[PS]Rhythmic Carbonate Versus Spiculite Deposition in Mississippian Hydrocarbon Reservoirs in the Midcontinent USA: Causative Factors and Resulting Reservoir Petrophysical Attributes*

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Abstract

Subsurface Osagean and Meramecian strata in the central Midcontinent USA (Kansas and northern Oklahoma) generally comprise stacked, shallow-water, carbonate-rock-dominated depositional sequences. Relatively thin sections of shallow- and deeper-water spiculites are present locally in this section, however, and they are interspersed with the carbonate rocks. In contrast, a considerably more prolonged period of spiculite deposition is represented by the Cowley Formation, which was deposited during the late Osagean to early Meramecian over a vast subsurface area encompassing parts of Kansas, Oklahoma, and possibly Panhandle Texas. Carbonate deposition was largely suppressed during this time, and instead, a thick (200-400 ft) section of shallow- to deep-water spiculite and shale was deposited. Such deposits are not present in surface exposures in the Midcontinent. Spiculites and associated carbonate rocks, particularly the thick spiculites in the Cowley Formation, comprise prolific carbonate reservoirs in Kansas and Oklahoma, and there are significant differences in reservoir petrophysical attributes and performance in these contrasting lithologies. Inasmuch as thick spiculites may be a major future play in the central midcontinent, knowledge of the factors that controlled carbonate versus spiculite deposition, and their subsequent diagenesis, are relevant to petroleum exploration and exploitation. Three main interrelated causative factors that appear to have effected rhythmic carbonate versus spiculite deposition are: (1) paleotopography of antecedent depositional surfaces; (2) paleo-latitudinal setting, and; (3) oceanic circulation patterns and upwelling within the precursor Anadarko Basin to the south. Possible controls on short-term versus longer-term periods of spiculite deposition, and on local versus regionally more widespread spiculite occurrence, remain enigmatic.

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RHYTHMIC CARBONATE VERSUS SPICULITE DEPOSITION IN MISSISSIPPIAN HYDROCARBON RESERVOIRS IN THE MIDCONTINENT USA: CAUSATIVE FACTORS AND RESULTING RESERVOIR PETROPHYSICAL ATTRIBUTES

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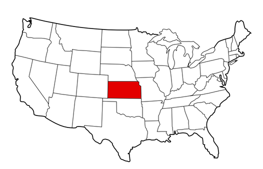
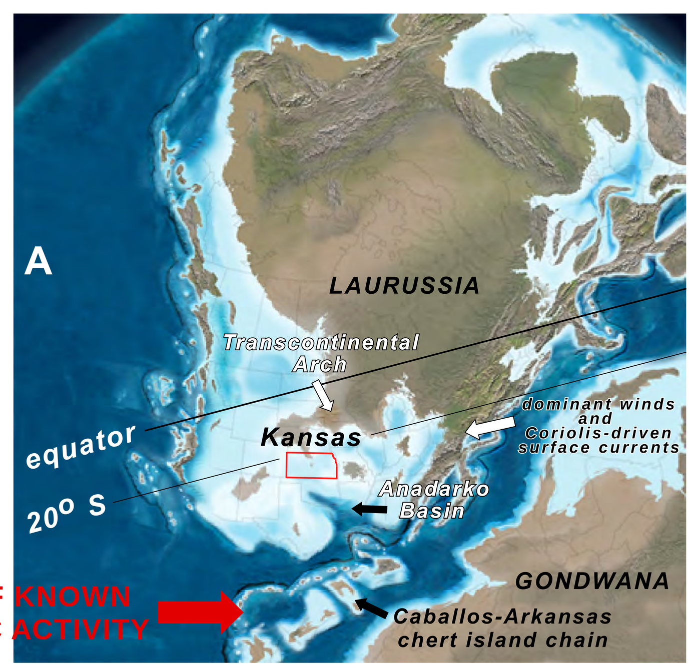
***Brian W. Wilhite** and **I. W. Woolsey**, Woolsey Operating Co. LLC, Wichita KS*

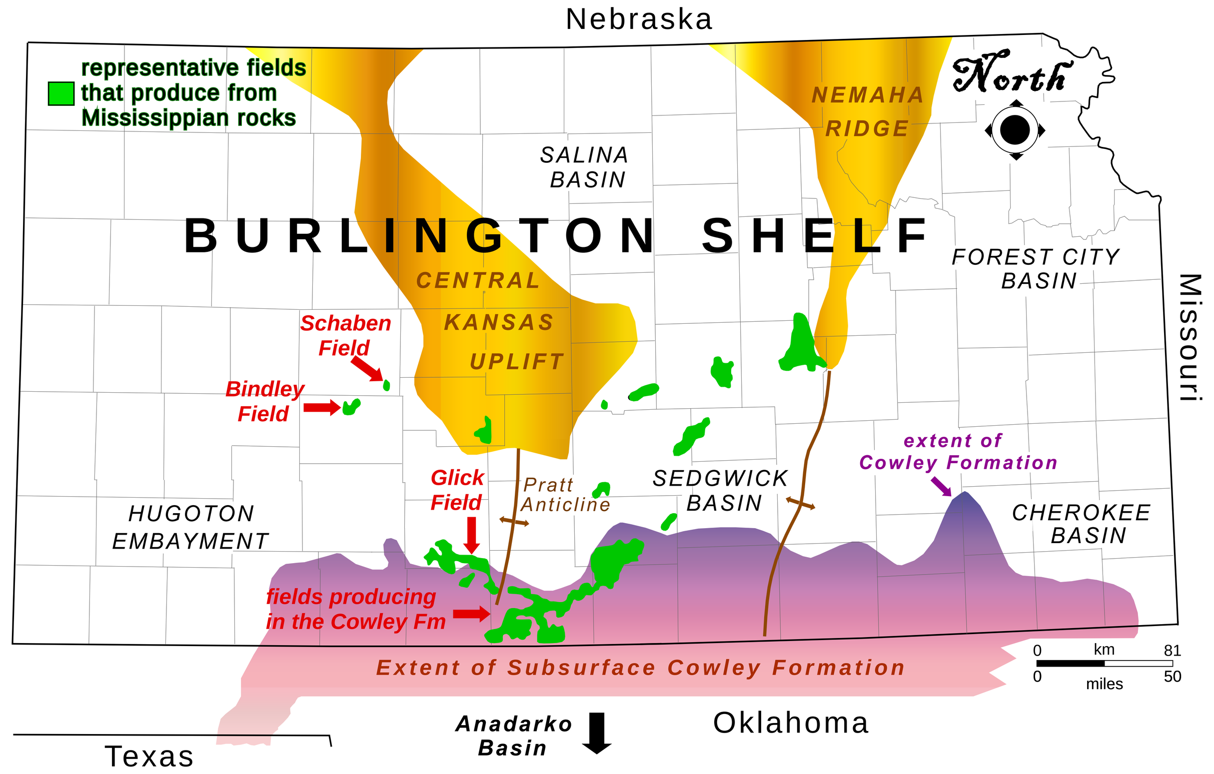
Subsurface Osagean and Meramecian strata in the central Midcontinent USA (Kansas and northern Oklahoma) generally comprise stacked,shallow-water, carbonate rock-dominated depositional sequences. Relatively thin sections of shallow- and deeper-water spiculites are present locally in this section, however, and they are interspersed with the carbonate rocks. In contrast, a considerably more prolonged period of spiculite deposition is represented by the Cowley Formation, which was deposited during the late Osagean to early Meramecian over a vast subsurface area encompassing parts of Kansas, Oklahoma, and possibly panhandle Texas. Carbonate deposition was largely suppressed during this time, and instead, a thick (200-400 ft) section of shallow- to deep-water spiculite and shale was deposited. Such deposits are not present in surface exposures in the midcontinent. Spiculites and associated carbonate rocks, particularly the thick spiculites in the Cowley Formation, comprise prolific carbonate reservoirs in Kansas and Oklahoma, and there are significant differences in reservoir petrophysical attributes and performance in these contrasting lithologies. Inasmuch as thick spiculites may be a major future play in the central midcontinent, knowledge of the factors that controlled carbonate versus spiculite deposition, and their subsequent diagenesis, are relevant to petroleum exploration and exploitation. Three main inter-related causative factors that appear to have effected rhythmic carbonate versus spiculite deposition are: (1) paleotopography of antecedent depositional surfaces; (2) paleo-latitudinal setting, and; (3) oceanic circulation patterns and upwelling within the precursor Anadarko Basin to the south. Possible controls on short-term versus longer-term periods of spiculite deposition, and on local versus regionally more widespread spiculite occurrence, remain enigmatic.

STUDY AREA



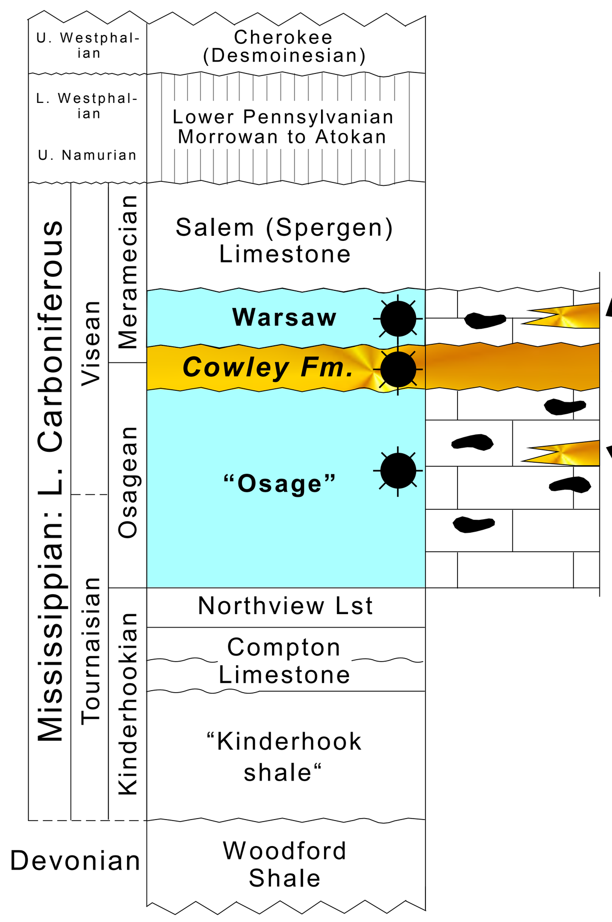


The study area is located in southern Kansas, which lay about 20°S of the paleo-equator during the Early Missisippian (late Tournasian to early Visean). To the south was the deep Anadarko Basin, and farther south, the even deeper-water Caballos-Arkansas chert island chain. Volcanic activity is known in the latter area during the middle Paleozoic.

