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IMPLICATIONS OF BRECCIATION IN PENNSYLVANIAN ATOKA BANK COMPLEX CARBONATES, EDDY COUNTY, NEW MEXICO

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Abstract: The Pennsylvanian Atoka bank carbonates were deposited on the northwest shelf of the Delaware Basin in Eddy County, New Mexico, forming a stratigraphic trap for natural gas. Brecciation is common in the core samples of some wells. This paper describes the brecciation in the phylloid algal limestones and discusses its origin. In the core samples, brecciated dark areas, consisting of irregularly shaped fragments, are seen together with internal sediment-filled pores, characterized by light gray coloured areas. Detailed examination of the core samples reveals that the brecciated dark areas correspond to open space areas between phylloid algal colonies, on the basis of comparison with the well-preserved primary rock texture in the cores. Brecciation is mainly due to the selective dissolution of phylloid algae that produced phylloid algal moulds, later filled by sandy internal sediments under subaerial conditions. The subsequent compaction of the limestone caused the rock to break up and formed a breccia *in situ*. The sandy internal sediment prevented the moulds from collapse as well as breccia formation in the pore-filling area, owing to its loose character. Overall, the brecciation process, including the dissolution of phylloid algae and breakage of the rocks, significantly improved the reservoir quality, whereas the internal sediment reduced the reservoir quality, for it reduced the porosity.

Key words: Algal bank complex, reservoir, carbonate, Delaware Basin, New Mexico.

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INTRODUCTION

The term “breccia” refers to a rock, composed of angular fragments larger than two millimetres, held together by a cement or matrix (Bates and Jackson, 1984). Brecciation results from igneous, sedimentary and tectonic processes or a combination of these (Blount and Moore, 1969; Shukla and Sharma, 2018; No *et al*., 2020). A breccia often is observed in carbonate rocks and mostly is attributed to dissolution-collapse mechanisms (Clifton, 1967; Blount and Moore, 1969; Vlahović *et al*., 2002; Eliassen and Talbot, 2005; Jaglarz and Rychliński, 2018; Shukla and Sharma, 2018). This paper describes brecciation in the Pennsylvanian Atoka bank carbonates in Eddy County, New Mexico, and discusses its origin and importance for the reservoir properties of the rocks.

GEOLOGICAL SETTING

The Permian Basin is one of the major hydrocarbon producing regions of North America, located in western Texas and southeastern New Mexico (Keller *et al*., 1980). The basin contains three major structural components, from west to east, the Delaware Basin, the Central Basin Platform and the Midland Basin (Fig. 1A; Hills, 1979, 1984). The study area is located on the northwest shelf of the Delaware Basin, in the southeast part of Eddy County, New Mexico (Fig. 1B). During Pennsylvanian Atoka time, sandy sediments, derived from the uplift to the northwest in central New Mexico, were deposited as prograding beaches and bars on the surrounding shallow shelves (James, 1985). In contrast, broad carbonates were deposited along the northwest shelf margin of the Delaware Basin and were interbedded with marine black shales (Fig. 1B; Adams, 1965; Hills, 1984). The Pennsylvanian Atoka age of the sediments in the Permian Basin is based on the presence of fusulinids and conodonts, such as *Idiognathodus* specimens (Jones, 1953; Krainer *et al*., 2017; Lucas *et al*., 2022). The Atoka carbonates in the study area represent a stratigraphic trap, from which gas has been produced

