ARKANSAS DEPARTMENT OF ENERGY AND ENVIRONMENT

OFFICE OF THE
STATE GEOLOGIST

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INFORMATION CIRCULAR 46

POTENTIAL FOR ADDITIONAL NATURAL GAS STORAGE CAPACITY IN THE ARKOMA BASIN IN ARKANSAS

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2023

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DISCLAIMER

This investigation was conducted in response to a recommendation from the Arkansas Energy Resources Planning Task Force to evaluate potential for additional gas storage in Arkansas following an extreme cold weather event in February 2021. Its intended purpose is only to recommend prospective storage reservoirs based solely on **preliminary** geologic analyses. Further investigations of wells, reservoir engineering studies, research on impacts on public safety, etc. are needed to create a successful underground natural gas storage operation. For more information on the rules and regulations related to underground natural gas storage projects, please consult the Arkansas Oil and Gas Commission General Rules, specifically rule D-23: General Rule for the Regulation of Underground Natural Gas Storage Projects: https://www.aogc.state.ar.us/rules/new.aspx

Potential for Additional Gas Storage Capacity in the Arkoma Basin in Arkansas

Jay Hansen, Peng Li, and Ciara Mills

ABSTRACT

In response to a disruption of fuel supplies during a historic winter storm that affected Arkansas and surrounding states in February 2021, Arkansas Governor Asa Hutchinson created the Energy Resources Planning Task Force. The Task Force recommended the Arkansas Department of Energy and Environment (E&E) conduct a preliminary study identifying mature gas fields suitable for future natural gas storage operations. Geologists at the Oil and Gas Commission (OGC) and Office of the State Geologist (OSG) reviewed the history of underground natural gas storage (UNGS) facilities in Arkansas. There are currently two active UNGS units and three inactive units in the Arkoma Basin in Arkansas. As of 2021, the U.S. Energy Information Administration reported that the average gas injection and withdrawal volumes in Arkansas are approximately 4,900 million cubic feet (MMcf) per year and the underground gas storage capacity for Arkansas is 21,972 MMcf.

For this study, a ratio of plugged wells to producing and temporarily abandoned wells was applied to natural gas fields in the Arkoma Basin in Arkansas to identify mature, nearly depleted fields that have potential for UNGS operations. Thirteen fields were chosen for further analysis. Well files, production data, well logs, and information from OGC orders and hearing dockets were used to analyze units with at least 5 billion cubic feet (Bcf) of void space and determine if their structural or stratigraphic settings provided a trapping mechanism for a potential storage operation. Sixty-six wells within the chosen fields had intervals that either produced at least 5 Bcf of gas or were located within the same trap with other high-yield wells. The greatest number of wells (21) and highest available void space in a single well (20 Bcf) both occur in the Massard Field.

BACKGROUND

In February 2021, Arkansas and surrounding states experienced record low temperatures and wintry precipitation during a historic winter storm, resulting in a disruption of fuel supplies and electricity generation. To reduce the strain on the energy supply, utility companies were forced to issue rolling power outages throughout the state which caused thousands of homes and businesses to lose electricity for short periods of time (Entergy, 2021; Hutchinson, 2021). As a result of these events, Arkansas Governor Asa Hutchinson issued Executive Order 21-05 in March 2021 creating the Arkansas Energy Resources Planning Task Force. The purpose of the Task Force was to review lessons learned from the storm and evaluate the vulnerability of the state's critical energy resources in extreme events.

After hearing testimony from stakeholders and public and private sector leaders, the Task Force identified areas of improvement for communication and energy infrastructure and presented recommended actions for ensuring adequate energy resources during extreme events. One of the recommendations for additional consideration was for the Arkansas Department of Energy and Environment's (E&E) Oil and Gas Commission (OGC) and Office of the State Geologist (OSG) to determine whether there were mature natural gas fields suitable for storing additional reserves of natural gas (Keogh et al., 2021). In response, the OGC and OSG commenced to review existing underground natural gas storage (UNGS) facilities in the state and examine nearly depleted natural gas fields in the Arkoma Basin.

The purpose of this report is to present potentially favorable storage settings in these fields based on their geologic structures, reservoir conditions, and storage volumes to encourage investigations into additional UNGS operations in Arkansas.

UNDERGROUND NATURAL GAS STORAGE OVERVIEW

History of U.S. Underground Gas Storage Facilities Development

When William Aaron Hart drilled the first commercial gas well in 1825 to supply lighting for the town of Fredonia, New York, he conveyed his natural gas using bamboo. At that time, limits in transmission line technology confined the gas delivery to relatively short distances from the fields. It wasn't until 1887 that United Natural Gas completed a pipeline over 100 miles from

Pennsylvania to Buffalo, New York. Long-distance, high-pressure transmission lines began operations in 1891 with the successful construction of two parallel 120-mile, 8-inch diameter lines from fields in northern Indiana to Chicago. During this time, it was common for producers to vent or flare gas since they had little incentive to capture gas. In 1909, the United States Geological Survey (USGS) recommended that surplus natural gas be stored in underground reserves (Day, 1909). As a result, gas companies sought ways to store natural gas to ensure that a year-round supply would be available to their customers.

The history of UNGS dates to 1915 when it was first completed in Ontario, Canada and to 1916 when gas was stored in the Zoar Field near Buffalo, New York. In 1919, some gas was stored in Menifee County, Kentucky by the Central Kentucky Natural Gas Company. UNGS grew in popularity shortly after World War II when peak demand for natural gas for heating in winter soared and could not feasibly be met by pipeline delivery alone. Since then, UNGS has played a vital role in effectively balancing a variable market with a nearly constant supply of natural gas.

In the early stage of its development, UNGS solely served as a buffer between transportation and distribution to ensure an adequate supply of natural gas was in place for seasonal demand shifts and unexpected demand surges. Generally, more natural gas was used during the winter because many homes were heated by natural gas. Therefore, natural gas was injected into storage fields during the summer (April – October) and withdrawn in the winter (November – March). Presently, in addition to serving those purposes, UNGS is also used by industry participants for commercial reasons. For instance, natural gas is injected and stored when prices are low and withdrawn and sold when prices are high.

Historically, when natural gas was a regulated commodity, storage was part of the bundled product sold by the pipelines to distribution utilities. This all changed in 1992 with the introduction of Federal Energy Regulatory Commission (FERC) Order 636, which requires pipelines to unbundle (i.e., separate) their sales services from their transportation services. This means that natural gas storage is now available to anyone seeking storage for commercial purposes or operational requirements.

As of the end of 2022, there were 412 underground storage facilities in 31 states in the U.S. with two in Arkansas (Fig. 1). The U.S. has 4.8 trillion cubic feet (Tcf) of working gas capacity and is capable of delivering up to 117 Bcf (billion cubic feet) per day of natural gas supplies (U.S. EIA, 2022). This maximum daily deliverability barely exceeds the U.S. highest historical average end-use natural gas consumption which occurred in January 2022. Approximately 55% of working gas capacity is owned and operated by pipeline companies, 26% by local distribution companies, investor-owned utilities, or municipalities (collectively "LDCs"), and the remaining capacity (18%) is owned by independent storage operators. Correspondingly, 54% of storage deliverability is owned by pipelines, 27% by LDCs, and 27% by independent storage service providers. Pipeline- or LDC-owned storage facilities are primarily low-deliverability fields while independent operators primarily own high-deliverability salt domes (Fang et al., 2016).

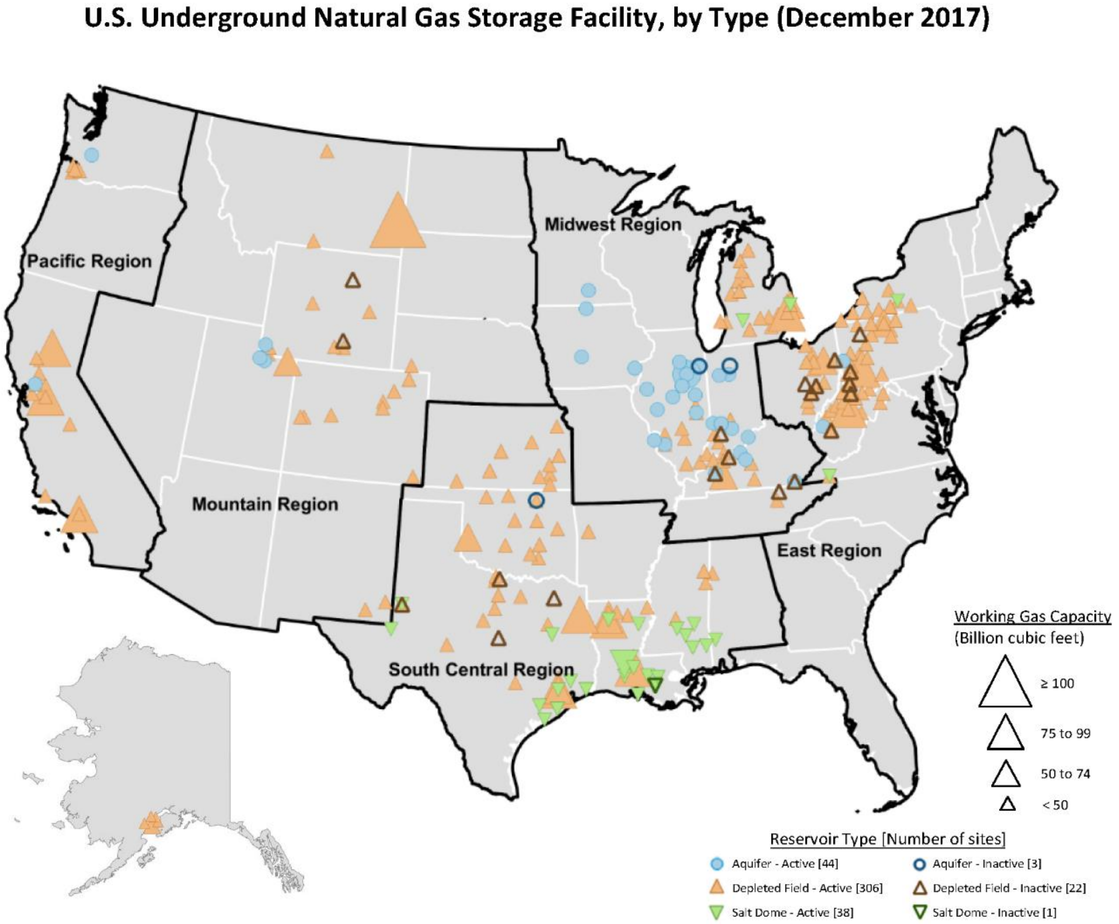

Figure 1. Types and count of U.S. underground natural gas storage facilities. Adapted from the U.S. Energy Information Administration.

Types of Underground Gas Storage Facilities

There are three basic types of UNGS facilities currently in use: depleted oil and gas fields, depleted aquifers, and salt caverns (Fig. 2). These types of facilities have different capabilities and characteristics that are discussed in the following sections.

Depleted Oil and Gas Fields

Depleted oil and gas storage facilities use oil and gas reservoirs whose hydrocarbons have been produced and further production is no longer economically viable. Conversion of a producing field to storage takes advantage of existing wells, gathering systems, and pipeline connections, which significantly reduces the cost of development. Depleted oil and gas fields are the most abundant UNGS sites in the U.S. due to their wide availability and cost effectiveness. Depleted fields are advantageous in that their large working gas capacity is effective for meeting seasonal requirements. Additionally, depleted gas fields have native gas present that can act as base gas.

The first UNGS facility in the U.S. was developed in the depleted Zoar Field near Buffalo, New York. It is still operational and is the longest operating UNGS facility in the world. Early gas storage projects in oil fields were initially conducted to enhance oil recovery but the fields were converted to gas storage once the oil resources were depleted.

As of 2022, the U.S. Energy Information Administration (U.S. EIA) reports that there are over 300 depleted fields across the U.S., which account for 80 percent of total existing facilities and 81 percent of working capacity (U.S. EIA, 2022). Pennsylvania has the highest number of depleted gas field storage facilities, followed by Michigan. The largest facility is the Baker Field in Montana with a working gas capacity of 164 Bcf. There are currently two active gas storage facilities in Arkansas, Lone Elm and White Oak Fields, which are depleted gas fields in Franklin County.

Depleted Aquifers

Since depleted oil and gas fields suitable for gas storage were not available everywhere, other types of gas storage were needed. In the 1930s, the Louisville Gas & Electric Company began experiments with gas storage in water-bearing sedimentary rock formations or “water sands." After more than a decade of efforts, the first aquifer gas storage facility successfully started operation at the Doe Run Field in Meade County, Kentucky in 1946 (Waples, 2012).

An aquifer is suitable for gas storage if the water-bearing rock is overlaid with an impermeable cap rock. Generally, aquifer storage is more expensive to develop and maintain than depleted reservoirs. New infrastructure, including injection and withdrawal wells, observation wells, pipelines, dehydration facilities, and compressor operations, must be installed to operate the facility. Unlike a depleted field, the geologic conditions necessary for successful storage at an aquifer site hasn't been extensively studied beforehand. As a result, seismic testing must be performed to determine its geologic profile. The potential capacity of the reservoir is also unknown and can only be determined as the site is further developed. No native gas is typically present in an aquifer formation. Therefore, base (cushion) gas must be introduced into the reservoir to build and maintain deliverability pressure. While base gas in depleted gas and oil storage reservoirs usually comprises about 50% of total capacity, base gas in aquifer storage may constitute as much as 80-90% by the time the site is fully developed for gas storage.

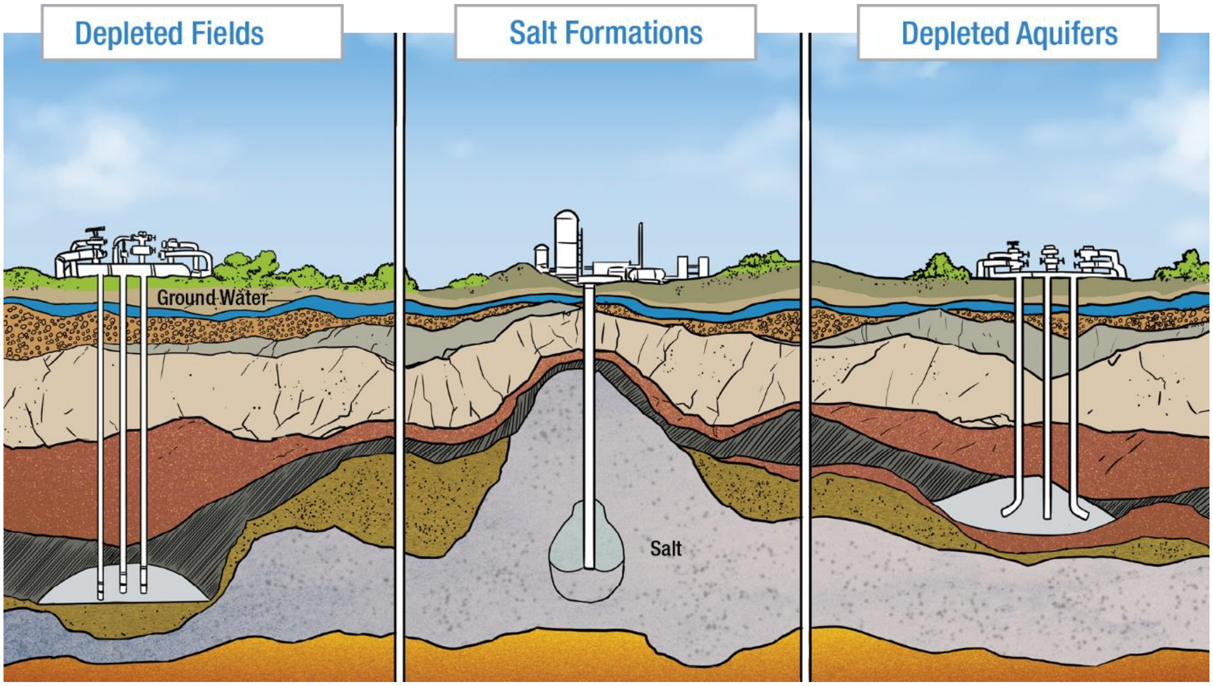

Figure 2. Types of underground gas storage facilities. Adapted from the Energy Infrastructure's website.

Despite the higher cost, aquifer gas storage facilities are a viable storage option in certain areas. As of 2022, there are 46 aquifer gas storage facilities in the U.S., which account for 8% of the total working gas capacity and daily deliverability (U.S. EIA, 2022). Over two-thirds of the U.S. aquifer storage facilities are in Illinois and Indiana.

Salt Caverns

Salt caverns are created by dissolution of salt in deep salt beds and domes by hot water circulation through wells drilled into the deposit. Gas storage in salt caverns is different from depleted fields or aquifers since the storage occurs in an empty void as opposed to pore spaces in rock. Solution mining the salt deposits to form the caverns, disposal costs, geologic characterization studies, and infrastructure development make salt cavern storage the most expensive type of storage available.

Since the gas in salt cavern storage is stored in a void, there is no movement through pore space during injection or withdrawal, resulting in short cycle times and high deliverability. Therefore, salt cavern facilities are best used for peak demand and short-term trading rather than long term seasonal storage.

The first use of a salt cavern for storing natural gas was in 1961 when Southeastern Michigan Gas Company leased an inactive salt solution mine near Marysville, Michigan from Morton Salt Company, and converted it to a gas storage facility (Vance, 1962). The first salt cavern created specifically for the storage of natural gas was constructed by Saskatchewan Power Corporation in Melville, Saskatchewan, Canada in 1963 (Allan, 1965). In the U.S., the first “purpose-built” gas storage salt cavern was completed in the Eminence Salt Dome in Covington County, Mississippi in 1970 by Transcontinental Gas Pipeline Corporation (Allen, 1972).

Since their origin in the 1960s, the use of salt cavern storage facilities has expanded and there are currently 38 salt cavern storage facilities in the U.S., the majority of which are located in Texas and Louisiana (U.S. EIA, 2022).

Desirable Characteristics for Underground Gas Storage Facilities

Factors that affect whether depleted gas reservoirs can be converted to storage reservoirs are both geographic and geologic. The higher the porosity of the rock, the faster the rate of injection and withdrawal. The size of the reservoir, the thickness of the reservoir strata, and the extent to which the strata are covered by cap rock are also important factors. Specifically, important storage reservoir characteristics include the following:

1. **Withdrawal and injection capability as a percentage of working gas.** The higher the percentage, the better the efficiency of storage. The maximum withdrawal and injection capability depends on the porosity and permeability of the reservoir. The porosity of the formation determines the amount of natural gas that it may hold, while its permeability determines the rate at which natural gas flows through the formation, which in turn determines the rate of injection and withdrawal of working gas. Some other determinants include the quality of the surface and downhole facilities, such as compression horsepower and pipe diameter. Horizontal wells have higher withdrawal and injection capability than vertical wells.
2. **Working gas as a percentage of total gas.** Total gas in storage consists of working gas and base (cushion) gas. Only working gas can be withdrawn from storage. Base gas represents permanent storage inventory to maintain adequate reservoir pressure to meet minimum gas deliverability demand. During heavy demand periods, some base gas may be withdrawn temporarily and delivered as working gas, but over the long term, base levels must be maintained to endure operational capability. Depleted gas fields may have natural gas already present (i.e., native gas), thereby reducing or eliminating the need for additional base gas supplies. Aquifer pools and salt domes require the purchase of base gas, although the proportion of base gas for salt dome storage is generally less than for aquifers.
3. **Pressure integrity of the reservoir.** The ability to increase storage reservoir pressure without leaking gas into adjoining formations is a required characteristic so that greater quantities of gas can be stored. Usually, salt caverns can be overpressured without problems. In contrast, overpressurizing an aquifer reservoir or depleted gas field with an underlying water column can result in pushing the gas down to the water zone and permitting escape from the storage pool.
4. **Composition of native gas.** Pipeline-quality base gas is preferable so that working gas injected into the reservoir will not be contaminated. If contamination occurs, then impurities must be removed.
5. **Depth of reservoir.** Generally, shallow reservoir depths are preferable because deeper storage reservoirs require higher drilling costs.

6. **Storage location.** If the reservoirs are not close to existing transmission lines or market areas, the developers may incur greater expenses to establish connections with pipelines.

Gas Storage Regulation

In the U.S., regulation of UNGS facilities is split between federal and state regulatory jurisdictions. Storage associated with interstate commerce is regulated by the Pipeline and Hazardous Materials Safety Administration (PHMSA) and the Federal Energy Regulatory Commission (FERC), while storage associated with intrastate commerce is regulated by the states.

Federal Regulation

In the early years, interstate natural gas transmission was essentially unregulated. In 1938, the federal government first became involved in the regulation of interstate natural gas with the passage of the Natural Gas Act. This act empowered the Federal Power Commission (FPC), a predecessor of FERC, to oversee the regulation of interstate natural gas transmission and rates that transmission companies charged. In 1978, Congress passed the Natural Gas Policy Act (NGPA) which formed and authorized FERC to regulate both intrastate and interstate natural gas production and transmission. The NGPA set price ceilings for wellhead first sales of gas, though these were repealed by the Natural Gas Wellhead Decontrol Act (NGWDA) in 1989. As of January 1, 1993, all NGPA price regulations were eliminated, allowing the market to completely determine the price of natural gas at the wellhead.

Historically, UNGS was included with transmission and distribution as a bundled commodity that was sold by the pipelines to distribution utilities. In 1985, FERC issued Order No. 436 that allowed for the voluntary unbundling of services. The final step toward unbundling was completed by FERC Order No. 636 issued in 1992. This Order states that pipelines must separate their transportation and sales services so that all pipeline customers have a choice in selecting their gas sales, transportation, and storage services from any provider in any quantity. FERC's unbundling rules encouraged construction of additional storage capacity and increased competition for the various parts of the downstream natural gas industry (transmission, storage, and distribution) with a common goal of keeping prices low and reducing volatility.

In response to the serious natural gas leak that occurred at the Aliso Canyon facility in California on October 23, 2015, the U.S. House and Senate passed the "Protecting our

Infrastructure of Pipelines and Enhancing Safety Act of 2016” (PIPES Act) which mandated PHMSA to regulate underground gas storage facilities. This law directed PHMSA to issue regulations for all interstate and intrastate underground natural gas storage and to consider industry standards and economic impacts. PHMSA responded to this mandate on December 19, 2016, by issuing an Interim Final Rule (IFR) that established federal regulations for the downhole components of underground natural gas storage facilities. This IFR incorporated by reference two American Petroleum Institute (API) Recommended Practices (RPs): API RP 1170, "Design and Operation of Solution-mined Salt Caverns used for Natural Gas Storage” (First Edition, July 2015); and API RP 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs" (First Edition, September 2015). The final rule was published in the Federal Register on February 12, 2020 (PHMSA, 2020).

State Regulation

Approximately half of the underground gas storage facilities in the U.S. are intrastate facilities. In Arkansas, the OGC has issued and enforced rules related to underground gas storage facilities in the state. These rules are stated in OGC General Rules D-23 (Regulation of Underground Natural Gas Storage Projects) and are available at the OGC website (https://www.aogc.state.ar.us/rules/rulesregs.aspx).

HISTORY OF UNDERGROUND NATURAL GAS STORAGE IN ARKANSAS

As of 2023, there are two active UNGS units and three inactive units in Arkansas. Both active gas storage units are in Franklin County and currently operated by Black Hills Energy Arkansas, Inc. Although the first permit for an UNGS project in Arkansas was issued in 1956, records of injection and withdrawal of gas from a storage facility commenced in 1967 (Figs. 3 and 4). Prior to the early 1990s, annual injection and withdrawal gas volumes remained consistently low – between several hundred and 2,000 million cubic feet (MMcf). In 1993, gas storage utilization in Arkansas rose rapidly, reaching a record high of 8,481 MMcf of natural gas withdrawn from underground storage. Since then, gas injection and withdrawal volumes have stayed at a relatively high level, averaging approximately 4,900 MMcf per year (Figs. 3 and 4). As of 2021, the U.S. EIA reports that the underground gas storage capacity for Arkansas is 21,972 MMcf, which has remained stable for the past two decades (Fig. 5).

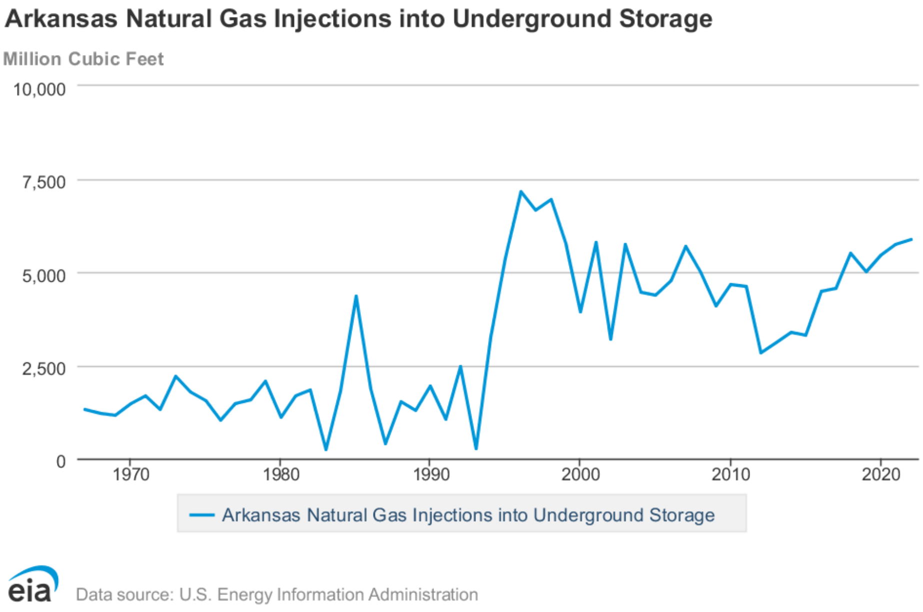

Figure 3. Arkansas natural gas injections into underground storage (1967-2022). Adapted from the U.S. EIA.

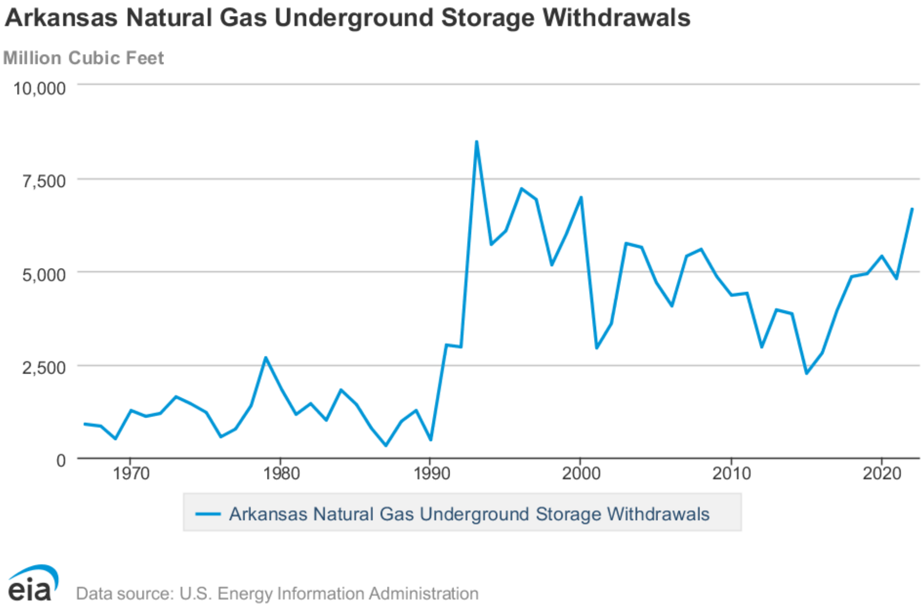

Figure 4. Arkansas natural gas withdrawals from underground storage (1967-2022). Adapted from the U.S. EIA.