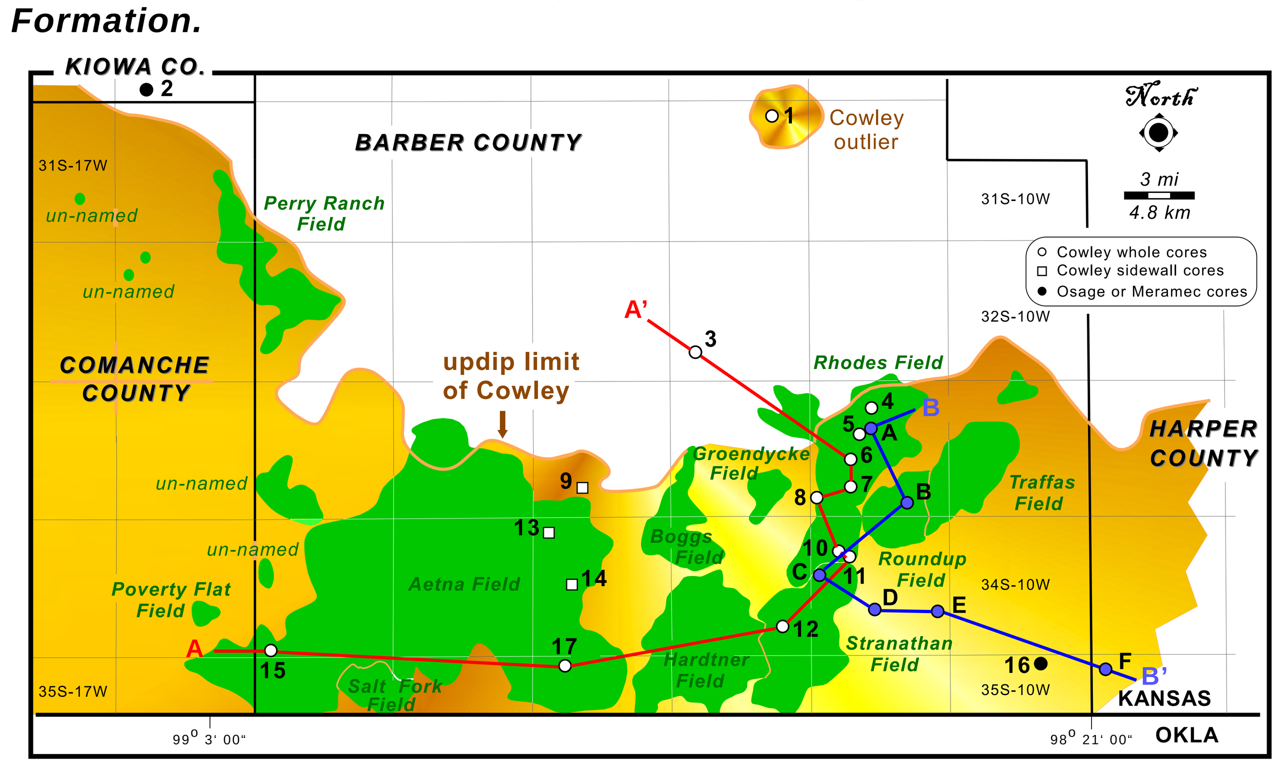


*The main tectonic-physiographic features in the study area are the Nemaha Ridge and Central Kansas Uplifts, and the intervening Cherokee and Salina-Sedgwick basins and the Hugoton Embayment. All of these areas were shallow shelves during the Kinderhookian to Meramecian (Tournaisian to Visean), with the uplift areas becoming embryonic positive emergent features during this time. The main period of uplift was during the late Mississippian to early Pennsylvanian. The shelf areas together comprise the Burlington Shelf during the Mississippian, which can be traced eastward into Missouri, northeastern Oklahoma, and northern Arkansas. **Fields known to produce from spiculitic rocks are indicated by red arrows.***

MISSISSIPPIAN STRATIGRAPHY IN THE STUDY AREA

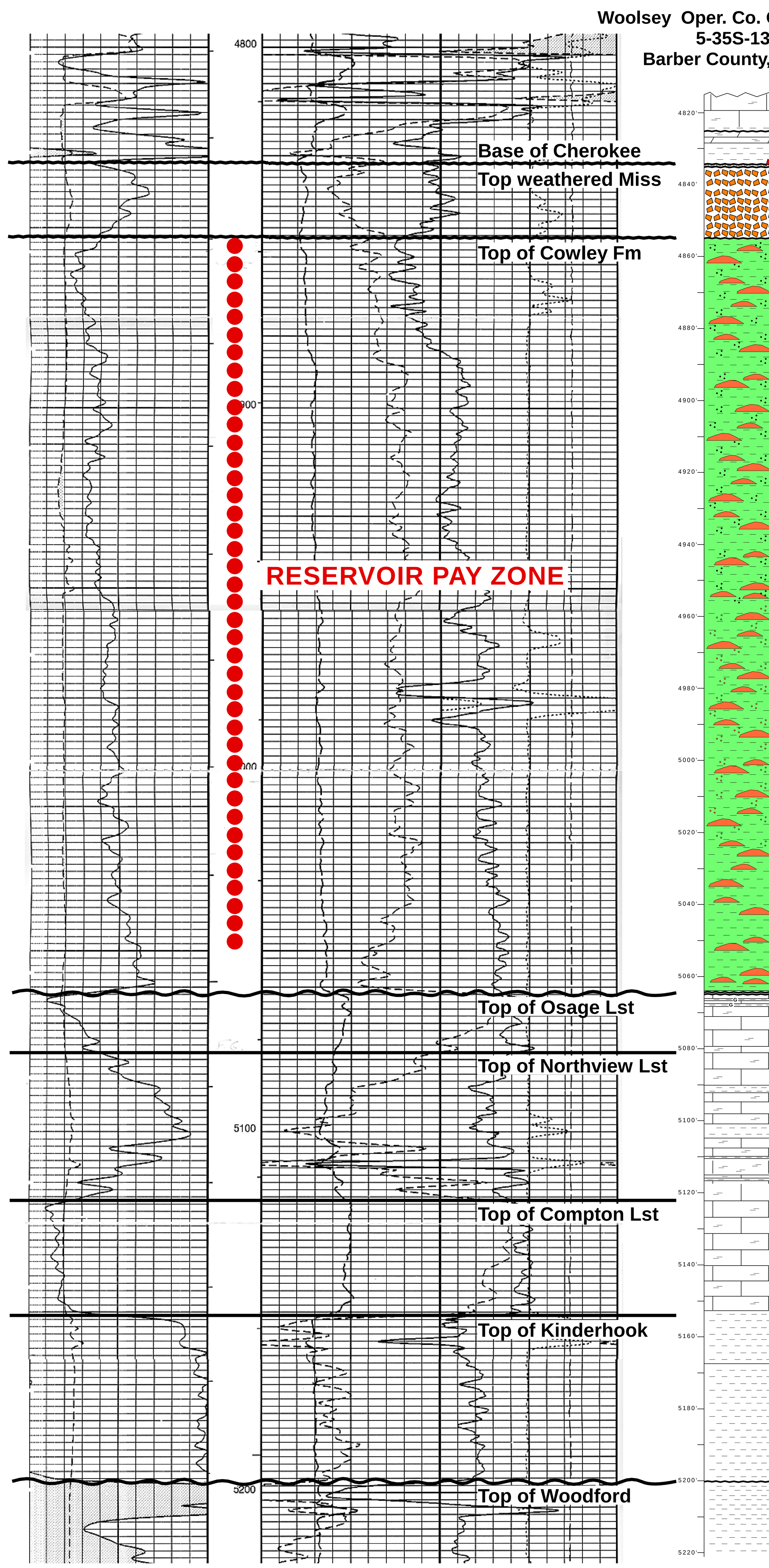


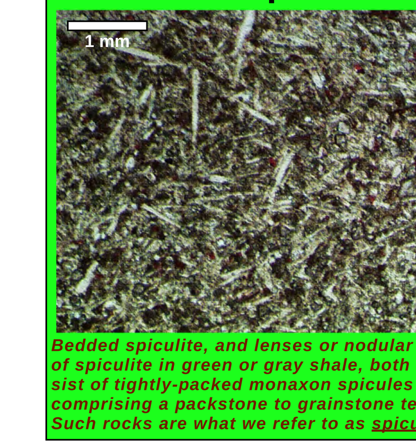
*Except for some exposures in the extreme southeastern part of the state, Mississippian rocks are present only in the subsurface of Kansas, but they are erosionally removed from higher parts of the Nemaha Ridge and the Central Kansas Uplift. Much of the Mississippian in Osagean and lower Meramecian rocks comprises limestone and cherty limestone, with lesser amounts of dolomite. Much of the oil and gas production in the state is from weathered cherts ("chats") and associated carbonate rocks in these sections. However, some fields such and Schaben, Bindley, and Glick, also produce from spiculitic rocks. **In contrast, along the southern tier of Kansas counties, fields such as Aetna, Rhodes, etc produce mostly gas and some oil solely from spiculite that comprises the Cowley Formation.***



