensive mining that Arbuckle Aggregates proposes, it is impossible to believe that dredged or fill material will not be discharged—either intentionally or accidentally—into the wetland. The maps given by Arbuckle Aggregates indicate the designated wetland will be completely surrounded by mining pits and other mining operations, including a railway that runs through the middle of the wetland. Just as the discharge of dredged or fill material is unavoidable when building the pipeline, so too is it unavoidable in constructing a railway.

Arbuckle Aggregates does not qualify for an exemption under section 404(f) and must therefore obtain a permit before proceeding with its mining operation. In certain, limited circumstances the discharge of dredged or fill material is not prohibited. Arbuckle Aggregates, however, does not meet any of those narrow exceptions. The first exception is from normal farming, silviculture and ranching activities. 33 U.S.C. § 1344(f)(1)(A). It does not include mining. The second exception applies only to maintenance activities. 33 U.S.C. § 1344(f)(1)(B). Arbuckle Aggregates has not begun to build its operations and thus cannot be exempt under the maintenance exemption. The third instance in which the discharge of dredged or fill material is not prohibited is for the purpose of construction or maintenance of farm ponds. 33 U.S.C. § 1344(f)(1)(C). Again, Arbuckle Aggregates is in the mining industry and cannot claim an agricultural exemption.

Likewise, Arbuckle Aggregates does not qualify under the exemption for the construction of temporary sedimentation basins, the exemption for the construction of temporary roads for moving mining equipment, or the exemption pertaining to State approved programs. 33 U.S.C. §§ 1344(f)(1)(D)-(F). While the exemption for the construction of roads for moving mining equipment may be applicable elsewhere in Arbuckle Aggregates operations, it does not affect the construction of a pipeline or the clearing of an area of operations.

The individual and cumulative adverse effects on the environment from Arbuckle Aggregates' mining operation require it to obtain an individual permit rather than a nationwide permit. Arbuckle Aggregates cannot operate solely under Army Corps of Engineers Nationwide Permit Number 44 because its activity will inflict serious harm on the surrounding environment. The mine proposed by Arbuckle Aggregates overlies the Arbuckle Simpson Aquifer ("ASA"), which has been designated by the Environmental Protection Agency ("EPA") as a Sole Source Aquifer ("SSA"). SSA's are protected because they supply at least half of the drinking water supply to area communities and there is no physically, legally, or economically feasible water supply alternative. Recent studies completed by the OWRB establish that the vast majority of springs and streams in the ASA region emanate from the ASA itself. Thus, any damage done to the ASA directly impacts the surrounding springs and streams—the same springs and streams which are tributaries to a traditional navigable water.

The Army Corps of Engineers' Nationwide Permit Number 44 only authorizes "mining activities that have no more than minimal individual and cumulative adverse effects on the aquatic environment." 72 Fed. Reg. 11,139 (Mar. 12, 2007). Moreover, Nationwide Permits cannot be issued in areas of High Quality Water, as in this case with Pennington Creek. Disrupting, degrading and demolishing wetlands, springs and streams in such a sensitive area will have a pronounced negative effect on the aquatic environment, both in the immediate streams as well as in the Washita River itself. Nationwide Permit Number 44 is inappropriate for Arbuckle Aggregates' operations due to the severe environmental impact its mining activity will have on the environment and waters of the United States.

As set forth above, wetlands are present in the area Arbuckle Aggregates proposes to use for construction and mining. These wetlands are protected by the CWA because they are adjacent to and have a continuous surface connection with traditional navigable waters, they would and/or could have a negative effect on interstate and foreign commerce, and they significantly affect the chemical, physical and biological integrity of a traditional navigable water.

Furthermore, Arbuckle Aggregates' activities constitute dredging and filling under the CWA and do not fall within any of the narrow exceptions to the permit requirement of Section 404. Additionally, Arbuckle Aggregates must obtain an individual permit, rather than a general or nationwide permit, because of the severity of environmental damage that will result from its actions.

Any action which results in the filling of waters of the United States must be permitted through the ACOE. 33 U.S.C. 1311(a); 33 U.S.C. 1342. In addition, any activity that impairs or alters the flow or circulation of jurisdictional waters must receive a section 404 permit. 40 CFR § 232.3(b). As a result, Arbuckle Aggregates' plan to discharge sand and gravel into the stream reaches and tributaries to the Washita River constitute illegal, unpermitted discharges of pollutants under the CWA §§ 301, 402 and 404. Furthermore, Arbuckle Aggregates must obtain a Section 404 permit before mining around the streams that bisect its property because of the impairments and/or alterations that will result to the stream's flow or circulation.

Section 402

Section 402 is applicable to the point source discharge of any pollutant into navigable waters. Navigable waters have been defined The Clean Water Act applies only to "navigable waters" which are defined as "waters of the United States." 33 U.S.C. § 1362(7). Section 402 of the CWA prohibits the discharge of a pollutant from a point source, unless the discharge is authorized by permit. 33 U.S.C. § 1311(a); 33 U.S.C. § 1342. A pollutant, as defined by the CWA and as adopted by the State, includes rock, sand and dirt. 13 U.S.C. § 1362(6); see also OAC 252:606-1-3(b)(3)(B). A point source is defined as "any discernible, confined and discrete conveyance . . . from which pollutants are or may be discharged," 33 U.S.C. § 1362(14), Oklahoma is authorized under the CWA to administer its own permit program regulating point source discharges, known as the Oklahoma Pollutant Discharge Elimination System Act ("OPDES"). 33 U.S.C. § 1342(b); 27A O.S. § 2-6-201. The OPDES requires an individual to obtain a permit before discharging any kind of pollutant from a point source.

Arbuckle Aggregates is in the business of producing rock, stone and dirt—all of which are considered pollutants under the CWA and the OPDES. In addition, Arbuckle Aggregates intends to pile its rock, stone and dirt in a designated wetland area. Thus, the placement of any rock, stone or dirt within the bounds of the wetland or tributary would be considered the discharge of a pollutant from a point source. Because the wetlands and the unnamed tributary are waters of the United States, such a discharge of a pollutant from a point source falls squarely within the CWA Section 402 and OPDES regulations. *See* Section 404, *supra*.

A multitude of steps in the mining process can be considered point sources, for which a 402 permit is needed. Additional information relating to point source discharges will be presented by CPASA at the formal hearing. Nonetheless, Arbuckle Aggregates will discharge pollutants from discernable points throughout its operation and is thus required by the CWA to obtain a Section 402 permit.

C. Regional Air Quality will be Severely Diminished by Arbuckle Aggregates' Mining Activities.

Arbuckle Aggregates proposes to conduct blasting as part of its mining activity, which is one of the leading causes of dust. Dust has been identified as "one of the most visible, invasive, and potentially irritating impacts associated with quarrying . . . ." *See* Potential Environmental Impacts of Quarrying Stone in Karst at 11. Numerous stages throughout the mining process can create dust, such as excavation, haul roads, blasting, drilling, crushing and screening. Arbuckle Aggregates plans to use each of those processes in its operation. Moreover, dust from mining can clog pores in the ground thereby hindering the recharge rate of the ASA.

Air quality will further be degraded by chemical emissions from Arbuckle Aggregates' proposed mine. It is estimated that, per year, Arbuckle Aggregates will release 2.024 tons of nitrogen oxide, .44 tons of carbon monoxide, .17 tons of volatile organic compounds and .13 tons of sulphur dioxide. These emissions cause both environmental devastation and human health issues. Arbuckle Aggregates' application must be denied due to the widespread environmental damage its emissions will cause and the severe health hazards it will create.

D. Arbuckle Aggregates' Proposed Mine will Negatively Affect Regional Wildlife and Aquatic Species.

Arbuckle Aggregates, even in its most infant stages of production, will have a pronounced negative effect on the region's wildlife and aquatic organisms. Preparation for Arbuckle Aggregates' proposed mine will destroy hundreds of acres of natural habitat. Vegetation will be destroyed, as will animals unable to escape the preparation area. Other more mobile wildlife will still struggle to find alternative habitats in which to survive after being displaced by Arbuckle Aggregates' actions. Further, the pollution, contamination and depletion of the ASA will have harmful, and in many cases fatal, effects on wildlife and aquatic organisms dependent on the springs and streams for survival.

Alterations in stream flow will have a direct adverse affect on the Tishomingo National Fish Hatchery (herein "TNFH"). The TNFH spawns and rears paddlefish at Tishomingo and has successfully returned the fish to waters where they have been missing for over 50 years. Additionally, the TNFH is developing new techniques to re-introduce the alligator gar and the leopard darter into waters they once inhabited. However, Arbuckle Aggregates' permit application, if granted, will impair the TNFH's mission. The proposed mine would diminish the amount of water available to the TNFH, as well as alter the chemical and physical characteristics of the streams. All of these changes would negatively affect the threatened species of fish that the TNFH is trying to protect.

Mining also has disastrous effects on terrestrial ecosystems. Karst environments are comprised of a complex series of caves, holes, and pores. These environments are divided into four categories based on differing degrees of darkness: the twilight zone, which is found near the entrance where light intensity, humidity, and temperature vary greatly; the transition zone of complete darkness, which has variable humidity and temperature; the deep zone of complete darkness, which has almost 100 percent humidity and a constant temperature; and the stagnant zone of complete darkness, which has 100 percent humidity. *See* Attachment 4 at 12. Animals living in zones of permanent darkness developed physiological, behavioral and morphological adaptations in order to survive. These adaptations, however, have restricted those animals to areas of total darkness—they cannot survive anywhere else. Oftentimes, species are confined to single cave systems and do not exist in other areas of the karst ecosystem. *Id*. at 13.

Quarrying destroys cave passageways and, as a result, the highly sensitive habitats of terrestrial species. Moreover, the changes in natural flows of groundwater cause entire underground hydrologic systems to dry up—taking with it any site-endemic fish and snail species that depended on the water body. Blasting also poses a serious risk to karst habitat and biota. Vibrations or shock waves caused by blasting can collapse cave roofs or crack existing karst structures. Death or displacement of cave communities can occur when light from a crack enters an otherwise dark cave or when water suddenly drains into a new opening. *Id*. at 13.

II. Extensive Property Damage will Result if the DOM Grants Arbuckle Aggregates' Permit Application, in Addition to a Gross Interference with Existing Individual Rights.

Environmental devastation is not the only harm that will be caused by Arbuckle Aggregates' mine. The quarry will cause tangible damage to property in the area and also substantially interfere with protected property rights. It is the duty of the DOM, however, to "protect and perpetuate the taxable value of property" in the affected area, as well as to promote the "general welfare" of citizens of Oklahoma. 45 O.S. § 722.

A. Arbuckle Aggregates' Proposed Mine Will Irreparably Harm Surrounding Real Property.

Arbuckle Aggregates' mine will cause extensive damage to surrounding real property. As stated above, dust is an inescapable byproduct of mining and although certain measures can be taken to mitigate the amount of dust discharged, it can never be completely eliminated. Dust from other active mines in the area already settle and accumulate on adjoining properties. The dust emitted from Arbuckle Aggregates' operation would only compound the problems citizens face regarding mining dust.

In addition, property damage will result from Arbuckle Aggregates' extensive "pit dewatering" efforts. Pit water is water that collects in excavation pits and may be composed of surface water runoff, groundwater seepage/infiltration, or both. DOM regulations impose a duty of care on mining operations "to prevent any excessive drainage or accumulation or release of excess water that may damage the adjoining property of other owners." OAC 460:10-17-14(4).

Arbuckle Aggregates fails to address pit water or the extensive property damage to adjoining property owners caused by water flowing and infiltrating the pit, rather than continuing on its normal path. Water that once supplied local springs and streams will begin flowing instead into the pit, creating an environmental nightmare for adjacent property owners and downstream citizens.

B. Numerous Federal and State Entities will be Negatively Affected by Arbuckle Aggregates' Mining Operations.

Many federal and state entities rely on the ASA. Communities, such as the City of Sulphur, the City of Tishomingo and the City of Ada, depend on the ASA as their principal water source. In addition, the very existence of the Chickasaw National Recreational Area, the Tishomingo National Wildlife Refuge and the Tishomingo National Fish Hatchery hinges on the continuous, unpolluted and constant flow of springs and streams fed by the ASA. Arbuckle Aggregates' mining activities will have an unpredictable and irreparable impact on the ASA, and as a result, on the three federal parks located within the ASA area. The foundational purposes of these three national landmarks will be frustrated—perhaps permanently—by Arbuckle Aggregates' mine.

Other local and state entities similarly rely on the ASA. For example, Turner Falls Park is a tourist destination that features a spectacular 77-foot waterfall, which is fed by Honey Creek and other ASA streams. Numerous charitable organizations, such as the Slippery Falls Boy Scout Ranch and the Falls Creek Baptist Church Camp, also utilize the ASA in furtherance of their altruistic missions.

The above-named state and federal entities are a reflection of the ideals and culture of the citizens living in the ASA. The DOM is statutorily required to take into account the rights of preexisting federal, state and local entities and the negative effects that Arbuckle Aggregates' mine will cause to those entities before making a decision on the application. Because these important and historic organizations would be devastated by the effects of Arbuckle Aggregates' mining operations, the DOM must deny the permit application.

C. Arbuckle Aggregates' Mining Activities will Substantially Interfere with Downstream Domestic Users and Senior Appropriative Users.

The waterways that Arbuckle Aggregates proposes to mine away provide water to downstream domestic water users, as well as to other senior appropriative users. Any disruption of these springs and streams will deprive domestic downstream users and appropriative users of water. Individuals riparian to a stream have a statutorily-protected right to "take stream water for domestic use" from streams or domestic wells. 82 O.S. § 105.2(A). However, Arbuckle Aggregates' permit application seeks to deprive downstream domestic users of this protected right by diverting surface water, as well as using the groundwater that feeds the surface streams, for its mining operations. Granting Arbuckle Aggregates' permit application would be tantamount to depriving Oklahoma citizens of their legally protected property interests.

Similarly, Oklahoma employs the prior appropriation method for distributing stream water, other than domestic use water. This method requires any individual seeking to beneficially use surface water to first obtain a permit from the Oklahoma Water Resources Board. 82 O.S. § 105.9. The idea of "first in time, first in right" is the cornerstone of the prior appropriation doctrine, meaning that senior appropriators have rights superior to junior appropriators. Arbuckle Aggregates' water use in its mining operation will illegally deprive senior appropriators of their permitted water. Because Arbuckle Aggregates' permit frustrates senior appropriators' legally protected water use right, its application must be denied.

III. Arbuckle Aggregates' Permit Application Must be Denied because it would Endanger the Health and Safety of the General Public.

The DOM must "protect and promote the health, safety and general welfare of the people of this state," yet Arbuckle Aggregates' proposed mine would place the health of local citizens in grave danger should it be granted. 45 O.S. § 722. Arbuckle Aggregates will emit, *inter alia*, varying levels of Nitrogen Oxide (NOx), Volatile Organic Compound (VOC), Carbon Monoxide (CO), and Sulphur Dioxide (SO2). All of these pollutants have been associated with human health issues—ranging from respiratory symptoms to cancers to premature death.

Moreover, Arbuckle Aggregates' calculates it will emit nearly 70 tons of particulate matter less than 10 micrometers.[3] The US Environmental Protection Agency (EPA) states that particles less than 10 micrometers present the greatest health problems "because they can get deep into your lungs, and some may even get into your bloodstream." The Environmental Protection Agency, Particulate Matter Health and Environment, http://www.epa.gov/air/particlepollution/health.html (last visited Jan. 10, 2011). More generally, particle pollution has been scientifically linked to the following health problems:

- Increased respiratory symptoms, including but not limited to irritation of the airways coughing, and difficulty breathing;
- Decreased lung function;
- Aggravated asthma;
- Chronic bronchitis;
- Irregular heartbeat;
- Nonfatal heart attacks; and
- Premature death in people with heart or lung disease.

Id.

---

[3] CPASA has serious concerns with the extraordinarily low number calculated by Arbuckle Aggregates with respect to particles 10 micrometers or less. It is CPASA's belief that Arbuckle Aggregates' actual emission of particles 10 micrometers or less will be greater than 100 tons per year. Evidence supporting CPASA's belief will be presented at the formal hearing.

More detailed information concerning the health issues associated with mining and, more specifically with Arbuckle Aggregates' proposed mine, will be presented by CPASA at the formal hearing. However, even without such information, the DOM cannot in good faith allow a mine to commence an operation that will emit such a hazardous particle in light of the EPA's verified scientific data linking that particle to serious health risks. It is the responsibility of the DOM to "protect and promote the health, safety and general welfare of the people of this state" and that responsibility dictates the denial of Arbuckle Aggregates' permit application. 45 O.S. § 722.

IV. The DOM Should Deny Arbuckle Aggregates' Permit Application because of the Widespread Negative Economic Affect it would have on the Region.

Likewise, issuing Arbuckle Aggregates' permit application would not protect the general economic welfare of people of the state. Indeed, the entire region surrounding the proposed mining site would suffer severe economic consequences from Arbuckle Aggregates' quarrying activities. The ASA is the primary water source for numerous municipalities, businesses, ranchers and individuals. Any change in the surface and groundwater flow pattern or increased pollution of the ASA is likely to require drinking water to be imported. It has already been established that obtaining potable water through other channels would be virtually impossible for the region. As noted by the EPA, "There is no existing alternative drinking water source or combination of sources which provides 50% or more of the drinking water to the area, nor is there any available cost-effective source capable of supplying the drinking water demands for the designated area." EPA's Notice to Designate the Arbuckle-Simpson Aquifer as a Sole Source Aquifer, II(2). The DOM, serving as an arm of the State with the responsibility to protect and promote "the health, safety and general welfare of the people of this state," should likewise recognize the importance of preserving the Aquifer by denying Arbuckle Aggregates' permit application. 45 O.S. § 722.

A potential repercussion of the DOM's approval of Arbuckle Aggregates' permit application is the withholding of federal monies. In this case, Arbuckle Aggregates' permit application threatens vital federal economic stimulus dollars that are much needed in Oklahoma. Denying Oklahoma citizens of critical federal monies flies in the face of the DOM's duty to "protect and promote the health, safety and general welfare of the people of the state." 45 O.S. § 722.

Property values would also suffer if the DOM grants Arbuckle Aggregates' permit application. Land values will decrease where there is no access to unpolluted water. Moreover, land dotted with sinkholes caused by the changes in the Aquifer's hydrologic system would become virtually useless—landowners would refuse to build homes over potential sinkholes, ranchers could not run livestock for fear of sinkholes and businesses would relocate to areas safe from potential collapse.

Additionally, the region would lose its appeal as a tourist destination if water supply became scarce or polluted. Turner Falls and the Chickasaw National Recreation Area (hereinafter "CNRA"), among a host of other attractions, draw millions of tourists to the vicinity each year. These tourists contribute substantially to the economies of surrounding communities. In 2005, the total impact of tourists to the CNRA area supported 249 jobs, generated $4.7 million in wages and salaries, and brought $7.0 million in value added. *See* **Attachment 6**, Daniel J. Stynes, Impacts of Visitor Spending on the Local Economy: Chickasaw National Recreation Area, 2005.

The CNRA and Turner Falls are but a portion of the recreational outlets that are supported by the ASA. Others include the Slippery Falls Church Camp, Falls Creek Baptist Church Camp, Camp Classen YMCA, Lake of the Arbuckles, Goddard Youth Camp, Camp Bond-Nazarene Church Camp, the Blue River Public Camp & Fish Area, Camp Simpson Boy Scout Camp, Durant State Fish Hatchery, and Pettijohn Spring Christian Camp; however, this list is far from exhaustive.

V. Arbuckle Aggregates' Permit Application Should be Denied because it does not Comply with DOM regulations.

Arbuckle Aggregates' permit application is not only substantively deficient, but procedurally inadequate, as well. The application fails to satisfy the requirements set forth in DOM regulations, which represent only the "minimum general criteria" for permits and permit applications. OAC 460:10-9-1. Thus, satisfaction of DOM minimum requirements does not necessarily mean that an application should be granted. Arbuckle Aggregates, however, fails to meet even these minimum general criterions.

A. The Mining Application Submitted by Arbuckle Aggregates Fails to Address the Removal and Storage of Surplus Groundwater.

The mining application submitted by Arbuckle Aggregates does not account for the thousands of acre-feet of pit water it will be forced to pump from its pits. Although pit water itself is currently unregulated, its disposal and effect on surrounding surface and ground water must factor into the DOM's decision.[4] As stated above, pit dewatering has disastrous effects on nearby waterbodies that result in irreparable harm to the environment. The DOM must deny Arbuckle Aggregates' permit application because of Arbuckle Aggregates' failure to account for the entirety of its operations.

B. Arbuckle Aggregates Does Not Have the Necessary Permits under the Clean Water Act.

Arbuckle Aggregates attempts to avoid the need for a section 404 permit under the Clean Water Act by carefully drawing its proposed mine around the various waterbodies encompassed within the mining area. However, as set forth above, activities which may impair or alter the reach, flow or circulation of jurisdictional waters must obtain a section 404 permit. *See* 40 CFR §232.3(b). The reach, flow and circulation of the tributaries running through Arbuckle Aggregates' property will be altered and/or impaired by the proposed 300-foot pits to be dug on either side. Although Arbuckle Aggregates has left a "buffer area" around the stream, it is disingenuous to claim that massive 300-foot pits on either side of a stream will not impair, alter and drain the stream and its wetlands—especially in light of the area's porous geologic characteristics. Arbuckle Aggregates' mining application must be denied because it has not obtained the statutorily-required section 404 permit.

Arbuckle Aggregates also failed to obtain a Section 402 permit for its discharge of pollutants from a point source into water of the United States. Arbuckle Aggregates indicates in

[4] Oklahoma water policy strictly forbids the waste of water. The OWRB categorizes waste into different categories, once of which is waste by depletion. Waste by depletion is the unauthorized use of wells or groundwater. OAC 785:30-1-3. Examples provided by the OWRB of waste by depletion seem to describe Arbuckle Aggregates' proposed operation. Examples include using fresh groundwater without a permit, taking more fresh groundwater than is authorized by permit and taking or using fresh groundwater so that it is lost for beneficial use. Arbuckle Aggregates openly admits it intends to use fresh groundwater that infiltrates the pits in its mining process. Arbuckle Aggregates has not, however, sought a permit for the use of such pit water. Thus, any pit water used by Arbuckle Aggregates would be waste by depletion because it is use without a permit, use in an amount greater than what is authorized by permit and use that denies other individuals the ability to make beneficial use of the water.

its application that it has received two general OPDES permits, one for air quality and one for storm water construction discharge authorization. It has failed, however to obtain an OPDES permit for point source discharges. *See* Section 402, *supra*. The DOM cannot grant Arbuckle Aggregates' permit application because it has failed to obtain the necessary permits required to legally perform its operations.

C. Arbuckle Aggregates' Reclamation Plan does not comply with DOM Regulations.

A non-coal mining permit application may only be approved if four elements are satisfied. First, the application must be accurate, complete, and in compliance with all statutory and regulatory requirements. Second, the applicant must demonstrate that the non-coal surface mining and reclamation operations, as contained in the application, are feasible. Third, the applicant and/or the operator does not control or has not previously controlled a mining operation with an established pattern of willful violations of DOM regulations such that irreparable damage was done to the environment. Lastly, the applicant must provide a performance bond or other equivalent guarantee. OAC 460:10-17-10. Arbuckle Aggregates' permit application does not satisfactorily meet each of these four elements and therefore must be denied.

1. Arbuckle Aggregates' Permit Application is not Accurate, Complete or in Compliance with all Statutory and Regulatory Requirements.

Arbuckle Aggregates' permit application does not satisfy even the "minimum general criteria" for permits and permit applications. OAC 460:10-9-1. The burden of providing all the information required by DOM regulations rests solely on the applicant, in this case Arbuckle Aggregates. OAC 460:10-11-3. Because Arbuckle Aggregates has wholly failed to comply with the minimum general criteria set forth in DOM regulations, DOM must deny the permit application.

The Reclamation Plan Submitted by Arbuckle Aggregates does not Comply with DOM Regulations.

The DOM identifies the foundational purpose of any reclamation plan as being the continuous establishment of "vegetative cover, soil stability, and water and safety conditions appropriate to the area." OAC 460:10-15-1 (emphasis added). The area in which Arbuckle Aggregates proposes to mine is extremely sensitive to water use. Moreover, verified scientific data establishes that mining conducted in karst geologic structures, such as the ASA, have far more pronounced negative impacts than mining in other geologic formations. Thus, the DOM must analyze Arbuckle Aggregates' reclamation plan with heightened scrutiny, as is appropriate for such an environmentally-delicate area.

Additionally, the DOM requires reclamation be conducted simultaneously with mining when feasible. OAC 460:10-15-2. Feasibility is the product of numerous factors, such as efficiency, productivity, harm to the environment, and cost. A mine may not claim simultaneous reclamation is infeasible simply because it costs money. Similarly, a mine is not exempt from simultaneous reclamation by claiming it is inconvenient. Feasibility, then, must weigh all the relevant factors; including environmental damage and conditions which are unique to the area.

With respect to the reclamation plan, Arbuckle Aggregates failed to comply with the black letter regulations, let alone the spirit behind requiring reclamation strategies. Specifically, DOM regulations require the applicant to provide the "methods to prevent or eliminate conditions that will be hazardous to animal or fish life in or adjacent to the affected land." OAC 460:10-15-3(a)(2). Affected land, as defined by the DOM, is any land or water upon which surface mining activities are located and/or conducted. OAC 460:10-3-5. Adjacent land refers to land "located outside the affected area or permit area . . . where air, surface or ground water, fish, wildlife, vegetation, or other resources protected by this Title may be adversely impacted by surface mining and reclamation operations." OAC 460:10-3-5. Thus, Arbuckle Aggregates is required to set forth its proposed methods to prevent or eliminate harmful conditions to wildlife and aquatic organisms found not only in its permitted area, but for any area which may be adversely affected.

Arbuckle Aggregates intends to implement the following "methods":

> While operating, the facility will adhere to federal, state and local regulations governing air, water, wastes, and hazardous substances—this greatly reduces the impact on wildlife in the future. During the reclamation process an erosion and water management plan will be developed to minimize potential impacts to aquatic life and water quality. Mining pits (or parts of) will be graded to allow reasonably safe ingress and egress for wildlife while being structurally stable. Berms, buffers or some type of barrier may be employed to restrict access to hazardous slopes.

See Arbuckle Aggregates Non-Coal Surface Mining Permit Application, May 7, 2010.

This nebulous statement is hardly a description of "methods" to be utilized or procedures to be followed, but rather a regurgitation of key environmental terms, which, when read as a whole, fail to provide even the slightest indication as to the techniques or processes to which Arbuckle Aggregates will adhere. Arbuckle Aggregates states it will abide by federal, state and local regulations—however, it refuses to obtain the necessary permits required by the very federal, state and local laws it vows to follow. *See* Section V.B., *supra*.

Protections for Wildlife and Aquatic Species within the Affected Area

Arbuckle Aggregates fails to identify the protections it will implement in order to prevent or eliminate harmful conditions to wildlife during its mining activities. The area of operation alone is over 500 acres, yet Arbuckle Aggregates cannot set forth any concrete steps it will take to ensure the wildlife in the area remain unharmed. Moreover, Arbuckle Aggregates will be mining away streams, springs and creeks. Yet no mention was made of the techniques to be employed to prevent harm from being inflicted upon the aquatic species living in the affected areas. Because Arbuckle Aggregates did not provide the techniques it would use to prevent or eliminate conditions harmful to wildlife and aquatic species within the affected area during the mining operations, its reclamation plan is administratively incomplete and thus the DOM cannot legally grant Arbuckle Aggregates' permit application.

Similarly, Arbuckle Aggregates did not identify the precautions it will take to prevent or eliminate conditions dangerous to fish and wildlife during the reclamation process. Promising that an erosion and water management plan "will be developed" is no substitute for actually providing the plan. It is critical that Arbuckle Aggregates develop an erosion and water management plan prior to commencing its operation in light of the ASA's designation as a Sole Source Aquifer.

Protections for Wildlife and Aquatic Species in Adjacent Areas

Absolutely no mention is made of methods to be employed in areas adjacent to the permitted land. This glaring omission is unacceptable. Scientific data has established that mining has a far-reaching effect in geologic formations such as the ASA. *See* Attachment 5. Mining operations in the close vicinity of Arbuckle Aggregates' proposed site have already had severe environmental impacts in the region.[5] These impacts will only continue to degrade and diminish the principle source of drinking water for tens of thousands of Oklahoma citizens.

---

[5] Operations in the area, such as Meridian Aggregates and U.S. Silica, have decreased the flow of Mill Creek to such an extent that it is often little more than a trickle. Additionally, dust has become increasingly a problem for residents of the area. These, and other pronounced effects, will only be compounded by adding yet another mining operation in the area. Indeed, scientific data predicts the environmental damage created by an additional mine will be disproportionately greater than the environmental impact of the first mine in the area.

DOM regulations are quite clear—describe the methods to be used in preventing or eliminating potentially harmful conditions to fish and wildlife in the permitted area and in the area adjacent to or affected by the mining operations. Arbuckle Aggregates cannot feign ignorance to such explicit requirements, nor can it be allowed to escape the mandates of the DOM by providing obtuse, uninformative answers. Because Arbuckle Aggregates failed to provide a detailed process for reclamation, as required by the 1994 revisions to the reclamation standards, its permit application must be denied.

The reclamation plan must also include the "[m]ethod of control and disposal of mine waste, rock, mineral scrap, tailings, slimes, and other material directly connected with the mining, cleaning, and preparation of mineral substances mined and includes all waste materials deposited on or in the permit area from any source." *See* Arbuckle Aggregates' Non-Coal Surface Mining Permit Application, Section 4(4), May 7, 2010. Without addressing the question asked, Arbuckle Aggregates stated that

> Crushed stone products will be produced at this facility. Overburden, fines or off-spec materials will either be sold as product or used during the reclamation phase for grading and stabilization purposes.[6]

See Arbuckle Aggregates' Non-Coal Surface Mining Permit Application, Section 4(4), May 7, 2010.

It comes as no surprise that crushed stone products will be produced—that is, in fact, the reason for Arbuckle Aggregates' permit application. Even less of a surprise is the fact that Arbuckle Aggregates has made a business decision to utilize overburden and other unmarketable products in the reclamation process. What is noteworthy, however, is Arbuckle Aggregates'

[6] Arbuckle Aggregates reference to a "reclamation phase" only exemplifies its inability to comply with Oklahoma statute and DOM regulations, which both require simultaneous reclamation rather than a separate reclamation phase.

failure to identify the steps, processes, and procedures to be used to prevent and control contamination and pollution caused during the reclamation process. For example, Arbuckle Aggregates is seemingly oblivious to the contamination and pollution that will occur from spreading crushed stone material throughout a karst geologic formation rife with streams, springs and creeks. Unless and until Arbuckle Aggregates complies with DOM regulations, no permit can be issued.

VI. The Permit Application must be Denied because of Fatal Administrative Flaws in the Permitting Process.

A. The one-mile limitation on protests violates due process.

45 O.S. § 721(H)(2) provides that "[a]ny property owner or resident of an occupied dwelling who may be adversely affected located within one (1) mile of the mining operation shall have the right to protest the issuance of a permit and request a public hearing." Further, OAC 460:10-17-6 provides the same one (1) mile limitation on the right to file written objections. This limitation violates the due process of both the State and Federal Constitutions. Individuals whose property interests will be substantially affected by the issuance of a permit are guaranteed a right to notice and "an opportunity to be heard through an individual proceeding . . . ." *DuLaney v. Okla. St. Dept. of Health*, 868 P.2d 676, 680 (Okla. 1994). As discussed above, the proposed mining operation would substantially affect the property interest of individuals well beyond the one (1) mile limitations. As such, the limitations are unconstitutional under due process principals.

B. The DOM's Permitting Procedures Deny Citizens the Right to Adequately and Meaningfully Participate in the Administrative Process in Violation of the Due Process Clause.

The DOM states that the purpose of its non-coal practice and procedure rules is to "ensure public access to the administrative legal process and to ensure due process of law to the citizens of the state of Oklahoma." OAC 460:3-1-1. Yet the permit application process for the DOM denies individuals the opportunity to adequately and meaningfully participate in the administrative process. Furthermore, DOM procedures functionally deny Oklahoma citizens their constitutionally protected due process rights.

Normally, an agency makes a decision after taking into account all evidence and testimony presented at a hearing—indeed, the entire purpose of a formal hearing is to elicit evidence and create a record from which an educated and informed decision can be made. However, the DOM makes its decision *before* holding a hearing and only after deciding whether to issue a permit.

The DOM's staff summary of the informal conference conflicts with current state law. The agency decision-maker relies on the informal conference summary when making the decision, however the decision is based only by the information put in the summary by an individual who has complete control over what information to include. There is an inherent risk that the conference summary will misconstrue or exclude relevant information. This risk becomes all the more acute since the decision is based on the conference conclusion.

Although a formal hearing is eventually conducted, practically speaking the DOM's decision is already made. Such a practice denies an individual the ability to fully and completely present evidence in support of his/her position. Additionally, this process improperly shifts the burden to the protester to prove that the permit should not be issued rather than requiring the applicant to establish the permit should be granted. The protester is at an immediate disadvantage in this process—not only must evidence be presented in support of the protester's case, but he/she must present sufficient evidence to overturn the agency's decision. In essence, the agency makes its decision without any evidence, let alone substantial evidence, and then leaves protesters with the formidable task of proving the agency wrong.

Further, DOM regulations do not allow protesters to engage in discovery prior to the informal conference. In fact, a protester is never guaranteed the right to conduct discovery. Discovery is contingent on two factors: first, an individual cannot engage in discovery unless and until the DOM determines a formal hearing is necessary. Second, discovery is only allowed at the hearing examiner's discretion. It is entirely possible that, even if a formal hearing is granted, a protester will be denied the right to conduct discovery or will be severely limited in the scope of discovery.

In this case, the DOM will make its decision after only the informal conference without the aid of a complete record containing evidence and testimony on the issues. Moreover, protestors will not have had the benefit of discovery when presenting their protests. The applicant is clearly in the best position to know all the facts relating to its application. Many of those facts will significantly impact the protests that CPASA and its members may ultimately lodge. However, DOM processes prevent CPASA from learning those relevant facts before presenting its protests at the informal conference. Indeed, the DOM will make its decision in this matter before the protesters ever have a chance to learn of all the facts relevant to this matter.

The Supreme Court of Oklahoma held that individuals whose property rights may be substantially affected by the issuance of a permit are guaranteed by the due process clauses of both the federal and state constitutions to notice and "an opportunity to be heard through an individual proceeding . . . ." *DuLaney v. Okla. St. Dept. of Health*, 868 P.2d 676, 680 (Okla. 1994). The opportunity must be one for a meaningful hearing, informed by all the relevant facts. CPASA and its members raised several property-oriented concerns, including the depletion and pollution of water resources, the deposit of dust and other particulates on nearby private properties, the decrease in area property values, and the contamination of the Arbuckle Simpson Aquifer—a water source utilized by many members of CPASA as a water supply. Thus, the DOM administrative process does not afford CPASA its constitutionally protected right to meaningfully and adequately participate in the administrative process.

Because the DOM permitting procedures inadequately protect the interests of CPASA and its members, Arbuckle Aggregates' permit application must be denied until a formal hearing had been held.

CONCLUSION

Arbuckle Aggregates bears the burden of establishing the necessary information to the DOM. For the reasons stated above, CPASA and its members believe that Arbuckle Aggregates wholly failed to meet that burden. Because Arbuckle Aggregates did not satisfy the mandatory statutory requirements, the DOM must deny its mining application. In the event that the DOM grants Arbuckle Aggregates' permit application, CPASA and its members demand a formal hearing.

Sincerely

Jason B. Aamodt, Esq. and
Krystina Hollarn, Esq.
The Aamodt Law Firm
1723 S. Boston Ave.
Tulsa, Oklahoma 74120
(918) 347-6169
(918) 398-0514 (fax)

Attorneys for CPASA

ATTACHMENT 1

FINAL REPORT

ANALYSIS OF SEISMIC REFLECTION DATA FROM THE HUNTON ANTICLINE

Funding Agency:	Oklahoma Water Resources Board
Project:	Development # 08S0733
Project period:	15 June2008 – 15 Sept 2008
Date of submission:	05 March 2009
Principal Investigator:	Professor Roger A. Young
Student participants:	Breanne Kennedy, Carlos Russian

Abstract

Seismic reflections from boundaries within the Cambrian-Ordovician Arbuckle-Simpson aquifer correlate with boundaries seen in well logs and rock samples. Seismic surveys at different geologic scales within this karst aquifer display the same fault character regardless of the survey's target depth. Faults observed at intermediate depths in the Arbuckle-Simpson aquifer extend upward to the location of mapped fault traces, and such faults are seen clearly on ground penetrating radar and electrical resistivity imaging surveys. Some of these faults also extend downward cutting the basement, and, in one instance, form a graben at the aquifer/basement boundary. This suggests that mapped fault locations, confirmed by near-surface geophysics, may be a fingerprint of steeply dipping faults extending through the carbonate section into the basement.

Introduction

The Arbuckle-Simpson aquifer of south-central Oklahoma (Figure 1a) is a fractured-karst aquifer that is the source of water for approximately 39,000 people in the area surrounding the cities of Ada and Sulphur. It also provides water to the Chickasaw National Recreation Area. Recently, proposals have been made to supply water from the aquifer to more distant population centers. In order to evaluate the groundwater resources of the aquifer, a 5-year study by the Oklahoma Water Resources Board was initiated in 2003 (Osborn, 2003). The work presented in the present paper is a component of the geophysical surveys conducted in conjunction with this study.

Geologic setting of three seismic surveys

A SW-NE geologic cross-section through the aquifer (line D-D' on Figure 1a) shows a broad dome, the Hunton Anticline, in the center of the cross-section (Figure 1b), and complex folding and faulting at the southern and northern margins of the cross-section. We have analyzed data from three seismic surveys crossing the lower Ordovician Arbuckle and Timbered Hills Groups comprising the anticline. The geologic scale of these surveys ranges from the deep aquifer/basement contact (at a depth of approximately 3500 ft), through intermediate boundaries within the aquifer (at depths of 3500- 600 ft), and extends through the shallow epikarst to the ground surface. The image of the shallowest features seen in the seismic surveys was also supplemented by electrical resistivity imaging (ERI) and ground-penetrating radar (GPR) surveys. Three seismic surveys are considered in the present paper (Figure 2).

Anschutz Line OK 3-80: basement, deep aquifer

Description of Anschutz Line OK 3-80

Seismograph Service Corporation Party M conducted initial test recording for Line OK 3-80 on 21 Feb 80. Optimal recording parameters were determined by stacking 10, 20, or 30 sweeps from a group of three Pelton vertical vibrators. The chosen sweep parameters were 15 to 20 sweeps per VP, up-sweeps from 14 to 56 Hz, and a sweep length of 16 s. A 48-channel DFS IV Instantaneous Floating Point system recorded the data. Geophones were model GSC 20D having a natural frequency of 8 Hz and a 3 in spike. There were 6 geophones per string, and 4 strings spanned 220 ft. The symmetric split spread length at each station was 11,440 ft. The shot interval was 220 ft giving a nominal fold of 24.

Production recording began on 22 Feb 80 and continued through 28 Feb 80. The sample rate was 4 ms. Professional Geophysics Inc. performed initial processing in March 1980, and Western Geophysical reprocessed the data in 2006, and the latter result was interpreted in the present study.

Basement reflection

The deepest continuous reflection on Line OK 3-80 (yellow horizon, Figure 3) is the reflection from the top of the igneous basement. The depth to this boundary was established by ray-trace modeling and well data to be approximately 3500 ft (Kennedy, 2008, p 38).

The most striking feature of the basement reflection is its horizontal disruption over a width in the seismic section of approximately 1.6 km and a coincident vertical disruption of 50 ms (equivalent to approximately 250 m). This substantial feature is larger than a karst dissolution feature such as a cave.

Fracturing

The enigma of the basement disruption is associated with large-scale and extensive faulting and fracturing (Figure 3). From the basement to the surface the aquifer is extensively chopped up. Steeply-dipping faults cut the basement reflection, and strong reflections above the basement show offset across a number of faults.

The association of the Blue River (top of Figure 3) and the basement disruption raised the possibility of inaccurate static correction in reprocessing by WesternGeco: the slow soil layer would be thicker in the Blue River valley than to either side and failure to account for this would cause an apparent sag in the basement reflection beneath the Blue River. Modeling, however, showed that this would be insufficient to cause a sag of 50 ms and an indistinct basement reflection (Kennedy, 2008). Furthermore, reflections directly above the basement are not blurred as would occur if inaccurate static corrections had been made. The inference is that B and C (Figure 3) are faults bounding a graben, a major structural feature in the basement.

Our interpretation is reinforced by an analogous seismic profile from the Ft. Worth Basin (Figure 4). Here the time equivalent of the Arbuckle-Simpson Group, the Ellenberger Formation, is buried below sediments to a much greater depth. But it exhibits the same through-going faults forming fault-bounded grabens. The linear fracture intensities in the two cases are 1.57 and 1.55 faults/km in the Oklahoma and Texas cases, respectively. Small synclines occurring above the basement are interpreted (Chopra and Marfurt, 2006) to be collapse features associated with reactivation of faults. This same process may have affected the formations underlying the Anschutz section.

Spears Ranch 3D cross-spread: intermediate aquifer depth

Exploration scale seismic profiles such as Line OK 3-80 are costly. The fact that basement-cutting faults from Line OK 3-80 extend to the surface motivated our attempt to locate such faults using less-costly, near-surface geophysical surveys. An obvious location for this attempt would have been at faults B and C along Line OK 3-80. However, the presence of well control, the need for an area in which to acquire a 3-D seismic survey, and the existence of electrical resistivity imaging results directed us to the Spears and Arbuckle-Simpson Ranch sites.

In 2007, the University of Oklahoma, assisted by the University of Texas, El Paso, and the PASSCAL facility of IRIS, acquired a single P-wave cross-spread 3D survey at the Spears Ranch (Figure 5). The sources were small dynamite charges and were recorded by Texan seismographs designed by Prof. Randy Keller. The basement boundary and intermediate to shallow boundaries within the aquifer were the primary targets of this survey. The Spears #2 well-logs and cuttings analysis provided control in identifying reflecting boundaries in the cross-spread.

Recorders were deployed along a N-S and a W-E line. Each shot along the lines was recorded at all stations resulting in high fold along the backbone of the survey (the N-S and W-E lines) and very low fold in between. The irregular shot spacing and non-orthogonality of the cross-spread contribute to sparse, highly variable fold. An example of successful groundroll attenuation by F-K filtering a shot gather is shown in Figure 6a, and Figure 6b identifies two reflections at approximately 160 ms and 640 ms on a CMP gather along the N-S backbone. The basement reflection seen on the Anschutz Line OK 3-80 (Figure 3) at approximately 400 ms could be the 640 ms event at the Spears Ranch. The shorter traveltime for the former may be explained by two factors: the former has been static-corrected to a datum of 1000 ft but the latter has not, and the former is 7 mi up-dip of the latter.

Although we have not completed processing the lowfold 3-D volume from the cross-spread, we have interpolated through the coverage area from the two high-fold lines to give some sense of the topography of the 160 ms reflection surface (Figure 7).

A-S Ranch profile: shallow aquifer and epikarst

We acquired a near-surface P-wave seismic reflection survey at the Arbuckle-Simpson Ranch 1 mile north of the Spears Ranch cross-spread. Targets were the lower part of the epikarst, which extends to at a depth of approximately 50 m (Sample, 2008) and sedimentary units in the aquifer itself beneath the epikarst. An 8-gauge Betsy gun was fired end-on into a roll-along spread and was recorded by a 24-channel StrataView system. We used vertical component geophones having a 40 Hz natural frequency. Minimal CMP processing included datum statics, surgical muting of groundroll, AGC gain, and bandpass filtering. The stacked section (Figure 8) reveals a reliable tie to boundaries logged and sampled in the Spears #2 well. The top of the Kindblade (Figure 8) is a strong reflection at approximately 100 ms. A reflection corresponding to the top of the Cool Creek agrees well with the early reflection identified on the Spears Ranch cross-spread (Figure 7), but the energy from the Betsy gun is unable to discern the 640 ms reflection identified on the cross-spread.

The most notable features revealed by the near surface seismic survey are two closely-spaced faults cutting the Cool Creek and Kindblade horizons (Figure 8). The faults do not appear to reach the surface, but this may be due to apparent blanketing by the refraction first arrivals, which were not muted before stacking. To investigate this further, supplemental geophysical surveys were conducted by OU and OSU in the same area as the Arbuckle-Simpson reflection survey. Superposed electrical resistivity Line ASR5.00B and ground-penetrating radar Line 2 intersect the seismic survey (Figure 9a) at the fault location. Both the ERI resistivity inversion (Figure 9b) and the GPR processed section (Figure 9c) show a fault extending to the surface in the same location as the fault identified on the seismic survey.

Correlation of fault location by geologic mapping and by geophysics

Geologic mapping of the Hunton Anticline as shown recently in Johnson (1990) identified the presence of faults long before the geophysical surveys described in the present paper were conducted. The map (Figure 10a) shows three major faults, which correspond very closely to the three faults we interpreted on Line OK 3-80. Projection upward of the interpreted basement disruption falls squarely between the faults. Faults A and B (Figure 10b) plunge through the entire aquifer, cutting the top of the basement and continuing into it. Faults B and C converge as they approach the basement, forming the graben described in Figure 3. Moreover, subsidiary faults were mapped between B and C (gray lines, Figure 10a), and reflections from these would add further to the indistinct reflection image of the graben observed on Line OK 3-80.

Conclusions

Seismic surveys such as OK 3-80 are costly. This paper has shown that faults and associated fractures can be located at intermediate depths by much smaller scale seismic surveys and even by electromagnetic and electrical surveys at shallow depths. This suggests that using near-surface geophysics to confirm the location of geologically-mapped fault traces may be an efficient strategy to locate basement-cutting faults.

Hydrologic significance

The need to delineate faults and fracture systems that may control groundwater flow is great. High fracture intensity, rapid vertical communication at a depth of 1820 ft in the Spears #1 well (Osborn, 2007), reported fresh water in exploration wells (Kennedy, 2008), and potential lateral flow in the Reagan sandstone at the base of the aquifer (Kennedy, 2008) all suggest the importance of deep fractures to groundwater recharge and their importance in groundwater flow simulation.

