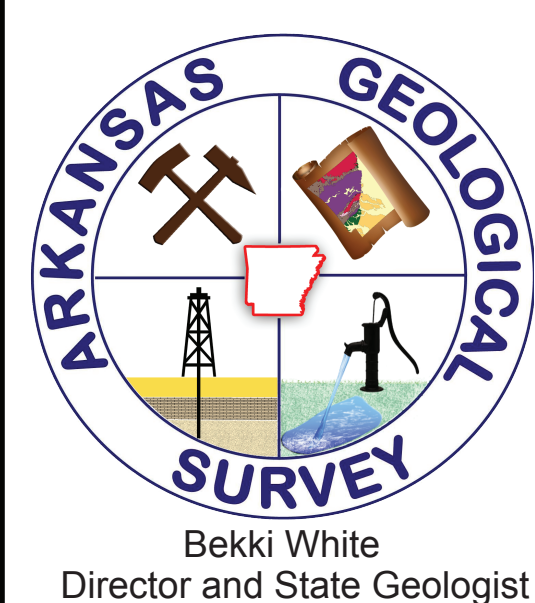


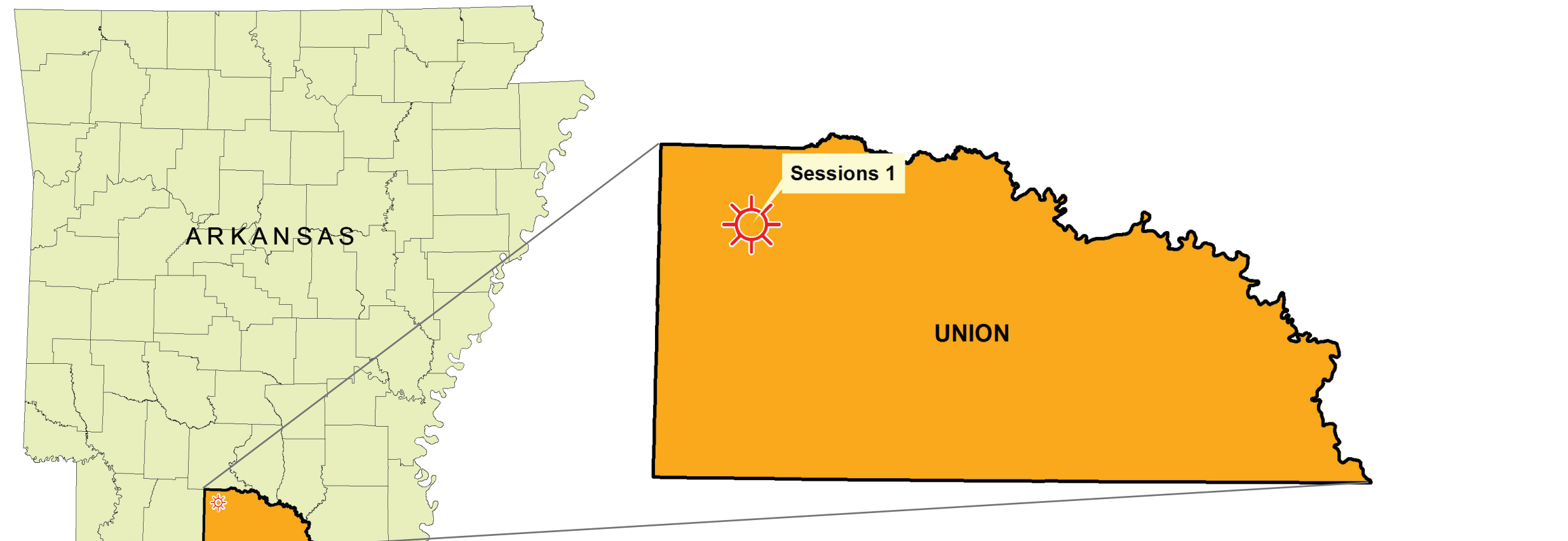


Bekki White
Director and State Geologist

Reservoir Characterization and Resource Assessment of the Brown Dense Mudstone (Lower Smackover Formation), Gulf Coastal Plain, South Arkansas

Peng Li¹, Michael E. Ratchford², Marc W. Charette¹, Bradley J. Walls³, and Richard P. Philp⁴

- Arkansas Geological Survey, Little Rock, AR 72204
- Idaho Geological Survey, University of Idaho, Moscow, ID 83844
- Weatherford Laboratories, Houston, TX 77086
- University of Oklahoma, Norman, OK 73019



Gas Chromatography / Mass Spectrometry and Carbon Isotope

Geochemical characterization based on biomarker components and isotopic data was used to characterize the crude oil from the Brown Dense Mudstone in the Sessions 1 well. The depositional environment parameters indicating the Sessions oil was derived from a carbonate source rock with little significant terrestrial organic matter contribution and deposited in a marine environment under highly reducing, anoxic conditions. The thermal maturity parameters suggest that the Sessions oil was generated from a source rock in the oil window, but not yet in the condensate window.

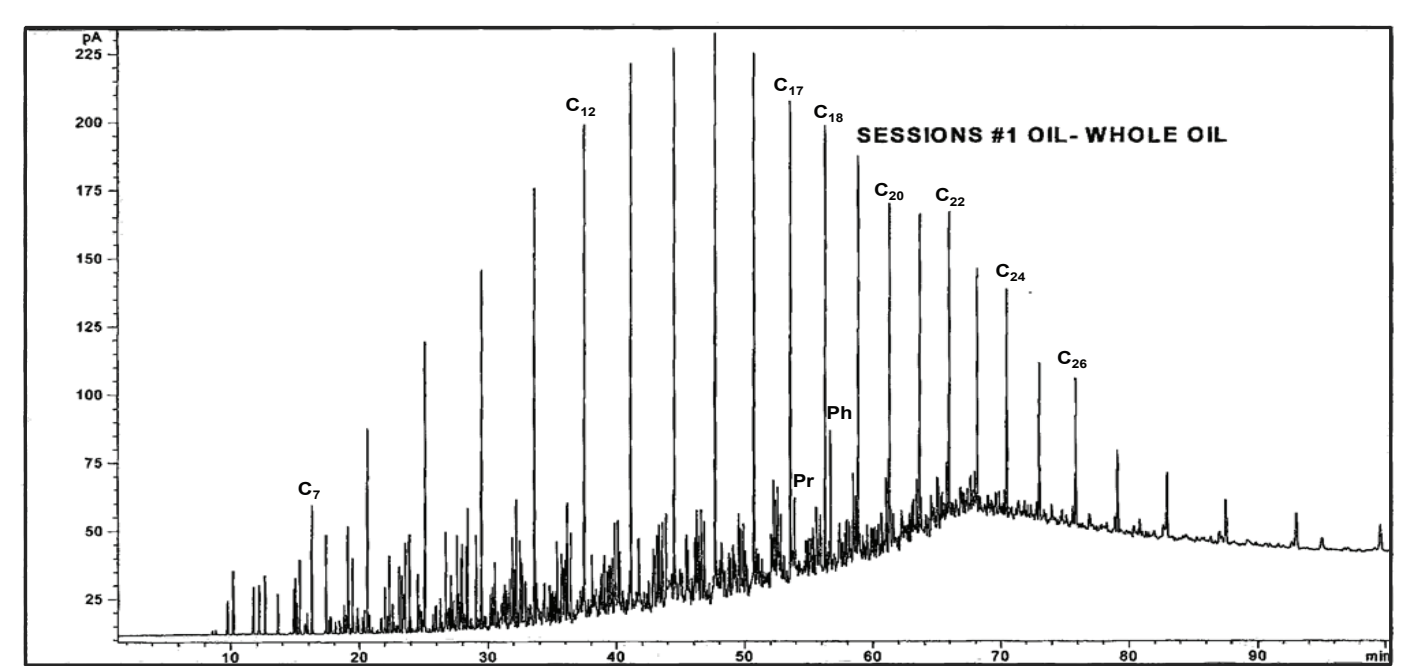


Figure 1. Gas chromatogram of whole oil. The odd-even preference (OEP) of 0.96 suggests a marine carbonate oil. The Pr/Ph ratio is 0.67, reflecting a reducing, probably marine, depositional environment.