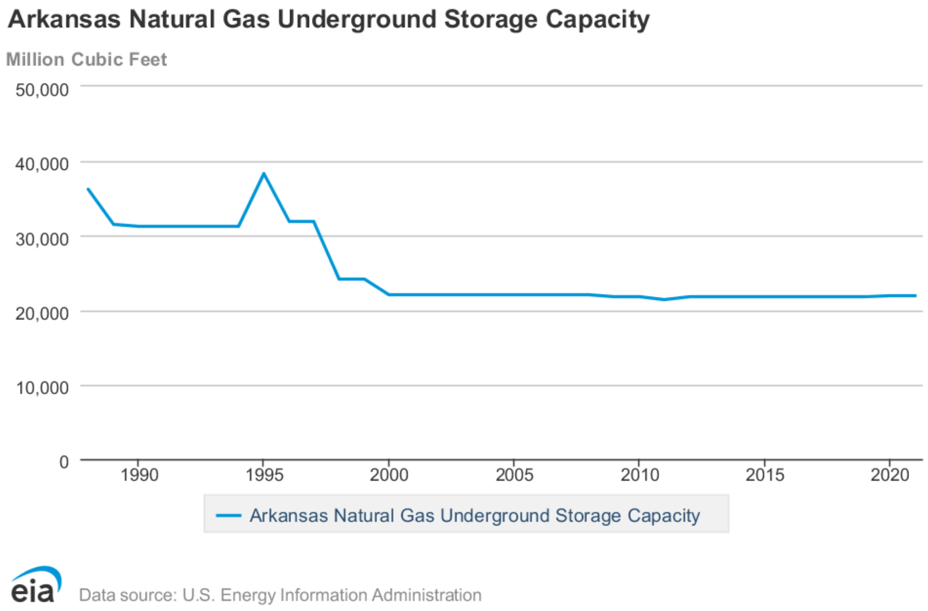

Figure 5. Arkansas natural gas underground storage capacity (1988-2021). Adapted from the U.S. EIA.

Inactive Underground Natural Gas Storage Projects

UNGS projects in Arkansas started in 1956 when Arkansas Western Gas Company converted a portion of the Watalula Field (sections 3, 4, 5, and 6 of T10N R27W) in Franklin County into a depleted gas storage facility known as Gas Storage Project #1 (OGC Order Ref. #12-1956). This area had been produced to a point beyond commercial value and was sufficiently enclosed by sealing faults. After more than 5 years of its last reported utilization, the Watalula gas storage facility was dissolved and terminated under the authority of the OGC on November 16, 2016 (OGC Order Ref. #106A-2016-11). The cumulative volumes of injection and withdrawal gas in the Watalula Field were 154,518 thousand cubic feet (Mcf) and 313,919 Mcf, respectively.

On April 24, 1959, Arkansas Western Gas Company proposed its second gas storage project in Arkansas, which was situated on the Carrollton Dome in Boone County (OGC Order Ref. #22-59). The company intended to operate the underground gas storage in the Gunter Sandstone, a member of the Lower Ordovician Gasconade Formation. This gas storage facility was not used for more than 10 years, so the OGC filed an application for dissolution and rescission of the Carrollton Dome gas storage project, which was approved on October 14, 2016 (OGC Order Ref. #082A-2016-09). There was no reported injection or withdrawal of gas from this facility.

In 1968, Arkansas Western Gas Company converted the Cane Hill sand in the Adams No. 1 well (section 33 of T11N R27W, Franklin County) in the Jethro Field to a gas storage facility. The pressure and production history indicated that the Cane Hill sand in this well was isolated from the same sand in surrounding wells, making it suitable for gas storage without waste or leakage. The cumulative volume of injection and withdrawal gas in this gas storage facility is 535,252 Mcf and 1,877,664 Mcf, respectively. On November 16, 2016, this gas storage unit was dissolved and terminated (OGC Order Ref. #105A-2016-11) after being idle for more than 10 years.

Active Underground Natural Gas Storage Projects

Stockton Gas Storage Unit

The Stockton gas storage unit was named after the Stockton No. 1, a depleted gas well, and is located within section 21 of T10N R28W in the Lone Elm Field in Franklin County. This gas storage unit was originally created by Arkansas Western Gas Company in 1968 (OGC Order Ref. #62-68). The Henson or Casey sand (names used interchangeably), a sandy interval of the middle Atoka Formation, was utilized as the storage reservoir. In 1997, the Stockton gas storage unit was amended to enlarge the reservoir area by 1,378.5 acres (OGC Order Ref. #34-97). The expanded gas storage area is bounded to the north and south by normal faults, creating a horst structure (Fig. 6). A porosity isopach also indicates stratigraphic closure within the structure (Fig. 7). There are currently 7 active gas storage wells located in section 21 of T10N R28W (Table 1). According to the U.S. EIA data released in 2022, the base gas of the Stockton unit is 8,205 MMcf and working gas is 6,216 MMcf. The maximum daily delivery capacity is 70.5 MMcf. In 2021, the OGC reported that 3,045 MMcf of natural gas was injected and 2,617 MMcf was withdrawn in the Stockton gas storage unit, with an ending balance of 10,577 MMcf of gas.

Table 1. Storage wells in the Stockton gas storage unit.

Permit	Field Name	Well Name	Location	Well Status
21634	Lone Elm	Stockton 2-21	21-10N-28W	Active
34662	Lone Elm	Wilson 4-21	21-10N-28W	Active
34946	Lone Elm	Crockett 1-21	21-10N-28W	Active
34954	Lone Elm	Wilson 5-21	21-10N-28W	Active
35161	Lone Elm	Crockett 2-21	21-10N-28W	Active
35183	Lone Elm	Crockett 4-21	21-10N-28W	Active
36080	Lone Elm	Wilson 6-21	21-10N-28W	Active

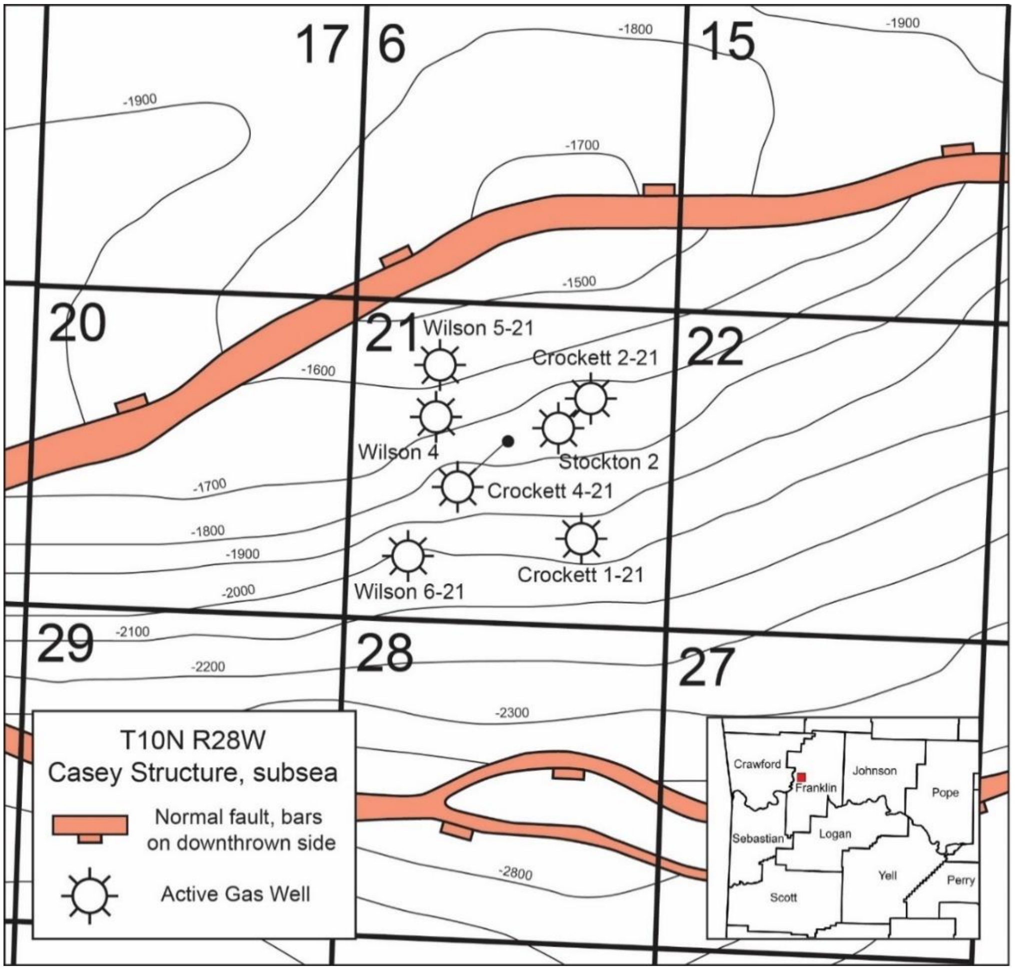

Figure 6. Structural map of the Casey sand in the Stockton gas storage unit. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #34-97.

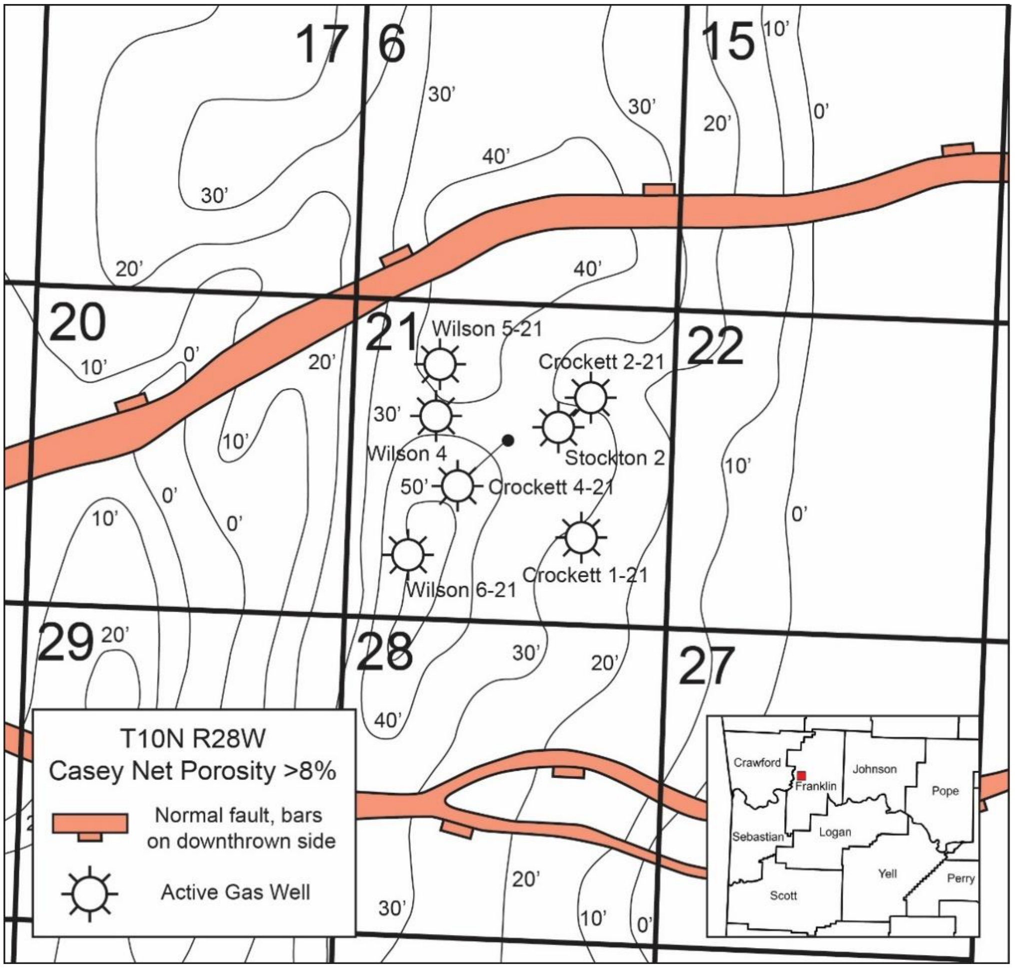

Figure 7. Isopach map of the Casey sand in the Stockton gas storage unit. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #34-97.

Woolsey Gas Storage Unit

The Woolsey gas storage unit (also known as the G.P.A. #1 unit) was named after the Woolsey sand (a producing interval in the middle Atoka Formation) encountered in the Vernon #1 well of the White Oak Field in Franklin County. The Woolsey sand in this well was largely depleted of commercial gas reserves, so it was converted to a gas storage well in 1959 (OGC Order Ref. #36-59). The structure of the Woolsey gas storage unit is similar to the Stockton gas storage unit. Normal faults bound the north and south sides of the unit, creating a horst structure (Fig. 8). The unit extends across all or part of sections 13, 14, 15, 22, 23, and 24 of T10N R27W (OGC Order Ref. #126-2000-10). There are currently 4 active wells in operation (Table 2). According to the U.S. EIA data in 2022, the base gas of the Woolsey unit is 4.873 Bcf and working gas is 2.678

Bcf. Although the Woolsey unit has a smaller total capacity than the Stockton unit, its maximum daily delivery capacity of 0.142 Bcf is two times greater. In 2021, the OGC reported that 2.743 Bcf of natural gas was injected and 2.205 Bcf was withdrawn in the Woolsey gas storage unit, with an ending balance of 6.887 Bcf of gas.

Table 2. Storage wells in the Woolsey gas storage unit.

Permit	Field Name	Well Name	Location	Well Status
18525	White Oak	Vernon 3-14	14-10N-27W	Active
19469	White Oak	Woolsey 2-13	13-10N-27W	Active
34939	White Oak	Woolsey 7-13	13-10N-27W	Active
35164	White Oak	Lakeview 1-13	13-10N-27W	Active

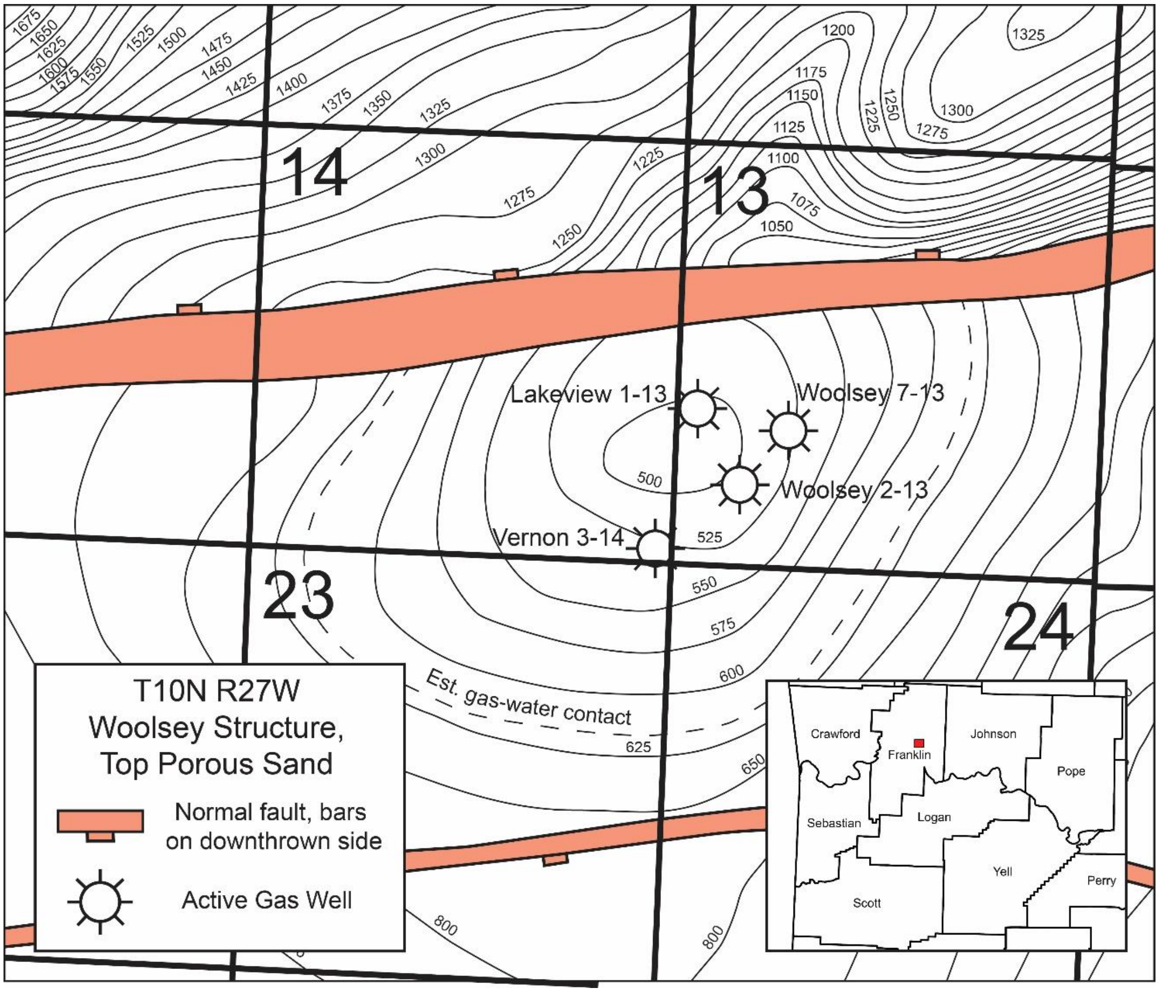

Figure 8. Structural map of the Woolsey sand in the Woolsey gas storage unit. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #126-2000-10.

GEOLOGIC SETTING

The Arkoma Basin is a peripheral foreland basin extending from southeastern Oklahoma to west-central Arkansas. In Arkansas, it lies immediately north of the Ouachita orogenic belt and south of the Boston Mountains Plateau (Fig. 9). The basin has been a prolific source of dry gas for over 100 years and operations continue today. Most of the conventional gas production in the Arkoma Basin has been from lenticular sandstone units within the Pennsylvanian Atoka Formation (Branan, 1968).

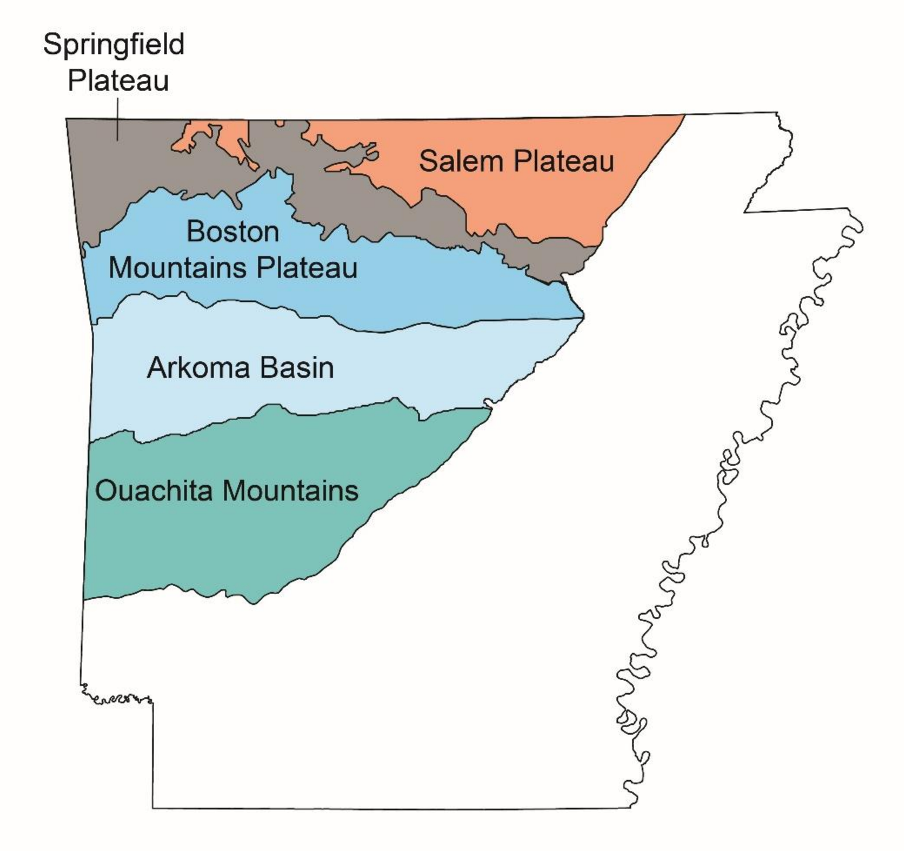

Figure 9. Geologic provinces in north and west Arkansas. Modified from Hutto and Johnson, 2015.

Arkansas was part of a passive continental margin environment on the southern shelf of North America from the Cambrian through the Mississippian. Most rocks deposited during this time included marine carbonates and clastics (Houseknecht, 1986). Starting in the late Mississippian and continuing through the Pennsylvanian, thick sequences of shale and sandstone of the Hale, Bloyd, and Atoka Formations were deposited in shallow marine environments and represented the transition from a passive margin to a foreland basin environment during the Ouachita orogeny (Fig. 10).

During middle Atokan time, continued loading from the Ouachita orogenic front caused flexural bending in the Arkoma Basin and led to development of east-west trending syndepositional down-to-the-south normal faulting in the Atoka Formation (Sutherland, 1988). Significant increases in thickness in the Atoka Formation in the hanging walls of these normal faults indicate faulting was contemporaneous with deposition (Fig. 11; Buchanan and Johnson, 1968). Faulting started in the southern part of the basin and migrated northward (Houseknecht, 1986). Desmoinesian rocks deposited above the Atoka Formation do not show obvious evidence for syndepositional fault movement, although recent work indicates faulting may have occurred in response to flexure from the orogenic load (Hudson, 2000). Continued compression from the orogenic front to the south also led to formation of east-west trending synclines and anticlines within the Arkoma Basin in addition to normal faults (Haley et al., 1993; Cannon and Chandler, 2016). Although most of the faults within the Arkoma Basin are downthrown to the south, thrust faults are present in the southern part of the basin closer to the orogenic front (Branan, 1968; Arbenz, 1989; Haley et al., 1993). For this study, special focus is given to the sealing nature of the normal faults as a trapping mechanism for potential storage reservoirs.

METHODOLOGY

This study focuses on identifying nearly depleted natural gas fields in the Arkansas Arkoma Basin that have desirable qualities for underground natural gas storage. Fields were chosen based on a calculated ratio of plugged and abandoned (PA) wells to producing (PR) and temporarily abandoned (TA) wells (PA/[PR+TA]) as of 2021-2022 (Table 3). Fields with ratios greater than 1 were considered nearly depleted and therefore warranted further examination. All wells with zones that produced at least 5 Bcf of gas were analyzed regardless of well status. For this study, volume produced is interpreted as potential available void space for gas storage. Spreadsheets were created for each field that listed wells by their producing zone, production numbers, and status. Thirteen fields were identified as potential gas storage fields for this study (Table 3, Plate 1).

Structural and isopach maps from OGC hearings were extracted from documents in the OGC's electronic document imaging cabinets. This information was used to examine zones with high void space for favorable trapping mechanisms such as anticlines and sealing faults. Wells that produced less than 5 Bcf were only included if they shared the same interval and structure as a high-producing well and therefore added to the cumulative available void space.

It is important to note that multiple active fields in the Arkoma Basin (PA/[PR+TA] ratio less than 1) have high void space from producing horizons but were not examined in this study since the fields are not considered sufficiently depleted.

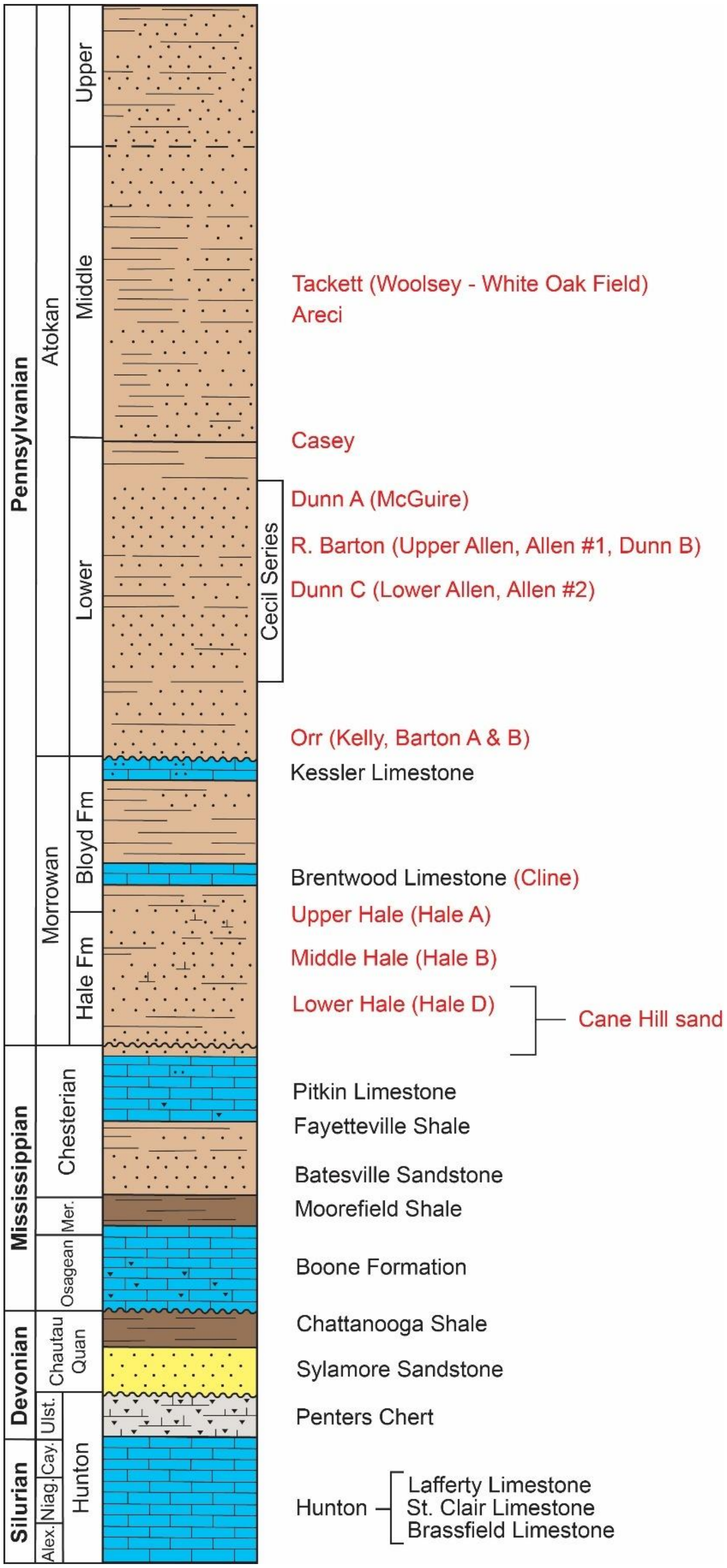

Figure 10. Middle Paleozoic column of the Arkoma Basin in Arkansas with subsurface nomenclature (in red) used in the gas industry and correlative surface names where applicable. Modified from the Fort Smith Geological Society (1988).

