Reflux Dolomite Crystal Size Variation in Cyclic Inner Ramp Reservoir Facies, Bromide Formation (Ordovician), Arkoma Basin, Southeastern Oklahoma

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ABSTRACT

In the subsurface Arkoma Basin of southeastern Oklahoma, the Bromide Formation (Upper Ordovician) consists of shallow-water inner ramp dolomitized facies deposited on the low-angle South Ozark Platform. The Bromide Formation is composed of repetitive, thin (3-10 ft. thick), shallow subtidal to peritidal, shallowing-upward cycles. Typically, cycles have a basal thin quartz sandstone unit, overlying subtidal dolomitized mudstones to grainstones, and capping peritidal facies. Peritidal dolomitized facies include stromatolitic and thrombolitic bindstones and diverse mudstones to grainstones with fenestral fabrics, dessication cracks, geopetal vadose silt pore fillings, collapse breccias, squared-off crystal molds, and sparse remnant enterolithic bands of former evaporites. Peritidal dolomitized packstones and grainstones are common and composed mostly of dark peloids and small mudstone intraclasts, many of which are microbial in origin. Oolitic grainstones are moderately common.

There is a significant increase in Bromide dolomite crystal sizes and porosity in a downdip direction on the ramp. In the more updip Red Oak Field, the Bromide dolostones are mostly composed of fabric-retentive microcrystalline dolomite, and have only microporosity. In the more downdip Wilburton Field area, the dolostones are composed of fine- to medium crystalline replacive dolomite in which grains are recrystallized beyond recognition or moldic, and have intercrystalline, skelmoldic, vuggy pores.

The dolomite crystal size change downdip is thought to be a result of variation in the reflux dolomitization process. The dolomitization of the updip microcrystalline Bromide by locally-derived supersaturated brines was penecontemporeous to very early diagenetic and was completed relatively quickly. The brines that refluxed through more downdip ramp facies became somewhat depleted (i.e., less saturated with Mg) and dolomitization proceeded more slowly, resulting in coarser planar dolomite crystallization. Later burial diagenesis served mainly to occlude macroporosity, but not the microporosity.

INTRODUCTION

Little sedimentological data are available on subsurface carbonates of the Bromide Formation (lower Upper Ordovician, Simpson Group) in the Arkoma Basin in southeastern Oklahoma (Suhm, 1997; Wahlman et al., 2006). The Bromide Formation is known primarily from open marine ramp limestone and shale facies that outcrop in the Arbuckle Mountains of southern Oklahoma (Longman, 1981) (Figure 1). Bromide sandstone facies also form important hydrocarbon reservoirs in the Anadarko Basin of central Oklahoma (Northcutt and Johnson, 1997) (Figure 1A).

This study is based on Arkoma Basin subsurface cores from Red Oak Field and the slightly more paleogeographically downdip Wilburton Field, Latimer County, Oklahoma (Figure 1B). The fields are about 12 miles (22 km) apart, with no cored wells in between. The Bromide in both fields is composed of cyclic inner ramp, subtidal to peritidal, sandy dolomitized carbonate facies, with subtidal facies increasing downdip and peritidal facies increasing updip and up-section (Figure 2). However, there are significant differences in the dolomite crystal sizes and associated reservoir characteristics between the two fields. Bromide dolostones in the more updip Red Oak Field are composed mostly of microcrystalline dolomite that preserves grain types and depositional fabrics, and essentially all porosity is microporosity (Figures 3-5). Bromide dolostones in the more downdip Wilburton Field are composed of fine- to medium-crystalline planar dolomite in which grains are recrystallized or moldic, and the porosity system is intercrystalline, moldic, and vuggy (Figures 3, 6). This pattern of the downdip increase in dolomite crystal sizes and porosity in inner ramp dolostones is considered largely the result of the downdip reduction of reflux dolomitizing brine saturations and the relative duration time of the dolomitization process, as described by Sibley and Gregg (1987).

GEOLOGIC SETTING AND STRATIGRAPHY

During the Ordovician, southeastern Oklahoma was the eastern shelf of the large Oklahoma Basin whose depocenter was the southern Oklahoma aulacogen (Johnson, 1991) (Figure 1A). Early Pennsylvanian continental collision created the present-day complex of Oklahoma structural basins. The Arkoma Basin is bounded on the north by the Ozark Dome, on the south by the Ouachita Trough, on the west by Anadarko Basin, and on the east by the Plattin carbonate shelf (Johnson, 1991; Suhm, 1997) (Figures 1A, B).