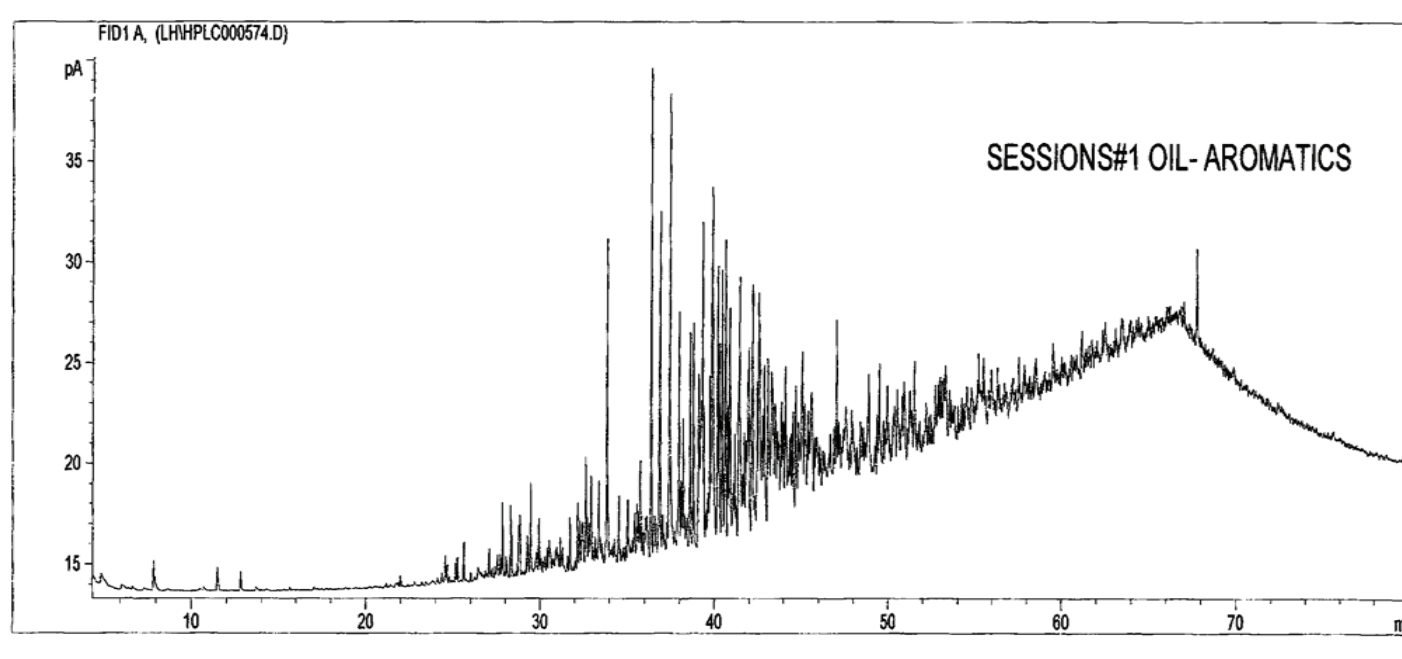


Figure 2. Gas chromatogram of aromatic hydrocarbon. The Sessions oil of 48.36 mg was fractionated into the following weights: saturates (11.8 mg), aromatic (24.02 mg), and NSO (0.22 mg). The compositional distribution of the Sessions oil suggests a terrestrial source, although this is unlikely based on other data.

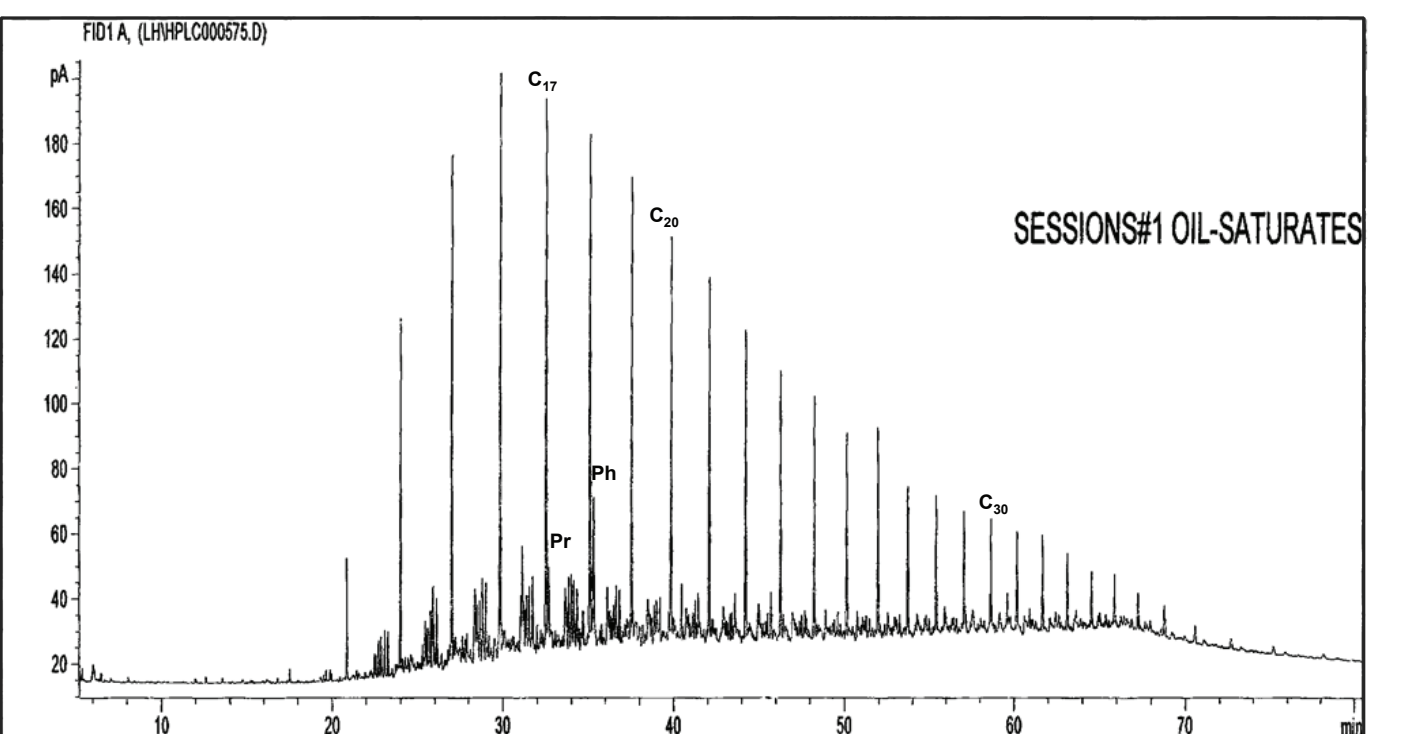


Figure 3. Gas chromatogram of saturated hydrocarbon from the Brown Dense, Sessions 1 well. The n-alkane distribution maximizes at n-C16 with low abundance in the high molecular-weight region, indicating marine organic material.

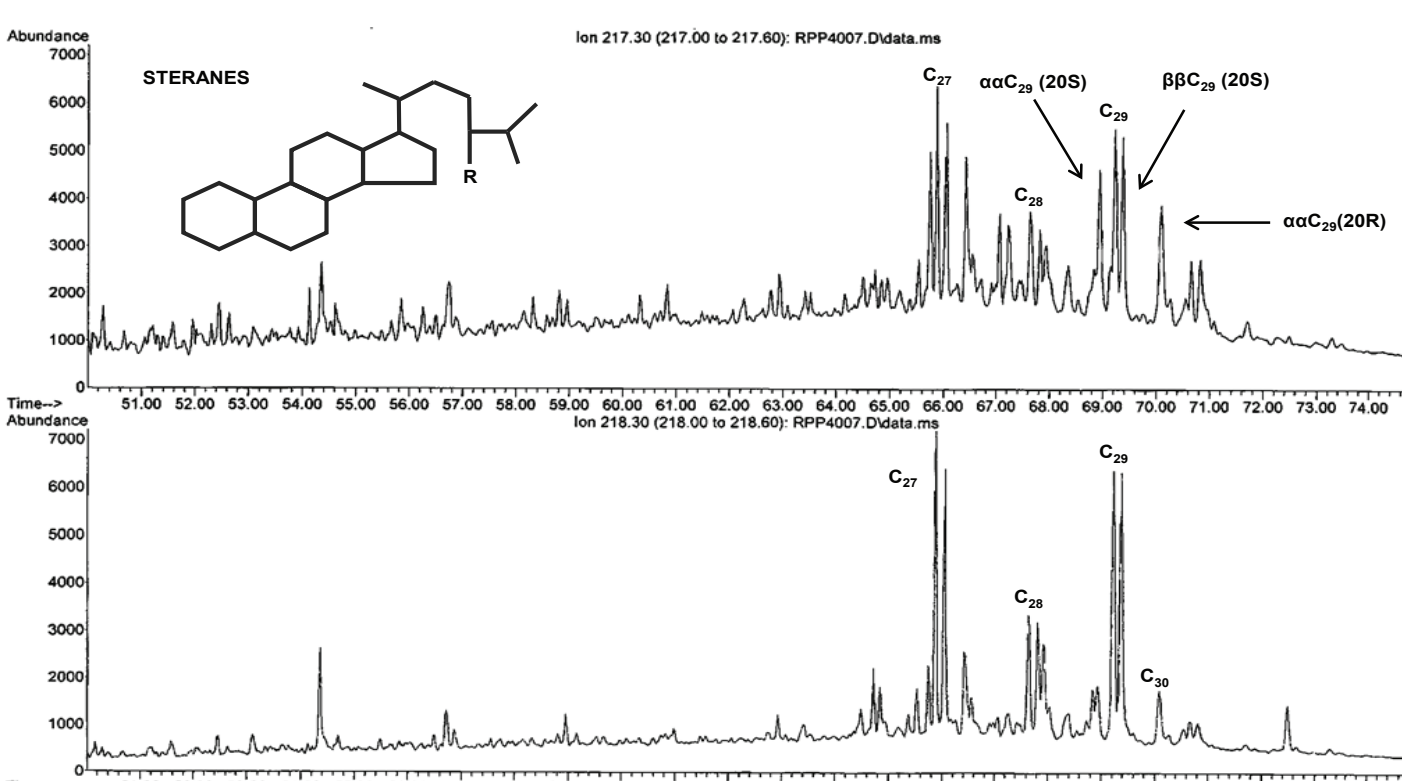


Figure 4. GCMs analysis of steranes in the saturate fraction of oil. Predominance of C27 steranes and the presence of C30 steranes suggest a marine source. 20S/(20S + 20R) and ββ/(ββ + αα) C29 steranes ratios are 0.55 and 0.53, respectively, indicating that this oil was generated from a mature source rock, but not yet in the condensate window.