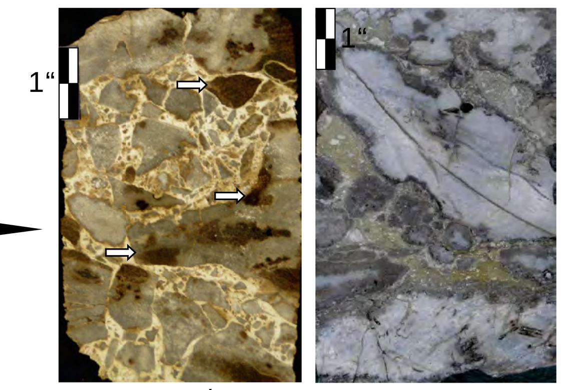
FIELDS IN SOUTH-CENTRAL KANSAS THAT PRODUCE FROM SPICULITES IN THE COWLEY FM

SPICULITES IN THE COWLEY FORMATION



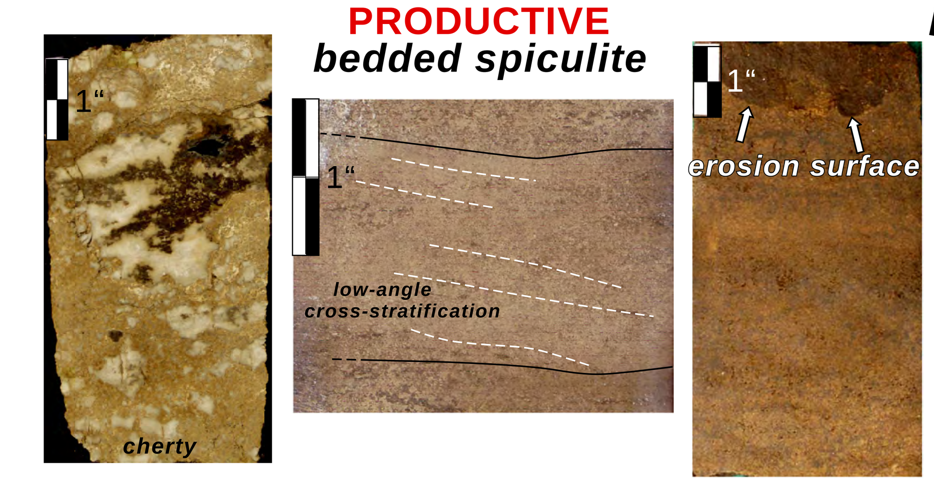


RARELY PRODUCTIVE
colluvial breccia

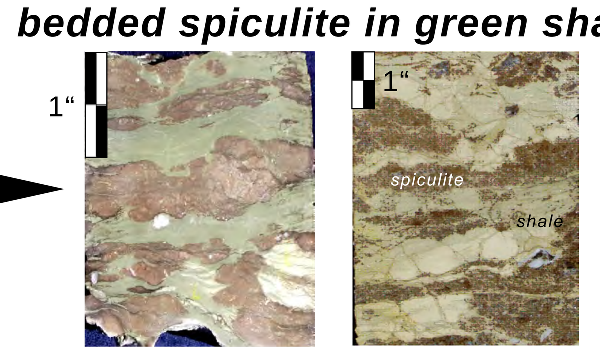


arrows point to oil stain

PRODUCTIVE
bedded spiculite

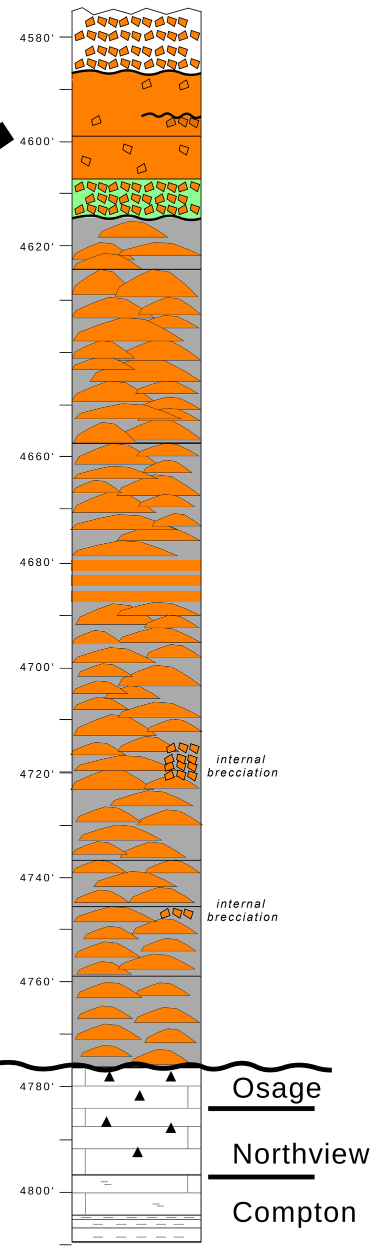


PRODUCTIVE
lenticular/nodular/flaser-bedded spiculite in green shale

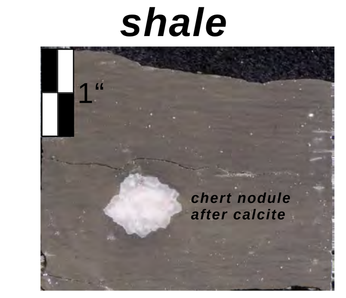


minor to no silicification — *shale and some spiculite lenses are silicified*

Woolsey Oper. Co. Wiley B-1
8-34S-11W
Barber County, Kansas

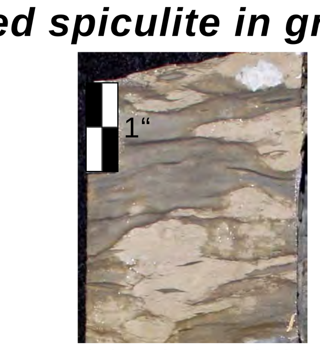


NON-PRODUCTIVE
deepest-water shale



dark gray shale, slightly spiculitic

PRODUCTIVE
lenticular/nodular/flaser-bedded spiculite in gray shale



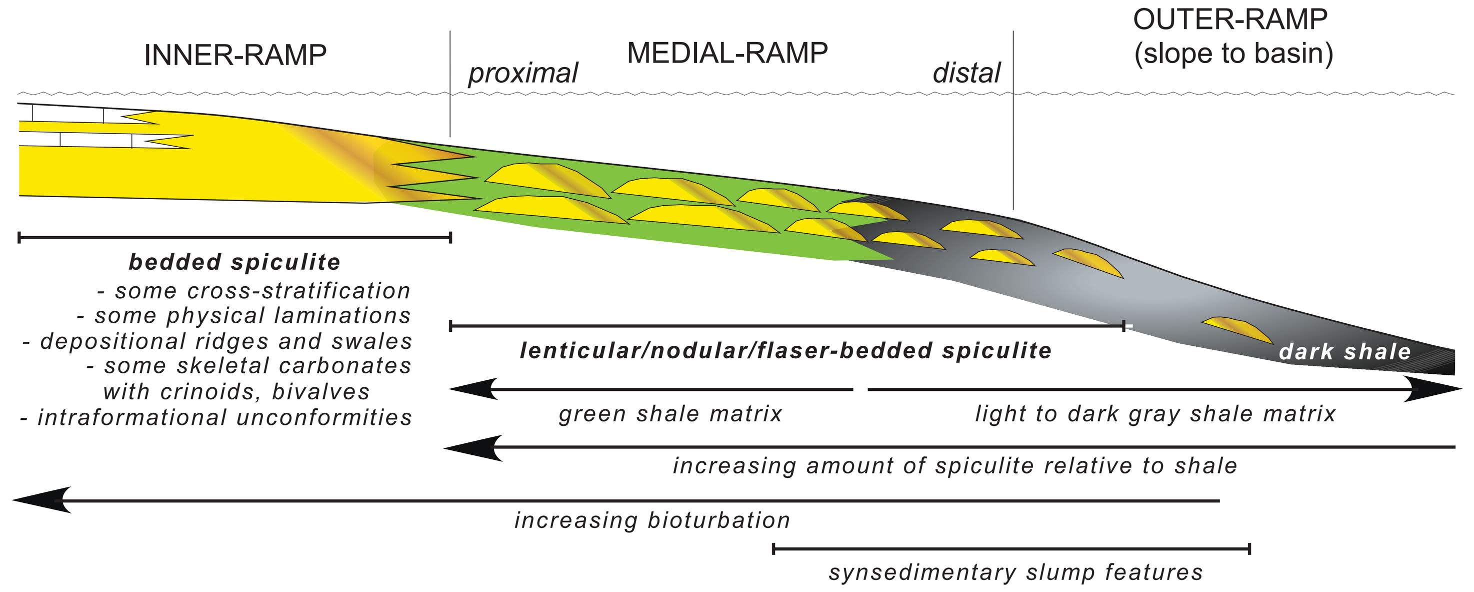
shale and some spiculite lenses are silicified

spiculite-clast breccia
bedded spiculite
spiculite lenses in shale
green shale in Cowley
gray shale in Cowley
limestone
shaly limestone
dolomite
shaly dolomite
chert nodules
unconformities

- ***The Cowley Formation is present throughout the study area in south-central Kansas, and can be traced as far eastward as Cherokee County in the far southeastern part of the state.***
- ***Lithologies comprising the Cowley Formation are:***
  - ***bedded spiculite***
  - ***lenticular/nodular/flaser-bedded spiculite and shale***
  - ***dark gray shale***
  - ***spiculite-clast breccia in light green and yellowish green shale immediately below the top-of-Mississippian unconformity. The shale and spiculite clasts typically are pervasively replaced by chert***
- ***The Cowley Formation section always coarsens upward from shale to lenticular/nodular/flaser-bedded spiculite and shale to bedded spiculite, although the latter lithology commonly has been removed by post-Cowley erosion***

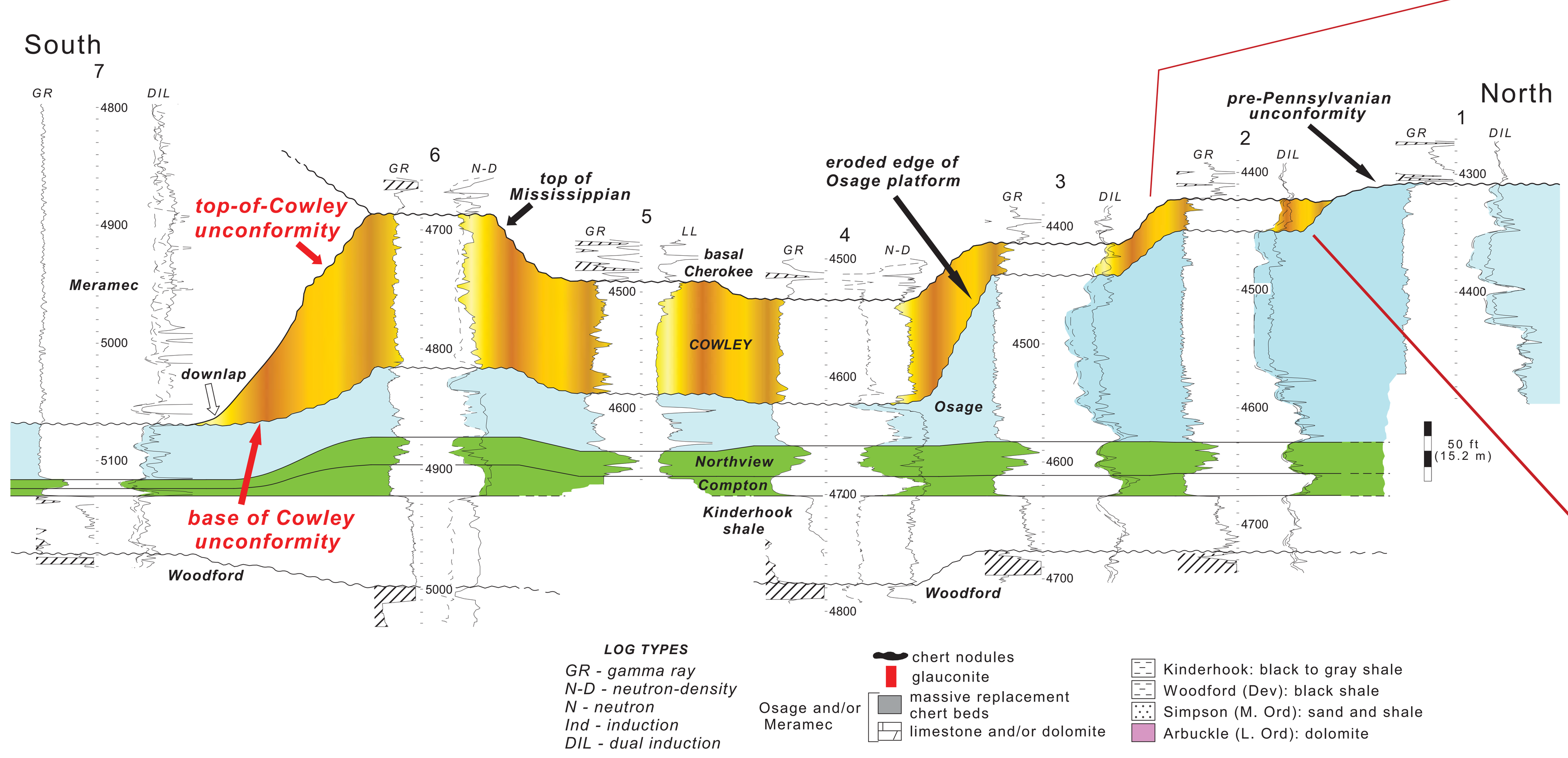
Reservoirs in the Cowley Formation are in bedded spiculites as well as in lenticular/nodular/flaser-bedded spiculite and shale

Depositional Environments of the Cowley Formation



- Bedded spiculites represent the shallowest water deposits in the Cowley Formation, deposited in moderate-energy environments. The spicules in the rocks are entirely monaxon types derived from demosponges
- Lenticular/nodular/flaser-bedded spiculite and shale represents progressively deeper, more offshore environments that grade distally from green shale to gray shale matrix (oxic to sub-oxic conditions)
- Dark shales are the deepest-water and most distal deposits
- The spatial arrangement of lithologies in the Cowley is interpreted to reflect deposition on a ramp