The Bromide Formation (Mohawkian (N.A), ~ Katyan (Global) series, Blackriveran stage) is the uppermost unit of the Middle and Upper Ordovician Simpson Group (Suhm, 1997, Sadler, 2009) (Figure 1C). Within the Arkoma Basin, the Bromide is composed of carbonates and sandy carbonates that are transitional between the sand-rich facies of the Anadarko Basin to the west and the Plattin carbonate platform to the east. According to Suhm (1997) (Figure 1A), the paleoclimate to the west of the Oklahoma Basin was humid, and the area to the east of the basin was arid. Several features of the Bromide dolomites on the South Ozark Platform show evidence of an arid paleoclimate in the study area (Figure 4).

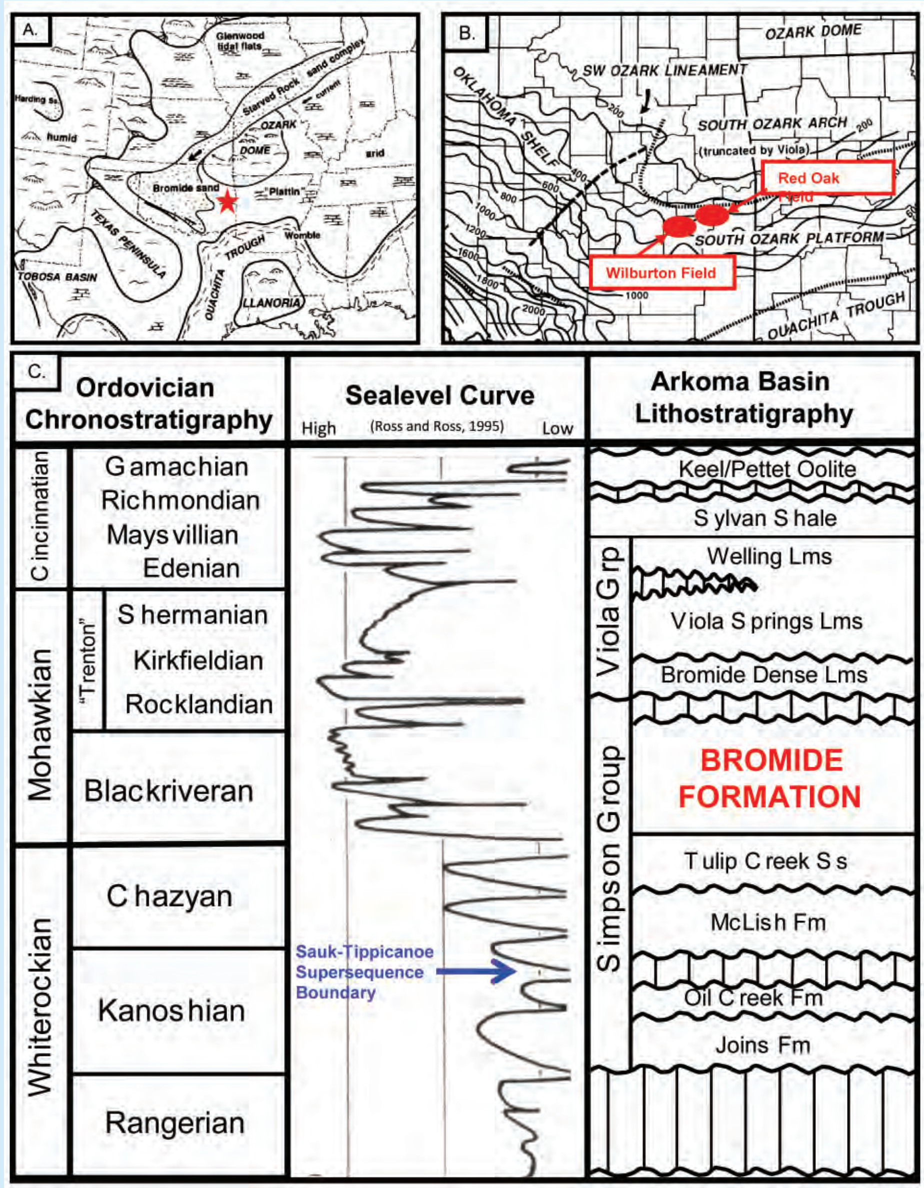

Figure 1. A. Late Ordovician paleogeography of Oklahoma and surrounding area. Red star marks study area. B. Simpson Group isopach map and paleogeographic features mentioned in text. Data are from Red Oak and Wilburton Fields. (Figures A-B from Suhm, 1997). C. Stratigraphic chart for Middle and Upper Ordovician of Oklahoma, with chronostratigraphy, a sealevel curve (Ross and Ross, 1995), and lithostratigraphy.

The Late Ordovician is characterized by relatively high-frequency sealevel changes related to early icehouse paleolimatic conditions (Figure 1C). The Bromide Formation is the uppermost of three 3rd order sequences in the Simpson Group (Candelaria and Handford, 1997), each of which has a basal transgressive quartz sandstone, and later transgressive and highstand marine carbonates and shales. In that scheme, the Bromide 3rd order sequence is composed of the LST to early TST Tulip Creek Sandstone and late TST to HST Bromide carbonates.