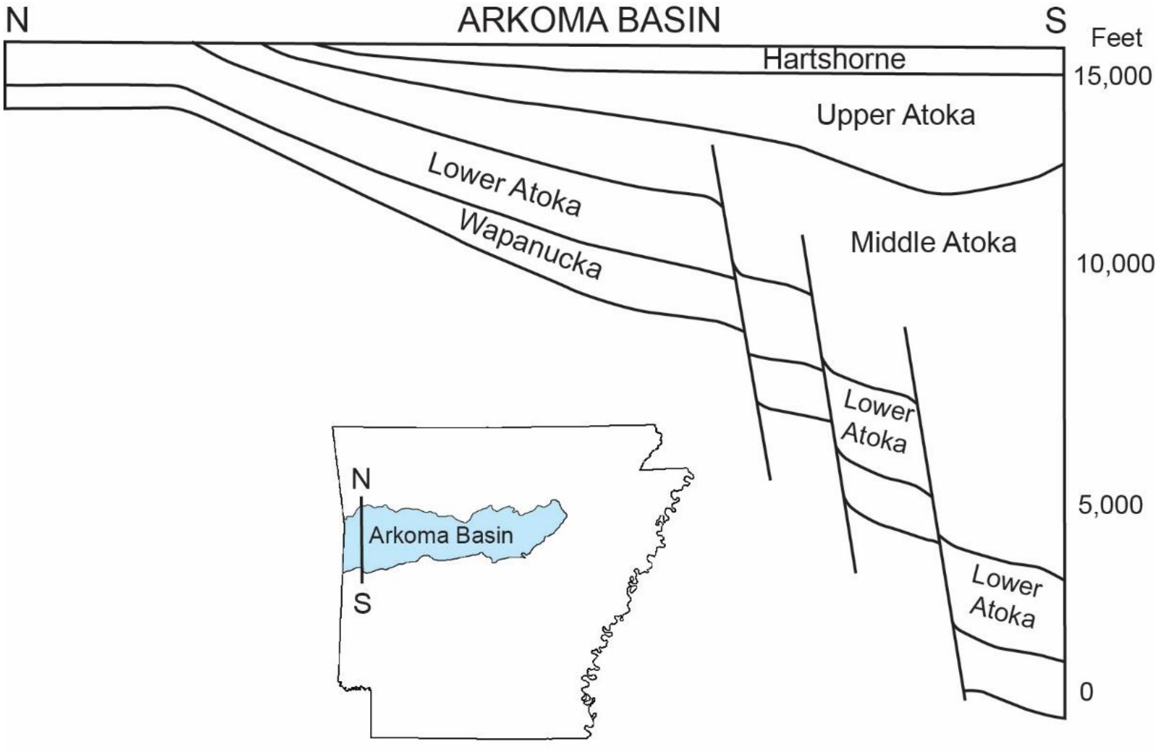

Figure 11. North-south section across the Arkoma Basin in western Arkansas depicting syndepositional normal faulting and subsequent thickening of the Atoka Formation. Modified from Sutherland, 1988.

Table 3. Calculated ratios to determine nearly depleted fields. Fields in bold were selected for this study. Data from 2021-2022.

Field	PA wells	TA wells	PR wells	PA/(PR+TA) Ratio
Aetna	116	7	175	0.64
Alma	45	1	14	3
Altus	57	1	38	1.46
Batson	51	0	22	2.32
Bonanza	27	1	34	0.77
Caulksville	21	1	22	0.91
Cecil	134	14	254	0.5
Clarksville	47	1	31	1.47
Coal Hill	47	1	15	2.94
Delaware	6	0	20	0.3
Dover	96	3	28	3.10
Dyer	22	0	35	0.63
Ewing	49	6	96	0.48
Furgerson	22	1	15	1.38
Hollis Lake	31	1	103	0.30
Jethro	32	0	29	1.10
Kibler-Williams	40	2	95	0.41
Knoxville	56	3	48	1.10
Ludwig	32	0	17	1.88
Massard	106	5	85	1.18
Moreland	106	5	12	6.24
New Hope	23	0	7	3.29
Oak Grove	23	0	19	1.21
Ozark	32	4	10	2.29
Ozone	14	0	10	1.4
Paris	24	2	21	1.04
Peter Pender	36	1	75	0.47
Possumtrot	15	0	3	5
Prairie View	5	0	20	0.25
Rock Creek	52	2	13	3.47
Ross	92	2	28	3.07
Scranton	36	1	33	1.06
Silex	22	1	10	2
Spadra	91	1	51	1.75
Union City	67	4	31	1.91
Ursula	15	0	22	0.68
Vesta	20	1	31	0.63
Watalula	3	0	4	0.75

RESULTS AND DISCUSSION

Batson Field

The Batson Field is located on the southern edge of the Boston Mountains Plateau just north of the Arkoma Basin. The primary areas of interest encompass sections 11 and 12 of T11N R25W in Johnson County. Two wells with cumulative production exceeding 5 Bcf are located on an anticlinal trap that is truncated by down-to-the-north normal faulting (Fig. 12). The Baskin #1-11 well produced 6.1 Bcf and 5 Bcf of gas from the Hale D and Hale A/Hale B (non-commingled) zones, respectively (Table 4). The Federal Estate 5262 #1 well has two Hale zones, middle Hale and Hale D. Shortly after the Hale D zone was completed in 1988, it was discovered that those two zones were connected. Therefore, they were commingled in 1989. The middle Hale produced 3.7 Bcf of gas and Hale D yielded 42 Mmcf of gas before they were commingled. The middle Hale/Hale D commingled zone has contributed an additional 6.3 Bcf of gas. Even though commingled zones are not generally included as potential gas storage targets in this report, it is worth mentioning this commingled zone since the middle Hale itself has produced a considerable amount of gas and the two Hale zones together contain at least 10 Bcf of voidage.

Table 4. Wells with high-volume production in the Batson Field.

Permit	API	Well Name	Location	Producing Zones	Production (Bcf)	Status
23063	03-071-10090-0000	Baskin #1-11	11-11N-25W	Hale D	6.1	PA
23063	03-071-10090-0000	Baskin #1-11	11-11N-25W	Hale A/Hale B	5	PA
22873	03-071-10071-0000	Federal Estate 5262 #1	12-11N-25W	middle Hale	3.7	PR
22873	03-071-10071-0000	Federal Estate 5262 #1	12-11N-25W	middle Hale/Hale D	6.3	PR

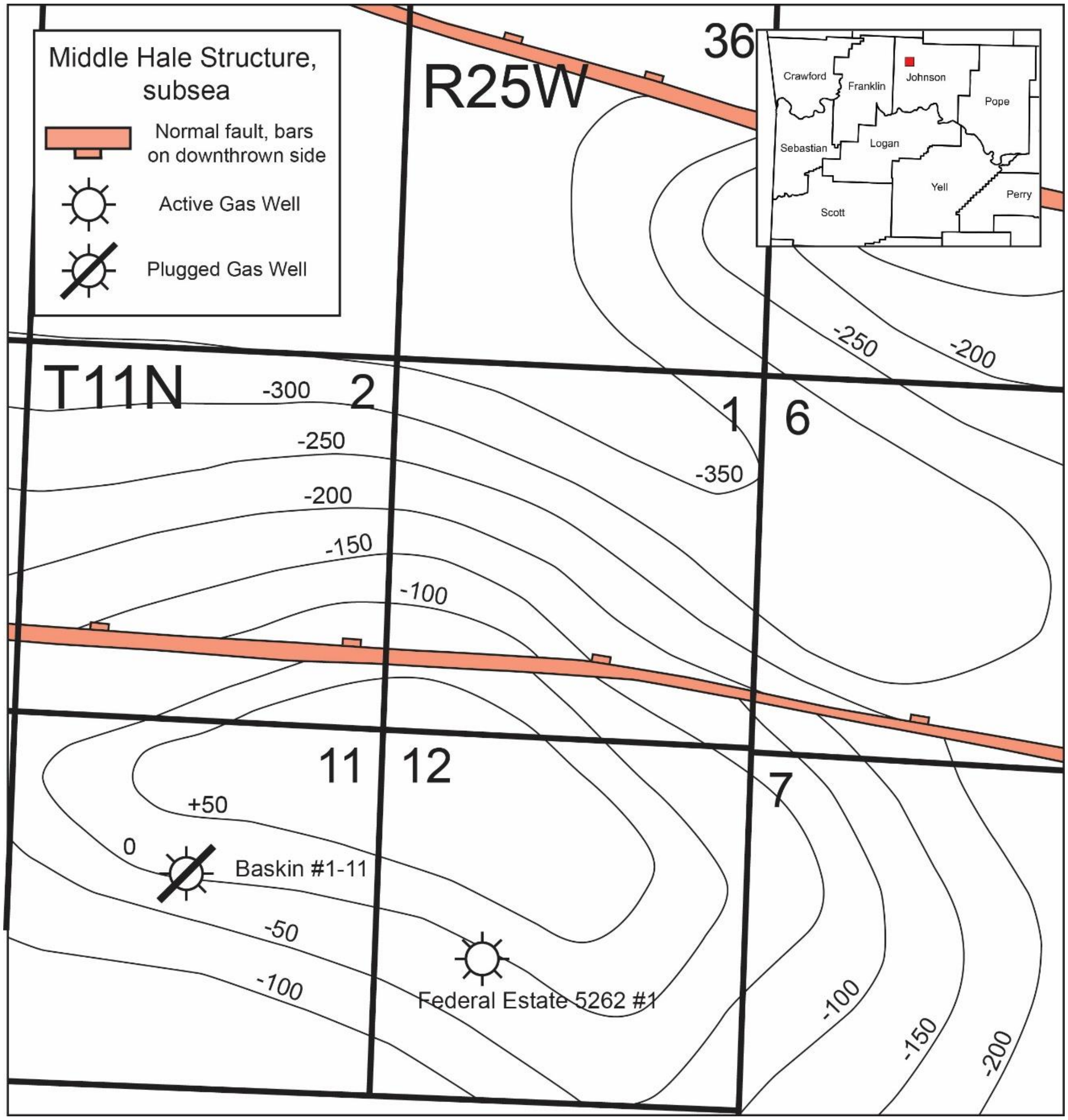

Figure 12. Structural map of the middle Hale sand in the Batson Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #177-83.

Clarksville Field

The primary areas of interest in the Clarksville Field are sections 12, 14, 15, and 16 of T10N R24W in the vicinity of the Ludwig Anticline. Wells are generally located on structural highs truncated by down-to-the-north normal faults (Fig. 13). In section 14, the Qualls #1, W.C. Hudson #2, and Mary E. Patterson #1 have produced in total over 28 Bcf of gas from the Pennsylvanian Atoka Formation (Table 5). However, the Atoka Formation includes multiple gas-producing sandstone units, and the "Atoka" producing zone depths listed for each well either cover a wide range or are not listed, so it is unknown which sand units contain the void space in the section.

In sections 12, 15, and 16, there is more than 26 Bcf of void space in the Morrowan Hale sand, with the possibility for more since all wells with significant yield in this area are still producing. The producing Hale zone in these wells occurs at similar depths, and well logs indicate that the Hilton #1, Blackburn #3-T, and Bean #1-T wells are producing from the lower Hale sand.

Table 5. Wells with high-volume production in the Clarksville Field.

Permit	**API**	**Well Name**	**Location**	**Producing Zone**	**Production (Bcf)**	**Status**
5285	03-071-05285-0000	Qualls #1	14-10N-24W	Atoka	11.9	PR
7147	03-071-07147-0000	W. C. Hudson #2	14-10N-24W	Atoka	9.6	PA
6147	03-071-06147-0000	Mary E. Patterson #1	14-10N-24W	Atoka	7	PA
21191	03-071-10004-0000	Hilton #1	12-10N-24W	Hale	9	PR
34727	03-071-10622-0000	Blackburn #3-T	16-10N-24W	Hale	6.3	PR
26456	03-071-10222-0000	Tice #1-T	15-10N-24W	Hale	5.7	PR
21348	03-071-10012-0000	Bean #1-T	12-10N-24W	Hale	5.3	PR

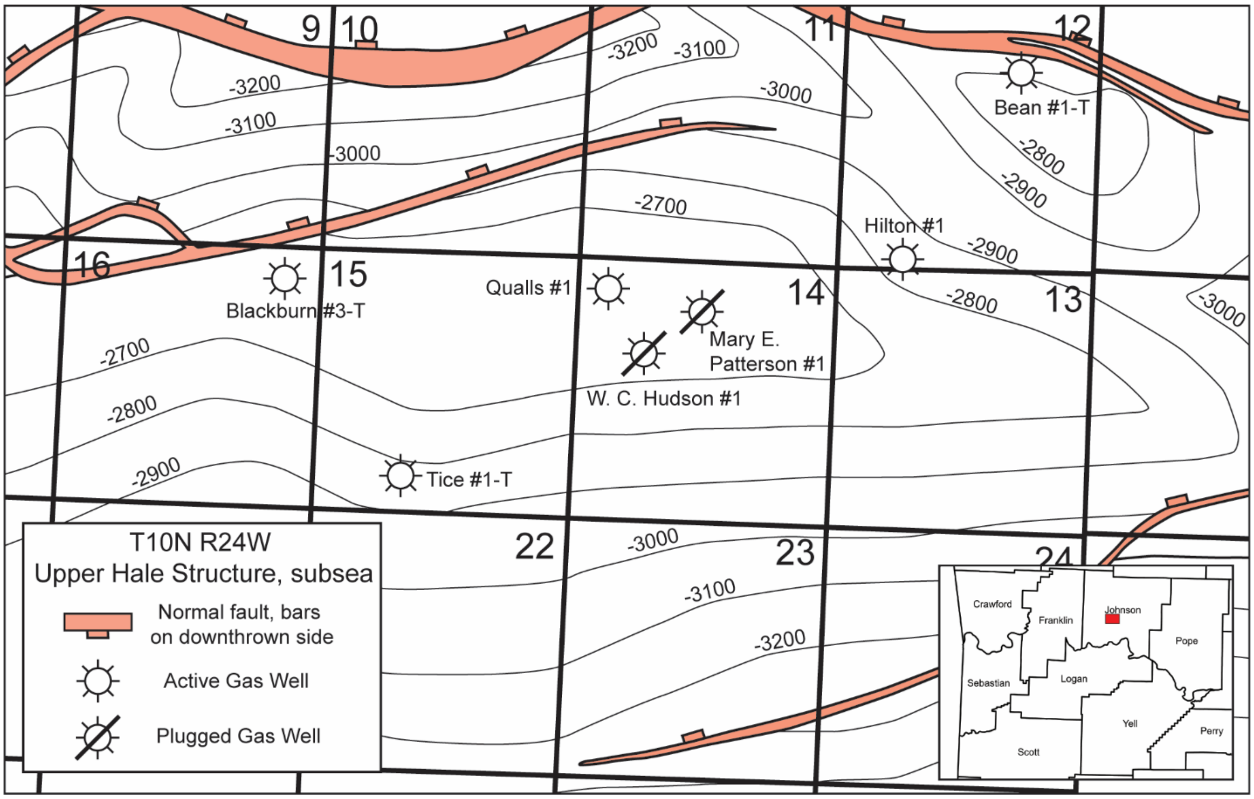

Figure 13. Structural map of the upper Hale sand in the Clarksville Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #96-13.

Dover Field

The Dover Field resides within and north of the northwest-southeast trending Dover Anticline mapped by Croneis (1930). Specific reservoirs and respective wells for consideration include the Morrowan Hale Formation in the Graham #1 well, which has produced 13 Bcf (Table 6). It is currently producing approximately 33 Mcf per day from this formation. The trapping mechanism is on the southern flank of a small anticline bound further south by a down-to-the-south normal fault. A structural map reveals structural closure to the southeast (Fig. 14).

Additional storage potential exists in the lower Pennsylvanian Barton A sand in sections 33 and 34 of T10N R20W. Currently producing at a rate of 38 Mcf per day, the Williams #1 well in section 33 has a cumulative production of 9 Bcf, and the plugged Arthur #1 well in section 34 produced 7.7 Bcf, bringing potential storage space to over 16.7 Bcf in this area (Table 6). The two sections reside on structural highs bounded by faults to the northwest, northeast, and southwest (Fig. 15).

Table 6. Wells with high-volume production in the Dover Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
17119	03-115-00076-0000	Graham #1	19-9N-19W	Hale	13	PR
22273	03-115-10010-0000	Williams #1	34-10N-20W	Barton A	9	PR
22384	03-115-10012-0000	Arthur #1	33-10N-20W	Barton A	7.7	PA

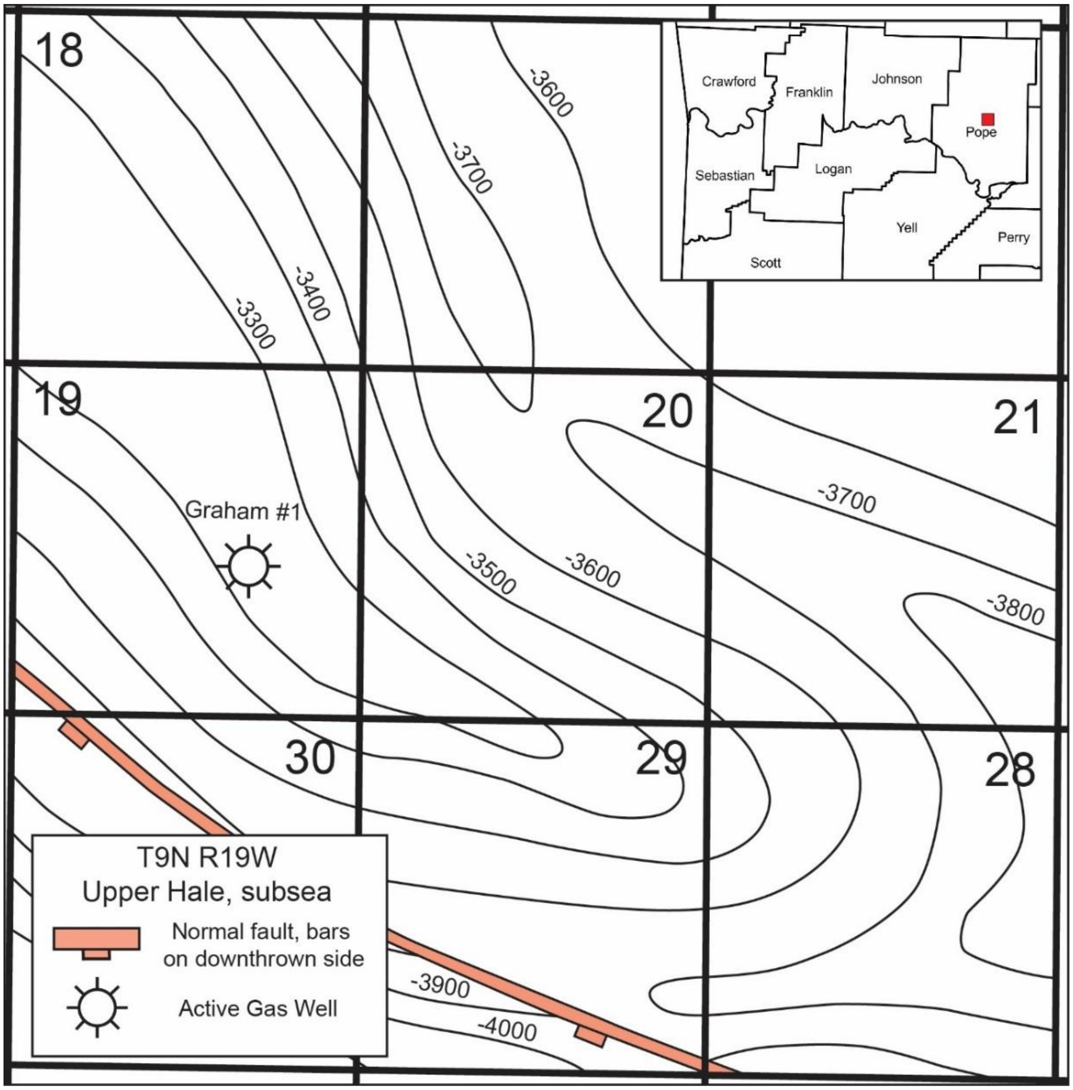

Figure 14. Structural map of the upper Hale sand in the Dover Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #158-81.

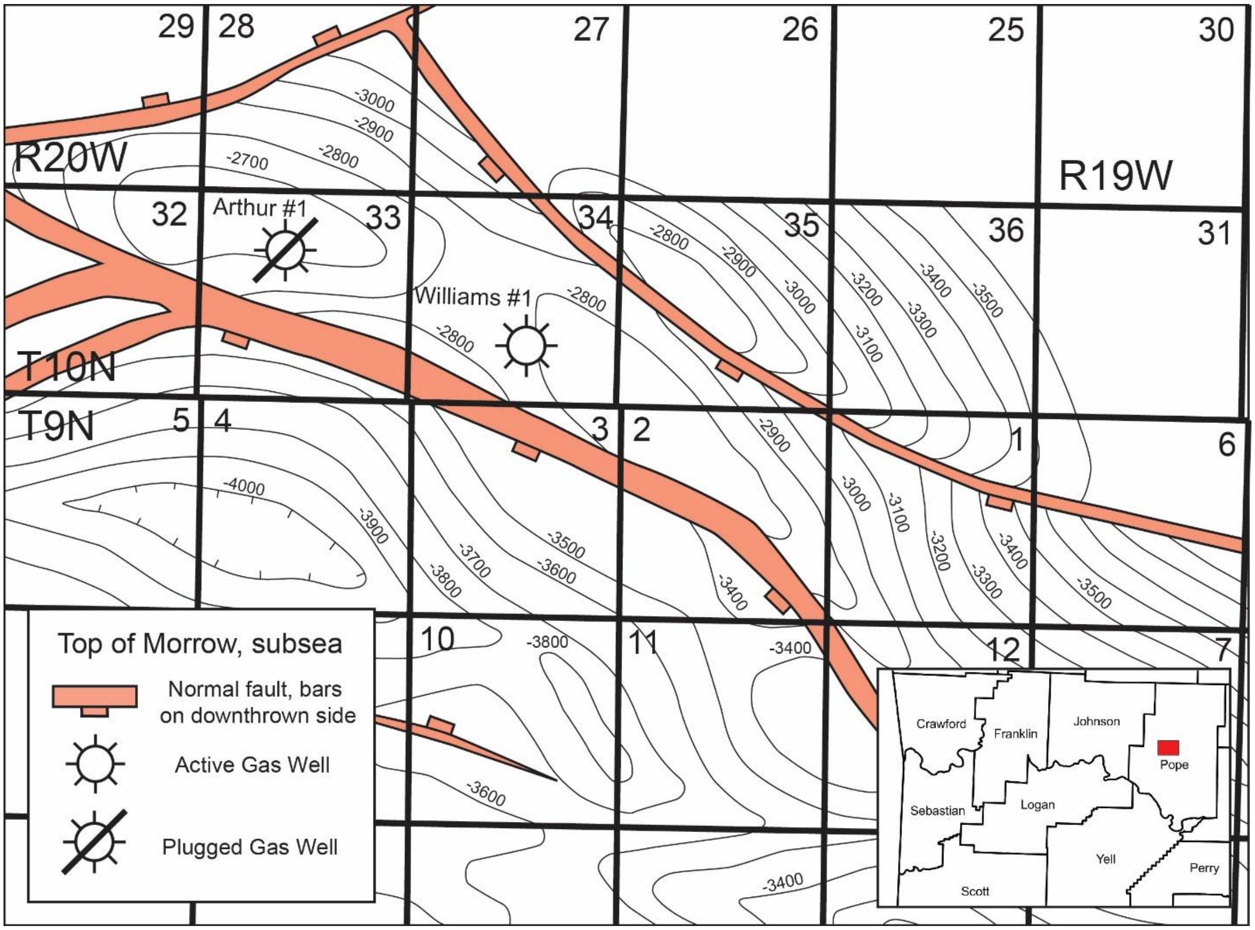

Figure 15. Structural map of the Morrowan in the Dover Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #114-88.

Furgerson Field

The intervals of interest in the Furgerson Field include the Barton A sand (basal Atokan/top Morrowan) and upper Hale sand (Morrowan) in sections 32, 33, and 34 of T9N R20W (Table 7). All wells with significant production are located on the northeast side of a southwest-dipping ramp that is truncated by a northwest-southeast trending normal fault to the north (Fig. 16). The fault likely provides a seal for both reservoirs since wells located to the northeast are either dry holes or produced out of different intervals. The upper Hale has at least 9 Bcf of voidage between the Forehand #1-T and Beard A #2 wells in sections 32 and 33. The Barton A interval has at least 10.4 Bcf of voidage between the Forehand #3-C and Singleton #2-34-C wells in sections 33 and 34.