Stratigraphic Architecture of the Cowley Formation



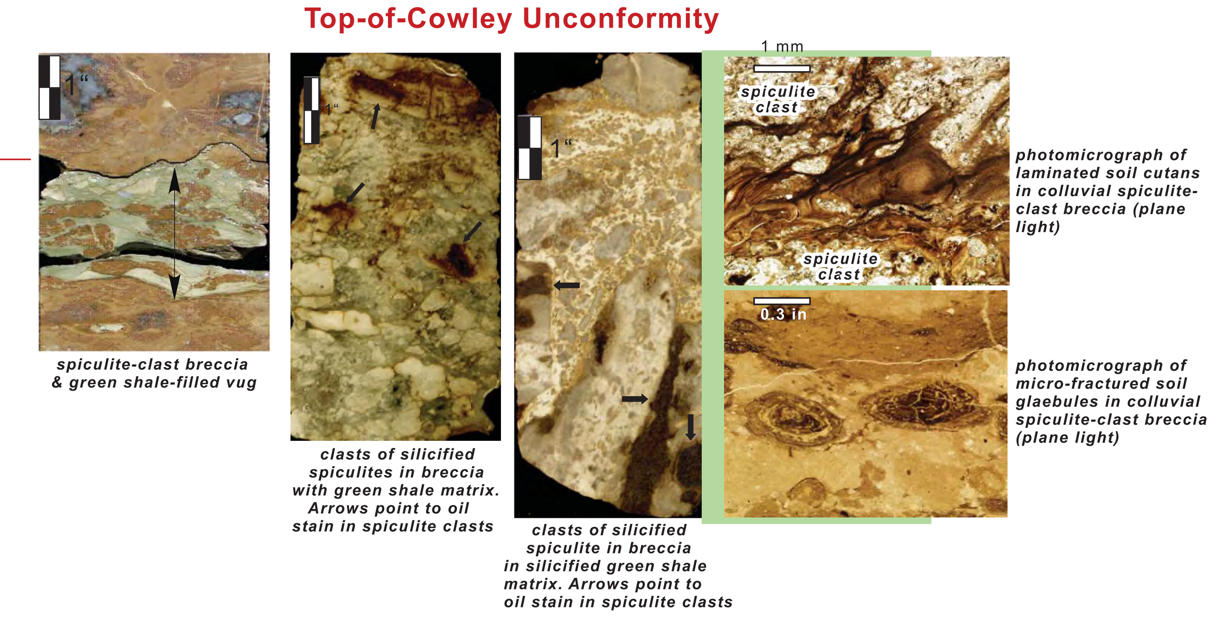
- The Cowley was deposited as a thick (as much as 400 ft) wedge of sediment upon a major unconformity at the top of the Osage. This unconformity is present throughout subsurface Kansas as well as in outcrops of Mississippian rocks in SW Missouri, NE Oklahoma, and NW Arkansas.
- The Cowley sedimentary wedge thins depositionally and by post-depositional erosion in an updip direction (to the north-northwest) as it onlapped underlying Osagean strata, and it thins depositionally in a basinward direction (to the south-southeast) by downlap.
- The top of the Cowley is an unconformity that was developed as a result of subaerial exposure in immediate post-Cowley time. This unconformity was overprinted by the unconformity at the top of the Mississippian, which represents a second-order, type-1 unconformity at the top of the Kaskaskia Sequence.

Evidence of Unconformities

Evidence of unconformities at the top and base of the Cowley, and within the Cowley, include:

- spiculite-clast breccias, which are progressively more silicified toward unconformities
- marine-reworked breccias
- breccia and/or green shale-filled vugs
- colluvium with incipient pedogenic features
- post-depositional (erosional) removal of bedded spiculite sections
- erosion surfaces

Top-of-Cowley Unconformity



spiculite-clast breccia & green shale-filled vug

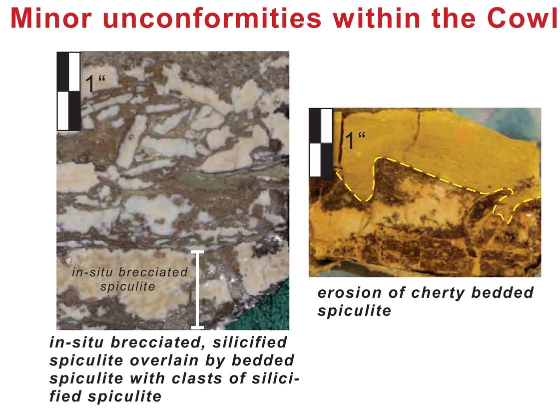
clasts of silicified spiculites in breccia with green shale matrix. Arrows point to oil stain in spiculite clasts

clasts of silicified spiculite in breccia in silicified green shale matrix. Arrows point to oil stain in spiculite clasts

photomicrograph of laminated soil cutans in colluvial spiculite-clast breccia (plane light)

photomicrograph of micro-fractured soil glaebules in colluvial spiculite-clast breccia (plane light)

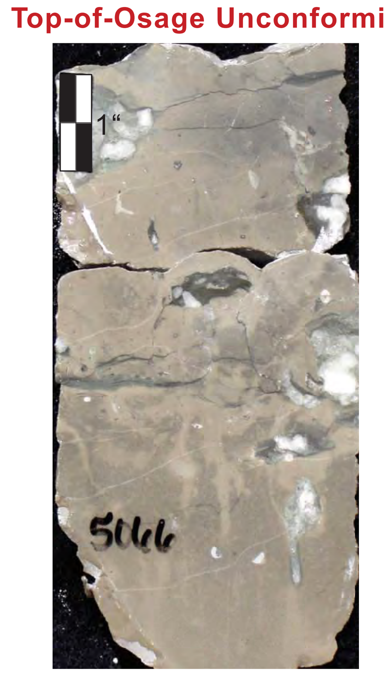
Minor unconformities within the Cowley



in-situ brecciated, silicified spiculite overlain by bedded spiculite with clasts of silicified spiculite

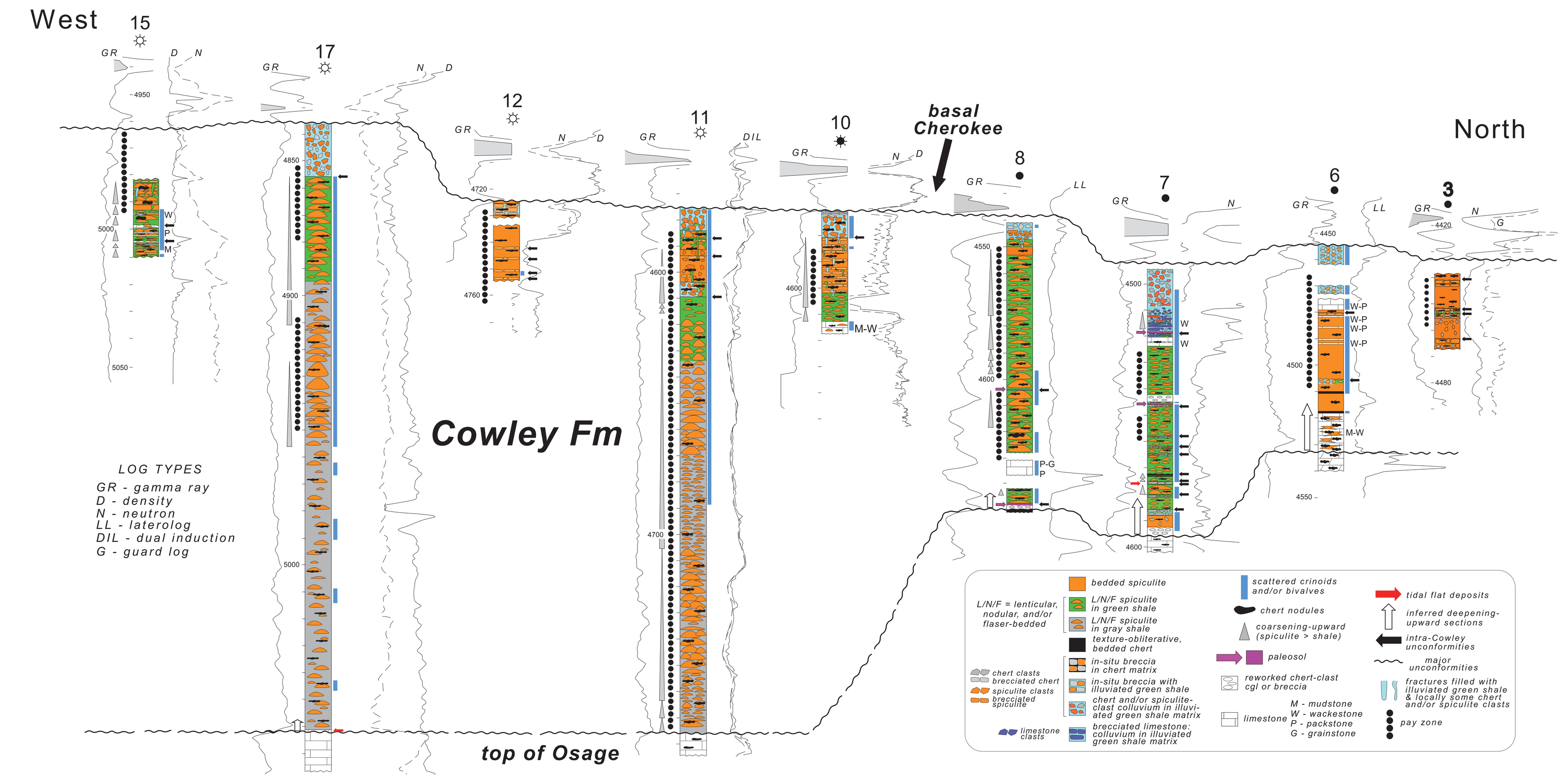
erosion of cherty bedded spiculite

Top-of-Osage Unconformity



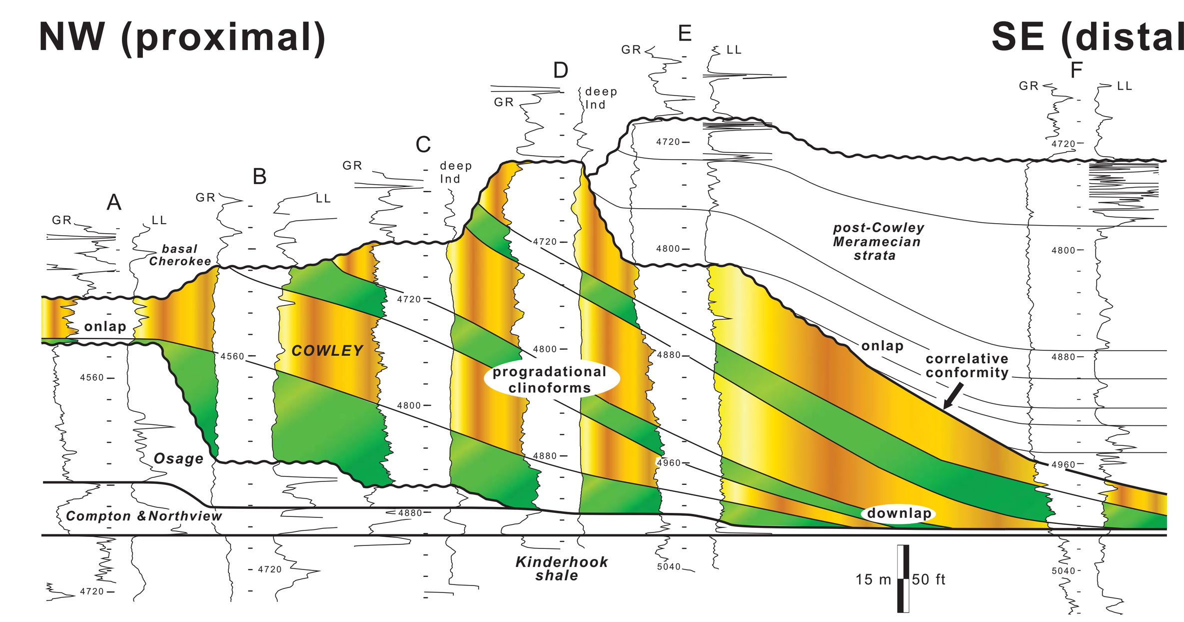
Clay-filled vugs and fractures immediately below the unconformity at the base of the Cowley Fm

