GCAGS JOURNAL A Publication of the Gulf Coast Association of Geological Societies www.gcags.org

Natural Microfractures in Unconventional Shale-Oil and Shale-Gas Systems: Real, Hypothetical, or Wrongly Defined?

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ABSTRACT

The debate about the existence and significance of natural microfractures in unconventional mudrock (shale) reservoirs is important because microfractures are commonly proposed as a principal pore and permeability network in the production of hydrocarbons from mudrocks. Many studies have addressed the existence of microfractures, but few have documented them with reliable criteria, or documented their abundance or connectivity. We define natural microfractures in mudrocks as fractures (generally mode I) up to several millimeters long (generally <10 mm) and several micrometers wide (generally <15 µm) that occur within mudrocks where they were buried in the subsurface. Our experience is that natural microfractures do occur in mudrocks but that they are relatively rare and do not contribute to forming a permeable pathway for fluid movement into induced hydraulic fractures. Many microfractures described as natural are actually artifacts created during coring or post-coring by the coring process, subsequent handling, and sample preparation. Also following coring, dehydration of clay-rich samples creates desiccation microfractures, and devolatilization of bitumen creates shrinkage microfractures. Nonsulfate-related cements in fractures indicate that microfractures are natural and not induced post-coring. Some microfractures could be produced in the matrix during hydraulic fracturing, but a post-fracking core would be needed to address this research question. Our investigation seeks to determine how interpretation of natural microfractures in mudrocks can be improved and how the importance of natural microfractures as fluid-flow pathways can be seriously addressed.

INTRODUCTION

The importance of microfractures in unconventional mudrock (shale) reservoirs has been a controversial subject (e.g., Gale et al., 2007; Grover, 2011; Slatt and O'Brien, 2011; Apiwathanasorn and Ehlig-Economides, 2012; Ding et al., 2012; Reed, 2013; Anders et al., 2014; Gale et al., 2014). Microfractures are mentioned in many studies, but few have documented them with reliable criteria, or documented their abundance or connectivity. Understanding microfractures is imperative because they have been proposed as a principal pore and permeability network in the production of hydrocarbons from mudrocks (e.g., Apiwathanasorn and Ehlig-Economides, 2012; Ding et al., 2012; Slatt and O'Brien, 2012; Apaydin, 2013).

Debate on the existence of microfracture pore networks can be confusing because each side may be using different definitions for microfractures or misinterpreting artifact-related microfractures as natural microfractures. Therefore, it is important to define what structural geologists refer to as microfractures and what criteria should be used to separate natural microfractures from artifacts. One must also address whether natural microfractures occur in mudrock reservoirs and, if so, are the microfractures abundant enough to connect and form fluid-flow pathways.

Interestingly, many studies that mention microfractures do not define them relative to their size or abundance (e.g., Apiwathanasorn and Ehlig-Economides, 2012; Ding et al., 2012; Apaydin, 2013; Martin, 2015). Some of the confusion in the literature about microfractures may be clarified by defining natural microfractures. Here, we follow a slightly modified general definition suggested by Gale et al. (2007), Anders et al. (2014), and Gale et al. (2014). Natural microfractures in mudrocks are fractures (generally mode I) up to several millimeters long (generally <10 mm) and several micrometers wide (generally <15 µm) that occur within mudrocks where they were buried in the subsurface (Fig. 1). This definition eliminates the macrofractures that are well described in many unconventional and conventional reservoirs. Gale et al. (2014) noted that engineers and geophysicists commonly refer to smaller macrofractures as

Manuscript received January 12, 2016; revised manuscript received May 10, 2016; manuscript accepted May 11, 2016.

GCAGS Journal, v. 5 (2016), p. 64–72.