The thin Bromide 4th-5th order sequences in the Arkoma Basin cores show the same lithofacies pattern as the larger 3rd order sequences (Figures 2). Those inner ramp high-frequency sequences have thin basal sandstones (<6 inches thick) that grade quickly upward into inner ramp subtidal dolostones that have sparse, mostly molluscan bioclasts, and some burrowing. The subtidal dolostones shallow upward into restricted marine subtidal to peritidal dolostones that consist of shoal/beach, lagoonal, and intertidal-supratidal facies. Many carbonates contain variable amounts of quartz sand. The 4th-5th order cycle model shown in Figure 2 is a typical complete subtidal-peritidal cycle, which is most characteristic of the middle Bromide Formation and in more downdip areas. Updip, and up-section in the Bromide, the proportion of peritidal facies increases.

BROMIDE DOLOMITE FACIES

The Bromide cores from Red Oak and Wilburton Fields represent a range of inner ramp, shallow subtidal to peritidal facies (Figure 5A-B, Figures 4-10). Four general facies associations are recognized: (1) Peritidal and restricted marine lagoon, (2) Shoal, beach, and channel grainstones-packstones, (3) Open marine ramp wackestone-packstones, and (4) Transgressive sandstones. Figure 2 outlines the general Bromide facies associations and the subtle differences between updip and downdip facies. The facies associations are present in both areas, but in general the more updip Red Oak Field area has a higher proportion of peritidal and restricted marine lagoonal facies. Facies contacts within the cycles are mostly gradational, but the contacts of the cycles are usually sharp erosional surfaces.

Bromide dolostones in the updip Red Oak Field area are composed of mostly microcrystalline dolomite. Much of the microcrystalline dolomite is replacing stromatolitic and thrombolitic micrite, micrite peloids and intraclasts, and micritic grain coatings, but many non-micritic bioclasts and oolitic grains are also well-preserved by microcrystalline to very fine-crystalline dolomite. Dolograinstones are common in the updip Red Oak Bromide, and the most abundant grains are microcrystalline dolomite peloids, small rounded micritic intraclasts, and oolites (Figures 3G-H, 5A-C and H). The intergranular areas in those grainstones are generally lined or filled by clear, medium-crystalline planar dolomite cements that can have minor intercrystalline porosity (Figures 5G, H). The microcrystalline dolomites usually have well-developed microporosity, which is visible only in thin-sections impregnated with fluorescent epoxy and viewed using ultraviolet light microscopy (Figures 5C,F,I). The porosities of those microporous dolomites is usually < 5%, and the permeabilities are commonly <0.01md.

The more downdip Wilburton Field Bromide has the same depositional facies, but the dolostones are composed of fine- to medium-crystalline planar dolomite with a porosity system of intercrystalline pores, skelmolds, vugs, and some microporosity. Porosity values commonly range from 5-12% and have relatively good permeabilities (e.g., >1.0md) (Figures 3C-F, 6A-G). Bioclasts are represented by skelmolds, and the coarser dolomite recrystallization has rendered most grains and many fabrics unrecognizable petrographically (Figures 6B-C).