Sequence Stratigraphic Architecture of the Cowley Formation

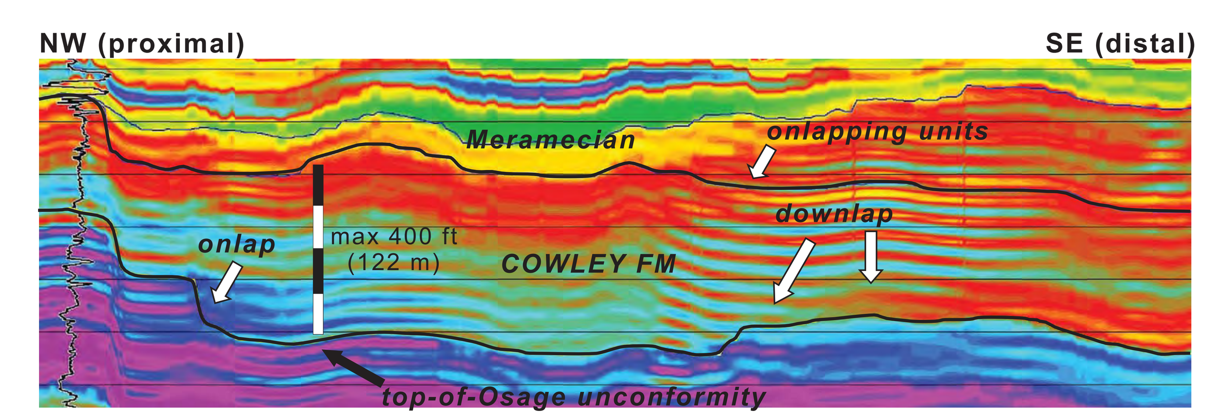


The fundamental sedimentologic attributes of the spiculite-dominated Cowley Formation section are:

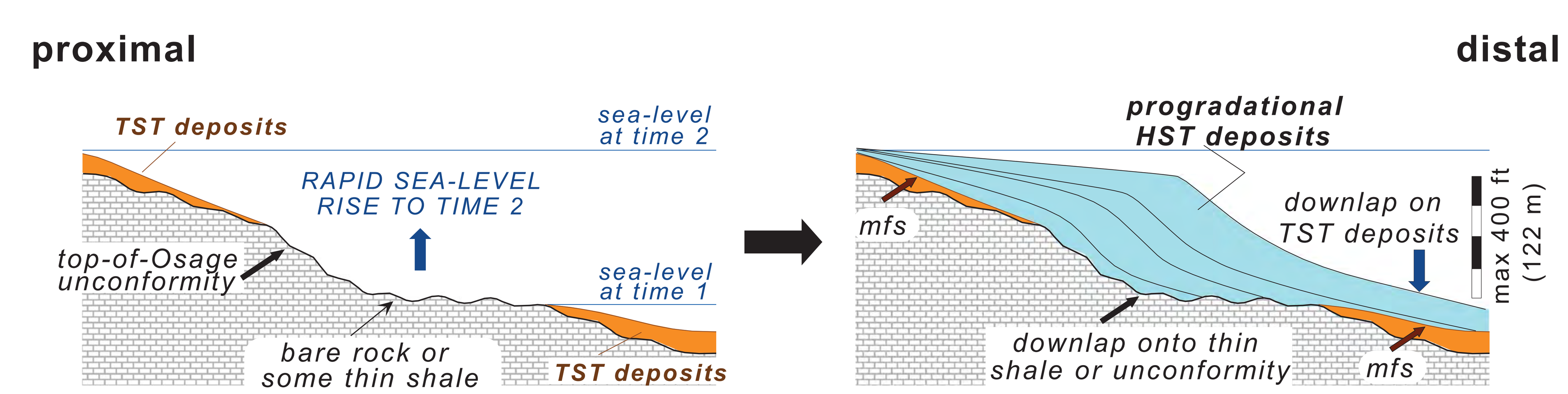
- the section coarsens upward, and also laterally in a distal-to-proximal transect, from dark gray shale to lenticular/nodular/flaser-bedded spiculite in lighter gray and then green shale, to bedded spiculite (where the latter has not been eroded)
- limestones are only a minor component in the section
- the section is bounded by major unconformities



- detailed log correlations suggest that the section comprises basinward (to the SE) prograding sediment wedges that downlap the erosional top of the Osage (i.e., clinoforms), some of which are separated by minor (type 2) unconformities
- basal beds in the Cowley locally onlap the eroded top of Osage surface
- younger Meramecian strata onlap the erosional top of the Cowley

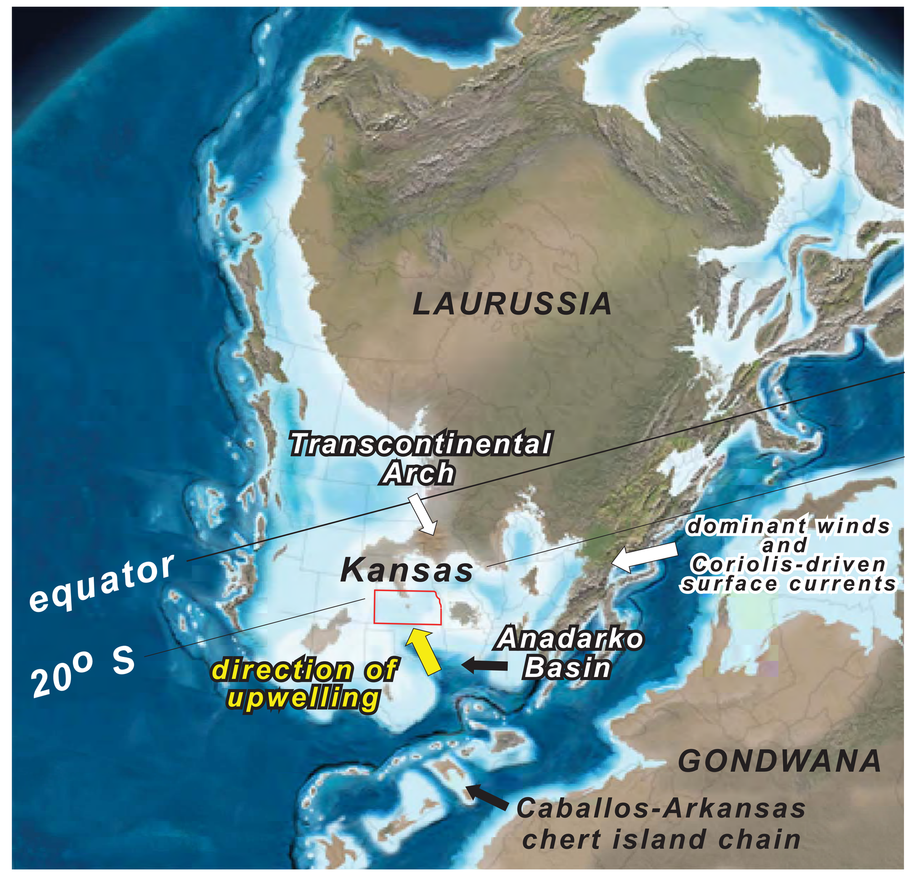


- proximal-to-distal 3-D seismic confirms an internal stratigraphic architecture of progradational clinoforms in the Cowley, onlapping of basal Cowley strata, and onlapping of overlying Meramecian strata on the top of the Cowley



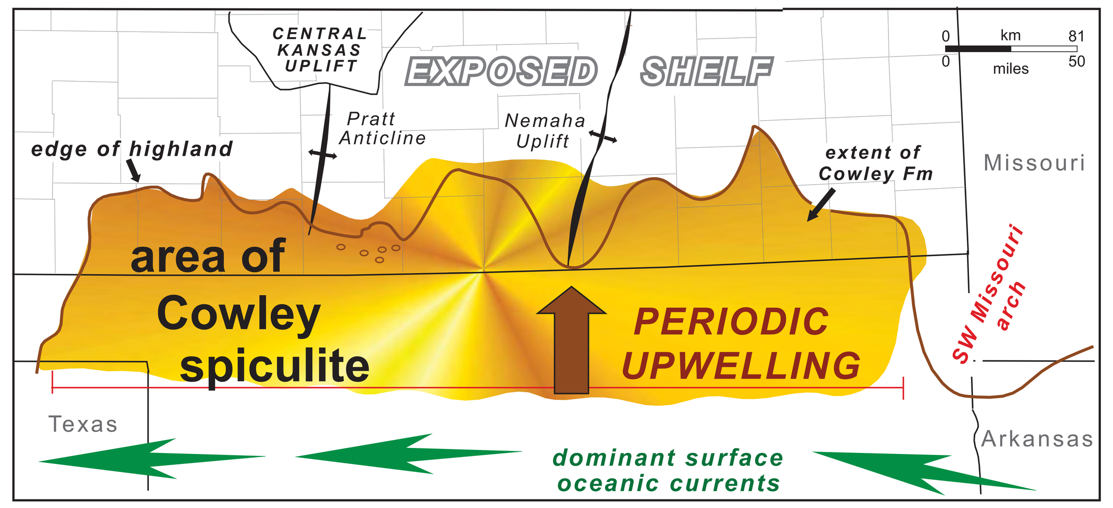
The spiculite-dominated Cowley section is therefore interpreted as a depositional sequence that is sandwiched between sequences in the underlying Osagean and overlying Meramecian sections.