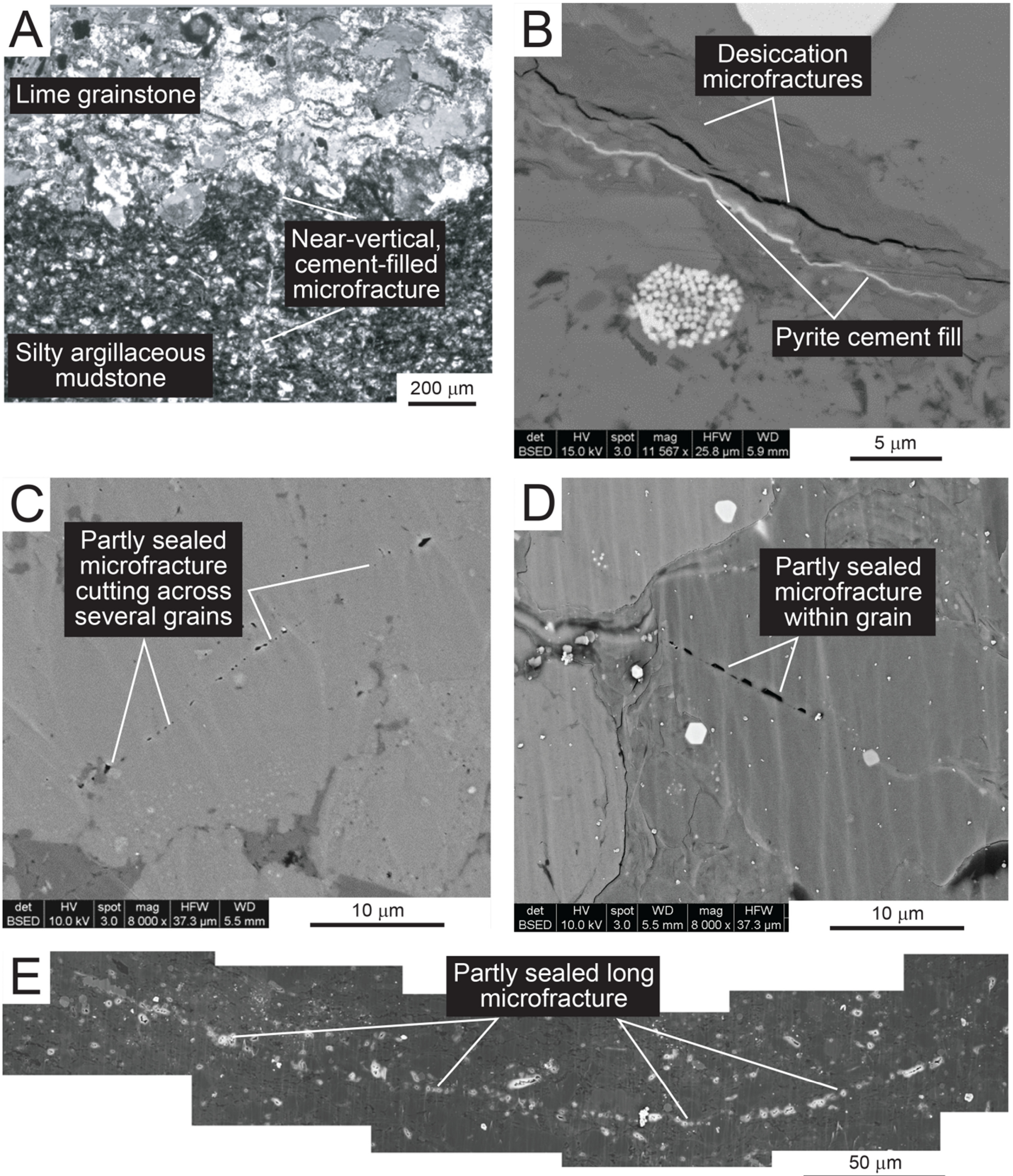

Figure 1. Natural microfractures as seen in thin-section and Ar–ion-milled SEM samples. (A) Slightly oblique natural microfracture filled with cement. Microfracture cuts boundary between silty argillaceous mudstone and lime grainstone. Lower Permian Wolfcamp Formation, Devon Energy Glass 12 No. 1V, 9618.5 ft, Martin Co., Tex. (B) Irregular, oblique natural microfracture filled with pyrite. Argillaceous layer in the Upper Cretaceous Austin Chalk Group, Proco Operating Co. Gise No. 1, 7213.75 ft, Dimmit Co., Tex. (C) Partly sealed natural microfracture that cuts several grains. Middle Pennsylvanian Atoka interval, Amoco Midland Farms No. AW1, 10,140 ft, Andrews Co., Tex. (D) Short, partly sealed natural microfracture within a single grain. Upper Cretaceous Tuscaloosa Shale, BEG Cranfield Unit No. 31–F2, 10,183.6 ft, Franklin Co., Miss. (E) Long, partly sealed natural fracture following curved bedding plane. Mississippian Barnett Shale, EOG Frank Wolf No. 1, 5700.5 ft, Archer Co., Tex.

"microfractures." Also eliminated from our definition are artifacts that are mistaken for natural microfractures.

The major goal of this paper is to discuss the existence and importance of natural microfractures in unconventional shale-oil and shale-gas systems and whether the microfractures are real, wrongly defined, or merely a mathematical construction designed to fit permeability data. Specific objectives are to: (1) show some examples of natural microfractures that fit the definition provided in this paper, (2) review the abundance of naturally occurring microfractures as seen by standard petrographic procedures, (3) describe how to recognize artifact-related microfractures, and (4) discuss unspecified microfractures proposed in reservoir modeling studies.

This review of microfractures will help in communicating the importance and abundance of natural microfractures in mudrocks, as well as in discovering whether natural microfractures are permeability pathways that will support the flow of oil or gas out of a mudrock matrix. The latter is vital because the existence of microfractures as flow pathways must be actually documented and not just assumed because the actual flow system was not recognized or understood.

DATA

Abundant literature covers many aspects of microfractures, including definition, origin, and proposed role in hydrocarbon production. Our investigation draws on this literature as well as providing new data and concepts derived from our research. As will be addressed later, examination of thin sections impregnated with visible blue dye and fluorescent blue dye should be able to identify some microfractures and their abundance, but caution must be taken to separate natural microfractures from artifacts (Grover, 2011). It is important to note that microfractures can be seen in fluorescent blue-dyed thin sections but that scanning electron microscope (SEM) analysis is needed for detailed study

The SEM is an important tool for recognizing and characterizing microfractures, especially those in their lower size range. Typical SEM samples cover only a small area, generally a few square millimeters, and may miss microfractures present in the sample. However, if natural microfractures are abundant enough to form a continuous flow pathway, it seems that they would have to be abundant enough to be captured in at least some SEM samples. SEM samples commonly are of three types: (1) rock chips, (2) polished thin sections, and (3) ion-milled samples. Broken rock chips may be an inferior sample type because the method of breaking a sample during preparation may create artifact fractures; these rock chips also have been shown to create artifact-related pores by the plucking of grains as the sample is separated. However, Slatt and O'Brien (2011) were able to view some pores with the SEM method in mudrocks. Polished thin sections have value because they allow a relatively large area for viewing, although care must be taken to separate fractures created by thin-section preparation (including sawing of the stub, slicing of the impregnated stub, and grinding of the thin section itself). Ion-milled samples are excellent for viewing nanopores (Loucks et al., 2009, 2012), and the approximate 2 by 0.5mm milled area is large enough to see natural microfractures. Ion-milled samples are slightly heated during preparation in a vacuum, and they are also viewed in a vacuum with the SEM. Heat and vacuum may create devolatilization microfractures in solid bitumen (Loucks and Reed, 2014).