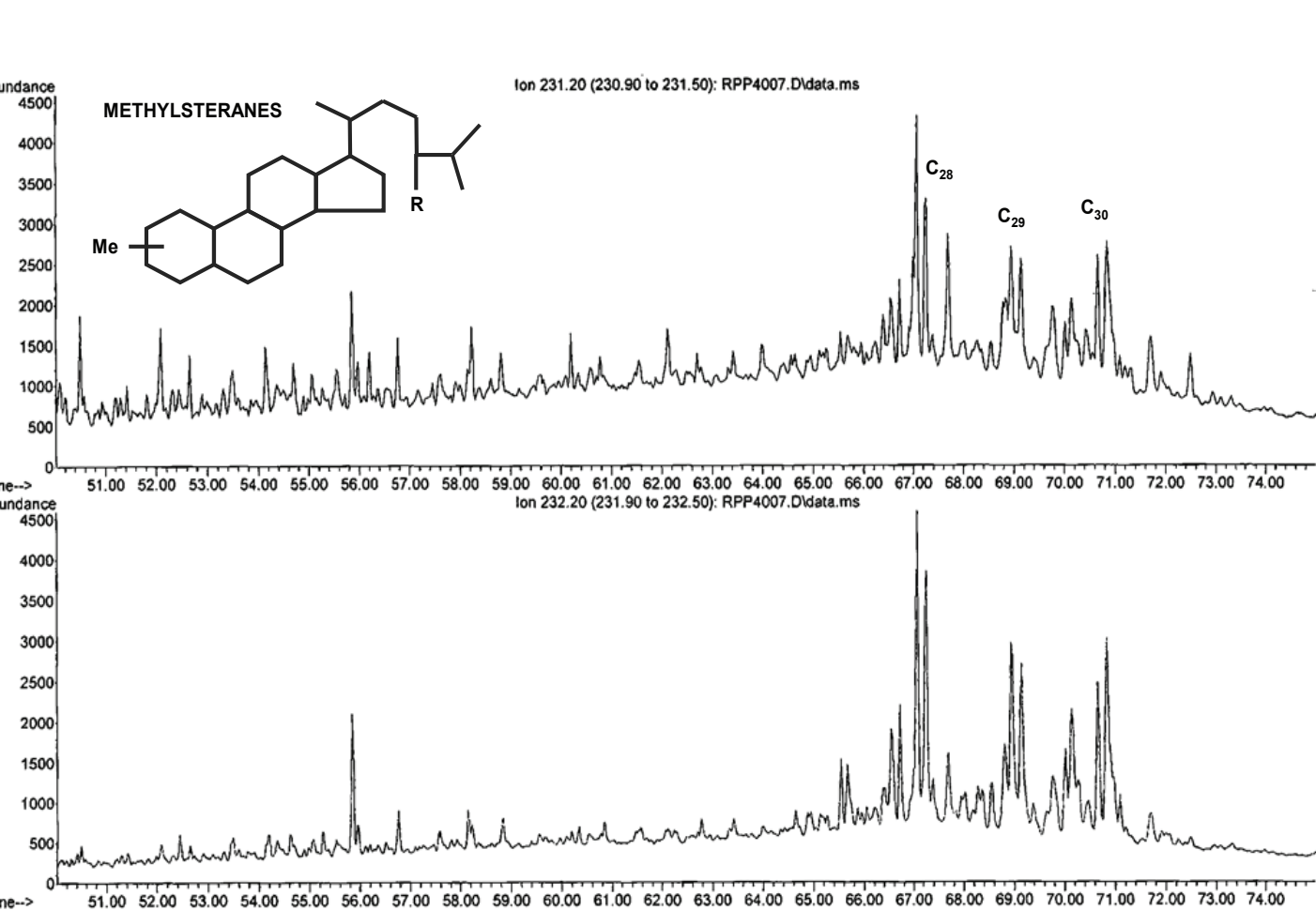


Figure 5. GCMs analysis of methyl steranes in the saturate fraction of oil. 4-methyl steranes are generally associated with marine sources. A series of this biomarker is observed in the Sessions oil.

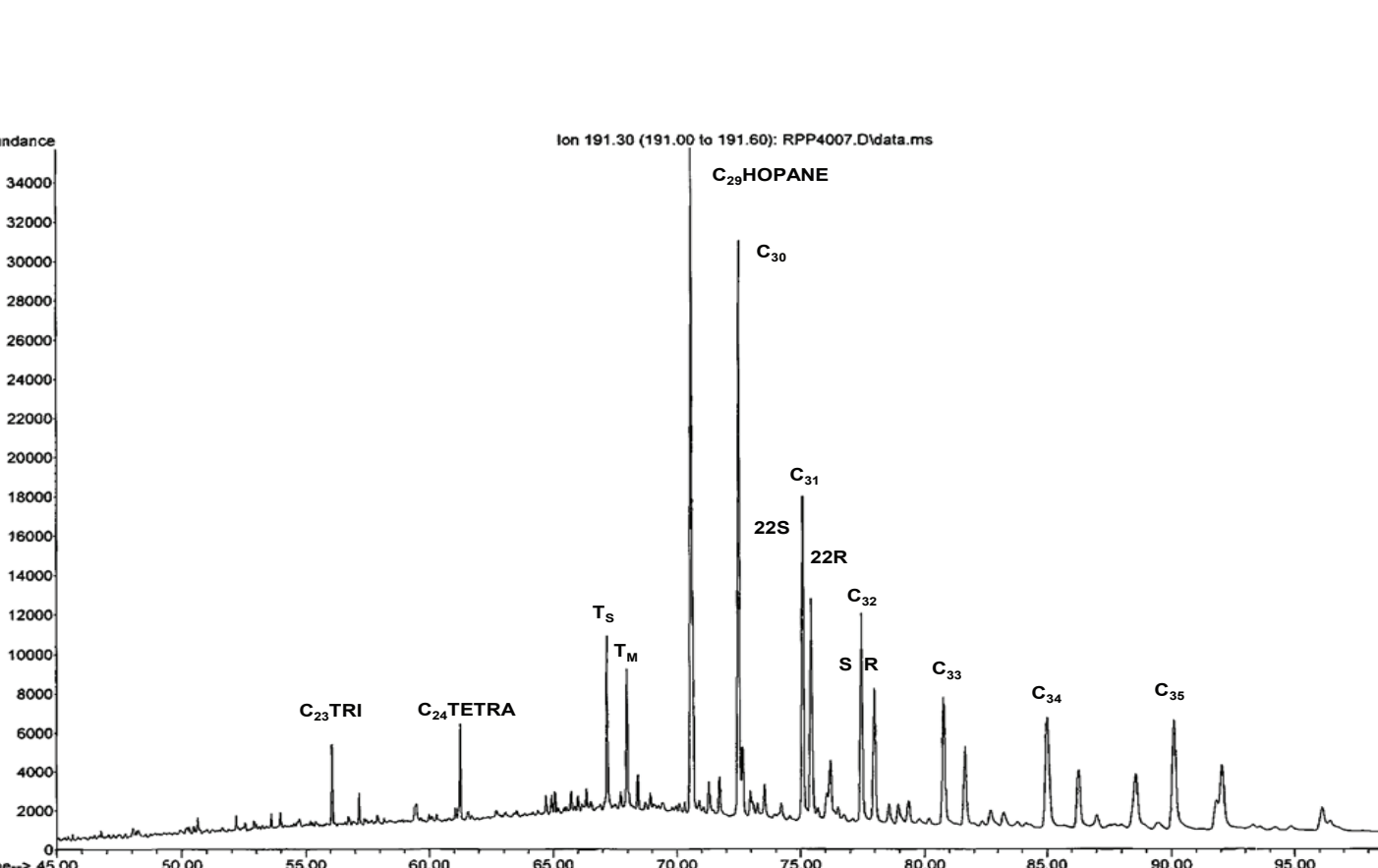


Figure 6. Terpane fingerprints (m/z 191) by GCMs for the saturate fraction of oil. The high values of C23 tricyclic and C24 tetracyclic terpanes are typical of oils being generated by a carbonate source rock. High C29/C30 hopanes ratio (>1) indicates the oil sample was generated from carbonate source rocks. The relatively high C30 homohopanes concentration suggests a highly reducing marine environment. 17α/(H22S/(22S + 22R)) homohopanes ratio of 0.59 and Ts/(Ts + Tm) ratio of 0.55 suggest that the oil reached equilibrium for oil window.