References

Chopra, S., and Marfurt, K., 2006, Seismic Attribute Mapping of Structure and Stratigraphy, Distinguished Instructor Series No. 9, ISBN 1-56080-125-2, SEG, Tulsa, 226 pp.

Davogustto, Oswaldo, Young, Roger Adams, Cemen, Ibrahim, 2008, Fracture pattern delineation using seismic attribute algorithms in a 3D GPR data set, SAGEEP 2008, accepted.

Johnson, K.S, 1990, Geologic map and sections of the Arbuckle Mountains, OK, Plate 1, *in* Hydrology of the Arbuckle Mountains Area, S-Central Oklahoma, OGS Circular 91.

Kennedy, B., 2008, Seismic features of the Arbuckle-Simpson aquifer determined from surveys at three different geologic scales, MS thesis, University of Oklahoma, Norman, 81 pp.

Osborn, N., 2007, The Arbuckle-Simpson Hydrology Study, OWRB Newsletter, March.

Osborn, N., 2003, The Arbuckle-Simpson Hydrology Study: management and protection of an Oklahoma water resource, OWRB Newsletter, November.

Sample, M.A., 2008, Characterization of the epikarst over the Hunton Anticline, Arbuckle-Simpson aquifer, OK, MS thesis, Oklahoma State University, Stillwater, OK, 81 pp.

Acknowledgements

We are grateful to Professors Randy Keller and Todd Halihan and their staffs and students at OU and OSU, respectively; to Mr. Steve Harder and Galen Kaip of UTEP; and to staff from the IRIS PASSCAL facility, Socorro, NM, for their assistance in design and execution of the Spears Ranch Survey. The Anschutz Corporation kindly granted us permission to publish our analysis of their line OK 3-80. Devon Energy, the Oklahoma Water Resources Research Institute (OWRRI) and the Oklahoma Water Resources Board (OWRB) all helped fund the surveys. Software crucial to data reduction was provided by Schlumberger (Petrel), Parallel Geoscience Corporation (SPW), Seismic Microtechnology (Kingdom), Hampson-Russell (Elog), ION (GX II), and Sensors and Software Corporation (Ekko-Deluxe). Mr. John Bruno and Mr. Walter Spears were gracious in providing access to their ranches. I am especially grateful to Dr. Neil Suneson, OGS, for discussion and Ms. Noel Osborn, OWRB, for access to the Anschutz data and for encouragement to synthesize all geological and geophysical evidence.

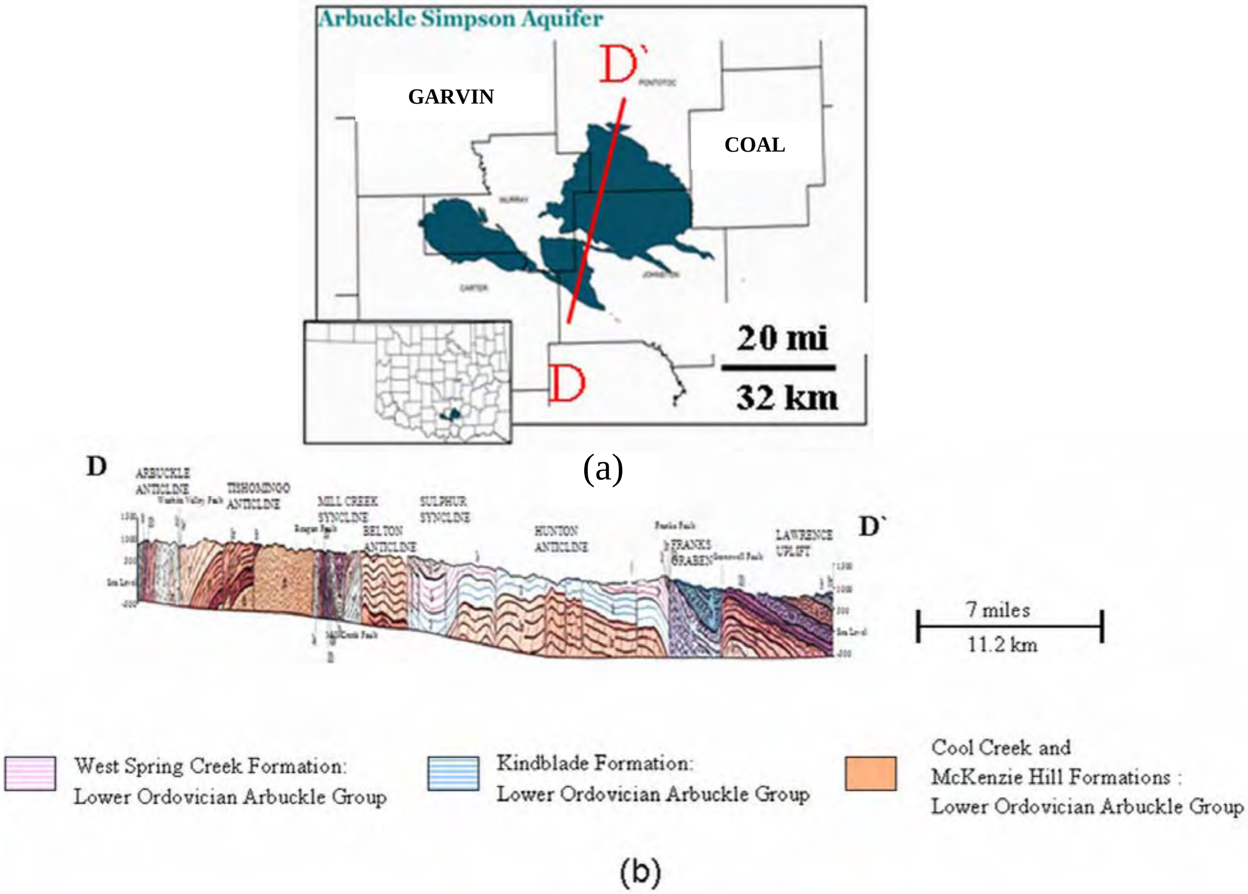


Figure 1 (a) The Arbuckle-Simpson aquifer of south central OK. D-D' is the approximate location of the geologic section shown in (b). The Hunton Anticline (b) is a broad uplift exposing the Lower Ordovician strata of the Arbuckle-Simpson aquifer.

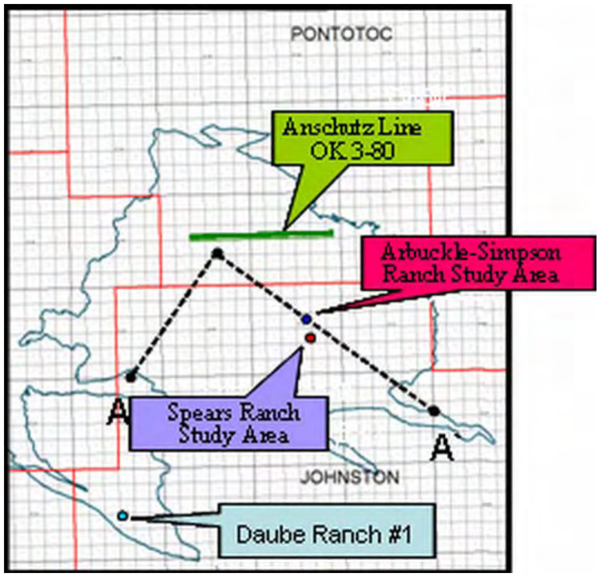


Figure 2 Locations of the three seismic surveys treated in the present paper. Logs from basement penetrating wells at the Daube Ranch, points A and A', and the point at the bend in-between, provide geologic control.

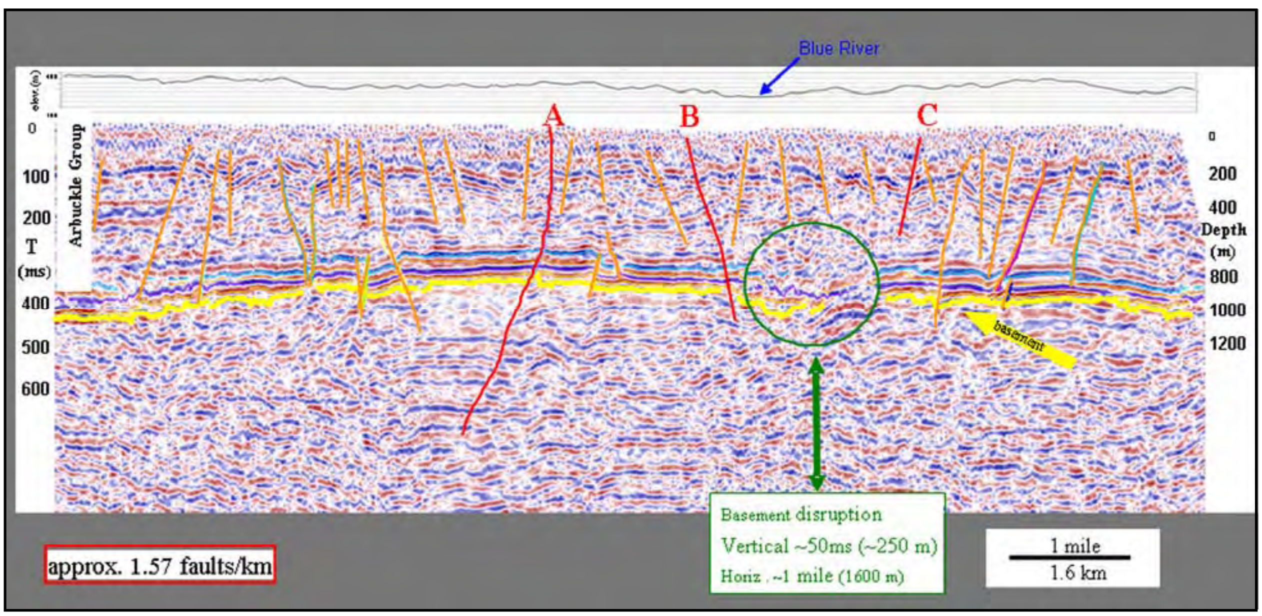


Figure 3 Anschutz Line OK 3-80. West is on the left. A,B, and C are major basement cutting faults, the latter two bounding a zone of basement disruption (green circle). The entire carbonate section above the basement is faulted and fractured.

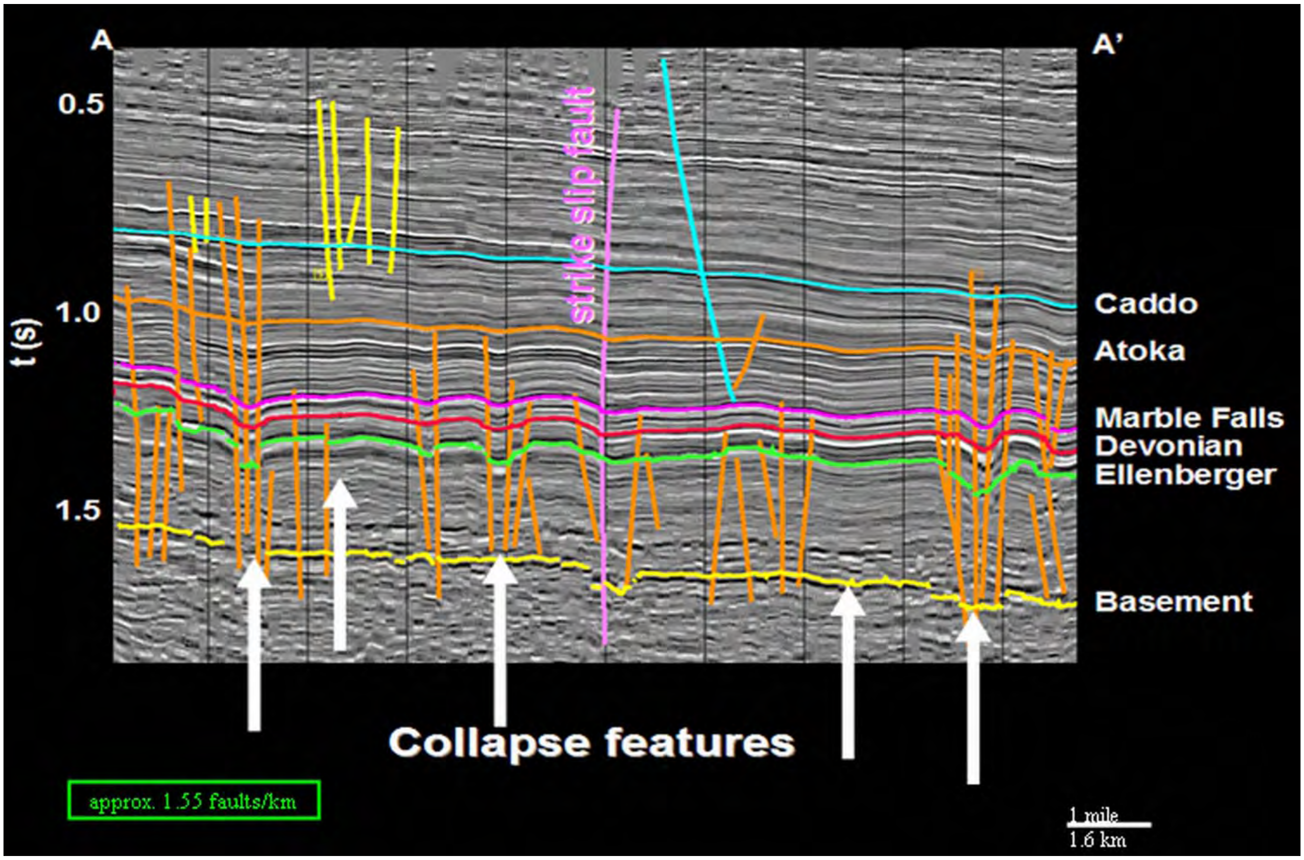


Figure 4 Profile from the Ft. Worth Basin through the Ellenberger Formation, a time-equivalent of the Arbuckle Group. Basement-cutting faults and extensive faulting and fracturing are associated with collapse features recognized in strata overlying the Ellenberger (from Chopra and Marfurt, 2006).

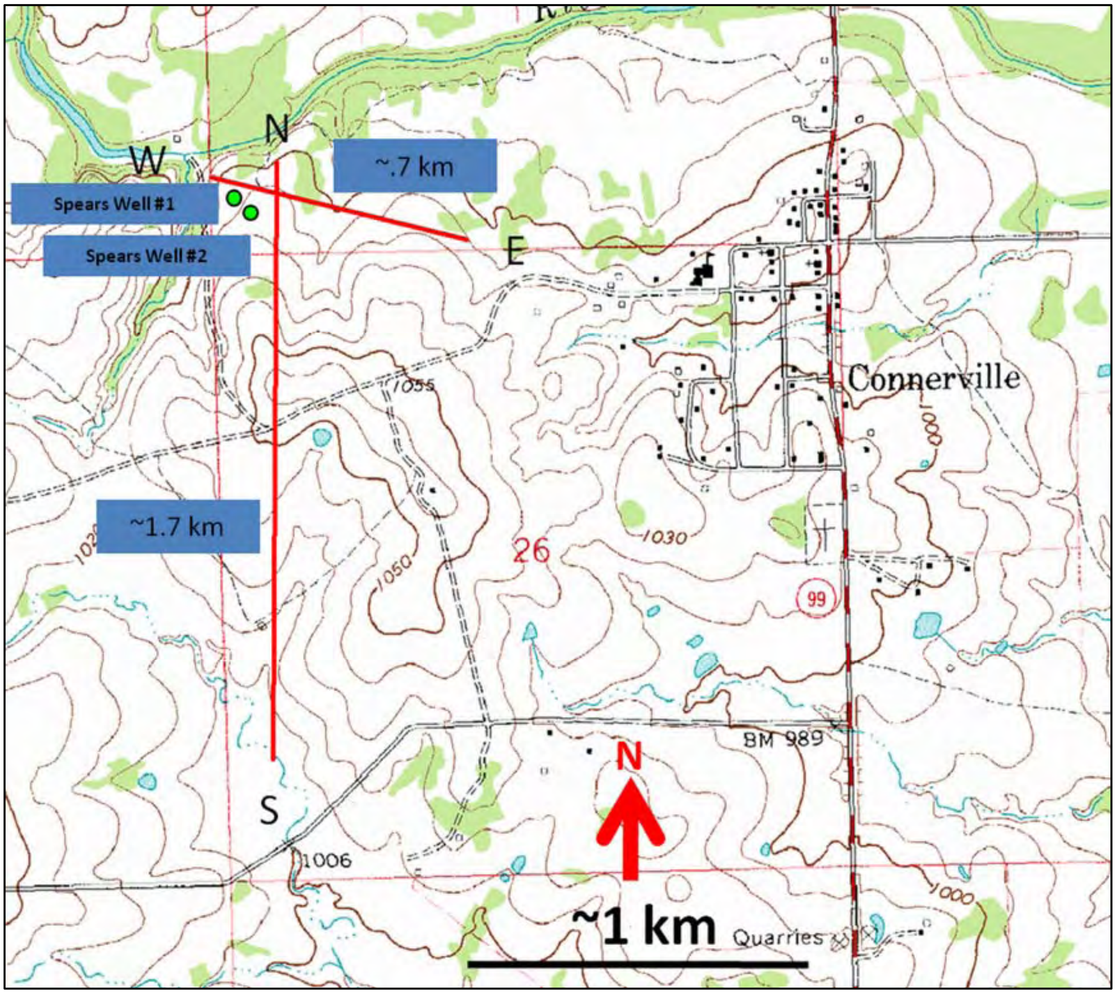
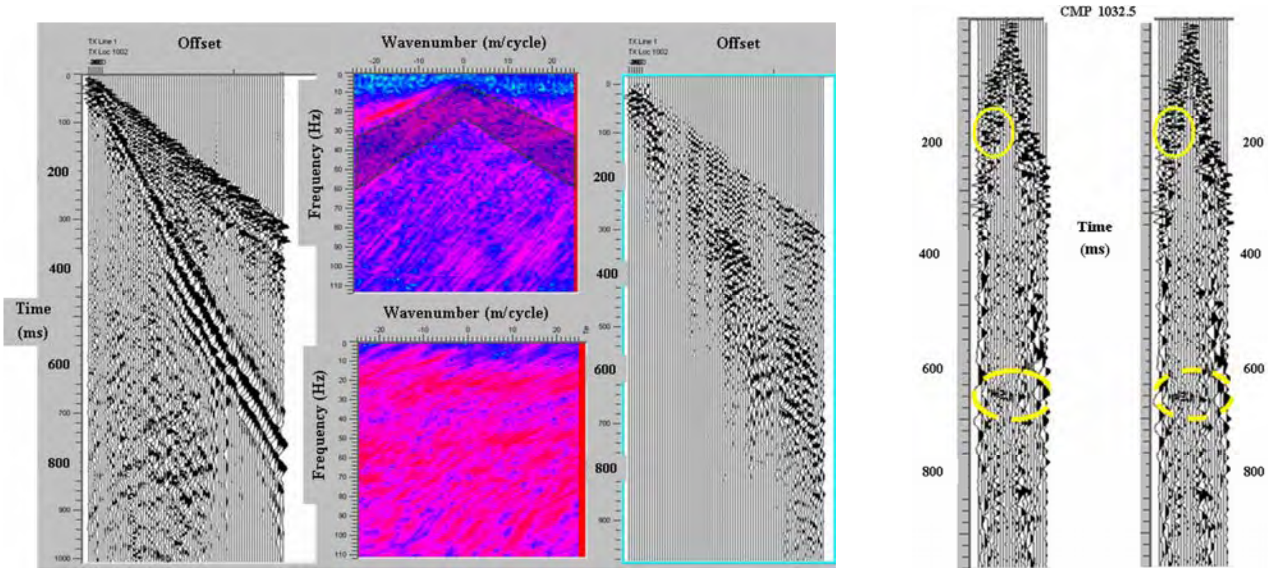


Figure 5 Cross-spread survey at the Spears Ranch. Recorders were located along the N-S and W-E lines, and each shot along the two lines was recorded by all recorders. The green dots are the Spears #1 and #2 wells.



(a) (b)

Figure 6 (a) Groundroll removal from a representative shot gather along the N-S line of the cross spread. (a) *left:* unfiltered shot gather; *center:* F-K spectrum before (above) and after (below) F-K filtering; *right:* filtered shot gather. (b) CMP gather before (left) and after (right) F-K and bandpass filtering, and NMO correction. Processing in (a) reveals reflections at 160 ms (solid yellow ellipse) and at 640 ms (dashed ellipse).

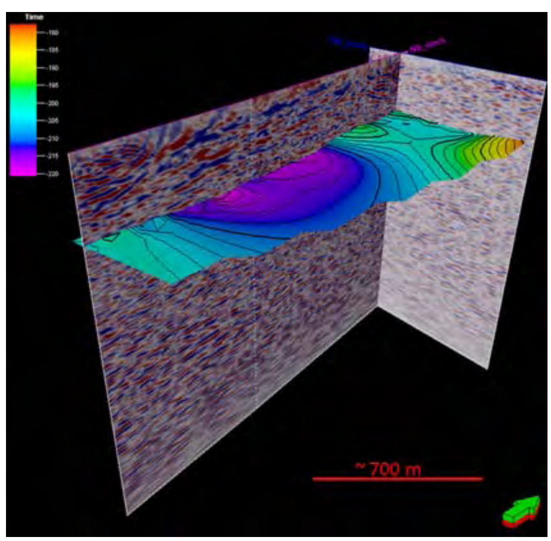


Figure 7 Horizon at 160 ms established by interpolation from picks on the N-S and W-E lines.

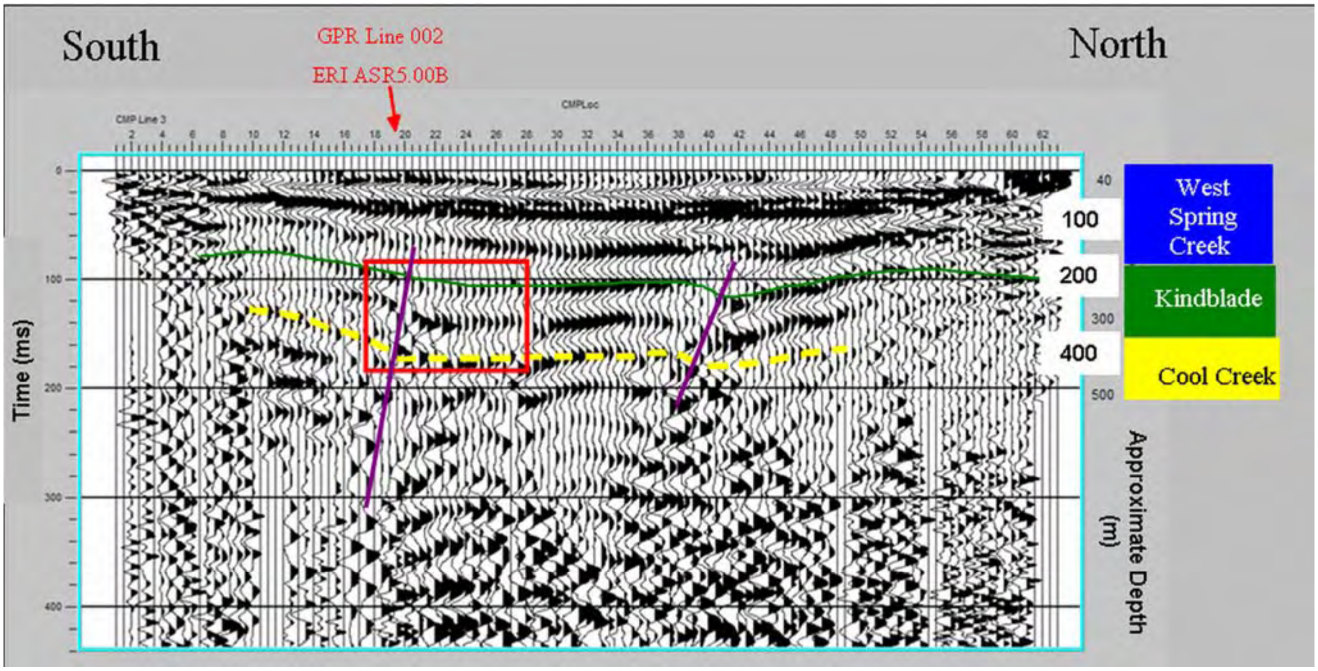
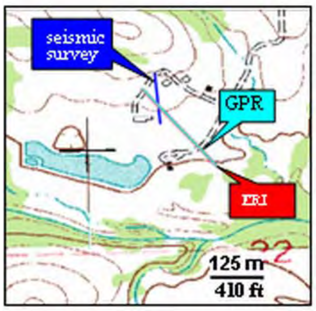
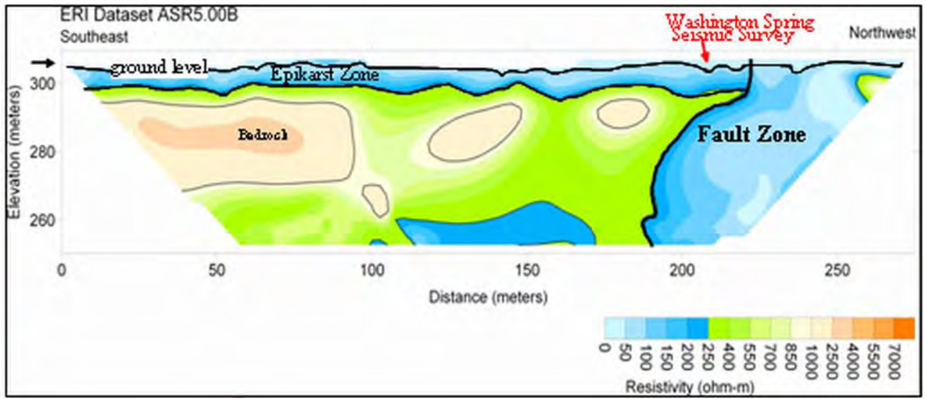


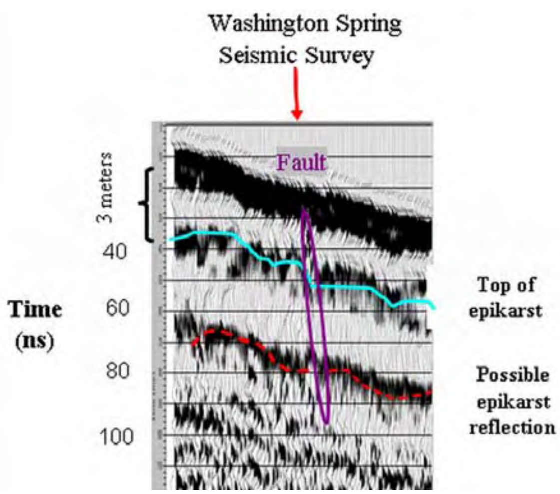
Figure 8 Arbuckle-Simpson Ranch near-surface seismic profile. Depth control from the Spears #2 well identifies the reflections from the top of the Kindblade and Cool Creek formations. Faults (purple) mark breaks in the reflections.



(a)

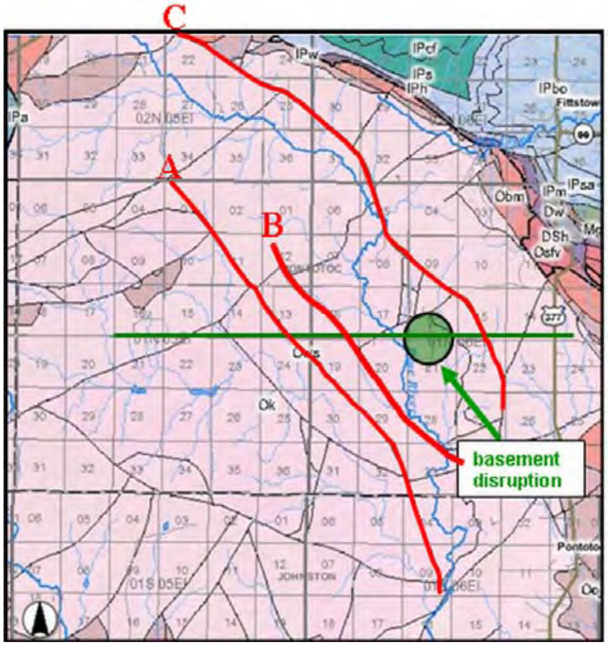


(b)

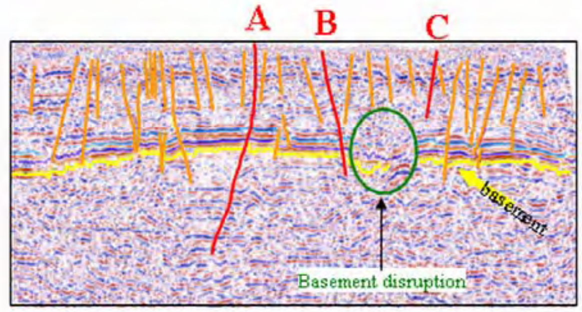


(c)

Figure 9 Coincident surveys (a) locate the same fault by (b) ERI (from Sample, 2008) and (c) GPR methods. This fault is also seen on the near-surface seismic survey (Figure 8).



(a)



(b)

Figure 10 (a) Very close correspondence of geologically-mapped fault traces and faults identified on (b) the Anschutz Line 3-80.

ATTACHMENT 2

Prepared in cooperation with Oklahoma State University and the Oklahoma Water Resources Board

Three-Dimensional Geologic Model of the Arbuckle-Simpson Aquifer, South-Central Oklahoma

By Jason R. Faith,[1] Charles D. Blome,[2] Michael P. Pantea,[2] James O. Puckette,[3] Todd Halihan,[3] Noel Osborn,[4] Scott Christenson,[5] and Skip Pack[6]

Open-File Report 2010-1123

[1]Oklahoma State University, Stillwater, OK

[2]U.S. Geological Survey, Denver, CO

[3]School of Geology, Oklahoma State University, Stillwater, OK

[4]Oklahoma Water Resources Board, Oklahoma City, OK

[5]U.S. Geological Survey, Albuquerque, NM

[6]Dynamic Graphics, Inc., Alameda, CA

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia 2010

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Faith, J.R., Blome, C.D., Pantea, M.P., Puckette, J.D., Halihan, Todd, Osborn, Noel, Christenson, Scott, Pack, Skip, 2010, Three-dimensional geologic model of the Arbuckle–Simpson aquifer, south-central Oklahoma: U.S. Geological Survey Open-File Report 2010–1123, 29 p.

Contents

Figures

Table

Three-Dimensional Geologic Model of the Arbuckle-Simpson Aquifer, South-Central Oklahoma

By Jason R. Faith, Charles D. Blome, Michael P. Pantea, James O. Puckette, Todd Halihan, Noel Osborn, Scott Christenson, and Skip Pack

Abstract

The Arbuckle-Simpson aquifer of south-central Oklahoma encompasses more than 850 square kilometers and is the principal water resource for south-central Oklahoma. Rock units comprising the aquifer are characterized by limestone, dolomite, and sandstones assigned to two lower Paleozoic units: the Arbuckle and Simpson Groups. Also considered to be part of the aquifer is the underlying Cambrian-age Timbered Hills Group that contains limestone and sandstone. The highly faulted and fractured nature of the Arbuckle-Simpson units and the variable thickness (600 to 2,750 meters) increases the complexity in determining the subsurface geologic framework of this aquifer.

A three-dimensional EarthVision™ geologic framework model was constructed to quantify the geometric relationships of the rock units of the Arbuckle-Simpson aquifer in the Hunton anticline area. This 3-D EarthVision™ geologic framework model incorporates 54 faults and four modeled units: basement, Arbuckle-Timbered Hills Group, Simpson Group, and post-Simpson. Primary data used to define the model's 54 faults and four modeled surfaces were obtained from geophysical logs, cores, and cuttings from 126 water and petroleum wells. The 3-D framework model both depicts the volumetric extent of the aquifer and provides the stratigraphic layer thickness and elevation data used to construct a MODFLOW version 2000 regional groundwater-flow model.

Introduction

The Arbuckle-Simpson aquifer is the principal water resource for south-central Oklahoma and is designated a sole source aquifer by the U.S. Environmental Protection Agency. The geology that confines the Arbuckle-Simpson aquifer crops out over an area of about 850 square kilometers according to the Oklahoma Water Resource Board at:
(http://www.owrb.ok.gov/studies/groundwater/arbuckle_simpson/arbuckle_study.php). The

subsurface geologic framework of the Hunton anticline area (fig. 1) was poorly defined prior to this study because of the folded, faulted, and fractured nature of the geology, variable unit thicknesses from 600 to 2,750 meters, and minimal well control.

Previous geologic mapping was conducted primarily by academic institutions and the Oklahoma Geological Survey in the mid-twentieth century. During the last half of this century, most petroleum wells drilled in the Arbuckle, Hunton, and Tishomingo anticlines (fig. 1) were found to be unproductive. In the 1990s, a renewed interest to better understand the regional geology and continental tectonics of southern Oklahoma occurred.

A three-dimensional (3-D) EarthVision™ (EV) geologic framework model, which characterizes the geometric relations and subsurface architecture of the geology of the Hunton anticline area, is summarized in this report. This 3-D EV model contains four modeled geologic units (table 1) and 54 primary and secondary faults. For this report, major faults are defined as having long linear extents and displacements greater than 200 meters. The construction of the model involved integrating geologic and geophysical data from existing maps and surveys, and data from 126 drill holes.

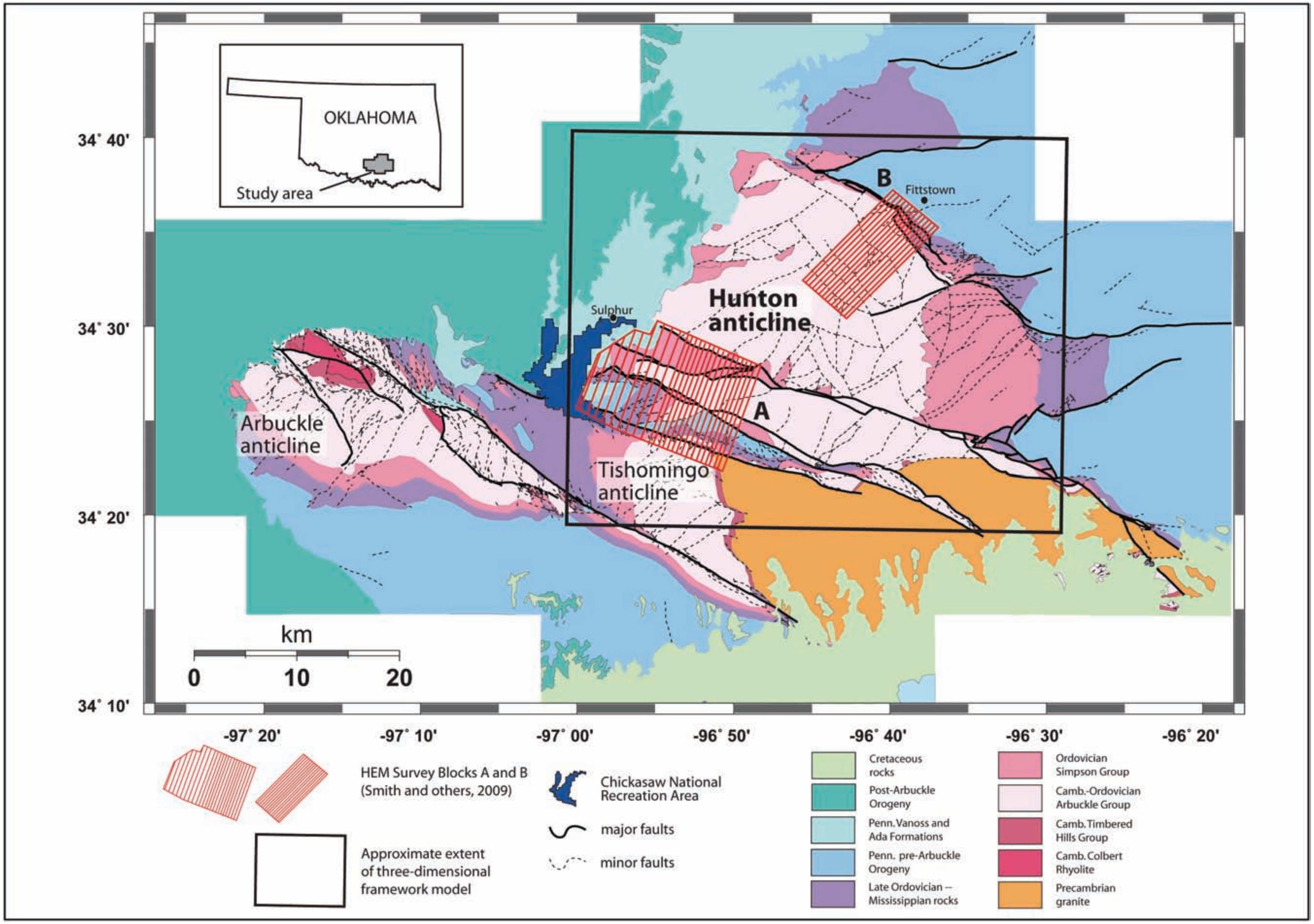


Figure 1. Generalized geology of the Arbuckle, Hunton, and Tishomingo anticlines, Oklahoma, and spatial extent of three-dimensional EarthVision™ model.

Purpose and Scope

In cooperation with the USGS Oklahoma Water Science Center, Okalahoma Water Resources Board, and Oklahoma State University, a three-dimensional geologic framework model was developed to more accurately define the Paleozoic geology and fault structures of the Hunton anticline area (fig. 1). This cooperative study was sought because the geologic framework of the Hunton anticline area affects groundwater-flow and aquifer volume. A 3-D EV model, supported by the USGS National Cooperative Geologic Mapping Program (NCGMP), was built to provide the stratigraphic and structural framework for constructing a MODFLOW (version 2000) groundwater-flow model of the Hunton anticline area. The USGS MODFLOW modeling effort was supported by the Oklahoma State- and federally-funded Arbuckle-Simpson Hydrology Study at: http://www.owrb.ok.gov/studies/groundwater/arbuckle_simpson/arbuckle_study.php.

Geologic Setting

The Arbuckle Mountains consist of folded and faulted Proterozoic granitic and metamorphic rocks, Cambrian rhyolitic rocks, and Cambrian through Early Permian sedimentary rocks. Within the Arbuckle Mountains, the Timbered Hills and progressively younger Arbuckle, and Simpson Groups, makeup the Arbuckle-Simpson aquifer (table 1). The Timbered Hills and Arbuckle Groups are modeled as a single unit because of limited subsurface control. These groups are underlain by Proterozoic and Cambrian rocks. Basement rocks within the 3-D EV model area crop out locally in a few small inliers within the Tishomingo anticline and in areas south of the Hunton anticline where intense faulting elevated the basement rocks to the surface (fig. 1). Basement rocks as deep as 2,500 meters below ground surface (Campbell and Weber, 2006), were identified in 11 drill-hole logs.

Paleozoic rock units thin across the Hunton anticline and thicken to the southwest in the Tishomingo and Arbuckle anticlines. The magnitude of structural deformation also increases to the southwest, with predominantly low-dip angle (less than 20 degrees) exposures of the Hunton anticline compared to complex faulting and steeply dipping to overturned stratigraphy in the Arbuckle anticline to the west (fig. 1).

Time-stratigraphic unit	Rock-stratigraphic unit		Aquifer unit	Model unit
Permian	Post-Simpson	Stratford Formation	Upper confining unit	Post-Simpson
Pennsylvanian		Vanoss Group		
		Ada Formation (Collings Ranch Conglomeratet)		
		Deese Group (Desmoinesian Series)		
		Atoka Formation		
		Wapanucka Formation		
		Springer Formation		
Mississippian		Caney Shale		
		Sycamore Limestone		
Devonian		Woodford Shale		
Silurian		Hunton Group		
Upper Ordovician		Sylvan Shale		
		Viola Group		
Middle Ordovician	Simpson Group	Bromide Formation	Arbuckle-Simpson aquifer	Simpson
		Tulip Creek Formation		
		McLish Formation		
		Oil Creek Formation		
		Joins Formation		
Lower Ordovician	Arbuckle Group	West Spring Creek Formation		Arbuckle-Timbered Hills
		Kindblade Formation		
		Cool Creek Formation		
		McKenzie Hill Formation		
		Butterly Dolomite		
Upper Cambrian		Signal Mountain Formation		
		Royer Dolomite		
		Fort Sill Limestone		
	Timbered Hills Group	Honey Creek Formation		
		Reagan Sandstone		
Middle Cambrian	Colbert Rhyolite		Lower confining unit	basement
Proterozoic	Tishomingo Granite, Troy Granite, granodiorite, and granitic gneiss			

Table 1. Comparison of time-stratigraphic, rock-stratigraphic, geologic, and model stratigraphic units in the Hunton anticline area

Stratigraphy

The oldest rocks in the Hunton anticline area include the Proterozic Tishomingo Granite, Troy Granite, unnamed granodiorite, and granitic gneiss as well as the Middle Cambrian Colbert Rhyolite. For this model, these rocks are combined as the "basement unit" (table 1).

The Cambrian-age Timbered Hills Group, consisting of the Reagan Sandstone and the Honey Creek Formation, unconformably overlies Proterozoic and Middle Cambrian basement rocks (fig. 1 and table 1). The Reagan Sandstone is a Paleozoic transgressive sandstone that lies directly on Precambrian basement rocks and its composition and texture are markedly influenced by the underlying basement. The Reagan Sandstone can either be quartzose, arkosic, feldspathic; or glauconitic, and ranges texturally from fine- to coarse-grained. The overlying Honey Creek Formation is a sandy dolomite in the Hunton anticline area. These units are up to 125 meters and 40 meters thick, respectively, in the model area. Because little is known about the water-bearing properties of the Timbered Hills Group, and there is no identifiable confining layer that separates the Timbered Hills Group from the Arbuckle Group, the Timbered Hills Group and Arbuckle Group are combined as the "Arbuckle-Timbered Hills model unit" (fig. 2 and table 1).

The Arbuckle Group of Late Cambrian to Early Ordovician age consists of a thick sequence of carbonate rocks, up to 2,050 meters thick in the western part of the Hunton anticline area. In areas where the Arbuckle Group is structurally high over the crest of the Hunton and Belton anticlines (fig. 2), the upper part has been eroded leaving it to be about 915 meters thick in the model area based on limited drill-hole data (Campbell and Weber, 2006). The Arbuckle Group is comprised of eight formations based on lithostratigraphy and biostratigraphy (table 1). These formations are, in ascending stratigraphic order, the Fort Sill Limestone, Royer Dolomite, Signal Mountain Formation, Butterly Dolomite, and the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations.

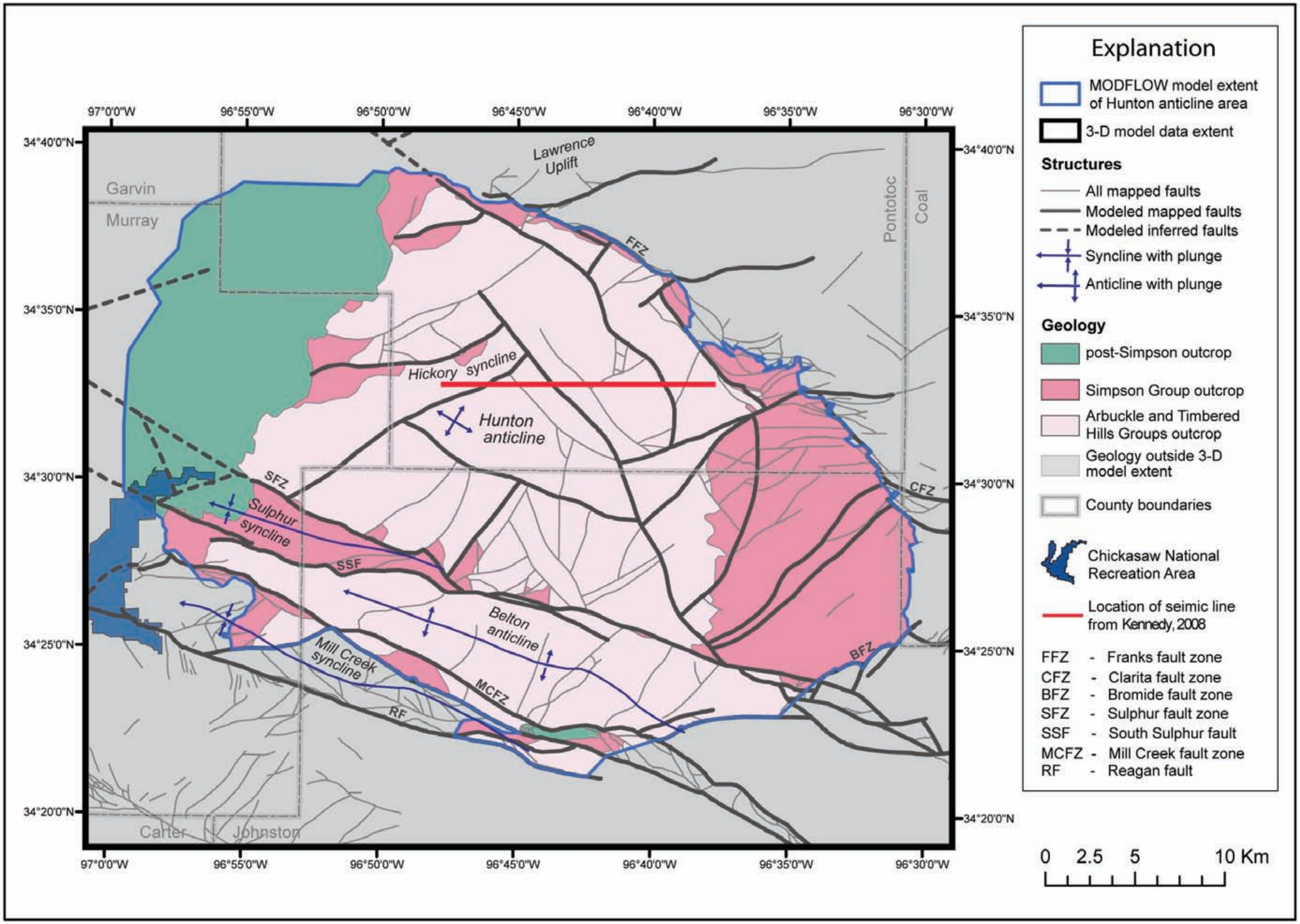


Figure 2. Three-dimensional EarthVision™ model area showing the generalized geology and associated fault structures.