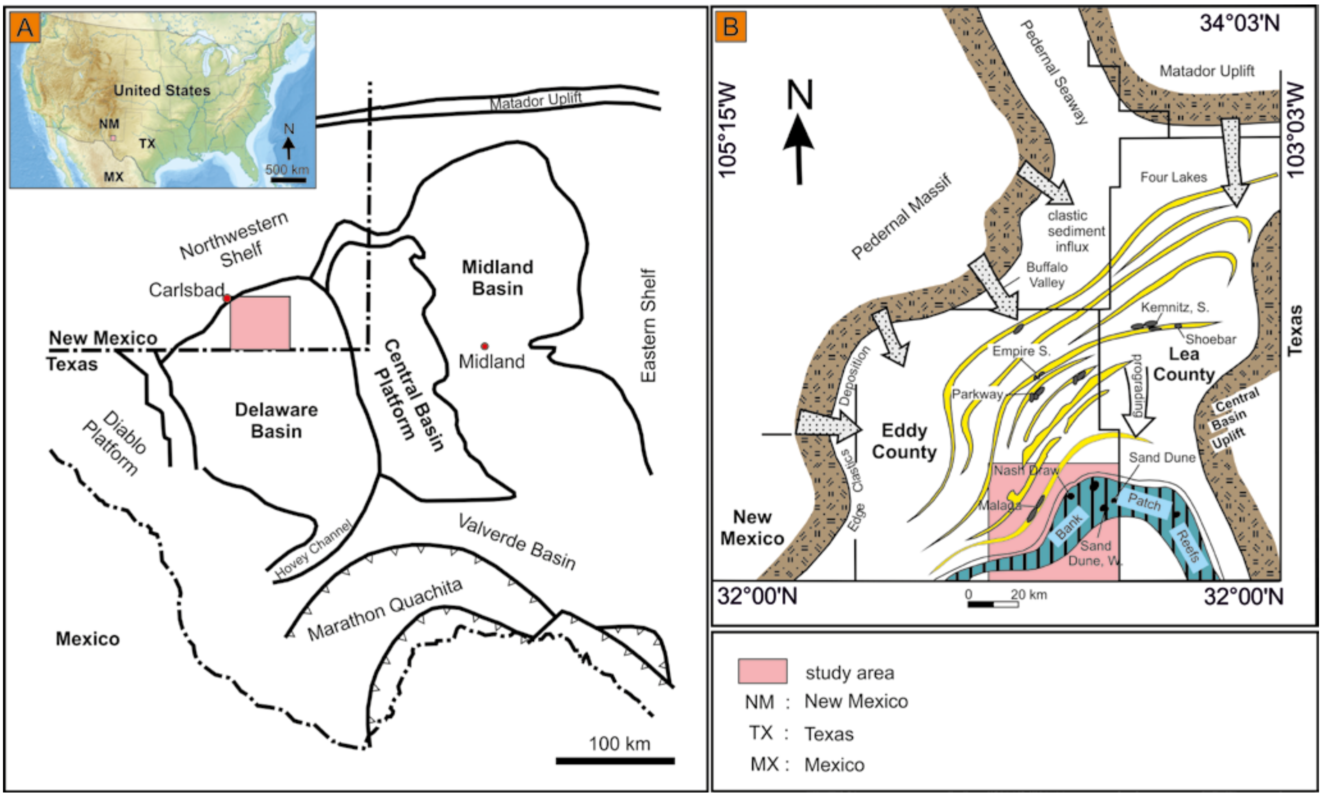

Fig. 1. Study area. **A.** Location of the study area and main structural units of the Permian Basin (adapted from Hills, 1984). **B.** Interpretation of the depositional palaeogeography of the north Delaware Basin and northwest shelf in southeastern New Mexico during Pennsylvanian Atoka time (James, 1985). Clastics, charaterized by a prograding system of beaches and bars (yellow), were deposited in a shallow-marine environment, while an extensive carbonate bank developed along the shelf margin (Hills, 1984; James, 1985).

economically from some of the 11 wells. The initial production of the wells ranges from non-producing to 3,315 mcfd (million cubic feet of gas per day).

MATERIALS AND METHODS

Data for the Atoka carbonate bank complex were obtained from 11 gas wells in Eddy County, New Mexico, and were provided by Santa Fe Energy Resources, Inc. All wells have petrophysical logs and core samples. The carbonate core samples from the 11 wells were etched on a tray, containing 10% HCl. The etched carbonate cores and core samples of shale were examined megascopically and with a binocular stereoscope. Eighty-two thin-sections were prepared from the carbonate core samples. Each thin-section was stained with a mixture of alizarin red S and potassium ferricyanide, following the Dickson (1965) method. Thin-sections were examined under a petrographic microscope. The depositional textures of the carbonate rocks under the microscope were classified according to the Dunham (1962) classification, as modified by Embry and Klovan (1971).

ALGAL BANK COMPLEX

The structure-contour map of the upper surface of the Atoka carbonates reveals that the carbonates contain several long biostromes that form a bank complex and have a maximum thickness of about 21 metres. Eight distinctive lithofacies are defined in the algal bank deposits and surrounding sediments: (1) crinoidal limestone; (2) nodular shaly limestone; (3) bank margin; (4) algal bank, (5) brecciated limestone; (6) basal bioclastic micritic pile; (7) limy shale; and (8) black shale (Figs 2–4).