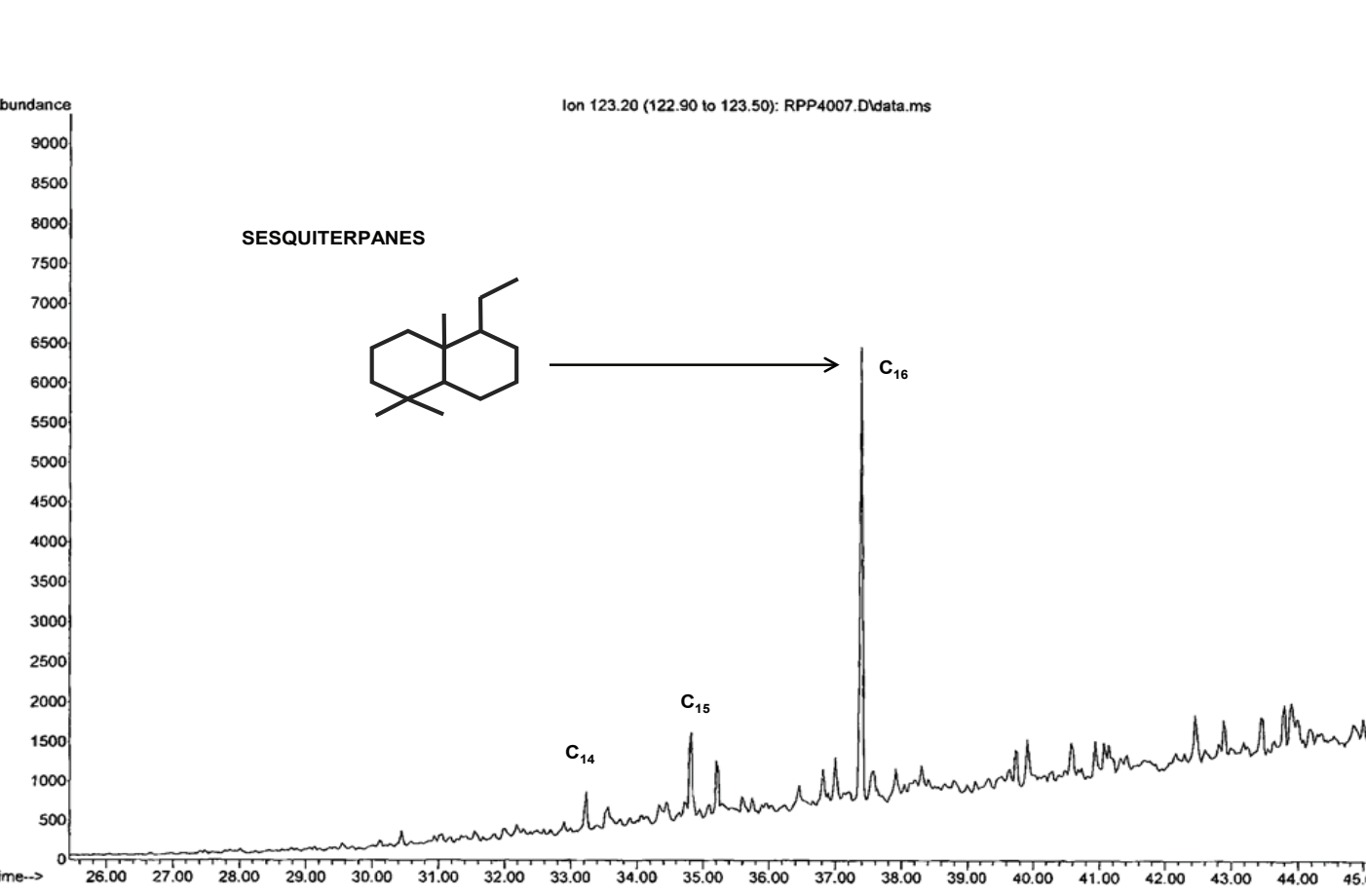


Figure 7. Aryl isoprenoid fingerprints by GCMs for the saturate fraction of oil. A series of aryl isoprenoids is observed in the Sessions oil, indicating that deposition of source rock for this oil is associated with oceanic anoxic events.

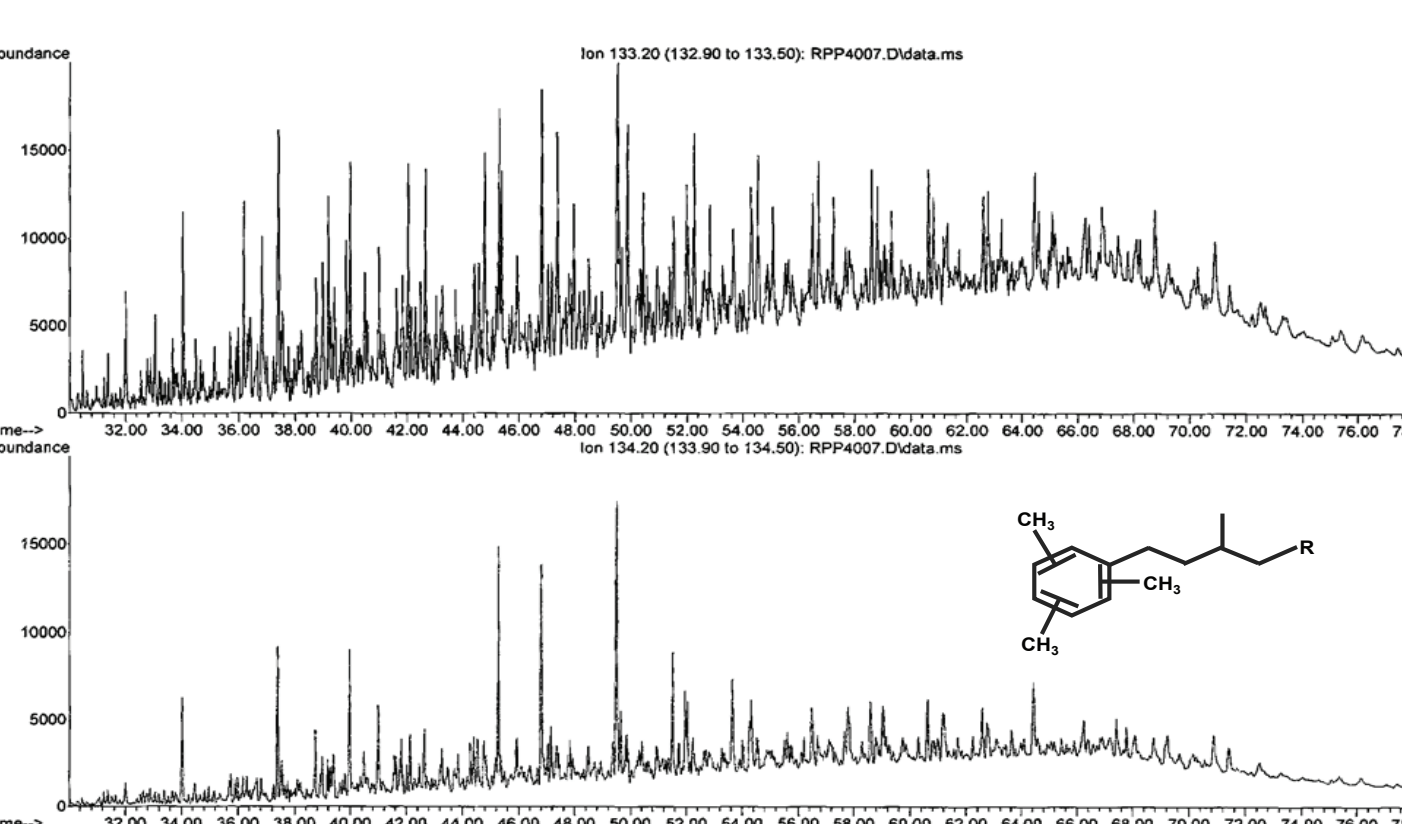


Figure 8. Carbon isotopic analysis of the saturate hydrocarbon. δ13C value of the saturate of averages -27.6‰.