Table 7. Wells with high-volume production in the Furgerson Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
29322	03-115-10251-0000	Forehand #3-C	33-9N-20W	Barton A	7.9	PR
28757	03-115-10209-0000	Singleton #2-34-C	34-9N-20W	Barton A	2.5	PR
27215	03-115-10136-0000	Forehand #1-T	33-9N-20W	Upper Hale	6.8	PR
36012	03-115-10588-0000	Beard A #2	32-9N-20W	Upper Hale	2.2	PR

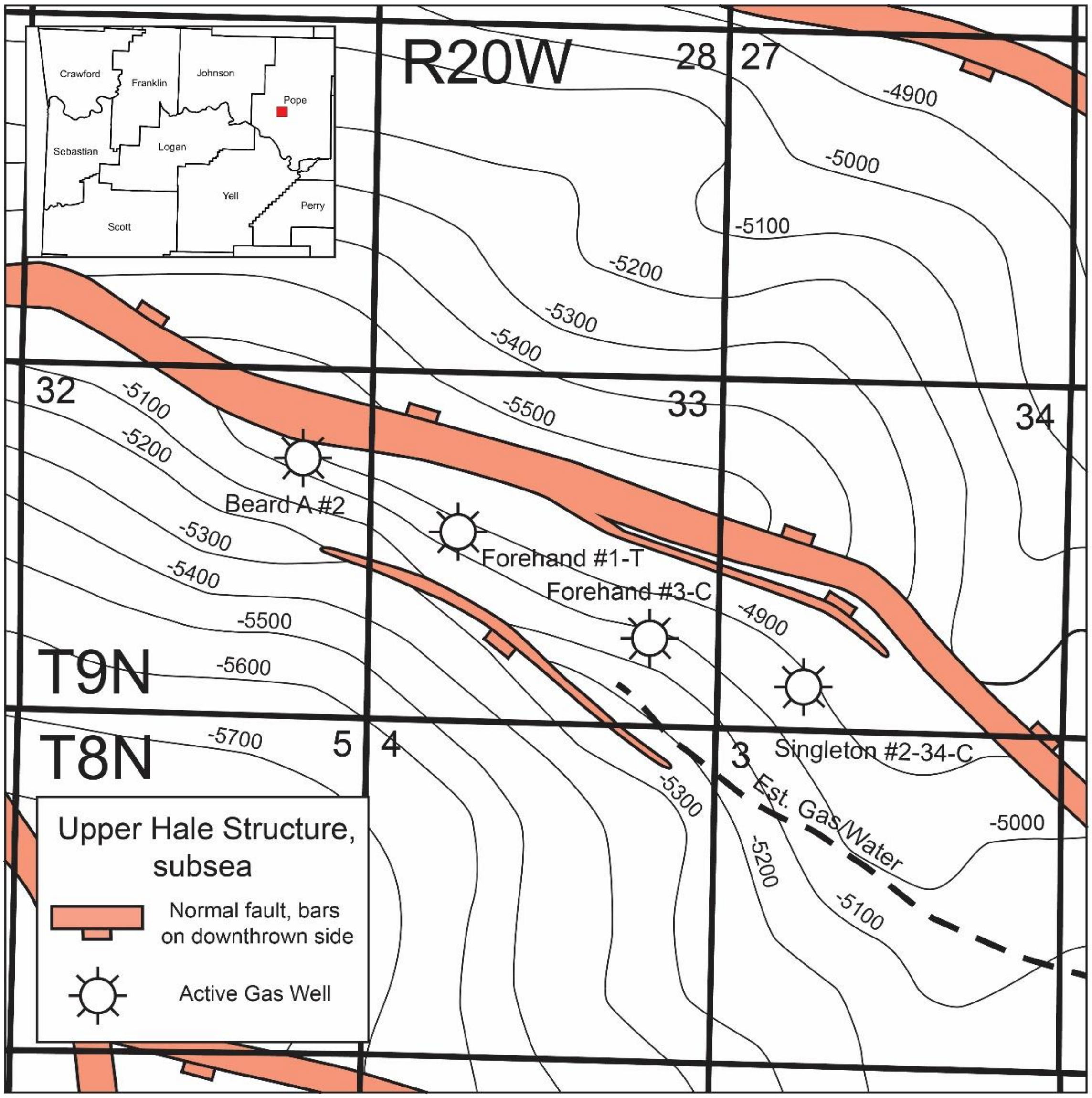

Figure 16. Structural map of the upper Hale sand in the Furgerson Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #A54-2002-04.

Jethro Field

The Jethro Field resides on the boundary between the Arkoma Basin and Boston Mountains Plateau. As previously mentioned, the Adams #1 in section 33 of T11N R27W was a gas storage well from 1968 to 2016. The last use of this well as a gas storage facility was in April 2001. Since then, the Adams #1 well has produced approximately 1.4 Bcf of native gas as of July 2023 from the Cane Hill (Table 8). There are no plugged wells with cumulative production exceeding 5 Bcf in the field. Among the producing wells, the Casey #1-23 in section 23 of T11N R28W has produced 5.3 Bcf of gas from the Hale sand (Table 8). This well sits on top of an anticline bounded by faults (Fig. 17).

Table 8. Wells with high-volume production in the Jethro Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
12925*	03-047-00123-0000	Adams #1	33-11N-27W	Cane Hill	1.4	PR
23841	03-047-10064-0000	Casey #1-23	23-11N-28W	Hale	5.3	PR

*former gas storage well

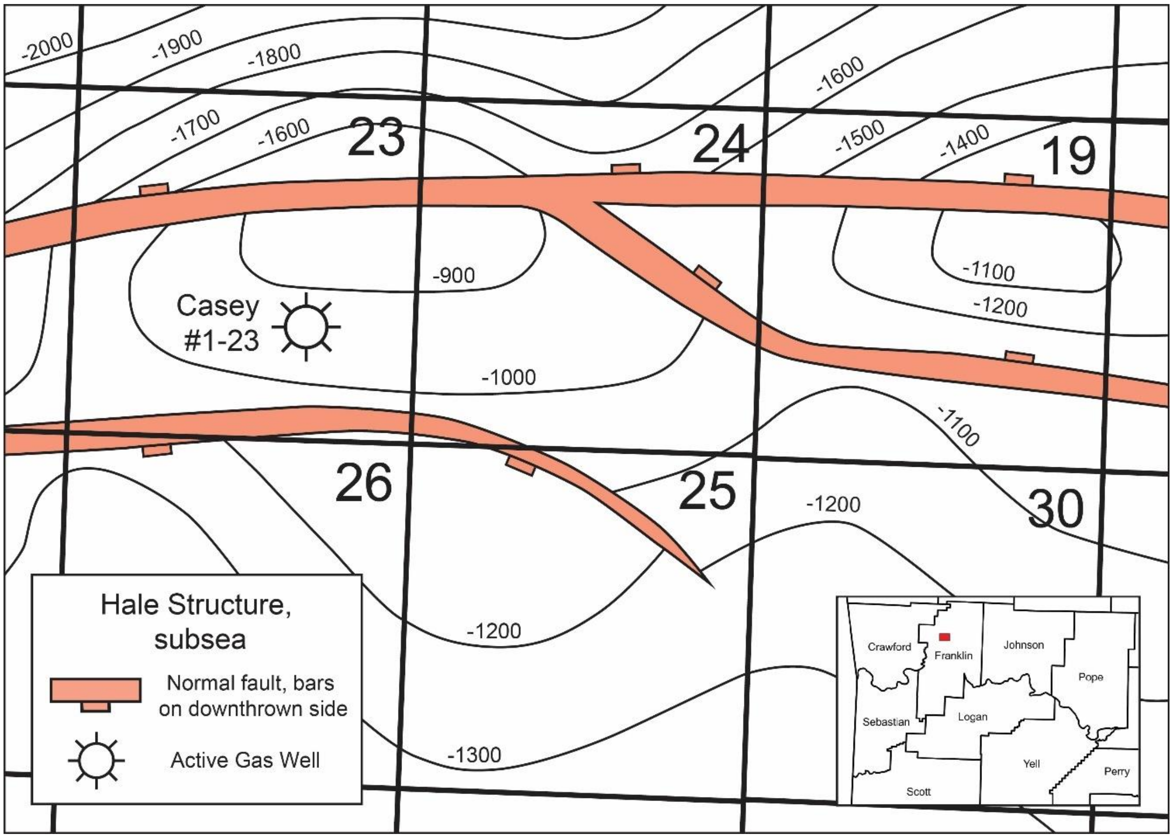

Figure 17. Structural map of the Hale sand in the Jethro Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #81-88.

Ludwig Field

The Ludwig Field is bounded to the south by an east-west trending down-to-the-south normal fault that separates it from the Spadra Field, and to the north by a down-to-the-north normal fault (OGC Hearing Dockets #60-93 and #193-86). There are no plugged and abandoned wells with cumulative production exceeding 5 Bcf in the field. However, the James M. Taylor #1 (section 24 of T10N R23W) and Taylor #1-14 (section 14 of T10N R23W) wells were examined since they are contiguous and produced a combined 5 Bcf of gas from the Dunn A sand (Table 9). A structural map indicates that they are located on the flank of a syncline and an isopach map shows that the Dunn A sand may form in channel sand deposits, therefore providing stratigraphic traps (Figs. 18 and 19).

The Nelson Schwartz #1 has produced 12.1 Bcf of gas from the Hale (Table 9), recording the highest production in the field and continues to produce 4,000+ Mcf per month. This well is located on an anticline south of a normal fault (Fig. 20). Dry holes north of the fault support its sealing nature.

Table 9. Wells with high-volume production in the Ludwig Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
21586	03-071-10021-0000	James M. Taylor #1	24-10N-23W	Dunn A	3.5	PA
35844	03-071-10715-0000	Taylor #1-14	14-10N-23W	Dunn A	1.5	PA
21167	03-071-10002-0000	Nelson Schwartz #1	7-10N-23W	Hale	12.1	PR

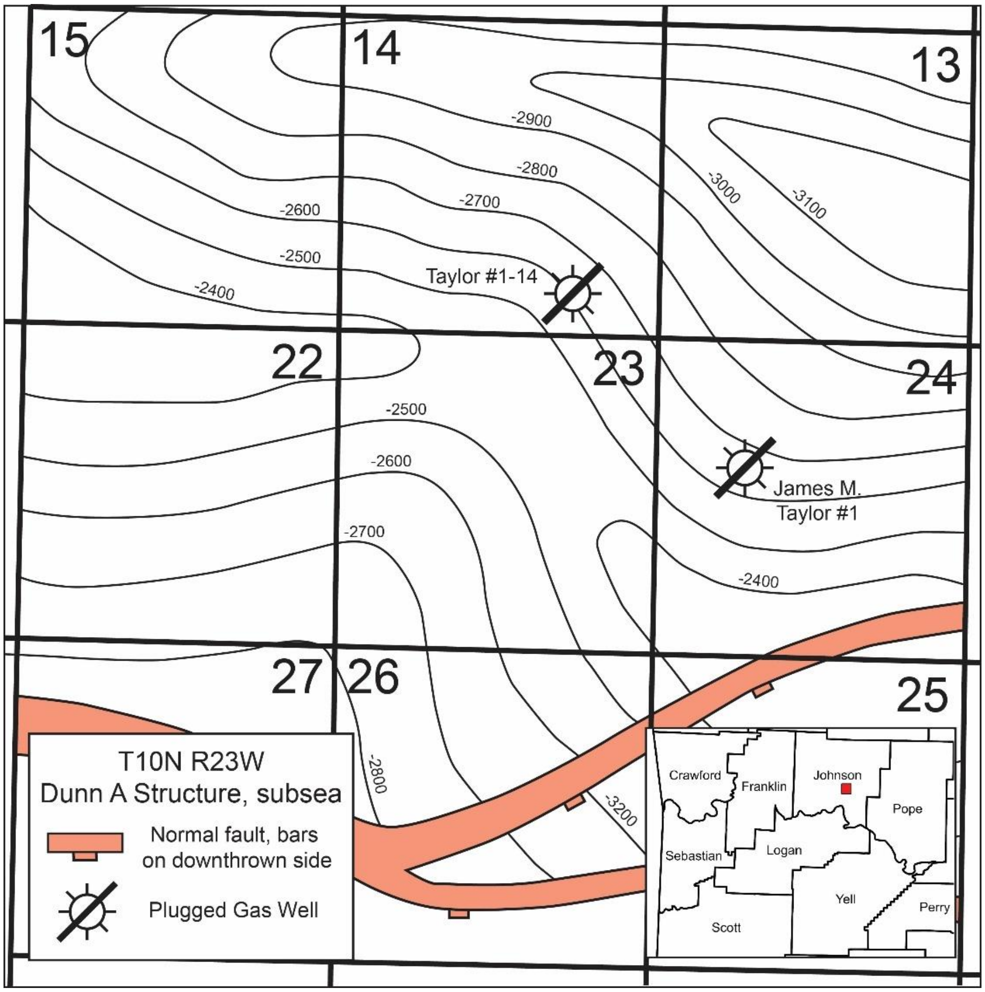

Figure 18. Structural map of the Dunn A in the Ludwig Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #193-86.

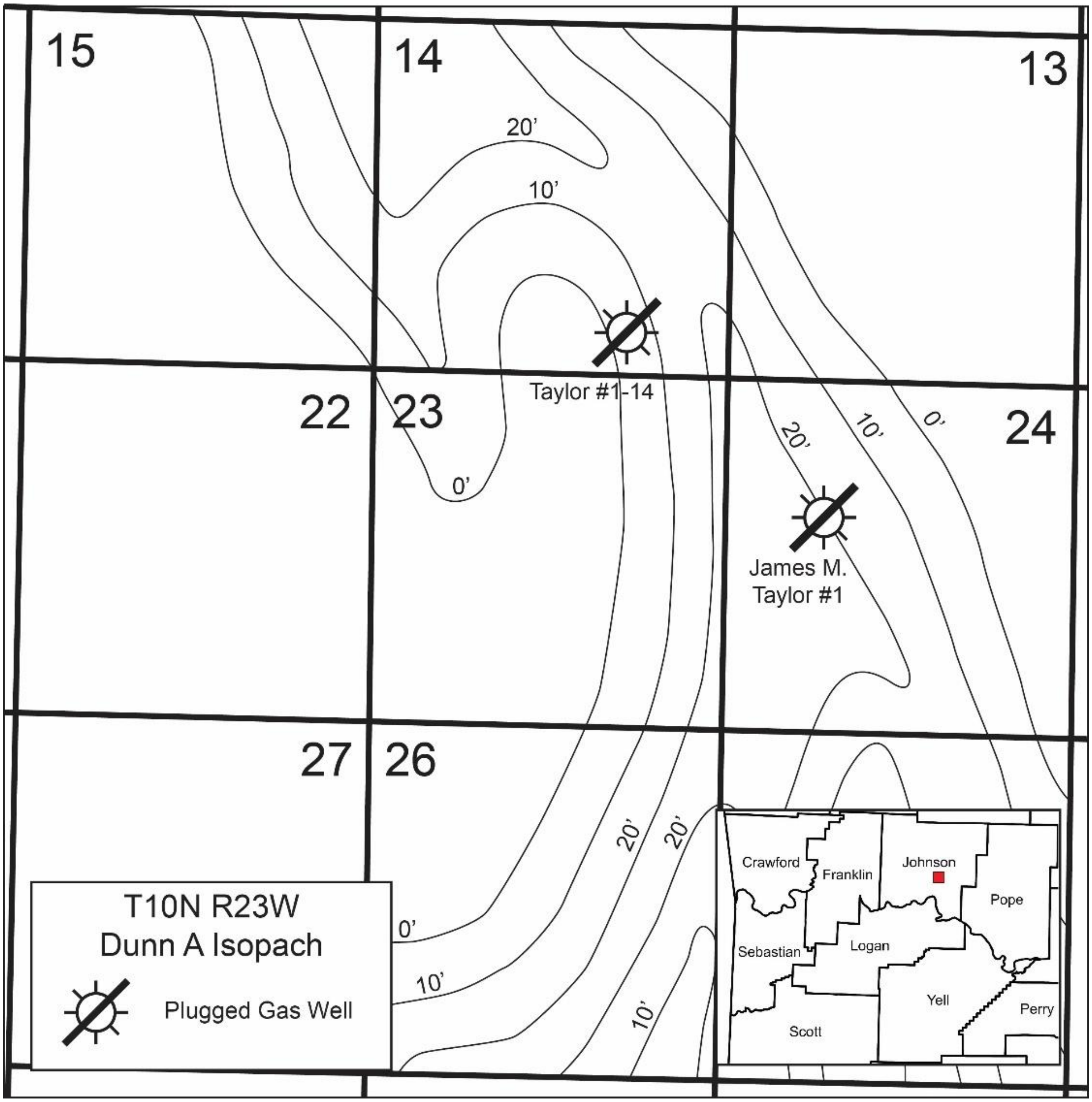

Figure 19. Isopach map of the Dunn A in the Ludwig Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #193-86.

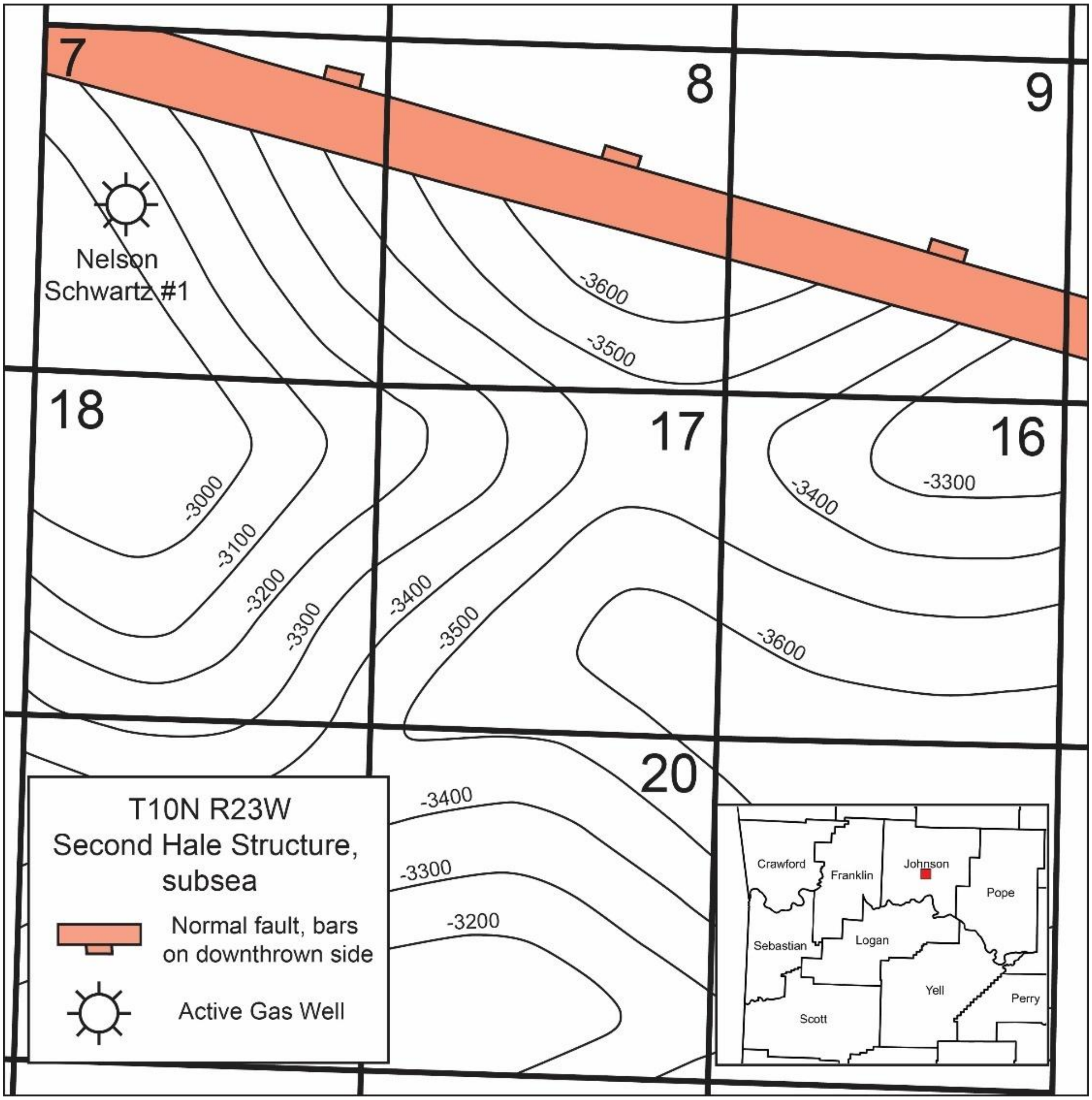

Figure 20. Structural map of the Hale in the Ludwig Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #40-81.

Massard Field

The Massard Field is located in the Fort Smith area in northwest Sebastian County and parts of southwest Crawford County. It has multiple high-yield wells with production ranging from the Silurian Hunton carbonates and Devonian Penters Chert to the Morrowan Hale Formation and basal Atokan Orr sand.

The Randolph Sengel #1 and Bertha Williams #1 have produced nearly 16 Bcf out of the Silurian Hunton carbonates in section 25 of T8N R32W and section 30 of T8N R31W, respectively (Table 10). They are located approximately along strike on the southeast flank of a southwest-northeast trending anticline (Fig. 21). The structure is bounded by normal faults to the northwest and southeast. These are likely sealing faults because wells north of the fault block are either producing out of different units or have produced less than 1 Bcf out of the Hunton. Additional structural closure occurs to the southwest as the anticline forms a nose.

The Mary Francis Allen #1 and M.F.F. Allen #2 are located near the top of a southeast-dipping ramp bounded by two normal faults in sections 30 and 31 of T8N R31W (Fig. 21). The Mary Francis well produced 10.8 Bcf out of the Hale, and the M.F.F. well produced 6 Bcf from the Hunton (Table 10). Gas reservoirs in this area appear to be limited by bounding faults. Hunton porosity decreases to the east (OGC Hearing Docket #66-2002-05).

The Municipal Airport #1-A and Municipal Airport #3 wells are located on a structural high bounded by both a normal fault and small thrust fault to the north in sections 35 and 36 of T8N R32W (Fig. 21). Both produced out of the Hunton and approximately 25.5 Bcf of void space is available in this interval between the two wells (Table 10). They are separated from the George Bieker #2, Bieker #1, and Sebastian County #2 wells by a minor structural low. The Bieker #2 produced 10.3 Bcf from the Hunton before being plugged, and the Sebastian County #1 well has produced at least 20 Bcf from the Hunton to date and continues to produce. The Bieker #1 is currently producing from the basal Atoka Orr sand and has 11.5 Bcf of void space available.

The Acme Brick #3 and Central Mall #1 wells are located on an anticline truncated by an east-west trending normal fault to the south in sections 22 and 23 of T8N R32W (Fig. 22). Both have produced out of the Silurian Penters Chert and the Acme well has also produced out of the underlying Hunton carbonates (Table 10). Production from the Penters in the Acme well was commingled with the Hunton, so specific yields from each formation are unclear. However, 8.8 Bcf of gas has been produced from this commingled interval and adds additional void space to the 5.5 Bcf produced out of the Penters in the Central Mall well. South of these wells in section 27, the Kelley A. #1 well also produced out of the Hunton and Penters intervals. At least 6 Bcf was produced out of the Hunton, and 5.7 Bcf was commingled with the Penters. This well is structurally separated from the wells in sections 22 and 23 and is situated between two normal faults near the top of a ramp (Fig. 22).

The Shale Pit #2, Spirit of ‘76 #1, Buell Ranch #3, and George Brown #1 have produced significant quantities of gas from the basal Atoka Orr sand in sections 3, 8, 9, and 17 of T7N R32W (Table 10). The Spirit of ‘76 and Buell Ranch wells are in the same fault block, and the Shale Pit and George Brown wells are isolated into separate fault blocks (Fig. 23). The George Brown #1 well produced about 5 Bcf of gas before being plugged. An isopach map of the lower lobe of the Orr sand shows that there is stratigraphic closure to the east and west in the block (Fig. 24). Another well, the George Brown #2, is located about 125 feet to the southeast of George Brown #1 and is currently producing about 1,000 Mcf per month from the Orr. This adds an additional 1.3 Bcf to the void space in this fault block. The Spirit of ‘76 and Buell Ranch wells are in a block bounded by faults to the north and south. No public well logs are available, so it is unknown whether these two wells are producing out of the upper or lower lobes of Orr sand. However, isopach maps show that both lobes exist in these wells, with the upper lobe possibly connected and the lower lobe isolated. These maps also show stratigraphic closure to the west for both wells (Figs. 24 and 25). The Shale Pit well is located on an east to southeast-dipping ramp bounded by faults that provide structural closure (Fig. 23).

The Sidney O. Terry #1 well has produced 12.2 Bcf out of the Orr sand in section 21 of T7N R32W (Table 10). It is located in the middle of a westward-dipping ramp (Fig. 26). Two normal faults provide structural closure to the north and south, and an isopach map shows stratigraphic closure to the east (Fig. 27).

The Port Authority #1 well has produced 5.8 Bcf from the Hale sand in section 20 of T8N R32W (Table 10). It is located on the northwest lobe of an anticline, but the positioning is not ideal for a structural trap alone (Fig. 28). An isopach map shows that there is stratigraphic closure to the east and west, and a normal fault to the north provides additional structural confinement (Fig. 29). Similarly, the Church B #1 well in section 33 of T8N R32W is not in an ideal position for a structural trap. It produces from the Orr sand and is located on the southeast limb of a northeast-southwest trending syncline (Fig. 28). However, a normal fault to the east and southeast provides some structural control on the reservoir. An isopach map shows that there is stratigraphic closure to the west and east (Fig. 30).

The Lincoln #2 well has produced 12 Bcf out of the Hale sand in section 16 of T8N R31W (Table 10). It is located on an anticline truncated by a northeast-southwest trending fault to the northwest, providing a trapping mechanism for the reservoir (Fig. 31).