The crinoidal limestone facies is characterized by an abundance of skeletal grains with predominant crinoidal debris, consisting mainly of grainstone/packstone and minor wackestone (Figs 3C, 5A). The grain-supported crinoidal limestones reflect deposition near the wave base on the upper and upper front slopes of the bank carbonates (Figs 2, 4; Wilson, 1975; Jach, 2005). The nodular shaly limestones are dark greenish gray to black, thinly bedded limestones with a nodular to wavy-bedded appearance (Fig. 3B). These are predominantly wackestone/mudstone, including small numbers of crinoids, brachiopods, pelecypods, bryozoans, foraminifera, sponge spicules, gastropods and corals. This facies indicates deposition under normal marine conditions and a relatively deep-water environment. The nodular shaly limestone is a transional facies between the crinoidal limestones and upper shales and interfingers with them (Fig. 2). The bank margin facies is one of the major facies in the bank complex with the algal bank facies. Both facies have a gradual transition and almost similar fossil contents. The bank margin facies is characterized by an abundance of broken phylloid alga (*Archaeolithophyllum*; Fig. 5B, D) and

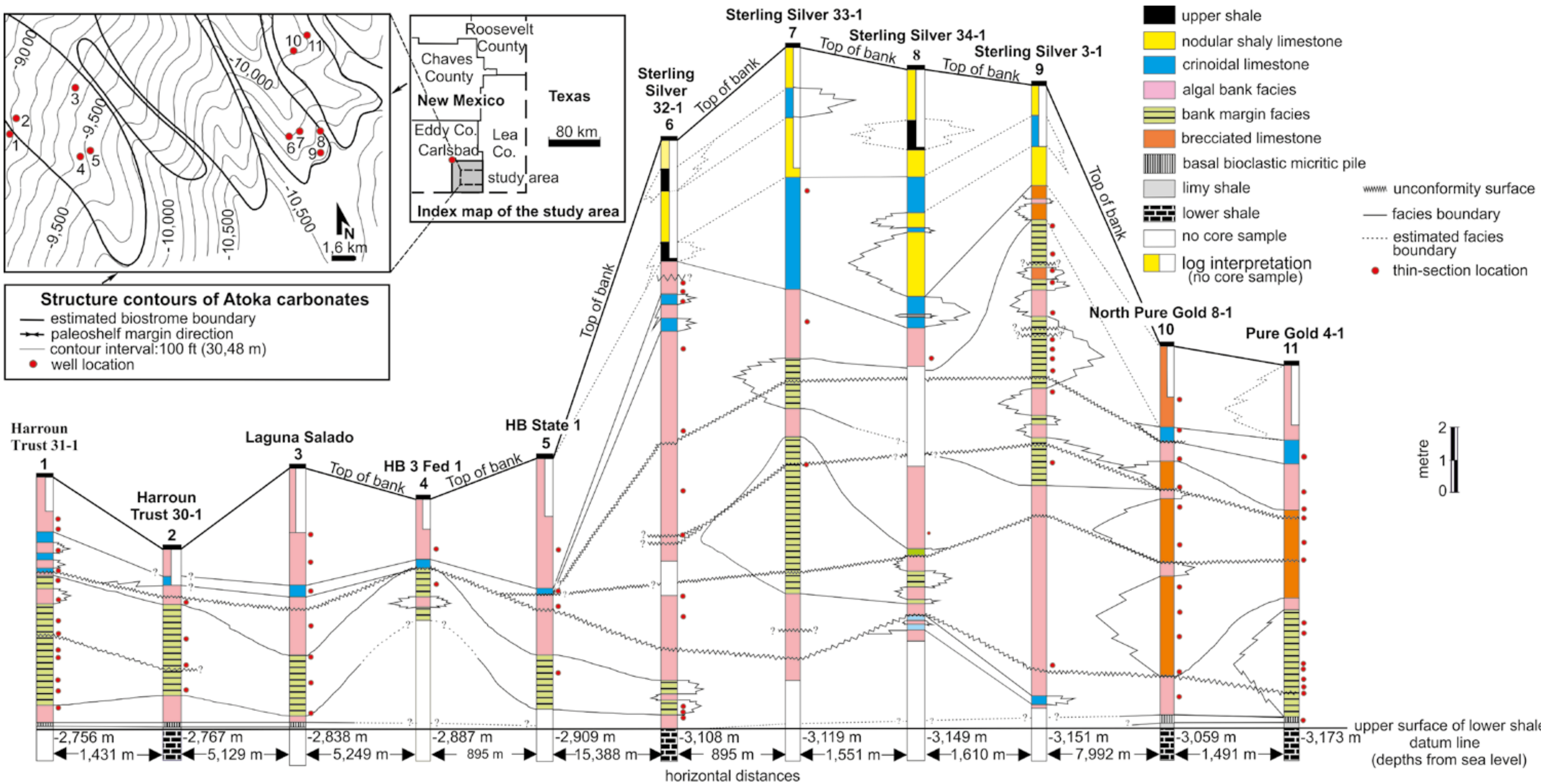

Fig. 2. Stratigraphic cross-section of Pennsylvanian Atoka carbonate bank complex, Eddy County, New Mexico, with the index map of study area and structure-contour map of the upper surface of the bank carbonates.