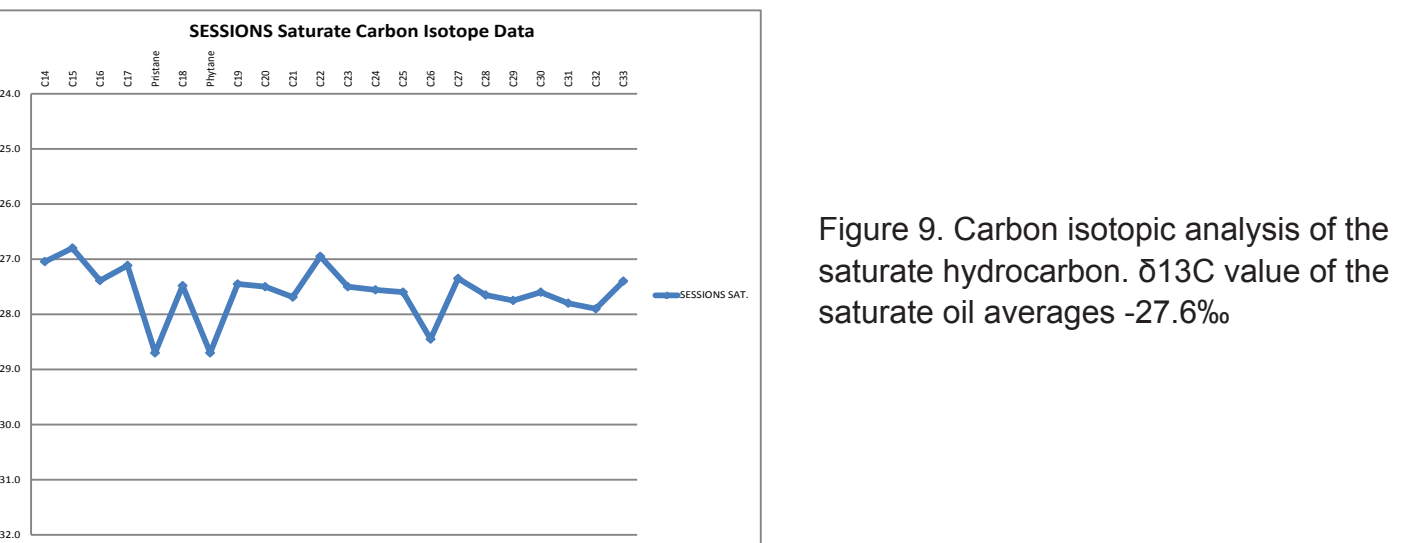


Figure 9. Carbon isotopic analysis of the saturate hydrocarbon. δ13C value of the saturate of averages -27.6‰.

Field Emission Scanning Electron Microscopy

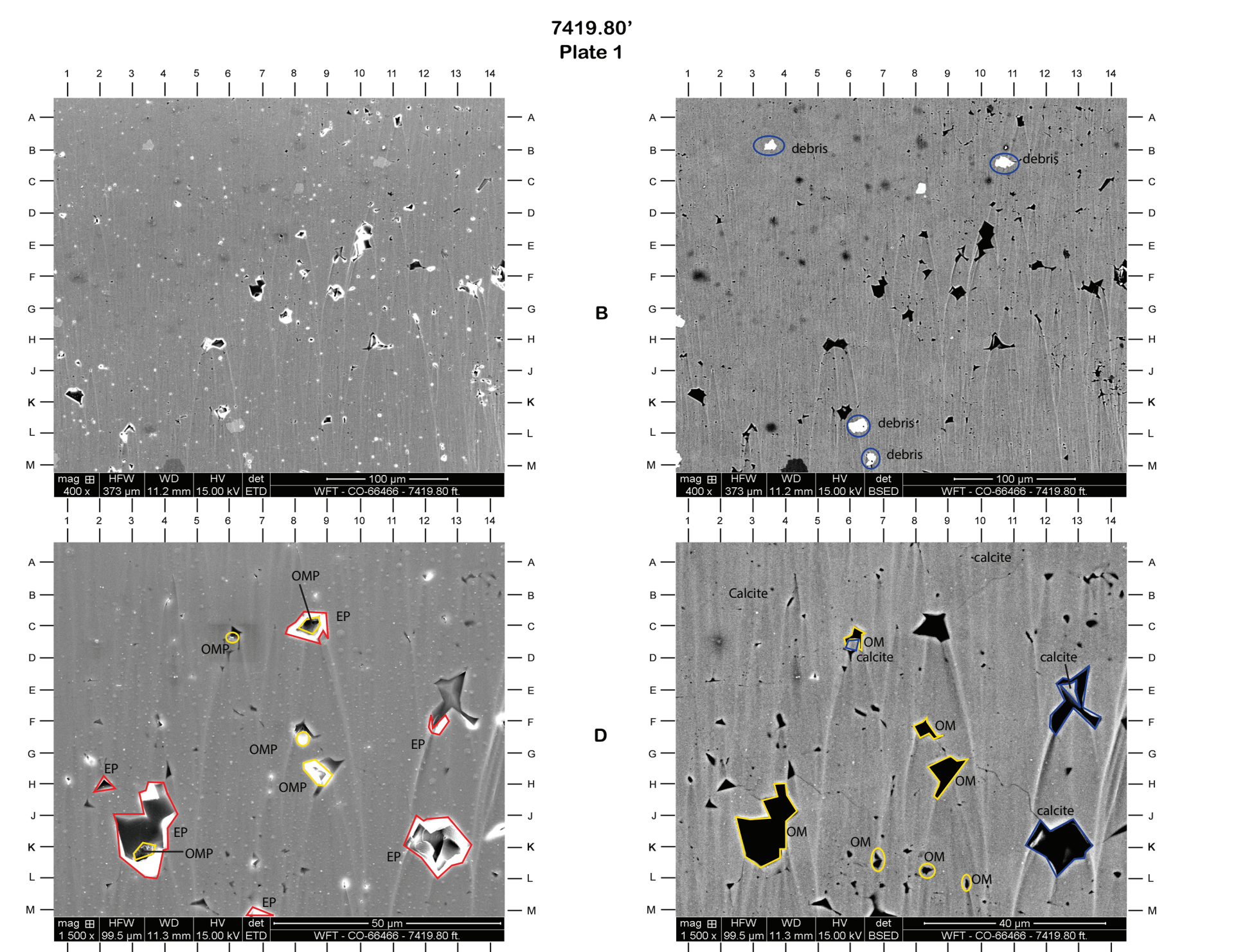
The surface of this argon-ion milled sample was photographed using secondary electron (SE) images, Photographs A and C) and backscattered electron (BSE) images, Photographs B and D) images to reveal detailed compositional and textural characteristics. Secondary electron (SE) images illustrate sample topography and allow for visual identification of micropores and/or nanopores. Backscattered electron (BSE) images, such as shown in photos B and D, display gray-scale atomic number contrast, which aids in the differentiation of minerals. Backscatter electron intensity (gray scale brightness) increases with mean atomic number (and density). Minerals with high atomic number are typically easily distinguished when present in grayscale images. Pyrite for example, has a high mean atomic number and is shown in the grayscale image as white. Comparisons between the image pairs assist in evaluating characteristics of the fabric and pore system. Analysis with energy dispersive spectroscopy (EDS) aids in identification of minerals. Vertical streaks, or "cutting" across the sample surface is a common artifact of the milling process.

Low magnification photomicrographs (Photographs A and B) provide an overview of the fabric of the argon-ion milled (AIM) surface. This sample consists of a limestone (based on the core description). Photographs C and D depict a high magnification view of the area around F8 in Photographs A and B. These photographs consist almost entirely of euhedral to subhedral calcite cement (BS, A10, C05-8, K12, E12-8). Organic material (JK3, J6, K2-9, KL5-3, L5-7) is present within intercrystalline pores.

The presence of pores can be evaluated by using the SE image (Photograph C) to identify the white "edge effect" that commonly occurs around sharp edges of pore boundaries. Both pores and organic material appear black in BSE images; however, organics lack the white "edge effect" associated with pores in the SE images. The primary pore type in this sample appears to be intercrystalline micropores (Photograph C: B8, E12-4, H2, M1) between calcite crystals. Possible micropores are present within the organic material as well (Photograph C: KL3-3, GH8-7, C06-1, F08-5). Possible organic material with micropores occurs within the intercrystalline micropores at C8-5.