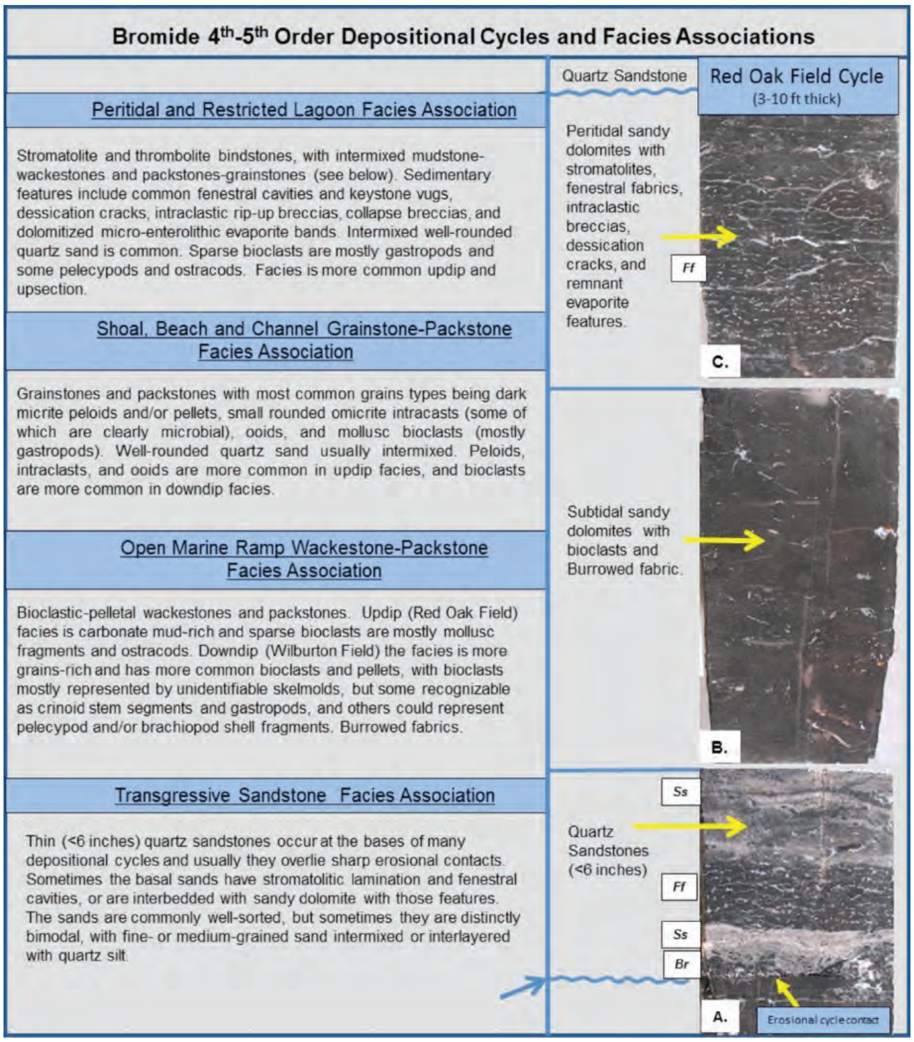

Figure 2. Summary of Bromide facies associations (left), and core slabs from a typical subtidal-peritidal cycle from Red Oak Field core (right). Dark color of dolostones is due to the disseminated bitumen content. A. Erosional cycle base overlain by a thin breccia (Br), quartz sand (Ss), sandy stromatolite with fenestral fabric (Ff), and another thin sand (Ss),12893 ft. B. Subtidal dolowackestone with sparse mollusc bioclasts, 12891.3 ft. C. Peritidal stromatolitic dolobindstone with fenestral fabric , thin intraclastic layers, and sheet cracks, 12888.2 ft. The dolostones have only microporosity values of 1.4-2.8% and permeabilities of 0.07-0.53md.

DOLOMITIZATION AND DIAGENESIS

The Bromide dolostones are interpreted to be the product of reflux dolomitization (Figure 3A) because of their inner ramp depositional setting, and features indicating a probable arid paleoclimate, including dessication cracks, and remnant features suggesting the presence of former evaporites, such as dolomitized micro-enterolithic bands, squared-off crystal molds, and isolated collapse breccias (Figures 4A-G). Reflux dolomitization of cyclic shallow subtidal and peritidal sediments in warm arid settings has been widely described and discussed in modern and ancient settings (e.g., Adam and Rhoads, 1960; Deffeyes et al., 1965; Illing et al., 1965; McKenzie et al., 1980; Hardie, 1987; Zenger, 1988; Mutti and Simo, 1994; Saller et al., 1994; Saller and Henderson, 1998), and results from evaporation of inner ramp, lagoonal and peritidal, shallow marine waters, creating Mg-supersaturated brines that sink and flow downdip dolomitizing the subsurface calcareous sediments. Dolomite textural and crystal size changes have also been attributed to the depositional position of the precursor within the reflux hydrology regime (Saller and Henderson, 2001, Machel, 2004, Saller, 2004).

In a study of cyclic Permian dolomite reservoirs in the Permian Basin of West Texas, Saller et al. (1994) and Saller (2004) envoked a process through which reflux dolomite porosity decreases in an updip direction toward the origin of the supersaturated refluxing fluids. They demonstrated that updip early dolomites can have a high initial porosity, but continued circulation of supersaturated brines through the updip dolostones results in additional precipitation of dolomite (over-dolomitization; e.g., Lucia, 2002, 2004; Saller and Henderson, 2001) that causes continued dolomite crystal growth and intercrystalline dolomite cementation, which in turn decrease porosity. These results have been confirmed by reactive transport modeling where maximum dolomitization rate is critically dependent on the rate of reflux flow and the reactive surface area of the mineral (Jones and Xiao, 2005, figure 18). In the Saller (2004) conceptual model, original dolomite crystal sizes are essentially the same in updip and downdip sites, but the updip crystals become larger and porosity decreases through the continued dolomite precipitation. When the reactive transport model results are coupled to the conceptual model of dolomite distribution, porosity and crystal size (e.g. Saller 2004) we see a much more transient and spatial differentiated evolution for porosity associated with dolomite.