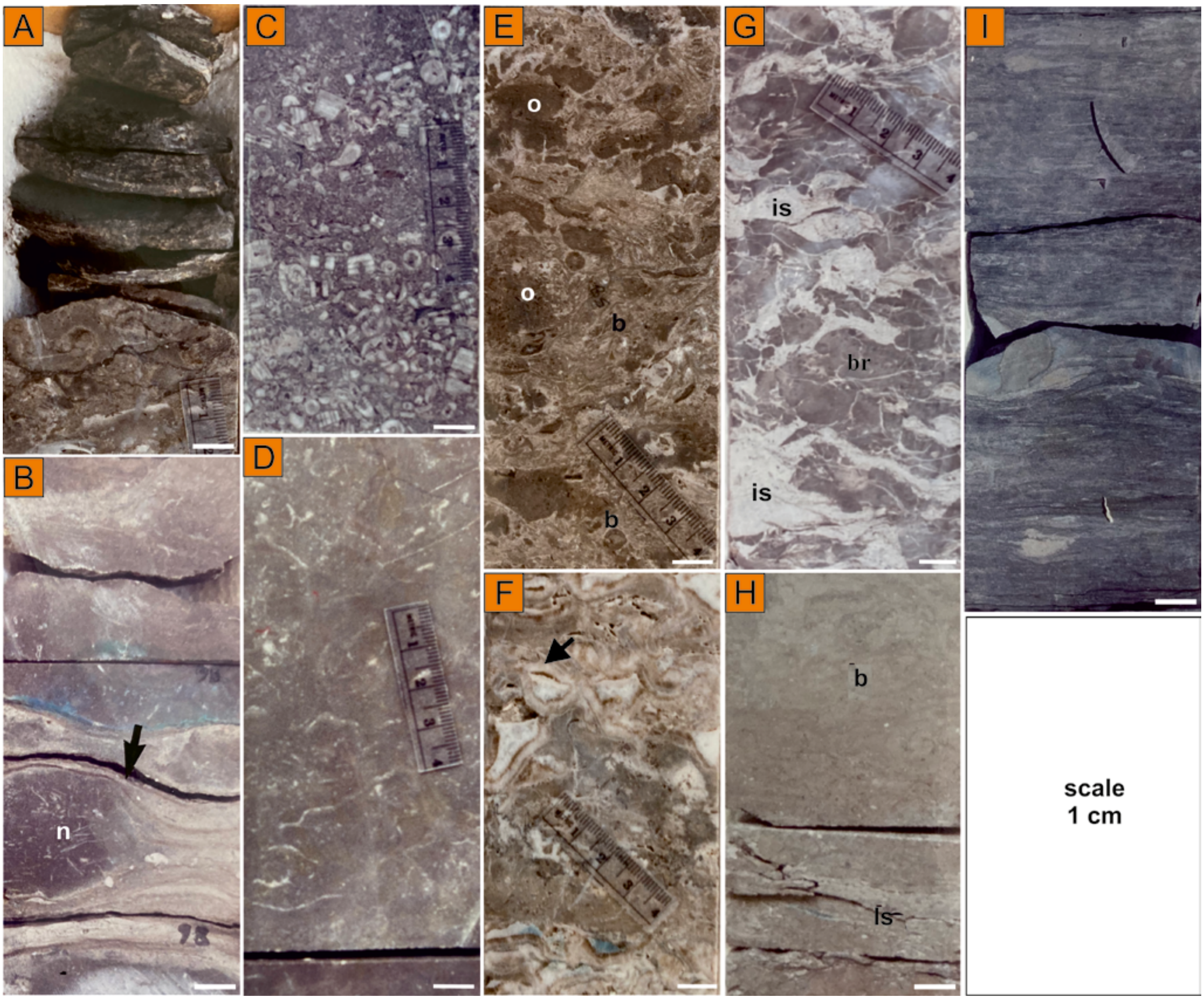

Fig. 3. Selected core photographs of the Atoka bank complex, showing its lithofacies and subfacies. **A.** Upper shale subfacies, represented by laminated black shales that overlie the carbonates of the algal bank facies with a sharp contact, Sterling Silver 32-1 well, 4123 m. **B.** Nodular shaly limestone, displaying limy nodules (n) and bent shale laminae (arrow), Sterling Silver 34-1 well, 4,175.1 m. **C.** Crinoidal limestone, Sterling Silver 33-1, 4,131.5 m. **D.** Algal bank facies, represented by phylloid algal wackestone, HB State 1 well, 3,839.6 m. **E.** Bank margin facies with boundstone fabric (b), which gives a brecciated appearance to the core sample, open space areas (o) between phylloid algal colonies, Harroun Trust 30-1, 3,667.7 m. **F.** Algal bank margin facies represented by algal grainstone, arrow indicates marine isopachous rim cement, Sterling Silver 3-1, 4,188.4 m. **G.** Brecciated limestone (br; dark area), is means internal sediment, North Pure Gold 8-1 well, 4,074 m. **H.** A gradual transition from limyshale (ls) to basal bioclastic micritic pile (b), Pure Gold 4-1 well, 4,191.2 m. **I.** Lower shale, represented by black-coloured, laminated shales, Sterling Silver 32-1 well, 4,139.8 m.