This present study did not analyze new samples using SEM, but rather used an extensive Bureau of Economic Geology (BEG) library of SEM images from numerous mudrock systems samples. The BEG database covered most rock types, thus eliminating any sample bias. Several examples of natural microfractures were supplied, as noted below by other researchers.

DOCUMENTATION OF NATURAL MICROFRACTURES

Natural microfractures do not appear to be abundant in mudrocks (Gale et al., 2007; Reed, 2013; Anders et al., 2014; Gale et al., 2014; this study). The authors of this paper have viewed many hundreds of thin sections and SEM samples and have noted the rarity of natural microfractures that could form production pathways in a mudrock matrix. All of our data is two-dimensional, but we assume that the numerous samples observed allowed us to see that our two-dimensional views are not biased and that numerous natural microfractures indeed do not occur in the third dimension. This rarity of microfractures in mudrocks, which might be related to high clay-mineral content, is surprising because cement-filled natural microfractures occur quite commonly in sandstones (e.g., Milliken, 1994; Anders et al., 2014) and carbonates (e.g., Gale et al., 2004). The occurrence of natural microfractures in mudrocks is generally attributed to tectonic processes (e.g., Gale et al., 2007), compaction associated with burial (Anders et al., 2014), volume changes in organic-rich source rock related to hydrocarbon generation (e.g., Vernik, 1994; Jin et al., 2010; Martin, 2015), or overpressuring or abnormal high pressure buildup (e.g., Ding et al., 2012).

We have documented a few examples of natural microfractures in mudrocks (as defined in the Introduction), especially in SEM (ion-milled sample) images (Fig. 1). However, in these images, the microfractures are isolated and do not form a connected flow pathway. Most are filled almost completely with cement and provide only limited permeability (Landry et al., 2014). Figure 1 shows examples of several natural microfractures. Orientation of microfractures can be horizontal, oblique, or vertical. Some are filled with cement (Figs. 1A and 1B). Others are partly occluded by bridges of cement (Figs. 1C–1E). All of the natural microfractures in Figure 1 are isolated and would not significantly contribute to any permeability pathway.

Chalmers et al. (2012), in their study of pore systems in mudrocks, showed a number of barren microfractures (their figs. 9A, 9F, 13A, and 13B) that they assume are natural, while also mentioning that some may be induced post-coring. The lack of cement in these microfractures suggests that they are artifacts. Walters (2013) showed microfractures barren of cement that fit our definition of natural microfractures relative to size. He measures gas transport in whole cores under reservoir conditions and finds that most rapid transport of gas occurs in features subparallel to bedding that appear to be microcracks within the matrix. Walters (2013) mentioned that it is not possible to prove that these microfractures are not artifacts, but the microfractures themselves support his conclusion that they are natural microfractures because well productivity and their presence correspond—a rare documentation of natural microfractures, but, as Walters mentioned, not conclusive evidence. If the microfractures were artifacts, they would also affect the experimental flow in the laboratory.

Other examples of natural microfractures from Upper Devonian Dunkirk Shale in western New York have been shown by Lash and Engelder (2005, their figs. 5 and 6). Some of the microfractures are filled with solid bitumen and pyrite crystals, whereas others appear to be barren of fill. The filled microcracks are definitely natural, while others may be artifacts. Slatt and O'Brian (2011, their fig. 15) show several examples of microfractures; some appear to be associated with cleavage within crystals, and another appears to be a microstylolite.

The literature has many references to microfractures in mudrocks, but most references do not present any photomicrographs or descriptive evidence that the microfractures are natural and not artifacts (e.g., Ding et al., 2012; Apaydin et al., 2013; Martin, 2015). Some studies have interpreted microfracture artifacts as natural because of the presence of post-coring gypsum cement (Capuano, 1993). Others have postulated microfractures in kerogen-rich rocks on the basis of sonic velocity experiments (Vernik, 1994). However, these experimental studies have never presented photodocumentation of the microfractures.

Natural microfractures should be considered separately from artifact-related microfractures. Many microfractures observed in mudrocks are artifacts related to coring processes, sample preparation, or post-coring dehydration and stress release of the mudrock matrix, especially those mudrocks rich in clays (Figs. 2 and 3). Some bitumen will undergo devolatilization, creating cracks in the solid bitumen (Fig. 4). The process of sample preparation for thin sections and SEM can also produce microfracture artifacts. Grover (2011) summarized the major processes that can produce artifact-related microfractures, including the coring-process, gas-expansion stress release as the core is brought to the surface, and core removal from barrel and associated handling. Gale et al. (2014) noted that some flat fossils, such as the bivalve *Inoceramus*, with prismatic crystal structure can be confused with horizontal fractures in core. For microfractures to be considered natural, they must contain some cement or solid bitumen. Gypsum is a suspect mineral in microfractures (Figs. 2 and 5A) because it can be precipitated after the core has been taken (Milliken and Land, 1994). Milliken and Land (1994) noted that after the exposure of a core sample to humid air, the pyrite can oxidize, producing available iron, dissolved sulfate, and acid. Dissolution of carbonate contributes calcium, and upon evaporation calcium sulfate is precipitated fairly rapidly. If the microfractures are totally barren of both nonsulfate cement and solid bitumen, then they must be considered questionable as natural. It appears that many barren microfractures noted in SEM have developed around grains and have not fractured the grains (Figs. 3A, 3D, 4C, and 5B). We suggest this is a consequence of breakage under low-confining pressure, indicating an artifact.