It can be difficult to identify the Arbuckle Group formations on the surface because few marker beds are identifiable. Lithologic description of the Arbuckle Group was derived mostly from outcrops along Interstate 35 through the Arbuckle anticline (Fay, 1989). Arbuckle Group Formations in the subsurface of the Hunton anticline area are difficult to identify because of the scarcity of drill holes that have penetrated the entire Group. In addition, pervasive dolomitization in the Hunton anticline area masks the original depositional textures. In spite of these limitations, some formations have distinct characteristics that can be identified on geophysical logs and drill cuttings.

A well (Wirick 1-12), drilled for oil exploration northeast of the study area on the Lawrence Uplift (fig. 3), penetrated the Arbuckle Group. The gamma-ray log of this drill hole is used as the type log for the Arbuckle Group in the model area. Formation contacts were estimated from analysis of rock cuttings and correlation of the gamma-ray log with other well logs in the study area. The total thickness of the Arbuckle Group in this drill hole is 944 meters.

The Simpson Group (table 1) of Middle Ordovician age is the youngest lithostratigraphic unit that contains rocks of the Arbuckle-Simpson aquifer and is up to 310 meters thick in the model area. Simpson Group rocks are exposed over approximately 235 square kilometers along the margins of the Hunton anticline area and in structurally low areas, such as the Sulphur syncline (fig. 2). Simpson Group rocks are eroded in the structurally higher areas, such as the Belton anticline (Ham and others, 1973). The most prominent outcrop of Simpson rocks occurs in the eastern part of the Hunton anticline area.

The Simpson Group consists of, in ascending stratigraphic order: Joins, Oil Creek, McLish, Tulip Creek, and the Bromide Formations. The Oil Creek, McLish, and Bromide Formations crop out in the model area, whereas the Tulip Creek and Joins Formations are minimal or absent. The Joins Formation consists of thin limestones and shales with a thin basal conglomerate. Each of the four overlying formations consists of a basal sandstone overlain by a sequence of shale and limestone. There are numerous unconformities recorded in the stratigraphic record following deposition of the Simpson Group. Many of the unconformities are the result of the erosion of the paleo-topographic highs formed by older anticlinal features.

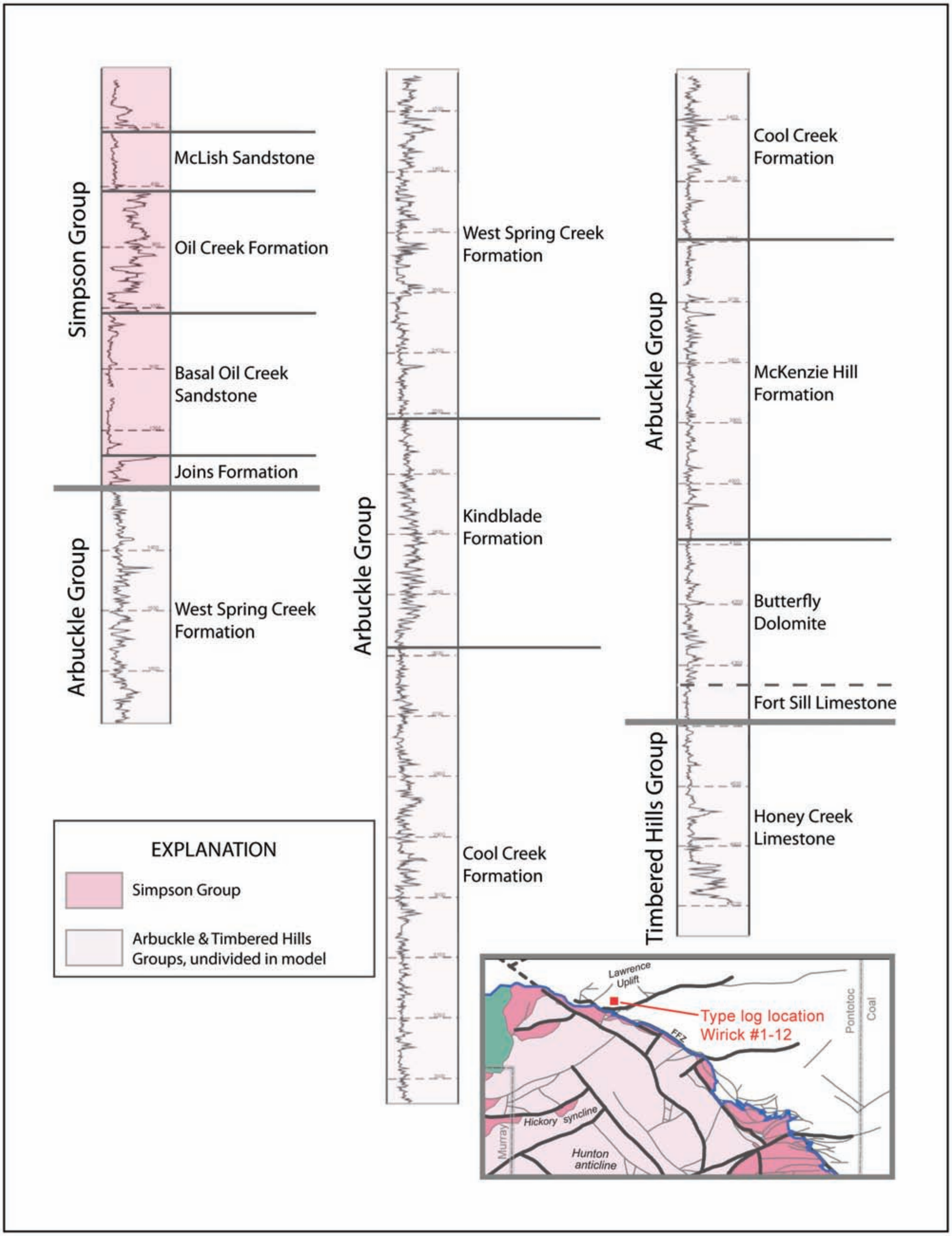


Figure 3. Type gamma-ray log of drill hole Wirick 1-12 showing subsurface geology of the Timbered Hills, Arbuckle and Simpson Groups.

All geologic units younger than the Simpson Group were combined and modeled as the "post-Simpson unit" (table 1). The post-Simpson geologic units include the Viola Group and Sylvan Shale (Upper Ordovician), Hunton Group (Silurian to Devonian), Woodford Shale (Upper Devonian to Lower Mississippian), Sycamore Limestone and Caney Shale (Mississippian), and a number of Pennsylvanian to Permian age units (table 1). The post-Simpson rocks are laterally discontinuous and are exposed as gently dipping strata west and east of the Hunton anticline area (fig. 1).

In the vicinity of Sulphur and the Chickasaw National Recreation Area (CHIC), the Arbuckle and Simpson Groups are unconformably overlain by the Pennsylvanian-age Vanoss Group. The Vanoss Group contains erosional remnants of the Simpson Group, Arbuckle Group, and underlying basement rocks, and has a maximum thickness of 198 meters (Ham and others, 1973). The lower Vanoss conglomerate member, west of the Hunton anticline area, consists of tightly cemented, well-rounded to subangular limestone and dolomite pebbles and boulders, with lesser amounts of sandstone, siltstone, shale, chert, granite, and gneiss. The Vanoss Group also contains an upper shale member and minor sandstone lentils of Late Pennsylvanian to Early Permian age that are mostly exposed outside the model area (fig. 1).

Epikarst/Karst

Epikarst refers to a portion of the bedrock that extends downward from the base of the soil zone and is characterized by extreme fracturing and enhanced solution pockets that may or may not be filled with water (Field, 1999). Epikarst, in general, is thought to be important in the near-surface hydrology of carbonate terrains (Klimchouk, 2004). Although recognized in the Hunton anticline area, epikarst is not consistently mapped. The Oklahoma Water Resources Board funded a study by Sample (2008), to characterize the geophysical, hydrologic, and geologic parameters of epikarst in the Hunton anticline area.

A helicopter electromagnetic (HEM) survey was flown over the Hunton anticline area to identify subsurface structures down to 200 meters below ground surface (Smith and others, 2009). Also identified were soil/epikarst signatures, that show resistivity variations in the resistivity-depth (less than 10 meters) inversions. Generally, the epikarst/soil has a markedly lower resistivity in comparison to the bedrock as verified by both ground and airborne geophysics. Epikarst/soil was mapped in the HEM survey block B (fig. 1). In figure 4, areas with epikarst/soil are stippled, whereas thin soil/bedrock outcrops are blank. The abundance of epikarst/soil in this geologic setting may have profound implications for groundwater recharge and storage.

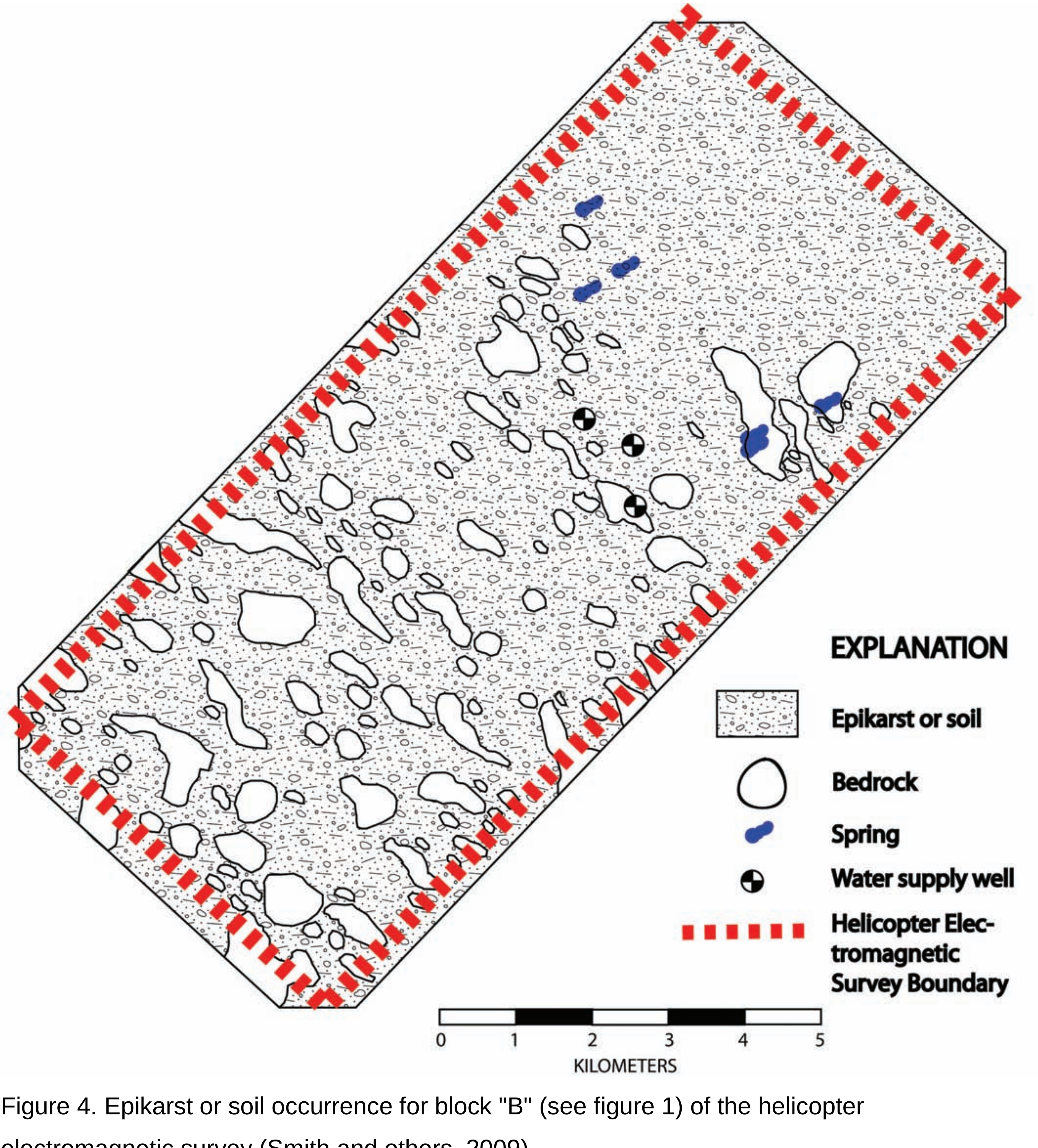


Figure 4. Epikarst or soil occurrence for block "B" (see figure 1) of the helicopter electromagnetic survey (Smith and others, 2009).

Small karst features can be seen over much of the Hunton anticline area, but caves large enough to explore are found only in a few locations. Lynch and Al-Shaieb (1991) have documented evidence of extensive paleokarst in Arbuckle Group rocks in Oklahoma. A test well drilled as part of their study encountered voids with red clay and calcite fillings that are indicative of carbonate dissolution and karst features at depth.

Geologic Structure

Information obtained from surface mapping and subsurface geophysical data indicate the rocks containing the Arbuckle-Simpson aquifer are highly faulted. The larger faults have been mapped at the surface (fig. 1), but many more have been identified through geophysical methods, including seismic, electric resistivity imaging (ERI), ground-penetrating radar (GPR), and HEM surveys (Scheirer and Hosford-Scheirer, 2006; Kennedy, 2008; Sample; 2008, Halihan and others, 2009; Smith and others, 2009). Numerous smaller faults throughout the region terminate against the major northwest oriented faults and against each other (fig. 2). These smaller faults are characterized by short linear lengths, small offsets of stratigraphic units, and a variety of orientations (Scheirer and Hosford-Scheirer, 2006).

A gravity geophysical survey by Scheirer and Hosford-Scheirer (2006) of the CHIC indicated that the South Sulphur fault (SSF) may project westward into the park, and an HEM survey flown in 2007 (Smith and others, 2009), substantiated their findings (fig. 1). The gravity survey also suggests that the South Sulphur fault dips steeply, faults in the Mill Creek fault zone (MCFZ) dip vertically, and the Reagan fault (RF) dips to the south, which is consistent with it being mapped as a thrust fault (fig. 2). In May, 2007, Scheirer and Aboud (2008) collected ground magnetic and gravity observations in the western part of the Hunton anticline area near Sulphur, Oklahoma, which complements the previous gravity work in CHIC.

A seismic survey interpreted by Kennedy (2008), suggests that the older rock units containing the Arbuckle-Simpson aquifer range from 270 to 1070 meters below ground level. Numerous faults are observed along a seismic line shown in figures 2 and 5, with a fault density of about 1.6 faults per kilometer. Figure 5 (Kennedy, 2008) shows that steeply dipping faults penetrate the granitic basement, at estimated depths of 800 to 1070 meters below ground level.

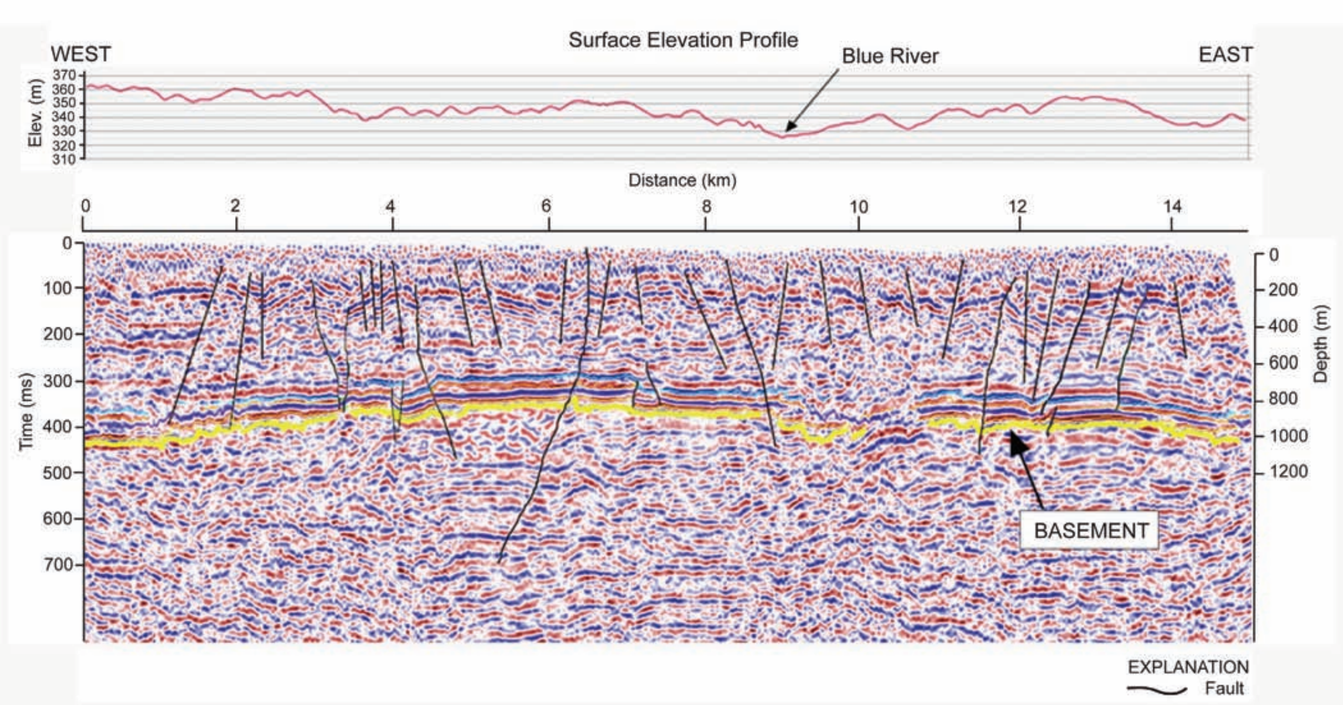


Figure 5. Seismic line across the Hunton anticline area (fig. 2) showing interpreted basement horizon and faults (modified from Kennedy, 2008).

Locally, on the western and eastern flanks of the Hunton anticline area, the strata dip gradually into the subsurface, such as near CHIC (fig. 2). In other locations to the north and northeast, the water-bearing strata are faulted downward and buried by thick sequences of younger rocks. To the south, uplift and displacement along reverse and strike-slip faults have juxtaposed Precambrian and Cambrian basement against the Timbered Hills, Arbuckle, and Simpson Groups. Deformation features characteristic of the study area include an abundance of fractures that represent joints, shears, broken folds, as well as faults, parallel folding, and pressure solution features (Donovan, 1991). Major strike-slip faults have lateral displacements over 60 kilometers according to Scheirer and Hosford-Scheirer (2006).

The Hunton anticline is a broad fold that is bounded on the northeast by the Franks and Clarita fault zones (FFZ and CFZ respectively, fig. 2), and on the south by the Sulphur fault zone (SFZ). The Franks fault zone is composed of a series of high-angle, down-to-the northeast faults. The southeastern boundary of the Hunton anticline area is the Bromide fault zone (BFZ). Arbuckle and Simpson Group strata are exposed in the central part of the anticline and dip gently beneath Middle Pennsylvanian formations on the northwestern and western flanks. On its eastern flank, the strata dip beneath progressively younger strata between the Clarita and Bromide fault zones (fig. 2).

To the south of the Hunton anticline, most major faults are high-angle (Halihan and others, 2009) and are considered to be the result of left-lateral strike-slip and thrust deformation. Found here is the northwest-plunging fault block of the Belton anticline (fig. 2). This anticline is bounded on the north by the South Sulphur fault (SSF) and Sulphur fault zone (SFZ, fig. 2), and on the south by the Mill Creek fault zone (MCFZ). Rocks of the Belton anticline are higher structurally than rocks of the Hunton anticline. As a result, the Simpson Group and upper Arbuckle Group units have been eroded exposing the lower Cool Creek and McKenzie Hill Formations.

The Sulphur syncline is wedged between the Belton and Hunton anticlines (fig. 2), bounded by the Sulphur fault zone to the north, and by the South Sulphur fault to the south. Preserved within the Sulphur syncline are rocks of the Simpson Group. Simpson Group exposures terminate east of CHIC and are unconformably overlain by Vanoss Group conglomerate. Geologic mapping by Ham and others (1990) show that the fault south of the Sulphur syncline deviates southward. Scheirer and Hosford-Scheirer (2006) named this fault the South Sulphur fault, and their gravity study suggests that a segment extends to the northwest through CHIC. Well data suggest that a segment of the Sulphur fault zone extends westward, to the north of CHIC. Drill hole data also suggest that two cross faults connect the South Sulphur fault and Sulphur fault zone in the vicinity of CHIC. Cates (1989) and Scheirer and Hosford-Scheirer (2006) suggest the Sulphur syncline does not extend beneath CHIC and may be a graben.

The Mill Creek syncline is bounded by the Mill Creek fault zone and Reagan fault (fig. 2). The Mill Creek syncline is a narrow, northwest-trending graben consisting of more than 2500 meters of tightly folded Paleozoic strata. Stratigraphic displacement along the Mill Creek fault zone is estimated to be 1,525 meters where Arbuckle and Simpson Group strata of the Belton anticline are juxtaposed against rocks of the Pennsylvanian Deese Group (Ham, 1945; table 1).

Three-Dimensional Modeling

A 3-D EV model characterizing the geologic framework and geometric relations of the rocks containing the Arbuckle-Simpson aquifer and its confining strata within the Hunton anticline area was constructed. The geologic layers were then discretized for the Arbuckle-Simpson hydrology study's regional groundwater-flow model. Other structures included in the model area are, from north to south, the Lawrence Uplift, Hickory syncline, Sulphur syncline, Belton anticline, and Mill Creek syncline (fig. 2).

Subsurface Geologic Data and Interpretation Methods

The geologic data used to interpret the subsurface were derived from geophysical logs, lithologic descriptions from municipal and domestic water supply-wells, oil and gas exploration wells, and subsurface geophysical surveys. The structural attitude of stratigraphic units was established by using geologic map and well-based data. In all, well records for more than 300 water supply and petroleum exploration wells in the study area were examined. Of these, stratigraphic tops from 126 wells were selected based on data quality and spatial distribution across the model area.

Software

Dynamic Graphic's EarthVision™ 3-D modeling software was used to create two-dimensional (2-D) and 3-D stratigraphic surfaces from x (easting/longitude), y (northing/latitude), and z (elevation) data, all in meters. The locations were compiled in an Albers Equal Area projection, GRS 1980/NAD83. In the model, x, y, and z input data values define the surfaces of the model geologic units. Unit volumes are constrained by two or more unit surfaces and/or their modeled or structural boundaries.

EarthVision™ software was used because of its ability to model various data types and accurately define faulted surfaces while maintaining both the stratigraphic and structural integrity and complexity in 3-D space. This software is designed to mathematically follow basic geologic and geometric rules of depositional, channel fill, or unconformable stratigraphic contacts. These rules can be modified by any or all of the following: (1) adding user-interpreted data points (designated by the prefix "Md" in the data files), (2) by altering gridding parameters or (3) using smoothing algorithms in any or all of the x, y, or z dimensions. This allows for considerable discretion to define a unit surface beyond the predefined "minimum surface-tension" gridding algorithm.

EarthVision™ uses minimum tension gridding to produce 2-D and 3-D surface grids from x, y, and z data (scattered data). Minimum tension gridding more closely models the data versus trend gridding which abstracts it. Specifically, EV uses a biharmonic cubic spline function to model the data. The gridded surfaces are generated in a two-stage process, an initial grid estimate followed by biharmonic iterations. Initial grid nodes are estimated from the scattered data. Data points used for the initial estimate depends on the distribution of the scattered data. Once the estimate is complete, a number of iterations using the biharmonic cubic spline function re-evaluate the grid nodes. So that grid nodes still adhere to the scattered data, a scattered data feedback algorithm follows each biharmonic iteration. These modeling steps result in the curvature of the surface being distributed rather than concentrated at data points. This generates a "more natural looking" modeled surface of the grid nodes that accurately reflect the scattered data. More information and other utilities are available from Dynamic Graphics Inc at: http://www.dgi.com.

Model Construction

Data for the geologic surfaces within the model were identified and defined from five primary data sources:

- 126 drill holes with well picks based on geophysical logs, cores, and cuttings
- Type log from Wirick drill hole 1-12 (fig. 3)
- Stratigraphic contacts and faults defined from surface geologic mapping by Ham and others (1990) and digitized by Cederstrand (1996)
- Fault extensions from Scheirer and Hosford-Scheirer (2006)
- Fault geometry, stratigraphic thickness, and tectonic-history data compiled from existing geologic and hydrogeologic reports and maps

The Arbuckle-Simpson 3-D EV geologic framework model (fig. 6) incorporates 54 faults and four modeled units: basement, Arbuckle-Timbered Hills unit, Simpson Group, and post-Simpson unit (table 1). Figure 7 is a west to east cross section through the model and figure 8 is a north to south cross section. With fault offsets greater than 2,000 meters along the flanks of the Hunton anticline area, the volumetric distribution of the model units is highly variable. This geologic framework model shows the volumetric extents of the Arbuckle-Timbered Hills and Simpson Group rocks, which are the primary water-bearing units of the aquifer (table 1). The top of the basement forms the lower confining unit of the aquifer. The post-Simpson rocks form the upper confining unit of the aquifer. A 10-meter U.S. Geological Survey (USGS) Digital Elevation Model (DEM) was used to define the surface topography and provides elevation data for the stratigraphic contacts from Cedarstrand’s (1996) digital geologic map of the area.

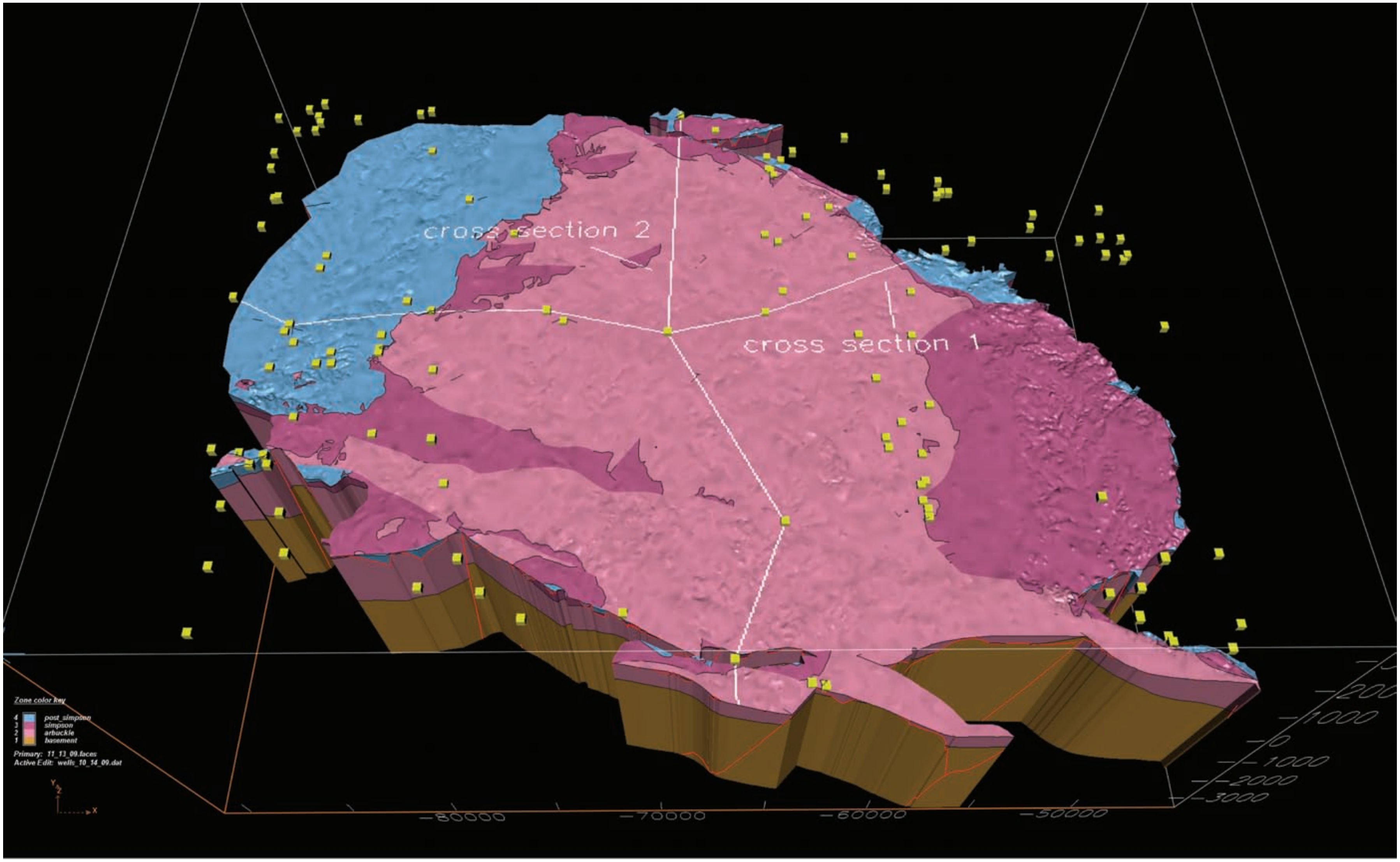


Figure 6. EarthVison™-derived block diagram showing the geologic units confining the Arbuckle-Simpson aquifer, selected drill hole locations, and locations of cross-sections shown in figure 7 and figure 8.

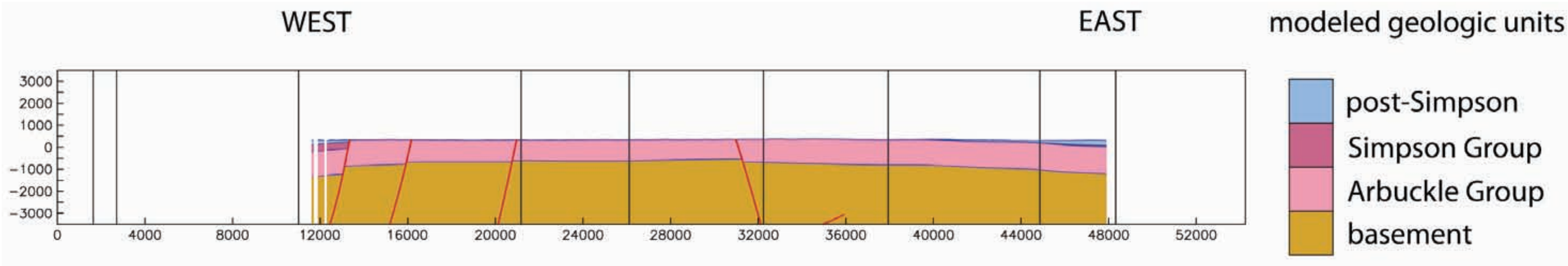


Figure 7. East to west cross-section showing the EarthVision™ modeled geologic units and fault structures.

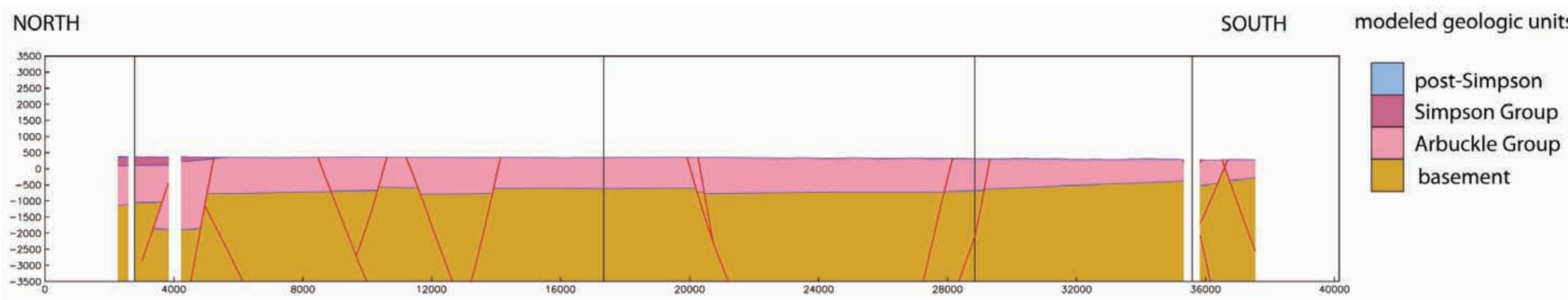


Figure 8. North to south cross-section showing the EarthVision™ modeled geologic units and fault structures.

Fault plane modeling was first conducted using approximately 20 normal and reverse faults dipping 80 degrees and 65 degrees, respectively. Fault complexity was increased to a total of 54 faults before the integration of stratigraphic control points. Fault structures included the geophysically-interpreted fault extensions of Scheier and Hosford-Scheier (2006, fig. 2). Drill-hole data constrained the model surfaces. The top of the basement was defined using data from 13 drill holes (fig. 9). The top of the Arbuckle-Timbered Hills Group was identified in data from 89 drill holes and represents the model's primary reference surface, which was used to define other model surfaces (fig. 10). The top of the Simpson Group was identified in 54 wells (fig. 11). Locally, pre-erosional surfaces for the Simpson Group and basement were projected based on x, y, and z values of a known contact. The post-Simpson model unit (fig. 12) was defined as the volume between the top of the Simpson Group and DEM surface. Over much of the model area, post-Simpson rocks are missing because of erosion.

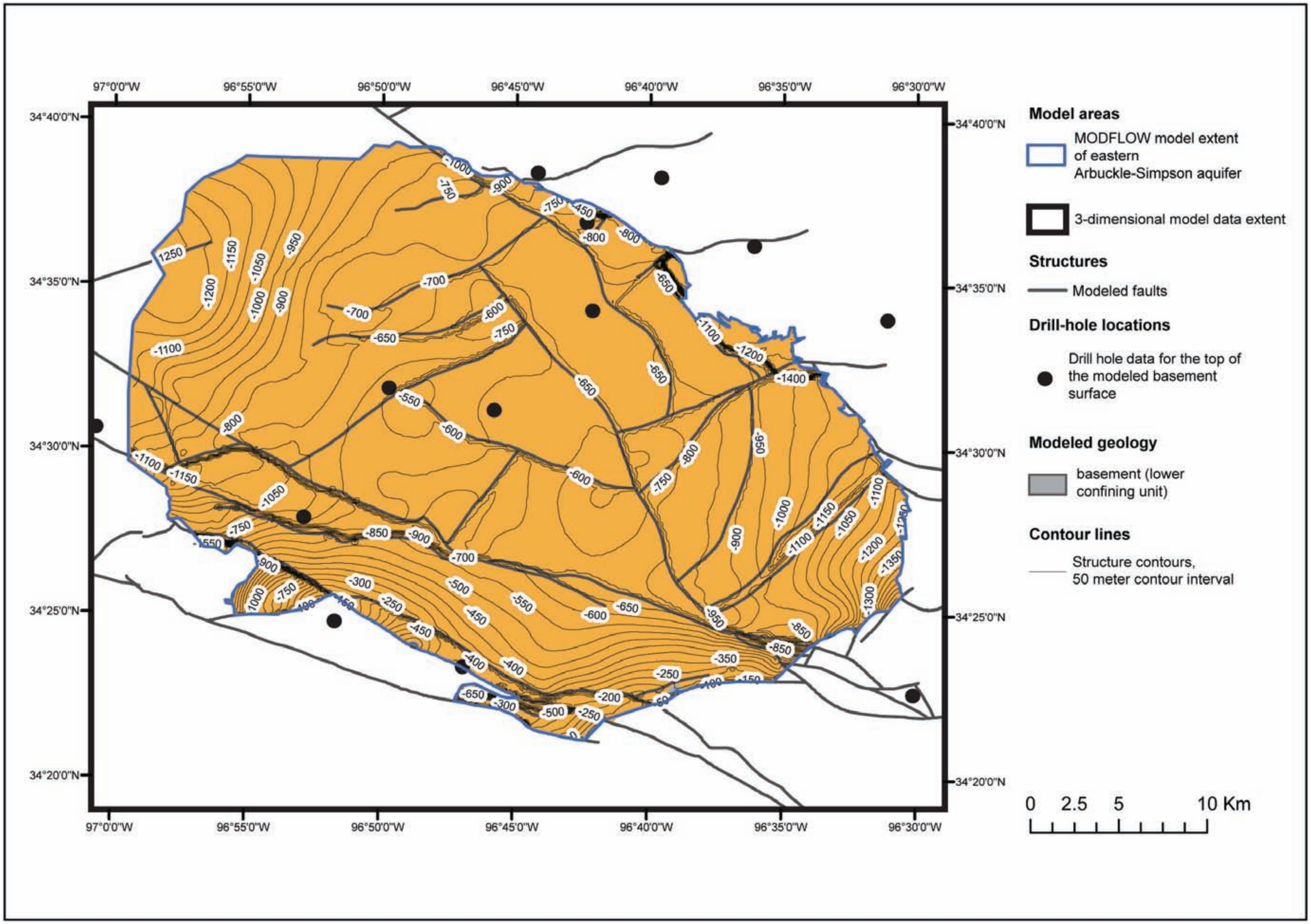


Figure 9. Structure contour map of the top of the modeled basement surface, fault structures, and data locations.

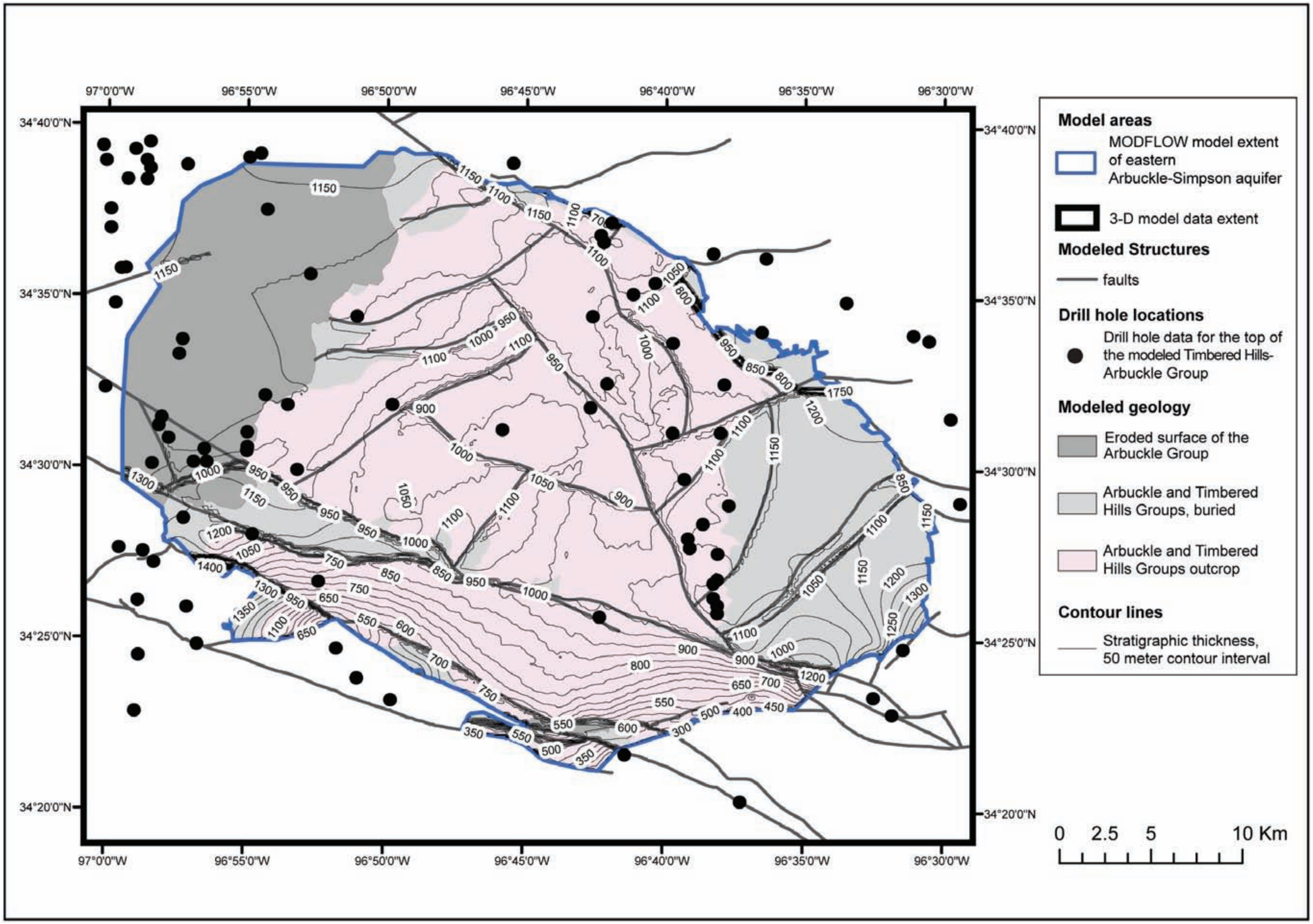


Figure 10. Stratigraphic thickness of the top of the modeled Timbered Hills-Arbuckle Group surface, fault structures, and data locations.

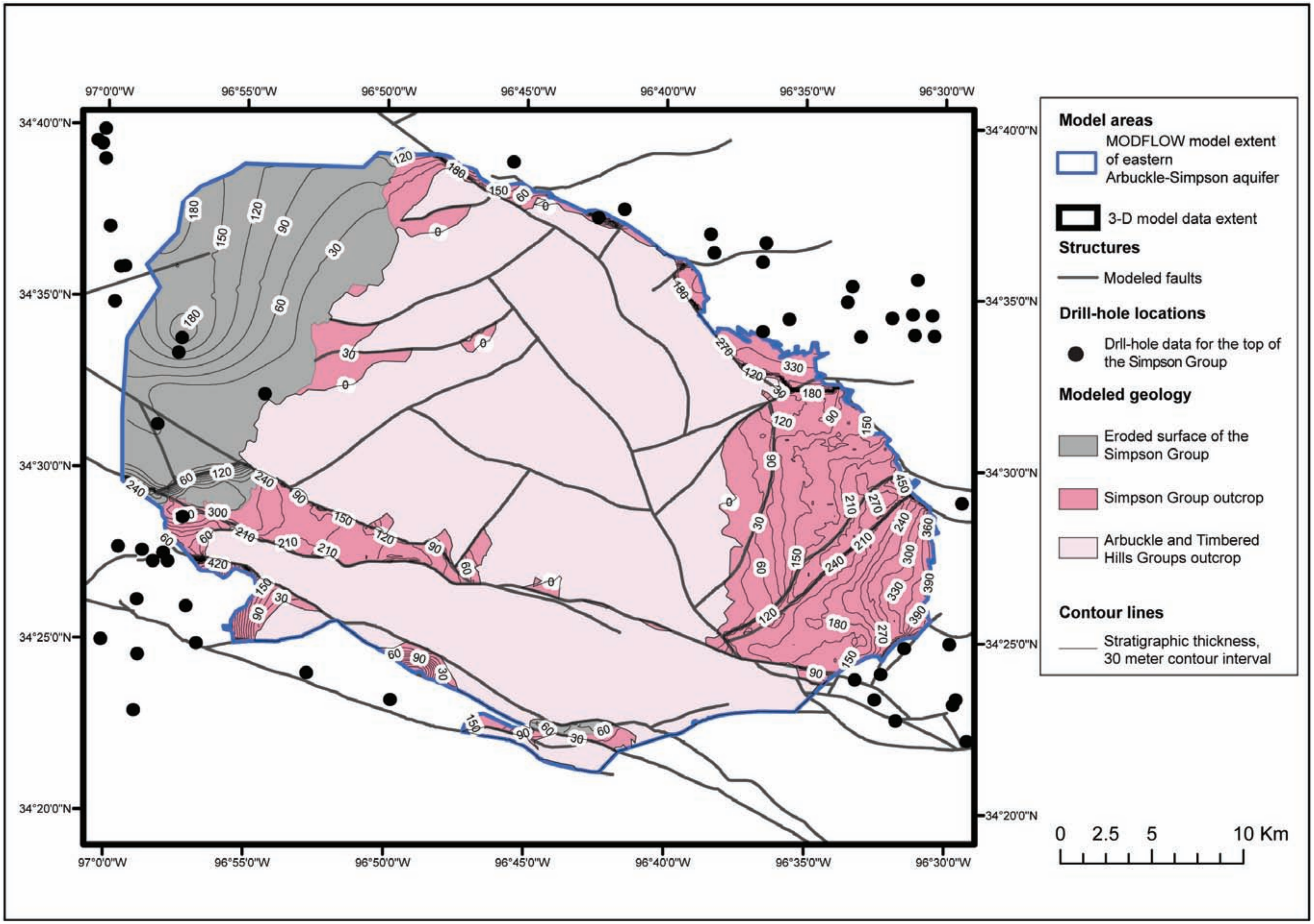


Figure 11. Stratigraphic thickness of the top of the modeled Simpson Group surface, fault structures, and data locations.

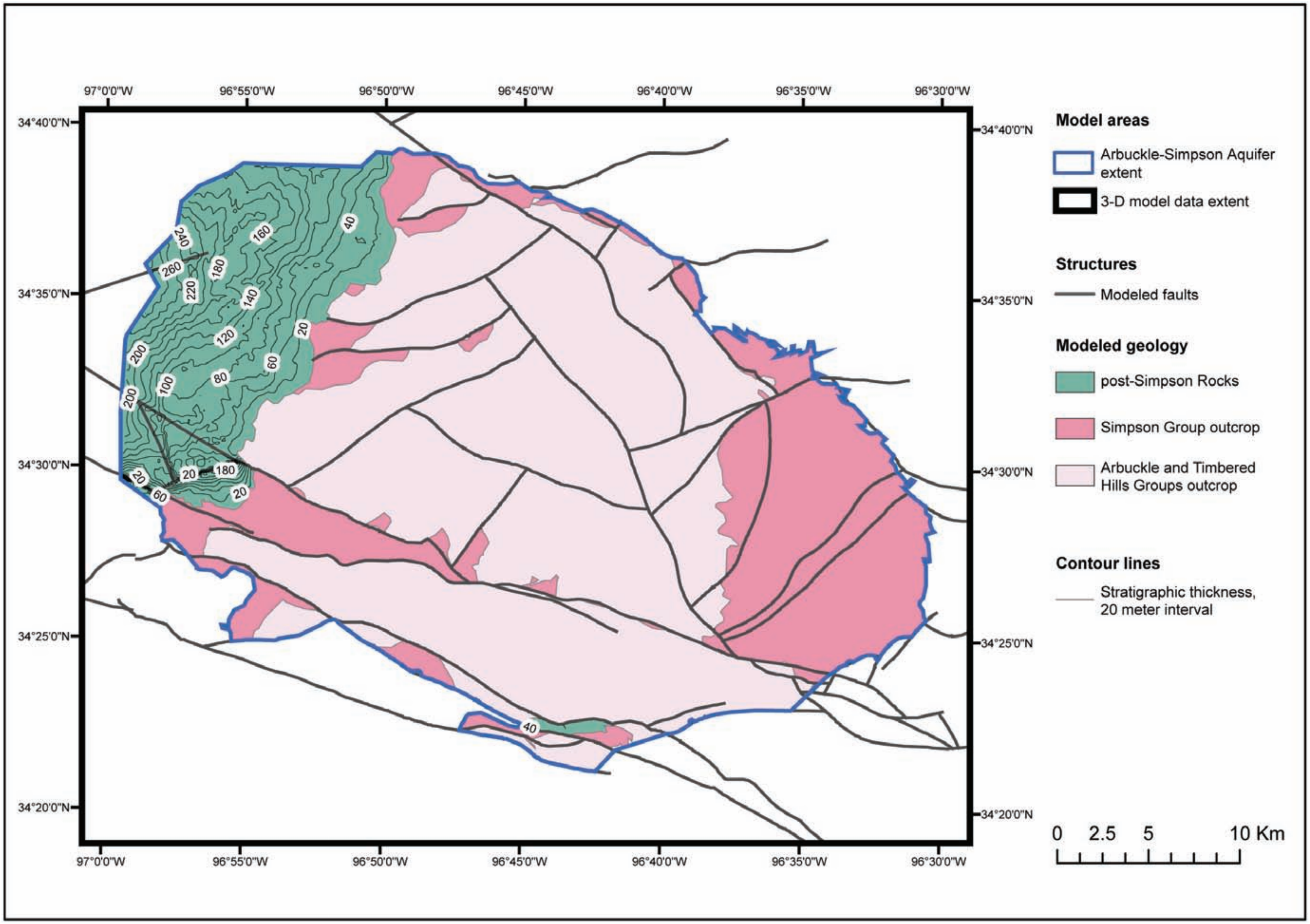


Figure 12. Stratigraphic thickness of the top of the modeled post-Simpson Group surface, fault structures, and data locations.