marine cements (Fig. 5D); it predominantly consists of algal grainstone and boundstone (Figs 3E, F, 5D). The other fossil constituents are foraminifers (mostly small benthic and rare fusulinids), brachiopds, pelecypods, gastropods, ostracods, echinodermal plates, and corals. The marine cements are: (1) abundant isopachous fibrous rim (former aragonite), surrounding the bioclasts (Fig. 5D), and intraclasts and relatively large primary cavity walls between them, and (2) former high-Mg-calcite rim and microspar-infill in micropores between the peloids in the matrix. The bank margin facies indicates deposition just below the wave base at depths of less than 30 m (Konishi and Wray, 1961; Wray, 1964; Toomey 1980). The algal bank facies basically consists of phylloid algal wackestone (Fig. 3D). Phylloid alga is a major fossil constituent, often represented by broad algal fronds, vase-shaped thalli (Fig. 5C), large blades (Fig. 5B) and multilayered forms. This facies differs from the bank margin facies in the abundance of well-preserved algal thalli, the absence of the marine isopachous fibrous rim cement, a reduced number of almost the same fossil components, and also rare *Donezella* lenses. The micrite-dominated algal bank facies indicates deposition in a shallow-marine environment below the wave base at depths of several to a few tens of metres in the photic zone (Krainer *et al.*, 2017) or in a low-energy environment behind the bank-margin barriers. The diversity of the fossil assamplage in the bank deposits, including the sessile benthic suspension feeders, such as bryozoans, brachiopods and echinoderms, indicates