Figure 5C and 5D presents two features that may be confused with features of natural microfractures. The sample in Figure 5C contains straight grain-edge pores several micrometers long that contain cement bridges. Because of the linear shape of the pores, without close observation some could be misinterpreted as natural microfractures. However, these elongate pores follow the crystal and grain outlines. The flattened and distorted kerogen in Figure 5D is an example of a commonly seen feature in compacted mudrocks. This flattened kerogen might be mistaken as a solid-bitumen-filled natural fracture based on its elongated shape. Between the compacted kerogen are bitumen-filled microfractures created by expulsion pressure caused by the kerogen converting to petroleum.

A vital point addressed in the Introduction is the separation of natural microfractures from natural macrofractures. Macrofractures are larger and more common in mudrocks (Gale et al., 2014). This differentiation is a simple thing to do; any paper defining natural fractures in a mudrock reservoir should describe or characterize the fractures or fracture system. Where possible, authors should publish images of the fractures and provide fracture measurements. An obvious example of misinterpretation is from Pollastro et al. (2012), where the authors stated that the Devonian-Mississippian Bakken Formation contains abundant microfractures. However, their photographs of fractures (their fig. 12) clearly show the cement-filled fractures to be greater than 110 mm long and 400 µm wide, a size that we contend indicates macrofractures.

ABUNDANCE OF NATURAL MICROFRACTURES

Gale et al. (2014) noted that thin sections have a low chance of sampling natural microfractures because, assuming a power-law distribution, the microfractures are relatively rare and dispersed. If the statement that natural microfractures would not be sampled by thin sections generally taken at 1 to 5 ft intervals in cores is correct, then one must ask how natural microfractures can form a connected permeability pathway for production out of the matrix into induced fractures.

Based on their size, if microfractures were at the abundance level needed to form a permeability pathway, they would readily show up in a blue-fluorescent-dye-impregnated thin section that generally covers an area of approximately 1000 sq. mm (~25 mm × ~40 mm). Figure 6 shows schematic thin sections: one sample with only a few microfractures and one with abundant connected microfractures. This schematic representation emphasizes the rarity of finding even a few natural microfractures in a thin section (Fig. 6A). If only a few microfractures are present, they could not form an effective, connected pore network; at best, these microfractures may slightly enhance the nanopore network

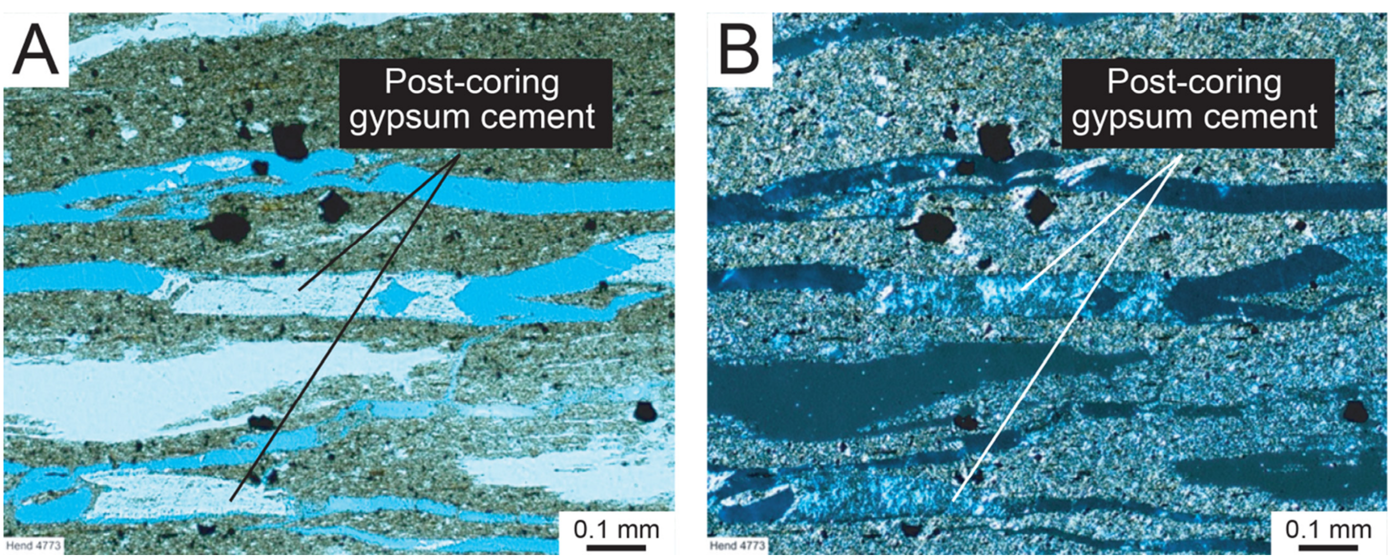

Figure 2. Desiccation-produced fractures as seen in thin section. Upper Cretaceous Lower Eagle Ford Group, Tesoro Hendershot No. 1, 4773 ft, Gonzales Co., Tex. (A) Distinct horizontal to subhorizontal desiccation cracks in argillaceous mudstone with patches of gypsum cement. Gypsum cement is post-coring. These fractures are larger than our definition of microfractures, but this thin section shows excellent examples of post-coring desiccation cracks with post-coring gypsum cement. (B) Same thin section, but with photomicrograph taken under polarized light.