Significance of Three-Dimensional Geologic Modeling for Groundwater Modeling

The data provided as input into the groundwater flow model included the following surfaces: basement (lower confining unit), Arbuckle-Timbered Hills unit, Simpson Group, and the undifferentiated post-Simpson (upper confining unit, table 1). These surfaces, representing the tops of the model units, were exported for conversion to a data format compatible with MODFLOW version 2000. Skip Pack (Dynamic Graphics, Inc.) was instrumental in the data conversion process used to produce surface elevation and thickness grids representing the model geologic units. The reformatted data were successfully incorporated into the ongoing Arbuckle-Simpson MODFLOW groundwater flow model. The structure contour map of the basement rocks in figure 9 shows that the model surface elevations ranges from sea level to more than 1,400 meters below sea level. The isopach map of the Arbuckle-Timbered Hills unit (fig. 10) shows a range in thickness from 200 to 1,800 meters. In many locations, more than half of the thickness of this model unit has been removed by erosion. Across the model area, the Simpson Group isopach map (fig. 11) illustrates thickness variations from zero to 480 meters. The thickness variations are a result of the Hunton anticline area's complex structure and surface erosion. The thickness of the post-Simpson rocks shown in figure 12, range from zero to 300 meters on the western flank of the Hunton anticline area.

This 3-D EV framework model represents the first volumetric depiction of rocks that form the Arbuckle-Simpson aquifer in the Hunton anticline area. The 3-D framework model also provided the geologic framework used to construct a MODFLOW version 2000 model of the aquifer. Three-dimensional models, like the Arbuckle-Simpson 3-D EV model, are also interactive tools for visualizing the subsurface geology of groundwater aquifer systems. Other applications of 3-D EV modeling called “property modeling” are evolving where other data types such as, rock properties or water levels, are being modeled in three- or even four-dimensions (time).

References Cited

Campbell, J.A., and Weber, J.L., 2006, Wells drilled to basement in Oklahoma: Oklahoma Geological Survey Special Publication 2006-1 (CD).

Cates, S. W., 1989, Fault distribution in the Sulphur, Oklahoma area based on gravity, magnetic and structural data: Norman, Okla., University of Oklahoma, M.S. Thesis, 106 p.

Cederstrand, J.R., 1996, Digital geologic map of Ardmore-Sherman quadrangles, south-central Oklahoma: U.S. Geological Survey Open-File Report 96-370, scale 1:250000 (available at: http://ok.water.usgs.gov/gis/geology.)

Donovan, R.N., 1991, The Arbuckle Group-An aide de memoire, *in* Johnson, K.S. (ed.), Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey Special Publication 91-3, p. 199-208.

Fay, O.R., 1989, Geology of the Arbuckle Mountains along Interstate 35, Carter and Murray Counties, Oklahoma: Oklahoma Geological Survey Guidebook 26, 50 p.

Field, M.S., 1999, A lexicon of cave and karst terminology with special reference to environmental karst hydrology: U.S. Environmental Protection Agency, National Center for Environmental Assessment, EPA/600/R-99/006, 201 p. Digital version by Karst Waters Institute.

Halihan, T., Puckette, J., Sample, M., and Riley, M., 2009, Electrical resistivity imaging of the Arbuckle-Simpson Aquifer: report submitted to the Oklahoma Water Resources Board, 93 p.

Ham, W.E., 1945, Geology and glass sand resources, central Arbuckle Mountains, Oklahoma: Oklahoma Geological Survey Bulletin No. 65, 103 p.

Ham, W.E., and others, 1973, Regional geology of the Arbuckle Mountains, Oklahoma: Oklahoma Geological Survey Special Publication 73-3, 61 p.

Ham, W.E., McKinley, M.E., Johnson, K.S., Dunham, R.J., Decker, C.E., Morgan, G.D., Barker, J.C., and Gilbert, M.P., 1990, Geologic map and sections of the Arbuckle Mountains, Oklahoma, Oklahoma Geological Survey, Geologic Map GM-31, scale 1:100,000.

Kennedy, Breanne, 2008, Seismic features of the Arbuckle-Simpson aquifer determined from surveys at three different geologic scales: Norman, Okla., University of Oklahoma, M.S. Thesis, 81 p.

Klimchouk, A., 2004, Towards defining and delimiting and classifying epikarst: Its origin, and variants of geomorphic evolution, *in* Jones, W.K., Culver, D.C., and Herman, J., eds., Karst Waters Institute Special Publication, v. 9, p. 13-35, republished (modified), 2004, *in* Speleogenesis and Evolution of Karst Waters, v. 2, no. 1, p. 1-13.

Lynch, M., and Al-Shaieb, Z., 1991, Paleokarstic features and thermal overprints observed in some of the Arbuckle cores in Oklahoma: Oklahoma Geological Survey Special Publication 91-3, p. 31-68.

Sample, M.S., 2008, Characterization of the epikarst over the Hunton anticline, Arbuckle-Simpson aquifer, Oklahoma: M.S. Theses, Oklahoma State University, 220 p.

Scheirer, Daniel S., and Hosford Scheirer, Allegra, 2006, Gravity investigations of the Chickasaw National Recreation Area, south-central Oklahoma: U.S. Geological Survey Open-file Report 2006-1083, 40 p.

Scheirer, Daniel S., and Aboud, Essam, 2008, Preliminary gravity and ground magnetic data in the Arbuckle Uplift near Sulphur, Oklahoma: U.S. Geological Survey Open-File Report 2008-1003, 34 p.

Smith, D.V., Deszcz-Pan, M., and Smith, B.D., 2009, Depth section imaging for portions of an airborne geophysical survey of the Hunton anticline, south-central Oklahoma, Final administrative report to the Oklahoma Water Resources Board in fulfillment of the cooperative agreement #08C7OK002032407, (available at: (http://www.owrb.ok.gov/studies/groundwater/arbuckle_simpson/pdf/2009_Reports/DepthSectionImagingAirborneGeophysicalSurveyHuntonAnticline_SmithDeszczPanSmith.pdf).

ATTACHMENT 3

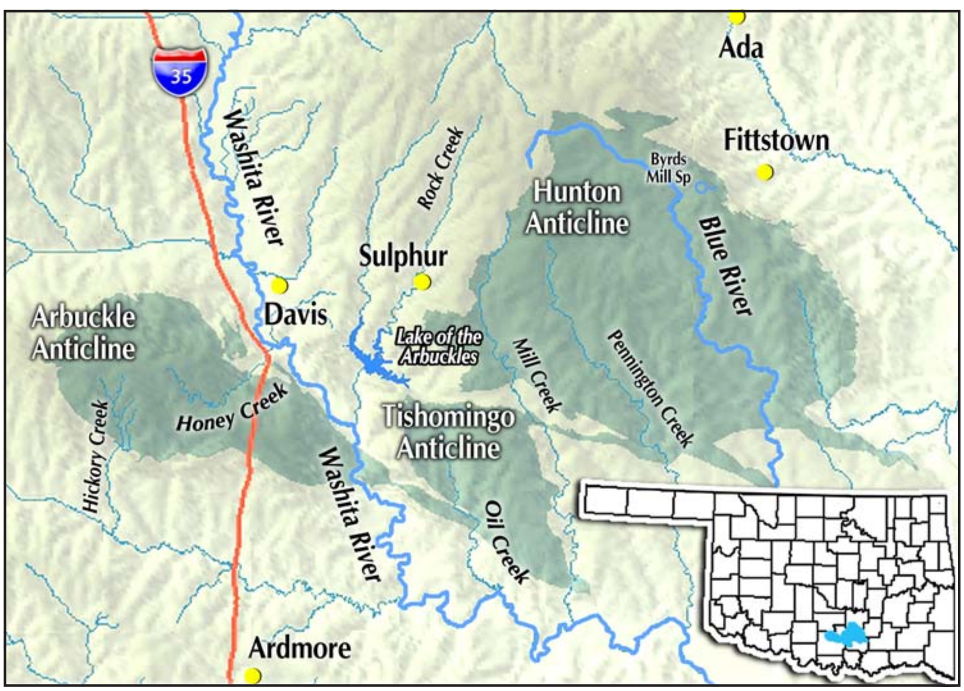
THE OKLAHOMA WATER RESOURCES BOARD November 2003

Background

The Arbuckle-Simpson aquifer, which underlies more than 500 square miles in south central Oklahoma, is the principal water source for approximately 39,000 people in Ada, Sulphur, and others in the region. The aquifer is also the source of a number of important springs in the region, including Byrds Mill Spring, Ada's primary drinking water source, and those in the Chickasaw National Recreation Area, the destination for about 3.4 million visitors each year. The U.S. Environmental Protection Agency has designated the aquifer's eastern portion as a Sole Source Aquifer, a mechanism to protect drinking water supplies in areas with limited water supply alternatives.

Local, federal, and state agencies and organizations have been lobbying for a comprehensive study of the Arbuckle-Simpson aquifer for more than a decade. However, recent requests for water use permits from the aquifer have generated sufficient concern to make the study a reality. Early in 2002, the Central Oklahoma Water Authority (COWA), consisting primarily of communities in Canadian County seeking future supply, proposed to pump as much as 80,000 acre-feet of water per year from the aquifer and transport it to central Oklahoma.

Although Oklahoma water law considers groundwater the private property of the landowner, local residents, citizens' groups, and the National Park Service are concerned that large-scale withdrawals of water from the Arbuckle-Simpson aquifer will result in declining flow in streams and springs and cause groundwater levels to decline. As a result, the state will also investigate development of a management strategy that would protect the aquifer's current and future benefits yet comply with the basic precepts of Oklahoma water law.



The general outcrop area of the Arbuckle-Simpson aquifer extends some 500 miles between Ada and Ardmore in south central Oklahoma.

Senate Bill 288

Senate Bill 288, passed by the State Legislature in May 2003, imposes a moratorium on the issuance of any temporary groundwater permit for municipal or public water supply use outside of any county that overlays, in whole or in part, a "sensitive sole source groundwater basin." (The Arbuckle-Simpson aquifer is the only such groundwater basin in Oklahoma.)

The moratorium prohibits municipal and political subdivisions outside the basin from entering into contracts for use of the water and it applies to both pending applications and any revalidation of existing temporary permits. The moratorium will remain in effect until the OWRB completes its study of the Arbuckle-Simpson and approves a maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer.

SB 288 also adds another requirement for groundwater permit approval for use within the basin: the Board must find that the proposed use is not likely to degrade or interfere with springs or streams emanating from the aquifer. Because current Oklahoma water law does not take into account the hydrologic interaction between surface and groundwater, the legislation sets a new precedent in the OWRB's permit approval process.

Plan of Study

State and federal water experts agree that information garnered from previous studies of the Arbuckle-Simpson aquifer--concentrating primarily on its geology and hydrology at or near the surface--is inadequate to address the aquifer's complex geology and management issues confronting local users. Investigation of the deeper portion of the aquifer (greater than 1,000 feet) is needed to understand the full extent of the fresh-water zone and the volume of water in storage in the aquifer. In addition, no sufficient information exists to predict the response of springs and streams to groundwater withdrawals. Critical to future study of the aquifer is an understanding of the formation's "plumbing system" that controls the interactions between groundwater levels and springflows.

To understand, as well as quantify, the region's complex geology and hydrology, the investigation will require five years for completion. Funded through a 50/50 state/federal cost-share agreement with the U.S. Bureau of Reclamation, the investigation will be the most intensive analysis of surface and groundwater relationships ever conducted in Oklahoma. Most importantly, study results will provide state and local decisionmakers with the necessary information to determine how water resources in the region should best be utilized while protecting area springs and streams.

The Arbuckle-Simpson study will be coordinated by the OWRB, but will involve participation from dozens of agencies and organizations, as well as private citizens. A technical peer review team consisting of experts from the U.S. Geological Survey, Oklahoma Geological Survey, Oklahoma State University, and EPA will review the scope of work and provide advice to ensure the use of sound science and appropriate methods.

Vendome Well, an artesian well in the Chickasaw National Recreation Area

The goal of the Arbuckle-Simpson study is to acquire understanding of the region's hydrology to enable development and implementation of an effective water resource management plan that protects the region's springs and streams.

Study Objectives

1. Characterize the Arbuckle-Simpson aquifer in terms of geologic setting, aquifer boundaries, hydraulic properties, water levels, groundwater flow, recharge, discharge, and water budget.
2. Characterize the area's surface hydrology, including stream and spring discharge, runoff, base flow, and the relationship of surface water to groundwater.
3. Construct a digital groundwater/surface water flow model of the Arbuckle-Simpson aquifer system for use in evaluating the allocation of water rights and simulating management options.
4. Determine the chemical quality of the aquifer and principal streams, identify potential sources of natural contamination, and delineate areas of the aquifer that are most vulnerable to contamination.
5. Construct network stream models of the principal stream systems for use in the allocation of water rights.
6. Propose water management options, consistent with state water laws, that address water rights issues, the potential impacts of pumping on springs and stream base flows, water quality, and water supply development.

Methods

A variety of methods will be used to characterize the aquifer, including evaluation of petroleum-related information, test well drilling, groundwater and surface water modeling, geochemistry, isotopic age dating of groundwater, and various other methods depending upon findings as the study progresses, as well as available funding. The first year of the investigation will consist of reviewing literature, compiling and reviewing existing data, conducting field investigations, initiating groundwater flow model simulations, and identifying data needs. As a vital tool to furthering understanding of the aquifer and assisting in the water resource decision-making process, development of the digital groundwater flow model will be a key component of the study.

Fieldwork will include installation of two stream gages (on the Blue River and Pennington Creek), updating the current inventory of water wells and springs, and collecting measurements from wells, springs, and streams in the area. A variety of hydrologic tests will be performed, with special emphasis on deep wells. The second and third years will be devoted primarily to field investigation, the fourth year to model development, and the fifth year to reviewing various management options.

Input from the public, especially those residing in the Arbuckle-Simpson aquifer region, will be integral to the study. Landowners and other interested parties will be counted on to provide vital information related to the location of springs, streams, wells, and other components of the aquifer's complex surface/groundwater system. The OWRB will hold public meetings to update citizens on the study's progress and results. In addition, the agency will publish regular Arbuckle-Simpson study newsletters and share the latest study developments through its Web site.

Hydrogeologic Setting

The Arbuckle-Simpson aquifer is contained within several rock formations. Rocks of the Arbuckle Group consist of limestones and dolomites that were deposited between 520 and 480 million years ago in Late Cambrian and Early Ordovician time. The carbonate sediments were deposited on a vast, shallow-water platform that extended from northeast New Mexico into northeast Canada. Rocks of the Simpson Group consist of sandstone, shale, and limestone that were deposited 480 to 460 million years ago in Middle Ordovician time.

Rocks of the Arbuckle and Simpson Groups are exposed at the land surface in three prominent uplifts separated from each other by large, high-angle faults. The southwestern outcrop is on the Arbuckle Anticline, a geological structure that was formed 300 million years ago when intensive folding and faulting of a thick sequence of Paleozoic rocks formed the ancestral Arbuckle Mountains. Originally rising several thousand feet above the surrounding plains, the mountains have been eroded to their present-day maximum relief of 600 feet. Topography over the steeply dipping strata is very rugged. Road cuts along Interstate 35 provide unique views of the thick sequence of Paleozoic rocks and complex structure of the Arbuckle Anticline.

The eastern outcrop is on several structural features, of which the Hunton Anticline is the most prominent. The central outcrop is on the Tishomingo Anticline. The Structural deformation on these two anticlines is much less pronounced than on the Arbuckle Anticline, and the topography consists of gently rolling plains formed on relatively flat-lying rocks.

Springs from the Arbuckle-Simpson Aquifer provide base flow to Travertine Creek, a popular recreation spot in the Chickasaw National Recreation Area.

Four (Five) Points of State Groundwater Law

In Oklahoma, surface water is considered public water while private property rights govern the use and ownership of groundwater. Prior to the OWRB's approval of a groundwater use permit, Oklahoma water law dictates that four points must be satisfied:

1) the applicant must own or lease the overlying land;
2) the land must overlie the groundwater basin;
3) the proposed purpose must be for a beneficial use; and
4) the water must not be wasted.

Senate Bill 288 would add a fifth precept to Board approval:

5) the proposed use is not likely to interfere with streams and springs emanating from a sensitive sole source groundwater basin.

Groundwater

The complex geologic features of the aquifer affect how water moves through the aquifer. Features such as folds, faults, bedding planes, and solution channels may have local influences on groundwater flow paths and flow rates. The numerous faults affect the movement of water through the aquifer because they can act as barriers to groundwater flow or as conduits through which water travels. The rate at which water moves through the aquifer can vary greatly. Water moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits.

About two-thirds of the aquifer consists of carbonate rocks (limestones and dolomites), which are soluble. Infiltrating water slowly dissolves the rock, leading to the formation of solution channels and cavities along bedding planes, fractures, and faults. Karst (solution) features, such as sinkholes and caverns, are most common where fractures and bedding planes have enhanced groundwater circulation.

The Arbuckle-Simpson aquifer receives water from infiltration of precipitation and from losing streams that cross the outcrop area. Most of the discharge from the aquifer is to streams, rivers, and springs and some is to well withdrawals, outflow to adjacent aquifers, and to evapotranspiration.

Generally, groundwater flows from topographically high areas to low areas, where it discharges to springs and streams. Groundwater flow in the Arbuckle Anticline region appears to radiate from the crest of the anticline. Regional groundwater flow in the Hunton Anticline region is southeast, but a small component is southwest. Where the Arbuckle-Simpson aquifer dips beneath rocks of lower permeability, the aquifer is confined, and wells that penetrate below the confining layer may be artesian. Several artesian wells flow in the valley of Rock Creek, near Sulphur. The most well known of these wells is Vendome Well in the Chickasaw National Recreation Area.

Groundwater and surface water interact in different ways. In some areas of the Arbuckle-Simpson aquifer, streams gain water from aquifer discharge, and in other areas, streams lose water to the aquifer. Where the altitude of the water table is higher than the altitude of the stream-water surface, groundwater discharges into the stream channels. The groundwater component of streamflow is known as base flow. About 60 percent of the streamflow in the outcrop area of the Hunton Anticline is base flow from the aquifer. Where the altitude of the water table is lower than the altitude of the stream-water surface, surface water recharges the aquifer. In karst aquifers, losing segments of streams commonly occur where streams cross sinkholes or highly fractured rock.

Hydrologic Budget

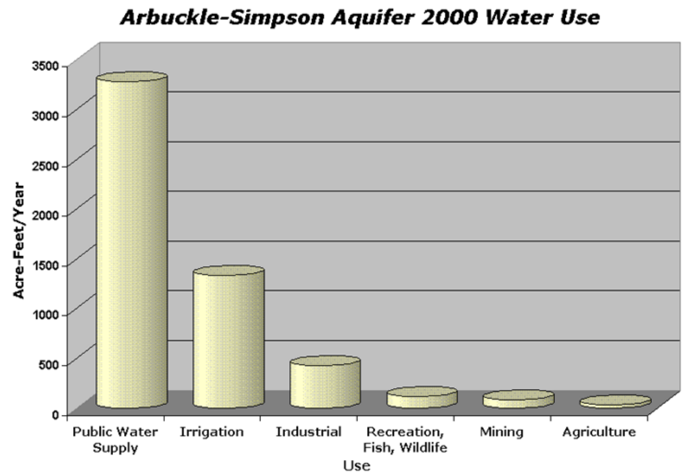
Understanding the hydrologic budget is important for managing and understanding the water resources of the Arbuckle Mountains. The U.S. Geological Survey developed a hydrologic budget of the Hunton Anticline region for a period of record in the 1970s. During this time, 80 percent of the average annual precipitation (38.4 inches) was returned to the atmosphere by evapotranspiration. The remaining 20 percent discharged from the area as surface runoff, of which 12 percent was base flow and 8 percent was direct runoff from land surface. Recharge to the aquifer was estimated from base flow to average 4.7 inches/year.

Buffalo Spring, part of the national park, is a freshwater spring originating from the Arbuckle-Simpson aquifer.

Water Use in the Arbuckle-Simpson

Wells in the Arbuckle-Simpson aquifer commonly yield 25 to 600 gallons per minute (gpm) of water, and deep wells have been known to yield as much as 2,500 gpm. To date, water in the aquifer has been produced in small amounts for municipal, irrigation, industrial, mining, agricultural, stock, and domestic purposes. Permit holders reported using about 5,000 acre-feet of groundwater in 2000, of which 62 percent was for municipal use and 25 percent was for irrigation.

Springs and streams receiving flow from the aquifer supply additional water for municipal, irrigation, industrial, mining, fisheries, recreation, and wildlife conservation purposes. Durant receives its water supply from the Blue River, Tishomingo from Pennington Creek, and Ada from Byrds Mill Spring.



Surface Water

Major streams emanating from the aquifer are the Blue River and Delaware Creek, which flow into the Red River, and Mill, Pennington, Honey, Hickory, and Oil Creeks, which flow into the Washita River. These streams are sustained throughout the year by groundwater discharge to springs and seeps.

At least 100 springs are known to discharge water from the aquifer to streams that drain the outcrop area. The largest is Byrds Mill Spring, located in the northeastern margin of the Hunton Anticline region, about 12 miles south of Ada. The spring flows an average 20 cubic feet per second (cfs) or 9,000 gallons per minute (gpm) and is the primary source of water for the City of Ada.

Also of importance are the freshwater and mineralized springs in the Chickasaw National Recreation Area. The two principal freshwater springs are Antelope and Buffalo Springs. These springs provide the primary source of flow in Travertine Creek, a popular recreation spot. The water is chemically similar to Arbuckle-Simpson water, and recharge to the springs is most likely from the outcrop of Arbuckle-Simpson rocks to the east. Several springs in the park and Vendome Well produce mineralized water, once valued for its medicinal qualities. Some of the waters have a strong sulfur odor, which is characteristic of hydrogen sulfide. The mineralized water–with large concentrations of sodium, chloride, and sulfate–appears to be a mix of fresh water from the Arbuckle-Simpson aquifer and saline water derived from a regional and/or deeper source.

Selected References

Cardott, B.J., and Chaplin, J.R., 1993, Guidebook for selected stops in the western Arbuckle Mountains, Southern Oklahoma: Oklahoma Geological Survey Special Publication 93-3, 55 p.

Fairchild, R.W., Hanson, R.L., and Davis, R.E., 1990, Hydrology of the Arbuckle Mountains area, south-central Oklahoma: Oklahoma Geological Survey Circular 91, 112 p.

Hanson, R.L. and Cates, S.W., 1994, Hydrology of the Chickasaw National Recreation Area, Murray County, Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 94-4102, 86 p.

Savoca, M.E., and Bergman, D.L., 1994, Effects of municipal ground-water withdrawals on the Arbuckle-Simpson aquifer, Pontotoc County, Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 93-4230, 37 p.

For digital data sets, visit the USGS Web site at wwwok.cr.usgs.gov.

For more information, visit the OWRB's Web site at www.owrb.state.ok.us.

OWRB the water agency

ATTACHMENT 4

science for a changing world

Potential Environmental Impacts of Quarrying Stone in Karst—A Literature Review

U.S. Geological Survey
Open-File Report OF-01-0484

U.S. Department of the Interior
U.S. Geological Survey

Potential Environmental Impacts of Quarrying Stone in Karst—A Literature Review

By William H. Langer

Open-File Report OF–01–0484

2001

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey (USGS) editorial standards nor with the North American Stratigraphic Code. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the USGS.

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

Version 1.0 2002

This publication is only available online at:
http://geology.cr.usgs.gov/pub/ofrs/OFR-01-0484/

Layout and cover design by Carol Quesenberry

Contents

Figures

Potential Environmental Impacts of Quarrying Stone in Karst—A Literature Review

By William H. Langer

Introduction

Limestone, dolomite, and marble - the carbonate rocks - are the principal karst-forming rocks. Karst is a type of topography that is formed on limestone, gypsum, and other rocks by dissolution that is characterized by sinkholes, caves, and underground drainage regions. Karst areas constitute about 10 percent of the land surface of the world (fig. 1) (Drew, 1999), and there is widespread concern for the effects that human activities have upon the karst environment. Much of the concern is motivated by the adverse environmental impacts of previous human activities in karst areas and the effects that those impacts have had on the quality of life. Many human activities can negatively impact karst areas, including deforestation, agricultural practices, urbanization, tourism, military activities, water exploitation, mining, and quarrying (Drew, 1999) (fig. 2).

Minerals associated with karst have been exploited for many years. Some carbonate rocks contain valuable supplies of water, oil, and gas, may weather to form bauxite deposits, and are associated with manganese and phosphate rock (guano). Coal is often found within thick carbonate rock sequences. Like other rocks, karst rocks may host ore deposits containing lead, zinc, iron, and gold.

Much of the resource extraction conducted in areas of karst is for the rock itself. Unweathered carbonate rocks provide crushed stone and dimension stone resources. The term "crushed stone" refers to the product resulting from the crushing of rocks such that substantially all faces are created by the crushing operation (ASTM, 2000). The term "dimension stone" is generally applied to masses of stone, either naturally occurring or prepared for use in the form of blocks of specified shapes and sizes, that may or may not have one or more mechanically dressed surface (Bowles, 1939: ASTM, 1998).

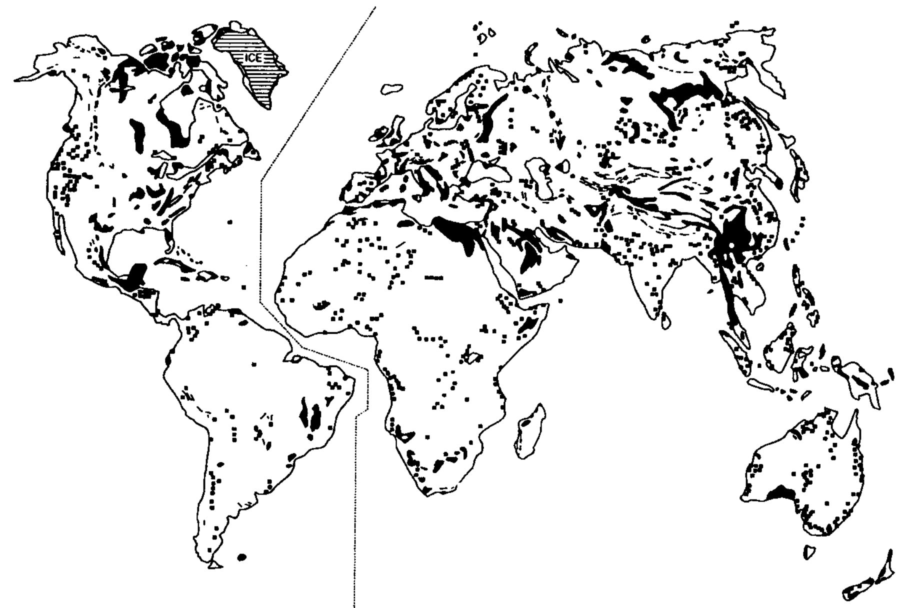


Figure 1. Major worldwide outcrops of carbonate rocks that exhibit at least some karstification *(after Ford and Williams, 1989).*

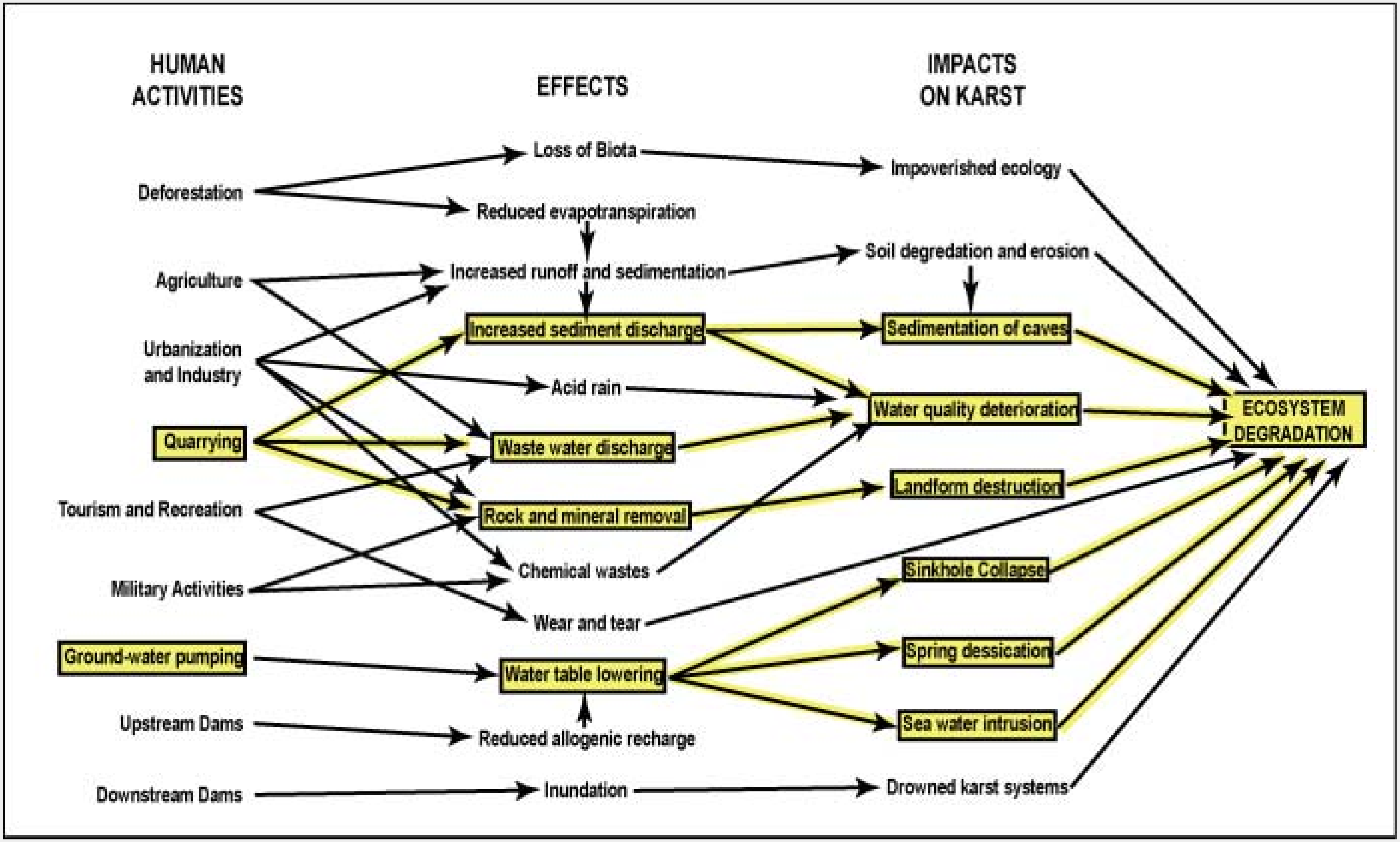


Figure 2. Summary of effects and impacts of various human activities on karst terrains. Effects and impacts from quarrying are highlighted in yellow. *(Modified from Williams, 1993a.)*

Carbonate rocks provide dimension stone, aggregate resources, and raw materials for cement and other industrial and agricultural uses. Over 70 percent of crushed stone produced in the United States is made from carbonate rock. The products derived from carbonate rocks provide essential materials for society –materials that we need to maintain our current standard of living. Quarrying[1] carbonate rocks for use as crushed stone and dimension stone can be accomplished with no significant impacts to the environment, if done carefully and within the limits set by nature. However, if proper precautions are not taken many human activities in karst, including extraction of carbonate rocks, can result in damage to the environment and associated increases in costs for environmental compliance or liability.

Purpose

This report describes the state-of-the-knowledge regarding the environmental impacts from quarrying carbonate rocks in karst. Documentation of the relationships between carbonate rock quarries and environmental problems in karst has existed for nearly fifty years, but is scarce. There are numerous articles in the literature that describe environmental impacts on karst from human activities other than quarrying, but there are relatively few articles that specifically refer to impacts from quarrying.

[1]In this report, the term "quarrying" applies to both surface quarries and underground mines from which cabonate rocks are extracted.

The reported environmental impacts have occurred in a wide variety of karst terrains, under a wide variety of climatic conditions, where the natural systems have been stressed by a wide variety of human activities. It should not be assumed that impacts in one karst terrain under a particular set of natural and man-made conditions will also happen in a different karst terrain with a different set of natural and man-made conditions.

Previous work

In recent years numerous publications have addressed issues related to karst in general, as well as issues specifically related to human impacts on karst. Publications addressing human impacts on karst include a special supplement of the journal Catena entitled Karst Terraines: Environmental Changes and Human Impact (Williams, 1993); a special issue of Environmental Geology with the theme of addressing Environmental Change in Karst Areas (Ford, 1993); a special issue of Engineering Geology with the theme Sinkholes and the Engineering and Environmental Impacts of Karst (Beck, 1999), and the publication Karst Hydrogeology and Human Activities (Drew and Hötzl, 1999). The Florida Sinkholes Research Institute has held symposiums concerned with sinkholes in karst at approximately two-year intervals (Beck, 1984, 1989, 1993; Beck and Pearson, 1995; Beck and Stephenson, 1997; Beck and Wilson, 1987; Beck and others, 1999). The American Geological Institute Environmental Awareness Series 4, Living With Karst, is a non-technical discussion of environmental issues in karst (Veni and DuChene, 2001). Few of the reports in the publications listed above are primarily concerned with quarrying in karst; however, those publications do illustrate the complexities of cause and effects of human activities in karst.

Although a relationship between environmental damage and quarrying of carbonate rock has been well documented for over fifty years (Foose, 1953), there are only a few reports that include major discussions of the environmental impacts of quarrying in karst. These reports include *Development of Sinkholes Resulting from Man's Activities in the Eastern United States* (Newton, 1987), *Ground Subsidence*, which includes a chapter *Sinkholes on Limestones* (Waltham, 1989), and *Karst Hydrogeology and Human Activities* (Drew and Hötzl, 1999), which includes a chapter on *Extractive Industries Impact* (Hess and Slattery, 1999). There are a few individual reports scattered through the literature that address the environmental impacts of quarrying carbonate rocks in karst. In addition, there are reports that describe environmental impacts on karst from mining resources other than carbonate rock. Theories about how extraction of carbonate rock can impact the environment can be extrapolated from some of these reports.

Natural Formation of Karst

There is a tremendous variety of carbonate rocks and these rocks exist in a broad range of climatic situations. Weathering of carbonate rocks produces diverse types of karst landscapes (fig. 3), far too many types to be described here. Instead, this report gives a simplified description of the karst forming processes. Readers interested in learning the details of karst formation are encouraged to consult the numerous textbooks and research reports that describe the geohydrologic and geomorphic processes involved with karst development. For example, Karst Geomorphology (Sweeting, 1981) contains benchmark papers about karst, including excerpts from Das Karstphänomen (Cvijíc, 1893). Process geomorphology (Ritter and others, 1995), a recent textbook, discusses karst from a process / response perspective. Karst Geomorphology (Jennings, 1985) is a technical description of karst written for the non-scientific audience. Karst Lands (White and others, 1995) is a concise article in American Scientist that describes karst formation and hydrology. Sinkholes in Pennsylvania (Kochanov, 1999) is a non-technical description of karst prepared for non-scientific audiences. The International Geographical Union Commission on Sustainable Development and Management of Karst Terrains published eight annotated bibliographies of karst research studies (for example, Urushibara-Yoshino, 2000).

Natural karst processes occur gradually over hundreds to thousands of years. The formation of karst includes interactions between carbonate rocks and slightly acidic water. (Actually karst can form on other soluble rocks such as gypsum; however, this report is restricted to carbonate rocks.) Carbonic acid is a mild acid formed when rainwater and carbon dioxide react. As the rainwater passes through the soil, the water absorbs more carbon dioxide and becomes more acidic. Carbonate rock contains openings between beds of rock and as fractures or joints created when the rocks were uplifted, uncovered, faulted, or folded (fig. 4). The slightly acidic water percolates into the rocks through these openings. The openings are enlarged by solvent action of acidic water. The dissolution process is self-accelerating: openings that are enlarged first will transmit more water, thus increasing the rate that acid is brought into contact with the rock, resulting in additional enlargement of the openings.

As underground flow paths controlled by joints, fractures, and bedding planes continue to enlarge over time, water movement changes from small volumes through many small, scattered openings in the rock to concentrated flow through a few well-developed conduits. As flow paths continue to enlarge, caves, conduits, and sinkholes may be formed (fig. 5). Surface streams may lose water to the subsurface or flow into cave entrances, only to reappear many miles away.

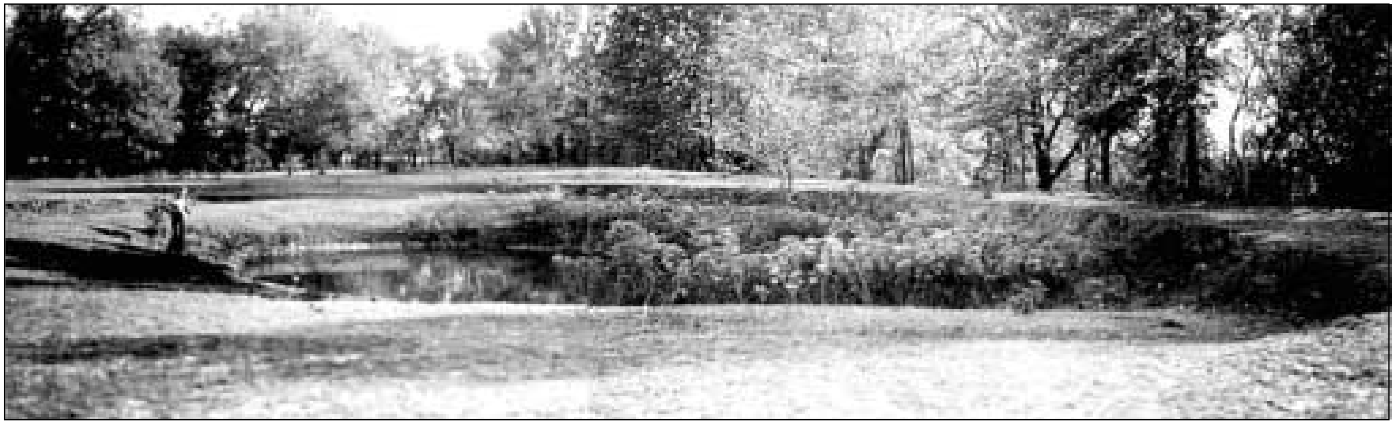


Figure 3. Shallow sinkhole typical of karst terrain in Cherokee County, Kansas. *(USGS photographic library - Pierce # 339, 340.)*

Unusual bedrock surfaces may be created as the carbonate rock is dissolved (fig. 6a and 6b). In temperate climates, some of the surfaces resemble abstract sculptures or contain pointed columns called pinnacles. A residual soil forms over the bedrock because there are minerals within limestone that are not affected by carbonic acid. As the process of dissolution continues, these insoluble minerals collect on top of the bedrock surface as clayey residual material. Some residual material is carried by water into openings in bedrock where they clog the openings. Other material, such as stream alluvium, may overly the clay. Depending on the climate, topography, and type of parent bedrock, soil on the bedrock surface can be non-existent or greater than 50 m thick.

Figure 4. Dimension stone quarry showing weathered outcrop (top) and smooth working face of quarry. Vertical solution channels following fractures and joints in the weathered outcrop extend down into the smooth working face. Horizontal solution features occur between beds of the rock. Notice ladder for scale. *(USGS photographic library - Loughlin 154.)*

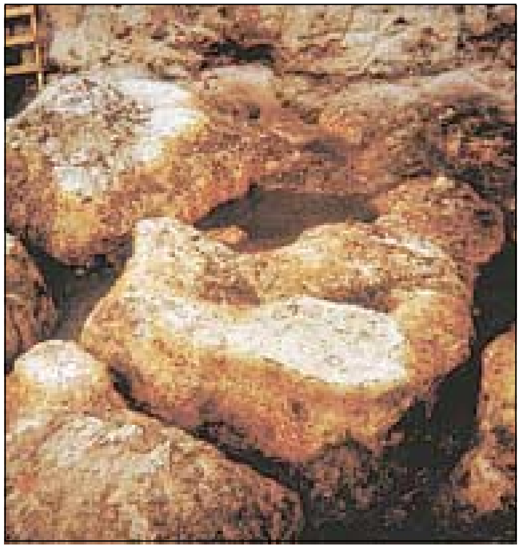


Figure 5 (above). Cave opening in karst terrain, Škocjan Cave, Slovenia.

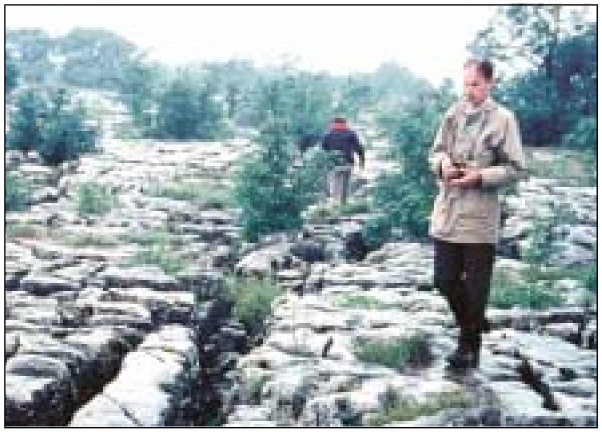


Figure 6-a (right). Limestone surface in karst area with no soil cover.

Figure 6-b (far right, top and bottom). Removal of overburden has exposed the furrowed and pitted surface of carbonate rock. *(Photograph courtesy of Keith Bennett, Williams Earth Sciences, Inc.)*

Quarrying Carbonate Rocks

The general objective of dimension-stone quarrying is to produce large rectangular blocks suitable for cutting into smaller, regularly-shaped products. The quarrying operation cuts a block of stone free from the bedrock mass by first separating the block on all four vertical sides and then undercutting or breaking the block away from the bedrock (fig. 7). Two of the oldest methods for quarrying are channel cutting and drilling and broaching. A channeling machine cuts a channel in the rock using multiple chisel-edged cutting bars that cut with a chopping action. In drilling and broaching, a drilling tool first drills numerous holes in an aligned pattern. The broaching tool then chisels and chops the web between the drill holes, freeing the block. Both channel cutting and drilling and broaching are slow and the cutting tool requires frequent sharpening. Both methods have generally been replaced with other more efficient methods.

Line drilling and sawing are more modern techniques for quarrying. Line drilling (also called slot drilling) consists of drilling a series of overlapping holes using a drill that is mounted on a quarry bar or frame that aligns the holes and holds the drill in position. Sawing can be accomplished with a variety of saws including wire saws, belt saws, and chain saws. The introduction of synthetic-diamond tools during the 1960's revolutionized stone working. A variety of explosive techniques may also be used to quarry dimension stone, but explosives generally are used in very small amounts, if at all, to avoid fracturing the stone block.

The general objective of crushed stone quarrying is to produce relatively small pieces of rock that are suitable for crushing into gravel-sized particles (fig. 8). To produce crushed stone, the rock is first drilled and blasted. Blasting commonly breaks the rock into pieces suitable for crushing. When the blasted material is dry, it can be extracted by using conventional earth-moving equipment, such as bulldozers, front loaders, track hoes, and scraper graders. Rock quarries that do not penetrate the water table, or where discharge from the water table naturally drains from the quarry, is offset by evaporation, or is otherwise insignificant, commonly are mined dry.

Figure 7. Working face of dimension stone limestone quarry in Lawrence County, Indiana, showing smooth surfaces from which large blocks have been removed. *(USGS photographic library – Burchard #556.)*

Where rock quarries penetrate the water table, the quarries commonly are dewatered by collection and pumping of the ground water. The rock is then mined by the procedures used in a dry quarry. Some operators may prefer not to dewater the quarry, or the inflow may be too great to be pumped. In those operations, the quarries are allowed to fill with water. The rock is drilled and blasted, and the rubble is extracted from under the water using draglines, clamshells, or other equipment. The aggregate may be processed wet or may be placed in windrows and allowed to dry before processing.

Carbonate rock is extracted from about 100 underground mines in the United States. Most of these mines are located in the Mid-Continent and produce crushed stone.

Figure 8. Working face of crushed stone operation showing rubble created by blasting. *(Photograph courtesy Luck Stone.)*

Production and Use of Carbonate Rocks

Worldwide production of carbonate rocks ranks third in terms of volume and fourth in terms of value for all non-fuel mineral commodities (fig. 9) (Lüttig, 1994). Over 70 percent of the crushed stone produced in the United States comes from carbonate rock, and about three fourths of that is consumed by the construction industry. Crushed carbonate rock also has numerous agriculture and industrial uses. Agricultural uses include fertilizers and insecticides. Industrial uses include the manufacture of cement, pharmaceuticals, processed food, glass, plastics, floor coverings, paper, rubber, leather, synthetic fabrics, glue, ink, crayons, shoe polish, cosmetics, chewing gum, toothpaste, and antacids. During 1999, over one billion tons of crushed limestone, dolomite, and marble valued at over $5.5 billion were produced from about 2,200 quarries operating in 48 states. The top 10 states (in decreasing order of production) each produced over 45 millions tons of crushed carbonate rocks – Texas, Florida, Illinois, Ohio, Missouri, Pennsylvania, Tennessee, Kentucky, Indiana, and Alabama (Tepordei, 1999). All of these states contain areas of karst.