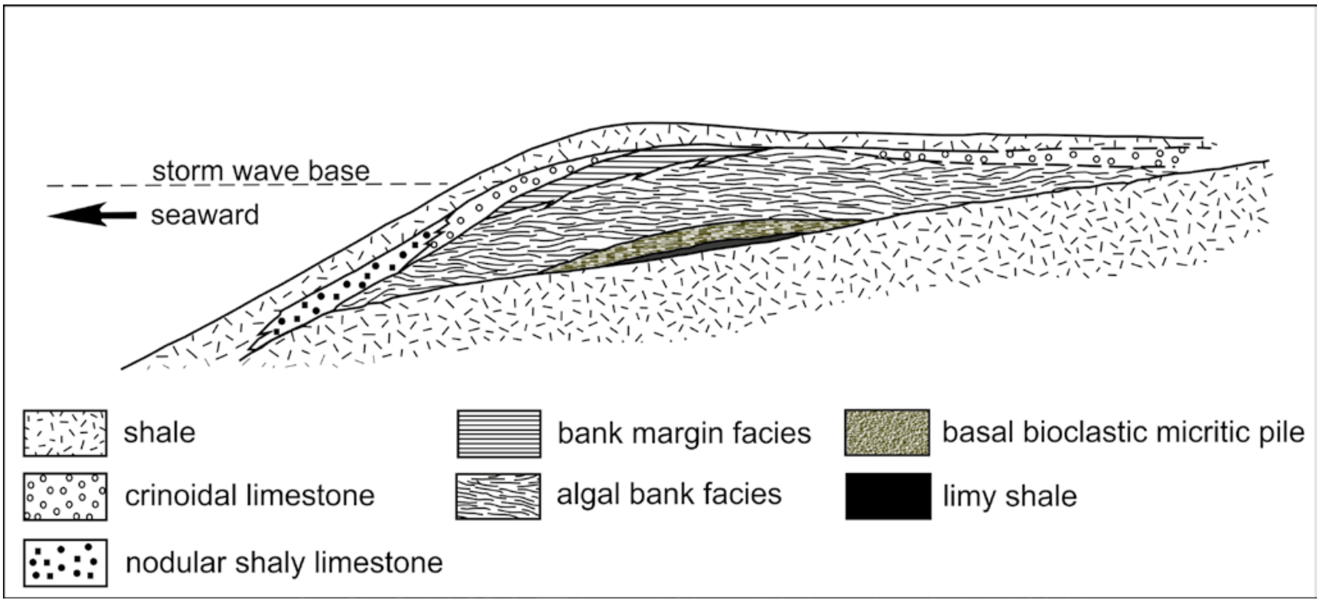

Fig. 4. An idealized individual algal bank, Eddy County, New Mexico, showing distribution of depositional lithofacies.

an open-marine shelf environment with normal salinity (Krainer *et al*., 2017). The basal bioclastic micritic pile (Fig. 3H) contains dark greenish gray, shaly, slightly pyritic, and stylolitic limestones, which are predominantly wackestone and packstone with phylloid alga, scattered crinoids, small brachiopods and spines, foraminifers, pelecypods, bryozoans, gastropods, indicating a relatively deep, quiet-water, marine environment. The brecciated limestone facies (Fig. 3G) is the subject of this article and is described and discussed in detail below. The limy shale (Fig. 3H) is a transitional unit between the lower black laminated shale and the basal bioclastic micritic pile, and represents greenish gray, thinly laminated, glauconitic and pyritic mudstone (micrite), including fossils, such as echinodern plates, brachiopod fragments, foraminifers, bryozoans and gastropods. This facies reflects a relatively deep-marine environment and the initial stage of the bank development. The shale facies consists of dark gray to black, fissile, thinly laminated, silty and sandy, slightly calcitic, glauconitic, and pyritic shales, including chert nodules and rhodoliths. The shale facies is divided into two subfacies as upper and lower shales, with regard to their position (Fig. 3A, I). Trilete spores are found in the upper shales, siliceous sponge spicules in the lower shales, with rare conodont specimens of the genus *Idiognathodus*. The black shales indicate a relatively deep-marine environment, slow sedimentation and reducing conditions.

Carbonate rocks of the Atoka bank complex have undergone a complex diagenetic history that includes marine, subaerial, and burial diagenetic modifications. The complexity comes from a wide variety of diagenetic events and their relative timing. The most important diagenetic events, affecting reservoir quality, are cementation and dissolution. While cementation in the Atoka bank complex developed in all diagenetic environments, dissolution occurred predominantly in freshwater environments. The effects of cementation and dissolution on the reservoir were to reduce and increase porosity, respectively. Dissolution also had an indirect effect on the brecciation of the Atoka carbonates.

BRECCIATED LIMESTONE

Description

Brecciation in the Atoka carbonates is typically observed in the North Pure Gold 8-1well and also in the Pure Gold 4-1 and Sterling Silver 3-1 wells (Fig. 2). In the core samples, dark and light gray-coloured areas are present (Fig. 3G). The dark areas display breccia fabric, whereas the light gray areas correspond to irregularly shaped, internal sediment-filled pores. The breccia consists of angular rock fragments with variable sizes of up to 6 cm, showing *in situ* formation. The components of the breccia consist of rare fossil-bearing wackestone/mudstone and peloidal grainstone. The breccia levels in the core samples reach a maximum thickness of 6.45 m and usually show a gradual transition to mainly algal bank and bank margin facies, and also crinoidal limestone.

The sandy internal sediments are mainly composed of detrital quartz grains 50–400 µm in size, muscovite flakes, altered feldspars (most K-felspar), and fragments of the host rocks (Figs 3G, 5E, F). The pores between the detrital sandy grains are filled predominantly with detrital clays. Most of the quartz grains are surrounded by overgrowth silica cement that has produced sharp corners and edges on the quartz grains. Later, small amounts of dolomite and dickite cements were precipitated in the intergranular pores of the sandy internal sediments.The detrital clay also was replaced locally by pyrite clusters.