Table 10. Wells with high-volume production in the Massard Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
21339	03-131-10008-0000	Sebastian County #2	1-7N-32W	Hunton	20	PR
22140	03-131-22140-0000	George Bieker #2	2-7N-32W	Hunton	10.3	PA
10626	03-131-80015-0000	Bieker #1	2-7N-32W	Basal Atoka (Orr)	11.5	PR
22181	03-131-10059-0000	Municipal Airport #3	35-8N-32W	Hunton	13.5	PA
22017	03-131-10050-0000	Municipal Airport #1-A	36-8N-32W	Hunton	12	PA
15927	03-131-00045-0000	Randolph Sengel #1	25-8N-32W	Hunton	6.8	PR
14179	03-131-00095-0000	Mary Francis Allen #1	30-8N-31W	Hale	10.8	PR
14980	03-131-00209-0000	Bertha Williams #1	30-8N-31W	Hunton	9	PR
20876	03-131-30036-0000	M. F. F. Allen #2	30-8N-31W	Hunton	6	PA
27633	03-131-10222-0000	Shale Pit #2	3-7N-32W	Orr	6.7	PA
23979	03-131-10108-0000	Spirit of ’76 #1	8-7N-32W	Orr	6.2	PA
18404	03-131-00001-0000	Buell Ranch #3	9-7N-32W	Orr	5.3	PA
20371	03-131-30023-0000	George Brown #1	17-7N-32W	Orr	5	PA
32749	03-131-10407-0000	George Brown #2	17-7N-32W	Orr	1.4	PR
29922	03-131-10286-0000	Church B #1	33-8N-32W	Orr	6	PR
28904	03-131-10283-0000	Port Authority #1	20-8N-32W	Hale	5.8	PR
20293	03-131-30012-0000	Sidney O. Terry #1	21-7N-32W	Orr	12.2	PR
22360	03-033-10025-0000	Lincoln #2	16-8N-31W	Hale	12	PR
28468	03-131-10260-0000	Kelley A. #1	27-8N-32W	Hunton, Penters/Hunton	6, 5.7	PA
33104	03-131-10435-0000	Acme Brick #3	22-8N-32W	Penters/Hunton	8.8	PR
29497	03-131-10306-0000	Central Mall #1	23-8N-32W	Penters	5.5	PR

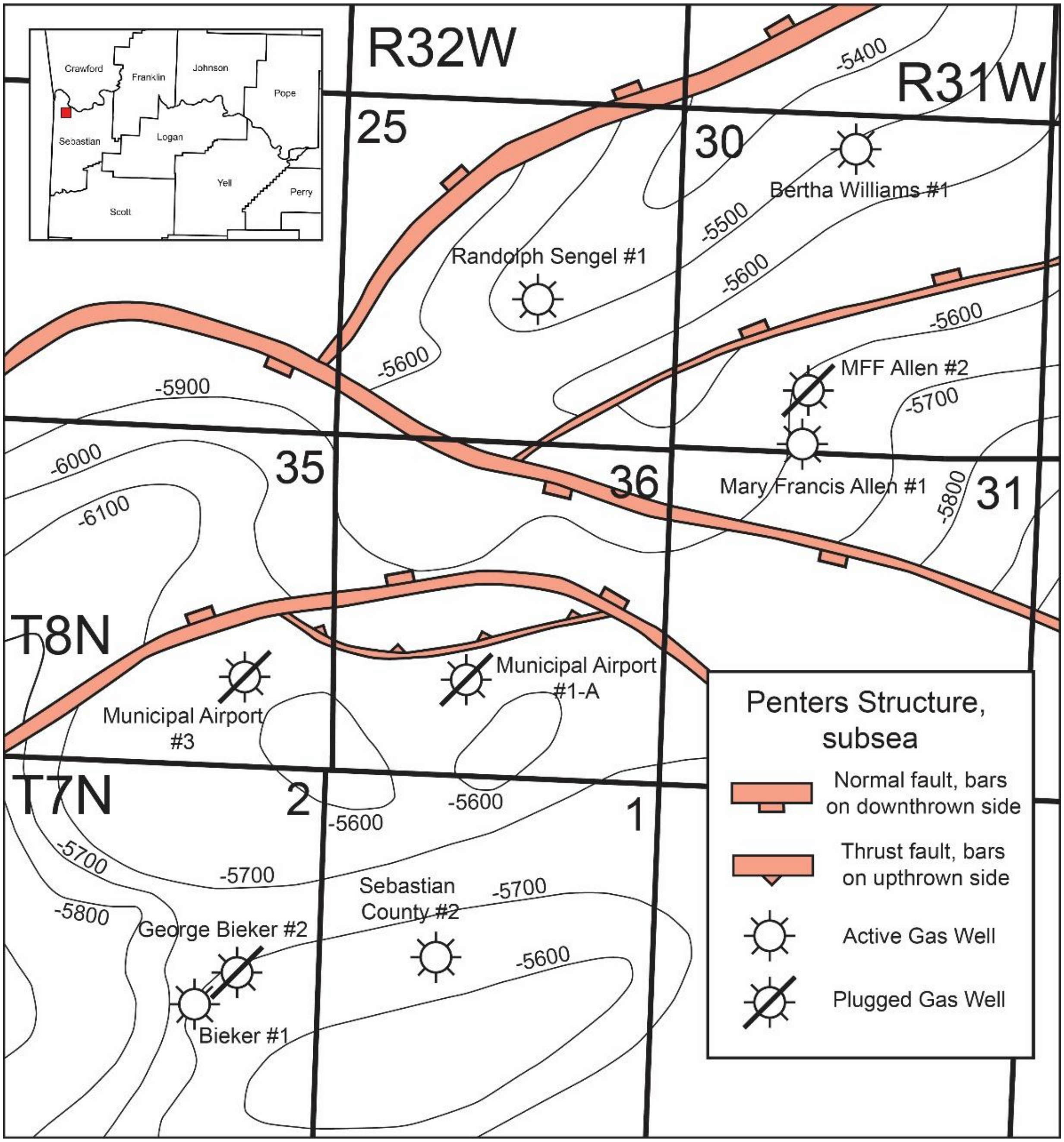

Figure 21. Structural map of the Penters Chert in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #98-90, #96-77, and #98-36.

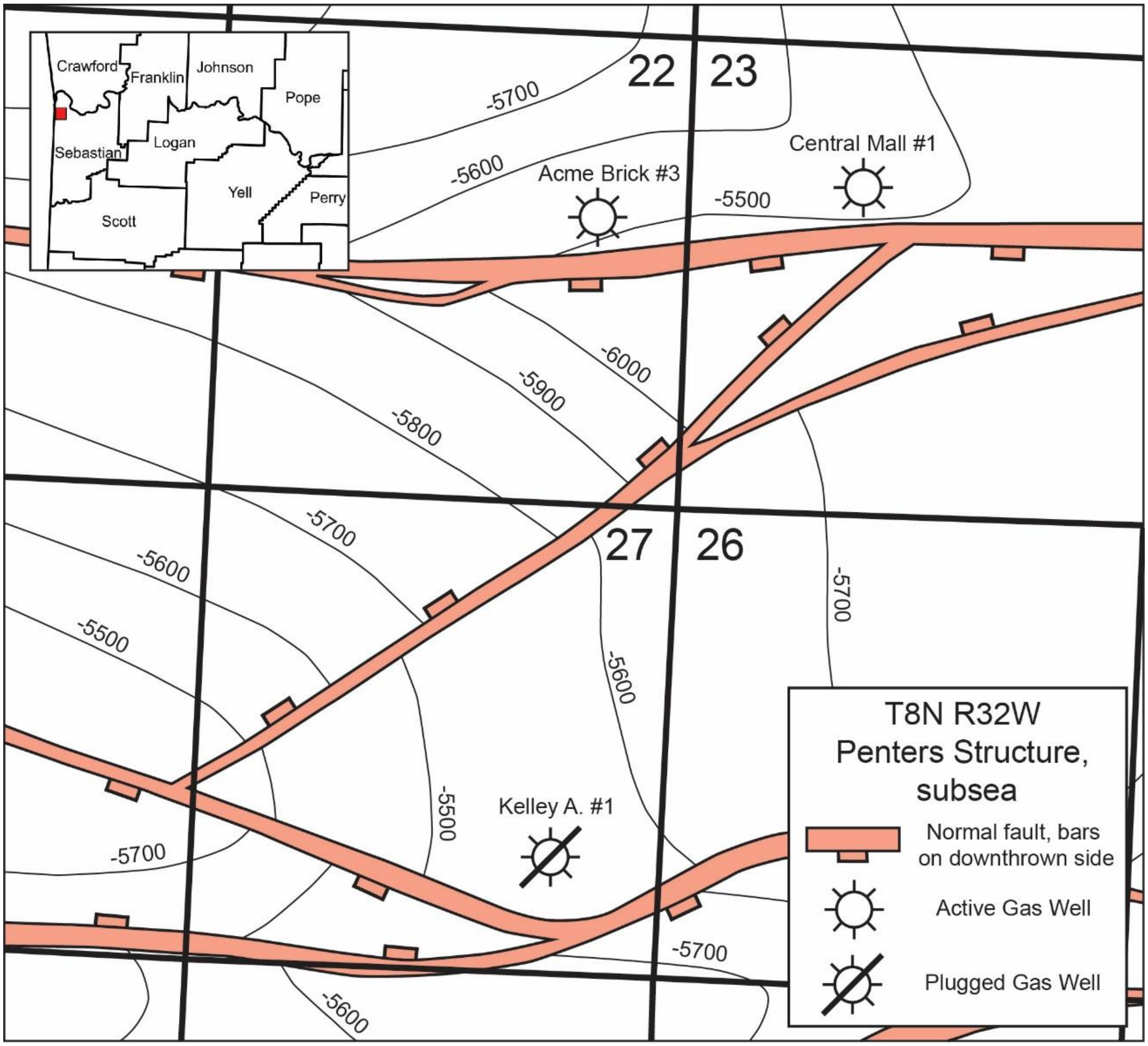

Figure 22. Structural map of the Penters Chert in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #93-93.

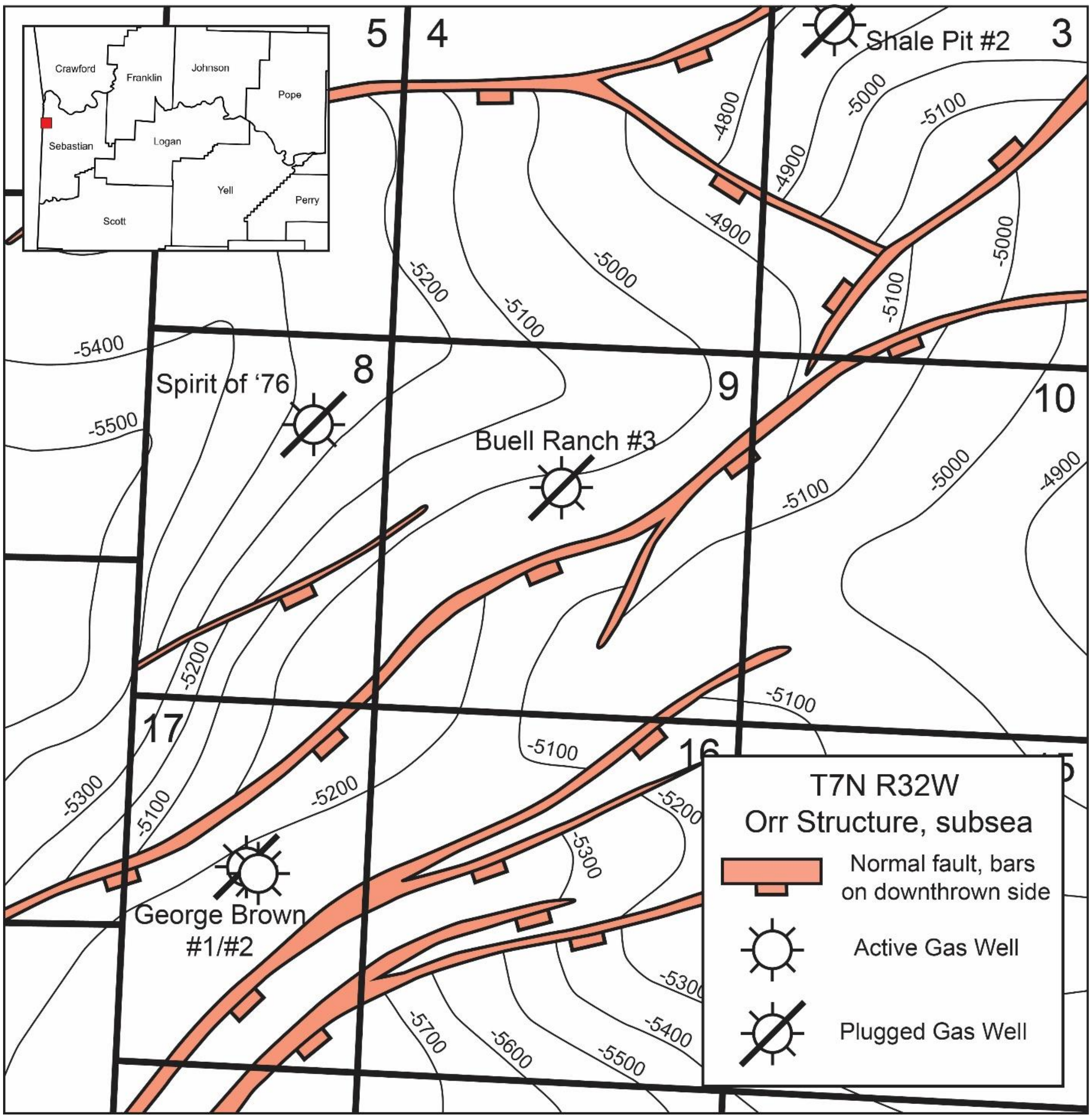

Figure 23. Structural map of the Orr sand in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #104-97 and #95-70.

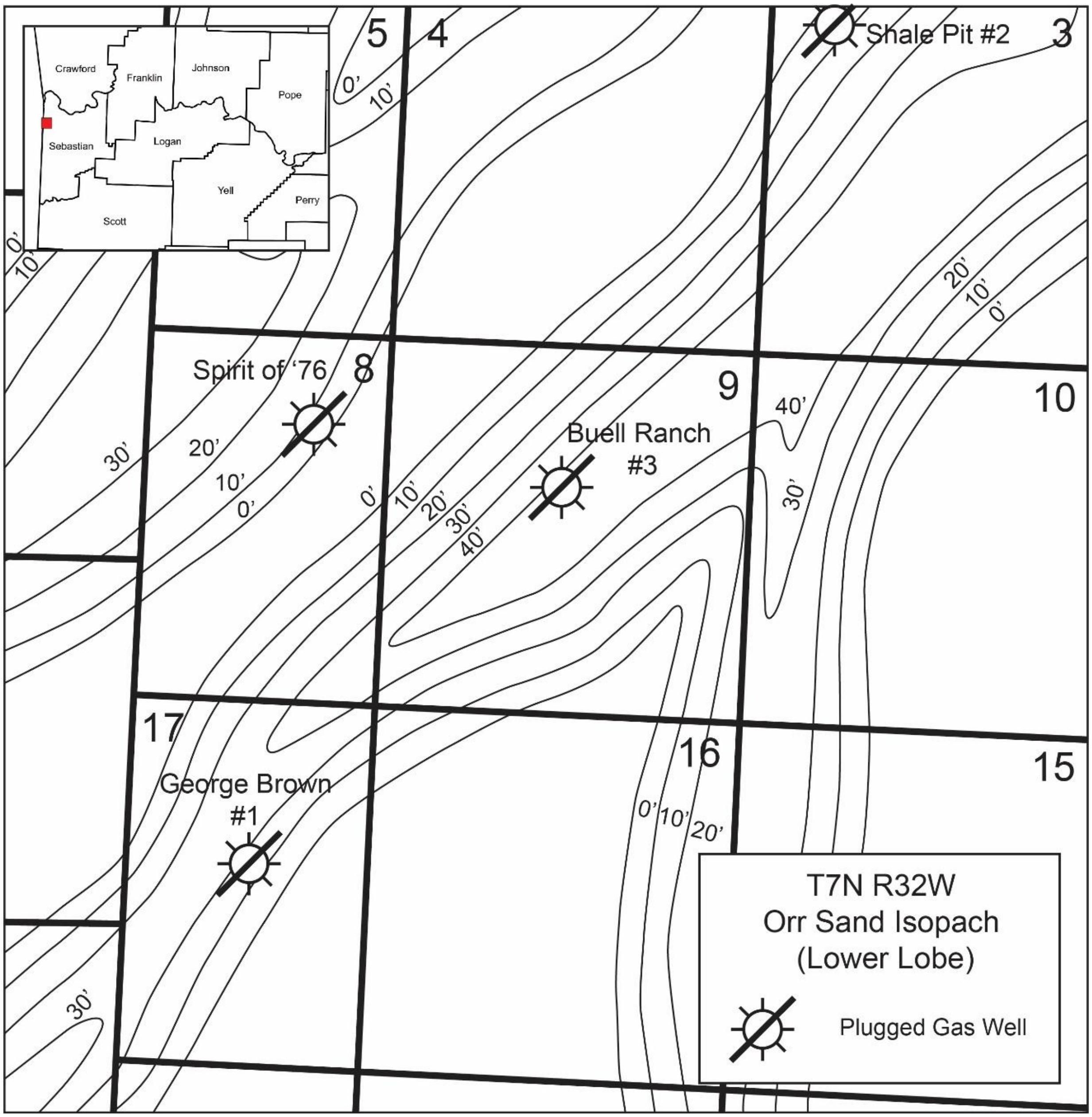

Figure 24. Isopach map of the Orr sand lower lobe in the Massard Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #95-70.

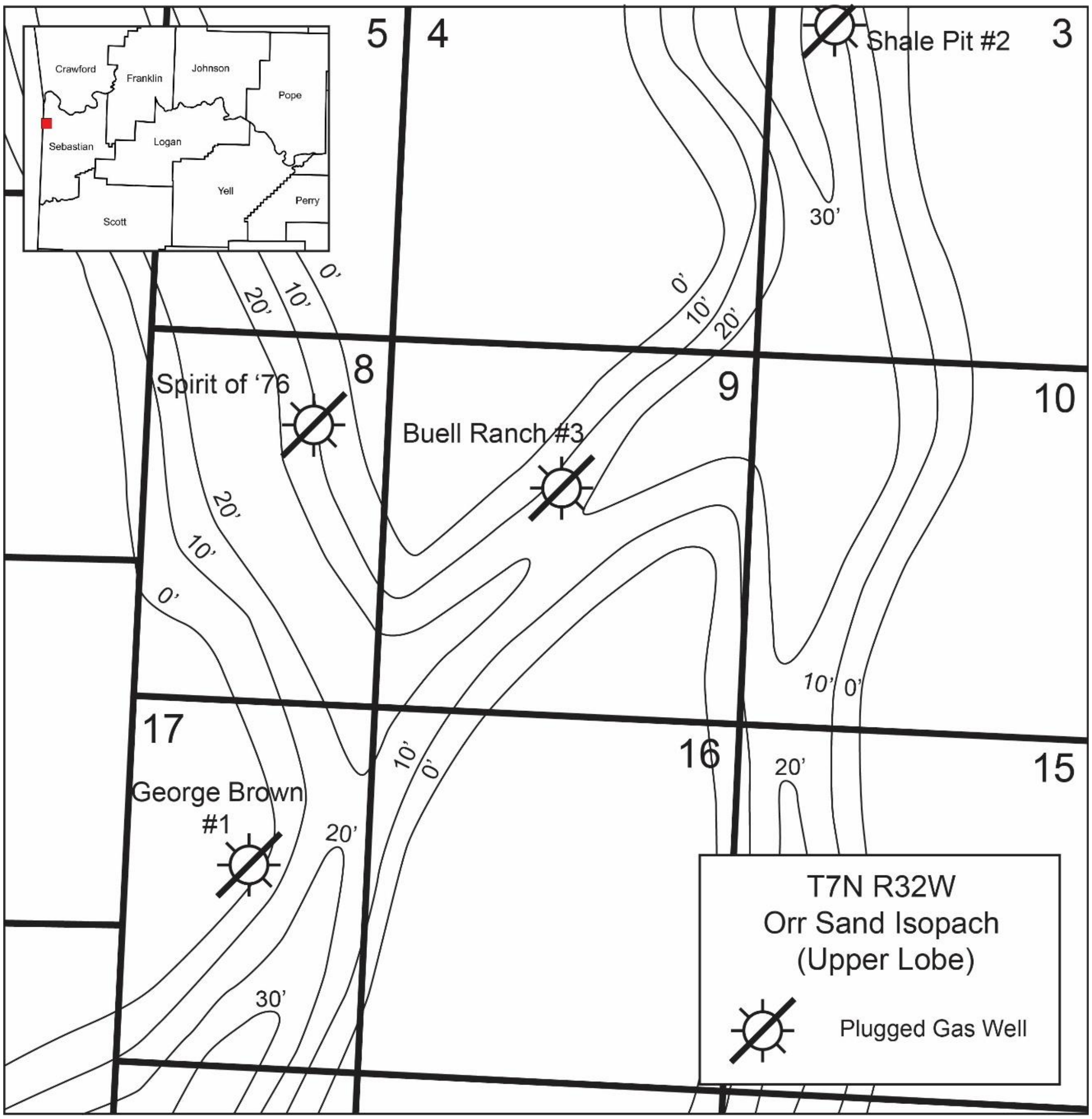

Figure 25. Isopach map of the Orr sand upper lobe in the Massard Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #95-70.

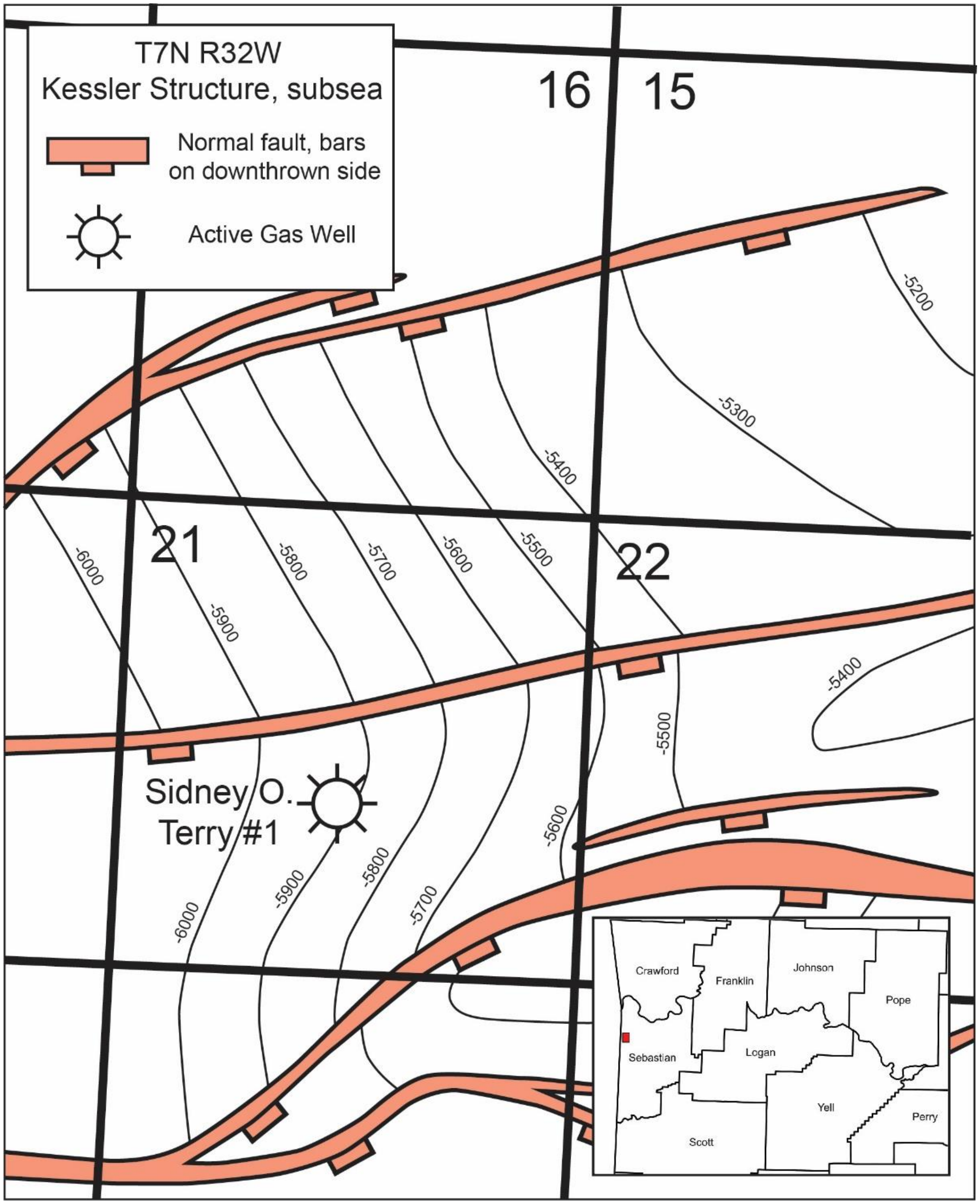

Figure 26. Map with the Kessler Limestone chosen as the structural datum in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #93-90.

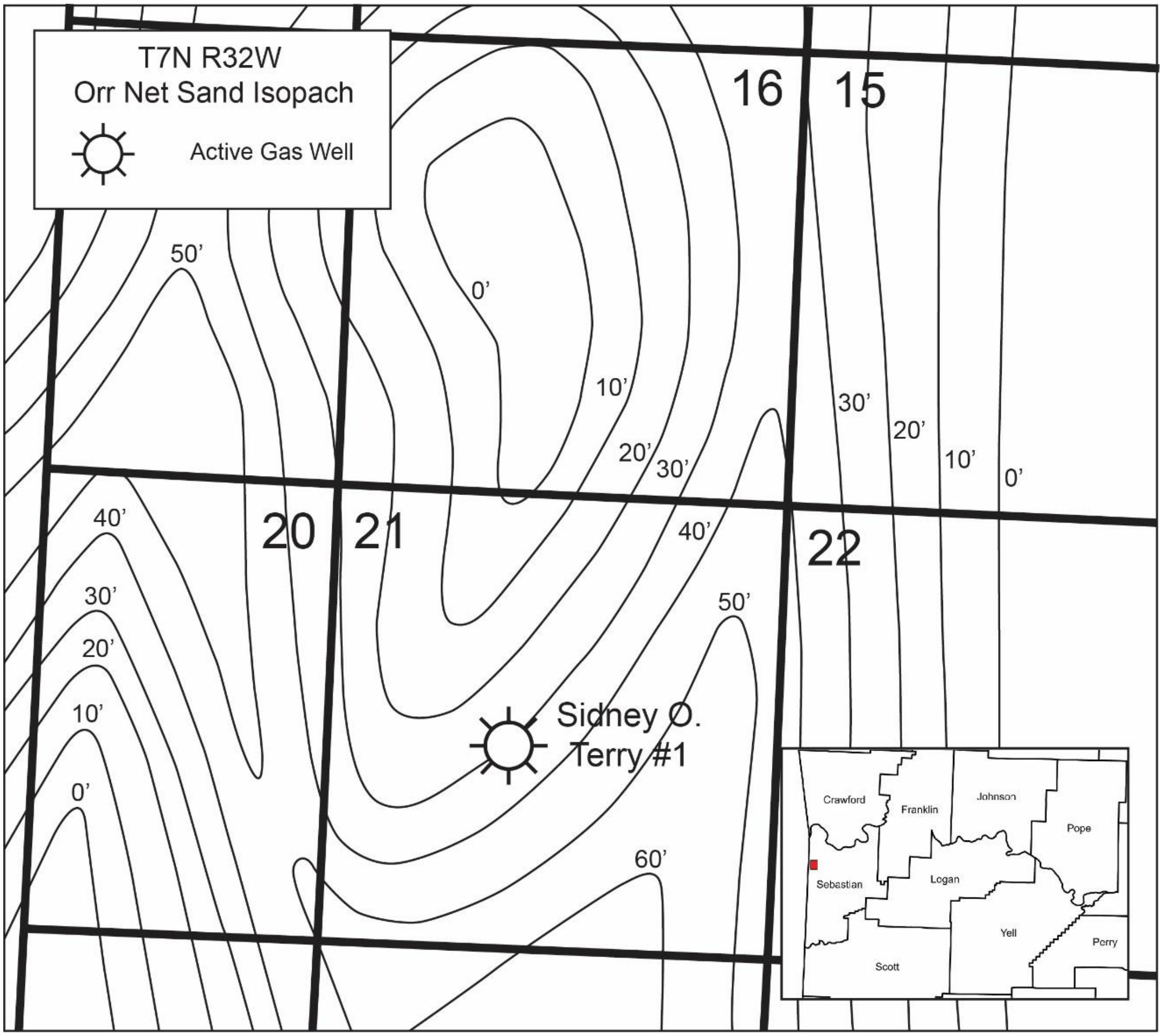

Figure 27. Isopach map of the Orr sand in the Massard Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #77-83.