Dimension stone has a large number of uses ranging from rustic walls and roughly-shaped paving stones to highly polished floor tile, counter tops, and building facades. The final use of the stone, as well as the methods to quarry and mill the stone, depend on the properties of the source rock. Today, stone is considered by many to be the premier building material and is experiencing resurgence in use for commercial and residential construction. During 1999, dimension limestone or dolomite were extracted from 33 quarries in 10 States. Production was 446,000 metric tons valued at $74.9 million. The top five producing states, in descending order by tonnage, were Indiana, Wisconsin, Texas, Minnesota, and Kansas. Other states producing dimension limestone or dolomite include Alabama, Arkansas, California, Ohio, and Vermont. Marble was extracted from 11 quarries in 5 states. Production was 40,300 metric tons valued at $9.5 million. Vermont was the leading producing State, followed by Tennessee, Georgia, Colorado, and Arkansas (Dolley, 1999).

Potential Environmental Impacts

Modern technology and scientific investigation methods have made it possible to reduce environmental impacts associated with extraction of carbonate rocks and manage impacts at acceptable levels that do not cause significant harm to the environment. Nevertheless, carbonate rock resources cannot be obtained from the landscape without causing some environmental impacts.

Engineering Impacts

Some of the environmental disturbance created by quarrying is caused directly by engineering activities during aggregate extraction and processing. The most obvious engineering impact of quarrying is a change in geomorphology and conversion of land use, with the associated change in visual scene. This major impact may be accompanied by loss of habitat, noise, dust, vibrations, chemical spills, erosion, sedimentation, and dereliction of the mined site. Some of the impacts are short-lived and most are easy to predict and easy to observe. Most engineering impacts can be controlled, mitigated, kept at tolerable levels, and restricted to the immediate vicinity of the aggregate operation by employing responsible operational practices that use available engineering techniques and technology (fig. 10). Some reports that generally describe engineering impacts include Barksdale (1991), Kelk (1992), Smith and Collis (2001), Lüttig (1994), Bobrowsky (1998), Primel and Tourenq, (2000) and Langer (2001).

Cascading Impacts

In karst environments, aggregate mining may alter sensitive parts of the natural system at or near the site thus creating cascading environmental impacts (Langer and Kolm, 2001). Cascading impacts are initiated by an engineering activity, such as the removal of rock, which alters the natural system. The natural system responds, which causes another impact, which causes yet another response by the system, and on and on. For example, aggregate mining in some karst might lower the water table, which will remove the buoyant support of rock that overlies water-filled caverns or other solution features, which might result in land collapse, which will create a sinkhole. Cascading impacts may be severe and affect areas well beyond the limits of the aggregate operation. Cascading impacts may manifest themselves some time after mining activities have begun and continue well after mining has ceased. Many of the impacts described below are cascading impacts.

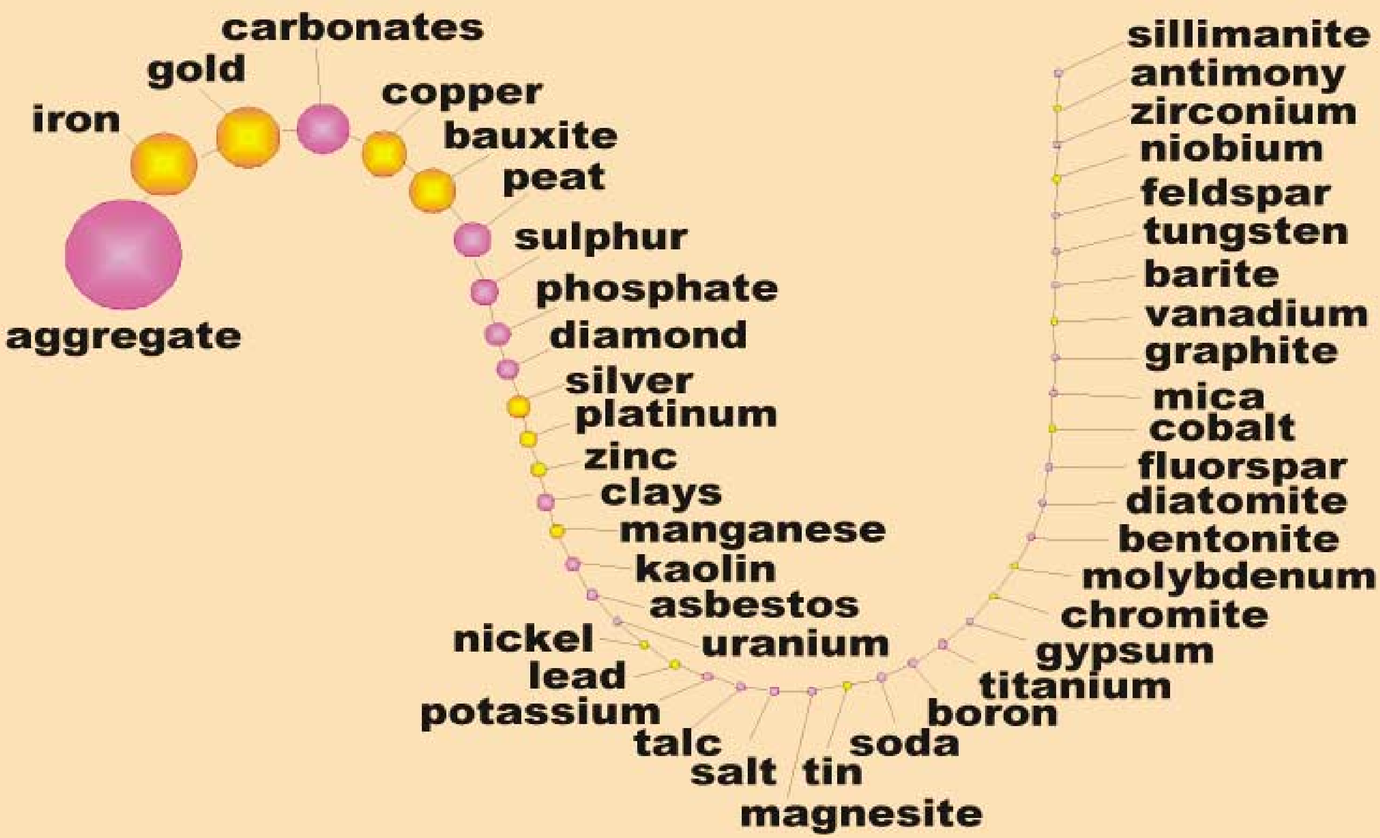


Figure 9. “Resource snake” graph showing relative values of non-fuel mineral resource production *(from Lüttig, 1994)*.

Geomorphic Impacts

Quarrying has an associated, often dramatic, visual impact. Karst terrain is commonly considered to be of high scenic value, thus compounding the effects of visual impacts of quarrying. The principal geomorphic impact of quarrying is the removal of stone, which results in the destruction of habitat including relict and active caves and natural sinkholes (Gunn and Gagen, 1987).

The extent of the geomorphic impact is a function of the size of the quarry, the number of quarries, and the location of the quarry, especially with respect to the overall landscape and the local landforms (fig. 11). The influence of quarry size on environmental impact is obvious: all other things being equal, the larger the quarry, the larger the geomorphic impact. The size of quarries has increased over time, and so has their impact.

Great numbers of quarries in a karst region amplifies the geomorphic impact (Sauro, 1993). Stanton (1966) suggested that the disturbance created by numerous smaller quarries is greater than that created by one large quarry and recommended that geomorphic disturbance be minimized by maximizing reserves through deep quarrying. (See section on ground water regarding the impacts of deep quarrying.) Stanton (1990) later suggested that limestone has more value *in situ* as a source of water and for its scenic value than as a source of crushed stone and recommended avoiding extraction of limestone altogether when alternatives are available.

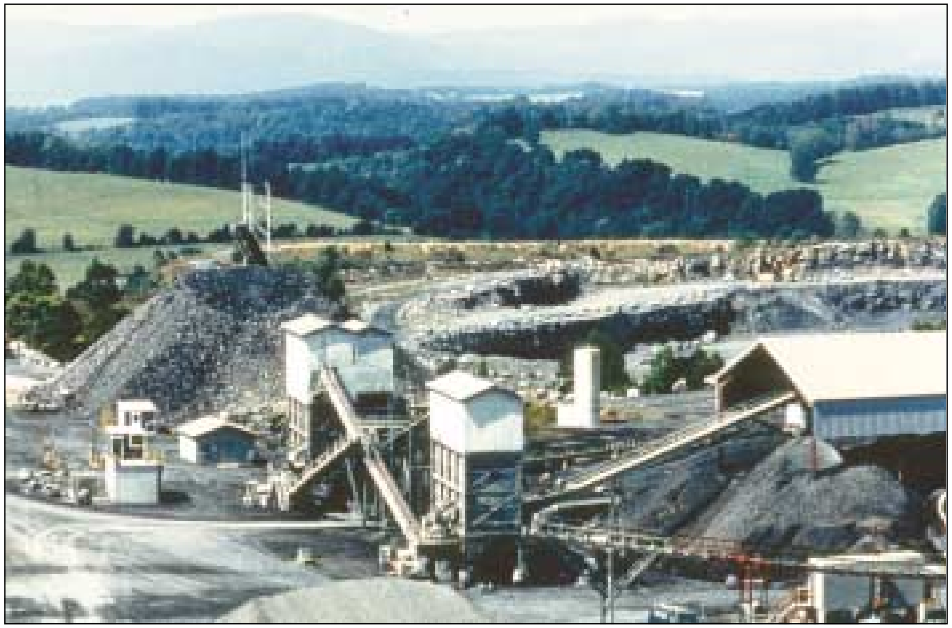


Figure 10. Engineering techniques, such as enclosing equipment and removing dust using vacuums, can mitigate impacts of noise and dust. *(Photograph courtesy of Luck Stone.)*

Figure 11. Quarries can occupy a significant part of the visual landscape.

In broad terms there are three situations where quarries can be located: 1) on flat ground, 2) along or into the side of a valley, and 3) on the side of a hill (Gunn, 1993; Gunn and Bailey, 1993). In most situations, quarries excavated into flat ground have a relatively small impact on geomorphology, which is limited to the removal of sinkholes and cave passageways. Quarries on valley sides can extend laterally along the valley side causing large geomorphic impacts, or they can work back into the valley wall, where the impact is less (Gunn, 1993; Gunn and Bailey, 1993). Quarries on hills generally have a large geomorphic impact. Gunn (1993) reports that crushed stone quarrying has removed an entire karst hill and large portions of other nearby karst hills in the Mendip Hills, UK.

Blasting

One of the most frequent complaints the public makes to the crushed stone industry situated near population centers is about blasting noise (National Academy of Sciences, 1980). Blasting may occur daily or as infrequently as once or twice a year. The blasting techniques used in crushed stone operations are significantly different than those used in dimension stone quarrying. Whereas large amounts of explosives are used in crushed stone operations to produce appropriate-sized rubble (fig. 12), the dimension stone industry uses only small amounts of explosives to loosen large blocks of stone.

Figure 12. Rock is drilled and blasted for use as crushed stone. In some isolated areas where people are not located nearby, larger amounts of explosives may be used.

Geology, topography, and weather affect the impacts of blasting. Blasting noise generally increases with the amount of explosive, with specific atmospheric conditions, and with proximity to a blast. The area in front of a blast commonly receives more noise than an area behind a blast. People differ greatly in their response to blasting (National Academy of Sciences, 1980).

The technology of rock blasting is highly developed, and when blasting is properly conducted, most environmental impacts should be negligible. By following widely recognized and well-documented limits on ground motion and air concussion, direct impacts from ground shaking and air concussion can be effectively mitigated. Those limits and methods to measure them are discussed in Moore and Richards (1999), Bell (1992), Berger and others (1991), and National Academy of Sciences (1980).

When an explosive is detonated enormous amounts of energy are released. Most of the energy of a properly designed blast works to displace rock from the quarry face. The remaining energy is released as vibrations through and along the surface of the earth and through the air. Most of the energy that goes through the earth comes to the surface within a few meters of the detonation and travels as surface waves, which may cause ground shaking. A small amount of the energy is transmitted through the rocks as shear waves, which commonly are insignificant.

When a blast is detonated, some energy will escape into the atmosphere causing a disturbance in the air. Part of this disturbance is subaudible (air concussion) and part can be heard (noise). Air concussion is most noticeable within a structure, particularly when windows and doors are closed. The air concussion creates a pressure differential between the outside and inside the structure causing it to vibrate.

Poorly designed or poorly controlled blasts may cause rocks to be projected long distances from the blast site (flyrock), which can be a serious hazard. Flyrock is not commonly a problem with carefully designed and executed blasting plans, but is a situation that deserves careful attention. The pinnacled bedrock in karst can complicate blasting, increasing the risks for flyrock.

Blast-induced vibrations and shock waves can cause stalagmites and stalactites to break off and cause cave roofs to crack or collapse. Blasting may cause fracturing of quarry walls, increasing permeability and increasing drainage towards quarry face (Gagen and Gunn, 1987, Gunn and Bailey, 1993). The blast zone beneath the quarry floor in sub-water table quarries may be considered as a separate aquifer with high fracture density, low primary porosity, and negligible conduit development (Smart and others, 1991).

Blasting-induced fracturing or aperture widening may play a role in initiating flooding events.

Lolcama and others (1999) describe a situation where blasting opened a conduit under the floor of a quarry. The conduit was connected to a nearby river and to a local water storage basin. Extensive grouting was required to stop the inflow of water from those sources.

Blasting can negatively impact karst biota and may cause problems with ground-water availability and quality (discussed below).

Noise

The primary source of noise from extraction of aggregate and dimension stone is from earth-moving equipment, processing equipment, and blasting (see above). The truck traffic that often accompanies aggregate mining can be a significant noise source. The impacts of noise are highly dependent on the sound source, the topography, land use, ground cover of the surrounding site, and climatic conditions. The beat, rhythm, pitch of noise, and distance from the noise source affect the impact of the noise on the receiver (Langer, 2001). Topographic barriers or vegetated areas can shield or absorb noise. Sound travels farther in cold, dense air than in warm air and travels farther when it is focused by atmospheric inversions than when inversions are not present.

An important factor in determining a person's tolerance to a new noise is the ambient (background) noise to which one has adjusted. In general, the more a new noise exceeds the existing background noise level, the less acceptable the new noise will be. In an urban or industrial environment, background noise may mask noise from a quarry operation, whereas the same level of noise in a rural area or quiet, residential neighborhood may be more noticeable to people. Furthermore, ambient noise generally is an accumulation of noises and does not have a single, identifiable source. If the mining noise is identifiable, the perception of noise probably will be great. For example, the noise from a single backup alarm can often be picked out from an equally loud engine noise.

Crushed stone operators and dimension stone quarriers are responsible for assuring that the noise emitted from the quarry does not exceed levels set by regulations. The impacts of noise can be mitigated through various engineering techniques. Landscaping, berms, and stockpiles can be constructed to form sound barriers. Noisy equipment (such as crushers) can be located away from populated areas and can be enclosed in sound-deadening structures (fig. 13). Conveyors can be used instead of trucks for in-pit movement of materials. Noisy operations can be scheduled or limited to certain times of the day. The proper location of access roads, the use of acceleration and deceleration lanes, and careful routing of trucks can help reduce truck noise. Workers can be protected from noise through the use of enclosed, air-conditioned cabs on equipment and, where necessary, the use of hearing protectors. Worker safety may include regular health screening.

Noise can negatively impact karst biota (discussed below).

Figure 13. Noisy equipment can be located away from populated areas and can be enclosed in sound-deadening structures. *(Photograph courtesy Luck Stone.)*

Dust

Dust is one of the most visible, invasive, and potentially irritating impacts associated with quarrying, and its visibility often raises concerns that are not directly proportional to its impact on human health and the environment (Howard and Cameron, 1998). Dust may occur as fugitive dust from excavation, from haul roads, and from blasting, or can be from point sources, such as drilling, crushing and screening (Langer, 2001). Site conditions that affect the impact of dust generated during extraction of aggregate and dimension stone include rock properties, moisture, ambient air quality, air currents and prevailing winds, the size of the operation, proximity to population centers, and other nearby sources of dust. Dust concentrations, deposition rates, and potential impacts tend to decrease rapidly away from the source (Howard and Cameron, 1998).

A carefully prepared and implemented dust control plan commonly can reduce impacts from dust (Kestner, 1994). Federal, state, and local regulations put strict limits on the amount of airborne material that may be emitted during site preparation and operation. Controlling fugitive emissions commonly depends on good housekeeping practices rather than control systems. Techniques include the use of water trucks, sweepers, and chemical applications on haul roads, control of vehicle speed, and construction of windbreaks and plantings (fig. 14). The impacts from plant-generated dust commonly can be mitigated by use of dry or wet control systems. Dry techniques include covers on conveyors, vacuum systems, and bag houses, which remove dust before the air stream is released to the atmosphere. Wet suppression systems consist of pressurized water (or surfactant treated water) sprays located at dust generating sites throughout the plant. Fugitive dust from blasting can be controlled by proper design and execution of blasts. Workers are protected from dust through the use of enclosed, air-conditioned cabs on equipment and, where necessary, the use of respirators. Worker safety may include regular health screening.

In some situations, dust on quarry floors and nearby areas can clog pores in the ground (fig. 15), thus altering recharge rates. In other situations, dust can enter conduits and smaller openings, and can be transported and deposited into caves (Gunn and Hobbs, 1999).

Dust can negatively impact karst biota (discussed below).

Habitat and Biota

Caves develop one of the most peculiar terrestrial ecosystems. One determining factor for life in karst solution features is the lack of light. The karst environment can be divided into four zones based on the degree of darkness (Vermeulen and Whitten, 1999): 1) The twilight zone, near the entrance where light intensity, humidity, and temperature vary and a large and varied fauna are found, 2) The transition zone of complete darkness, variable humidity and temperature where a number of common species live, some of which make sorties to the outside world, 3) The deep zone of complete darkness, almost 100 percent humidity, and constant temperature where fully cave-adapted species that never venture outside the cave live, and 4) The stagnant zone of complete darkness, 100 percent humidity, where there is little air exchange and carbon dioxide concentrations may become high.

Many species of bats, including nectar-feeding bats and insectivorous bats, roost in the twilight zone or transition zone of caves. Insectivorous bats make up the largest known colonies of mammals in the world (Veni and DuChene, 2001). Birds, other animals, and plants also inhabit these zones.

To cope with the permanent darkness, extreme scarcity of food, and relatively constant climate of the underground voids in the deep and stagnant zones, animals have developed physiological, behavioral, and morphological adaptations (fig. 16), losing many of the essential functions of aboveground species. Eyes are reduced or absent, and they have little or no pigment. These animals are able to cope with the highly alkaline environment created by the abundance of soluble calcium carbonate. They have developed means of expelling water in 100 percent humidity without losing body salts. If their ancestors had wings, cave animals have lost them. Diurnal rhythms are lost. Their life span increases and their fertility decreases dramatically. These adaptations have confined cave species to their habitat; they cannot survive elsewhere (Vermeulen and Whitten, 1999).

Figure 14. Dust control techniques include the use of water trucks and sweepers on haul.

Figure 15 (right). Dust on quarry floors can clog pores in the ground, thus altering ground-water. recharge.

The biodiversity of karst ecosystems is highly restrictive. Some species are restricted to single cave systems and are little known. For example, about 47 species of aquatic and terrestrial invertebrates have been collected from the Movile Cave and nearby springs in southern Romania. Thirty of the 47 species were previously unknown and appear to be endemic to the system (White and others, 1995).

As rock is removed by quarrying, any cave passage is destroyed, along with any sediments it may have contained. The habitat provided by the caves and passages will cease to exist. Animals that inhabit the twilight or transition zone, and are mobile and able to find new homes, might survive; the rest will die. Creatures that have adapted to the deep and stagnant zones will perish.

Figure 16a (top left). Karst inhabitant – Bamazomus. *(Photograph courtesy Elery Hamilton-Smith.)*

Figure 16b (bottom left). Karst inhabitant – Milyeringa. *(Photograph courtesy Elery Hamilton-Smith.)*

Quarrying may intersect active ground-water conduits, or cause their blockage, with adverse consequences for aquatic communities. Ground-water withdrawal and diversion of surface water may cause aboveground and underground hydrologic systems to dry up. Water bodies, which may be inhabited by small, site-endemic fish and snail species, will disappear and with them, the species. Alterations of flow volumes and patterns and the availability of nutrients can profoundly change the limestone environment and may lead to the extinction of whole communities (Vermeulen and Whitten, 1999). Lowering the water table will increase the thickness of the unsaturated zone, which can change the pH of the water in the unsaturated zone, which will change the biotic environment in small voids in the rock, which will kill species that live there.

Blasting can negatively affect karst habitat and biota. Blast-induced vibrations and shock waves can cause cave roofs to crack or collapse, and karst environmental conditions can be altered by just one new crack. Light may enter an otherwise dark cave or passage, or streams and ponds may suddenly drain into a new crack in the floor. Either situation can result in the death or displacement of cave communities (Vermeulen and Whitten, 1999).

Noise and air concussion may disturb colonies of bats and swiftlets, causing them to leave their roosting sites. This type of disturbance can occur as far away as 1,500 meters from the quarry if the opening of the roosting cave happens to be facing in the direction of the blast (Vermeulen and Whitten, 1999). Noise can adversely affect wildlife by interfering with communication and masking the sounds of predators and prey, and in the extreme, result in temporary or permanent hearing loss (Fletcher and Busnel, 1978).

Dust, if uncontrolled, may spread over the surroundings during dry weather, leach into the soil during storms, and create harmful conditions for the flora and fauna (Vermeulen and Whitten, 1999). When dust smothers leaf surfaces, vegetation can be damaged through the blocking of leaf stomata, thus inhibiting gas exchange and reducing photosynthesis (Howard and Cameron, 1998).

Changes in the humidity of karst openings, presence of water, and quality of water (see below) can all impact karst biota. The impacts of quarrying on surface water and ground water (see below) can impact wetland riparian, and aquatic habitat which, in turn, can impact biota.

Water Quality

Karst systems have very low self-purification capabilities (Kresic and others, 1992), which makes karst water very susceptible to pollution. A major concern is that polluted materials, including pathogens, can be carried long distances without being filtered because of high flow velocities (several hundreds of thousands of meters per day) (Assad and Jordan, 1994).

The sources of pollutants do not necessarily have to be man-made; there also are natural sources of pollution (Kresic and others, 1992). Generally, karst occurs in areas that contain large amounts of organic material and bacteria, which can naturally degrade water quality. Erosion, especially at boundary areas between karst and nonkarst areas, and washout of terra rossa and clay residue from fissures can cause increased turbidity at karstic springs. Ground-water drainage from ore deposits act as natural pollutants.

Quarrying can substantially modify the routing of recharge and water quality may be degraded (Gunn and Hobbs, 1999). Commonly the first impact of quarrying is to remove the overlying vegetation and soil. In temperate areas removing vegetation and soil reduces evapotranspiration and increases the effective rainfall. Unless measures are taken to control runoff and sedimentation, deterioration of ground water is likely. In some karst areas the soil overlying the rock normally is a zone of filtration and water purification (Gunn and Hobbs, 1999). In aggregate mining, the target limestone, if unsaturated, may also act as a protective cover for the underlying aquifer. If the protective soil cover or unsaturated rock is removed, the hole created by the mining may focus surface water to the ground-water system. If the surface water is contaminated, the ground water can quickly become polluted (Hobbs and Gunn, 1998; Ekmekçi, 1993).

Quarrying can cause sinkhole collapse, which can result in capture of surface water. In the Tournaisis area, southern Belgium, about thirty sinkholes opened up along the Escaut River downstream from the city of Tournai. As a consequence, the ground water was polluted by an extensive loss of contaminated river water into the karst aquifer (Kaufmann and Quinif, 1999).

Dust can enter conduits and smaller openings and can be transported by ground water (Gunn and Hobbs, 1999). The fine debris produced by the cutting of marble can be worked through the ground-water system during storm events (Drysdale and others, 2001).

Blasting may cause problems with ground-water quality, but may also be erroneously identified as a cause of problems. Spigner (1978) reported that shock waves from blasting operations loosened clay particles from solution cavities causing “muddying” of the ground water. Elsewhere, Moore and Hughes (1979) investigated the impact of quarry blasting on ground-water quality and determined there was no relationship between blasting and quality of water in wells in the situation that they studied.

The risk of ground-water pollution may increase if the direction of ground-water flow is modified. New source areas of recharge may be introduced, and those sources may contain contaminated water. This situation can arise because of ground-water pumping (Adamczyk and others, 1988; Sedam and others, 1988) or can occur if old choked passages are flushed and become operational again. Ekmekçi (1993) reported that blasting associated with quarrying may close existing karst ground-water passages, or may open up new passage, resulting in a change in direction of ground-water flow.

Figure 17a. Fuel oil spills can rapidly contaminate karst aquifers. *(Photograph courtesy Elery Hamilton-Smith.)*

Figure 17b. Properly constructed containment facilities can protect the aquifer from potential fuel spills. *(Photograph courtesy Lafarge.)*

Large amounts of silt and other effluents from quarries (waste, fuel, oil) may pollute rivers as well as underground water bodies within and far beyond the boundaries of the limestone area (fig. 17a and b). Rivers in Indo-China, for example, host hundreds of species of large freshwater clams and snails, many of which are site endemic to a section of one stream. Development puts great pressure on these animals, which are very vulnerable because they are easily smothered in mud or killed by chemical pollution when silt is allowed to seep into a river. Fish communities are equally vulnerable (Vermeulen and Whitten, 1999).

Surface Water

Engineering activities associated with quarrying can directly change the course of surface water. Sinkholes created by quarrying (see below) can intercept surface water flow. Conversely, ground water being pumped from quarries changes streams from gaining streams to loosing streams and can drain other nearby surface water features such as ponds and wetlands. Similarly, blasting (see above) can modify ground-water flow, which ultimately can modify surface water flow. Discharging quarry water into nearby streams can increase flood recurrence intervals.

Ground Water

Overall, quarrying in the unsaturated zone is likely to result in relatively local impacts such as increased runoff, reduced water quality, rerouting of recharge water through the aquifer, and localized reduction in ground-water storage. In karst areas, the unsaturated zone commonly contains only a small percentage of storage, and where the unsaturated zone is thin, impact on ground-water quantity generally is minimal (Hobbs and Gunn, 1998). However, Smart and Friederich (1986), Dodge (1984), and Gunn (1986) all describe areas where a thick, well-developed unsaturated zone is present. In those areas, the unsaturated zone may store significant quantities of water. Following rainfall, water may be collected and temporarily stored in the unsaturated zone, until it subsequently joins the ground-water system.

The major impact of quarrying in the karst saturated zone relates to quarry dewatering and the associated decline of the water table. It should be noted that there are many human activities other than quarrying that can affect ground-water levels, including municipal, industrial, and private ground-water withdrawals, irrigation, use of ground water for freeze protection, and mine drainage from other mineral resource extraction activities. Drought is a natural cause for water table declines. Many of the reports of dramatic declines of the water table refer to underground mines, rather than surface quarries.

If quarrying intersects a phreatic conduit (a conduit in the saturated zone), the water-transporting function of that conduit will be severely impacted. Dye studies have demonstrated that, even without intersecting conduits, quarry dewatering can affect the function of a conduit by inducing leakage into diffuse flow zones (Edwards and others, 1991; Sedam and others, 1988). In cross section, the path of a conduit often has a wave shape. If the water table is lowered to where at least the crests of the waves no longer contain water, water will be trapped in the troughs of the waves and the conduits will no longer be able to transmit water.

If a quarry intersects the water table, ground water commonly will flow out of the rock into the quarry. Water may just trickle into the quarry or it may flow into the quarry at a rate of hundreds or thousands of liters per second (L/s), especially if quarrying intercepts a phreatic conduit. Foose (1953) reported an inrush of 500 to 630 L/s that occurred when an underground limestone quarry intersected a conduit, and Lolcama and others (1999) reported a flow of about 2,525 L/s when a surface quarry intersected a conduit that was in hydraulic connection to a nearby river. In some situations, it may be necessary to drain or pump the water from the quarry to protect people, quarry workings, and equipment.

Pumping from a quarry will reduce hydraulic head and, thus, draw down water levels in the rock draining into the quarry. In the simplest case, the part of the water table impacted by quarry dewatering would look like a downward-pointing cone that has been depressed into the water table, thus its name – cone of depression. If the quarry were the only major source of ground-water draw down in the area, it would be located over the apex of the cone of depression.

The actual shape of a cone of depression depends on many factors including the direction, volume, and velocity of water moving past the site; rock properties, including permeability of rock layers, attitude of rock layers, amount of fractures in the rock, size of fractures, fracture orientation, continuity of fractures, and regional stresses keeping fractures open or closed; other sources of ground-water withdrawals, natural or manmade discharge points, recharge points, conduits, whether conduits recharge or drain aquifer, and so forth. Homogeneous rocks yield a classic circular cone of depression, but the anisotropic nature of most limestones produces an irregular zone of depression, with preferential development along zones of highest permeability (Gunn and Hobbs, 1999). Depending on local conditions and quarrying practices, cones of depression can be almost as small as the quarry itself, or can be as large as 25 km^2.

Figure 18. Natural sinkhole near Ste. Genevieve, Missouri *(USGS photographic library-Shaw #891)*.

Water pumped from a quarry is likely to be lost from the local ground-water system. Within the cone of depression, wells, springs, and streams can go dry or have their flows significantly reduced, and the overall direction of ground-water flow may be changed (Hobbs and Gunn, 1998). It is within this cone of depression that many human-induced sinkholes are formed.

Karst aquifers are often separate from overlying shallow surficial aquifers. Fraser and Grapes (1998) determined that a shallow aquifer in drift and the underlying karstic limestone aquifer in South Wales are separate hydraulic systems with distinct water chemistries and distinct responses to hydraulic stress. They determined that dewatering the deep aquifer would not affect plant communities supported by the shallow aquifer.

Sinkhole Collapse

Sinkholes are depressions formed in karst by either slow, downward solution or rapid collapse of the land surface. Sinkholes in carbonate rocks occur world wide, with notable concentrations in the eastern USA, southeast Asia, and parts of Europe. Sinkholes can occur naturally or can be induced by activities of man (Newton, 1976).

Figure 19. Human-induced sinkholes formed during the development of an irrigation well affected a 20-acre area and ranged in size from less than 1 foot to more than 150 feet in diameter. *(Photograph courtesy Ann Tihansky, USGS.)*

Natural sinkholes (fig. 18) can form through the dissolution of rock (solution sinkhole) or through the failure of a bedrock roof overlying a cavern (collapse sinkhole). The formation of both of these types of sinkholes occur over periods of geologic time, not within a human lifetime. The solution of rock has little to do with the final cause of sinkhole collapse, however, it can set the stage for some human-induced event in the future (Thorpe and Brook, 1984; White and White, 1995). Of an estimated 4,000 sinkholes formed in Alabama between 1900 and 1976, only 50 were natural collapses (Newton, 1976).

Human-induced sinkholes are those caused or accelerated by human activities and commonly are characterized by catastrophic subsidence (Newton, 1976; LaMoreaux and Newton, 1986; LaMoreaux, 1997). If human activities had not taken place, these sinkholes would not have occurred, would not have occurred when they did, or, under natural conditions, would have occurred as subsidence, not rapid collapse (Newton, 1987). Human-induced sinkholes (fig. 19) commonly form as a result of ground-water withdrawal, construction activities, or a combination of both.

Ground-Water Withdrawal

Human-induced sinkholes in karst commonly are caused by human activities that lower the water table below the rock/soil interface (fig. 20). Many human activities, in addition to quarrying, can lower the ground-water table. While quarrying commonly is restricted to relatively small areas, other activities tcan be spread out, which may increase their relative impacts on the environment. Regardless, in some situations quarrying includes ground-water withdrawals and should be carefully addressed.

A classic case of sinkhole development caused by dewatering an underground limestone quarry occurred in the Hershey Valley, Pennsylvania (Foose, 1953, 1969; Foose and Humphreville, 1979). In 1949, increased pumping from the quarry created a cone of depression covering 600 hectares. Nearly 100 subsidence sinkholes formed above the cone of depression within three months of the increased pumping. Sinkhole development ceased after quarrying dewatering stopped and the water table returned to normal.

Figure 20a. Hypothetical cross section showing karst area under conditions prior to quarry development. The water table (1) is generally above the soil / bedrock contact. Natural ground-water discharges to a spring (2), and a perennial stream (4), which support a wetland (3) and a riparian woodland (5). The surface of the bedrock is highly irregular (6), and is referred to as pinnacled bedrock. A natural sinkhole occurs where the water table is below the soil / bedrock contact (7).

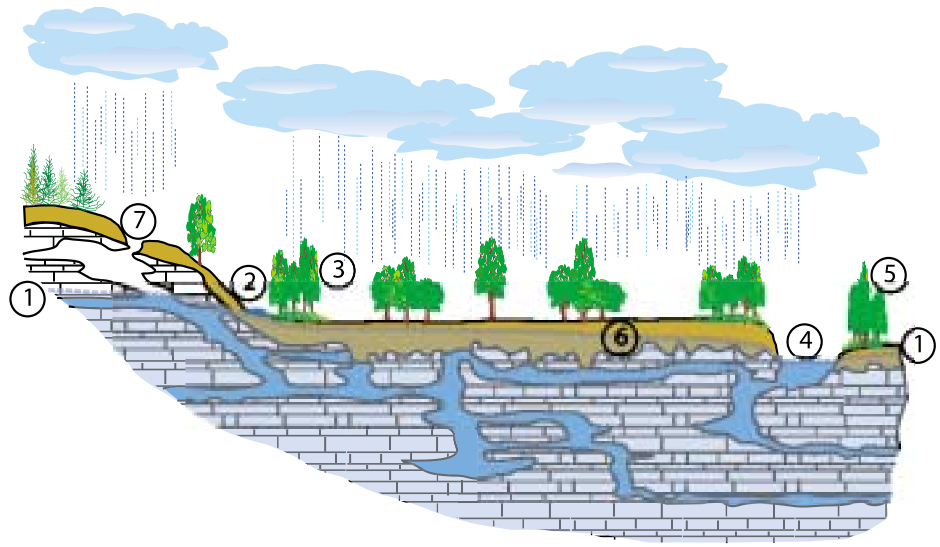
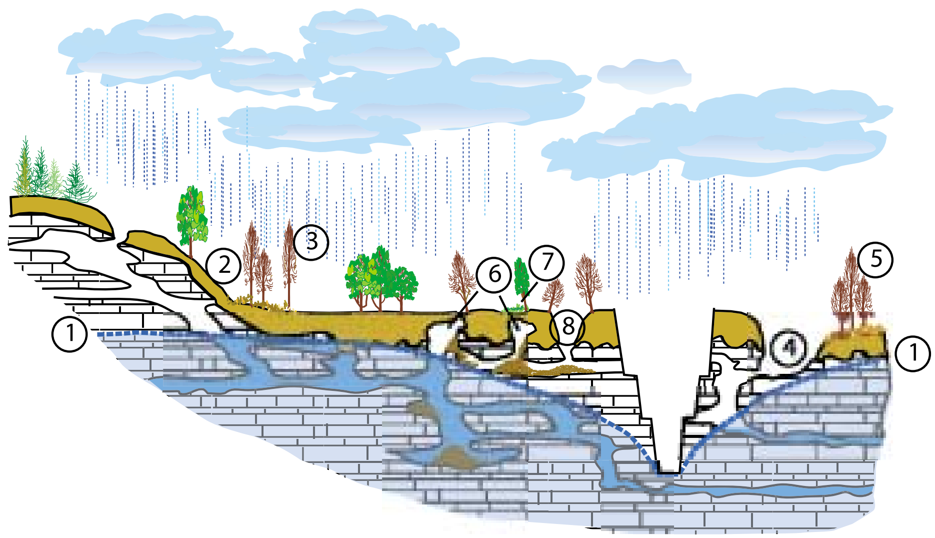


Figure 20b. Hypothetical cross section showing karst area under worst-case conditions after quarry development. Under actual conditions, none, some, or all of these conditions may exist. Quarry dewatering has lowered the water table (1) below the soil / bedrock contact. Natural ground-water discharge to a spring (2) and perennial stream (4) has stopped, resulting in destruction of the wetland (3), drying up of the stream (4) and destruction of the riparian woodland (5). Underground cavities formed in the soil in the area of the pinnacled bedrock due to loss of buoyant support and piping (6). The ground above the cavity has subsisded, resulting in the formation of a wet area, and the tilting of fence posts or trees (7). Ultimately these cavities could collapse, creating a collapse sinkhole (8).



LaMoreaux and Newton (1986) document a similar occurrence in the Dry Valley area of Alabama where several thousand sinkholes formed above a cone of depression in the period 1967 – 1984. Ground-water withdrawals from two quarries in the Jamestown, South Carolina, area resulted in the formation of 42 sites of subsidence and collapse from 1976 – 1978 (Spigner, 1978; Newton, 1987). Ground-water withdrawal caused by limestone quarrying appears to be the cause of sinkhole collapse at Railtown in northwestern Tasmania (Kiernan, 1989). Other areas of sinkhole collapse related to quarry dewatering have been described by Newton (1976, 1986, 1987), and Newton and Hyde (1971).

Sinkhole collapse related to ground-water pumping can also result from some other dewatering activity in combination with quarrying. A number of sinkhole collapses near Calera, Alabama, occurred in an area dewatered by wells, quarries, and an underground mine (Warren, 1976). Intense pumping for domestic and industrial water supply, combined with dewatering of deep limestone quarries, has caused sinkhole development in the Tournaisis area, Belgium, since the beginning of the 20th century (Kaufmann and Quinif, 1999).

Quarrying begins at the top of bedrock and deepening occurs over a period of years. Sinkhole development may begin after quarrying penetrates the water table (fig. 20). When the depth below the water table is shallow, sinkhole development generally is confined to the vicinity of the quarry. As the quarry is deepened, the cone of depression enlarges and sinkholes occur further away (Newton, 1987). Sinkhole development following dewatering associated with subsurface mining commonly occurs more rapidly than that resulting from surface quarrying because the depth of dewatering and cones of depression are relatively large (Newton, 1987).

Triggering Mechanisms

The act of lowering the water table commonly does not by itself create a sinkhole. Most often land subsidence will occur only if support to overlying unconsolidated material is removed (Foose, 1967) and some other activity commonly “triggers” sinkhole formation. Triggering mechanisms include: 1) water level fluctuations, 2) loss of buoyant support by the water, 3) volume shrinkage, 4) piping or induced recharge, and 5) increased gradient and water velocity (fig. 21) (Newton and Hyde, 1971; Newton, 1987).

Subsidence or collapse of soil overburden into the fissures and caves of an underlying limestone creates subsidence sinkholes without involving failure of the rock (Waltham, 1989). Bedrock caves do exist beneath some sinkholes, but their role is merely to swallow the debris. Almost all sinkholes occur where cavities develop in unconsolidated deposits overlying solution openings in carbonate rocks (LaMoreaux and Newton, 1986), and given sufficient time, sinkholes can develop above bedrock containing only narrow rock fissures (Waltham, 1989).

Water Level Fluctuations

Pumping of ground water, particularly in seasonally-operated quarries, may result in ground-water fluctuations that are of greater magnitude than fluctuations that occur under natural conditions. The magnitude of fluctuation principally depends on the amount and duration of pumping and on the transmissivity and storage coefficient of the aquifer. The unconsolidated material bridging bedrock pinnacles can be weakened by the alternate wetting and drying, lubrication, and addition or subtraction of buoyant support brought about by fluctuating water levels (Newton and others, 1973).

Loss of Buoyancy Support

In some karst areas residual clay soil spans or fills space between bedrock pinnacles. If the soil is saturated, about 40% of the weight of the residual clay soil overlying a bedrock opening is supported by ground water (Newton and Hyde, 1971; Newton, 1987). When the ground-water level is lowered, buoyant support is lost (fig. 21, block B). The loss of buoyant support can trigger sinkhole collapse (fig. 21, block D) or cause spalling that ultimately trigger collapse. (Newton, 1984a, 1984b, 1984c, 1987).

In artesian areas, hydrostatic pressure provides support to the confining bed and to overlying material (Newton, 1987). Weakening of buoyant support in artesian carbonate rocks may be caused by a decline of piezometric levels of the confined aquifer system. A one meter decline in piezometric level corresponds to a 1 ton/m^2 increase of effective loading of overburden. Local or distant withdrawals of karst aquifer could cause such a decline (Prokopovich, 1985).

Volume Shrinkage

As ground water is lowered in areas of pinnacle weathering, volume shrinkage due to compaction of the unconsolidated debris takes place. If two pinnacles are less than 10 – 15 m apart, the weight of the sediment load between the pinnacles can be carried as an arch (Foose, 1967). As spalling occurs, the cavity grows upward, enlarging the vaulted roof. There is a limit to the weight that the arch can hold, and when the ability of the arch to hold the load is exceeded, rapid upward propagation of the arch by continuous spalling results in sudden collapse of the surface.

Soils with low cohesive strength, such as dry sands, tend not to form a stable arch. There is a continuous flow of soil down the drain (raveling) and instead of an abrupt collapse, the sinkhole forms by a process of continuous subsidence. Human influences, particularly dewatering, can greatly modify the rate of soil transport (Newton and others, 1973).

Piping or Induced Recharge

When cavities in the soil or bedrock are filled with ground water (fig. 21, block A), surface water cannot flow into the cavities. When the water table is lowered, the cavities drain, thus allowing the inflow of surface water. Surface water passes through the residual soil, eroding it and carrying it downward into the air-filled cavities by a process called piping or subsurface mechanical erosion (LaMoreaux, 1997) (fig. 21, block C). Soil is piped down into the bedrock creating a void within the soil mantle. As time passes, more and more soil is piped down the drain and the void grows with an arched roof held up only by the cohesive strength of the soil. Eventually, the void becomes too large for the soil arch to support its own weight and there is a collapse (fig. 21 block D). The fallen roof may obscure the bedrock surface and the drain. The freshly-formed sinkhole is usually roughly circular in outline and has near vertical walls (Lolcama and others, 1999; White and White, 1995). Piping is well-documented by observations of the pumping of "muddy water" during quarry dewatering (Foose, 1953, 1967). Piping is most active during periods of heavy or prolonged rainfall.

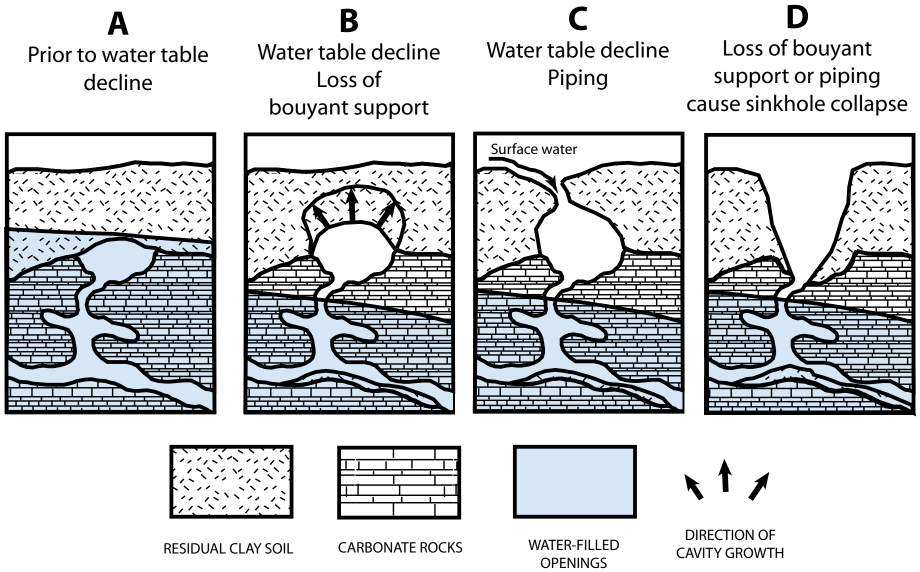


Figure 21. Diagram showing mechanics of sinkhole development.

Increased Velocity of Ground Water

Surface structures, such as storm drains, parking lots, and roof drains, concentrate recharge into a single inlet point in the carbonate rock, thus encouraging piping. Construction activities of various kinds can also raise hydraulic heads, increase velocities in the drain, and thus also enhance the rate of sediment transport leading to accelerated sinkhole development (Newton, 1986).

Ground-water withdrawal creates an increased hydraulic gradient, which results in an increased velocity of ground-water movement. Increased water velocity results in flushing of sediments filling openings in cavity systems. In turn, downward movement of overburden sediments into newly created bedrock openings, results in a sinkhole (Newton, 1976, 1984a, 1984b, 1984c).

A decline in potentiometric surface under artesian conditions produces increased head differential, which results in increased velocity of recharge through the confining bed. The energy of this movement is diffuse, and unless the confining bed is breached, will not be expected to contribute to sinkhole development (Newton, 1987).

Figure 22. "A giant sink hole opened up on Thursday, September 19 [1975] at a drilling site near Tampa, Florida and swallowed up a well-drilling rig, a water truck, and a trailer loaded with pipe all valued at $100,000. The well being drilled was down 200 ft when the ground began to give way to what turned out to be a limestone cavern. Within 10 minutes all the equipment was buried way out of sight in a crater measuring 300 ft deep, and 300 ft wide. Fortunately, the drilling crew had time to scramble to safety and no one was hurt." -from National Water Well Association newsletter. *(Photograph courtesy Tom Scott.)*

Construction Activities

Some sinkhole failures are induced by construction activities and are of major significance because they directly affect the site being developed, either immediately or some years later. Construction activities that can trigger sinkholes include 1) diversion or impoundment of drainage, 2) removing overburden, 3) drilling, augering, or coring 4) blasting, 5) loading, and 6) removal of vegetation. A lowered water table may leave sections of ground in a critical state awaiting construction activity to triggers their failure; however, even without a water-table decline, the same activity may prompt failure, but statistically less often.