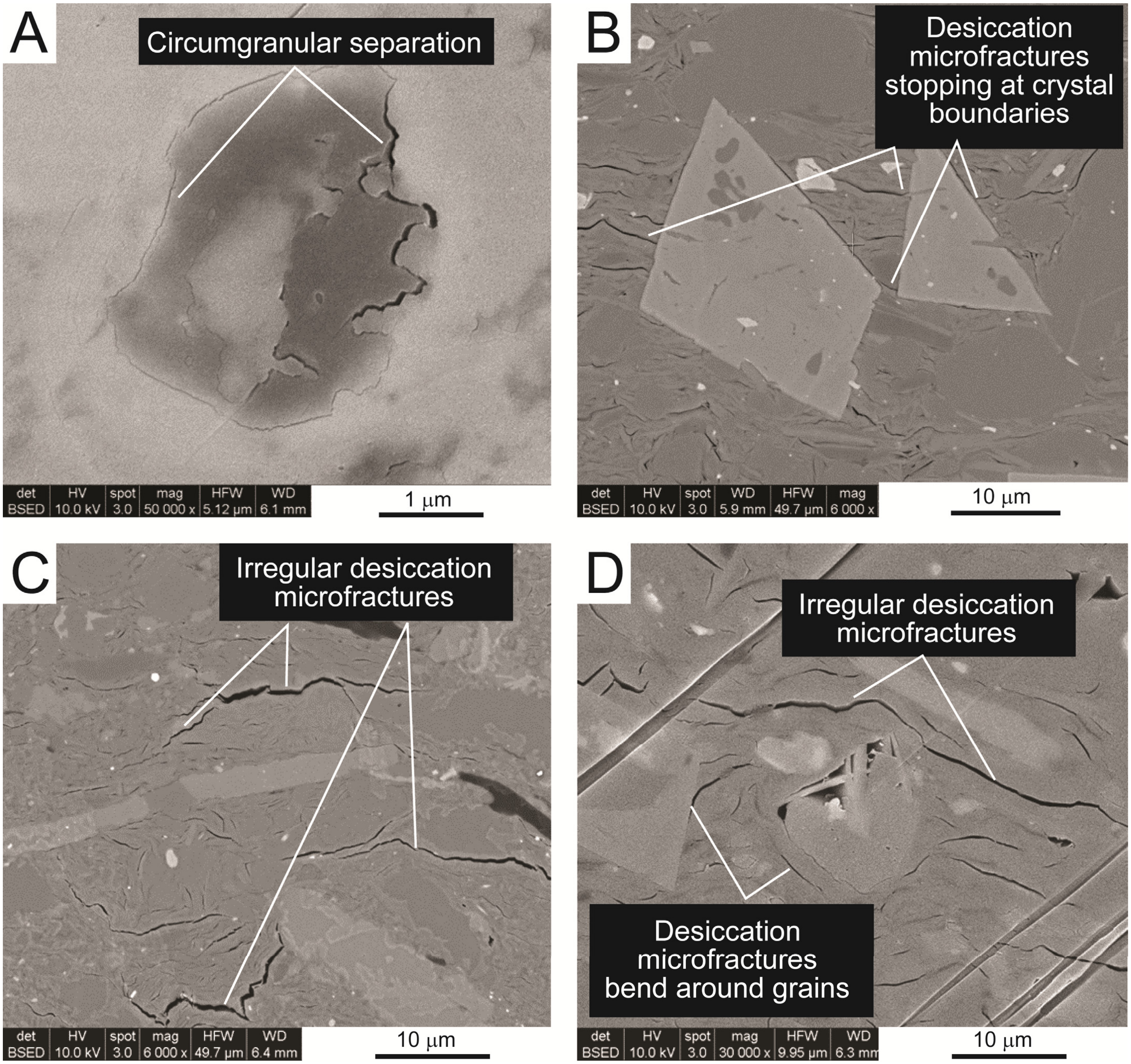

Figure 3. Examples of post-coring, artifact-related desiccation or stress-release microfractures as shown in Ar–ion-milled SEM samples. (A) Barren circumgranular crack around complete organic particle. A circular crack such as this has to be by desiccation. Many other desiccation microfractures we observed have same irregular morphology. Mississippian Upper Bakken Formation, Brigham Anderson 28–33 1H, 10,063.75 ft, Mountrail Co., N. Dak. (B) Multiple desiccation or stress-release microfractures abruptly terminate at crystal boundaries. Jurassic Haynesville Group, Crown Zellerbach 5–7 No. 1, 16,418', Winn Par., La. (C) Numerous irregular desiccation or stress-release microfractures, some very torturous. Middle Pennsylvanian Atoka interval, Amoco Midland Farms No. AX4, 10,460 ft, Andrews Co., Tex. (D) Desiccation or stress-release microfractures curving around grains instead of cutting through grains. Middle Pennsylvanian Atoka interval, Amoco Midland Farms No. AX4, 10,460 ft, Andrews Co., Tex.

in very localized areas. If the natural microfractures were abundant enough to connect to form an effective fluid pathway as shown in Figure 6B, then microfractures would be obvious in blue-fluorescent-dyed thin sections.

It is very easy to epoxy-impregnate a sample with submicrometer-sized openings, as is done routinely with commercially prepared thin sections. This high density of natural microfractures in thin sections has not been documented, nor has the density been documented with SEM-based samples. Therefore, if it is so difficult to observe natural microfractures in thin sections, the microfractures are most likely rare and will not create an effective pore or permeability network in a mudrock matrix.