The Bromide dolomites in the Arkoma Basin demonstrate another process through which reflux dolomite porosities of cyclic inner ramp dolostones decrease in the updip direction. Updip Bromide porosity decrease appears directly attributable to dolomite crystal size decrease, that is in turn thought to be related to the relative saturation levels of the dolomitizing fluids and length of time for dolomitization. Sibley and Gregg (1987), in their discussion of dolomite rock textures, noted that dolomitization and dolomite crystal sizes are a function of fluid supersaturation and nucleation sites. Micritic carbonate sediments have a high surface to volume ratios and dolomitize rapidly. High density of nucleation sites (e.g., micrite) and high supersaturation should produce a finely crystalline dolomite. In their figure 11, Sibley and Gregg (1987) show that at high fluid saturations a wackestone becomes a relatively fine crystalline dolomite and bioclasts are replaced and preserved. But as dolomitizing fluid saturation states decrease, and residence time of the wackestone in the dolomitizing solution becomes longer, dolomite crystal sizes increase and bioclasts become skelmoldic. Sibley et al. (1993) further studied dolomite crystal size distributions and demonstrated the complexity of the subject. The observations and interpretations presented in this brief study do not involve detailed measurements and research data required to support or refute the saturation state, residence time, crystal size model. But observational data presented here illustrate a marked downdip change in Bromide dolomite crystal size that supports Sibley and Gregg's (1987) model, and demonstrates the significant effect such a change in dolomite crystal size distribution can have on reservoir quality.

