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 affected rhythmic carbonate versus spiculite deposition are: (1) paleotopography of antecedent depositional surfaces; (2) paleolatitudinal 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.

Selected References


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

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MISSISSIPPIAN STRATIGRAPHY IN THE STUDY AREA

The study area is located in southern Kansas, which lay about 20°S of the pale-equator during the Early Mississippian (late Tournaisian to early Viséan). 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 Cowley Formation section always coarsens upward from shale to lenticular/nodular/flaser-bedded spiculite and shale. The Cowley Formation, composed of carbonate and associated spiculitic rocks, is commonly considered an excellent reservoir in the subsurface of Kansas. The Cowley Formation section is commonly 1000 to 2000 ft thick and overlies the Top-weathered Mississippian unconformity. In Glick Field, reservoirs are in spiculitic rocks in the Cowley Formation.

SPICULITES IN THE COWLEY FORMATION

What are spiculites?

Mississippian rocks are present only in the subsurface of Kansas, but they are extensively removed from higher parts of the Nemaha Ridge and the Central Kansas Uplift. Much of the Mississippian in Osagean and lower Meramecian rocks comprises chert and shale limestone, with lesser amounts of dolomite. Much of the oil and gas production in the state is from weathered cherts ("shats") and associated carbonate rocks in these sections. However, some fields such as Schaben, Blinkey, 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.

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.

1. What are spiculites?

The Cowley Formation section always coarsens upward from shale to spiculitic rocks. Reservoirs in the Cowley Formation are in bedded spiculite, as well as in lenticular/nodular/flaser-bedded spiculite and shale.

2. 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.
Evidence of Unconformities

Evidence of unconformities at the top and base of the Cowley, and within the Cowley, include:
- spicule-clast breccias, which are progressively more silicified toward unconformities
- marine-rewilded breccias
- breccia and/or green shale-filled vugs
- colluvium with incipient pedogenic features
- post-depositional (erosional) removal of bedded spiculate sections
- erosion surfaces

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/clast-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 thinns depositionaly and by post depositional erosion in an updip direction (to the north-northwest) as it onlaps underlying Osagean strata, and it thins deposionally 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.
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 Arkabutla Basin in the south. Farther north there is evidence of 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 INFERR DEEP-WATER DEPOSITION, OR COOL BUT SHALLOW-WATER DEPOSITION OF THE COWLEY, BECAUSE IT WAS DEPOSITION CLOSED 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

Example of Such a Model for Spiculite Deposition:

- Occurrence of southwestern Australia (James & Bum, 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)
  - Lumden (1988)
  - Wright (1991)
  - Fransen (2006)
- Gutschick & Sandberg (1983)

Other Mississippian Spiculitic Rocks Associated with Carbonate Rocks in Kansas

- Clair (1948)
- Montgomery et al. (1988)
- Watney et al. (2001)
- Rogers et al. (1995)
- Ebanks (1991)
- Ebanks et al. (1977)
- Johnson et al. (1994)

Recurrent Periods of Spiculite Deposition in Midcontinent Mississippian Rocks

- Chouma and Elkins (1974)
- Gutschick & Sandberg (1983)
- Lindsay (1985)
- Witte & 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/feather-bedded spiculite in Astina, Rhodes, Traffes, Roundup, Boggs, Stratathan, 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 (triplolite) that is spiculitic in Glick Field (Osagean)
- in middle-shelf positions -- in relatively thin interbeds of spiculitic dolomites 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 Spiculitic Rocks

Those in Middle-Shelf Locations

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

BINDLEY FIELD -- the main reservoir facies here actually is a low-relief, bioclastic mound in the lower Meramecian Warren Formation (Ebanks et al., 1977, Ebanks, 1991; Johnson & Bridg, 1943). Associated spiculitic dolomites are present, and they contribute only a minor amount to reservoir production. These rocks contain monaxon spicules and some crinoidal and bioclastic, and they are interpreted as low-energy, shallow-marine deposits. Typical average values of porosity and permeability in these rocks is 15% (range 5-21%) and 34 md (range 0.5 to 5-md, respectively). Permeabilities are consistently less than in the main reservoir in low-relief mounds. Based on their bioclastic composition, however, they are not considered to be spiculites sensu stricto, but rather, they are considered to be spiculitic dolostones. Similar rocks are present are thin, areally restricted lenses in other nearby fields, including Stalley, Pawnee Branch, Goebel, Hummel, Hummel SE, and Rainell fields (Johnson, 1984).

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 Fransen, 2009, pg. 42). The rocks have spiculo-moldic pores, vugs, and some intercrystalline porosity in reworked dolomits. Values of reservoir porosity and permeability of these rocks were not provided by Fransen (2009).

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 25-50%, and permeabilities that range from 0-50 md; per-well reserves are 1.2-10 BCF gas (Duren, 1980; Evens, 1981; 1989; Rogers et al., 1990; Rogers et al., 2001). Anadarko Basin to the south. Farther south there is evidence of Mississippian volcanism in the Caballos Chert-ArkansasNovaculite island chain and, possibly, also elevated dissolved silica concentrations (Lowe, 1975). Upwelling can be inferred based on dominant wind directions (Parrish, 1992)

Periodic upwelling of deep-basin waters from the south

Periodic upwelling brings colder, silica-rich and nutrient-rich water into the Cowley embayment

Periodic suppression of carbonate deposition and, instead, promotion of spiculite deposition

In Glick Field (Osagean)

- the influx and effect of upwelling waters decreased in a shelfward direction; and
- upwelling and influx of such waters was episodic -- but why?

Hence, some oceanographic factors must have periodically suppressed carbonate deposition and instead promoted spiculite deposition here in shallow to deeper-water environments.

Typical Porosities-Permeabilities in Non-Spiculitic "Chats"

Porosities in non-spiculitic "chats" typically ranges from 5-20%, and per-field average generally is 15-30%. 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?**

Spiculitic rocks comprise petroleum reservoirs in Osagean and Meramecian rocks in Kansas. Deposition of these spiculitic rocks in otherwise carbonate-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 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 triplicite 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.

**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 care 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 4-15%, although neutron-density log cross-plots commonly indicate porosity in excess of 20%. Permeability ranges in available cores is 0.5-1.2 md, although values as high as 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 22-37% porosity) and 0.1 to 337 md, respectively. Other (Woolsey) cores in the area have porosities and permeabilities of 2-14% and generally <1.5 md, respectively.

**Production from Bedded Spiculites** – 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.

**Production from L/N/F-Bedded Rocks** – wells in fields with reservoirs in this facies typically cumulatively produce 0.25-1.5 BCF, which is less than reservoirs in bedded spiculite. 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-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 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 triplicite 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 lithofacies that has been largely overlooked in southern Kansas and northern Oklahoma.