HYPOTHETICAL MICROFRACTURE FLOW PATHWAYS

An interesting postulate relative to microfractures is the concept tendered by many engineering studies that natural

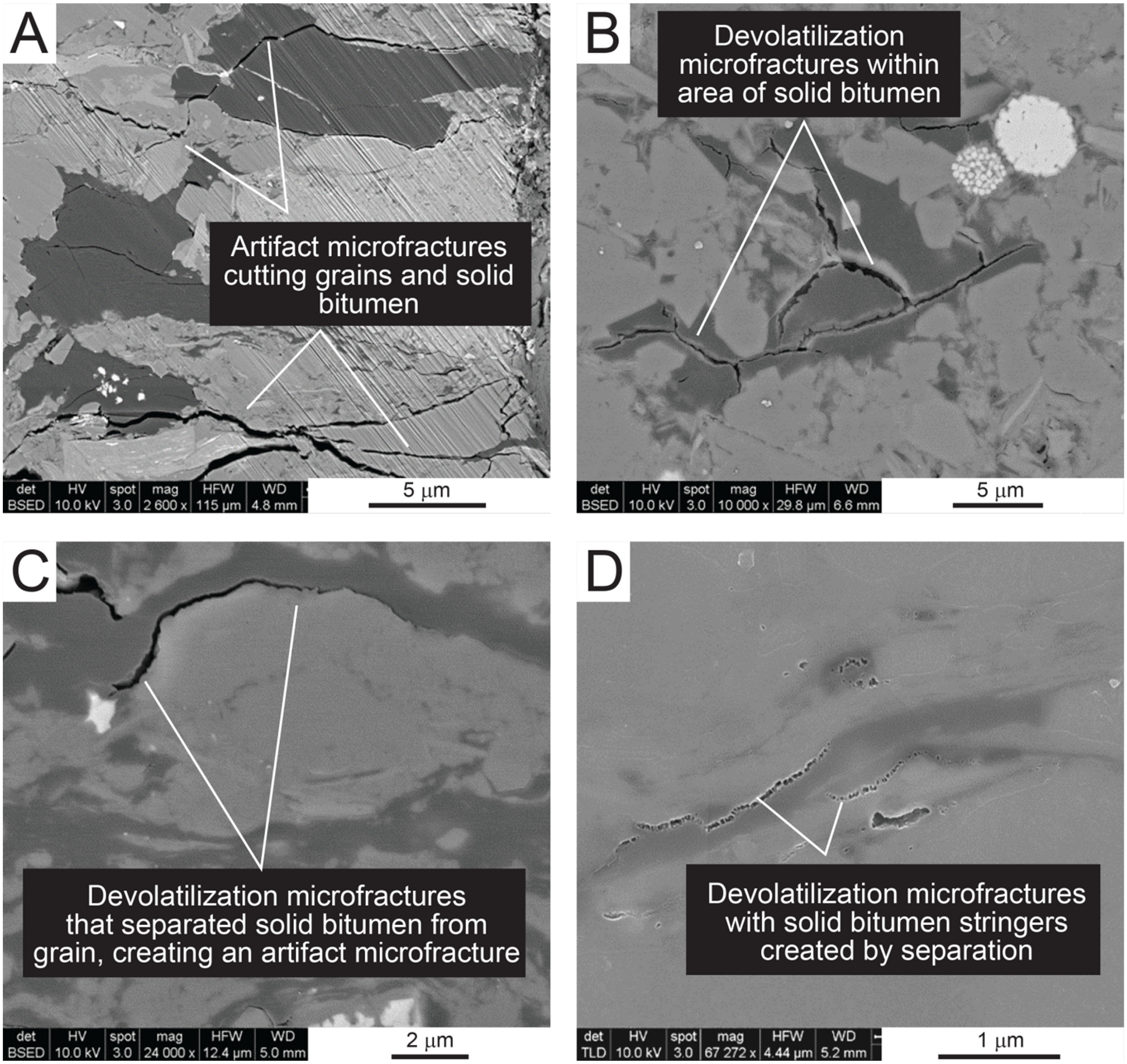

Figure 4. Examples of post-coring, artifact-related desiccation and devolatilization microfractures as shown in Ar–ion-milled SEM samples. (A) Microfractures cut across both grains and solid bitumen, suggesting both desiccation and devolatilization. Upper Triassic Yanchang Formation. (B) Devolatilization microfractures within center of solid bitumen. Note that directions of microfractures generally follow shape of solid-bitumen-filled pore. Permian Bone Spring Formation, Sun Oil Company Leroy Housells No. 1, 10,258.9 ft, Reeves Co., Tex. (C) Devolatilization microfractures follow contact between solid bitumen and grain. Mississippian Bakken Formation, Brigham Anderson 28–33 1H, 10,060 ft, Mountrail Co., N. Dak. (D) Devolatilization microfractures within solid bitumen. Microfractures have perpendicular stringers of solid bitumen within them. Lower Cretaceous Pearsall Formation, Humble Pruitt No. 46, 9700 ft, Atascosa Co., Tex.

microfractures must be present for a mudrock reservoir to produce. Models have been constructed suggesting a dual or triple porosity system consisting of matrix nanopores, microfracture pores, and fracking-induced artificial pores (e.g., Apaydin et al., 2012; Apiwathanasorn and Ehlig-Economides, 2012). These authors presented no description of the microfracture system, and their main evidence for the existence of microfractures is that microfractures must be necessary for the reservoir to flow. Therefore, we deem these microfractures as hypothetical: they exist only in the context of the model and might not exist in reality. Gale et al. (2014) mentioned that engineering studies may be confusing microfractures with the more common macrofractures. However, if these authors (e.g., Apaydin et al., 2012; Apiwathanasorn and Ehlig-Economides, 2012) were actually referring to natural microfractures, they may have been modeling a geologic feature that does not exist and might want to reconsider the matrix-pore contribution for flow into induced fractures and reinvestigate how flow actually operates in nanopore networks.