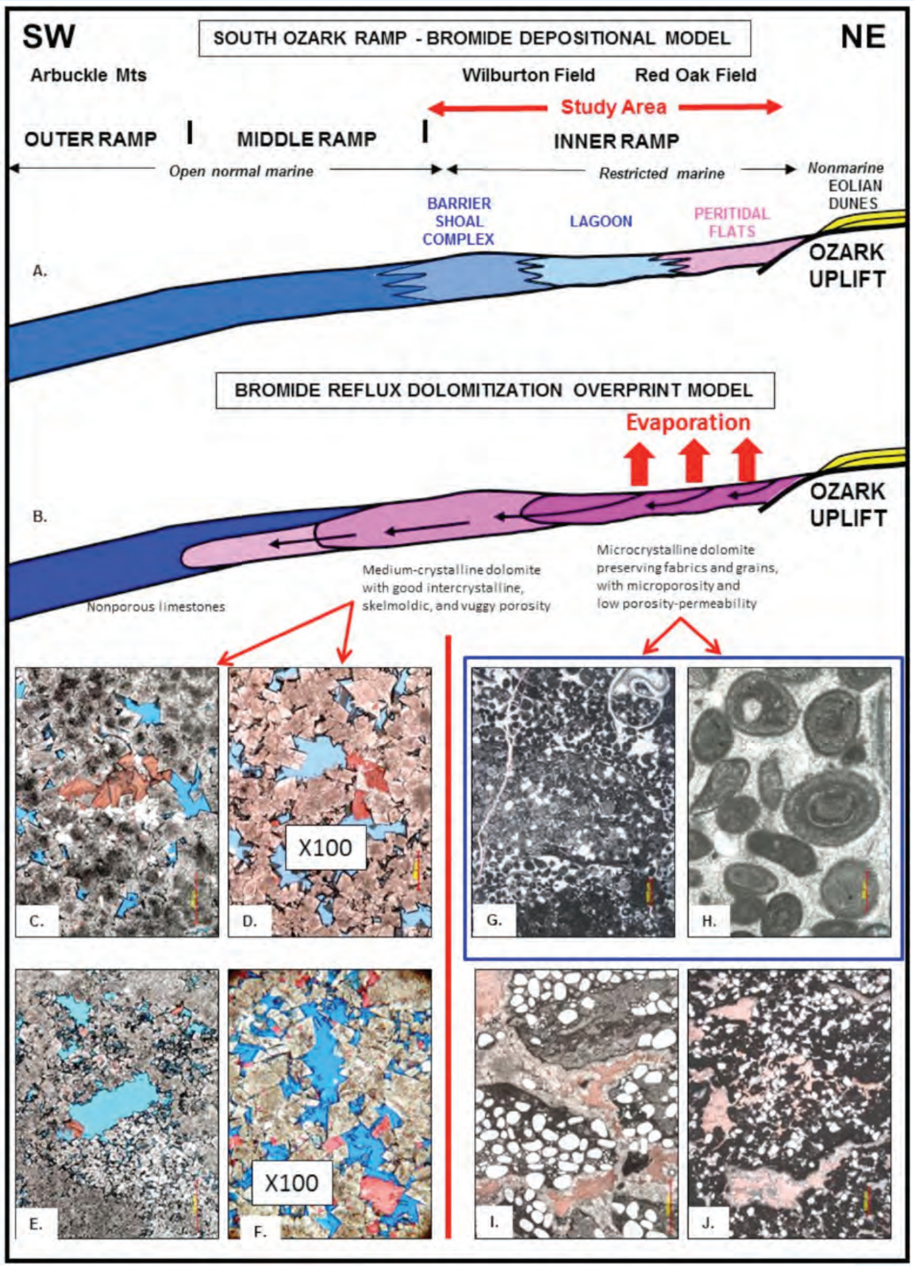

***Figure 3.** A. Schematic depositional model for Bromide inner ramp facies. B. Model for the reflux dolomitization overprint of carbonate ramp, with evaporative Mg-supersaturated brines flowing downdip through the ramp sediments. Carbonates nearest the source of the supersaturated brines underwent rapid dolomitization resulting in fabric-preserving microcrystalline dolostones with microporosity (dark pink), as seen in the updip Red Oak Field. Downdip brines became depleted, and so downdip carbonates (Wilburton Field) underwent slower dolomitization, resulting in coarser crystalline dolomite with intercrystalline,, skelmoldic, vuggy porosity. C-F. Photomicrographs of Wilburton Field downdip coarser crystalline, replacive dolomites with skelmoldic and intercrystalline porosity. C. Pelletal-skeletal packstone with pellet ghosts (X50). D. Medium-crystalline planar dolomite, and skelmolds lined by bitumen (X100). E. Fine-crystalline pelletal dolomite (X50). F. Medium- to coarse-crystalline dolomite (X100). G-J. Red Oak Field microcrystalline dolostones with microporosity only. G-H. Oolitic-peloidal dolograinstone with preserved gastropods and ooids (X12.5 and X100). I. Brecciated sandy stromatolitic dolobindstone with microbial fabric, and interclast coarse dolomite and calcite cements (X25). J. Thrombolite with fenestral cavities lined by dolomite cements and filled by late calcite cement (X25).*

In the Bromide, updip porosity reduction appears to be controlled mainly by an updip reduction in dolomite crystal sizes. Bromide dolomites in the more updip Red Oak Field are mostly microcrystalline and fabric-preserving (mimetic), which is common for penecontemporaneous and very early diagenetic dolomites, especially in micrite-rich settings (e.g., Machel, 2004). The updip Bromide facies have common dolopackstones and dolograinstones composed largely of micritic microbialites, peloids and intraclasts, but other non-micritic grains such as ooids and bioclasts are also preserved as microcrystalline to very fine-crystalline dolomite. It is proposed that near the updip source of the supersaturated refluxing brines, dolomitization was relatively quick, resulting in recrystallization to microcrystalline dolomite and the preservation of recognizable grains and depositional fabrics. As discussed by Lucia (2004), dolomitization of lime mud increases the crystal sizes and thus the porosity, and because dolomudstone undergoes less compaction than lime mud, that porosity is better preserved during burial.

In contrast, within the more downdip Wilburton Field area, the cyclic facies are generally similar (Figures 2 and 6), but the Bromide dolostones are composed of fine- to medium-crystalline dolomite, the dolomite recrystallization rendered many grains and fabrics unrecognizable, and most bioclasts are skelmoldic.. It is proposed that as the supersaturated brines flowed downdip through the inner ramp carbonates, their Mg-saturations were depleted and dolomitization proceeded more slowly, allowing coarser dolomite crystal growth. Both mud-rich peritidal stromatolitic facies and subtidal pelletal-skeletal packstones-grainstones are relatively more coarsely recrystallized and skelmoldic (Figures 3A-F, 6A-G).

The burial diagenetic overprint of the Bromide served mainly to occlude primary and secondary macroporosity, but not the microporosity. Post-reflux dolomitization events that were documented petrographically include: (1) precipitation of coarse clear planar dolomite cements in primary and early secondary macropores; (2) a period of minor solution-enhancement of pores, probably by pre-hydrocarbon front acidic fluids; (3) migration of hydrocarbons into the reservoirs; (4) continued burial resulting in hydrocarbons cracking to gas and leaving a pervasive bitumen residue; and (5) a final stage of porosity occlusion by late diagenetic calcite cements.

Although the microporous dolostones in the more updip Red Oak Field generally have <5% microporosity and very low permeabilities, they produce moderate amounts of natural gas and provide secondary producing zone in the field. As pointed out by Wahlman (2009), such microporosity-dominated carbonate reservoirs generally need other associated macroporosity types (e.g., vugs, fractures) in order to be economic primary reservoirs. The coarser crystalline Bromide dolostones in the more downdip Wilburton Field commonly have porosities in the 5-12% range and good permeabilities, and so the Wilburton Bromide serves as a primary gas reservoir.