Diversion or Impoundment of Drainage

A major influence from construction is the diversion of natural drainage. Concentration of drainage at the surface, such as leaking pools, impoundments, pipes, canals, and ditches, can all create point discharge into the soil, inducing ground water to move through overburden into bedrock. This can result in an increased velocity of ground water, piping, saturation of overburden, and loss of cohesiveness of unconsolidated deposits (LaMoreaux, 1997). These effects can result in collapse of the overburden into openings below.

Runoff from roads or buildings commonly is disposed of into ditches, soakaway drains, or dry wells in soil over carbonate rock. Ditches and drainage wells cased into the limestone should perform safely, but, if poorly installed, leakage may cause adjacent or nearby failures (Crawford, 1986). In Pennsylvania, 7 km of highway induced 184 sinkholes along its associated drainage channels within 12 years (Meyers and Perlow, 1984).

Removing Overburden

Excavation of part of a soil cover may thin the roof of a soil cavity to a point of failure. Removal of a clay soil may permit drainage through previously sealed sands. Some Missouri railroads stand on banks made from soil excavated adjacent to them, and the marginal hollows frequently develop sinkholes (Aley and others, 1972).

Drilling, Augering, or Coring

These activities cause erosion of overburden into underlying openings. Unsealed boreholes can allow surface water to gain new access to the subsurface or may allow a perched soil aquifer to drain into a bedrock cavity. Drilling has resulted in collapses at or near working drill rigs (fig. 22) or the holes created (LaMoreaux, 1997). During 1960 an USGS driller was killed when a sinkhole formed around a test hole in Florida (Newton, 1987). Installation of wells at Westminster, Maryland, in 1940 and 1948 was associated with nearby sinkhole collapse (Newton, 1987). A sinkhole collapsed next to a USGS test well near Dickson, Tennessee, in May 1981 (Newton, 1987).

Blasting

Explosives create vibrations that can disturb the overburden and trigger its downward movement into solution openings in bedrock (Stringfield and Rapp, 1976; Ekmekçi, 1993; LaMoreaux, 1997). The village of Liangwu, in southern China, was abandoned when nearby blasting triggered 40 sinkholes, and another 100 followed soon after in an area 1800m long (Yuan, 1987).

Loading

Heavy construction equipment and other traffic can disturb the overburden and trigger its downward movement into solution openings in bedrock (LaMoreaux, 1997). The weight of construction alone can trigger sinkholes (Newton, 1976).

Removal of Vegetation

The removal of vegetation permits increased infiltration and also deprives the soil of its root mat. In Alabama, sinkholes are more common in the parts of Dry Valley where timber has been cut (LaMoreaux and Newton, 1986) and failures occurred on a Birmingham, Alabama, construction site when foundation trenches stripped areas of topsoil (Newton and Hyde, 1971). Modern sinkhole development in Tasmania has been attributed to timber cutting and pasture development (Kiernan, 1989).

Analysis of Triggering Mechanisms

Two independent studies, one in Missouri and one in Florida, indicate that altered drainage is the triggering mechanism responsible for over half of the sinkhole collapses. Williams and Vineyard (1976) conducted a study of 46 reported sinkhole collapses in Missouri and determined the cause of collapse to be; altered drainage (52 percent, water impoundments (22 percent), dewatering (15 percent), highway construction (7 percent), and blasting (4 percent). The Florida Department of Transportation analyzed 96 roadway-related collapses and determined the triggering mechanisms to be related to; heavy rainfall (58 % percent), construction (11 percent), lowering of the water table (8 percent), blasting (5 percent), drilling (5 percent), and other (11 percent). (Numbers do not add to 100 due to rounding.) Runoff collected during heavy rainfall is concentrated by highway drainage, thus supporting the findings of Williams and Vineyard (1976) that altered drainage is the dominant triggering mechanism for collapse (Thorpe and Brook, 1984).

Sinkhole Size, Occurrence, and Area Impacted

Collapse sinkholes in fissured bedrock occur in the soil overlying cavernous bedrock, and the depth, therefore, is limited to the thickness of the soil. In cavernous bedrock the depth of collapse sinkholes is limited to the combined depth of the soil and the cavern. The width of a collapse sinkhole near the surface depends on the thickness of the soil and on the slope stability, which, in turn, relates to the cohesiveness of the soil (Waltham, 1989). Geometry dictates that thick soils develop sinkholes with greater diameters than thin soils (White and White, 1995). Cohesive clayey soils maintain steeper slopes that sandy soils with low cohesiveness and, consequently, maintain wider sinkholes.

Size

Data relating to the size of sinkholes resulting from ground-water withdrawals are limited and not all the figures below refer to sinkholes related to quarrying. Sinkhole collapses in general range from 1 m to 145 m in their longest dimension. One of the largest sinkholes resulting from the withdrawal of ground water from carbonate rocks in Alabama is about 145 m long, 115 m wide, and 50 m deep (LaMoreaux and Warren, 1973) (fig. 23). A study of an area in the Birmingham, Alabama, containing over 200 sinkhole collapses (Newton and Hyde, 1971) reported that the average sinkhole was 3.7 m long, 3 m wide, and 2.4 m deep. A similar study of an area near Greenwood, Alabama, containing over 150 sinkholes (Newton and others, 1973) reported that the average elongated sinkhole was about 6.1 m long, 4 m wide, and 2.1 m deep. Some sinkholes near Sylacauga, Alabama, (Newton, 1986) had surface diameters of 9 to 30 m. In Shelby County, Alabama, (Newton, 1986) six collapses had diameters approaching or exceeding 30 m. Collapse sinkholes near Orlando, Florida, have a mean diameter of 9.4 m and a mean depth of 4.7 m (Wilson and Beck, 1992). A collapse sinkhole in central

Figure 23. The "December giant," a large sinkhole, developed rapidly in Shelby County, Alabama, in December 1972. The sinkhole measures 145 m long, 115 m wide, and 50 m deep. *(USGS Photographic Library-USGS #140.)*

Maryland (Martin, 1995) was approximately 9 m in diameter and 6-7 m deep. Collapse sinkholes resulting from quarry dewatering in North Carolina are up to 5 m in diameter and 3 m deep (Strum, 1999). Sinkholes in Pennsylvania (Kochanov, 1999) generally range from 1.2 m to 6.1 m in diameter and have approximately the same range in depth. In Hershey Valley, Pennsylvania, (Foose, 1953) 100 new sinkholes were reported to be 0.3 to 6.1 m in diameter and 0.6 to 3 m deep. The largest of 42 sinkhole collapses described in South Carolina (Spigner, 1978) was over 8 m in diameter and the greatest depth exceeded 3 m. The largest of 64 sinkhole collapses near Tampa, Florida, also has these same dimensions (Sinclair, 1982).

Occurrence

The numbers of collapse sinkholes that occur in an area and the size of the effected area varies from a single sinkhole in (about 1 m) to about 1,000 sinkholes in area of about 45 km2. Seven sinkholes developed at a distance of 600 m from a quarry in North Carolina (Strum, 1999). Newton (1986) similarly reports that most induced sinkholes in Alabama related to quarry operations were found within 600 m of the point of withdrawal. In contrast, Sowers (1976) reports that quarries less than 60 m deep near Birmingham, Alabama, have been related to sinkhole development as far away as 1.6 km. Sinclair (1982) also reports that 64 collapses occurred within a 1.6 km radius of a well field near Tampa, Florida. In one area in Alabama, an estimated 1,700 collapses or related features have occurred in five areas with a combined area of 36 km2 (Newton, 1976). In another area of Alabama, it was estimated that 1,000 collapses or other related features formed in an area of about 41.5 km2 (Warren and Wielchowsky, 1973). Near Jamestown, South Carolina, 42 collapses occurred within a cone of depression (Spigner, 1978). In Pennsylvania, about 100 collapses occurred in a cone of depression near Hershey where the ground-water surface had been lowered in an area greater than 25.9 km2. Impacts were observes 2.4 km from the point of dewatering (Foose, 1969; Foose and Humphreville, 1979). At Friedensville, Pennsylvania, 128 sinkholes formed from 1953-57 in an area around the point of withdrawal at a zinc mine, and 25 new sinkholes were recorded during a four-month period ending January 1971 (Newton, 1987; Metsger, 1979). Sites of similar intense development, in addition to those described above, were identified in Alabama, Georgia, Maryland, North Carolina, Pennsylvania, South Carolina, and Tennessee (Newton, 1986).

Area Impacted

The size of the impacted areas varies with the amount of ground-water withdrawal. Rates of withdrawal at the Friedensville zinc mine were between 440 and 1,310 liters per second (L/s), and the cone of depression covered an area exceeding 10.3 km2 (Newton, 1987; Metsger, 1979). Pumping by wells, quarries, and an underground mine west of Calera, Alabama, exceeded 883 L/s, creating a cone of depression of about 26 km2 (Newton, 1976, 1987; Warren, 1976). Ground-water withdrawal from two quarries with a combined rate in excess of 1,575 L/s has lowered water levels in wells over 2.4 km from the quarries (Spigner, 1978). Near Hershey, Pennsylvania, an average of 347 L/s of water was pumped from the underground quarry, impacting areas 2.4 km away (Foose, 1953, 1969). In Craven County, North Carolina, a quarry pumped at a rate of about 440 L/s, which resulted in sinkholes 600 m away (Strum, 1999).

Predicting Collapse Sinkholes

It is only possible to predict sinkhole subsidence events in the broadest of terms. However, it is possible to identify zones where sinkhole risk is increased. A number of researchers have identified specific karst features that are diagnostic in pinpointing areas having a likelihood of collapse and subsidence. Williams and Vineyard (1976) cited nine features that can foretell of collapse or subsidence in karst terrain. Foose (1969) lists seven conditions that are common in areas of karst topography subject to collapse. Aley and others (1972) described seven features of karst terrain where catastrophic collapse had occurred, although they were primarily concerned with collapses induced by construction of impoundments.

The indicators cited may have limited regional usefulness because of the tremendous number of variables among various karst terrains and the various climatic conditions in those terrains. While this report is not intended to challenge the significance of the indicators, it is important to remember that the physical properties of karst are the result of local conditions.

Guidelines that repeatedly emerge from case studies is that sinkhole development most commonly occurs where four conditions exist: 1) residual soil overlies pre-existing fractures or cavities in pinnacled carbonate bedrock; 2) a solutionally widened fracture or shaft leading down into bedrock can act as a drain to transport sediment; 3) there is some provision to store or remove soil from the drain; and 4) the water table has declined past the bedrock/soil contact (Waltham, 1989; White and White, 1995).

Collapse sinkholes form most often where and when the water table first declines past the bedrock/soil contact. This condition occurs where the water level, previously above the bedrock/soil contact during all or most of the year, is maintained below the contact by ground-water withdrawal (Waltham, 1989; Newton, 1987; LaMoreaux and Newton, 1986; Foose, 1969). All the mechanisms that trigger sinkhole development in unconsolidated deposits can be activated by the decline in water table (LaMoreaux and Newton, 1986).

LaMoreaux and Newton (1986) state that sinkholes will not occur in areas where the water table was below the bedrock/soil contact prior to dewatering. However, Foose (1969), states that sinkholes have formed where the original water table was below the bedrock/soil contact as a consequence of flushing out underlying bedrock openings during ground-water lowering.

Wilson and Beck (1992) relate sinkhole occurrence in Florida to declines in the potentiometric surface. When the surface declines 3 m below its mode, more than 10 times as many collapse sinkholes as expected per unit of time begin to occur.

Many authors also pointed out that sinkholes occur where the bedrock weathering is irregular, where the bedrock is pinnacled, or where there are extensive cavernous openings and major structural elements in the underlying bedrock (Foose, 1968; Newton, 1984a, 1984b, 1984c; Waltham, 1989).

The thickness of the residual soil has some control on the likelihood of collapse sinkholes, although the actual values appear to be site and soil-type dependent. Williams and Vineyard (1976) pointed out that sinkhole collapses are more likely to occur in residual soil ranging in thickness from 12 to 30 m. Foose (1969) observed that few sinkholes occur where the overburden is less than 10 m thick. Waltham (1989) states that the most hazardous zone is where the soil is 2 to 20 m thick. Sinclair and Stewart (1985) state sinkhole collapses are rare where limestone is at surface or the ground is thinly covered with soil; sinkhole collapse is common where overlying material is 5-50 m thick, especially between 5 and 25 m thick; sinkhole collapses are found but are rare in areas of soil cover over 50 m thick. Williams and Vineyard (1976) pointed out that sinkhole collapses are more likely to occur in residual soil that retains the fabric of the parent material and in soil where the clay fraction has low plasticity common to kaolinitic and halloysitic clays.

Geomorphology influences collapse sinkhole formation. Newton (1984a) reports induced sinkhole formation is most common in terrain that is geomorphically youthful, exhibits little karstification, is usually a lowland area, has a water table above or near the top of bedrock, and contains perennial or near-perennial streams. Williams and Vineyard (1976) found that collapses are more likely to take place in valleys with losing streams and watersheds than in gaining ones. Waltham (1989) states that the most hazardous zone is a valley floor. Many collapse sinkholes occur where concentrations of surface water are greatest, such as streambeds, natural drains, or poorly drained areas. Wilson and Beck (1992) report that near Orlando, Florida, 85 percent of new sinkholes occur over high recharge areas on slightly elevated, sandy ridges. Few or no sinkholes occur in discharge areas where net downward erosion of surficial sediment is very unlikely. Kaufmann and Quinif, (1999) related sinkhole orientation in southern Belgium to structure, and reported that almost every sinkhole they investigated lies in three parallel linear zones that reflect the orientation of a shear fault about 1 km away.

Hobbs and Gunn (1998) outline a method to characterize the nature of a karst aquifer in terms of the likelihood of impacts from carbonate rock extraction on the ground water. They classify carbonate aquifers into four groups based on storage, type of flow, and type of recharge. Storage ranges from high to low; flow ranges from conduit to diffuse, and recharge ranges from concentrated to dispersed.

- Group 1 represents aquifers with high storage, conduit flow, and variable recharge. Predicting the impact of quarry dewatering is very difficult and is dependent on the likelihood of the workings intersecting an active conduit.
- Group 2 represents aquifers with low storage, conduit flow, and variable recharge. Predicting the impact of quarry dewatering is very difficult, but with low storage, the number of water supplies and size of springs supported by the aquifer is likely to be small.
- Group 3 represents aquifers with low storage, diffuse flow, and dispersed recharge. These are thin limestones with seasonal springs and typically are minor or non-aquifers. These aquifers present no problem from a geohydrologic point of view, and the potential impact can easily be predicted by treating them as homogenous aquifers.
- Group 4 represents aquifers with high storage, diffuse flow, and variable recharge. These aquifers provide a useful resource and may support moderately large springs that may, in turn, provide stream base flow. The potential impact can easily be predicted by treating them as homogenous aquifers.

A holistic systems analysis technique to investigate impacts of aggregate extraction on the environment is described by Langer and Kolm (2001). The method requires analyzes of various systems making up the environment, including land surface, geomorphic, subsurface, and ground-water systems (Kolm, 1996). After system characterization is complete, the method focuses on risk analysis techniques for identifying and evaluating potential environmental impacts to determine acceptable mining strategies (Langer, in press).

There may be warning signs of impending sinkhole collapse. There may be slow localized subsidence and, although new depressions may be hard to identify, the depressions may be enhanced by the ponding of water. Circular cracks may appear in the soil or pavement. Fence posts or other objects may be tilted from the vertical. Vegetation may be distressed due to lowering of the water table. Muddy water in wells may indicate the early stages of a nearby developing sinkhole.

Reclamation

Reclamation commonly is considered to be the start of the end of environmental impacts from mining. The development of mining provides an economic base and use of a natural resource to improve the quality of human life. Equally important, properly reclaimed land can also improve the quality of life. Wisely shaping mined out land requires a design plan and product that responds to a site's physiography, ecology, function, artistic form, and public perception.

There are numerous examples of successfully reclaimed aggregate quarries, including residential, commercial, recreational, and natural uses (Arbogast and others, 2000). Many of the examples are independent of rock type. However, there are a few studies that relate specifically to reclamation of carbonate rock quarries to near natural conditions.

The oldest design approach around is nature itself. Given enough geologic time, a suitable small site scale, and stable adjacent ecosystems, disturbed areas may recover without mankind's input. Ursic and others (1997) studied the Niagara Escarpment and recognized natural cliffs as special places that provide refuge for rare species of plants and animals. They also inventoried vegetation on the walls of 18 carbonate rock quarries abandoned from 20 to 100 years ago and discovered that many of the older quarry walls naturally revegetated in such a way as to replicate the biodiversity of natural landforms.

In other areas, long-term natural recovery alone may not bring about the specific changes people find desirable. The natural reclamation process of abandoned quarries can be accelerated through a process called landform replication. Through carefully designed blasting, referred to as restoration blasting, talus slopes, buttresses, and headwalls of carbonate rock quarries can be created that can be revegetated to produce landform and plant assemblages similar to those that occur on natural valley sides (fig. 24) (Gunn and Bailey, 1993; Gunn and others, 1997).

Gillieson and Houshold (1999) describe reclamation projects in Australia that are specifically designed to return carbonate rock quarries to as close as possible to their original state. The key issues were the integrity of the underground drainage, its water quality, and the cave invertebrate populations.

Legal Aspects

The legal situation concerning induced sinkholes and other environmental impacts in karst is reviewed by Quinlan (1986), LaMoreaux (1997), and LaMoreaux and others (1997).

Quinlan (1986) summarizes case law, legal concepts of ground water and surface water, liability, and law review articles. He reviews the rationales of plaintiffs and defendants, including the allegations that serve as the basis of liability for damages and the defenses against those allegations.

LaMoreaux (1997), and LaMoreaux and others (1997) primarily discuss regulatory standards and the geologic and hydrologic conditions that lead to legal disputes. The authors point out that nearly every State in the United States has implemented legislation, rules, and regulations that apply in part or totally to karst terrain and give examples of State and local laws.

An example of the difficulties in determining the proximate cause of a sinkhole is demonstrated by the investigation of a catastrophic sinkhole that occurred near Westminster, Maryland (Gary, 1999). On March 31, 1994, a sinkhole opened up in the middle of a State road. The sinkhole measured approximately 8 m by 6 m, and was 4.5 m deep. A man drove into the sinkhole and was killed. An active quarry operation was located about 600 m away, and two municipal water supply wells were within 1.6 km of the sinkhole. An isolated pinnacle of limestone occurred in the center of the roadway alignment. A dye trace was conducted to determine if there was a hydraulic connection between the sinkhole and the quarry or other pumping locations. Sampling stations were placed throughout the surrounding valley and in the nearby quarry. There was no dye recovered in the sample sites, therefore, there was no conclusive evidence that quarry dewatering was the cause for the sinkhole.

Figure 24. Face of limestone quarry after restoration blasting and habitat reclamation. *(Photograph courtesy John Gunn.)*

Case Studies

There are numerous causes of environmental damage in karst, many that do not relate to quarrying. These case studies are primarily those directly related to quarrying or engineering activities, such as drilling and blasting, that are used by a number of activities, including quarrying. Units of measurements in case studies are as reported by the original authors.

Blasting - A sinkhole collapse occurred in 1983 while blasting for new highway construction near Erwin in Unicoi County, Tennessee (Newton and Tanner, 1987).

Blasting - A number of rural residents near Oxford, Alabama, reported recurring problems in turbidity of water from their individual water-supply wells and, occasionally, decreases in yield. Many residents associated the problems with blasting operations in a local rock quarry. Research identified no relationship between blasting events and the quality of water in wells. Most turbidity problems occurred during the dry period of the year (October—December) when water levels in some wells are as much as 40 feet lower than during summer months. Turbid or muddy water in some wells resulting from heavy rainfall and heavy use of ground water, particularly during extended dry periods, contributes significantly to the problem (Moore and Hughes, 1979).

Blasting - Collapse sinkholes formed at a quarry (location not given) in Paleozoic dolomitic limestone following a routine blasting event. Ground water entered through the floor of the quarry from an unsuspected conduit. The conduit connected the quarry with a karst cavern network that extended to a nearby river. Immediately following the blasting event, water flowed into the quarry at a rate of about 15,000 gpm, carrying with it eroded karst-fill from the cavern. For the first few weeks, the inflow decreased in response to a rapid decline of the water table within the karst aquifer. The drainage may have led to enlargement of subsurface voids, creating a continuous connection between the river and the quarry. Subsequent river inflow to the pit further eroded fill material from the conduit and the rate of inflow increased over the next several months to over 40,000 gpm (Lolcama and others, 1999).

Drilling - Collapse at a U.S. Geological Survey test well near Keystone Heights, Florida, in 1959-60 buried a driller's helper to a depth of 30 feet and partially buried the geologist at the site. Drilling was at a depth of about 80 feet near the contact between the unconsolidated surficial material and the underlying limestone aquifers. Water level in the shallow aquifer was reportedly higher than in underlying aquifer. The well being drilled was a replacement for another recently completed and abandoned well about 12 feet away. Blasting in the abandoned well to increase yield had damaged the bottom of the casing set at depth of about 80 feet. The casing was removed prior to drilling the new well (Newton, 1987).

Drilling - Installation of wells at Westminster, Maryland, in 1940 was associated with nearby sinkhole collapse. In 1948, the well was replaced by two new wells. During a 72-hour test, the two wells were pumped at a combined rate of 950 to 1050 gpm. A sinkhole formed near the wells and cracks reportedly formed in two nearby buildings (Newton, 1987).

Drought - As many as 40 collapses sinkholes formed in downtown Sylacauga, Alabama, during a prolonged drought in 1953-56. The largest sinkhole was as much as 30 to 40 feet in diameter and 30 to 40 feet in depth. Collapses occurred under streets, water lines, drains, and other structures including a church and football field. Sinkhole activity ceased with recovery of the water table at the end of the drought. Limited activity occurred briefly in 1981 during similar decline in water table. Some water withdrawals contributed to declines during both periods (Newton, 1987)

Freeze Protection – Collapse sinkholes formed near Pierson, Florida, during the period 1973-1979 in the cone of depression created by ground-water withdrawals. Most of the sinkholes are known to have occurred during periods of drawdown caused by irrigation for freeze protection. The remainder formed in secluded locations, but were discovered soon after periods of freeze protection pumping (Rutledge, 1982).

Mine - Many sinkholes developed coincidently with major dewatering (started 1960) of a portion of the Far West Rand mining district near Johannesburg, South Africa. Between December 1962 and February 1966, eight sinkholes greater than 50 m in diameter and 30 m in depth formed. The area is characterized by deep weathering and a thick mantel of surficial material. The depth to bedrock is as much as 400 m and commonly is about 100 m. Ground water was lowered from about 100 m below surface to 550 m below surface in July of 1966. Eight large sinkholes formed after ground water was lowered to 160 m or more. Smaller sinkholes formed in the outer part of the cone of depression where the drawdown was between 60 and 160 m. Several sinkholes formed where rapid seepage of water from the surface hastened the process of roof spalling and cavern enlargement. The largest of the sinkholes formed after a few days of torrential rainfall (Foose, 1967).

Mine - Dewatering a zinc mine near Friedensville, Pennsylvania began in 1953. Active sinkhole collapse occurred in an area of large ground-water withdrawals. Records indicate that 128 sinkholes formed around the dewatering site during period 1953-57. Twenty-five new sinkholes occurred from October 1970 to January 1971. The number of sinkholes occurring during the intervening 13 years was not inventoried. The water table in lowland areas prior to withdrawals was generally at a depth of less than 30 feet. Depth to top of bedrock exceeds 30 feet in numerous areas. Rates of withdrawal between 1953 and 1977 varied between 10 and 30 million gallons per day. The cone of depression in 1967 exceeded 4 mi^2 in area (Metsger, 1979).

Multiple Causes - Collapse sinkholes have been reported since the beginning of the 20th century in the Tournaisis area, southern Belgium. The sinkholes developed from reactivated paleokarsts. Intensive pumping for domestic and industrial water supply, combined with the dewatering due to deep limestone quarries, resulted in the lowering of ground-water levels. This triggered the reactivation of paleokarstic systems resulting in sinkhole collapse (Kaufmann and Quinif, 1999).

Multiple Causes – An estimated 1,000 collapses west of Calera, Alabama include sites of subsidence, fracturing, and significant piping. One collapse, the "December Giant" (fig. 23), measures 145 m long, 115 m wide, and 50 m deep (LaMoreaux and Warren, 1973). The area was dewatered by wells, quarries, and an underground mine. The cone of depression in October 1973 was about 10 mi^2 (26 $km^{2)}$ in area. Pumpage at that time exceeded 14,000 gallons per minute (883 liters per second). Significant sinkhole development began about 1964. The greatest hazards in this ural area were collapses beneath highways and major gas pipelines. Sinkholes in part of the area were still active in 1981 (Newton, 1976, 1987; Warren, 1976).

Multiple Causes - More than 150 sinkholes, depressions, and related features formed in and adjacent to the proposed right-of-way of Interstate Highway 459 near the community of Greenwood in Bessemer, Alabama. Sinkhole collapse began about 1950 and continued through March 1972. A general lowering of the water table occurred during the early 1950's, or the preceding decade de to large withdrawals of ground water from more than 1,070 wells (1,500 gpm) and deep mines (9,500 gpm), compounded with a prolonged drought during the 1950's (Newton and others, 1973).

Quarry and underground mining - Quarry and mine dewatering extended to within 1.5 miles (2 km) of Farmington, Missouri. Collapses were recorded at least 30 years prior to quarrying and mining and have continued for 10 years subsequent to the completion of mining activities. Although deep mines exist in areas subject to catastrophic collapse in Missouri, and continuous dewatering is required for mining, only minor surface effects have been noted (Williams and Vineyard, 1976).

Quarry and underground quarry, Hershey, Pa. – A series events in surface and underground quarrying near Hershey, Pennsylvania, between 1946 and 1953 altered ground-water levels over an area of 10 mi. About 100 new sinkholes formed within the area where there was a drastic lowering of the water table. Recovery of water levels to nearly normal conditions in 1950 was accompanied by a cessation of sinkhole development (Foose, 1953, 1969).

A blast of August 1946, Hershey, Pa. - Blast in the hanging wall of the underground quarry near Hershey, Pa. exposed a 6-inch-wide solution channel about 275 or 375 feet below the surface. Water flowed at 8,000 to 10,000 gpm, flooding the quarry in one day. Near-by wells dried up, ground-water seepage into a nearby quarry ceased, Derry Spring 1½ miles to the southwest dried up on second day, and water in two nearby wells at the Hershey Chocolate Corporation (1½ miles northeast) rapidly declined. After many months the opening was sealed. Adjacent wells had water in them again, and flow at spring and water levels in corporate wells were restored (Foose, 1953, 1969).

Pumping Test of August 1948, Hershey, Pa. - From August 30 to September 4, 1948, an average of 5,500 gpm was pumped from the underground quarry near Hershey, Pa. as a test preliminary to permanent installation of pumps for deeper quarry operations. The water level was maintained at about 200 feet below the quarry floor. On September 2 the newly drilled Derry Spring well 1½ miles southwest (yield of 2100 gpm) dried up; water level fell from an elevation of 355 ft to 313 ft, which was below the pump intake. On September 8, water level began to rise, and within a couple of days normal pumping operations resumed (Foose, 1953, 1969).

Increased pumping during May 1949, Hershey, Pa. - The quarry operation near Hershey, Pa. inaugurated its new pumping program at about 6,500 gpm normal discharge from pumps with the intake at 340 ft. below the land surface. Derry Spring well dried up. Spring Creek dried up. Many wells throughout the valley went dry. During the second month of the new pumping program, sinkholes began to form in the valley of Spring Creek. The size of the sinkholes ranged from 1 to 20 ft in diameter and 2 to 10 ft deep. Nearly 100 sinkholes formed. More new sinkholes formed during the late summer of 1949 than had previously existed in the areas. During February and March of 1950, grouting in the underground quarry reduced flow into the quarry (flow had reached 8,000 gpm). Springs began to flow again, wells could be pumped, and Spring Creek began to flow. In 1953, the quarry was allowed to flood and became a water storage reservoir. Sinkhole formation ceased after dewatering stopped and the water table had recovered (Foose, 1969).

Quarry - In 1950, a quarry at Pelham, Alabama, was in its early stages of development and sinkholes were not actively occurring. As the excavation progressed, it became necessary to dewater. In 1959, 11 open collapses were observable on aerial photographs and by 1967 34 open collapses were observable. The total distance of sinkhole migration was about 0.4 mile. At some time prior to October 1967, the quarry was abandoned and ground-water pumping stopped, along with sinkhole formation (Newton, 1976).

Quarry - More than 18 sinkhole collapses occurred along a planned highway corridor near Castle Hayne, North Carolina in 1980-81. These sinkholes were under the pavement of an existing road and in or adjacent to its right-of-way near a dewatered quarry. Four sinkholes were triggered by torrential rains in August 1981 (Newton, 1987).

Quarry - In August and September 1994, seven sinkholes up to 5 m in diameter and 3 m deep developed at a residential property adjacent to a limestone quarry in Craven County, North Carolina. The quarry operates about 600m southeast of the sinkholes and pumps water at a rate of 38 million liters per day. Water levels in wells on the perimeter of the quarry site have declined by as much as 5 meters below pre-pumping conditions. Large changes in hydraulic head were observed in monitoring wells at the quarry as the active pit was developed across the quarry site. The collapse of the sinkholes concurrent with large changes in water levels at the quarry suggests that head changes in the limestone aquifer may have been a triggering mechanism for sinkhole collapse (Strum, 1999).

Quarry - In about 1986, a limestone quarry in the Valley and Ridge Province in the southeastern United States began expansion by deepening the quarry to a new level about 60 m (200 ft) below the original water table. Extensive dewatering triggered sinkhole development in a nearby town and along a local railroad track. The ground-water surface was depressed in and around the quarry and appeared to affect the ground-water flow regime in and around the quarry and town. Ground-water levels were lowered 18 to 24 m (60 to 80 ft) at a distance of about 0.8 km (one half mile) from the quarry. Collapse sinkholes began to develop around the quarry, occurring as much as 1.6 km (one mile) from the quarry. A perennial stream was captured by a sinkhole, a sinkhole drained a local wastewater treatment pond, and sinkholes and ground subsidence began to threaten the local railroad track. The summer of 1987 was a drought year for the region, and the likely impact of the drought on sinkhole development in the area was investigated. The investigation concluded that quarry dewatering related to quarry expansion was the primary cause of the sinkholes and subsidence that occurred around the town that year. A few years after the expansion, quarry operations ceased and the quarry naturally filled with water. The writers did not document any further sinkhole or subsidence activity since that time (Kath and others, 1995).

Quarry - Artificial drawdown is the probable cause of a sinkhole problem at Railton in northwestern Tasmania where limestone is excavated from a deep quarry on the floor of a broad valley beneath about 20m of overburden. Prior to quarrying there was little evidence of sinkholes. Local anecdotes suggest minor sinkhole problems arose during the early years of the operation. A new bench was developed in the quarry during the early-mid 1980's, deepening the quarry by 15-20m, and sinkhole collapses increased. The sinkholes appeared to occur within a cone of ground-water depression around the quarry. The town sewage main was ruptured by one sinkhole. A nearby abandoned water-filled quarry drained rapidly. Other sinkholes appeared in pasture close to the quarry and in the backyards of at least two village dwellings. Exposures in the quarry reveal that the limestone surface beneath the overburden consists of pinnacles with a relief of 10 – 15 m. At least two small caves and one major spring were encountered at depth in the quarry. Artificial lowering of the ground-water table due to the quarrying together with differential settlement of the overburden between the limestone pinnacles was reported as the most likely cause of the problem. Inadequate drainage of runoff from the roofs of houses and outbuildings contributed to at least one collapse (Kiernan, 1989).

Quarry - Numerous sinkholes and sites of subsidence developed in a borrow pit area near Andrew Johnson Highway west of Morristown, Tennessee. The borrow pit was active as early as April 1976. Most sinkholes occurred between 1983 and 1986. The site exhibits three distinct levels of excavating with sinkholes occurring on all levels. Ten sinkholes occurred on the lower level, two sinkholes on the middle level, and one sinkhole on the upper level. The number of sinkholes occurring on each level was correlative with amounts of drainage received by each. Three additional sinkholes occurred across a road adjacent to the borrow pit, and collapses in the road have reportedly occurred on more than one occasion (Newton and Tanner, 1987).

Quarries – Ground-water withdrawals from two quarries in the Jamestown, South Carolina area resulted in 42 sites of subsidence and collapse in 1976-78. Collapses range in size from less than 1 ft to over 24 ft in diameter. Most dramatic collapses occur within 5,000 ft of, the point of largest ground water withdrawal. About 20 feet of unconsolidated sands and clays overlie the cavernous limestone that was being quarried. Pumpage was estimated to periodically be in excess of 36 million gallons per day, causing a water level decline of over 35 feet. Water levels in wells over 1.5 miles from the center of pumping have been affected. Blasting has caused “muddying” of water (Spigner, 1978).

Quarries – Ground-water withdrawal from two deep quarries in Birmingham, Alabama, resulted in two overlapping cones of depressions, with apexes being at quarries. More than 200 sinkholes formed in an area of less than 0.5 mi^2 during a period of about 8 years. The formation of many of the sinkholes coincided with periods of heavy rain. Movement of water to one quarry was verified by dye tests. Estimated total average discharge from both quarries exceeds 1.0 mgd. Withdrawals from other sources were not identified (Newton and Hyde, 1971).

References

Adamczyk, A.F., Motyka, Jacek, Wilk, Zbigniew, and Witczak, Stanislaw, 1988, Mine drainage of a karstic aquifer and the related protection problems – Olkusz Mining District, Poland: Proceedings if the IAH 21st Congress, Guilin, China, Geologic Publishing House, Bejing, China, pp. 1097-1104.

Aley, T.J., Williams, J.H., and Massello, J.W., 1972, Groundwater contamination and sinkhole collapse induced by leaky impoundments in soluble rock terrain: Missouri Geological Survey Engineering Geology Series 5, 32 p.

Arbogast, B.F., Knepper, D.H., Jr., and Langer, W.H., 2000, The human factor in mining reclamation: U.S. Geological Survey Circular 1191, 28 p.

Assad, F.A., and Jordan, H., 1994, Karst terranes and environmental aspects: Environmental Geology, v. 23, pp. 228 – 237.

ASTM, 1998, Standard terminology relating to dimension stone, American Society of Testing and Materials Designation C 119-98: American Society of Testing and Materials Annual Book of ASTM Standards, v. 04.07, pp. 6-9.

ASTM, 2000, Standard terminology relating to concrete and concrete aggregates, American Society of Testing and Materials Designation C 125-00: American Society of Testing and Materials Annual Book of ASTM Standards, v. 04.02, pp. 60-63.

Barksdale, R.D., ed., 1991, The aggregate handbook: National Stone Association, 717 p.

Bates, R.L., and Jackson, J.A., eds., 1987, Glossary of Geology: American Geological Institute, 788 p.

Beck, B.F., ed., 1984, Sinkholes - Their geology, engineering and environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, A.A. Balkema, 429 p.

Beck, B.F., ed., 1989, Engineering and environmental impacts of sinkholes and karst: Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, 384 p.

Beck, B.F., ed., 1993, Applied karst geology: Proceedings of the Fourth Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, 295 p.

Beck, B.F., ed., 1999, Sinkholes and the Engineering and Environmental Impacts of Karst: Engineering Geology, v. 52, nos. 1-2, 152 p.

Beck, B.F., and Pearson, F.M., eds., 1995, Karst geohazards – Engineering and environmental problems in karst terrane: Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, 581 p.

Beck, B.F., and Stephenson, J.B., eds., 1997, The engineering geology and hydrogeology of karst terranes: Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, 516 p.

Beck, B.F., and Wilson, W.L., eds., 1987, Karst hydrology: Engineering and environmental applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, 467 p.

Beck, B.F., Pettit, A.J., and Herring, J.G., eds., 1999, Hydrogeology and engineering geology of sinkholes and karst: Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, 478 p.

Bell, F.G., 1992, Open excavation in rock masses, *in*, Bell, F.G., ed., Engineering in rock masses: Buterworth, Heinemann, Oxford, England, p. 400-422.

Berger, P.R., Ford, W.C., Graham, E.K., Long, J.F., Jr., Rohrs, D.M., West, J.R., and Willard, R.B., 1991, Environmental and community concerns, *in* Barksdale, R.D., The Aggregate Handbook: National Stone Association, p. 5-1 – 5-59.

Bobrowsky, P.T., ed., 1998, Aggregate resources - A global perspective: A.A. Balkema, Rotterdam, Netherlands, 470 p.

Bowles, Oliver, 1939, The Stone Industries: McGraw Hill Book Company, 519 p.

Crawford, N.C., 1986, Karst hydrological problems associated with urban development – ground water contamination, hazardous fumes, sinkhole flooding and sinkhole collapse in the Bowling Green area, Kentucky: Field Trip Guide Book, Centre for Cave and Karst Studies, Western Kentucky University, 86 p.

Cvijíc, J., 1893, Das karstphanomen: Versuch einer morphologischen Monographie, Geographische Abhandlungen herausgegeben von A Pench, Bd., V. H, 3. Wien.

Dodge, E.D., 1984, Les characteristiques hydrogeoloqigues des aquifers kartisques du Causse Comtal (Aveyron, France): Hydrogeologie-Geologie de l'ingenieur, v. 3, pp. 241-252.

Dolley, T.P., 1999, Crushed stone: U.S. Geological Survey Minerals Yearbook, pp. 73.1-73.11.

Drew, David, 1999, Chapter 1 – Introduction, *in* Drew, David, and Hötzl, Heinz, eds.: Karst hydrology and human activities – Impacts, consequences and implications, A.A. Balkema, pp. 3-12.

Drew, David, and Hötzl, Heinz, eds., 1999: Karst hydrology and human activities – Impacts, consequences and implications, A.A. Balkema, 322 p.

Drysdale, R., Pierotti, L., and Baldacci, F., 2001, Suspended sediments in karst spring waters near Massa (Tuscany), Italy: Environmental Geology, v. 40, pp. 1037-1050.

Edwards, A.J., Hobbs, S.L., and Smart, P.L., 1991, Effects of quarry dewatering on a karstified limestone aquifer; a case study from the Mendip Hills, England, *in* Proceedings of the Third Conference on Hydrogeology, ecology, monitoring and management of groundwater in karst terranes, National Water Well Association, pp. 77-91.

Ekmekçi, M., 1993, Impact of quarries on karst groundwater systems, *in* Günay, G., Johnson, A.I., and Back, W., eds, Hydrogeological processes in karst terranes: Proceedings of the Antalya Symposium and Field Seminar, October 1990, IAHS Publication no. 207, p. 3-6.

Fletcher, J.L., and Busnel, R.G., 1978, Effects of noise on wildlife: Academic Press, New York.

Foose, R.M., 1953, Ground-water behavior in the Hershey Valley, Pennsylvania: Geological Society of America Bulletin, v. 64, pp. 623-646.

Foose, R.M., 1967, Sinkhole formation by groundwater withdrawal; Far West Rand, South Africa: Science, v. 157, pp. 1045-1048.

Foose, R.M., 1969, Mine dewatering and recharge in carbonate rocks near Hershey, Pennsylvania, *in* Kiersch, G.A., Cleaves, A.B., Adams, W.M., Pincus, H.J., and Ferguson, H.F., eds., Legal aspects of geology in engineering practice: Geological Society of America, Engineering Geology Case Histories no. 7, pp. 46-60.

Foose, R.M., and Humphreville, J. A., 1979, Engineering geological approaches to foundations in the karst terrain of the Hershey Valley: Bulletin of the Association of Engineering Geologists, v. 16, no. 3, pp. 355-381.

Ford, D.C., ed., 1993, Environmental change in karst areas: Environmental Geology, v. 21, no. 3, pp. 107-200.

Ford, D.C., and Williams, P.W., 1989, Karst geomorphology and hydrology: Unwin-Hyman, London, 601 p.

Fraser, Hannah, and Grapes, Tim, 1998, Impact of quarry dewatering on a water dependent conservation site,*in* Van Brahana, John, Eckstein, Yoram, Ongley, L.K., Schneider, Robert, and Moore, J.E., eds., Gambling with groundwater – Physical, chemical, and biological aspects of aquifer-system relations: American Institute of Hydrology, pp. 469-474.

Gagen, Peter, and Gunn, John, 1987, A geomorphological approach to restoration blasting in limestone quarries, *in* Beck, B.F., and Wilson, W.L., eds., Karst hydrology: Engineering and environmental applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp. 457-461.

Gary, M.K., 1999, Maryland's zone of dewatering influence law for limestone quarries,*in* Beck, B.F., Pettit, A.J., and Herring, J.G., eds., Hydrogeology and engineering geology of sinkholes and karst – 1999: Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, pp. 273-277.

Gillieson, David, and Houshold, Ian, 1999, Chapter 6.3 – Rehabilitation of the Lune River Quarry, Tasmanian Wilderness World Heritage Area, Australia: *in* Drew, David, and Hötzl, Heinz, eds. Karst hydrology and human activities – Impacts, consequences and implications, A.A. Balkema, pp. 201-205.

Gunn, John, 1986, A conceptual model for conduit flow dominated karst aquifers, *in*Günay, Gültekïn, and Johnson, A.I., eds., Karst water resources: IAHS Publication 161, pp. 587-596.

Gunn, John, 1993, The geomorphic impacts of limestone quarrying, *in* Williams, P.W., ed., Karst terrains – Environmental changes and human impact: Catena Supplement 25, Catena Verlag, Cremlingen, pp. 187-197.

Gunn, John, and Bailey, Debra., 1993, Limestone quarrying and quarry reclamation in Britain: Environmental Geology, v. 21, pp. 167 – 172.

Gunn, John, Bailey, Debra, and Handley, John, 1997, The reclamation of limestone quarries using landform replication: Department of Geographical & Environmental Sciences, University of Huddersfield, Queensgate, Huddersfield, U.K., 176 p.

Gunn, John, and Gagen, Peter, 1987, Limestone quarrying and sinkhole development in the English Peak District, *in* Beck, B.F., and Wilson, W.L., eds., Karst hydrology: Engineering and environmental applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp. 121-125.

Gunn, John, and Hobbs, S.L., 1999, Chapter 6.2 Limestone quarrying: hydrogeological impacts, consequences, implications: *in* Drew, David, and Hötzl, Heinz, eds.: Karst hydrology and human activities – Impacts, consequences and implications, A.A. Balkema, pp. 192-201.

Hess, J.W., and Slattery, L.D., 1999, Chapter 6.1 Overview of extractive industries impact,*in* Drew, David, and Hötzl, Heinz, eds.: Karst hydrology and human activities – Impacts, consequences and implications, A.A. Balkema, pp. 187-192.

Hobbs, S.L., and Gunn, John, 1998, The hydrogeological effect of quarrying karstified limestone: options for protection and mitigation: Quarterly Journal of Engineering Geology, v. 31, pp. 147-157.

Howard, Bob, and Cameron, Ian, 1998, Dust control: Best Practice Environmental Management in Mining, Environment Australia, 73 p.

Jennings, J.N., 1985, Karst geomorphology: Bell and Bain Ltd., Glasgow, 293 p.

Kath, R.L., McClean, A.T., Sullivan, W.R., and Humphries, R.W., 1995, Engineering impacts of karst: Three engineering case studies in Cambrian and Ordovician carbonates of the Valley and Ridge Province,*in* Beck, B.F., and Pearson, F.M., eds., Karst geohazards – Engineering and environmental problems in karst terrane: Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp. 469-457.

Kaufmann, Oliver, and Quinif, Yves, 1999, Cover-collapse sinkholes in the "Tournaisis" area, southern Belgium: Engineering Geology, v. 52, nos. 1&2, pp. 15-22.

Kelk, B., 1992, Natural resources in the geological environment,*in* Lumsden, G.I., 1992, ed. Geology and the environment in Western Europe: Oxford University Press, New York, p. 34 – 138.

Kestner, M., 1994, Developing a dust control plan: Stone Review v.10, no. 1, p. 22-23.

Kiernan, Kevin, 1989, Sinkhole hazards in Tasmania, *in* Beck, B.F., ed., Engineering and environmental impacts of sinkholes and karst: Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, pp. 123-128.

Kochanov, W.E., 1999, Sinkholes in Pennsylvania: Pennsylvania Geological Survey, 4th Series, Educational Series 11, 33 p.

Kolm, K.E., 1996, Conceptualization and characterization of ground-water systems using geoscientific information systems, *in* May, J. and Kolm, K. E., eds, 1996, Special Issue: Advanced Techniques for Solving Groundwater Contaminant Problems: Engineering Geology, Vol. 42; Nos. 2 - 3, Elsevier Publishers, p. 111 - 118.

Kresic, Neven, Papic, Petar, and Golubovic, Radosav, 1992, Elements of groundwater protection in a karst area: Environmental geology Water Science, v. 20., no. 3, pp. 157-164.

LaMoreaux, P.E., 1997, Legal aspects of karst and insurability, *in* Günay, Gültekïn, and Johnson, A.I., eds., Karst waters & environmental impacts: Proceedings of the 5th International Symposium and Field Seminar on Karst Waters and Environmental Impacts, Antalya, Turkey, A.A. Balkema, pp. 11-17.

LaMoreaux, P.E., Powell, W.J., and LeGrand, H.E., 1997, Environmental and legal aspects of karst areas: Environmental Geology, v. 29, no. 1/2, pp. 23 – 36.

LaMoreaux, P.E., and Newton, J.G., 1986, Catastrophic subsidence: An environmental hazard, Shelby County, Alabama: Environmental Geology Water Science, v. 8, no. 1/2, p. 25-40.

LaMoreaux, P.E., and Warren, W.M., 1973, Sinkhole: Geotimes, v. 18, no. 3, p. 15.

Langer, W.H., 2001, Environmental impacts of mining natural aggregate, *in* Bon, R.L., Riordan, R.F., Tripp, B.T., and Krukowski, S.T., eds., Proceedings of the 35th Forum on the Geology of Industrial Minerals—The Intermountain West Forum: Utah Geological Survey Miscellaneous Publication 01-2, p. 127-138.

Langer, W.H., in press, Environmental Risk Analysis and Aggregate Mining, *in* Proceedings of the 37th Forum on the Geology of Industrial Minerals, 2001: British Columbia Ministry of Energy and Mines.

Langer, W.H., and Kolm, K.E., 2001, Hierarchical systems analysis of potential environmental impacts of aggregate mining: Society for Mining, Metallurgy, and Exploration, Inc., Annual Meeting, 2001, Preprint No. 01-103, 10 p.