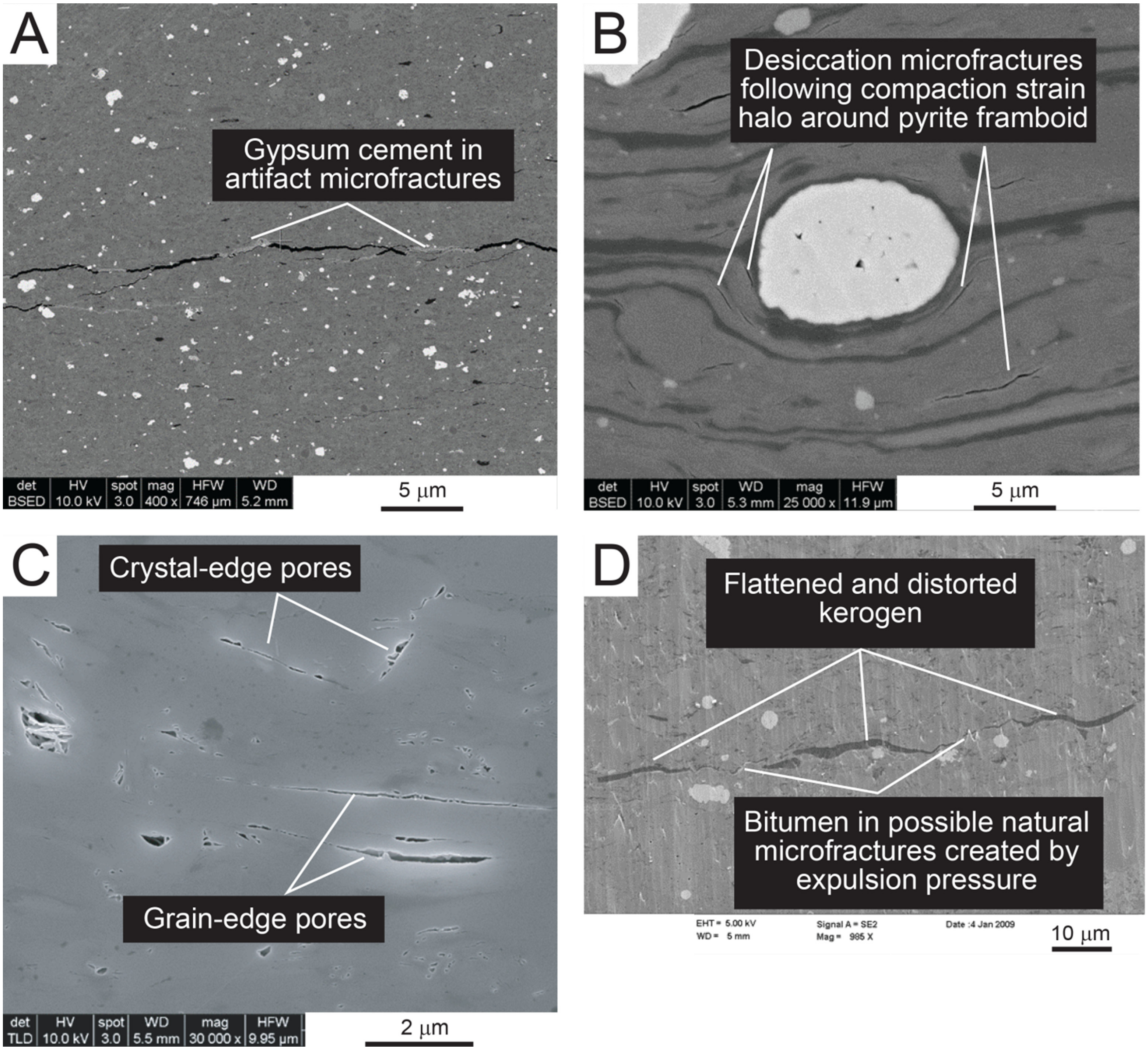

Figure 5. Ar–ion-milled SEM samples showing artifact-related microfractures and examples of possible misinterpreted natural microfractures. (A) Desiccation microfracture with patchy post-coring gypsum cement. Upper Cretaceous Eagle Ford Group, Shell J. A. Leppard No. 1, 13, 564.3 ft, Bee Co, Tex. (B) Numerous short microfractures formed along compacted laminae around early formed pyrite framboid. Orientation of desiccation microfractures was controlled by orientation of laminae. Unidentified Carboniferous mudstone from Germany. (C) Straight grain-edge pores that have appearance of microfractures. Lower Cretaceous Pearsall Formation, Skelly Oil La Salle No. 1A, 11,795.8 ft, La Salle Co., Tex. (D) Flattened and distorted kerogen. May be mistaken for solid-bitumen-filled microfracture. Between compacted kerogen are thin bitumen-filled microfractures. Mississippian Barnett Shale, United Blakely No. 1, 7191 ft, Wise Co., Tex.

POSSIBILITY OF FRACKING-INDUCED MICROFRACTURES

The literature on microfractures concentrates on natural or perceived natural microfractures that are already present in the rock before drilling. We suggest that the hydraulic-fracturing process might actually create microfractures within the matrix, but we cannot prove this concept. These microfractures would be documented only if a post-fracking core were obtained, and then it still would be difficult to absolutely document the induced microfractures because they would not contain cement or bitumen. An interesting study by Dehghanpour et al. (2013) recognized that imbibition of fracturing fluids into the host rock is a cause of fluid loss. Dehghanpour et al. (2013) suggested that brine intake in organic-rich mudstones can induce microfractures and an associated increase in permeability. Therefore, it is possible that the hydraulic-fracturing process or the fracking-fluid/matrix interaction may create post-drilling microfractures.