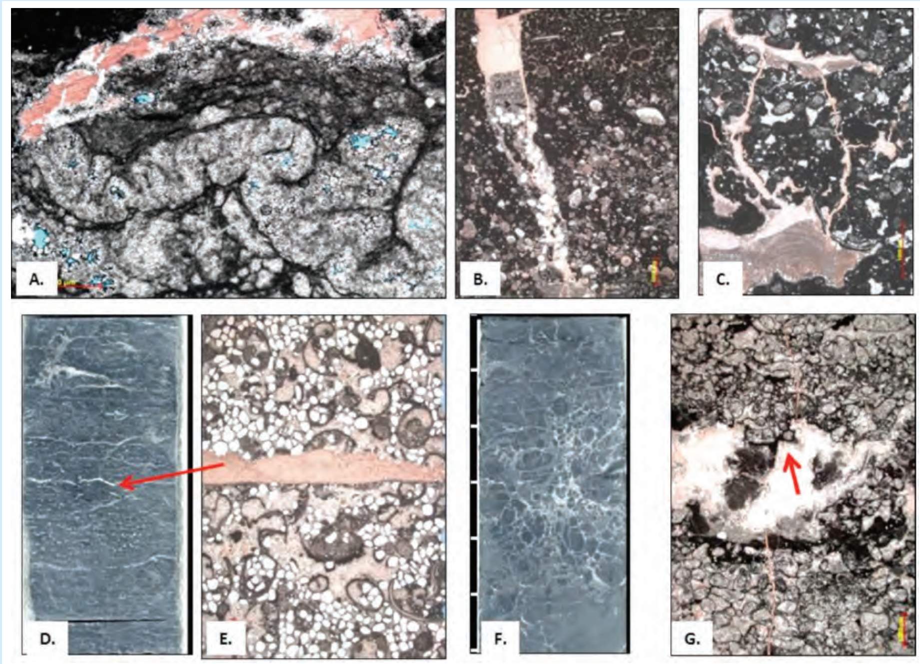

Figure 4. Photomicrographs showing dessication and evaporitic features from the Bromide Formation. A. Dolomitized remnant of enterolithic evaporate (X50). B. Dessication crack with geopetal filling (X12.5). C. Fenestral cavities with geopetal vadose silt and dessication cracks (X12.5). D-E. Core slab and photomicrograph (X25) of sheet cracks in sandy bioclastic grainstone. F. Core slab of collapse breccia in peritidal stromatolitic bindstones. G. Photomicrograph showing squared-off margin of fenestral cavity that might represent former halite crystal (X25). In photomicrographs, white cements are dolomite and red cements are calcite stained with alizarine red.

CONCLUSIONS

The Upper Ordovician Bromide Formation in the subsurface of the Arkoma Basin consists of thin, inner ramp, shallow subtidal-peritidal depositional cycles. The entire section is dolomitized, and the dolomites display a marked spatial variability in their replacement textures and dolomite crystal size. Reflux dolomitization of Bromide carbonates resulted in an increase of dolomite crystal sizes downdip. In the more updip Red Oak Field, the Bromide dolomites are microcrystalline, preserving grains and depositional fabrics, and are dominated by microporosity of generally <5%. In the more downdip Wilburton Field, dolomites are fine- to medium-crystalline, grains are recrystallized or moldic, and the pore system includes intercrystalline, skelmoldic and vuggy porosity that is commonly 5-12%. The downdip increase in dolomite crystal size and porosity are thought to be the result of reflux dolomitization, where updip facies near the source of the supersaturated brines are quickly dolomitized to microcrystalline dolomite, and downdip facies are more slowly dolomitized by Mg-depleted brines resulting in coarser replacive dolomite crystals, and skelmoldic and vuggy porosity. This study highlights the importance of fluid saturation and fluid flow efficiency and reaction kinetics in the early dolomitization process, which are not currently well understood or quantified. Such observational datasets provide a starting point for more detailed geochemical and numerical modeling analyses.

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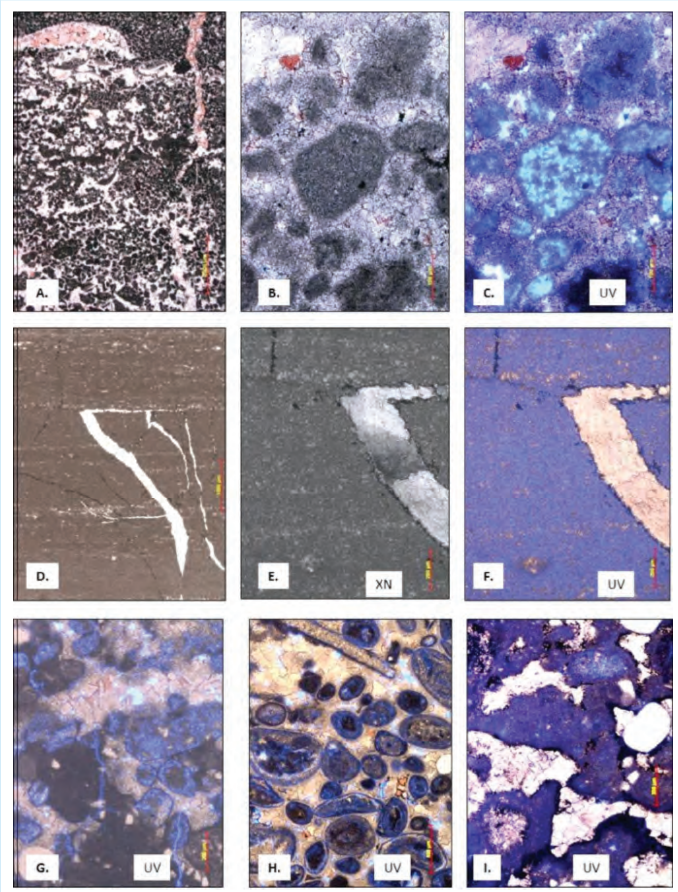