Mechanism for brecciation and its effect on the reservoir

In comparison, brecciated carbonates in the core samples (Fig. 3G) have a similar appearance to the algal limestones, especially the boundstones in the bank margin facies (Fig. 3E). This similarity indicates that the brecciation in the Atoka carbonates is due to diagenetic modification (leaching) of the algal limestones and subsequent compaction. Dissolution of the algal components in the Atoka

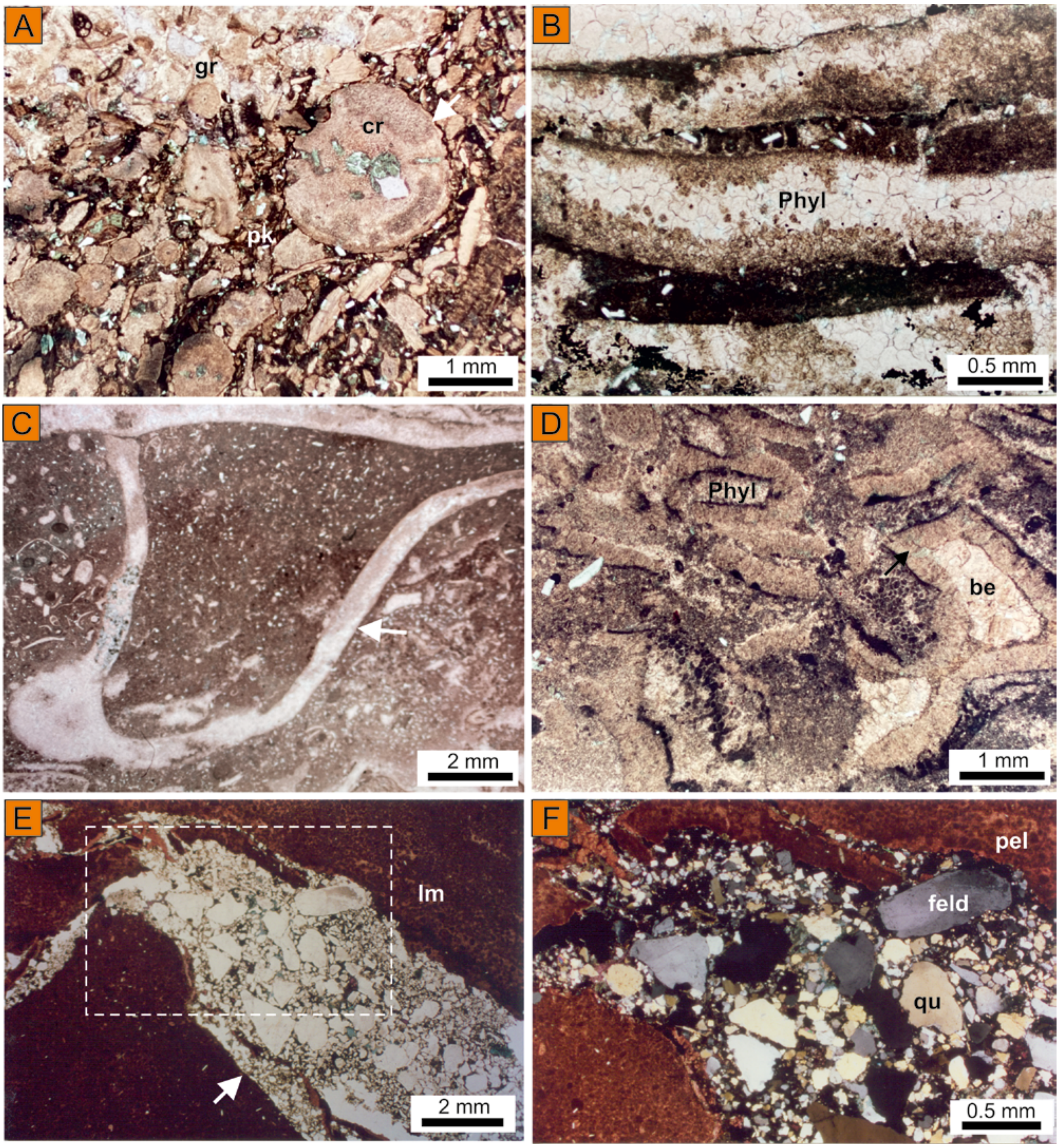

Fig. 5. Microfacies of the studied sediments. **A.** The crinoidal limestone (packstone pk/grainstone, gr) showing crinoidal grains (cr) with peripheral stylolites (blue arrow), Laguna Salado well, 3,740.2 m. **B.** Phylloid alga (Phyl – *Archaeolithopyllum*), showing remains of polygonal internal structure, Pure Gold 4-1, 4,185.8 m. **C.** A vase shaped phylloid algal thalli (arrow) in growth position, Pure Gold 4-1, 4,184.2 m. **D.** An algal grainstone in the bank margin facies, Phyl indicates phylloid alga, arrow shows isopachouus marine rim cement (former aragonite), be denotes blocky equant calcite cement (freshwater cement), Sterling Silver 3-1 well 4,185.6 m. **E, F.** Non-marine internal sediment (arrow) including most quartz (qu) and feldspar (feld) grains filling the Phyl – Archaeolithopyllum algal mould, lm: micrite (E – under plane-polarized view, F – enlarged view of the frame in E – under polarized light), North Pure Gold 8-1 well, 4,072.7 m.

carbonates produced the phylloid algal mouldic cavities that were later completely filled with sandy internal sediments (Figs 3G, 5E, F), indicating that the bank carbonates were exposed to subaerial conditions. After filling the mouldic pores with the internal sediments, compaction caused breakage of the rock that produced brecciation in the bank carbonates. The brecciated dark areas in the core samples correspond to areas of open space between phylloid algal colonies (cf. Fig. 3G, E). Although brecciation occurred after filling in the phylloid algal mouldic pores with internal sediments, the internal sediments do not show brecciation because of their loose character, but they prevented the collapse of the mouldic pores. This mechanism differs significantly from the widely accepted dissolution-collapse mechanism, proposed for breccia in evaporite-bearing carbonate rocks (Blount and Moore, 1969; Vlahović *et al*., 2002; Eliassen and Talbot, 2005; Jaglarz and Rychliński, 2018; Shukla and Sharma, 2018).