Lolcama, J.L., Cohen, H.A., and Tonkin, M.J., 1999, Deep karst conduits, flooding and sinkholes: Lessons for the aggregates industry, *in* Beck, B.F., Pettit, A.J., and Herring, J.G., Hydrogeology and engineering geology of sinkholes and karst – 1999: Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, pp. 51–55.

Lüttig, G.W, 1994, Rational management of the geo-environment – A view in favour of "geobased" planning – with special reference to aggregate resources, *in* Lüttig, G.W., ed., Aggregates -- Raw materials' giant: Report on the 2nd International Aggregate Symposium, Erlangen, 346 p.

Martin, A.D., 1995, Maryland Route 31 sinkhole, *in* Beck, B.F., and Pearson, F.M., eds., Karst geohazards – Engineering and environmental problems in karst terrane: Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp. 331-334.

Metsger, R.W., 1979, Mining problems in a karst valley – Technical and social: Bulletin of the Association of Engineering Geologists, v. 16, n. 3, pp. 427-447.

Meyers, P.B., Jr., and Perlow, M., Jr., 1984, Development, occurrence, and triggering mechanisms of sinkholes in the carbonate rocks of the Lehigh Valley, eastern Pennsylvania,*in* Beck, B.F., ed., 1984, Sinkholes - Their geology, engineering and environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, A.A. Balkema, pp. 11-15.

Moore, J.D., and Hughes, T.H., 1979, Effect of quarry blasting on ground-water quality in a limestone terrane in Calhoun County, Alabama: Water Resources Research Institute Bulletin 38, Auburn University, 72 p.

Moore, A.B., and Richards, A.J., 1999, Blast vibration assessment for planning and control: Quarry, v.7, no. 4, p. 28-32.

National Academy of Sciences, 1980, Surface mining of non-coal minerals - Appendix I - Sand and gravel mining, and quarrying and blasting for crushed stone and other construction minerals: National Academy of Sciences, Washington, D.C., 91 p.

Newton, J.G., 1976, Induced sinkholes – A continuing problem along Alabama highways, *in* International Association of Hydrologic Sciences, Land Subsidence Symposium: Proceedings of the Second International Symposium on Land Subsidence held at Anaheim, California, IAHS-AISH Publication no. 121, pp. 453-463.

Newton, J.G., 1984a, Review of induced sinkhole development, *in* Beck, B.F., ed., Sinkholes: Their geology, engineering and environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, A.A. Balkema, pp. 3-9.

Newton, J.G., 1984b, Sinkholes resulting from ground-water withdrawals in carbonate terranes-an overview, *in* Holzer, T.L., ed., Man-induced land subsidence: Geological Society of America, Reviews in Engineering Geology, v. 6, pp. 195-202.

Newton, J.G., 1984c, Case History No. 9.11. Alabama, U.S.A., *in* Poland, J.F., ed., Guidebook to studies of land subsidence due to ground-water withdrawal: UNESCO, pp. 245-251.

Newton, J.G., 1986, Natural and induced sinkhole development in the eastern United States, *in* Johnson, A.I., Carbognin, Laura, and Ubertini, L., eds., Land Subsidence: Proceedings of the Third International Symposium on Land Subsidence held in Venice, Italy, IAHS Publication No. 151, pp. 549-564.

Newton, J.G., 1987, Development of sinkholes resulting from man's activities in the Eastern United States; U.S. Geological Survey Circular 968, 54 p.

Newton, J.G., Copeland, C.W., and Scarbough, L.W., 1973, Sinkhole problem along proposed route of Interstate Highway 459 near Greenwood, Alabama: Alabama Geological Survey Circular 83, 53 p.

Newton, J.G., and Hyde, L.W., 1971, Sinkhole problem in and near Roberts Industrial Subdivision, Birmingham, Alabama – A reconnaissance: Geological Survey of Alabama Circular 68, 42 p.

Newton, J.G., and Tanner, J.M., 1987, Case histories of induced sinkholes in the eastern United States, *in* Beck, B.F., and Wilson, W.L., eds., Karst hydrology: Engineering and environmental applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp. 15-23.

Primel, Louis, and Tourenq, Claude, 2000, eds., Aggregates: Balkema, 590 p.

Prokopovich, N.P., 1985, Development of karst sinkholes and fluctuations of aquifer levels, *in* Günay, Gültekïn, and Johnson, A.I., eds., Karst water resources: IAHS Publication 161, pp. 387-397.

Quinlan, J.F., 1986, Legal aspects of sinkhole development and flooding in karst terranes - 1. Review and synthesis; Environmental Geology and Water Sciences, v. 8, nos. 1/2, pp. 41-61.

Ritter, D.F., Kochel, R.C., and Miller, J.R., 1995, Process geomorphology – Third edition: Wm C. Brown Publishers, Chicago, 546 p.

Rutledge, A.T., 1982, Hydrology of Floridian aquifer in northwest Volusia County, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 82-108, 116 p.

Sauro, U., 1993, Human impact on the karst of the Venetian Fore-Alps, Italy: Environmental Geology, v. 21, pp. 115-121.

Sedam, A.C., Eberts, S.M., and Bair, E.S., 1988, Ground-water levels, water quality, and potential effects of toxic-substance spills or cessation of quarry dewatering near a municipal ground-water supply, southern Franklin County, Ohio: U.S. Geological Survey Water-Resources Investigations report 88-4138, 93 p.

Sinclair, W.C., 1982, Sinkhole development resulting from groundwater withdrawal in the Tampa area, Florida: U.S. Geological Survey Water Resources Investigation 81-50, 19 p.

Sinclair, W.C., and Stewart, J.W., 1985, Sinkhole type, development, and distribution in Florida: Florida Bureau of Geology, Map series No. 110.

Smart, P.L., Edwards, A.J., and Hobbs, S.L., 1991, Heterogeneity in carbonate aquifers: Effects of scale, fissuration, lithology and karstification,*in* Proceedings of the Third Conference on Hydrogeology, ecology, monitoring and management of groundwater in karst terranes: National Water Well Association, pp. 373-388.

Smart, P.L., and Friedrich, H., 1986, Water movement and storage in the unsaturated zone of a maturely karstified carbonate aquifer, Mendip Hills, England, *in* Proceedings Environmental Problems in Karst Terranes and Their Solutions Conference: National Water Well association, 59-87.

Smith, M.R., and Collis, L., eds., 2001, Aggregates -- Sand, gravel and crushed rock aggregates for construction purposes, 3rd Edition: Geological Society of Engineering Geology Special Publication No. 17, London, The Geological Society, 339 p.

Sowers, G.F., 1976, Mechanisms of subsidence due to underground openings, *in*, National Academy of Science, Subsidence over mines and caverns, moisture and frost actions, and classification: Transportation Research Record 612, pp. 2-8

Spigner, B.C., 1978, Land surface collapse and ground-water problems in the Jamestown area, Berkley County, South Carolina: South Carolina Water Resources Commission Open-File Report 78-1, 99 p.

Stanton, W., 1966, The impact of quarrying on the Mendip Hills, Somerset: Proceedings of the University of Bristol Speleological Society, v. 11, p. 54-62.

Stanton, W., 1990, Hard limestone – Too valuable to quarry: Minerals Planning, v. 43, pp. 3-9.

Stringfield, V.T., and Rapp, J.R., 1976, Land subsidence resulting from withdrawal of ground water in carbonate rocks, *in* International Association of Hydrologic Sciences, Land Subsidence Symposium: Proceedings of the Second International Symposium on Land Subsidence held at Anaheim, California, IAHS-AISH Publication no. 121, pp.447-452.

Strum, Stuart, 1999, Topographic and hydrogeologic controls on sinkhole formation associated with quarry dewatering,*in* Beck, B.F., Pettit, A.J., and Herring, J.G., Hydrogeology and engineering geology of sinkholes and karst – 1999: Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, A.A. Balkema, pp. 63 – 66.

Sweeting, M.M., 1981, Karst Geomorphology: Benchmark Papers in Geology / 59, Hutchinson Ross Publishing Company, Stroudsburg, Pennsylvania, 427 p.

Tepordei, V.V., 1999, Crushed stone: U.S. Geological Survey Minerals Yearbook, pp. 72.1-72.32

Thorp, M.J.W., and Brook, G.A., 1984, Application of double Fourier series analysis to ground subsidence susceptibility mapping in covered karst terrain, *in* Beck, B.F., ed., Sinkholes: Their geology, engineering and environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, A.A. Balkema, pp. 197-20?.

Ursic, K.A., Kenkel, N.C., and Larson, D.W., 1997, Revegetation dynamics of cliff faces in abandoned limestone quarries: Journal of Applied Ecology, v. 34, pp. 289-303.

Urushibara-Yoshino, K., 2000, Newsletter on annotated bibliography, No. 8: International Geographical Union, Department of Geography, Hosei University, Tokyo, 71 p.

Veni, George, and DuChene, Harvey, eds., 2001, Living with karst: American Geological Institute Environmental Awareness Series, 4, 64 p.

Vermeulen, Jaap, and Whitten, Tony, 1999, Biodiversity and cultural property in the management of limestone resources: World Bank, Washington, D.C., 120 p.

Waltham, A.C., 1989, Ground subsidence: Blackie & Son Limited, London, 195 p.

Warren, W.M., 1976, Sinkhole occurrence in western Shelby County, Alabama: Geological Survey of Alabama Circular 101, 45 p.

Warren, W.M., and Wielchowsky, C.C., 1973, Aerial remote sensing of carbonate terranes in Shelby County, Alabama: Ground Water, v. 11, no. 6, p. 14-26.

White, W.B., and White, E.L., 1995, Thresholds for soil transport and the long term stability of sinkholes, *in* Beck, B.F., and Pearson, F.M., eds., Karst geohazards – Engineering and environmental problems in karst terrane: Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, pp.73-78.

White, W.B., Culver, D.C., Herman, J.S., Kane, T.C., and Mylroie, J.E., 1995, Karst lands: American Scientist, v. 83, pp. 450-459.

Williams, J.H., and Vineyard, J.D., 1976, geologic indicators of subsidence and collapse in karst terrain in Missouri, *in*, National Academy of Science, Subsidence over mines and caverns, moisture and frost actions, and classification: Transportation Research Record 612, pp. 31-37.

Williams, P.W., ed., 1993, Karst terrains – Environmental changes and human impact: Catena Supplement 25, Catena Verlag, Cremlingen, 268 p.

Wilson, W.L., and Beck, B.F., 1992, Hydrogeologic factors affecting new sinkhole development in the Orlando area, Florida: Ground Water, v. 30, no. 6, pp. 918-930.

Yuan, Daoxian, 1987, Karst hydrology: Engineering and environmental applications, *in* Beck, B.F., and Wilson, W.L., eds., Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst: A.A. Balkema, pp.1-11.

ATTACHMENT 5

Department of Mines - Reported Production Calendar Year 2008 as of March 20, 2009

Class	County	Company	Total Tonnage
			81,313,941
DS	Haskell	A & M Blaylock - LE-1873	5,058.10
S&G	Pottawatomie	A C & D Sand - LE-1763	35,806.00
DS	Haskell	A-1 Stone - LE-1918	1,581.59
Clay	Logan	Acme Brick Co. - LE-1638	30,008.00
Clay	Oklahoma	Acme Brick Co. - LE-1658	44,000.00
Clay	Tulsa	Acme Brick Co. - LE-1659	0.00
Clay	Rogers	Acme Brick Co. - LE-1724	72,600.00
DS	Haskell	Adams Stone, Inc. - LE-1936	385.62
S&G	McClain	Adkins, B. & Y- LE-1908	53,432.00
S&G	Pottawatomie	Allen Farms, Inc. - LE-2034	1,150.70
Gypsum	Major	Allied Custom Gypsum - LE-1733	1,717,256.31
Gypsum	Woodward	Allied Custom Gypsum - LE-2109	252,795.87
S&G	Jackson	Altus Sand & Gravel - LE-1285	0.00
Gypsum	Jackson	American Gypsum - LE-1350	0.00
Gypsum	Jackson	American Gypsum - LE-1584	854,576.00
Gypsum	Jackson	American Gypsum - LE-1778	0.00
Tripoli	Ottawa	American Tripoli Co. - LE-1562	95,762.00
Limestone	Rogers	Anchor Stone Co. - LE-1261 - Rock Plant #2	2,288,886.00
S&G	Tulsa	Anchor Stone Co. - LE-1527 - Delaware	572,133.00
S&G	Tulsa	Anchor Stone Co. - LE-2006 -Jenks	0.00
Limestone	Tulsa	APAC-Okla. - LE-1274 - E. Quarry	213,590.00
Limestone	Tulsa	APAC-Okla. - LE-1699 - 36th Street	0.00
Limestone	Craig	APAC-Okla. - LE-1798 - J-6	375,677.00
Limestone	Delaware	APAC-Okla. - LE-1800 - Fisher Quarry	1,966.88
Limestone	Mayes	APAC-Okla. - LE-1820 - Standard	0.00
S&G	Kiowa	APAC-Okla. - LE-1987 - McPhail Sand	5,722.94
Limestone	Tulsa	APAC-Okla. - LE-1990 - 46th Street	154,479.00
S&G	Carter	Arbuckle Materials - LE-1777 - GeneAutry	49,621.15
Limestone	Murray	Arbuckle Materials - LE-1888 - Shaffer	0.00
S&G	Love	Arbuckle Materials - LE-1928 - Jimtown Sand	0.00
S&G	Pawnee	Arbuckle Materials - LE-2212	130,370.69
Limestone	LeFlore	Arbuckle Materials - LE-2275	0.00
Clay	Tulsa	Ark Wrecking Co. - LE-2281	2,070.00
S&G	Muskogee	Arkhola Div. Apac - LE-1185 - Muskogee	493,467.00
Limestone	Cherokee	Arkhola Div. Apac - LE-1647 - Roberts Quarry	372,875.00
Limestone	Wagoner	Arkhola Div. Apac - LE-1814 - Okay	338,796.00
S&G	LeFlore	Arkhola Div. Apac - LE-1988 - Spiro	70,375.00
S&G	Rogers	Ashlock, Tom - LE-1944	16,356.00
S&G	Tulsa	Ashlock, Tom - LE-2135	18,120.00
S&G	Cleveland	Austin Enterprises - LE-1384	14,278.00
Granite	Johnston	Autumn Rose Quarry - LE-1304	888.77
S&G	Seminole	B & B Sand & Gravel - LE-1910	105,482.63
DS	Haskell	B & C Stone - LE-2165 - LeQuire #1	2,516.40
DS	Haskell	B & C Stone - LE-2182 - LeQuire #2	1,267.00
DS	Haskell	B & C Stone - LE-LeQuire #3	71.60
DS	Haskell	B & C Stone - LE-LeQuire #4	119.00

DS	Muskogee	B & P Stone - LE-1934	255.22
S&G	McClain	B & R Sand - LE-1619	4,893.44
Bentonite	Dewey	B/J Ranch, LLC - LE-2129	0.00
S&G	Love	Barrick, Sam - LE-1982	1,200.00
S&G	Tulsa	Basore, Bill - LE-2254	10,500.00
S&G	Tulsa	Basore, Bill - LE-1767	9,000.00
Limestone	Murray	BCM Oklahoma - LE-1669	933,662.00
S&G	Oklahoma	BCM Oklahoma - LE-1802	114,313.00
S&G	Oklahoma	BCM Oklahoma - LE-2054	319,303.00
S&G	Comanche	Beaver Creek Tractor - LE-2051	2,761.00
DS	Haskell	Bedrock Stone - LE-2175	796.17
DS	Haskell	Bedrock Stone - LE-2192	1,742.27
DS	Haskell	Bedrock Stone - LE-2205	13,326.92
S&G	Texas	Behne Construction - LE-2282	0.00
S&G	Texas	Behne Construction - LE-1700	33,720.67
Clay	Creek	Belk, Bob Shale - LE-2036	8,680.00
Limestone	Nowata	Bellco Materials - LE-1198 - #1, 1-1, 1-2	118,436.00
Limestone	Rogers	Bellco Materials - LE-1199 - #2, 2-1	269,184.00
Limestone	Washington	Bellco Materials - LE-1200 - #3 &3-1	325,118.48
Limestone	Washington	Bellco Materials - LE-1201 - #6	28,274.00
Limestone	Washington	Bellco Materials - LE-1202 - #7	0.00
Limestone	Osage	Bellco Materials - LE-1403 - #4, 4-1	813,245.50
S&G	Bryan	Bennett, Benny - LE-2046	0.00
Clay	Mayes	Best Dump Trucking - LE-1975	0.00
S&G	Cleveland	Big (4) Pit - LE-1528	60,340.00
S&G	Choctaw	Big Valley S&G - LE-1779	20,271.00
Clay	Canadian	Biggs Backhoe, Inc. - LE-2184+D135	29,433.00
S&G	Okfuskee	Bill's Backhoe - LE-1822	3,790.00
S&G	Bryan	Bill's Sand & Gravel - LE-2218	32,403.31
S&G	Bryan	Bill's Sand & Gravel - LE-2293	1,953.00
S&G	Cleveland	Bird Ranch LLC- LU-015	420.00
Clay	LeFlore	Blake Construction - LE-2163	0.00
Clay	LeFlore	Blake, Ronny J. - LE-2084	10,000.00
S&G	Lincoln	Blakley Lumber - LE-1613	8,525.00
DS	LeFlore	Blasdel, Brett - LE-1913	21,653.80
DS	Haskell	Blaylock, Kenny - LE-2128	0.00
DS	LeFlore	Blaylock, Kenny - LE-2190	2,460.00
DS	Haskell	Blaylock, Kenny - LE-2241	0.00
DS	LeFlore	Blaylock, Kenny - LU-006	744.00
DS	LeFlore	Blaylock, Kenny - LU-011	415.00
S&G	Johnston	Blessing Gravel Co. - LE-2152	387,841.45
S&G	Lincoln	Block Sand Co. - LE-1265	38,129.00
Limestone	Pittsburg	Blue Creek Stone - LE-1923	113,033.54
Limestone	Haskell	Blue Mountain Quarry - LE-1475	0.00
DS	LeFlore	Bluebird Stone - LE-1978	15,012.00
DS	Haskell	Bluebird Stone - LE-2124	10,440.00
DS	LeFlore	Bluebird Stone - LE-2125	0.00
DS	LeFlore	Bluebird Stone - LE-2150	104.00
DS	Haskell	Bluebird Stone - LE-2244	11,019.00
DS	Haskell	Bluebird Stone - LE-2241	0.00
DS	LeFlore	Bluebird Stone - LE-2257	6,357.00
S&G	Choctaw	Bluff Materials - LE-1617	20.00

S&G	Cleveland	Bogart, Toby & Kathy - LE-1196	0.00
DS	Haskell	Boggy Construction - LE-2169	1,710.00
DS	Haskell	Boggy Construction - LE-2229	3,869.00
S&G	Bryan	Bonham Concrete - LE-1459	0.00
S&G	Bryan	Bonham Concrete - LE-1516	263,664.42
S&G	Bryan	Bonham Concrete - LE-2256	0.00
Clay	Muskogee	Boral Bricks, Inc. - LE-1824	0.00
Clay	Canadian	Boral Bricks, Inc. - LE-2114	81,870.00
Clay	Tulsa	Bowers, V. & A. - LE-1898	0.00
Limestone	Sequoyah	Brazil Creek Minerals - LE-1365	0.00
Limestone	Sequoyah	Brazil Creek Minersls - LE-1398	496,123.94
S&G	Canadian	Breshears Farms - LE-1960	0.00
S&G	Caddo	Bright, C. and/or T. - LE-1917	64,695.00
S&G	Canadian	Briscoe, Bernerd - LE-1959	148,744.00
S&G	Murray	Brown, C. D. Const. - LE-2191	20,237.00
Clay	LeFlore	Brown, Foy - LE-2040 -Allen	0.00
Limestone	LeFlore	Brown, Foy & Judy - LE-1810	400.00
S&G	Carter	Brown, Joe Co. - LE-2131 - Brown #2	29,209.05
DS	Latimer	Browne, Clayton - LE-2004	1,655.06
S&G	Comanche	Buchwald, Larry - LE-2062	7,888.00
Clay	Cherokee	Buford, J. & J. - LE-2186	9,168.00
S&G	Oklahoma	Butler Bros. Sand - LE-1294	0.00
S&G	Canadian	Butler Bros. Sand - LE-1684	53,925.00
S&G	Oklahoma	Butler Bros. Sand - LE-1839	188,006.00
S&G	Oklahoma	Butler Bros. Sand - LE-2047	0.00
S&G	Oklahoma	Butler Bros. Sand - LE-2258	76,128.00
S&G	Logan	Butler Bros. Sand - LE-2259	61,440.00
DS	Pontotoc	C & B Stone - LE-1954	4,186.00
DS	Pontotoc	C & B Stone - LE-1995	3,771.00
S&G	Pottawatomie	C & L Sand Mater. - LE-2048	3,607.00
S&G	Sequoyah	C F Sand - LE-1752	120.00
S&G	Sequoyah	C F Sand & Gravel - LE-1971	0.00
S&G	McClain	CAA Development - LE-1436	68,740.00
Shale	Blaine	C Farms Inc. - LU-013	52,686.60
S&G	Tulsa	Cambridge DSG - LE-1601	0.00
S&G	Tulsa	Cambridge DSG - LE-2022	189,864.00
S&G	Canadian	Campbell's Sand - LE-1383	119,976.40
DS	Haskell	Capitol Stone - LE-2069	1,153.92
S&G	Creek	Cardwell, Roy - LE-1981	13,000.00
Salt	Woods	Cargill, Inc. - LE-1602	151,210.00
S&G	Wagoner	Carter & Son - LE-1568 - Muskogee	0.00
S&G	Tulsa	Carter & Son - LE-1692 - 65th W. Ave.	0.00
S&G	Tulsa	Carter & Son - LE-1892 - 49th Street	0.00
S&G	Bryan	Carter, Wayne - LU-004	3,276.00
S&G	Sequoyah	CBHD - LE-2252	0.00
Gypsum	Major	Cephas Resources - LE-2148	0.00
Clay	Rogers	Chandler Materials - LE-1326 - Tulsa Lite Wate Pi	0.00
Limestone	Tulsa	Chandler Materials - LE-1334 - Garnett Quarry	0.00
Clay	Tulsa	Chandler Materials - LE-1495 - Larkin Bailey	9,812.00
Granite	Greer	Chapel Rose - 00-1442	657.00
S&G	Creek	Cherry Trucking - LE-1915	42,555.00
S&G	Pottawatomie	Childers Const. - LE-1909	0.00

DS	Choctaw	Choctaw Materials - LE-2012	3,859.72
S&G	Wagoner	Choska Sand - LE-2216	1,560.00
S&G	Bryan	Clark, Gary - LE-1899	36,142.00
DS	Haskell	Cloud, Marvin - LE-2080	1,947.86
Limestone	LeFlore	Comer Mining Co. - LE-1648	0.00
Clay	Seminole	Commercial Brick - LE-1297	280,629.00
S&G	Carter	Conway, Mike - LE-1559	33,395.00
DS	LeFlore	Corner Stone Quar. - LE-1925	9,548.23
DS	Haskell	Corner Stone Quar. - LE-2123	0.00
DS	LeFlore	Corner Stone Quar. - LU-002	82.70
DS	LeFlore	Cougar Stone - LE-2041	2,060.00
Limestone	Woodward	Cowboy Crushing - LE-1905	0.00
Limestone	Pawnee	Cowboy Rock & Gravel - LE-1973	41,218.81
S&G	Muskogee	Coweta Sand - LE-2217	0.00
DS	Haskell	Coyle Production - LE-2295	0.00
DS	Haskell	Coyle Production - LU-003	3,364.65
DS	Haskell	Coyle Production - LU-010	9.94
S&G	Oklahoma	C-P Integrated Serv. - LE-1783	3,886.00
Clay	Canadian	CPI Pipe & Steel, Inc. - LE-1991+D167	128,766.00
Limestone	Craig	Craig County - LE-1792	36,585.00
DS	LeFlore	Crandell Stone - LE-2251	0.00
S&G	Wagoner	Crittenden Trucking - 01-1480	37,500.00
DS	Haskell	Crooked Creek - LE-1726	3,503.64
DS	Haskell	Crooked Creek - LE-2105	9,368.49
Limestone	Ellis	Crow Caliche - LE-2228	5,852.00
S&G	Pontotoc	Cummins Const - LE-1693	800.00
S&G	Pontotoc	Cummins Const - LE-2239	0.00
S&G	Major	D & S Materials, Inc. - LE-2157+D215	24,900.01
Clay	Cleveland	Daniels, Deborah - LE-1631	0.00
Clay	Cherokee	David's Const., Inc. - LE-2026	0.00
Clay	Cherokee	David's Const., Inc. - LE-2076	0.00
S&G	Canadian	Davis Const. & Dem. - LE-1736	1,239.91
Gypsum	Kingfisher	Diamond Gypsum #1 - LE-1739	8,184.00
Gypsum	Blaine	Diamond Gypsum #2 - LE-1966	209,707.00
DS	Latimer	Diamondback Stone - LE-2144	2,495.23
Limestone	Kay	Dig-It-Rocks - LE-1893	50,640.59
Limestone	Atoka	Dolese Bros. - LE-1170 - Coleman	1,219,206.00
Granite	Greer	Dolese Bros. - LE-1251 - Granite	31,621.00
S&G	Oklahoma	Dolese Bros. - LE-1566 - Prairie Park Sand	398,777.00
S&G	Oklahoma	Dolese Bros. - LE-1574 - East Sand Plant	0.00
S&G	Canadian	Dolese Bros. - LE-1579 - Yukon Sand	0.00
Limestone	Murray	Dolese Bros. - LE-1646 - Davis	3,010,465.00
Limestone	Carter	Dolese Bros. - LE-1651 - Ardmore	817,152.00
Limestone	Pittsburg	Dolese Bros. - LE-1652 - Hartshorne	1,516,366.00
Limestone	Kiowa	Dolese Bros. - LE-1653 - Cooperton	2,793,669.00
Limestone	Comanche	Dolese Bros. - LE-1654 - Richards Spur	4,188,667.00
Limestone	Caddo	Dolese Bros. - LE-1655 - Cyril	146,478.00
Limestone	Murray	Dolese Bros. - LE-1656 - Big Canyon Quarry	0.00
S&G	Kingfisher	Dolese Bros. - LE-1657 - Dover	556,193.00
S&G	Logan	Dolese Bros. - LE-1887 - Guthrie	222,609.00
S&G	Canadian	Dolese Bros. - LE-2082 - Mustang	444,206.00
S&G	Caddo	Dolese Bros. - LU-018-School Land Quarry	0.00

DS	Latimer	Donaho Stone - LE-1757 - #6	0.00
DS	LeFlore	Donaho Stone - LE-1818 - #7	0.00
DS	LeFlore	Donaho Stone - LE-2121 - #14	0.00
DS	Latimer	Donaho Stone - LE-2132 - #15	73.62
DS	LeFlore	Donaho Stone - LE-2134 - #12	5,217.56
DS	Haskell	Donaho Stone - LE-2168 - #16	3,223.55
DS	Haskell	Donaho Stone - LE-2247 - #18	5,413.15
S&G	Choctaw	Drake, Richard Const.- LE-1891	36,162.67
S&G	Delaware	Dummitt, Robert - LE-1491	3,986.00
S&G	Creek	Duncan, Bruce - LE-1747	7,695.00
Limestone	Ellis	Durango Services - LE-1950	44,592.00
Clay	Sequoyah	Durden & Hicks - LE-2204	15,117.00
Clay	Sequoyah	Dyer Shale Co. - LE-2195	23,680.00
S&G	Cotton	E & A Materials, Inc. - LE-1604	370,535.00
S&G	Cotton	E & A Materials, Inc. - LE-1683	0.00
S&G	Cotton	E & A Materials, Inc. - LE-2020	0.00
S&G	Logan	E & M Trucking - LE-2100	38,860.00
S&G	Major	Eagle Sand & Gravel - LE-1938	4,792.50
DS	Haskell	Eagle Stone - LE-2154	707.19
S&G	Atoka	Eastok, Inc. - LE-2161	227,549.34
S&G	Wagoner	Elite Service Co. - LE-2207	2,450.00
S&G	Pontotoc	Engel Sand - LE-1400 - Ada Plant	265,602.00
S&G	Pontotoc	Engel Sand - LE-1828 - Byng #1	11,511.00
S&G	Pontotoc	Engel Sand - LE-2239 - Byng #2	0.00
S&G	Pottawatomie	Enrem Materials - LE-2194	78,160.07
S&G	Kay	Evans & Associates - LE-1378	0.00
S&G	Kay	Evans & Associates - LE-1884	29,125.18
S&G	Choctaw	Evans D. L. Const. - LE-2278	2,422.96
S&G	Johnston	FG Minerals - LE-2189	17,035.00
Limestone	Seminole	Falcon Materials - LE-1866	0.00
Limestone	Seminole	Falcon Materials - LE-1980	593,355.23
DS	Haskell	Fargo Stone, Inc. - LE-1867	3,364.00
Limestone	LeFlore	Farrell-Cooper - LE	78,156.23
S&G	Wagoner	Fill Dirt, Inc. - LE-1555	17,798.00
S&G	Cleveland	First Properties - LE-1927	0.00
Limestone	Pontotoc	Fittstone, Inc. - LE-1930	524,066.00
S&G	Hughes	Ford,Dane J.-LU-007	585.00
Clay	LeFlore	Forsgren, Inc. - LE-1748	6,966.00
S&G	Texas	G & G Ag., Inc. - LE-1789	1,122.84
S&G	Mayes	Garrison Trucking - LE-1823	16,103.00
S&G	Tulsa	Gem Dirt Sales - LE-1554	51,320.00
S&G	Creek	Gem Dirt Sales - LE-2173	69,120.00
S&G	Oklahoma	General Materials - LE-1259 - Sooner Rd.	100,158.42
S&G	Cleveland	General Materials - LE-1260 - MacArthur Pit	402,792.94
S&G	Cleveland	General Materials - LE-1320 - Norman	10,617.73
S&G	Oklahoma	General Materials - LE-2201 - 63rd St.	54,437.88
DS	LeFlore	General Shale Brick - LE-1803	18,649.13
S&G	Oklahoma	Goddard Concrete - LE-1882 - Jones	43,347.90
S&G	Pittsburg	Gonzales Sand Co. - LE-1992	126.00
S&G	Oklahoma	Grand Pit - LE-1545	6,256.00
DS	Pittsburg	Green Stone Co. - LE-2030	14,550.04
Limestone	Rogers	Greenhill Materials - LE-1745	2,234,049.30

Limestone	Tulsa	Greenhill Materials - LE-2146	1,657,694.53
S&G	Marshall	Grotts Landscaping - LE-1935	2,408.00
S&G	Oklahoma	GSD Materials - LE-2199	164,465.28
Clay	Logan	Habben Dirt - LE-2068	0.00
S&G	Cherokee	Halpain, H & L - LE-1952	0.00
S&G	McClain	Handy Sand Co. - LE-2096	30.00
Granite	Murray	Hanson Natural Res. - LE-1277	1,332,104.17
S&G	Beaver	Hardberger & Smylie - LE-2193	27,701.25
DS	Pittsburg	Harp, Terry - LE-2113	1,068.00
Clay	LeFlore	Harris Co. of Ft. Smith - LE-1640	0.00
Clay	LeFlore	Harris Co. of Ft. Smith - LU-0001	10,584.00
Gypsum	Caddo	Harrison Gypsum #1 - LE-1264	200.00
Gypsum	Caddo	Harrison Gypsum #2 - LE-1606	577,117.20
Gypsum	Comanche	Harrison Gypsum #3 - LE-1772	0.00
Gypsum	Caddo	Harrison Gypsum #4 - LE-2009	0.00
Gypsum	Caddo	Harrison Gypsum #5 - LE-2087	649,057.93
S&G	Wagoner	Haskell Sand, LLC - LE-2014	165,912.00
DS	Latimer	Heartland Stone - LE-2028	1,309.55
S&G	Oklahoma	Hefner Sand LLC - LE-2054	281,661.00
S&G	Seminole	Henson Gravel - LE-1142	44,808.75
S&G	Carter	Highway 53, LLC - LU-009	0.00
S&G	Texas	Highway Contractors - LE-1342	0.00
Clay	Cherokee	Hinds, R & T - LE-2222	26,257.00
S&G	Jackson	Hokett Construction - LE-1677	21,671.00
DS	Latimer	Hokie Okie Stone - #5	0.00
DS	LeFlore	Hokie Okie Stone - #6	0.00
DS	Haskell	Hokie Okie Stone - #7	0.00
DS	Latimer	Hokie Okie Stone - LE-2071 - #1	0.00
DS	Latimer	Hokie Okie Stone - LE-2115 - #2	0.00
DS	LeFlore	Hokie Okie Stone - LE-2147 - #3	0.00
DS	LeFlore	Hokie Okie Stone - LE-2177 - #4	0.00
Limestone	Pontotoc	Holcim (US) Inc. - LE-1382	1,148,565.00
S&G	Osage	Holcomb, Earl W. - LE-1924	0.00
S&G	Tulsa	Holliday S & G - LE-1298 - Bixby	104,635.00
S&G	Wagoner	Holliday S & G - LE-1553 - Coweta	236,330.00
S&G	Tulsa	Holliday S & G - LE-1560 - BA #15	400,134.00
S&G	Tulsa	Holliday S & G - LE-1886 - Leonard	18,546.00
S&G	Washington	Hoppock Builders - LE-1678	0.00
S&G	Atoka	Horton Sand & Mater. - LE-1977	0.00
S&G	Atoka	Horton, Charles - LE-2236	19,996.00
S&G	Cherokee	Howe, Samuel L. - LE-1953	0.00
DS	LeFlore	Ibison Stone Sales - LE-1522	6,758.63
Clay	Tulsa	Inter. Amer. Ceramics - LE-1688 - Laufen	0.00
S&G	Tulsa	J & J Sand - LE-1504 - Jones Pit	25,825.00
S&G	Wagoner	J & J Sand - LE-1591 - #3	410,698.00
S&G	Tulsa	J & J Sand - LE-1704 - West	22,736.00
S&G	Beaver	J & R Sand - LE-1623 - Winchell	157,310.00
S&G	Beaver	J & R Sand - LE-1897 - Hutton	192,224.00
S&G	Garvin	Jacobson, L. A. - LE-1967	0.00
Limestone	Caddo	Jenkins Equipment - LE-1793	56,150.83
S&G	Kiowa	Jenkins, H. G. Con. - LE-1758	0.00
S&G	Comanche	Jenkins, H. G. Con. - LE-1957	12,255.88

S&G	Cotton	Jenkins, Harvey - LE-2108	30,128.00
DS	Pontotoc	Jennings Rock - LE-1995	3,870.00
Clay	Pontotoc	Jennings Stone Co. - LE-2098	2,775.00
S&G	LeFlore	Job Construction Co. - LE-1756	21,624.00
Clay	LeFlore	Johnson, H. L. Const. - LE-1958	0.00
Clay	LeFlore	Johnson, H. L. Const. - LE-2181	47,177.00
DS	Haskell	Johnson, Roy Don - LE-1879	0.00
S&G	Garfield	Jones Backhoe Serv. - LE-2133	2,750.00
S&G	Kiowa	Jones Fill Sand - LE-1791	0.00
S&G	Wagoner	Jones, Bob - LE-1707	40.00
S&G	Okfuskee	K & K Sand - LE-1531	1,826.00
S&G	Pottawatomie	K & M Sand Co. - LE-1570	2,041.00
S&G	Tulsa	K. Ross Trucking - LE-1774	65,402.00
Limestone	Caddo	Karlin Co., Inc. - 98-1194	0.00
Limestone	Kay	Kay County Lime. - LE-1608	66,215.06
Limestone	Ottawa	Kemp Stone Co.- LE-1620	286,500.00
Limestone	Cherokee	Kemp Stone Co.- LE-2089	254,300.00
S&G	Payne	Kerns Const. - LE-1222	43,026.00
S&G	Osage	Keystone S & G - 05-1794	885.50
Clay	Lincoln	Kinder Dozer, Inc. - LE-1723	2,200.00
S&G	Cleveland	King Trucking - LE-1946	90,443.10
S&G	Cleveland	Kinsey Sand & Gravel - 98-1118	7,129.00
S&G	Woodward	Kline Materials, Inc. - LE-1357	37,895.95
S&G	Dewey	Kline Materials, Inc. - LE-1790	188,568.10
S&G	Oklahoma	Knox Construction - LE-2118	0.00
S&G	Tulsa	Kornegay, Larry R. - LE-1537	13,678.00
DS	LeFlore	Kully Chaha Native Stone	15,206.93
DS	Pittsburg	L & W Stone Corp. - LE-2038	0.00
DS	Pittsburg	L & W Stone Corp. - LE-2106	0.00
DS	Pittsburg	L & W Stone Corp. - LE-2140	0.00
DS	Pittsburg	L & W Stone Corp. - LE-2196	0.00
DS	Pittsburg	L & W Stone Corp. - LE-2208	912.83
Limestone	Tulsa/Rogers	LaFarge Bldg. Mater.- LE-1053	911,314.00
S&G	Wagoner	LaFarge West, Inc.- LE-1595 - Coweta	65,651.11
S&G	Seminole	Laird, Bill Oil Co. - LE-1711	0.00
Limestone	Ellis	Latta Caliche - LE-2224	25,858.00
Limestone	Atoka	Lattimore Materials - LE-1360	0.00
Limestone	Bryan	Lattimore Materials - LE-1546	0.00
S&G	Love	Lattimore Materials - LE-1742	576,175.27
S&G	Love	Lattimore Materials - LE-2018	449,088.25
Limestone	Atoka	Lattimore Materials - LE-2079	2,004,183.00
S&G	Garfield	Lavicky Sand - LE-2057	84,673.95
S&G	Comanche	Lawton Transit Mix - LE-1815	2,424.00
S&G	Harper	LeRoy's Ready Mix - LE-2083	15,210.00
S&G	Kingfisher	Lightle Sand Co. - LE-1838	56,202.26
DS	Pittsburg	Liles Quarries - LE-2137	484.53
S&G	Oklahoma	Little, James & John - LE-1737	1,200.00
S&G	Pittsburg	Livingston, Robert - LE-1518	3,060.00
S&G	Logan	Logan County Asph. - LE-1858	63,324.00
Limestone	Mayes	Lone Star Industries - LE-1771	1,048,530.00
Clay	Cherokee	Loyd's Bar Pit - LU-012	
DS	LeFlore	Luman Rock - LE-1890	3,092.78

DS	Pittsburg	M & G Rock & Stone - LE-2119LLC	1,060.95
S&G	Kingfisher	M & M Sand - LE-2248	93,997.91
S&G	Cleveland	M & M Wrecking - LE-1804 - #2	850.00
S&G	Cleveland	M & M Wrecking - LE-1851 - #1	7,600.00
S&G	Logan	M & S Dirt & Sand - LE-2060	0.00
DS	LeFlore	M.M.H.F., LLC - LE-1616	135,259.93
Clay	Greer	Mangum Brick Co. - LE-1687	29,869.00
DS	Haskell	Maranatha Stone - LE-2088 - #3	6,836.64
DS	Haskell	Maranatha Stone - LE-2139 - #4	14,577.16
DS	Sequoyah	Marble City Stone - LE-1712	362.00
Limestone	Murray	Material Producers - LE-1603	1,346,854.55
Limestone	Rogers	Material Service - LE-1775	0.00
Limestone	Mayes	Material Service - LE-1841	0.00
Limestone	Kiowa	Material Service - LE-2021	0.00
S&G	Seminole	McCraw, Mayfield - LE-1943	11,280.78
DS	LeFlore	McGee Creek - LE-1819 - #1 Wister	5,450.00
DS	Haskell	McGee Creek - LE-1889 - #2	3,350.00
DS	Pittsburg	McKee Stone - LE-1983	0.00
S&G	Beckham	McLemore Sand - LE-1394	83,249.00
Clay	Tulsa	Melody Development - LE-1788	0.00
S&G	Choctaw	Meridian Aggre. - LE-1482 - Kiamichi	0.00
Limestone	Choctaw	Meridian Aggre. - LE-1492 - Hugo-Apple	0.00
S&G	Choctaw	Meridian Aggre. - LE-1492 - Sawyer	1,710,950.00
Limestone	Marshall	Meridian Aggre. - LE-1551 - Rushing-Willis	0.00
Limestone	McCurtain	Meridian Aggre. - LE-1572 - Williams	303,147.00
Granite	Johnston	Meridian Aggre. - LE-1605 - Quarry 900	1,950,579.00
Limestone	Choctaw	Meridian Aggre. - LE-1612 - Custer	7,919.00
Granite	Kiowa	Meridian Aggre. - LE-1714 - Snyder	1,115,628.54
S&G	Choctaw	Meridian Aggre. - LE-1821 - Red River Sand	0.00
Limestone	Johnston	Meridian Aggre. - LE-1856 - N. Troy	2,816,615.00
Limestone	Marshall	Meridian Aggre. - LE-1999 - Willis-Beasley	9,640.00
S&G	Johnston	Meridian Aggre. - LE-2056 - Hugo-Caldwell	608,184.00
S&G	McCurtain	Meridian Aggre. - LE-2227 - Broken Bow	467,559.00
S&G	Bryan	Michael, Wesley K. - LE-2037	6,318.20
Limestone	Ottawa	Midwest Minerals - LE-1452	176,510.00
S&G	Cleveland	Milam Tool Co. - LE-2081	99,386.00
S&G	Stephens	Miller Construction - LE-1847	2,119.00
S&G	LeFlore	Miller Stone Co. - LE-1513	343.60
Clay	Mayes	Minerals Solutions - LE-1732	0.00
S&G	Tulsa	Miser, R. G. - LE-2010	66,066.00
S&G	Garvin	MLB Backhoe/Dozer - LE-2250	312.00
DS	Haskell	Morris Stone Co. - LE-2011	14,204.80
DS	LeFlore	Morris Stone Co. - LE-2243	8,582.80
S&G	Creek	Morris, Ron - LE-2043	0.00
DS	Haskell	Morrison, Jeanne Lee - LE-1894	2,254.72
DS	Latimer	Mule Creek Stone - LE-2015	0.00
DS	Latimer	Mule Creek Stone - LE-2122	1,872.57
DS	Latimer	Mule Creek Stone - LE-2269	438.29
S&G	Wagoner	Muskogee Paving - LE-2246	1,286.40
S&G	Wagoner	Muskogee Sand - LE-1318	47,700.00
S&G	Wagoner	Muskogee Sand - LE-2151	355,800.00
Limestone	Johnston	Mustang Stone Quarries, LL LE-2279	0.00

S&G	Tulsa	Myers, Robert - LE-2264	2,856.00
S&G	Cleveland	Norman Select Fill - LE-1502	280.00
Clay	Carter	North Bay Homes - LE-2145	16,258.00
S&G	Creek	Oilton Sand Plant - LE-1929	60,750.00
DS	Pittsburg	OK Rock Quarries - LE-2053	278.55
DS	Haskell	OK Rock Quarries - LE-2154	96.00
DS	Pittsburg	OK Rock Quarries - LE-2166	0.00
DS	Pittsburg	OK Rock Quarries - LE-2240	15,391.19
S&G	Pottawatomie	Oklahoma Aztec - LE-1521 - Asher I	0.00
S&G	Pottawatomie	Oklahoma Aztec - LE-1650 - Asher II	0.00
S&G	Pottawatomie	Oklahoma Aztec - LE-1996 - Asher II	45,612.59
S&G	Pottawatomie	Oklahoma Aztec - LE-2107 - Konawa #1	13,394.20
Chat	Ottawa	Oklahoma Flint Rock Products	275,627.00
Granite	Greer	Oklahoma Red Granite - LE-1575	63.00
DS	Haskell	Oklahoma Sandstone - LE-2111	534.81
DS	Haskell	Oldham Enter. - LE-2143	4,793.00
Clay	Oklahoma	Orange & Son's Trk - LE-2075	844.00
S&G	Garvin	Owens, Glen S & G - LE-1850	7,100.00
S&G	Mayes	Ozark Materials Co. - LE-1843	15,342.00
S&G	Bryan	P P & J, Inc. - LE-1833	6,900.00
S&G	Cherokee	Park Hill Plants - LE-1769	0.00
ds	Haskell	Parker & Sons - LE- #4	8,974.71
DS	Haskell	Parker & Sons - LE- #5	60.12
DS	Haskell	Parker & Sons - LE-2023 - #1	0.00
DS	Haskell	Parker & Sons - LE-2070 - #2	3,304.94
DS	Haskell	Parker & Sons - LE-2072 - Bailes #2	171.93
DS	Haskell	Parker & Sons - LE-2138 - #3	8,804.86
DS	Haskell	Parker Chop Stone - LE-2174	0.00
DS	Haskell	Parker Rock - LE-1903	6,287.00
Clay	Cleveland	Payne, Bruce - LE-1728	42,179.25
Limestone	Nowata	Peerless Materials - LE-1183	0.00
S&G	Cleveland	Pellegrino, Joseph - LE-1920	16,279.20
S&G	Payne	Perkins Sand - LE-1755	43,930.81
Limestone	LeFlore	Pine's Stone Co. - LE-1443	1,731.29
S&G	Beaver	Pioneer Aggregates - LE-2078	0.00
S&G	Garfield	Porter, Dennis L. - LE-1968	0.00
S&G	Beckham	Potter, J. C. Ranch - LE-1901	0.00
S&G	McIntosh	Pruitt, Marshall - LE-1831	276.00
S&G	Muskogee	Pryor Sand Co. - LE-1238	28,083.22
Limestone	Mayes	Pryor Stone, Inc. - LE-1195	589,950.00
Limestone	Haskell	Pryor Stone, Inc. - LE-1607	0.00
Clay	Mayes	Pursley, Klint - LE-2171	2,895.00
DS	Haskell	Quality Production - LE-2231	20,405.31
Limestone	McCurtain	Quality Rock, Inc. - LE-1902	388,778.13
S&G	Creek	Quapaw Company - LE-1293	8,855.00
Limestone	Pawnee	Quapaw Company - LE-1598	279,525.00
Limestone	Creek	Quapaw Company - LE-1636	816,220.00
S&G	Oklahoma	Quickway Exc. - 94-749	0.00
S&G	Canadian	R & M Resources - LE-1296 - #1	108,071.67
S&G	Canadian	R & M Resources - LE-1931 - #2	102,521.47
Gypsum	Woodward	RB & J Materials - LE-2086	0.00
Gypsum	Woodward	RB & J Materials - LE-2136	0.00