SUPPRESSION OF CARBONATE DEPOSITION DURING DEPOSITION OF THE COWLEY SPICULITE



The spiculite-dominated Cowley Formation was deposited within an embayment of the Burlington Shelf adjacent to the deeper Anadarko Basin to the south. Farther south there is evidence of Mississippian volcanism in the Caballos Chert-Arkansas Novaculite island chain and, possibly, also elevated dissolved silica concentrations (Lowe, 1975). Upwelling can be inferred based on dominant wind directions (Parrish, 1992)

- *WE CANNOT INFER DEEP-WATER DEPOSITION, OR COOL BUT SHALLOW-WATER DEPOSITION OF THE COWLEY, BECAUSE IT WAS DEPOSITED CLOSE TO THE EQUATOR*
- *HENCE, SOME OCEANOGRAPHIC FACTORS MUST HAVE PERIODICALLY SUPPRESSED CARBONATE DEPOSITION AND INSTEAD PROMOTED SPICULITE DEPOSITION HERE IN SHALLOW TO DEEPER-WATER ENVIRONMENTS*



INFERRED PROCESSES		INFERRED PRODUCTS
dominantly easterly winds & Coriolis-driven surface currents	➡	*periodic upwelling of deep-basin waters from the south*
upwelling brings colder, silica-rich and nutrient-rich water into the Cowley embayment	➡	*periodic suppression of carbonate deposition and, instead, promotion of spiculite deposition*

Example of Such a Model for Spiculite Deposition:

- *Eocene of southwestern Australia (James & Bone, 2000), related to suppression of shallow-water carbonate deposition because of upwelling of nutrients and silica-rich waters (e.g., James, 1997)*

Upwelling Inferred in Other Mississippian Shelf Areas in the Midcontinent

Lane & DeKeyser (1980) Lumsden (1988) Wright (1991) Franseen (2006)

Gutschick & Sandberg (1983) Lasemi et al. (1998, 2003)

Other Mississippian Spiculitic Rocks Associated with Carbonate Rocks in Kansas

Clair (1948) Lane & DeKeyser (1980) Gutschick & Sandberg (1983)
Montgomery et al. (1988) Watney et al. (2001) Rogers et al. (1995)
Ebanks (1991) Ebanks et al. (1977) Johnson (1994)
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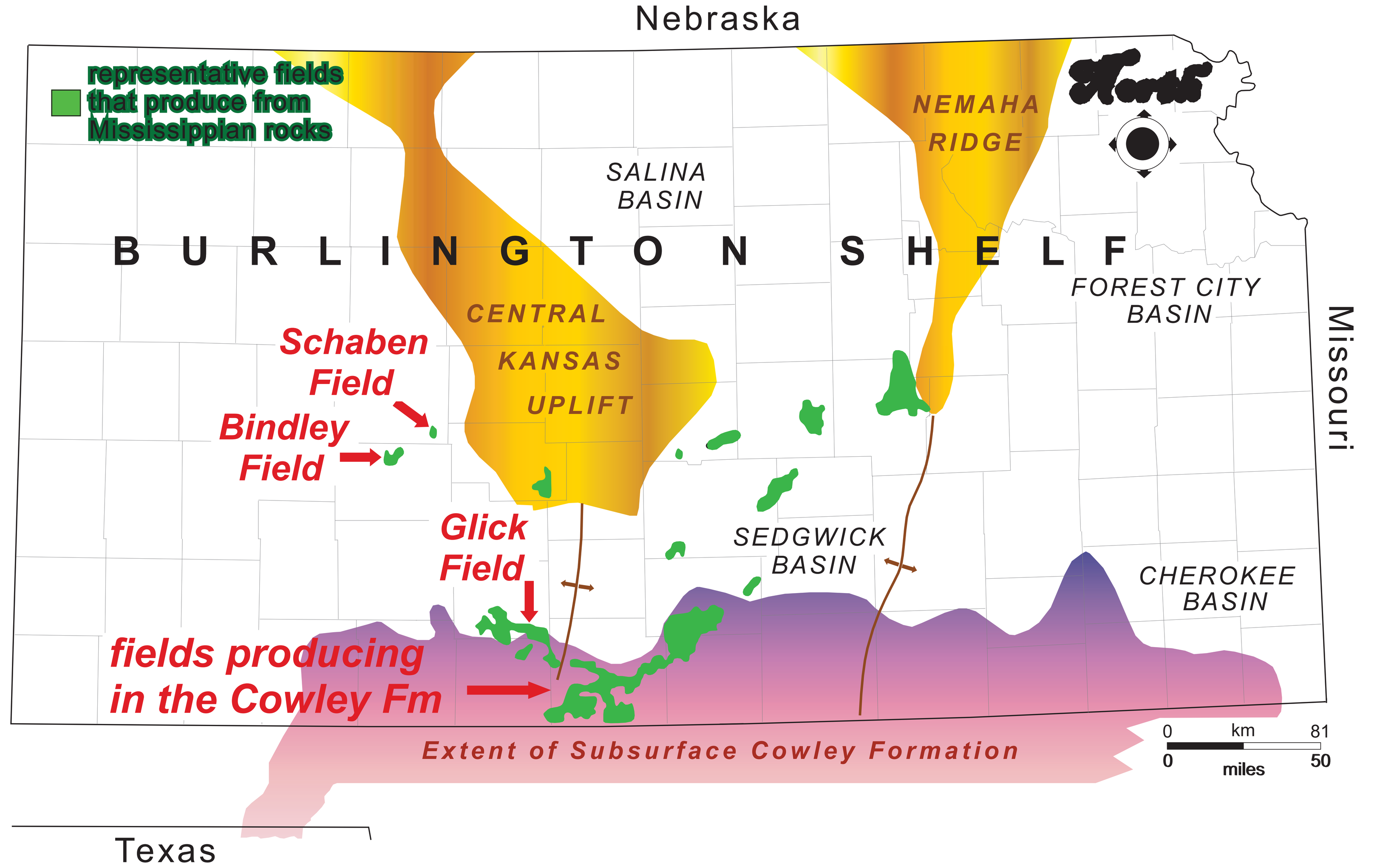
Recurrent Periods of Spiculite Deposition in Midcontinent Mississippian Rocks

Chowns and Elkins (1974) Gutschick & Sandberg (1983) Lindsay (1985) Witzke & Bunker (1996)

PETROLEUM RESERVOIRS IN SPICULITIC ROCKS IN SUBSURFACE KANSAS (Osagean-Meramecian)



Reservoirs in non-spiculitic rocks of Mississippian (Osagean to Meramecian) age in Kansas most commonly are developed in porous limestones and dolomites, and in typically high porosity--low resistivity tripolitic cherts and "chats" (e.g., Watney et al., 2001).

In contrast, reservoirs in spiculitic rocks of Osagean to Meramecian age also are present in Kansas, and they are distinct from "chats". They are present in three paleodepositional settings:

- *along the extreme southern edge of the Burlington Shelf in the Cowley Formation -- in both bedded spiculite and also in lenticular/nodular/flaser-bedded spiculite in Aetna, Rhodes, Traffas, Roundup, Boggs, Stranathan, Hardtner, Groendycke, Salt Fork, Perry Ranch, and several un-named fields*
- *along the edge of the Burlington Shelf to the immediate north of the Cowley depocenter -- in weathered chert (tripolite) that is spiculitic in Glick Field (Osagean)*
- *in middle-shelf positions -- in relatively thin interbeds of spiculitic dolomite in otherwise carbonate-dominated reservoirs in Bindley and Schaben fields (Meramecian)*

IF UPWELLING OF NUTRIENT-RICH AND SILICA-RICH WATERS WAS THE CAUSE OF CARBONATE SUPPRESSION AND, INSTEAD, SPICULITE DEPOSITION, THEN:

- the amount of spiculite that was deposited during any given time decreased northward from the edge of the Burlington Shelf, hence;

- the influx and effect of upwelling waters decreased in a shelfward direction; and

- upwelling and influx of such waters was episodic -- but why?

Reservoirs in Non-Cowley Spiculites

Those in Middle-Shelf Locations

Spiculitic dolomites are present as thin units in otherwise carbonate-dominated shallow-shelf deposits of Meramecian age in Bindley Field (Hodgeman Co.) and in Schaben Field (Ness Co.).

BINDLEY FIELD -- the main reservoir facies here actually is a low-relief, bryozoan mound in the lower Meramecian Warsaw Formation (Ebanks et al., 1977; Ebanks, 1991; Johnson & Budd, 1994). Associated spiculitic dolomites are present, and they contribute only a minor amount to reservoir production. These rocks contain monaxon spicules and some crinoids and bryozoans, and they are interpreted as low-energy, shallow-marine deposits. Typical average values of porosity and permeability in these rocks are 16% (range 5-21%) and 3.4 md (range 0.1 to 5 md), respectively; permeabilities are consistently less than in the main reservoir bryozoan-mound facies. Based on their biotic composition, however, they are not considered to be spiculites sensu stricto, but rather, they are considered to be spiculitic dolowackestones. Similar rocks are present as thin, areally restricted lenses in other nearby fields, including Stairett, Pawnee Branch, Goebel, Hummel, Hummel SE, and Hallet fields (Johnson, 1994).

SCHABEN FIELD -- the main reservoir facies here are in carbonate rocks and spicule-rich wackestone to packstone, inferred to be low-energy shallow-marine deposits. These rocks also are not considered to be spiculites sensu stricto, although spicules locally are quite abundant (see Franseen, 2006, fig. 4C). The rocks have spicule-moldic pores, vugs, and some intercrystalline pores in replacive dolomite. Values of reservoir porosity and permeability of these rocks were not provided by Franseen (2006).

Those at Shelf-Marginal Locations

GLICK FIELD -- the main reservoir facies here is Osagean tripolitic chert (referred to as "chat") with porosities as high as 30-50% and permeabilities that range from 0-50 md; per-well reserves are 1-20 BCF gas (Duren, 1980; Euwer, 1965, 1968; Rogers et al., 1995, Longman and Rogers, 1996; Colleary et al., 1997; Montgomery et al., 1998; Watney et al., 2001). Pores in these rocks include spicule-moldic pores, vugs, and micro-pores in chert.Maximim thickness of the reservoir facies is about 70 ft. The chert here includes monaxon spicules and also non-spicular cherts, and the former contain 25-35% spicules, which we would not consider to be spiculites sensu stricto. In all likelihood, silicification of these rocks obliterated most of the other (carbonate) components, thereby leaving spicules as the most readily identifiable particles. We refer to the rocks as heavily weathered chert -- tripolite.

Core slab of stylolitic (arrows) micro-porous tripolite. Scale 1". General Atlantic #1-A Tjaden, 4372 ft.

Thin-section photomicrograph of micro-porous tripolite; 40x magnification, crossed nicols. General Atlantic #1-A Tjaden, 4377 ft.

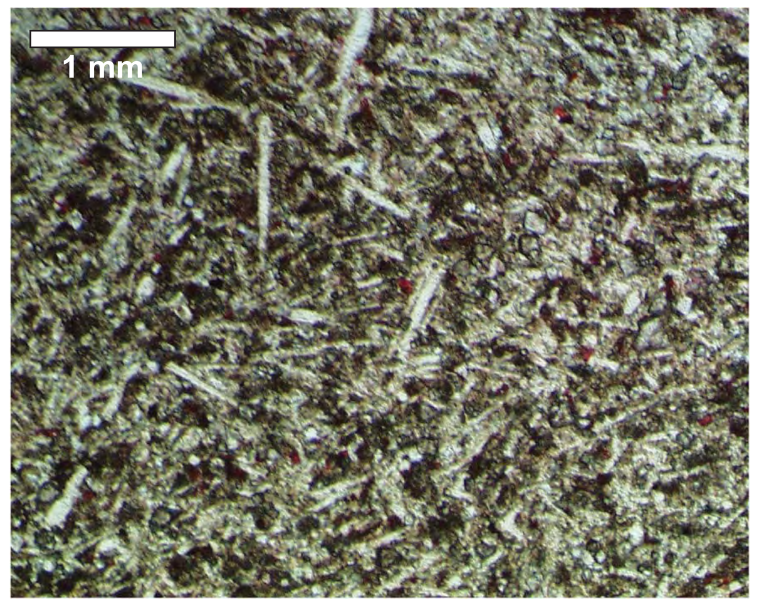
Core slab of brecciated spiculitic tripolite. General Atlantic #1-A Tjaden, 4348 ft.