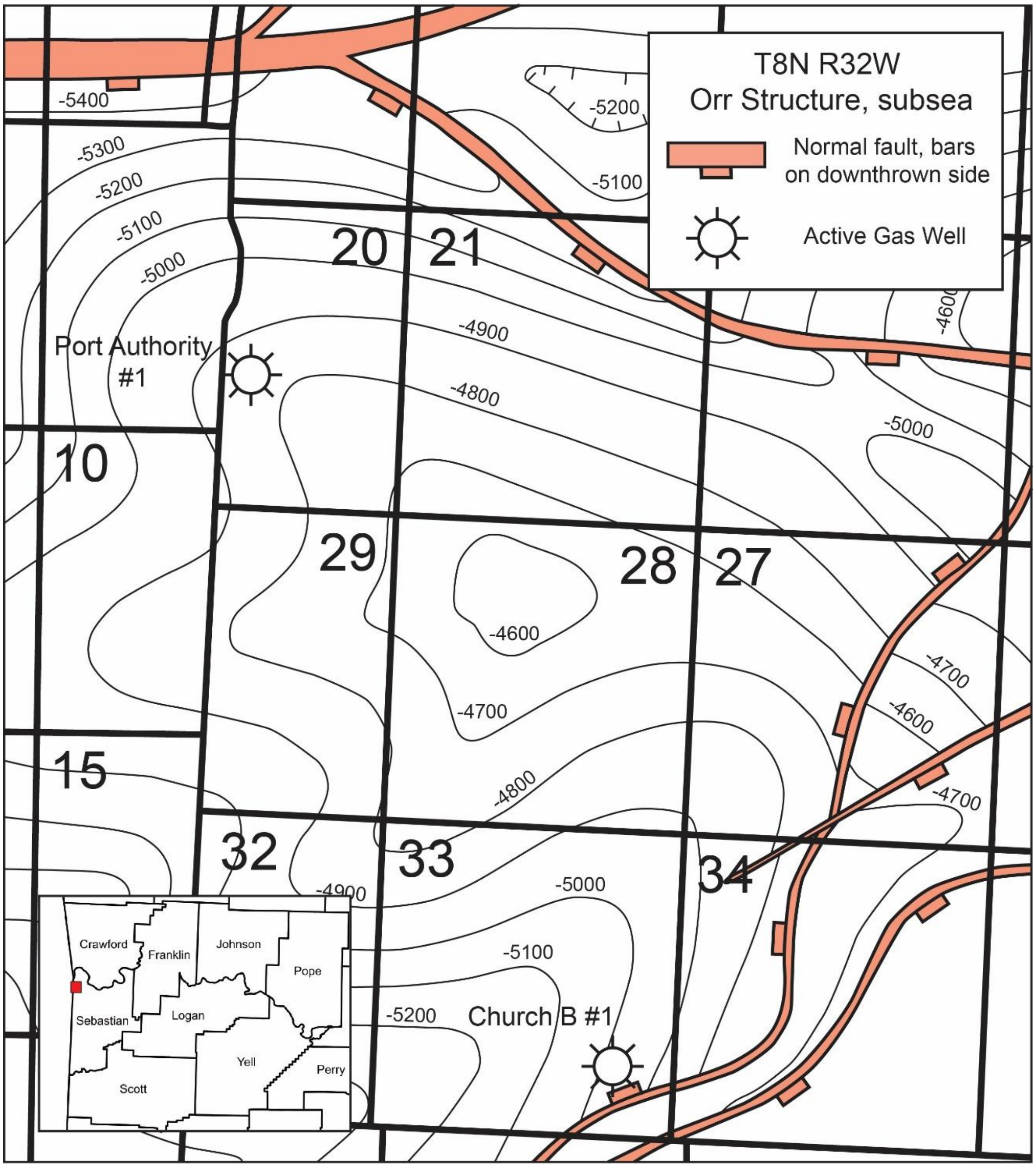

Figure 28. Structural map of the Orr sand in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #017-2014-01.

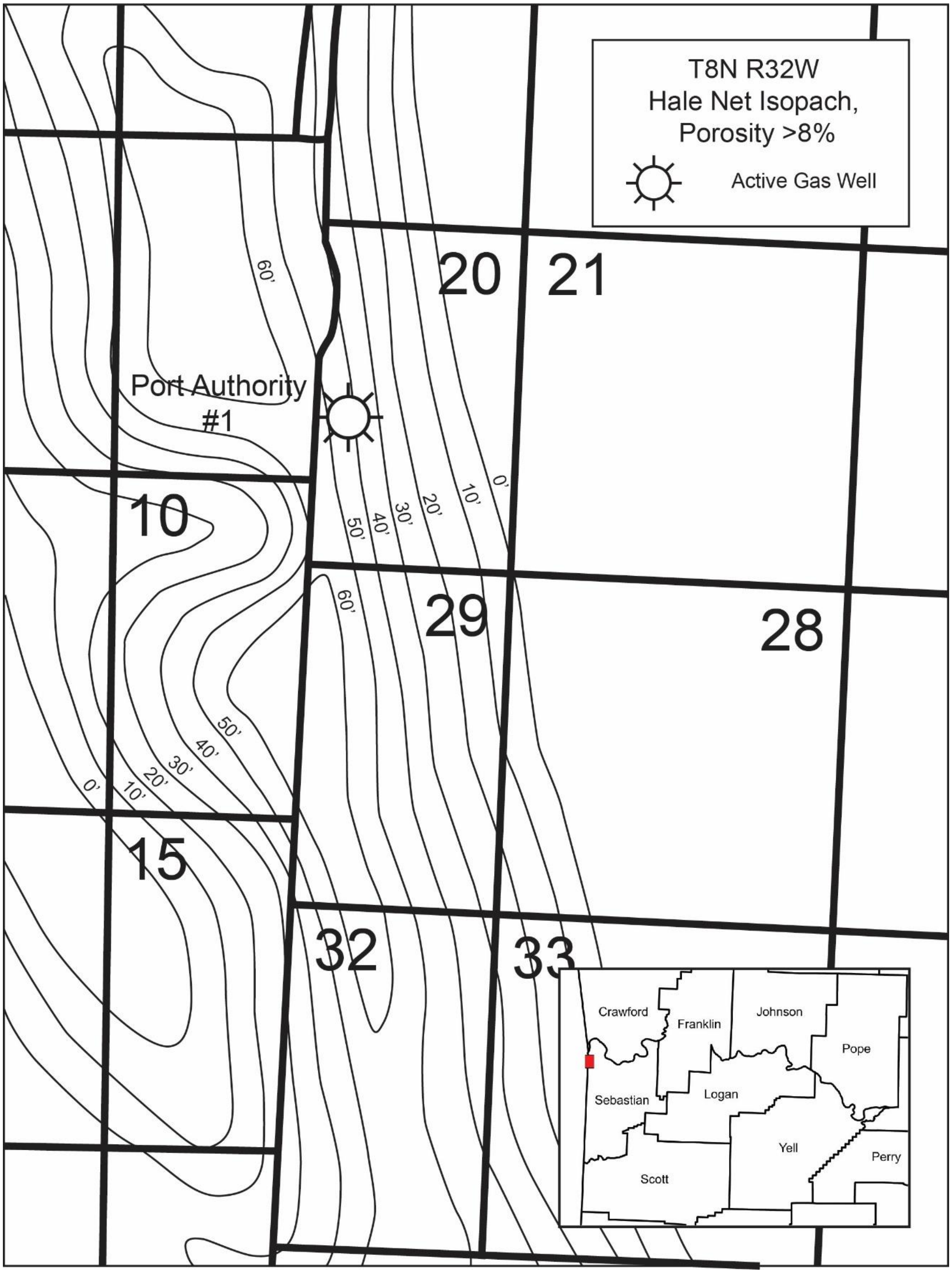

Figure 29. Isopach map of the Hale sand in the Massard Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #A33-2004-03.

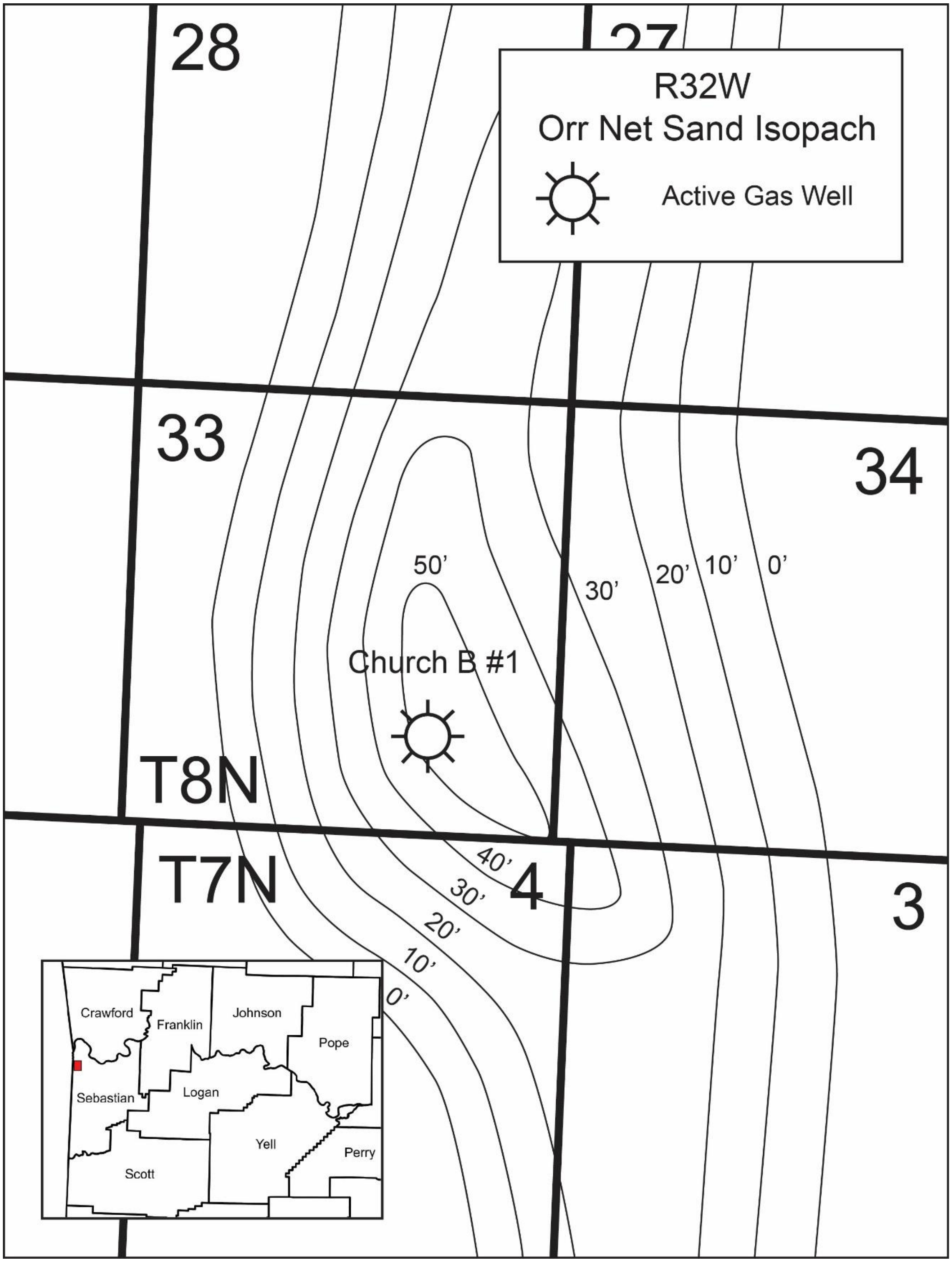

Figure 30. Isopach map of the Orr sand in the Massard Field. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #166-86 and #92-59.

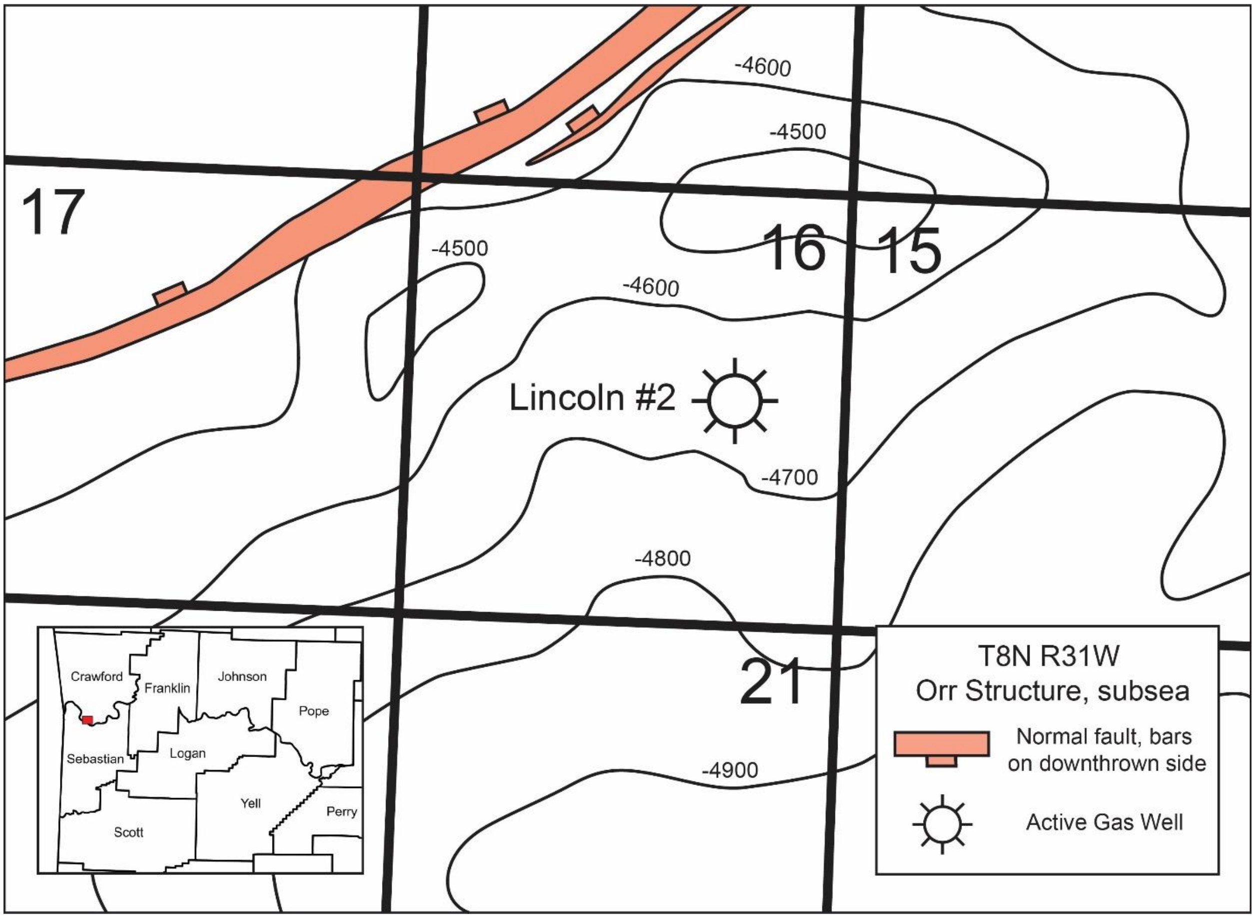

Figure 31. Structural map of the Orr sand in the Massard Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #96-41.

Moreland Field

The Barton A sand at the base of the Pennsylvanian Atoka Formation has the greatest potential for gas storage in this field. The cumulative production from the Barton A across three wells in sections 3, 10, and 11 of T8N R19W has exceeded 20 Bcf (Table 11). The structural setting is an anticline bounded by east-west trending down-to-the-south sealing normal faults (Fig. 32).

The Chronister #1 well continues to produce from the Barton A sand. As of October 2015, the well was producing about 130 Mcf per day and was forecast to continue producing gas for another 20 years and to recover an additional 1 Bcf of gas (OGC Hearing Docket #123-2015-10). The Minnie Turner #1 and C. A. Rainwater #1 wells were plugged because they no longer produced gas after the water table migrated updip. Scientists at OGC hearings noted that the Barton

A reservoir had become constricted by the encroachment of water with the original gas-water contact moving up from an original depth of -3,245 feet (subsea) to -3,161 feet (subsea) in 1990 (OGC Hearing Docket #60-97). Once production ceases from the Chronister #1 well, the prospect may have potential, especially if the gas-water contact can be pushed downdip. Reservoir engineering studies are needed to determine the feasibility of this as an option.

Table 11. Wells with high-volume production in the Moreland Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
13670	03-115-60000-0000	Chronister #1	3-8N-19W	Barton A	10.2	PR
19684	03-115-60016-0000	Minnie Turner #1	10-8N-19W	Barton A	6.3	PA
14914	03-115-00003-0000	C. A. Rainwater #1	11-8N-19W	Barton A	5	PA

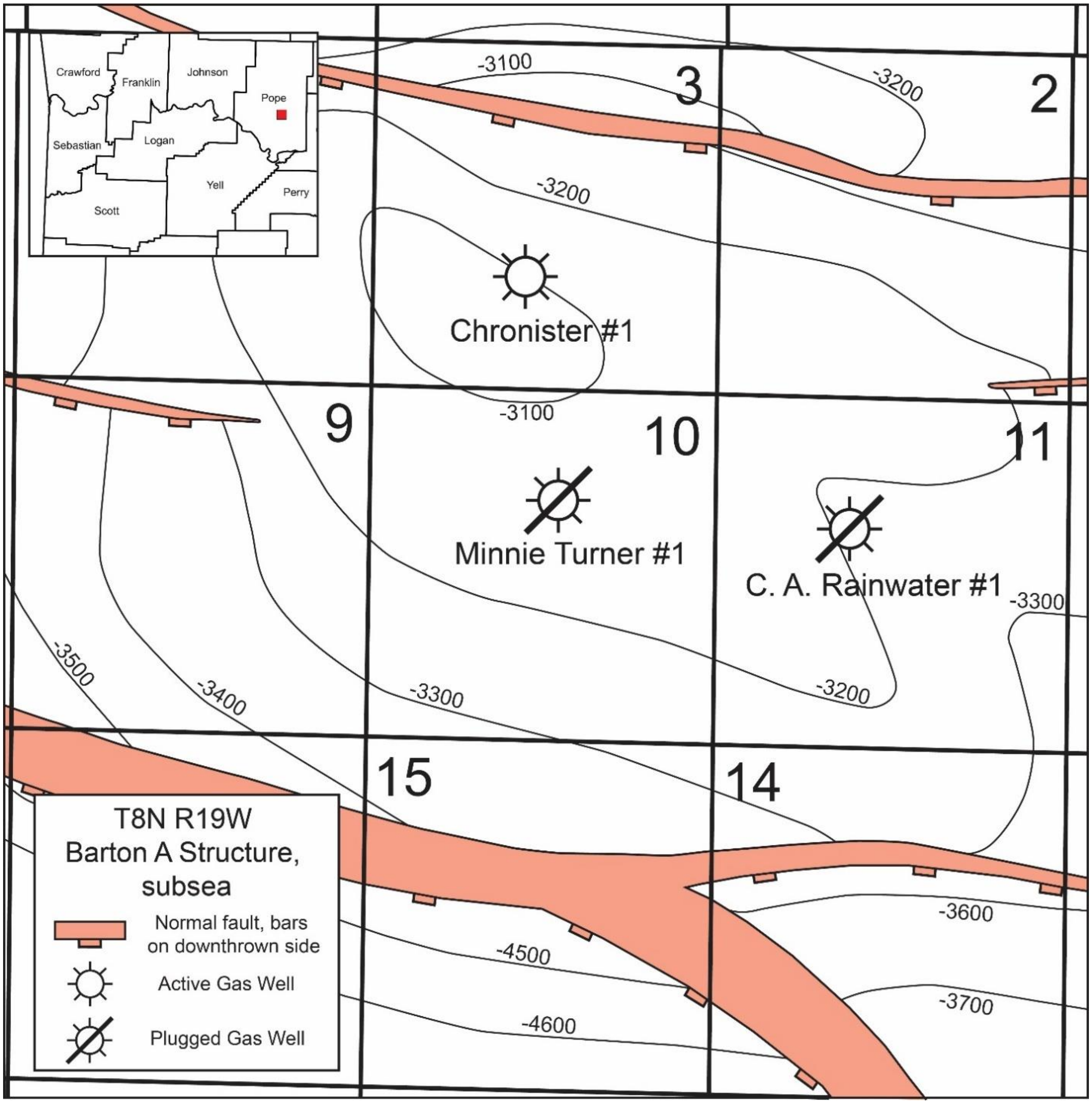

Figure 32. Structural map of the Barton A sand in the Moreland Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #99-3 and #216-2013-08.

Ross Field

Several east-west trending normal faults, including New Hope Fault, Piney Creek Fault, and Dover Fault, are present in the Ross Field in Pope and Johnson Counties (OGC Hearing Docket #55-76). The primary areas of interest in the field encompass sections 1, 9, 14, and 22 of T9N R21W. The largest cumulative production was attained from the Bibler #1 well, which is situated on top of a southward-dipping ramp on the upthrown side of a down-to-the-north normal fault (Fig. 33). The Bibler #1 has two producing zones, the Barton A and Barton B sands. Before being commingled, each of them contained a cumulative production of 6.3 Bcf and 10.8 Bcf, respectively (Table 12). The Barton A/Barton B commingled zone contributed another 1.4 Bcf of gas afterward. The Holland A #3 well is located on the downthrown side of a down-to-the-south normal fault (Fig. 34). It has produced 7.7 Bcf of gas from the Tackett sand. The Hogrefe #1 well is located on an anticline truncated by a normal fault to the north (Fig. 35). It has produced 6.1 Bcf of gas from the upper Allen zone. The H.F. Smith #1 well is situated on a horst structure north of the Hogrefe #1. It is the top producer in the field with 7 Bcf of gas from the McGuire sand. The Milsap #1 has produced a total of 8 Bcf from three zones: middle Hale, lower Hale, and Casey. The middle Hale is the primary reservoir, having produced 5.7 Bcf of gas before commingling with the other two zones. The well is located on the northern limb of an east-west trending syncline south of a fault which provides structural closure to the north (Fig. 36). A lower Hale net sand isopach map shows that the well is in a north-south trending channel, providing stratigraphic closure to the east and west (Figure 37).

Table 12. Wells with high-volume production in the Ross Field.

Permit	API	Well Name	Location	Producing Zone(s)	Production (Bcf)	Status
25462	03-115-10067-0000	Bibler #1	9-9N-21W	Barton A, Barton B	6.3, 10.8	PA
25462	03-115-10067-0000	Bibler #1	9-9N-21W	Barton A/Barton B	1.4	PA
28643	03-115-10201-0000	Holland A #3	14-9N-21W	Tackett	7.7	PA
24243	03-115-10037-0000	Hogrefe #1	22-9N-21W	upper Allen	6.1	PA
30194	03-115-10269-0000	Milsap #1	1-9N-21W	lower Hale	5.7	PA
18083	03-115-00062-0000	H.F. Smith #1	17-9N-21W	McGuire	7	PR

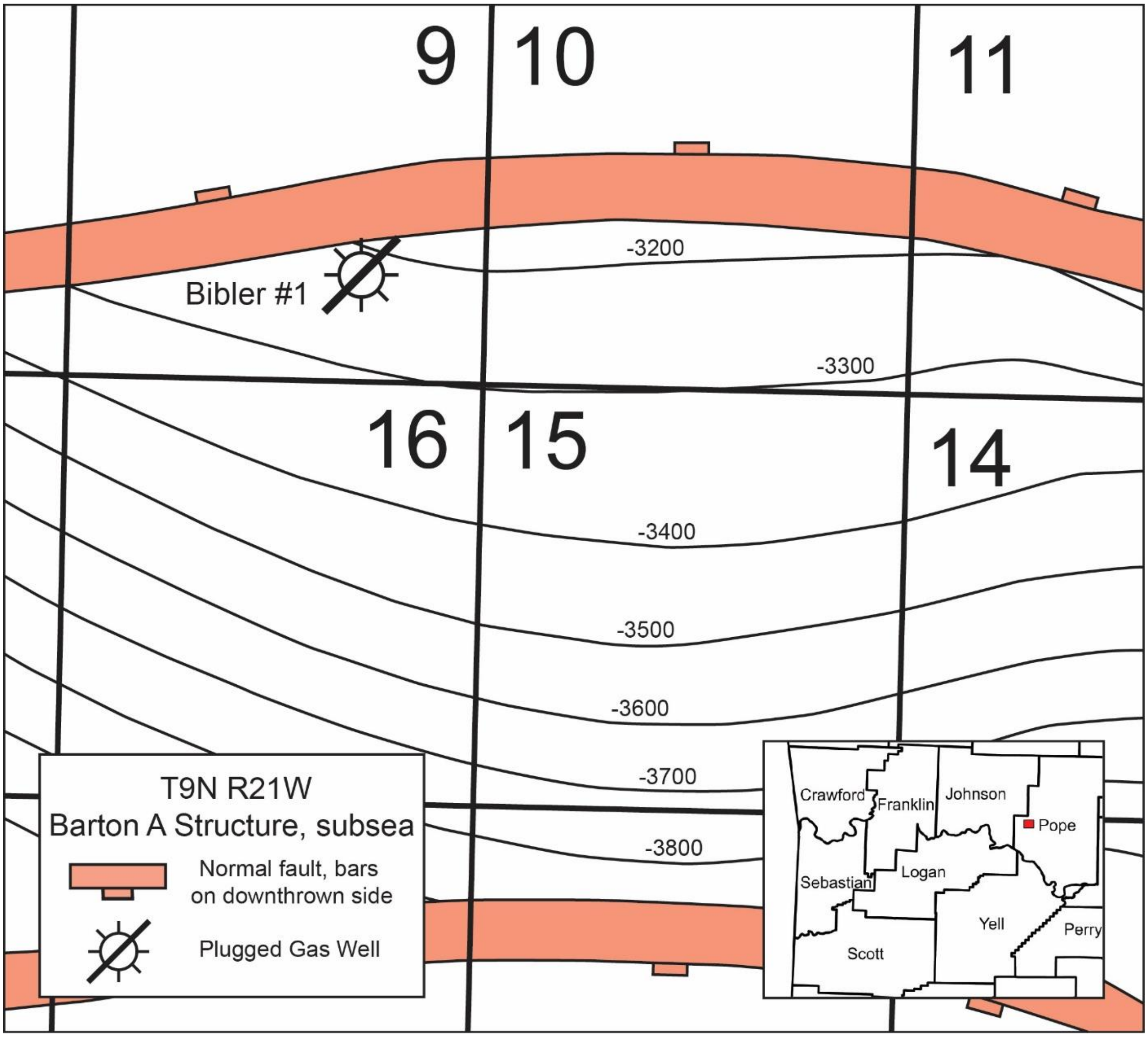

Figure 33. Structural map of the Barton A sand in the Ross Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #279-84.