Phylloid algae are usually too strongly neomorphosed (Wray, 1977) under meteoric water conditions at a near-surface setting that makes their identification difficult. These diagenetic processes often involved replacement and recrystallization that changed the original mineralogy and/or fabric of the sediments (Tucker and Bathurst, 1990; Tucker and Wright, 1990; Tucker, 1991). The susceptibility of phylloid algae to neomorphism and also dissolution is a function of their original metastable mineralogy (aragonite or high-Mg calcite) and the highly porous nature of their original skeletal microstructure (Corrochano and Vachard, 2014). In the Atoka carbonates, the phylloid algae are represented by *Archaeolithophyllum* (Fig. 5A). Its original composition is controversial and widely suggested to be high-Mg calcite and also aragonite (Corrochano *et al*., 2013). The pervasive dissolution of the phylloid algae in the Atoka carbonates may indicate that former aragonite composition for *Archaeolithophyllum* is more likely because aragonite has the tendency to dissolve more easily than calcite in a freshwater environment (Tucker and Bathurst, 1990).

The presence of sandy internal sediments required the transportation of terrigeneous material to the bank complex areas and later the discharge of vadose fluids, sufficient to transport this detritus into the host rocks under near-surface conditions.

The Pennsylvanian phylloid algal banks form reservoir rocks on the northwest shelf of the Delaware Basin. Reservoir quality is controlled by many factors (Longman, 1981). Subaerial conditions during bank evolution, due to a fall in relative sea level, indicate interruption in the bank development. Under subaerial conditions, pervasive dissolution generated secondary mouldic porosity that increased the overall porosity and reservoir quality, whereas internal sediment in the mouldic pores decreased the porosity and reservoir quality. Later, brecciation in the carbonates generated new secondary pores (Moore, 1989), increasing the overall porosity and permeabilty of the reservoir rocks.

CONCLUSION

The Pennsylvanian Atoka bank carbonates, which form a stratigraphic trap for natural gas, were deposited on the northwest shelf of the Delaware Basin, in Eddy County, New Mexico. The phylloid alga, *Archaelithopyllum*, is the main fossil component of the bank complex and indicates deposition in a shallow-marine environment at depths of less than 30 m. The brecciation in the carbonates is due to the selective dissolution of phylloid algae and compaction. The dissolution of phylloid algae produced phylloid algal moulds, which were later filled with sandy internal sediment under subaerial conditions. Consequently, the rock was subjected to compaction that caused the breakage of the rock, producing a breccia texture. Overall, the dissolution and brecciation processes increased the reservoir quality, as opposed to the internal sediment, which reduced the pore volume.

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