Typical Porosities-Permeabilities in Non-Spiculite "Chat"

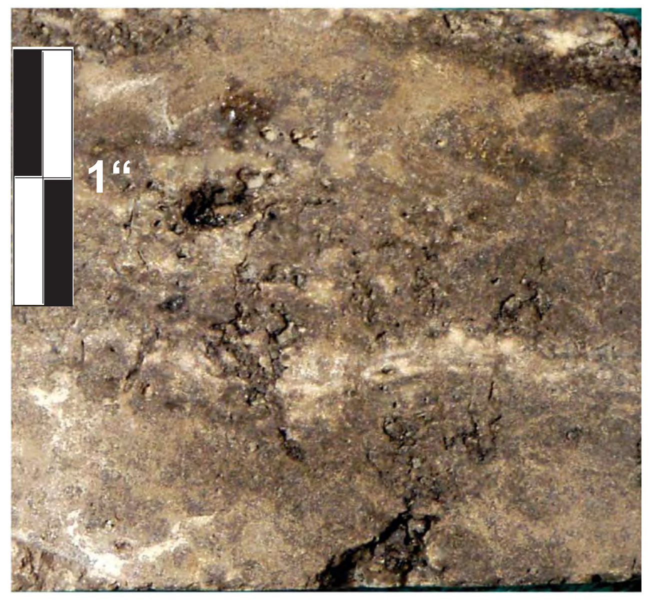
Porosity in non-spiculitic "chats" typically ranges from 5-52%, and per-field average generally is 16-32%. Permeabilities in these rocks typically ranges from 0-100 md, with per-field averages of 32-38 md. The highest porosities and permeabilities are in Glick Field (Osagean).

Reservoirs in Cowley Spiculites and Petroleum Production

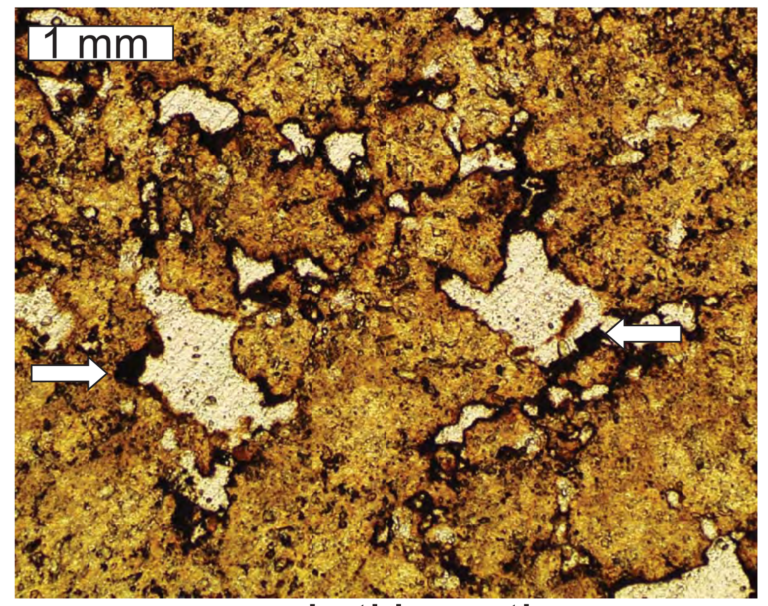
What are spiculites?



Bedded spiculite and lenses or nodular beds of spiculite in green or gray shale both consist of tightly packed monaxon spicules comprising a packstone to grainstone texture Such rocks are what we refer to as spiculite.

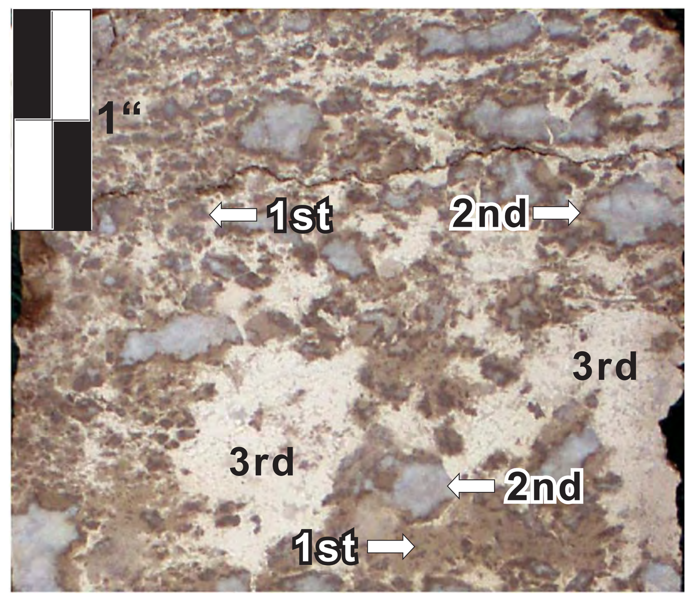


vugs in core slab



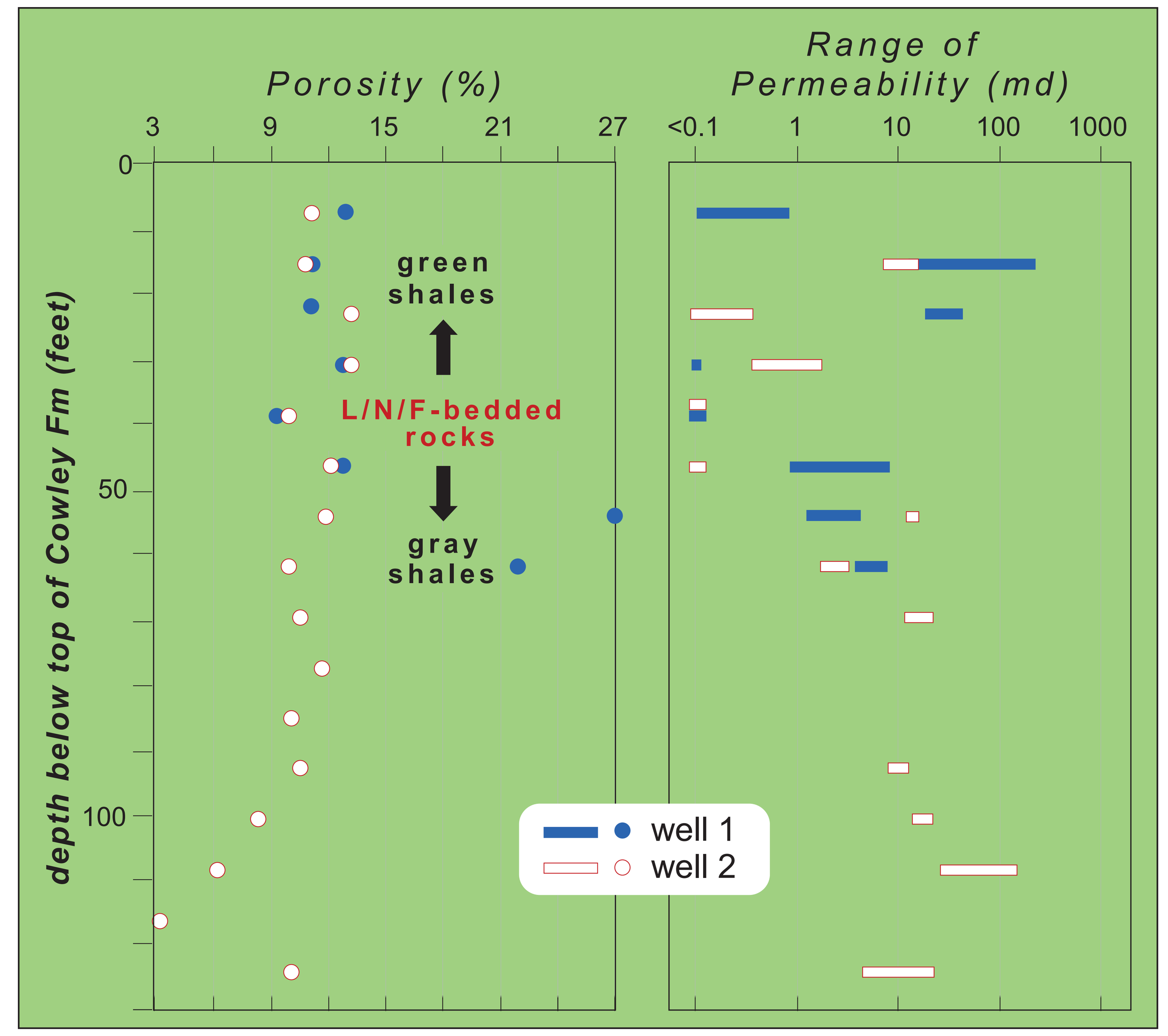
vugs in thin section

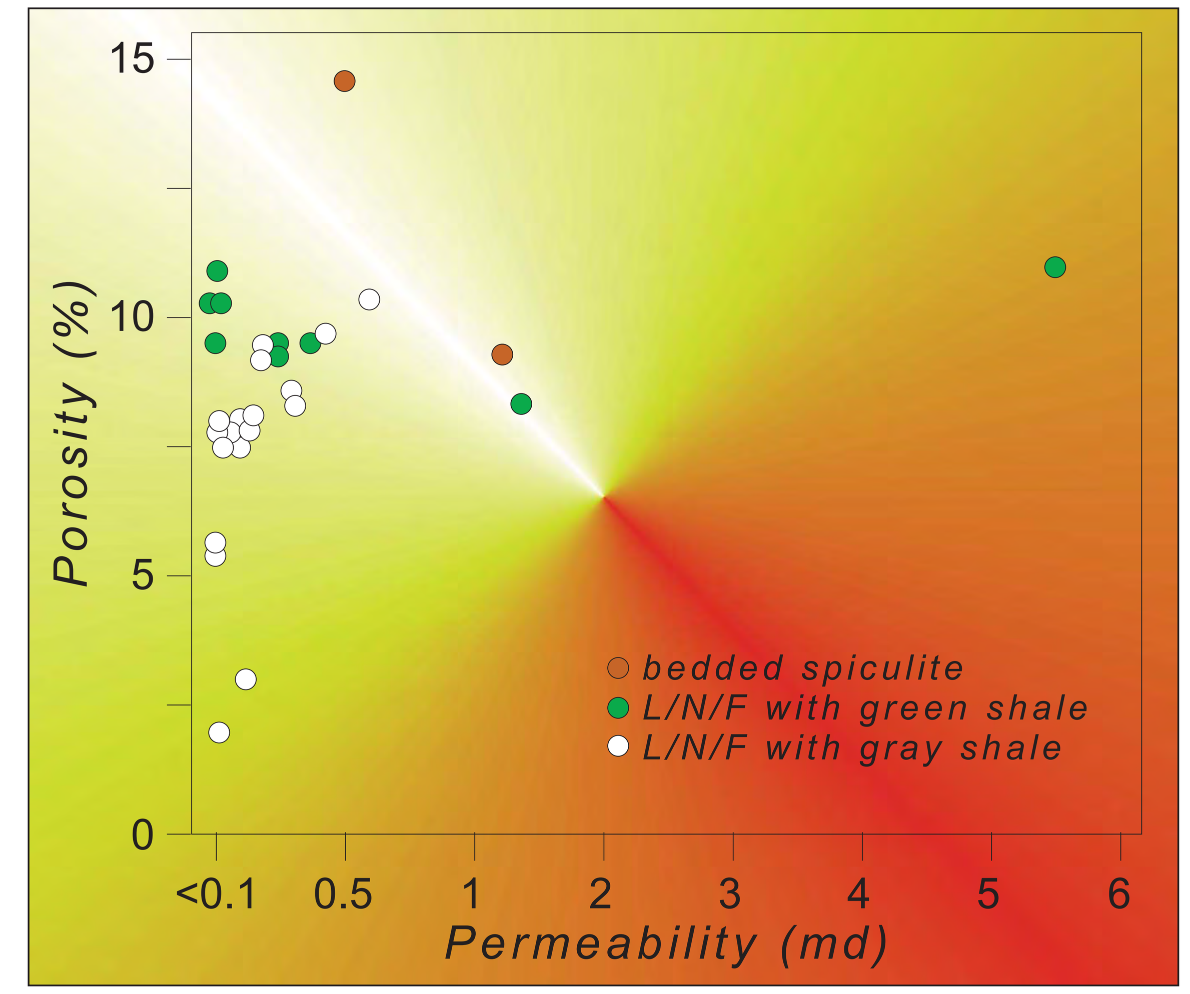
Aside from fractures, there basically is just one pore type in producing reservoirs in both the bedded spiculite and the lenticular/nodular/flaser-bedded spiculites and shales -- vugs of varying size. Only a minor amount of intra-spicule porosity is present in some rocks.