Magnification: A: 400X B: 400X C: 1500X D: 1500X

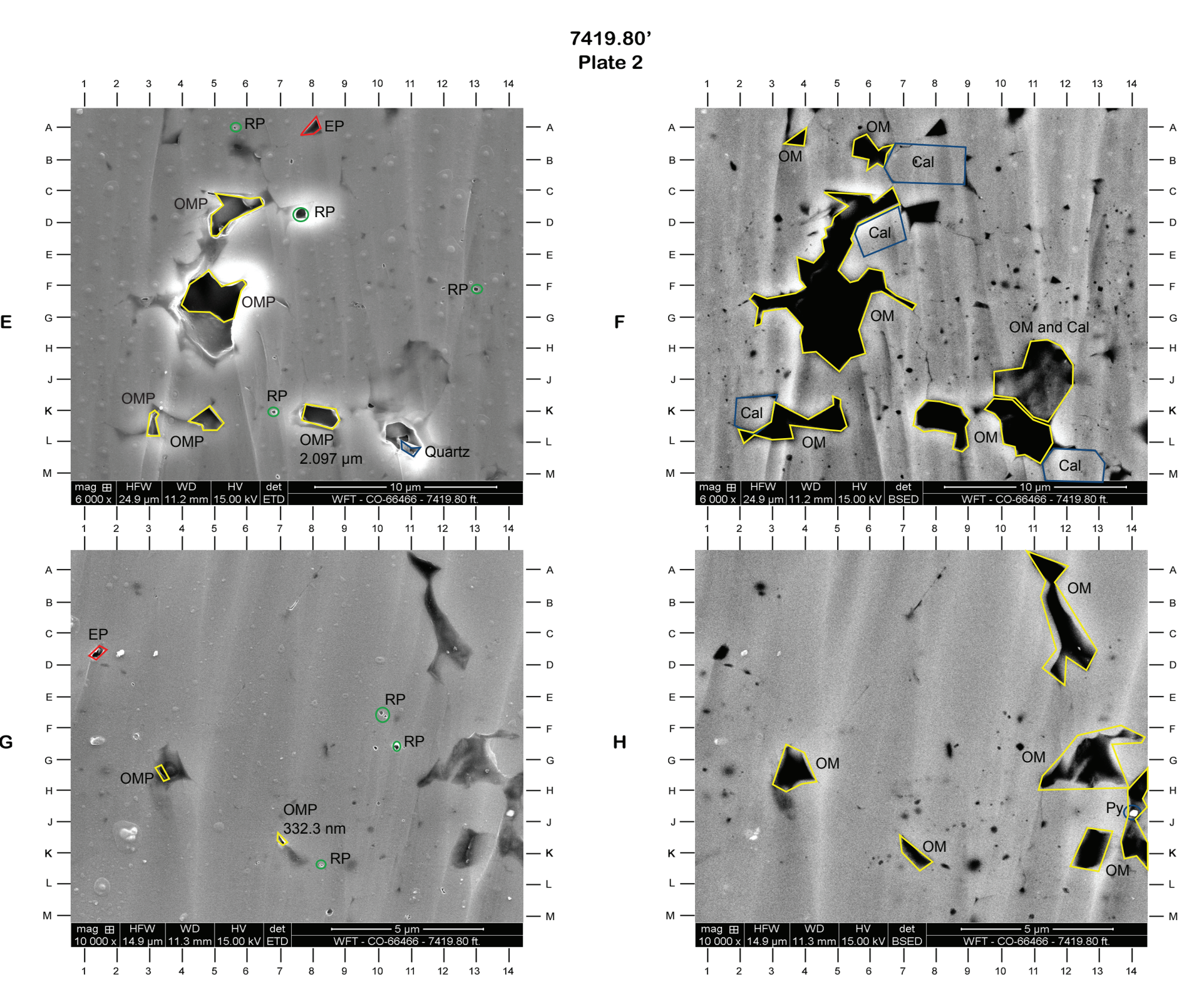
EP Intercrystalline Pore OM/OMP Organic Matter / Organic Matter Pore
RP Intracrystalline Pore Minerals



Additional features of this limestone are shown in Photographs E-H. Secondary images (SE) are shown in Photographs E and G, and backscattered electron images (BSE) are shown in Photographs F and H. Euhedral to subhedral authigenic calcite is the dominant constituent in this sample (Photographs E and F: B8, D2, C13, J11, K2-3, M11-13, Photographs G and H: B9, A13, L2, H13). Other constituents include authigenic quartz (Photographs E and F: L10-9) and possible pyrite (Photographs G and H: J17-8). Organic material in Photographs G and H at GH12-13 appears to completely occlude an intercrystalline pore. Organic material is present in numerous other places in these photographs (Photographs E and F: C5-5, F4-7, KL3-5, KL10-11, Photographs G and H: A11-13, GH3-4, K7-8, JK1-4).

Even though organic material and pores both appear black in BSE images, pores present within the organic material can generally be identified in the SE images based on the white "edge effect". Pore types consist of intercrystalline micropores (Photograph E: A8; Photograph G: CD1-3) and intracrystalline micropores (Photograph E: CD1-3, B8-7, F13, K6-8; Photographs G: EF1-2, FG1-7, KL8-2). Micropores are also present within possible organic material (Photograph E: KL3; Photograph G: H3-2, JK6-9). It is difficult to determine whether some of the micropores in Photograph E are intercrystalline micropores or micropores within organic material (C05-6, F04-6, KL4-8). Pore diameters were measured at 2.007 microns (Photograph E: K7-9) and 332.3 nanometers (Photograph G: JK6-9).

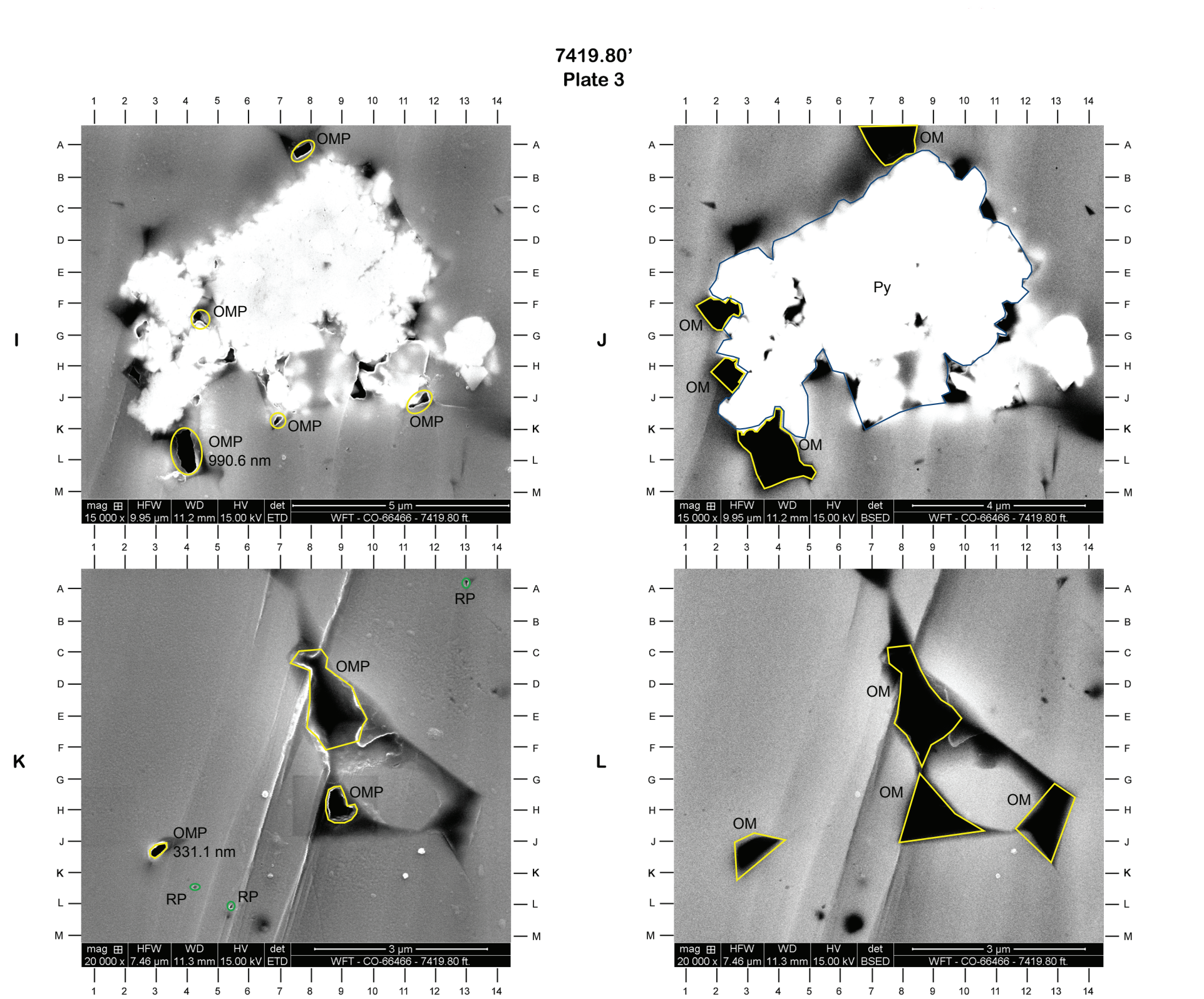
Magnification: E: 6000X F: 6000X G: 10000X H: 10000X



Euhedral to subhedral calcite cement is common in these plates (Photographs I and J: B4, J1, A13, JK5-5, L10; Photographs K and L: C3, B12, GH11, L10). Pyrite (Photographs I and J: B8, E7, GH13, J3) partially replaces organic material. Organic material occurs between calcite crystals (Photographs I and J: AB7-8, FG2, KL3-5, H2-3; Photographs K and L: DF8-9, H12-13, G8-9). The majority of the nanopores and micropores in these photographs appear to be within the organic material (Photograph I: AB7, K4, F04-4, J11-12, JK6-9; Photograph K: C3-5, GH4-9, JK3). Intercrystalline nanopores (Photograph K: KL4-5, L5-3, A1-3) are also present between the calcite crystals. Pore diameters were measured at 990.6 nanometers (Photograph I: KL4) and 331.1 nanometers (Photograph K: JK3).

Magnification: I: 15000X J: 15000X K: 20000X L: 20000X

The lithology of this sample is a limestone. The vast majority of this sample is dominated by fine crystalline, euhedral to subhedral calcite cement. Authigenic quartz and pyrite are rare. Pyrite appears to partially replace organic material while the authigenic quartz occurs as a pore-filling cement. Organic material occurs primarily as an intercrystalline micropore to nanopore fill. Micro- to nanopores are also present within the organic material in many places. In fact, most of the micro- and nanopores seem to be associated with organic material. However, some micro- and nanopores occur within calcite cement without organic material.