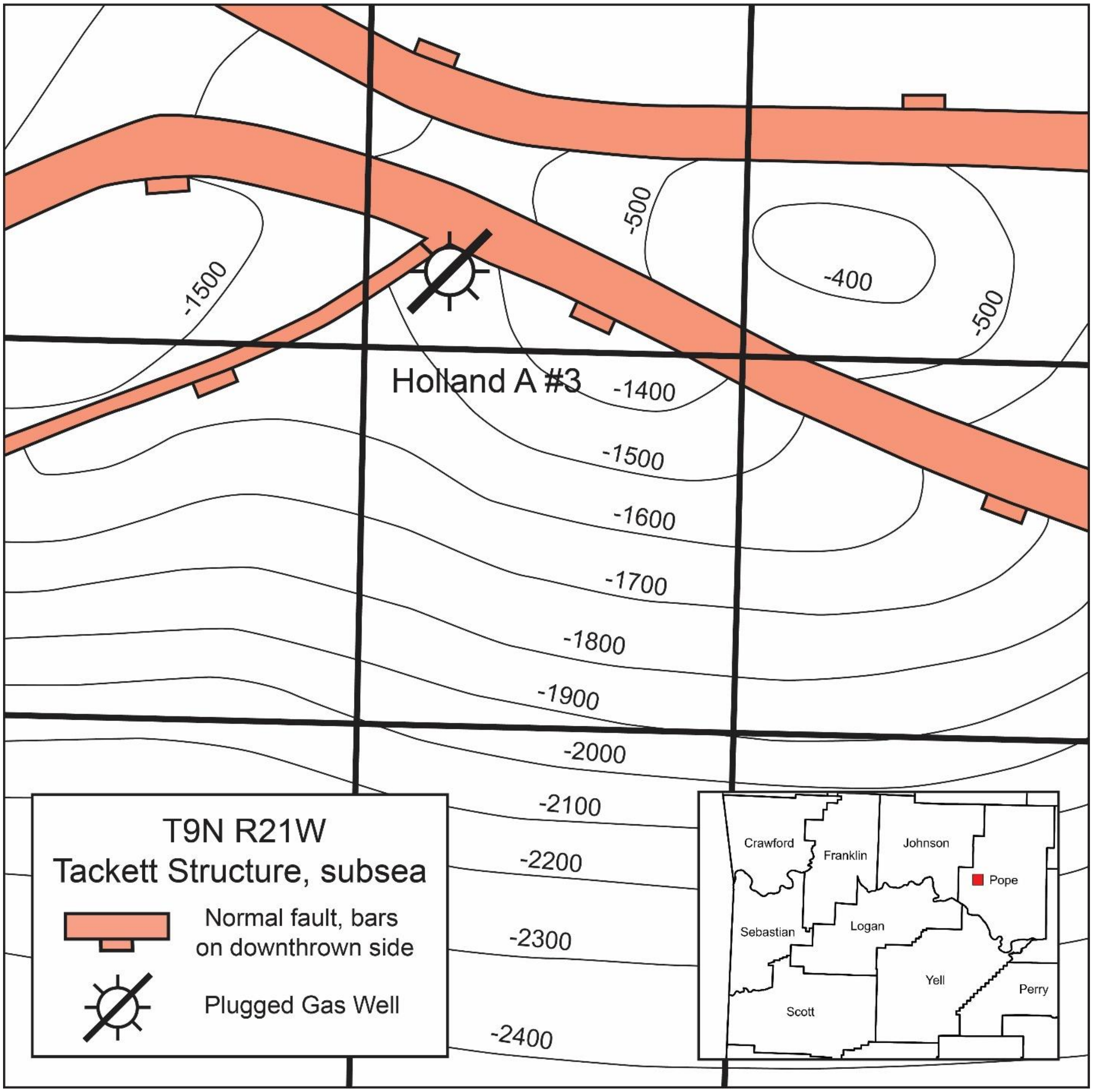

Figure 34. Structural map of the Tackett sand in the Ross Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #164-81.

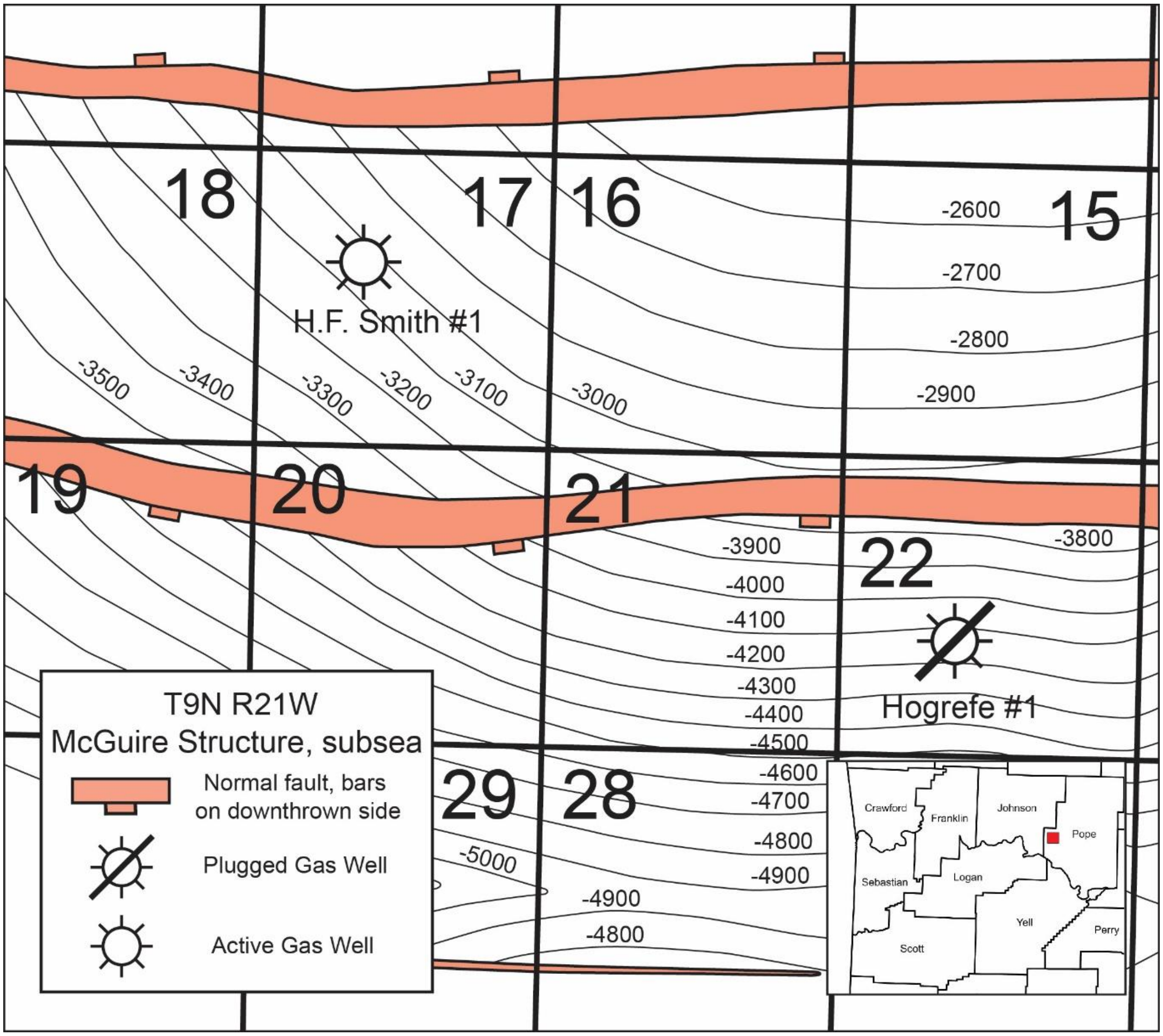

Figure 35. Structural map of the McGuire sand in the Ross Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #71-86 and #89-8.

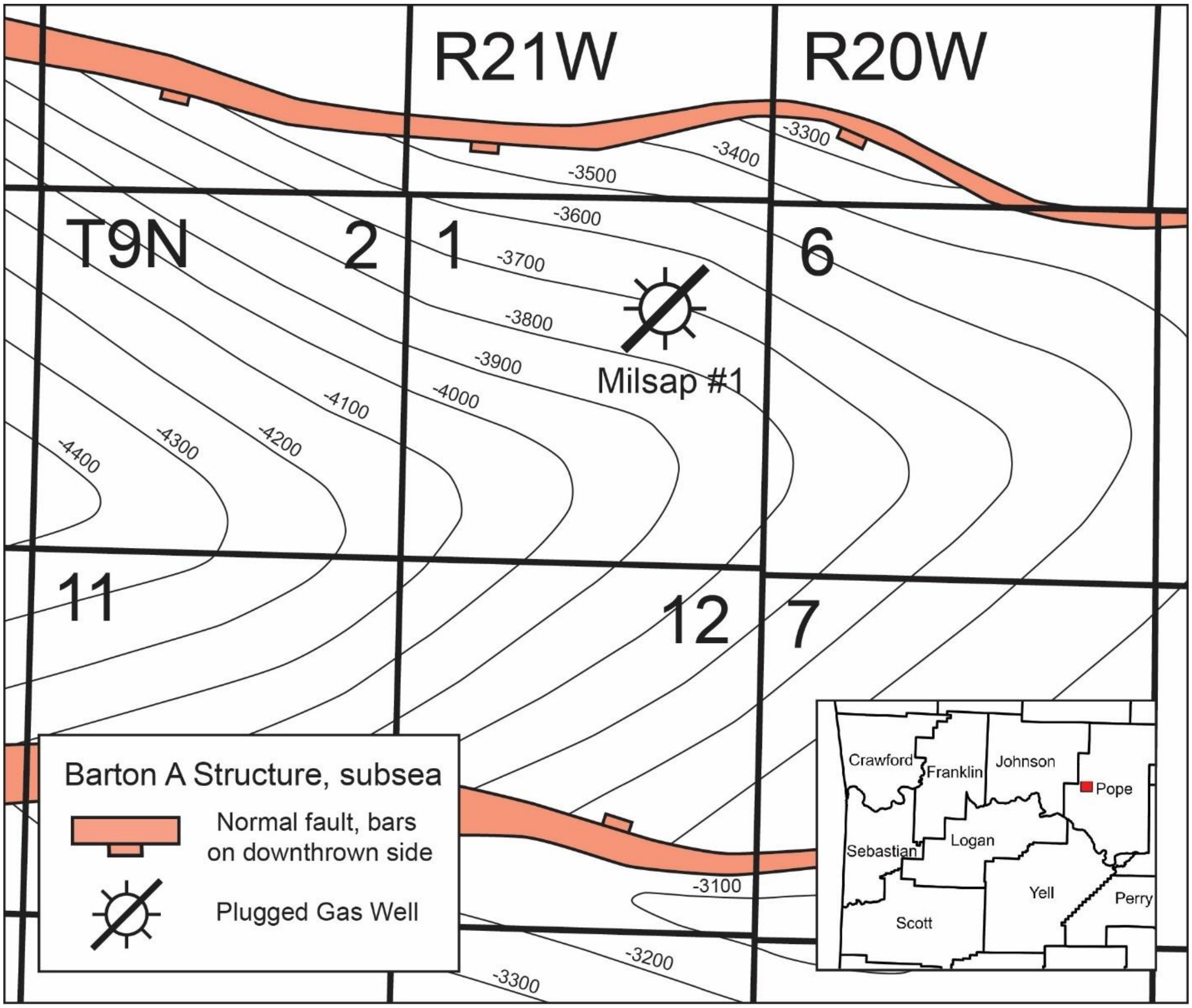

Figure 36. Structural map of the Barton A sand in the Ross Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #345-85.

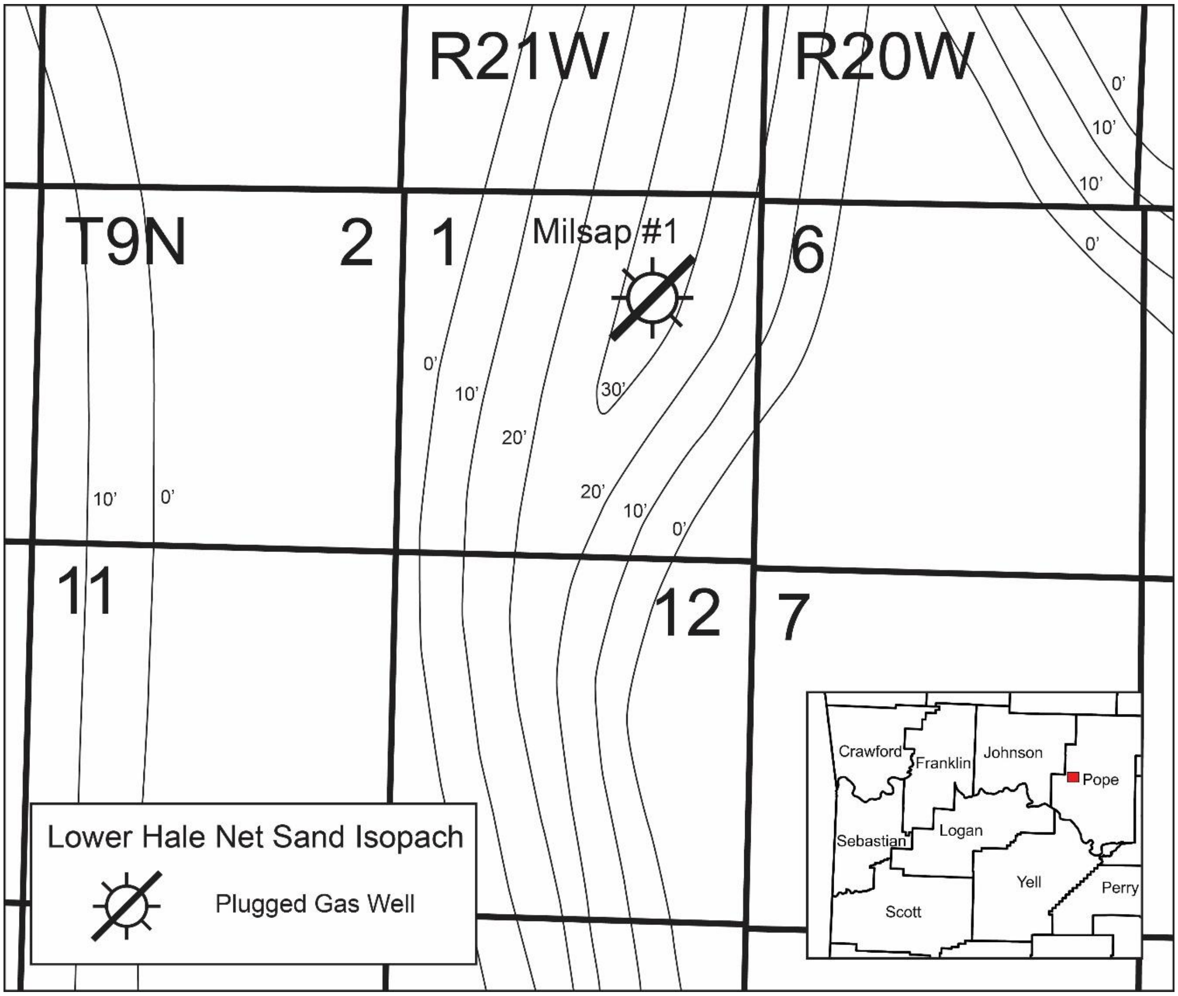

Figure 37. Isopach map of the lower Hale sand in the Ross Field. Modified from map in OGC Hearing Docket #345-85.

Scranton Field

The Scranton Field is characterized by east-west trending normal faults, covering parts of T8N and 9N, R24W and 25W in Johnson and Logan Counties (Figs. 38 and 39). The Kimes #1 was the most productive well in the Scranton Field, producing 10.3 Bcf of gas from the Hale sand prior to plugging (Table 13). It is located in a fault block with east-west trending normal faults to the north and south, providing structural closure for the reservoir (Fig. 38). The Kimes #4 well was drilled on the same pad as the Kimes #1 and has produced an additional 2.3 Bcf from the Hale.

The second most productive well is the Ozark Real Estate #2-21, which is also located between two east-west trending normal faults (Fig. 39). It produced 4.4 Bcf of gas from the Orr sand. The Yeager #1 and Ozark Real Estate #2-19 wells appear to be situated in the same structure as the Ozark Real Estate #2-21. The Ozark Real Estate 2-19 well has produced 5.3 Bcf of gas from the Orr sand. The Yeager #1 well has produced a total of 7.5 Bcf of gas, with 5.4 Bcf from the Orr and 1.2 Bcf from an Orr/Dunn B commingled zone. An isopach map shows stratigraphic closure to the east and west for the Orr reservoir (Fig. 40).

Table 13. Wells with high-volume production in the Scranton Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
18509	03-071-00027-0000	Kimes #1	6-8N-24W	Hale	10.3	PA
37420	03-071-10844-0000	Kimes #4	6-8N-24W	Hale	2.3	PR
21598	03-071-10022-0000	Ozark Real Estate #2-21	21-9N-24W	Orr	4.4	PA
21059	03-071-30041-0000	Yeager #1	20-9N-24W	Orr & Orr/Dunn B	5.4, 1.2	PR
24835	03-071-10154-0000	Ozark Real Estate #2-19	19-9N-24W	Orr	5.3	PR

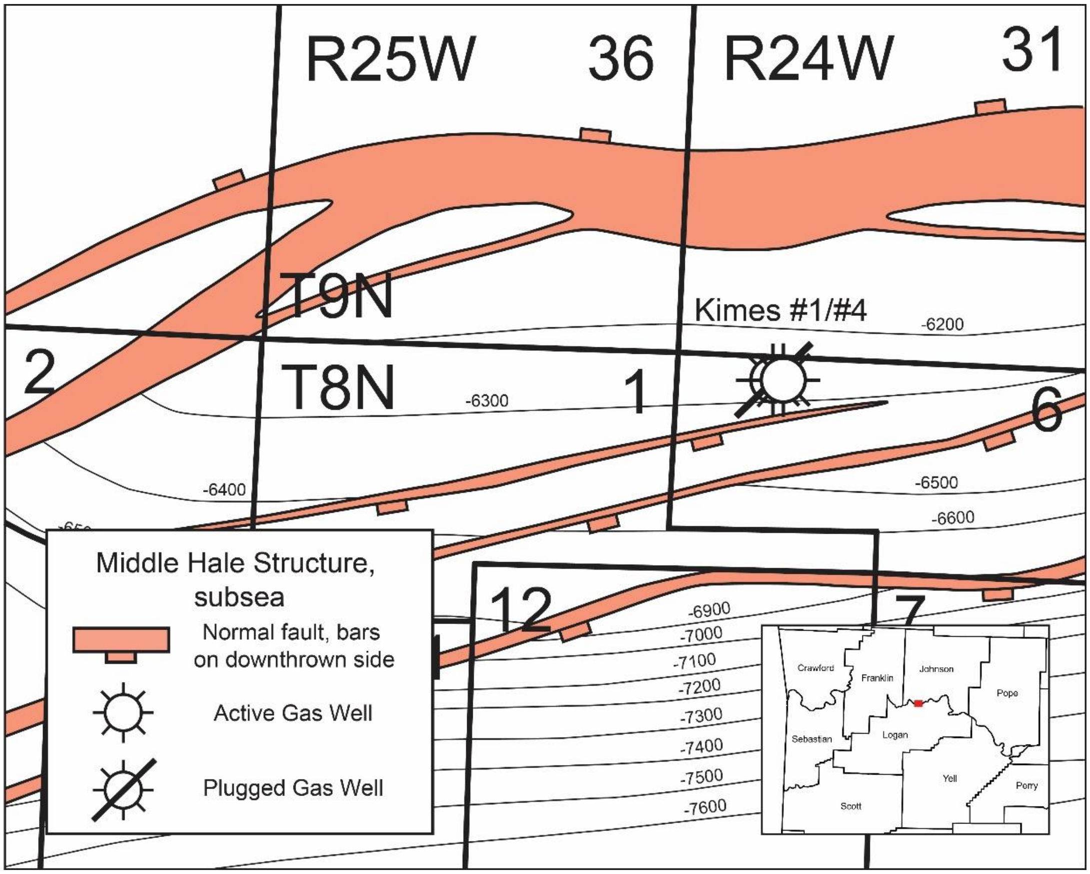

Figure 38. Structural map of the middle Hale sand in the Scranton Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #65-2002-05.

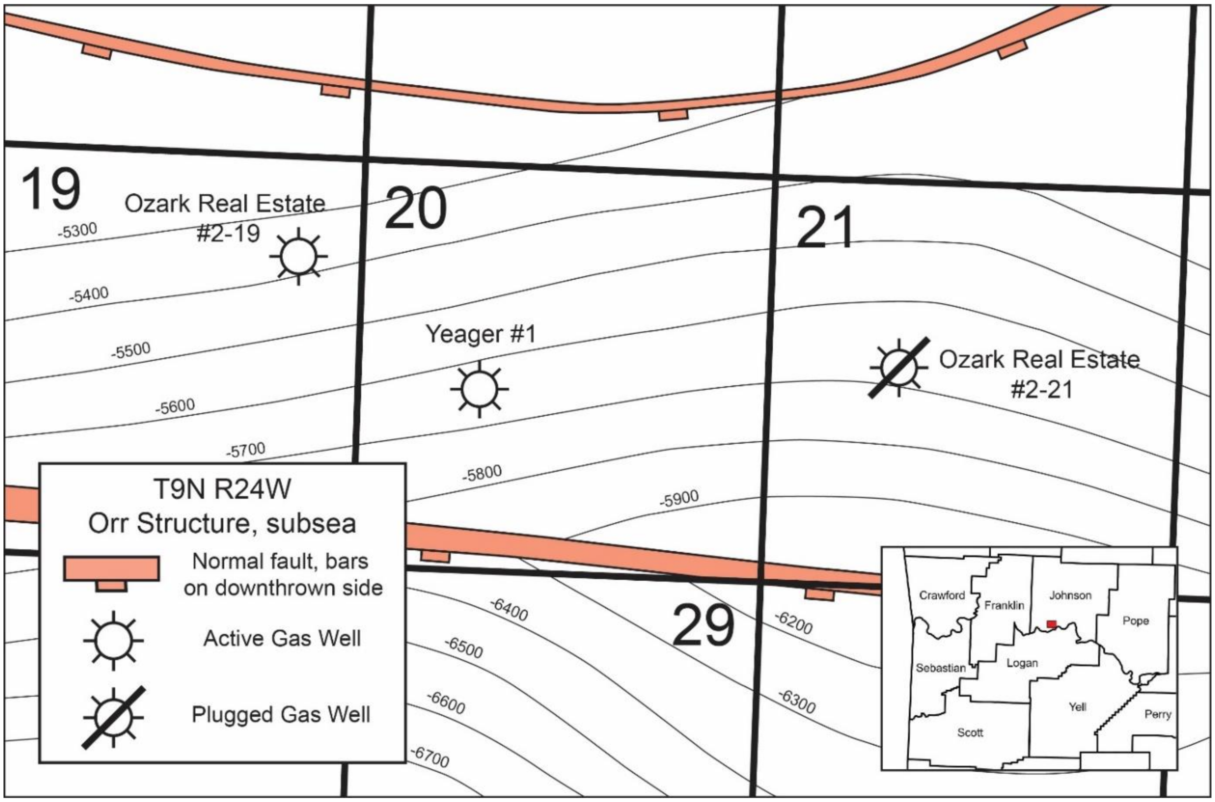

Figure 39. Structural map of the Orr sand in the Scranton Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #4-2000-01 and #12-87.

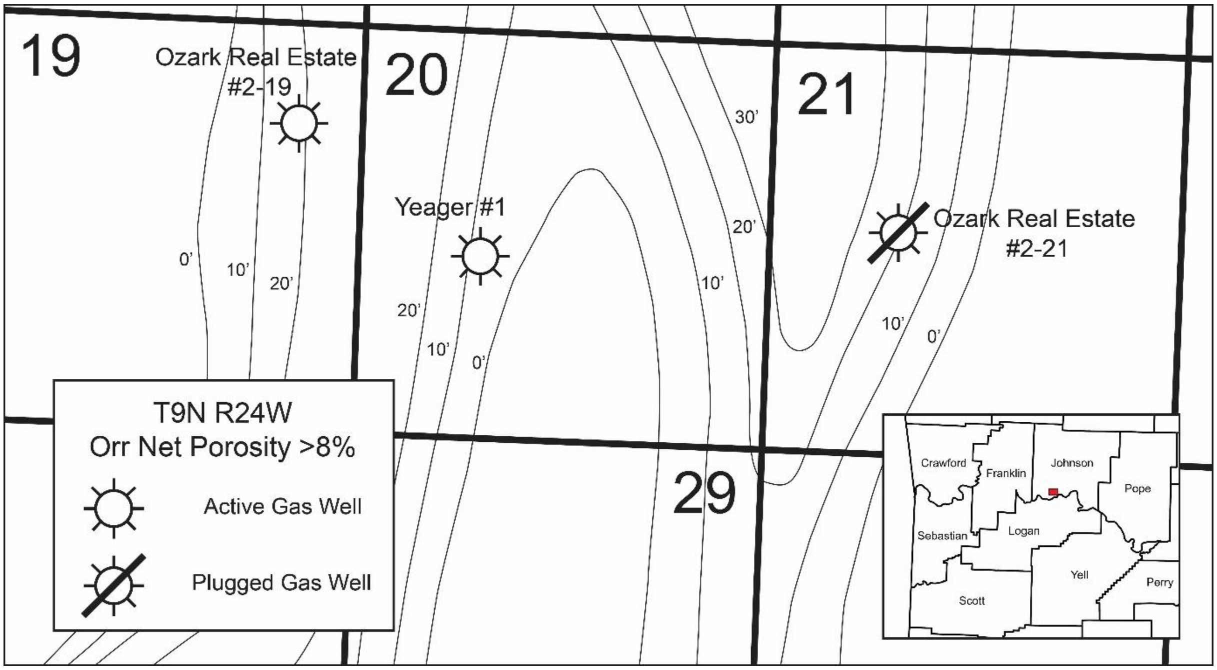

Figure 40. Isopach map of the Orr sand in the Scranton Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #4-2000-01.

Silex Field

The primary area of interest in the Silex Field encompasses sections 32, 33, and 34 of T10N R21W in Johnson County. The Stumbaugh #1 and Casey D. #1 wells have produced over 14 Bcf from the lower Hale sand (Table 14). These wells are located on a south-dipping ramp that terminates at an east-west trending normal fault to the north (Fig. 41). In 2011, an application was submitted to drill a saltwater disposal well in this interval in section 32 (OGC Hearing Docket #286-2011-10). Application and hearing documents stated that the initial bottomhole pressure of 1984 psi in this interval indicated that there are no open faults or fractures into the lower Hale in this area. Therefore, the normal fault located to the north must be a sealing fault. The Strong-Taylor #1 well also penetrates the lower Hale and is still classified as a producing well, though production records indicate it hasn't been active since 2016. This adds about 5.5 Bcf of voidage to the lower Hale, increasing the total void space to about 20 Bcf.

A second, smaller area of interest occurs in sections 21 and 22 of T10N R21W in the lower Hale sand in the Silex #10 well. Structural maps of the Dunn A interval indicate that it is located on an anticline north of a northwest-southeast trending normal fault (Fig. 42). The presence of multiple dry holes on the south side of the fault indicates the fault is a seal. The voidage in the lower Hale in this reservoir is approximately 5.5 Bcf.