Gypsum	Woodward	RB & J Materials - LE-2162	179,318.55
Gypsum	Major	RB & J Materials - LE-2234	153,143.11
S&G	McCurtain	Red River County - LE-1746	1,777.50
S&G	McCurtain	Red River County - LE-2104	705.60
S&G	Tulsa	Redbird Investment - LE-1846	0.00
S&G	Hughes	Reid Sand - LE-1762	624.00
Clay	Osage	Remediation Serv. - LE-1675	0.00
S&G	Pawnee	Renfro Sand & Conc. - LE-1663	452.00
Clay	Bryan	Richard's Dozer Serv. - LE-2170	700.00
S&G	Bryan	Ritchey, Alan - LE-1989	675,466.27
Clay	Mayes	Robertson, Douglas - LE-1465	3,164.00
S&G	Tulsa	Rock Hill, LLC - LE-2045	45,184.00
DS	LeFlore	Rock Investments - LE-1541	10,508.44
DS	LeFlore	Rock Investments - LE-1698	60.56
DS	LeFlore	Rock Investments - LE-2117	742.75
DS	LeFlore	Rock Investments - LE-2249	4,311.04
DS	LeFlore	Rock-It Natural Stn. - LE-1740 - Wister (Horne)	0.00
DS	LeFlore	Rock-It Natural Stn. - LE-1741 - Wister (Ben)	972.19
DS	Haskell	Rock-It Natural Stn. - LE-1855 - Stigler West #2	5,005.29
DS	LeFlore	Rock-It Natural Stn. - LE-1865 - Wildhorse	761.89
DS	LeFlore	Rock-It Natural Stn. - LE-1921 - Cameron #1	0.00
DS	Haskell	Rock-It Natural Stn. - LE-1998 - Stigler South #1	6,622.44
DS	Haskell	Rock-It Natural Stn. - LE-2007 - LeQuire South #1	8,687.70
DS	Haskell	Rock-It Natural Stn. - LE-2027	1,335.83
DS	Haskell	Rock-It Natural Stn. - LE-2042	0.00
DS	Haskell	Rock-It Natural Stn. - LE-2049 - McCurtain No. 2	7,973.32
DS	Haskell	Rock-It Natural Stn. - LE-2093 - Tamaha #1	13,877.95
DS	Haskell	Rock-It Natural Stn. - LE-2102 - Stigler South #2	0.00
DS	Haskell	Rock-It Natural Stn. - LE-2130 - Stigler West #5	196.85
DS	Haskell	Rock-It Natural Stn. - LE-2141 - Stigler East #4	1,277.31
DS	LeFlore	Rock-It Natural Stn. - LE-2142 - Sulphur #1	0.00
DS	Haskell	Rock-It Natural Stn. - LE-2156	5,412.40
DS	LeFlore	Rock-It Natural Stn. - LE-2215	259.47
DS	LeFlore	Rockland Systems - LE-1881	0.00
DS	LeFlore	Rockland Systems - LE-2160	0.00
Limestone	Bryan	Rodman, LLC - LE-1532	0.00
DS	Haskell	Rodman, LLC - LE-1533	0.00
Limestone	Haskell	Rodman, LLC - LE-1750	29,885.00
DS	Haskell	Rodman, LLC - LE-1849	0.00
DS	Haskell	Rodman, LLC - LE-1942	17,060.00
Limestone	Caddo	Rodman, LLC - LE-2200	309,456.00
DS	Johnston	Rolen Stone Co. - LE-1844	2,030.12
Select Fill	Bryan	Rushing Pit - LE-1706	12,000.00
S&G	Bryan	Rustin Concrete - LE-1361 - Rustin	19,583.86
S&G	Marshall	Rustin Concrete - LE-1512 - Weaver	0.00
S&G	Bryan	Rustin Concrete - LE-1906 - #2	45,697.63
S&G	Cherokee	Ryals, Phillip Gravel - LE-1716	1,623.00
DS	Muskogee	S & S Industrial - LE-2188	146.52
DS	Muskogee	S & S Industrial - LE-2220	0.00
DS	Haskell	San Bois Stone - LE-1986	0.00
S&G	McClain	Sand Express, Inc. - LE-2110	15,510.00
S&G	Cleveland	Sand Express, Inc. - LE-2198	0.00

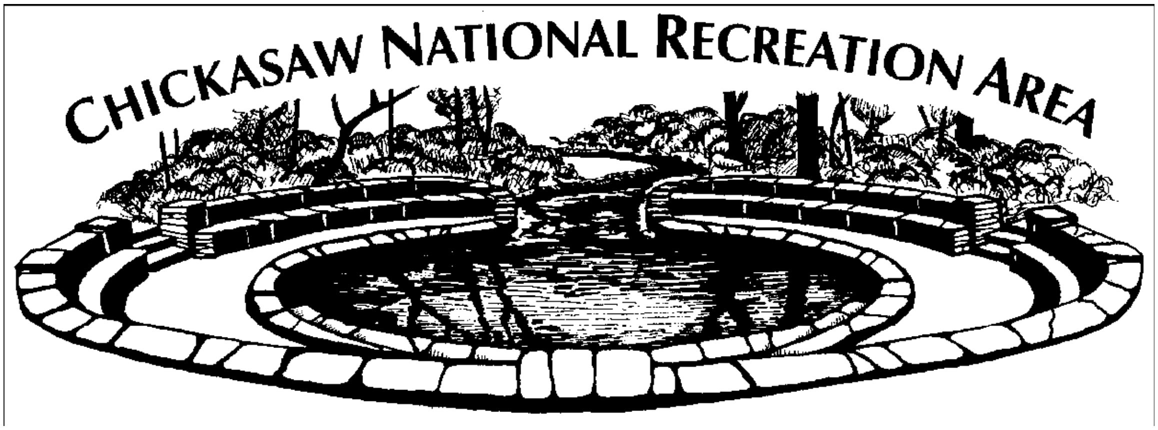
S&G	Cleveland	Sand Express, Inc. - LE2274	55,017.00
S&G	Tulsa	Sand Springs S & G - LE-1187	43,747.00
S&G	Garfield	Schulz, Jack L. - LE-1926	9,693.00
DS	LeFlore	Schwartz, Bob - LE-2197	893.01
S&G	Oklahoma	Schwarz Ready Mix - LE-1665 - #3	0.00
S&G	Oklahoma	Schwarz Sand, LLC - LE-1408	0.00
S&G	McClain	Schwarz Sand, LLC - LE-1947	0.00
Clay	Tulsa	Schwickerath Dirt Sales - LE-1916	64,735.00
Limestone	Choctaw	SCS Materials, L.P. - LE-1834	961,412.17
Clay	Ottawa	Select Fill, LLC - LE-2232	13,310.00
S&G	Oklahoma	Sharp Sand Co. - LE-1358	0.00
S&G	Pittsburg	Sherman Trucking - LE-1883 - #1	4,650.00
S&G	Pittsburg	Sherman Trucking - LE-1919 - #2	13,675.00
S&G	Cleveland	Shirley's Sand - LE-1484	76,130.00
DS	Haskell	Shore Stone, LLC - LE-2183	0.00
Clay	Tulsa	Signature Trans. - LE-1688	0.00
S&G	Cleveland	Silver Star Const. - LE-2029	0.00
Clay	Cleveland	Simpson Properties - LE-2064	29,619.00
DS	LeFlore	Slim's Stone - LE-1674	5,548.00
S&G	Kay	Sober Brothers - LE-1972	248,306.33
DS	LeFlore	Solid Rock Stone - LE-2178	11,257.85
DS	Haskell	Solid Rock Stone - LE-2242	2,479.00
S&G	Cleveland	Sooner Shale Pit - LE-1458	11,678.00
S&G	Love	Southern Aggregates - LE-1505	2,404.18
Limestone	Rogers	Southwest Stone - LE-1660	822.00
S&G	Tillman	Southwestern State - LE-1499	130,444.39
S&G	LeFlore	Spiro S & G Co. - LE-1806	52,694.00
S&G	Love	Sprouse, Margaret - LE-1985	0.00
Limestone	Tulsa	Stagedoor Motors - LE-1870	0.00
S&G	Murray	Stanley & Son Const. - LE-2031	1,470.00
DS	Haskell	Star Stone Quarries - LE-1840	2,350.38
Limestone	Pawnee	Stewart Stone - LE-1270 - Wilson	0.00
Limestone	Payne	Stewart Stone - LE-1397 - Holderread	280,308.50
Limestone	Pawnee	Stewart Stone - LE-1760 - Dallas	0.00
Limestone	Haskell	Stigler Stone - LE-1629 - Barbee	173,900.36
Limestone	Haskell	Stigler Stone - LE-1632 - Tiger	293,982.33
Limestone	McIntosh	Stigler Stone - LE-1635 - Scott	420.43
Limestone	Haskell	Stigler Stone - LE-1979 - Parks	0.00
DS	Haskell	Stigler Stone - LE-1984 - Roye	4,532.98
S&G	Payne	Stillwater S & G - LE-1862	29,217.00
Clay	Tulsa	Stokely, J. & P. - LE-1355	32,234.00
DS	LeFlore	Stone Ridge Quarry - LE-2179	11,432.67
DS	Haskell	Stone Splitters, Inc. - LE-2008	2,065.00
DS	Haskell	Stone Splitters, Inc. - LE-2153	907.50
DS	Haskell	Stone Supply - LE-2225	3,173.00
Clay	Cherokee	Stratton, Phyllis B. - LE-2065	0.00
DS	Haskell	Stricklin Const - LU-005	1,502.50
S&G	Comanche	T & G Construction - LE-1473	12,689.00
S&G	Kiowa	T & G Construction - LE-1649	43,455.00
S&G	Sequoyah	T & M Sand & Gravel - LE-1666	65,652.02
S&G	Sequoyah	T & M Sand & Gravel - LE-2016	0.00
DS	LeFlore	T & T STONE LE-2039	0.00

DS	LeFlore	T N T Stone - LE-2237	750.00
Limestone	Pushmataha	Talihina Stone - LE-1567	3,791.95
Limetone	Atoka	Talihina Stone - LE-2263	14,434.58
Select Fill	Oklahoma	Tandem Services, Inc.	4,104.00
S&G	Johnston	Tate Trucking Co. - LE-1863	9,183.33
Limestone	Pittsburg	TDM Quarry - LE-1447	8,397.00
S&G	Sequoyah	Terrell Dump Trucking - 03-1437	4,910.00
Granite	Greer	Texas Granite Corp. - LE-1389	0.00
S&G	Johnston	The Red Rock Pit - LE-2223	192,882.53
S&G	Love	Thompson, J. R. - LE-1610	0.00
S&G	McCurtain	Thrasher, J. - LE-2044 - Glen Berry	1,958.00
S&G	Tulsa	Thurman, S. or J. - LE-1776	17,967.60
S&G	Johnston	Tishomingo S & G - LE-1719	53,108.86
Clay	Muskogee	Tonto Construction - LE-1786	1,460.00
DS	Haskell	Treadway Ranch - LE-2073	176.50
S&G	Bryan	Trinity Materials - LE-2033	0.00
Limestone	Ellis	Triple B Rolling Hills -LE-2167	146,231.30
DS	Pittsburg	T-Stone - LE-2113	2,449.00
S&G	Tulsa	Tulsa Grass - LE-1667	1,854.00
DS	Latimer	Turkey Creek Stone - LE-2090	2,095.42
S&G	Choctaw	Two Rivers S & G - LE-2180	0.00
S&G	Jefferson	TXI Industries - LE-1461 - Terrall	0.00
S&G	Bryan	TXI Industries - LE-1639 - Wade Sand	1,419,310.00
Limestone	Johnston	TXI Industries - LE-1805 - Mill Creek	5,103,956.00
Gypsum	Blaine	U. S. Gypsum - LE-1425	0.00
Gypsum	Blaine	U. S. Gypsum - LE-1530	277,197.00
Gypsum	Blaine	U. S. Gypsum - LE-1676	0.00
Limestone	Sequoyah	U. S. Lime Co. - LE-1451	492,556.00
S&G	Johnston	U. S. Silica - LE-1662 - #39	1,200,969.95
S&G	Johnston	U. S. Silica - LE-1708 - Mill Creek So.	0.00
S&G	Johnston	Unimin Corp. - LE-1380 - Mill Creek South	217,188.00
S&G	Pontotoc	Unimin Corp. - LE-1565 - Roff Plant	979,858.00
Limestone	Kiowa	V J Stone, LLC - LE-2116	522,672.28
Clay	Canadian	V. K. Blasting - LE-1432	0.00
S&G	Cleveland	Vanderburg - LE-1749	29,114.00
Clay	Tulsa	Vandiver, Grady Roe - LE-1932	3,660.00
S&G	Pottawatomie	Vanlandingham, Brent - LE-2024	66,647.20
S&G	Grady	Vickrey, Eugene - LE-2005	6,355.00
S&G	McCurtain	Voss, James - LE-1864	7,865.00
S&G	Cherokee	Wade's Backhoe - LE-1392	0.00
S&G	Tulsa	Wallace, Floyd - LE-1344	33,580.00
S&G	Pottawatomie	Wallgren, Kenneth R. - LE-1524	5,958.00
S&G	Okmulgee	Wallick, Scott - LE-2159	525,000.00
S&G	McClain	Walnut Creek Sand - LE-2055	14,674.00
S&G	Tulsa	Watkins Sand - LE-1433 - ABC	0.00
S&G	Tulsa	Watkins Sand - LE-1433 - Jenks	0.00
S&G	Tulsa	Watkins Sand - LE-1487 - Rickner	148,687.84
S&G	Tulsa	Watkins Sand - LE-1643 - #4	71,144.00
S&G	Tulsa	Watkins Sand - LE-1853 - 129th Ave. East	194,629.00
S&G	Lincoln	Wayland, Bill Const. - LE-1467	8,748.00
S&G	Lincoln	Wayland, Bill Const. - LE-2255	3,012.00
DS	LeFlore	Webb, Johnny - LE-2092	8,976.87

S&G	Oklahoma	West, Dan Invest. LE-2127	15,216.25
Gypsum	Major	Western Plains Mate. - LE-1498	0.00
DS	LeFlore	Wildhorse Quarries - LE-2209	0.00
S&G	Carter	Wilkins, Dale W. - LE-2172	17,878.00
S&G	Hughes	Woods, Louis R. - LE-1744	300.00
S&G	Harper	Woodward Trans. - LE-1922 - Laverne S & G	16,544.00
S&G	Beaver	Woodward Trans. - LE-2187	4,158.60
S&G	Adair	Worley's Gravel - 99-1352	1,915.80
S&G	Haskell	Worsham Sand - LE-1690	1,985.00
Clay	Pontotoc	Wyche Quarry - LE-1543	26,803.00
S&G	Creek	Yocham Enterprises - LE-1538	0.00
S&G	Wagoner	Yocham Trucking - LE-1387	41,080.00
S&G	Creek	Yocham, Robert - 02-1577	0.00
Limestone	McIntosh	Youngman Rock - LE-1701	299,318.86

ATTACHMENT 6

Impacts of Visitor Spending on the Local Economy: Chickasaw National Recreation Area, 2005



Daniel J. Stynes
Department of Community, Agriculture, Recreation and Resource Studies
Michigan State University
East Lansing, Michigan 48824- 1222

June 2008

National Park Service

Social Science Program

Department of Community, Agriculture, Recreation and Resource Studies
Michigan State University

Impacts of Visitor Spending on the Local Economy: Chickasaw National Recreation Area, 2005

Executive Summary

Chickasaw National Recreation Area (NRA) hosted 1,295,212 recreation visits in 2005. Based on the 2005 visitor survey 23% of the visitors are local residents, 42% are visitors from outside the local area not staying overnight within 50 miles of the park, and 35% are visitors staying overnight in the local area. About 38% of the overnight visitors are camping, 28% are staying in motels, and 35% are staying with friends or relatives or other unpaid lodging.

The average visitor party spent $82 in the local area. Visitors reported expenditures of their group inside the park and within 50 miles of the park. On a party trip basis, average spending in 2005 was $63 for local residents, $52 for non-local day trips, $307 for visitors in motels, $127 for campers and $99 for other overnight visitors. On a per night basis, visitors staying in motels spent $193 in the local region compared to $62 for campers and $48 for other overnight visitors. The average per night lodging cost was $95 per night for motels and $6 for campgrounds.

Total visitor spending in 2005 within 50 miles of the park was $15.93 million. Overnight visitors staying in motels, cabins or B&B's accounted for 29% of the total spending. Visitors on day trips from beyond the local area accounted for 35% of the spending. Thirty-one percent of the spending was for gas and oil, 26% for groceries, 16% for restaurant meals and bar expenses, and 14% for lodging.

About a quarter of the non-local visitors indicated the park visit was not the primary reason for coming to the area, so only a portion of their expenses can be attributed to the park visit. Omitting spending by local visitors and reducing spending attributed to the park visit for visitors in the area for other reasons yields a total of $11.37 million in spending attributed to the park, about 71% of the $15.93 million spent by park visitors on the trip.

The economic impact of park visitor spending is estimated by applying this spending to a model of the local economy. The local region was defined as a fourteen county area in south central Oklahoma. The tourism spending sales multiplier for the region is 1.61.

Visitor spending in 2005 directly supported 183 jobs in the area outside the park, generating $3.1 million in wages and salaries and $4.4 million in value added. Value added includes wages and salaries as well as profits and rents to area businesses and sales taxes. An additional 65 jobs are supported through secondary effects. The total impact on the local economy including direct and secondary effects is 249 jobs, $4.7 million in wages and salaries and $7.0 million in value added. Visitor spending supports 52 jobs in hotels, 58 jobs in area restaurants, and 46 jobs in retail trade.

The park itself employed 74 people in FY 2005 with a total payroll including benefits of $3.34 million. Including secondary effects, the local impact of the park payroll in 2005 was 94 jobs, $3.73 million in personal income and $4.11 million total value added. Including both visitor spending and park operations, the total impact of the park on the local economy in 2005 was 343 jobs and $11.1 million value added. Park operations account for 27% of the employment effects and 37% of value added.

Impacts of Visitor Spending on the Local Economy: Chickasaw National Recreation Area, 2005

Daniel J. Stynes
June 2008

Introduction

The purpose of this study is to document the local economic impacts of visitors to Chickasaw National Recreation Area (NRA) in 2005. Economic impacts are measured as the direct and secondary sales, income and jobs in the local area resulting from spending by park visitors. The economic estimates are produced using the Money Generation Model 2 (MGM2) (Stynes and Propst, 2000). Three major inputs to the model are:

1) Number of visits broken down by lodging-based segments,
2) Spending averages for each segment, and
3) Economic multipliers for the local region

Inputs are estimated from the Chickasaw NRA Visitor Survey, National Park Service Public Use Statistics, and IMPLAN input-output modeling software. The MGM2 model provides a spreadsheet template for combining park use, spending and regional multipliers to compute changes in sales, personal income, jobs and value added in the region.

Chickasaw NRA and the Local Region

Chickasaw NRA is located in south central Oklahoma just south of the town of Sulpher. The park is 90 miles south of Oklahoma City and 120 miles north of Dallas. The park hosted 1,295,212 recreation visitors and 82,585 overnight stays in 2005 (Table 1).

The local region was defined as a fourteen county area within 50 miles of the park. The region includes Atoka, Bryan, Carter, Coal, Garvin, Hughes, Johnston, Love, Marshall, McClain, Murray, Pontotoc, Pottawatomie, and Seminole counties in Oklahoma. This region roughly coincides with the area for which visitor spending was reported in the visitor survey. The region had a population of about 350,000 in 2001.

A park visitor study was conducted at Chickasaw NRA from July 1-10, 2005 (Manni and Hollenhorst, 2006). The study measured visitor demographics, activities, and travel expenditures. Questionnaires were distributed to a sample of 883 visitors at five sampling locations within the park. Visitors returned 475 questionnaires for a 54% response rate. Data generated through the visitor survey were used as the basis to develop the spending profiles, segment shares and trip characteristics for Chickasaw NRA visitors.

Table 1. Recreation Visits to Chickasaw NRA, 2005-2007

Month	2005	2006	2007
January	44,725	51,204	27,660
February	54,433	53,535	59,030
March	94,818	93,203	109,630
April	90,602	137,435	102,469
May	146,250	171,651	171,329
June	200,615	188,290	190,491
July	204,678	202,793	226,801
August	165,938	111,569	160,526
September	94,193	106,340	111,181
October	79,784	96,876	89,359
November	70,646	65,835	67,131
December	48,530	65,062	53,199
Total	1,295,212	1,343,793	1,368,806

Source: NPS Public Use Statistics

Since visitors were sampled at campgrounds, picnic areas, and boat ramps inside the park, visitors with longer stays had a higher probability of being sampled. To adjust for this length of stay bias, cases were weighted inversely to the number of days spent in the park. Weighting reduces the estimate of the percentage of visitors staying overnight in the area from 56% to 39%.

About half of the non-local visitors came to the area primarily to visit the Chickasaw NRA. Twenty-four percent of visitors came to visit other attractions in the area; ten percent were visiting friends or relatives in the area.

MGM2 Visitor Segments

MGM2 divides visitors into segments to help explain differences in spending across distinct user groups. Five segments were established for Chickasaw NRA visitors:

Local day users: Day visitors who reside within the local region, defined as a 50 mile drive of the park.
Non-local day users: Visitors from outside the region, not staying overnight in the area. This includes day trips as well as pass-through travelers, who may be staying overnight on their trip outside the region.
Motel: Visitors staying in motels, hotels, cabins, or B&B's within a 50 mile drive of the park
Camp: Visitors staying in private or public campgrounds within a 50 mile drive of the park
Other OVN: Other visitors staying overnight in the area with friends or relatives or not reporting any lodging expenses

The 2005 visitor survey was used to estimate the percentage of visitors from each segment as well as spending averages, lengths of stay and party sizes for each segment. The weighted survey percentages were adjusted to be consistent with park overnight stay figures. Twenty-three percent of the visitors are local residents, 42% are visitors from outside the local area not staying overnight within a sixty minute drive of the park, and 35% are visitors staying overnight within a sixty minute drive of the park. About two thirds of the overnight visitors (63%) are staying in motels, cabins or B&B's, 13% are camping and 24% are staying with friends or relatives or other unpaid lodging (Table 2). The average spending party was 4 people.

Local residents were assumed to be making the trip primarily to visit the park. Non-local visitors on day trips and campers were more likely to make the trip primarily to visit the park than visitors staying in motels or with friends and relatives.

Table 2. Selected Visit/Trip Characteristics by Segment, 2005

Characteristic	Local	Day trip	Motel	Camp	Other OVN	Total
Segment share (survey)	22%	40%	10%	17%	12%	100%
Segment share (adjusted)[a]	23.4%	42.0%	9.6%	13.0%	12.0%	100.0%
Average Party size	4.06	4.05	3.83	3.93	4.48	4.05
Length of stay (days/nights)	1.08	1.00	1.59	2.05	2.06	1.37
Re-entry rate[b]	1.52	1.24	2.17	3.24	3.64	1.97
Percent primary purpose trips	100%	81%	55%	81%	74%	77%[c]

a. Shares were adjusted to take into account more local visitors and fewer campers during periods not covered by the visitor survey. The camping percent was adjusted to be consistent with park overnight stays in 2005.
b. The re-entry rate is the number of times a visitor is counted as a park visitor during their stay in the area.
c. Excludes local visitors.

The 1.295 million recreation visits to Chickasaw NRA were allocated to the five segments using the adjusted segment shares in Table 2. These visits are converted to 195,164 party trips by dividing by the average party size and park re-entry rate for each segment (Table 3).

Table 3. Recreation Visits and Party Trips by Segment, 2005

Measure	Local	Day trip	Motel	Camp	Other OVN	Total
Recreation visits	303,080	543,989	124,340	168,378	155,425	1,295,212
Party visits/trips	49,081	108,366	14,924	13,260	9,533	195,164
Person trips	199,350	438,565	57,208	52,046	42,725	789,893
Percent of party trips	25%	56%	8%	7%	5%	100%
Party nights	52,801	108,366	23,686	27,154	19,613	231,620

Visitor spending

Spending averages were computed on a party trip basis for each segment. The survey covered expenditures of the travel party within a 50 mile radius of the park.

The average visitor party spent $82 in the local area[1]. Visitors reported expenditures of their group within a 50 mile radius of the park. On a party trip basis, average spending in 2005 was $63 for local residents, $52 for non-local day trips, $307 for visitors in motels, $127 for campers and $99 for other overnight visitors (Table 4).

On a per night basis, visitors staying in motels spent $193 in the local region compared to $62 for campers and $48 for other overnight visitors (Table 5). The average

Table 4. Average Visitor Spending by Segment ($ per party per trip)

Spending Category	Local	Day trip	Motel	Camp	Other OVN	All Visitors
In Park						
Camp, boat, pavilion	0.18	0.04	0.00	0.40	1.32	0.16
Souvenirs and other expenses	1.51	2.63	1.01	3.03	1.88	2.22
In Community						
Motel, hotel cabin or B&B	0.00	0.00	150.29	0.00	0.00	11.49
Camping fees	0.00	0.00	0.99	12.03	0.00	0.89
Restaurants & bars	6.74	10.03	55.74	13.66	15.67	13.22
Groceries, take-out food/drinks	24.73	13.37	31.89	49.14	38.63	21.31
Gas & oil	25.45	21.56	37.93	35.37	29.94	25.14
Local transportation	0.46	1.17	0.50	0.20	3.51	0.99
Admissions & fees	0.27	1.38	20.89	2.09	1.73	2.65
Souvenirs and other expenses	3.88	1.68	7.67	11.37	6.20	3.57
Grand Total	**63.22**	**51.86**	**306.91**	**127.29**	**98.87**	**81.64**

Table 5. Average Spending per Night for Visitors on Overnight Trips ($ per party per night)

Spending category	Motel	Camp	Other OVN
Motel, hotel cabin or B&B	94.70	0.00	0.00
Camping fees	0.63	6.07	0.64
Restaurants & bars	35.12	6.67	7.61
Groceries, take-out food/drinks	20.09	23.99	18.77
Gas & oil	23.90	17.27	14.55
Local transportation	0.32	0.10	1.70
Admissions & fees	13.16	1.02	0.84
Souvenirs and other expenses	5.47	7.03	3.93
Total	**193.38**	**62.16**	**48.05**

Note: Excludes fees paid to the park

[1] The average of $82 is considerably lower than the $243 spending average in the VSP report (Manni and Hollenhorst 2006) due to the omission of outliers, adjustments of segment shares, weighting of cases for a length of stay bias and treatment of missing spending data.

per night lodging cost was $95 per night for motels and $6 for campgrounds. The sampling error (95% confidence level) for the overall spending average is 13%. A 95% confidence interval for the spending average is therefore $82 plus or minus $11 or ($71, $93).

Chickasaw NRA visitors spent a total of $15.93 million in the local area in 2005 (Table 6). Total spending was estimated by multiplying the number of party trips for each segment by the average spending per trip and summing across segments.

Overnight visitors staying in motels, cabins or B&B’s accounted for 29% of the total spending. Visitors on day trips from beyond the local area accounted for 35% of the spending. Thirty-one percent of the spending was for gas and oil, 26% for groceries, 16% for restaurant meals and bar expenses, and 14% for lodging.

Table 6. Total Visitor Spending by Segment, 2005 ($000s)

	Local	Day trip	Motel	Camp	Other OVN	All Visitors
In Park						
Camp, boat, pavilion	9.05	4.52	0.00	5.32	12.60	31.50
Souvenirs and other expenses	73.92	285.36	15.02	40.22	17.90	432.43
In Community						
Motel, hotel cabin or B&B	0.00	0.00	2242.92	0.00	0.00	2242.92
Camping fees	0.00	0.00	14.83	159.57	0.00	174.40
Restaurants & bars	330.96	1087.28	831.79	181.06	149.34	2580.43
Groceries, take-out food/drinks	1213.97	1448.50	475.93	651.54	368.23	4158.16
Gas & oil	1248.90	2336.20	566.10	469.06	285.39	4905.65
Local transportation	22.63	126.43	7.51	2.66	33.42	192.64
Admissions & fees	13.04	149.00	311.76	27.69	16.47	517.96
Souvenirs and other expenses	190.44	182.42	114.48	150.79	59.13	697.26
Grand Total	**3,103**	**5,620**	**4,580**	**1,688**	**942**	**15,933**
Total excluding park fees	3,094	5,615	4,580	1,683	930	15,902
Segment Percent of Total	19%	35%	29%	11%	6%	100%

Not all of this spending would be lost to the region in the absence of the park as 21% of the visitors are local residents and some non-residents came to the area for business, visiting friends and relatives, and other reasons. Spending directly attributed to the park visit was estimated by counting all spending for trips where the park was the primary reason for the trip[2]. Half of the spending outside the park was counted for day trips if the trip was not made primarily to visit Chickasaw NRA. The equivalent of one night of spending was attributed to the park visit for overnight trips made to visit other attractions, friends or relatives or on business.[3] All spending inside the park was counted, but all spending by local visitors outside the park was excluded.

[2] Visitors who identified a recreation activity as their primary reason were also included as primary purpose trips.
[3] This assumes that these visitors spent an extra night in the area to visit Chickasaw NRA.

These attributions yield a total of $11.37 million in visitor spending attributed to the park visit (excluding park admission fees), representing 71% of the overall visitor spending total (Table 7).

Table 7. Total Spending Attributed to Park Visits, 2005 ($000s)

Spending Category	Local	Day trip	Motel	Camp	Other OVN	All Visitors
In Park						
Admissions	9	5	0	5	13	31
Gift shop	74	285	15	40	18	432
In Community						
Motel, hotel cabin or B&B		0	1,866	0	0	1,866
Camping fees		0	12	145	2	159
Restaurants & bars		985	692	164	130	1,970
Groceries, take-out food/drinks		1,312	396	589	319	2,617
Gas & oil		2,117	471	424	248	3,259
Local transportation		115	6	2	29	152
Admissions & fees		135	259	25	14	434
Souvenirs and other expenses		165	95	136	51	448
Total Attributed to Park	**83**	**5,119**	**3,813**	**1,531**	**823**	**11,368**
Percent of spending attributed to the park	3%	91%	83%	91%	87%	71%

Economic Impacts of Visitor Spending

The economic impacts of Chickasaw NRA visitor spending on the local economy are estimated by applying the spending attributed to the park (Table 7) to a set of economic ratios and multipliers representing the local economy. Multipliers for the region were estimated with the IMPLAN system using 2001 data. The tourism sales multiplier for the region is 1.61. Every dollar of direct sales to visitors generates another $ .61 in secondary sales through indirect and induced effects[4].

Impacts are estimated based on the visitor spending attributed to the park in Table 7, excluding fees paid to the park[5]. Including direct and secondary effects, the $11.37 million spent by park visitors[6] supports 231 jobs in the area and generates $12.7 million in sales, $4.0 million in labor income and $5.6 million in value added (Table 8).

[4] Indirect effects result from tourism businesses buying goods and services from local firms, while induced effects stem from household spending of income earned from visitor spending.
[5] The local economic impact of all $15.93 million in visitor spending (Table 6) is reported in Appendix C.
[6] Revenues received by the park (park admissions and donations) are excluded in estimating visitor spending impacts as the impacts resulting from park revenues are covered as part of park operations.

Labor income covers wages and salaries, including payroll benefits. Value added is the preferred measure of the contribution to the local economy as it includes all sources of income to the area -- payroll benefits to workers, profits and rents to businesses, and sales and other indirect business taxes.

Table 8. Economic Impacts of Visitor Spending Attributed to the Park, 2005.

Sector/Spending category	Sales $000's	Jobs	Labor Income $000's	Value Added $000's
Direct Effects				
Motel, hotel cabin or B&B	1,972	52	865	1,396
Camping fees	168	1	24	56
Restaurants & bars	2,082	58	837	945
Admissions & fees	458	10	168	282
Local transportation	161	7	74	84
Grocery stores	700	18	275	369
Gas stations	768	18	278	362
Other retail	426	10	207	290
Wholesale Trade	346	4	129	225
Local Production of goods	2,616	4	284	393
Total Direct Effects	9,696	183	3,141	4,401
Secondary Effects	5,845	65	1,529	2,624
Total Effects	15,541	249	4,670	7,025

a. Total direct sales are less than visitor spending as direct sales exclude the cost of goods sold at retail unless the good is locally made.

The largest direct effects are in motels and restaurants and bars. Spending associated with park visits supports 52 jobs in hotels, 58 jobs in restaurants and 46 jobs in retail trade. The contribution to the local economy in terms of value added is $1.4 million in the hotel sector, $945,00 in the restaurant sector and $1.02 million in retail trade.

Impacts of the NPS Park Payroll

The park itself employed 74 people in FY 2005 with a total payroll including benefits of $3.34 million. Including secondary effects, the local impact of the park payroll in 2005 was 94 jobs, $3.73 million in labor income and $4.11 million total value added. Including both visitor spending and park operations, the total impact of the park on the local economy in 2005 was 343 jobs and $11.1 million value added. Park operations account for 27% of the employment effects and 37% of value added.

Study Limitations and Error

The accuracy of the MGM2 estimates rests on the accuracy of the three inputs: visits, spending averages, and multipliers. Recreation visit estimates rely on counting procedures at the park, which may miss some visitors and count others more than once during their visit. Recreation visits were adjusted for double counting based on the number of days respondents reported visiting the park during their stay in the area.

Spending averages are derived from the 2005 Chickasaw NRA Visitor Survey. Estimates from the survey are subject to sampling errors, measurement errors and seasonal/sampling biases. The overall spending average is subject to sampling errors of 13%.

Spending averages are also sensitive to decisions about outliers and treatment of missing data . To carry out the analysis incomplete spending data had to be completed and decisions had to be made about the handling of missing spending data and zero spending reports. Conservative assumptions were adopted.

First, cases reporting some expenses but leaving other categories blank were completed with zeros. Respondents that did not complete the spending question were assumed to spend no money on the trip. Fifteen percent of the cases had missing spending data. Dropping these cases instead of treating them as zeros would increase the overall spending average from $82 to $96.

The small samples make the spending averages somewhat sensitive to outliers. One case reporting spending of $6,598 (mostly on restaurants and groceries) and another eleven cases reporting more than $1,000 in spending were dropped in computing the spending averages. Another 33 cases involving large parties (more than nine people) and 18 cases staying more than seven nights were also omitted, yielding a final sample of 412 cases for the spending analysis[7]. The overall spending average was $82 omitting outliers compared to $109 with outliers (See Appendix B for details).

Although sample sizes are small for most segments, the spending averages are consistent with those at similar recreation areas. Estimated nightly room and campsite rates are also reasonable for the area. As the sample only covers visitors during a single week, we must assume these visitors are representative of visitors during the rest of the year to extrapolate to annual totals.

There is a length of stay bias in the VSP sampling procedure as longer stay visitors will have a greater chance of being sampled. This bias was corrected for in the analysis by weighting cases inversely to the number of days spent in the area. Along with

[7] Reports of spending for long stays and large parties are deemed unreliable. Spending reported for large parties may not include everyone in the party. Recall of spending for very long stays may also be unreliable and such stays frequently involve multiple stops and activities, so that much of the spending is unrelated to the park visit. Since spending averages are applied to all visits, the procedures are equivalent to substituting the average of visitors in the corresponding visitor segment for these outliers.

handling of outliers, this adjustment partially explains some of the differences in segment mixes, average lengths of stay, and spending averages between the VSP report and this report.

Multipliers are derived from an input-output model of the local economy using IMPLAN. Input-output models rest on a number of assumptions, however, errors due to the multipliers will be small compared to potential errors in visit counts and spending estimates.

Somewhat more problematic than the errors in visits, spending or multipliers is sorting out how much of the spending to attribute to the park. It is difficult to separate the park from other attractions in the area. As the park was not the primary motivation for the trip to the region for all visitors, some of the spending would likely not be lost in the absence of the park. The procedures for attributing spending to the park are somewhat subjective, but reasonable. They result in 71% of all spending being attributed to park visits.

REFERENCES

Manni, M and Hollenhorst, S.J. (2006). Chickasaw National Recreation Area Visitor Study. Summer 2005. Visitor Services Project Report #166. Moscow, ID: National Park Service and University of Idaho, Cooperative Park Studies Unit.

National Park Service Public Use Statistic Office. (2006). Visitation DataBase. http://www2.nature.nps.gov/stats/. Data retrieved on March 30, 2008.

Stynes, D. J., Propst, D.B., Chang, W. and Sun, Y. (2000). Estimating national park visitor spending and economic impacts: The MGM2 model. May, 2000. Final Report to National Park Service. East Lansing, Michigan: Department of Park, Recreation and Tourism Resources, Michigan State University.

Appendix A: Definitions of Economic Terms

Term	Definition
Sales	Sales of firms within the region to park visitors.
Jobs	The number of jobs in the region supported by the visitor spending. Job estimates are not full time equivalents, but include part time positions.
Labor income	Wage and salary income, sole proprietor's income and employee payroll benefits.
Value added	Personal income plus rents and profits and indirect business taxes. As the name implies, it is the net value added to the region's economy. For example, the value added by a hotel includes wages and salaries paid to employees, their payroll benefits, profits of the hotel, and sales and other indirect business taxes. The hotel's non-labor operating costs such as purchases of supplies and services from other firms are not included as value added by the hotel.
Direct effects	Direct effects are the changes in sales, income and jobs in those business or agencies that directly receive the visitor spending.
Secondary effects	These are the changes in the economic activity in the region that result from the re-circulation of the money spent by visitors. Secondary effects include indirect and induced effects.
Indirect effects	Changes in sales, income and jobs in industries that supply goods and services to the businesses that sell directly to the visitors. For example, linen suppliers benefit from visitor spending at lodging establishments.
Induced effects	Changes in economic activity in the region resulting from household spending of income earned through a direct or indirect effect of the visitor spending. For example, motel and linen supply employees live in the region and spend their incomes on housing, groceries, education, clothing and other goods and services.
Total effects	Sum of direct, indirect and induced effects. ▪ Direct effects accrue largely to tourism-related businesses in the area ▪ Indirect effects accrue to a broader set of businesses that serve these tourism firms. ▪ Induced effects are distributed widely across a variety of local businesses.

Appendix B: Handling of Missing Spending Data and Outliers

To compute spending averages and to sum spending across categories, spending categories with missing spending data had to be filled. If spending was reported in any category, the remaining categories were assumed to be zero. This yielded 411 cases with valid spending data, 7 cases reporting zero spending and 57 cases not completing the spending question. Cases with no spending data were on day trips or overnight trips reporting no lodging expenses. It was assumed that these cases spent no money in the local area.

Table B-1. Cases with Valid, Zero and Missing Spending Data by Segment

	Local	Day trip	Motel	Camp	Other OVN	Total
Report some spending	64	105	53	124	65	411
Missing spending data	12	21	0	0	24	57
Zero spending	3	4	0	0	0	7
Total cases	79	130	53	124	89	475
Percent zero	4%	3%	0%	0%	0%	1%
Percent missing	15%	16%	0%	0%	27%	12%

Thirty eight cases were omitted from the spending analysis. Thirty-three of these were large parties of more than nine people. Eighteen cases reported stays of more than seven nights. Half of these were campers. Twelve cases reported expenses of more than $1,000. The overall spending average is $82 omitting outliers compared to $109 with outliers.

Table B-2. Spending Averages by Segment, with and without outliers

	With outliers			Without outliers			
Segment	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Pct Error[a]
Local	72	79	92	63	70	96	35%
Day trip	67	130	89	52	120	65	23%
Motel	460	53	594	307	41	215	21%
Camp	190	124	237	127	102	114	17%
Other OVN	124	89	228	99	79	129	29%
Total	109	475	258	82	412	110	13%

Note: Spending averages exclude park fees.

a. Pct errors computed at a 95% confidence level

Appendix C. Impacts of all Visitor Spending, 2005

Table C1 gives the impacts of $15.93 million in visitor spending on the local economy. All visitor spending in the region except park fees and donations is included in this analysis. Impacts including all visitor spending are roughly 30% higher than those reported in Table 8, which count only spending directly attributable to the park visits.

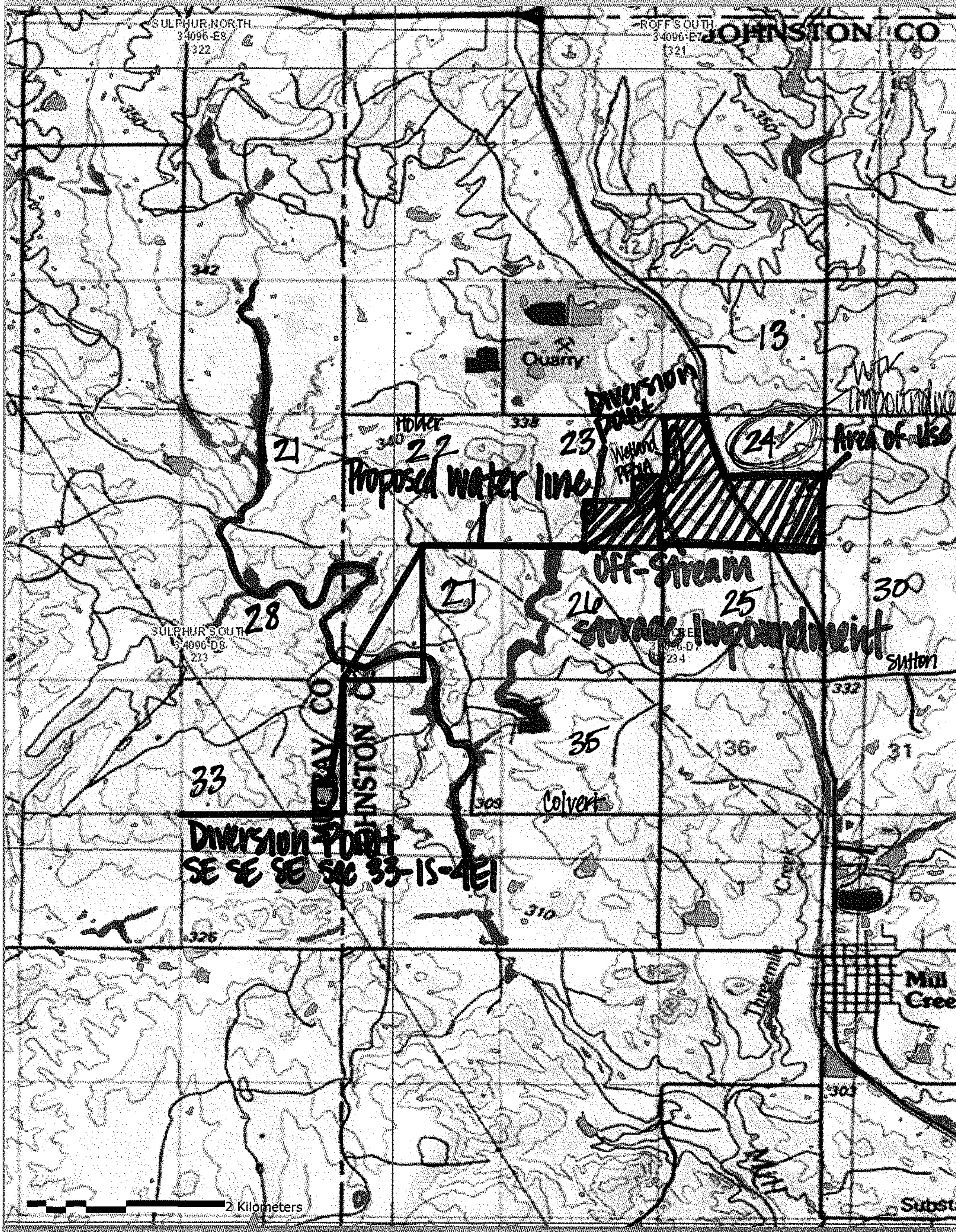
Table C-1. Impacts of all Visitor Spending on the Local Economy, 2005

Sector/Spending category	Sales $000's	Jobs	Labor Income $000's	Value Added $000's
Direct Effects				
Motel, hotel cabin or B&B	2,243	57	983	1,588
Camping fees	192	1	28	65
Restaurants & bars	2,580	70	1,037	1,171
Admissions & fees	532	12	195	327
Local transportation	193	8	88	100
Grocery stores	1,052	26	414	554
Gas stations	1,094	23	396	515
Other retail	565	13	274	384
Wholesale Trade	500	6	186	326
Local Production of goods	3,768	5	406	562
Total Direct Effects	12,719[a]	222	4,009	5,593
Secondary Effects	7,793	86	2,021	3,472
Total Effects	20,512	308	6,030	9,064

a. Total direct sales are less than visitor spending as direct sales exclude the cost of goods sold at retail unless the good is locally made.

ATTACHMENT 7

Section	County	Wetland Type	Wetland Acres
Sec 23	Johnston	Wetland PUBHh Freshwater Pond	0.253429
Sec 23	Johnston	Wetland PUBHh Freshwater Pond	0.093524
Sec 23	Johnston	Wetland PUBHh Freshwater Pond	0.471386
Sec 24	Johnston	Wetland PFO1A Freshwater Wetland	5.32166
Sec 24	Johnston	Wetland PUBHh Freshwater Pond	0.419666
Sec 24	Johnston	Wetland PUBHh Freshwater Pond	0.373522
Sec 24	Johnston	Wetland PUBHh Freshwater Pond	0.474094
Sec 24	Johnston	Wetland PUBHh Freshwater Pond	0.769376
Sec 26	Johnston	Wetland PFO1A Wetland Freshwater Forested/Shrubs Wetland	64.957306
Sec 33	Mayes	Wetland PFO1Hh Freshwater Foreseted/Shrubs Wetland	0.491343
Sec 33	Mayes	Wetland PFO1Hh Freshwater Foreseted/Shrubs Wetland	3.878472
		Total Acres of Wetlands Affected	**77.503778**


SULPHUR NORTH
34096-E8
322
ROFF SOUTH
34096-E7
321
JOHNSTON CO
13
Quarry
Diversion Point
WR Impoundment
Hober
21
22
23
24
Area of Use
Wetland PFO1A
Proposed water line
Off-Stream
Storage Impoundment
28
27
26
25
30
SULPHUR SOUTH
34096-D8
233
Sutton
332
MURRAY CO
JOHNSTON CO
35
36
31
33
Colvert
Diversion Point
SE SE SE Sec 33-1S-4E1
310
326
Mill Creek
Threemile Creek
2 Kilometers
Subst