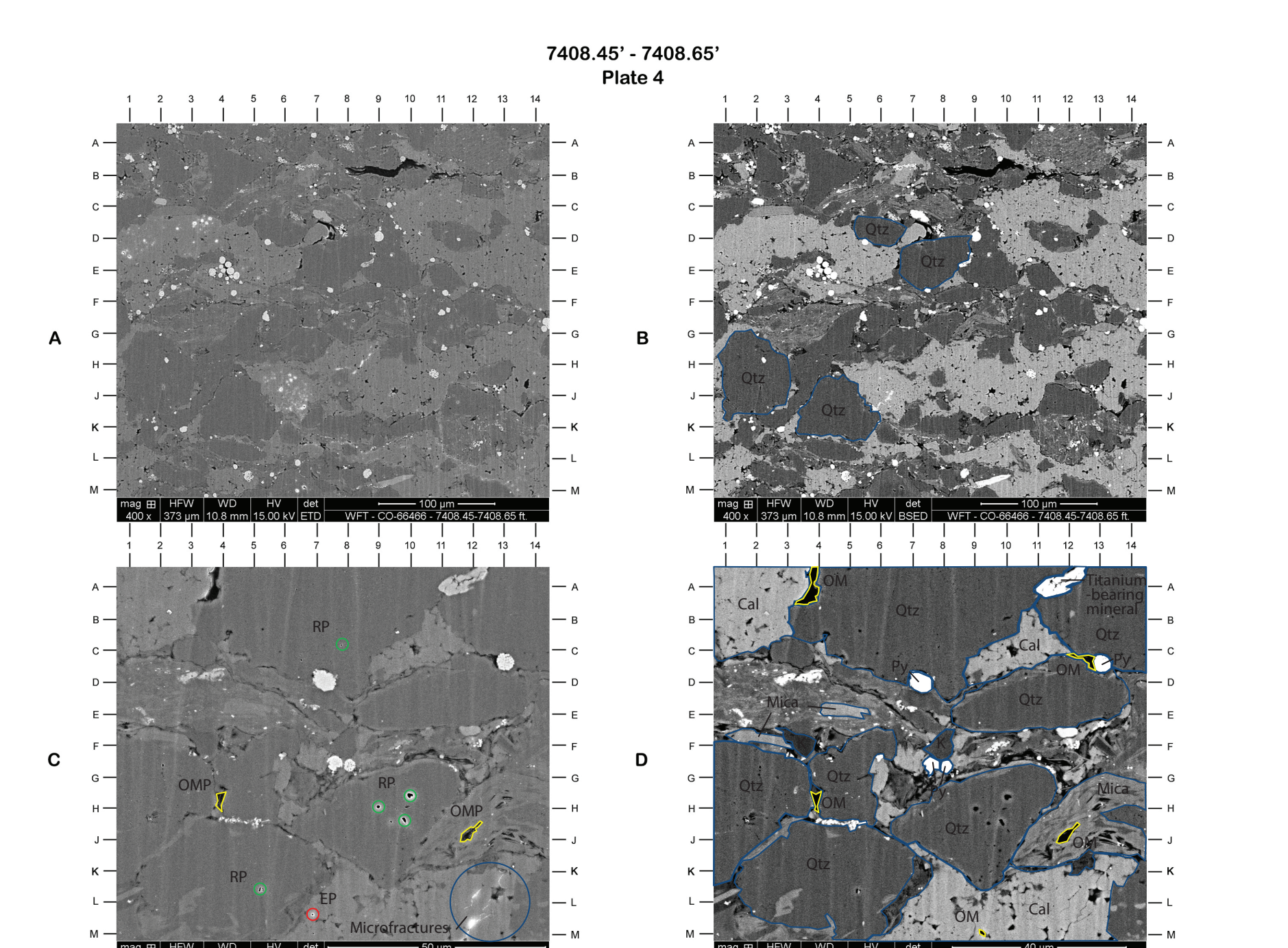
Low magnification photomicrographs (Photographs A and B) provide an overview of the fabric of the argon-ion milled (AIM) surface. This sample consists of a silty/sandy limestone (based on the core description). Quartz grains (C06, D7, H2, JK4-5) are the primary detrital grain identified by EDS. Pyrite is identified by the white color (F02-8, KL2-9, JK4-8, L5-8). Organic material is somewhat common (K12-4, M1-3, J12-JK13-8).

Photographs C and D represent a high magnification view of Photographs A and B at F7. Detrital grains identified in these photographs include quartz (A7, B14, DE8-13, H2, F05, JK4) and mica (E11-3, DE4-5, GH4-JK10). A titanium-bearing mineral occurs at A11 to A12. Illite and chlorite are associated with a possible incipient microcrystalline extending from DE1 to FG13. Authigenic kaolinite (E5-4, F7-8) is not common. The fine crystalline nature of the calcite is visible in these photographs (AC1-3, BD9-11, KM7-13). Most of the black in these photographs is likely organic material (A3-4, GH5-8, CD12-7, H11-18, M6-3).

The presence of pores can be evaluated by using the SE image (Photograph C) to identify the white "edge effect" that commonly occurs around sharp edges of pore boundaries. Both pores and organic material appear black in BSE images; however, organics lack the white "edge effect" associated with pores in the SE images. Pores are sparse in this field of view and include intraparticle micro to nanopores within detrital grains (BC7-7, GH10, H8, H4-9, K14-9), microfracture porosity (sampling induced? M11-14-13), intercrystalline micro to nanopores (LM6-8), and possible nanopores within organic material (GH4-0, H11-7, J11-6, JK11-3).

Magnification: A: 400X B: 400X C: 1500X D: 1500X

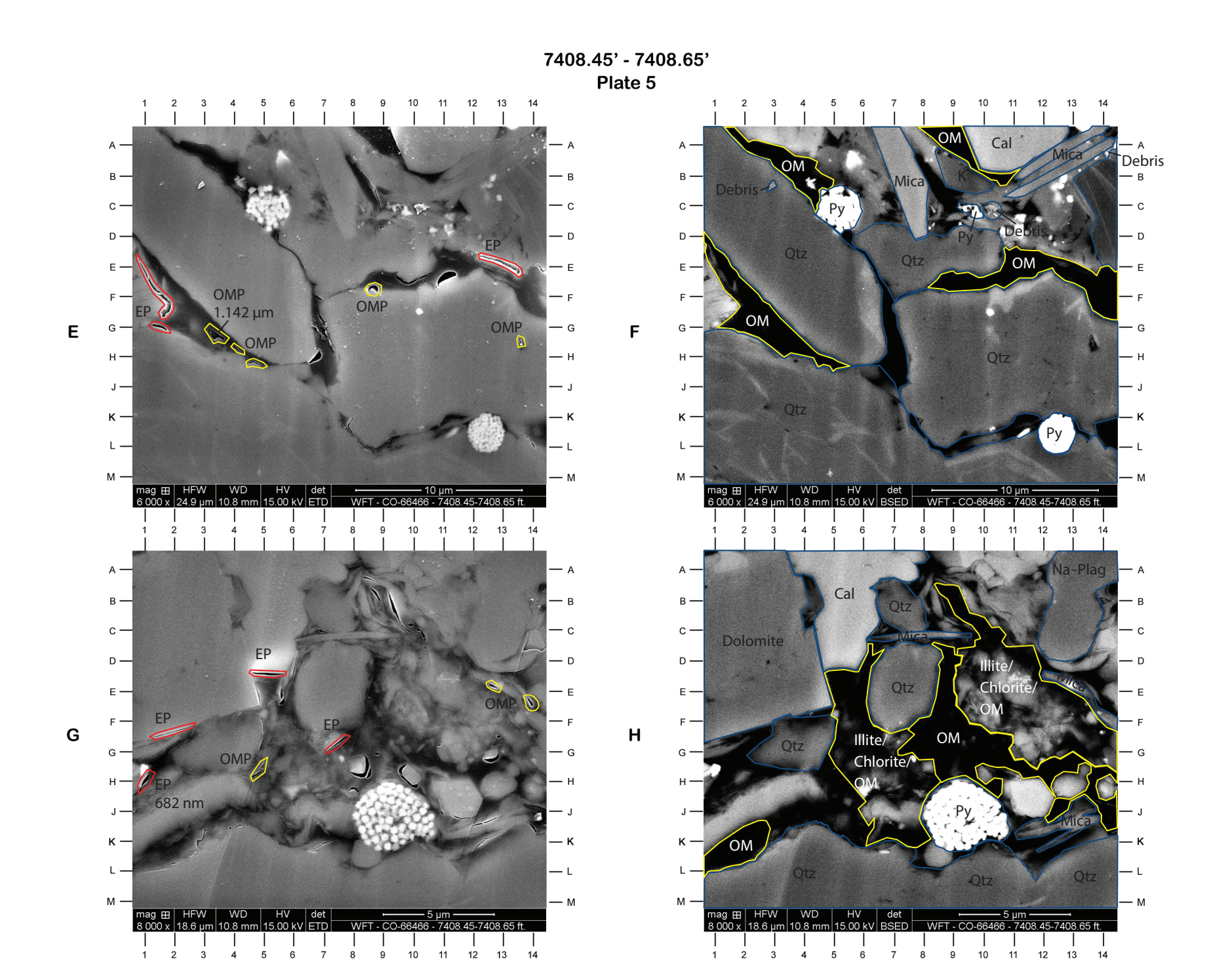
Field Emission Scanning Electron Microscopy



