Gas storage in the Upper Devonian-Lower Mississippian Woodford Shale, Arbuckle Mountains, Oklahoma—How Much of a Role Do the Cherts Play?

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How gas is stored in shale-gas systems is a critical element in characterizing these potentially prolific, low-porosity/permeability reservoirs. An integrated mineralogic, geochemical, and porosity/permeability study is of the Upper Devonian-Lower Mississippian Woodford Shale, Arbuckle Mountains, southern Oklahoma, at locations previously described through detailed stratigraphic and spectral gamma surveys, was undertaken to provide insights into possible mechanisms by which natural gas might be stored in Woodford reservoirs in the adjacent Anadarko Basin. The outcrops in the Arbuckle Mountains are an ideal location to study the Woodford because here the formation is immature or marginally mature for oil generation (Comer and Hinch, 1987; Lewan, 1987), so deep burial and thermal maturation are much less pronounced than is the case for the Woodford in the basin, and as such the samples we studied are not overprinted by possible alterations resulting from deep burial and heating.

Rock types studied in the Woodford Shale are broadly divided into chert (n = 8) and mudstone (n = 10) lithologies that display different characteristics from the outcrop to thin section scales. Woodford cherts, based on quantitative X-ray diffraction (XRD), contain >85 weight (wt) % quartz, <5 wt% clays, <2 wt% potassium feldspar (K-spar), and have an average total organic carbon (TOC) content of 4.5%. Quartz in chert beds is present as (1) equigranular, subhedral to euhedral crystallites that occur throughout chert beds, and (2) fibrous to granular chalcedony, present as an infilling of radiolarian tests. Quartz in the cherts formed diagenetically from recrystallization of radiolarian skeletal parts; the uncollapsed nature of some originally fragile and delicate radiolaria microfossils indicates that quartz authigenesis was an early diagenetic event. The abundance of quartz coupled with the intergrowth or interlocking character of quartz crystallites together provide the rigid fabric of the cherts. Mercury injection capillary pressure (MICP) analyses (at 50% Hg saturation) reveal that cherts have (1) variable porosity (0.59-4.90%), (2) low calculated permeability (0.003-0.274 microdarcies (D)), and (3) small mean pore apertures (5.8-18.6 nannometers (nm)). Detailed petrography and scanning electron microscopic examination reveals that porosity in the cherts occurs as (1) "slots" between euhedral or subhedral quartz crystal faces and pyrite crystallites within framboids, (2) micropores that exist between colloform, bulbous masses of chalcedony and equigranular quartz, and (3) minor moldic porosity after partial dissolution of K-spar. Importantly, organic matter in the cherts is present as amorphous organic material (AOM) that fills some of the micropores described above.

Mudstones (26-77 wt% quartz, 10-40 wt% clays, as much as 6% K-spar) are more organic rich (average TOC 13.1%) than cherts. The organic matter is present largely as AOM (comparative geochemical studies are underway to determine similarity/differences in organic character as a function of lithology) and *Tasmanites* microfossils (sporelike cysts of possible green algae). Quartz in mudstones is both detrital and authigenic, with unequivocal authigenic quartz occurring as monocrystalline "grains" that can partly or even completely infill *Tasmanites*; as in the case of the cherts, authigenic quartz in mudstones must have precipitated soon after deposition before significant burial and collapse of the soft, delicate *Tasmanites* cysts. MICP analyses (at 50% Hg saturation) reveal that, with one exception, mudstones have (1) porosities ranging from 1.97-6.31%, (2) low calculated permeabilities (0.011-0.089 D), and (3) small mean pore apertures (6.2-17.8 nm). Porosity in the mudstones occurs as (1) "slots" between clay mineral grains or plates, (2) micropores within *Tasmanites* as well as between differing mineral grains (e.g., clays adjacent to detrital quartz or feldspar), and (3) moldic porosity after partial dissolution of K-spar.

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Microfractures also contribute to Woodford Shale porosity but they appear to be lithologically controlled. Fractures are relatively well-developed and are typically perpendicular to bedding in cherts, but these fractures typically end abruptly or become much more diffuse in adjacent mudstones. The brittle nature of the cherts, due to their high quartz content, is most likely the reason for their excellent fracture development, particularly relative to the mudstones, which are composed of much more ductile clay and *Tasmanites* constituents.

Interestingly, the overlap of some petrophysical properties of cherts and mudstones (e.g., porosity, pore apertures) in the Woodford Shale for samples from the Arbuckle Mountains indicates that for shallowly-buried (i.e. minimally compacted) parts of the formation, both lithologies may have exhibited similar behavior relative to fluid movement. Where the Woodford has been more deeply buried and subjected to more intense compaction (i.e. in the Anadarko Basin), the petrophysical characteristics of cherts are likely to have changed only minimally due to their rigid fabric, whereas the petrophysical characteristics of the mudstones are likely to have changed significantly due to compaction and the resultant compression and collapse of ductile constituents such as clays and *Tasmanites* microfossils (those without quartz infilling). Moldic porosity, which could be expected to develop in kerogen as a consequence of maturation (Loucks and others, 2009), is more likely in the high TOC mudstones, but would also occur in Woodford cherts, which contain lower TOC contents.

Owing to the potential for Woodford cherts to better retain porosity, coupled with their contained TOC, cherts may indeed provide important overlooked intervals of gas generation and overall gas storage in the formation. Thus, Woodford cherts may contribute a significant portion of the gas that is produced from the formation. As such, chert beds may play a very significant, heretofore overlooked role as source and reservoir intervals within the Woodford in the Anadarko Basin.

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