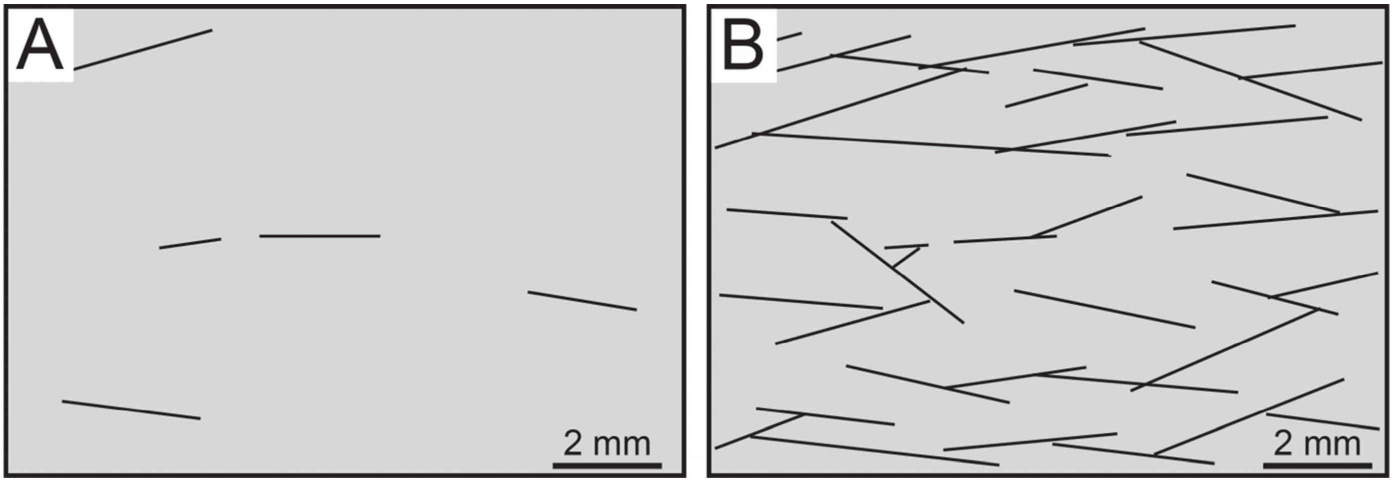

Figure 6. Schematic of disconnected and connected microfracture network as would be seen in thin section. (A) A small number of disconnected microfractures would not be able to produce a pore network allowing hydrocarbon flow. (B) If abundance of microfractures was great enough to produce a connected pore network allowing hydrocarbon flow, microfractures would be readily apparent in blue-fluorescent-impregnated thin sections.

CONCLUSIONS

Natural microfractures relative to the definition presented in this paper do exist in mudrocks, but they appear to be relatively rare and most likely do not significantly contribute, if at all, to fluid flow out of the mudrock matrix into induced hydraulic fractures. Our approach to recognition and quantification of natural microfractures is rock based. As Figure 6B suggests, if natural microfractures were abundant enough to form a connected fluid-flow pathway, they would be readily visible in samples. In our experience, we have not seen this abundance of natural microfractures. In fact, we are challenged to find many natural microfractures at all.

Misunderstanding about an abundance of natural microfractures is related to three things: (1) terminology confusion between microfractures and macrofractures, (2) mistaking fracture-related artifacts for natural microfractures, and (3) a need for a permeability pathway to make flow models work. As Gale et al. (2014) noted, many studies that mention microfractures are actually referring to macrofractures. There is no disagreement that macrofractures are present in mudrock reservoirs and contribute to fluid flow. A significant problem still exists in distinguishing natural microfractures from artifact-related microfractures created during coring and through sample preparation as well as stress release, dehydration, and devolatilization. Artifact-related microfractures are very common in mudrocks because of clay-mineral abundance, solid bitumen content, and bedding-plane weaknesses. Relative to assuming the prerequisite for an undocumented microfracture system in fluid-flow models, we may want to consider in more detail how hydrocarbon flow occurs in matrix nanopore systems.

This paper has addressed natural microfractures in mudrocks, but we recognize that the hydraulic-fracturing process may induce microfractures into a reservoir. This concept can only be tested if a post-fracking core is taken in a nearby well and kept at in situ conditions as best as possible.

If natural microfractures are more common than suggested by this study, then case examples documenting them should be published. Until case histories are verified, one must use caution in depending upon naturally occurring microfractures to contribute to fluid flow.

ACKNOWLEDGMENTS

This study was supported by the Mudrock Systems Research Laboratory (MSRL) at the Bureau of Economic Geology (BEG), Jackson School of Geosciences, University of Texas at Austin. Sponsoring companies include: Anadarko, BP, Cenovus, Centrica, Chesapeake, Chevron, Cima, Cimarex, Concho, ConocoPhillips, Cypress, Devon, Encana, ENI, EOG, EXCO, ExxonMobil, Hess, Husky, Kerogen, Marathon, Murphy, Newfield, Penn Virginia, Penn West, Pioneer, Samson, Shell, StatOil, Talisman, Texas American Resources, The Unconventionals, US Enercorp, Valence, and YPF. We also would like to express appreciation to Lucy Ko, Stephen Ruppel, and Julia Gale of the BEG for providing discussion and insight relative to natural microfractures in mudrocks. Ryan Phelps of ConocoPhillips and an anonymous reviewer reviewed the manuscript, and we express our appreciation for their comments and suggestions. Also, we want to thank Owen Broyles of Devon Energy and Ursula Hammes and Jiemin Lu of the BEG for allowing us to use some of their images of microfractured mudrocks. Stephanie Jones of the BEG kindly edited the manuscript. Publication was authorized by the Director, Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin.

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