Figure 5. Photomicrographs of Red Oak Field Bromide dolostones with microporosity shown with ultraviolet (UV) microscopy. A-C. Fine-grained peloidal dolograinstone with sparse mollusc bioclasts. A. Peloidal dolograinstone with pelecypod shell and fracture filled by dolomite (white) and late calcite (red) cements (X25). B. Same at X100 under plane light showing microcrystalline peloids. C. Same at X100 under UV light showing microporosity in peloids and cements. D-F. Stromatolite with dessication cracks. D. At X25 under plane light. E. At X100 under cross-polarized light showing pelleted mud matrix and saddle dolomite in fracture. F. Same at X100 under UV light showing 10% microporosity. G. Peloid-intraclast dolograinstone under UV light showing 2.0% microporosity and microfracture (X100). H. Oolitic-skeletal dolograinstone under UV light showing 4.5% microporosity (X100). I. Thrombolitic micrite under UV light showing 1.1% microporosity (X100).

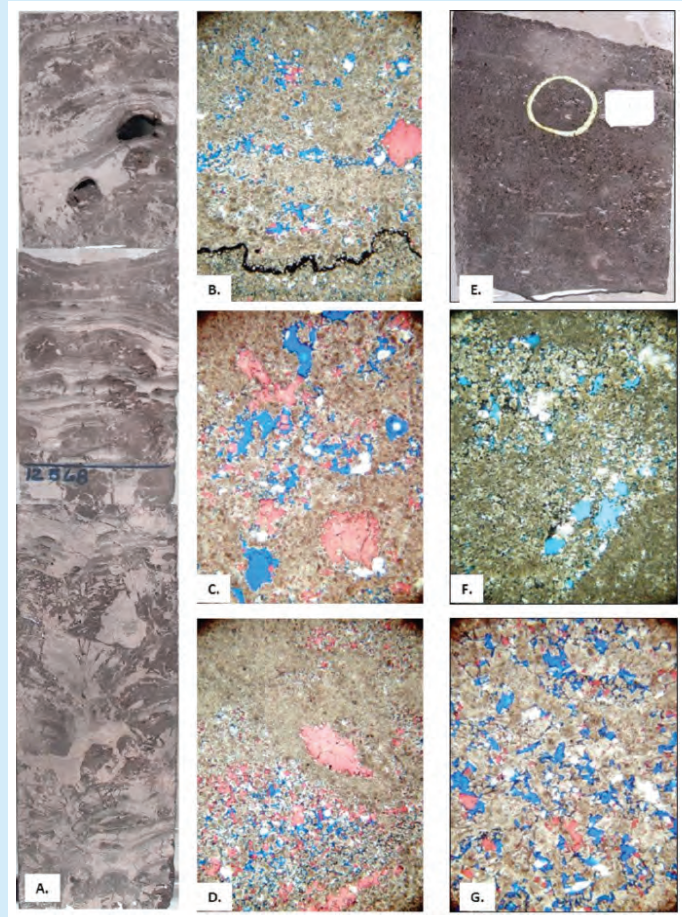

Figure 6. Wilburton Field dolostones. Core slabs (A) and photomicrographs (B-D) of stromatolitic peritidal facies. A. Core slab (2 ft) of stromatolitic dolobindstone with breccia in lower part. Vugs near top probably anhydrite molds. B. Photomicrograph of medium-crystalline dolomite with open fenestral cavities and fine intercrystalline porosity (por = 13.1%, K = 18.3 md) (X25). C. Fenestral cavities and small vugs (X40). D. Patchy intercrystalline and small vug porosity in disrupted breccias (por 6.5 %, K = 0.71 md) (X25). E-G. Wilburton subtidal facies. E-F. Core slab and photomicrograph of burrowed pelletal-skeletal medium-crystalline dolopackstone with skelmolds and intercrystalline porosity (por = 9.5%, K = 1.69 md) (X25). G. Burrowed pelletal-skeletal dolopackstone with skelmolds, small vugs, and intercrystalline porosity (por = 12.2%, K = 25.8 md) (X25).

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