core slab

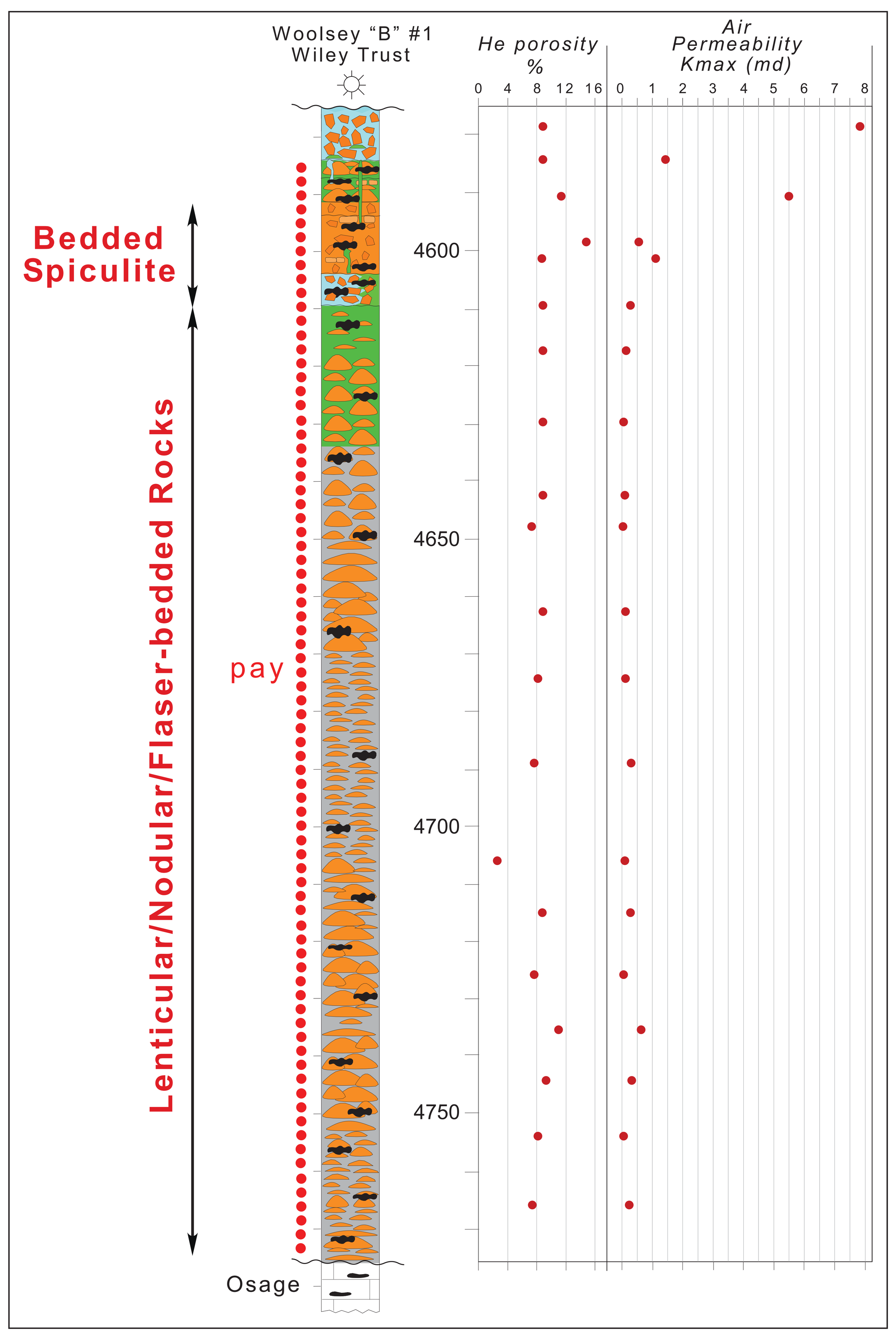
There are three generations of chert recognized on the basis of cross-cutting relationships. The 1st-generation chert formed syndepositionally. Several periods of silicification represent the 2nd-generation chert, which alternated with periods of dissolution and porosity formation attending subaerial exposure. The 3rd-generation chert formed during and after final subaerial exposure of the Cowley, and it occludes some porosity in the rocks.

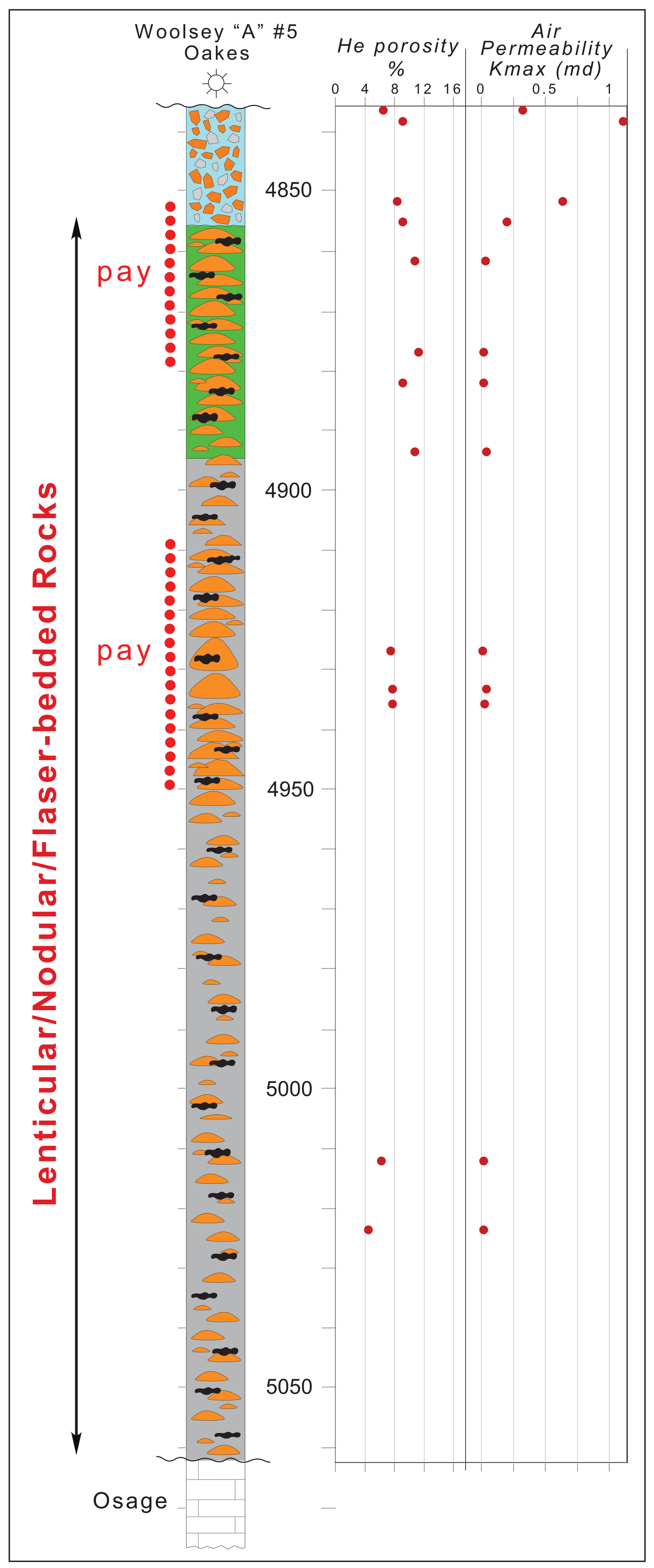




Bedded Spiculites - **post-Cowley erosion has removed sections of this facies in many wells in the study area. Most of the wells that did penetrate this facies did not core it. Hence, there are only few core-derived porosity and permeability measurements of these rocks. Based on available cores, porosity in these rocks ranges from 8-15%, although neutron-density log cross-plots commonly indicate porosity in excess of 28%. Permeability range in available cores is 0.5-1.2 md, although values as high as 5.5 md are recorded in some samples.**

Lenticular/Nodular/Flaser-Bedded Spiculite and Shale - **these shaly rocks also are reservoirs in the Cowley, with porosity and permeability developed within the component spiculite lenses. These rocks, however, generally have less porosity and permeability than bedded spiculite reservoirs. In two cores from Rhodes Field (green panel, above), measured porosity and permeability range from 3.4-13% (some samples with as much as 22-27% porosity) and <0.1 to 337 md, respectively. Other (Woolsey) cores in the area have porosities and permeabilities of 2-15% and generally <1.5 md, respectively.**





<u>Production from Bedded Spiculites</u> -- fields with reservoirs in this facies, such as Stranathan and Hardtner, typically have produced in excess of 152 BCF and 5 MMBO. Per-well cumulative gas production generally ranges from 1-5 BCF, although 4 offsetting wells in Hardtner Field have cumulatively produced 44 BCF.

<u>Production from L/N/F-Bedded Rocks</u> -- wells in fields with reservoirs in this facies typically cumulatively produce 0.25-1.5 BCF, which is less than reservoirs in bedded spiculites. In fields such as Aetna, however, cumulative production is as much as 240 BCF and 0.9 MMBO. The reasons for such large volumes of produced gas in these relatively tight reservoirs are: (a) Aetna is an areally large field with hundreds of wells; (b) the thickness of sections of L/N/F-bedded rocks in most wells far exceeds the thickness of preserved bedded spiculite sections in the study area; and (c) sections of L/N/F-bedded rocks locally can comprise very thick gas columns (e.g., see the perforations in the Woolsey "B" #1 well in the panel to the left).

CONCLUSIONS

- *Spiculitic rocks comprise petroleum reservoirs in Osagean and Meramecian rocks in Kansas. Deposition of these spiculitic rocks in otherwise carbonate-rock-dominated environments is believed to reflect periodic upwelling onto the Mississippian Burlington Shelf of nutrient- and silica-rich waters in the Anadarko Basin to the south.*
- *The amount of spiculitic rocks decreases from the southernmost edge of the Burlington shelf northward into central Kansas. Fields in the interior Burlington Shelf (such as Schaben and Bindley), for example, partly produce from spiculitic wackestones rather than spiculites sensu stricto. Fields such as Glick, to the immediate north of our study area, produce from deeply-weathered tripolitic chert with less than 30% spicules.*
- *In contrast, the Cowley Formation along the southern end of the Burlington Shelf produces gas and associated oil from nearly pure spiculites, including bedded spiculite and lenticular/nodular/flaser-bedded spiculite with associated shale. These rocks have produced in excess of 0.5 TCF gas + 6 MMBO from a lithofacies that has been largely overlooked in southern Kansas and northern Oklahoma.*