Table 14. Wells with high-volume production in the Silex Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
28445	03-071-10295-0000	Stumbaugh #1	32-10N-21W	lower Hale	8.7	PA
28065	03-071-70011-0000	Casey D. #1	33-10N-21W	lower Hale	6.2	PA
28378	03-115-10185-0000	Strong-Taylor #1	34-10N-21W	lower Hale	5.5	PR
32673	03-071-10460-0000	Silex #10	21-10N-21W	lower Hale	5.5	TA

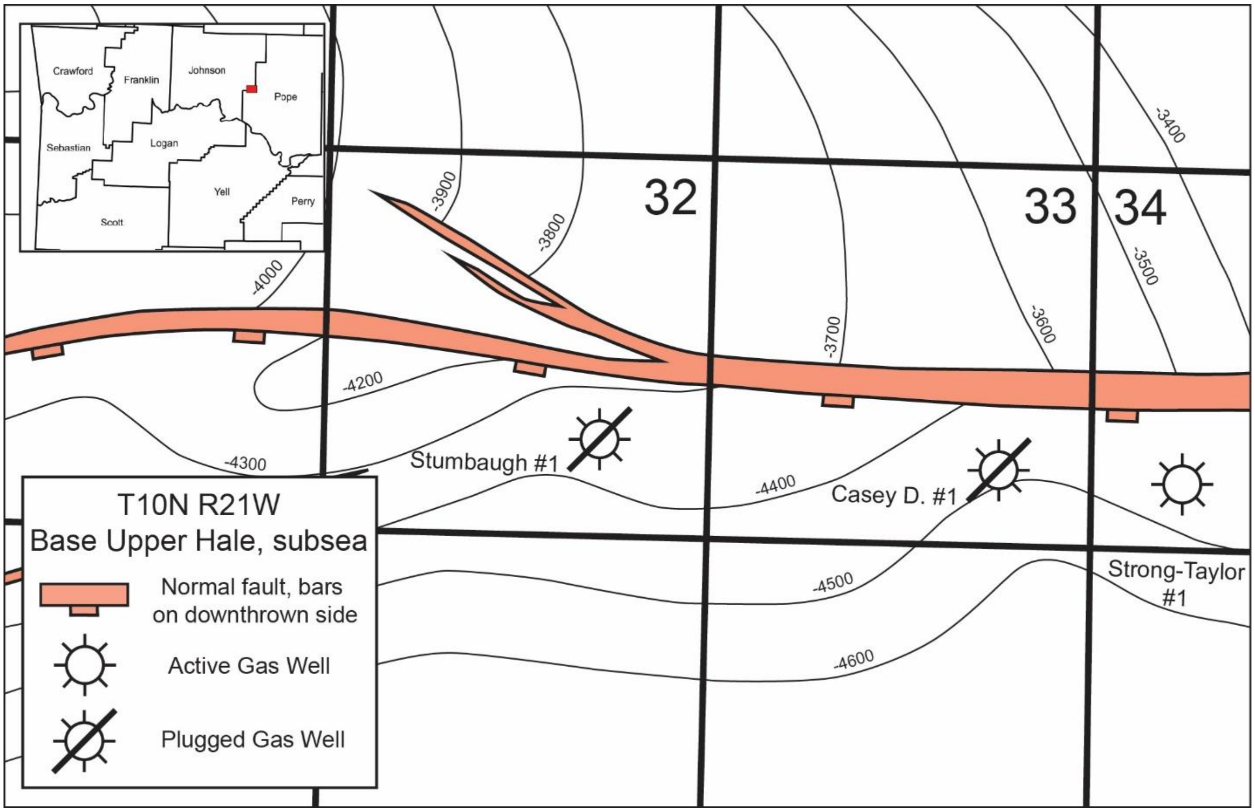

Figure 41. Structural map of the base of the upper Hale sand in the Silex and Ross Fields. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #A18-2006-02.

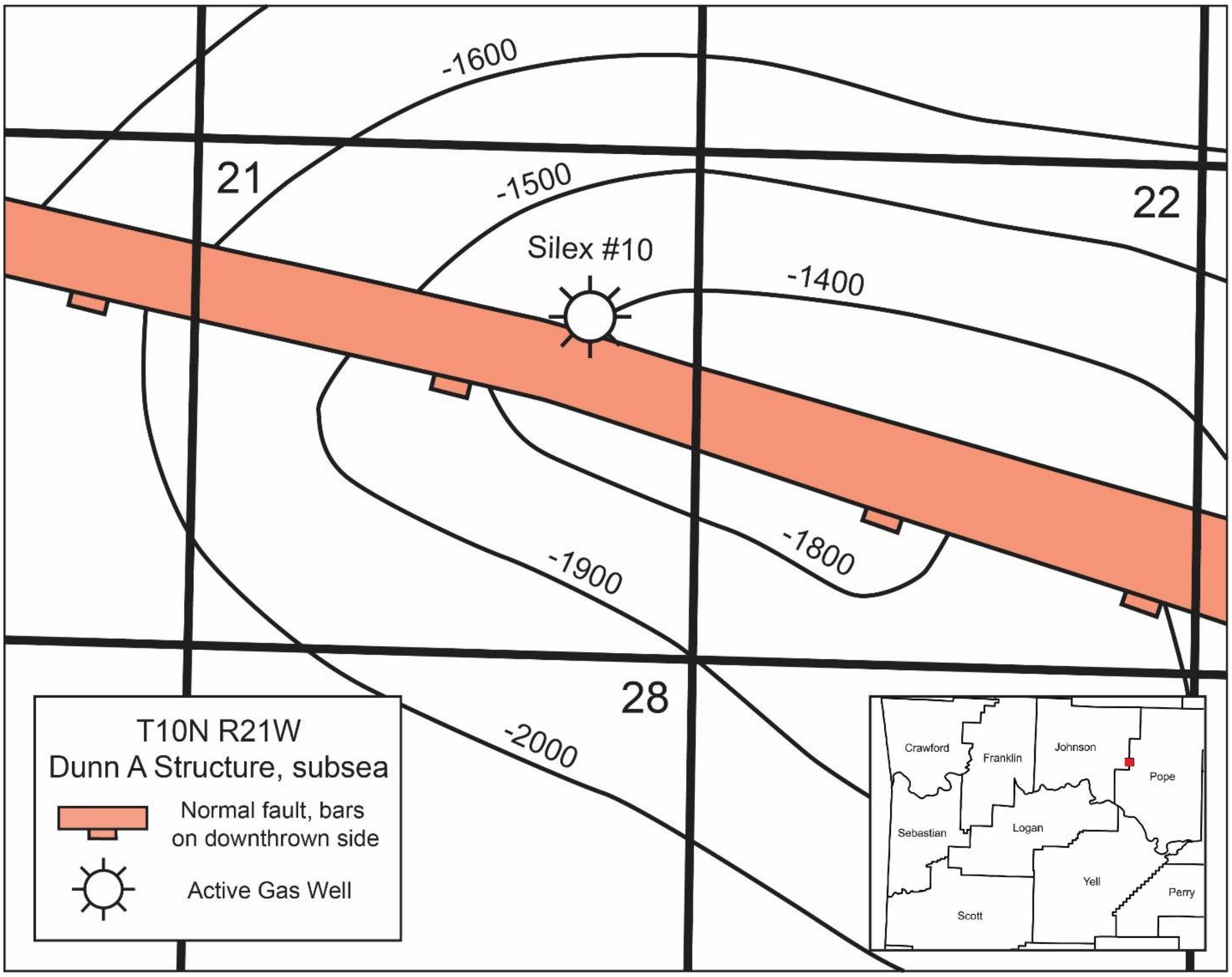

Figure 42. Map with the Dunn A chosen as the structural datum in the Silex Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #180-84.

Spadra Field

The Spadra Field spans Johnson and Logan Counties. The primary areas of interest encompass sections 10, 22, and 23 of T9N R23W (Table 15). The Spadra Bottoms #1 had the largest cumulative gas production among plugged wells (6.7 Bcf) and produced from the R. Barton sand. This well sits on the eastern flank of an anticline truncated by east-west trending, down-to-the-south normal faults (Fig. 43).

The Guyth W. Rogers #1 well, which is adjacent to a normal fault on its north side, has been producing without hiatus since 1968 (Fig. 44). A cumulative 11.4 Bcf of gas has been produced from the middle Atoka Areci sand. The Callahan #1 well, located in a faulted block on an anticline, has produced a total of 13.6 Bcf of gas (Fig. 43). It was a dual gas well with production from the Allen #1 and Allen #2 sands. Until being commingled, 7.4 Bcf and 4.7 Bcf of gas was produced from the Allen #1 and #2, respectively.

Table 15. Wells with high-volume production in the Spadra Field.

Permit	**API**	**Well Name**	**Location**	**Producing Zone**	**Production (Bcf)**	**Status**
17245	03-071-00051-0000	Spadra Bottoms #1	22-9N-23W	R. Barton	6.7	PA
20921	03-083-30021-0000	Guyth W. Rogers #1	33-9N-23W	Areci	11.4	PR
19387	03-071-00025-0000	Callahan #1	10-9N-23W	Allen #1	7.4	PR
19387	03-071-00025-0000	Callahan #1	10-9N-23W	Allen #2	4.7	PR

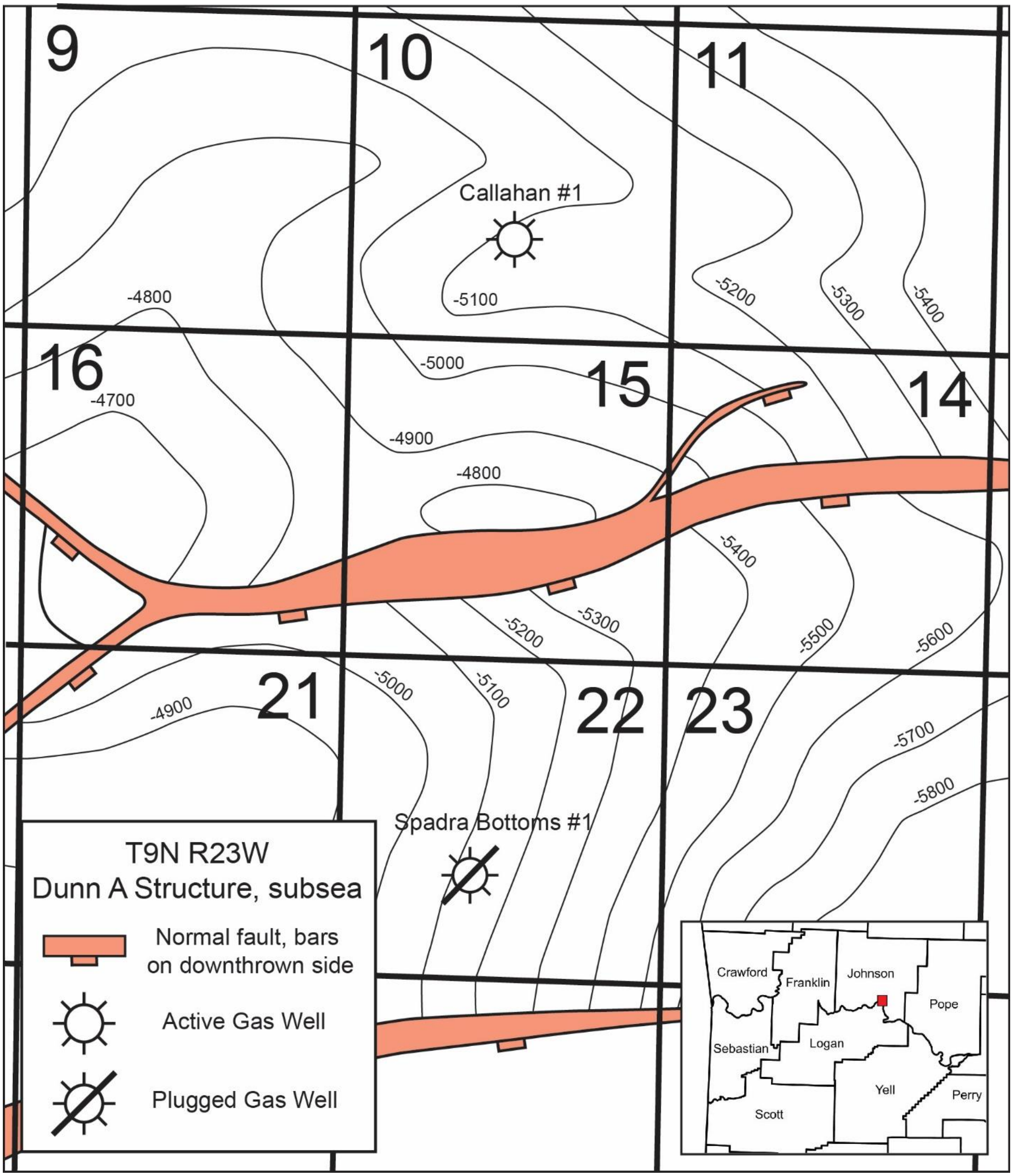

Figure 43. Map with the Dunn A sand chosen as the structural datum in the Spadra Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Dockets #96-27 and #83-2004-07.

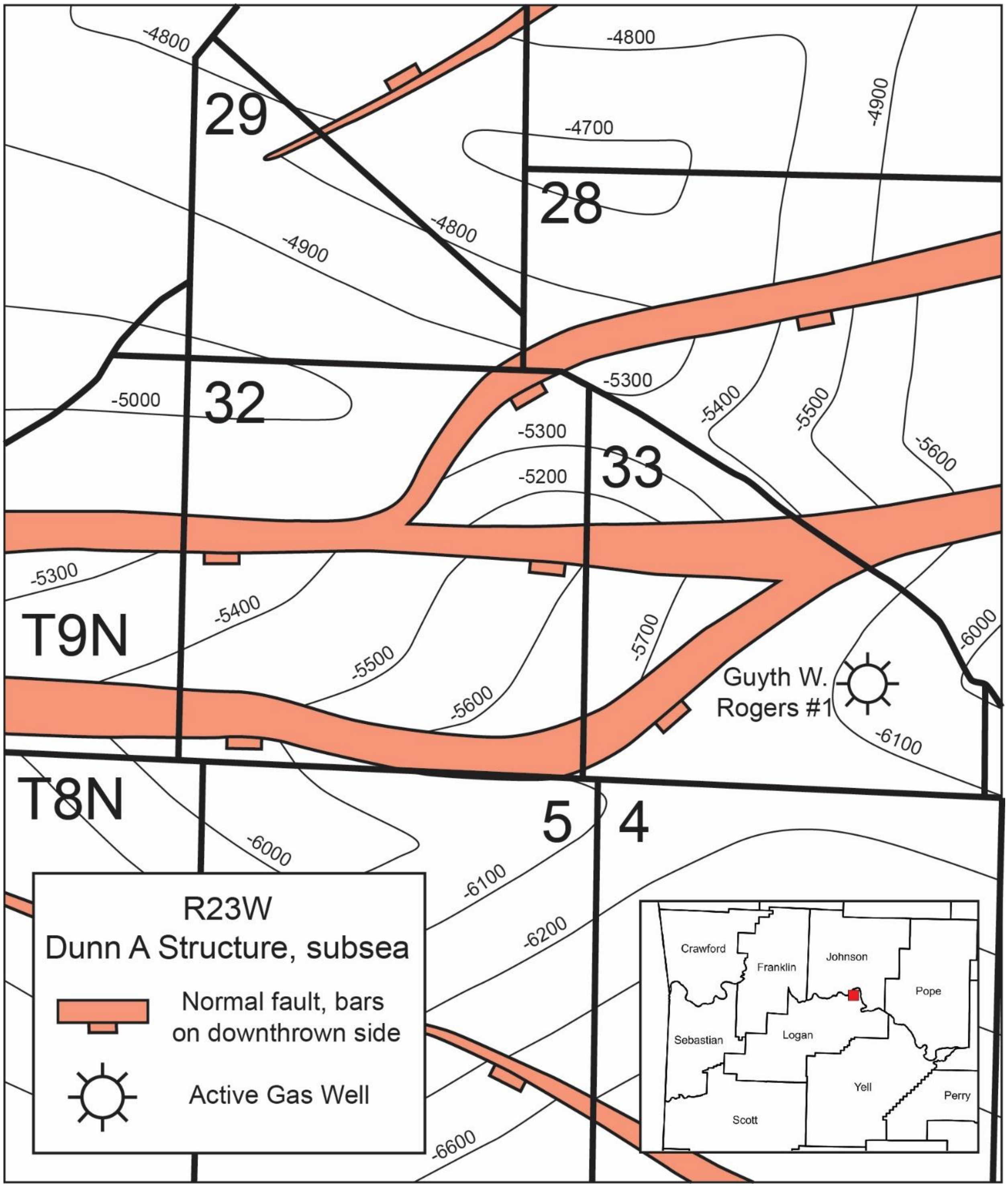

Figure 44. Map with the Dunn A sand chosen as the structural datum in the Spadra Field. Structure contours in feet. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #95-40.

Union City Field

There are no plugged and abandoned wells with significant production values in the Union City Field. Therefore, only producing wells were examined for gas storage potential. The primary areas of interest encompass sections 5, 8, 11, and 17 of T9N R24W in Johnson County. The Kelly sand interval in the B. E. Cobb #1, Ozark Real Estate D #1, and Virgil L. Looper #1 wells in sections 8, 11, and 17 has approximately 25 Bcf of void space (Table 16). Additionally, the Cline sand in the Ben Hardgrave #1 well contains 8.7 Bcf of void space. A structural map of the Kelly sand indicates that there are no favorable structural trapping mechanisms in sections 8 and 17 and likely not in section 11 either (Fig. 45). However, an isopach map of the Kelly sand shows that stratigraphic traps were formed by channel sand deposits (Fig. 46). The reservoir in the Ben Hardgrave #1 well is located on a structural high south of an east-west trending normal fault, providing sufficient structural confinement (Fig. 45).

Table 16. Wells with high-volume production in the Union City Field.

Permit	API	Well Name	Location	Producing Zone	Production (Bcf)	Status
17120	03-071-00048-00-00	B. E. Cobb #1	8-9N-24W	Kelly	9.6	PR
21242	03-071-10009-00-00	Ozark Real Estate D #1	17-9N-24W	Kelly	8.7	PR
21652	03-071-10024-00-00	Virgil L. Looper #1	11-9N-24W	Kelly	6.6	PR
14665	03-071-00009-00-00	Ben Hardgrave #1	5-9N-24W	Cline	8.7	PR

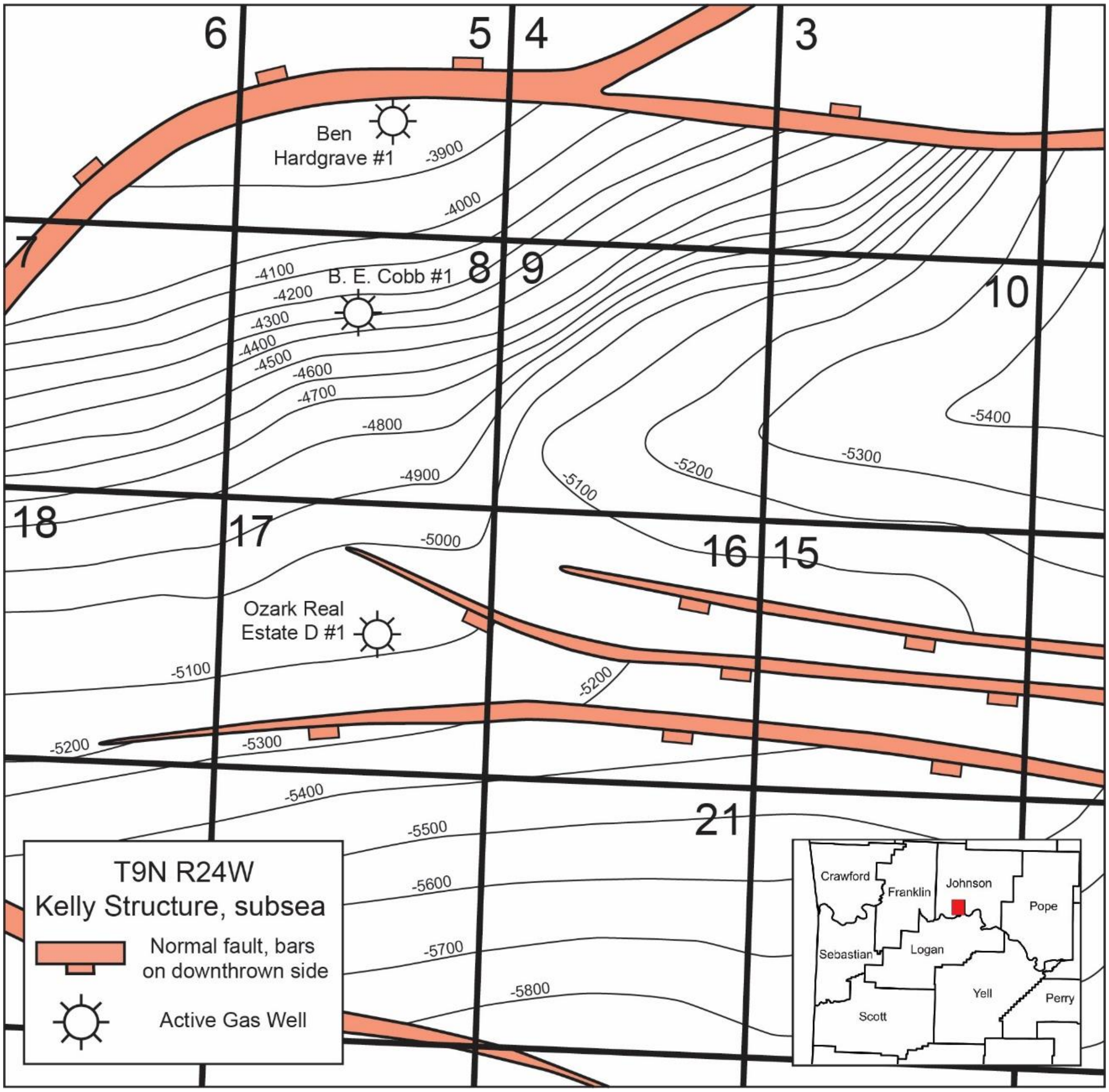

Figure 45. Structural map of the Kelly sand in the Union City Field. Structure contours in feet. Each section is approximately one square mile. Modified from maps in OGC Hearing Docket #148-87.

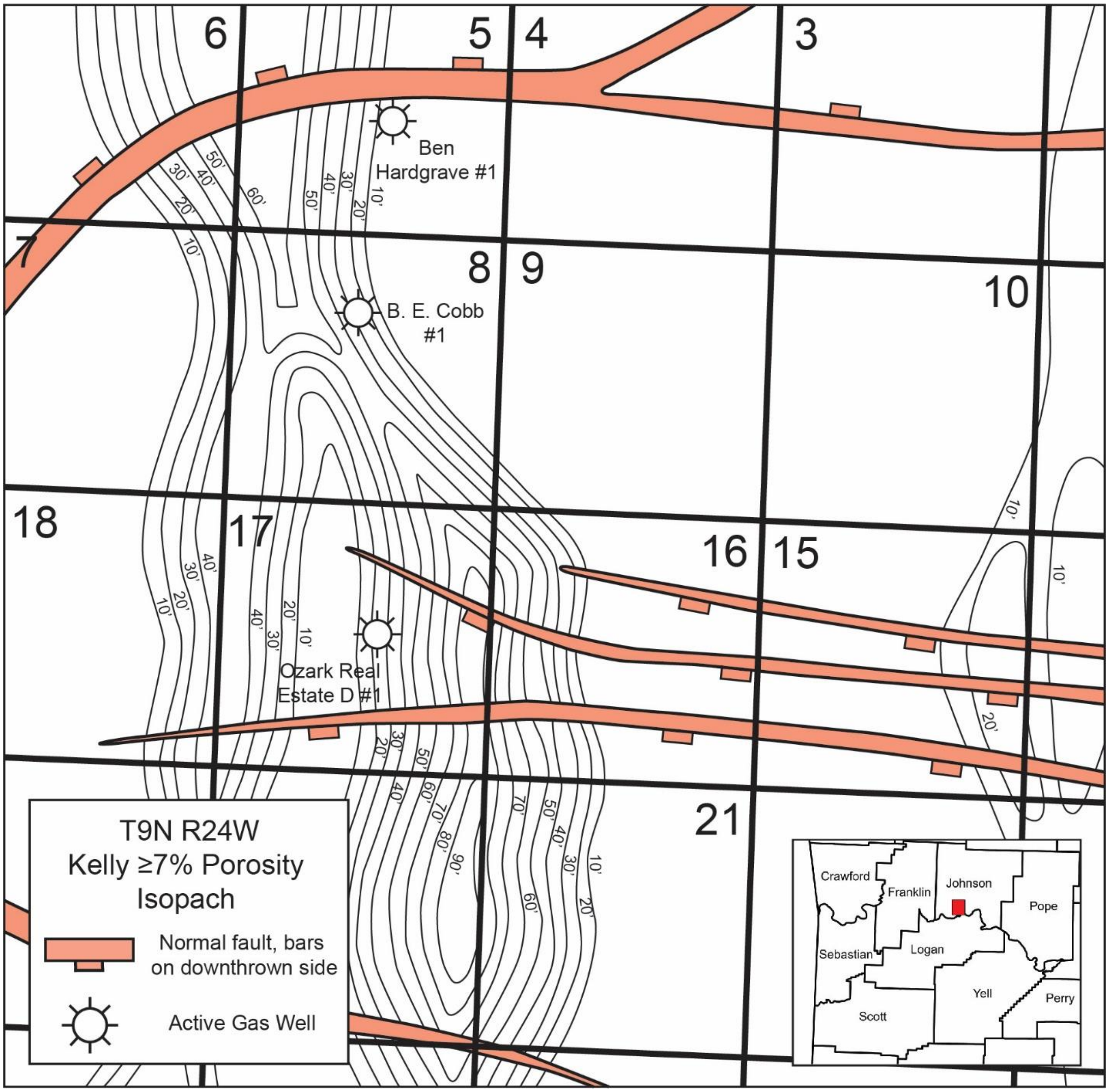

Figure 46. Isopach map of the Kelly sand in the Union City Field. Each section is approximately one square mile. Modified from map in OGC Hearing Docket #148-87.

CONCLUSIONS AND FUTURE WORK

In response to the historic winter storm of February 2021, natural gas fields in the Arkoma Basin in Arkansas were analyzed for favorable conditions for additional gas storage facilities. Thirteen nearly depleted natural gas fields were identified for this study and present large volumes of void space and favorable structural settings that warrant future investigation for underground natural gas storage projects. Among these fields, 66 wells either produced greater than 5 Bcf of gas in a single unit or were situated on the same trap with other highly productive wells. Multiple units in these fields have cumulative available void spaces greater than 10 Bcf. The greatest number of high-yield wells (21) and largest void space in a single well (20 Bcf) occur in the Massard Field.

Future work includes investigating the potential for gas storage in depleted or nearly depleted oil fields in south Arkansas, as this area has sufficient infrastructure to support natural gas storage.

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