Additional features of this limestone are shown in Photographs E-H. Secondary images (SE) are shown in Photographs E and G, and backscattered electron images (BSE) are shown in Photographs F and H. Detrital grains include quartz (Photographs E and F: A1-GH6, HM1-M14, PK7-GK14, DE8-10; Photographs G and H: BC7-8, DF7-8, FG3-5, LM1-7, LM9-11, KM12-14), sodium plagioclase feldspar (Photographs G and H: A13-14, BD12-13), and mica (Photographs E and F: A7-D7-8, B11-A14; Photographs G and H: C05-6, JK11-14, E13). Authigenic kaolinite (Photographs E and F: B013-14, B9), calcite (Photographs E and F: A10-12; Photographs G and H: A05-6), dolomite (Photographs G and H: A1-4), and pyrite (Photographs E and F: C5, KL12-13, CD9-7; Photographs G and H: HK8-10) are also present. Debris caused by sampling is rare (Photographs E and F: BC2-9, C10-2, AB14). Organic material is common between detrital grains in these photographs (Photographs E and F: A9, AB3-5, FQ2-3, F14). Organic material intermixed with illite and chlorite in the matrix in Photographs G and H (B9, F5-5, F11, H6-5). The darkest portions of Photograph G likely represent the organic material mixed with little to no clay within the matrix (KL1-5, F9, KL2, GH12).

Even though organic material and pores both appear black in BSE images, pores present within the organic material can generally be identified in the SE images based on the white "edge effect". Micro to nanopores are predominantly associated with organic material and/or the matrix (Photograph G: GH3-5, GH4-2, EF8-6; Photograph H: GH13-7, GH4-7, EF12-9). Many of these micro to nanopores occur at the contact between a grain and organics (Photograph E: E1-FG1-6, G1-7, E12-13; Photograph G: F01-2, DE5, GH2). It is difficult to determine whether the nanopores at GH15-6 in Photograph E occur within organic material that occluded a pore within a quartz grain or if that space represents a grain boundary between two quartz grains. Pore diameters were measured at 1.142 microns (Photograph E: GH3-3) and 628.0 nanometers (Photograph G: H1-2).

Magnification: E: 6000X F: 6000X G: 8000X H: 8000X

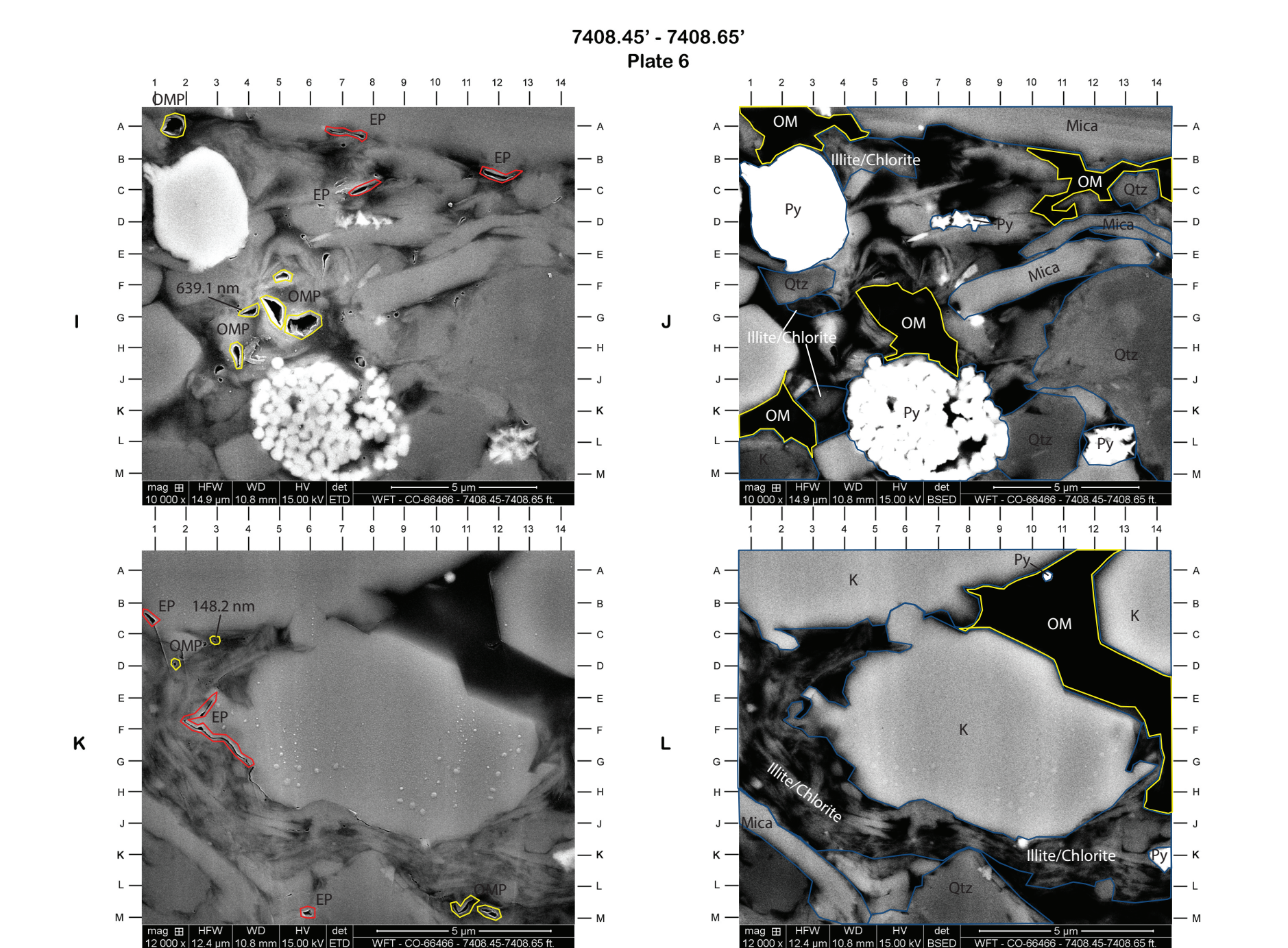


Detrital grains in these photographs include mica (Photographs I and J: AS-AB14, DE10-14, F08-E12; Photographs K and L: H1-M14) and quartz (Photographs I and J: F2-3, C13-14, FH12-14, KM6-11; Photographs K and L: LM7-9). Authigenic minerals include pyrite (Photographs I and J: BE1-3, JM4-9, L12-13, CD7-9; Photographs K and L: AB14-4, K14) and kaolinite (Photographs I and J: LM1-5; Photographs K and L: AB1-A10, AD12-13, DH4-FH13). Microcrystalline crystal growths (Photographs K and L: CH4-9, GH5-1, H11-8) occur after the sample has been milled. According to EDS, illite and chlorite (Photographs I and J: BC4-4, G2-3, K1-4; Photographs K and L: CD3-4, EG1-JK7, KL10-14) are the dominant clays within the matrix. The darker portions of the matrix likely represent organic material with little to no intermixed clay (Photograph I and J: AB2, B11-2, GH6-7, K1-1; Photographs K and L: B9-14). Nanopores are more commonly associated with organic material (Photograph I: A1-5, EF5, FG5, GH5-7, H43; Photograph K: LM10-8, M11-8, D1-7, CD2-8). Several nanopores are associated with grain boundaries (Photograph I: BC12, AB6-7-5, C7-8; Photograph K: BC1, EF2-6, H4, J7-8). A rare possible intercrystalline nanopore is present at LM5-9 in Photograph K. Pore diameters were measured at 839.1 nanometers (Photograph I: FG4-2) and 148.2 nanometers (Photograph K: CD2-6).

Magnification: I: 10000X J: 10000X K: 12000X L: 12000X

Detrital grains in these photographs include mica (Photographs I and J: AS-AB14, DE10-14, F08-E12; Photographs K and L: H1-M14) and quartz (Photographs I and J: F2-3, C13-14, FH12-14, KM6-11; Photographs K and L: LM7-9). Authigenic minerals include pyrite (Photographs I and J: BE1-3, JM4-9, L12-13, CD7-9; Photographs K and L: AB14-4, K14) and kaolinite (Photographs I and J: LM1-5; Photographs K and L: AB1-A10, AD12-13, DH4-FH13). Microcrystalline crystal growths (Photographs K and L: CH4-9, GH5-1, H11-8) occur after the sample has been milled. According to EDS, illite and chlorite (Photographs I and J: BC4-4, G2-3, K1-4; Photographs K and L: CD3-4, EG1-JK7, KL10-14) are the dominant clays within the matrix. The darker portions of the matrix likely represent organic material with little to no intermixed clay (Photograph I and J: AB2, B11-2, GH6-7, K1-1; Photographs K and L: B9-14). Nanopores are more commonly associated with organic material (Photograph I: A1-5, EF5, FG5, GH5-7, H43; Photograph K: LM10-8, M11-8, D1-7, CD2-8). Several nanopores are associated with grain boundaries (Photograph I: BC12, AB6-7-5, C7-8; Photograph K: BC1, EF2-6, H4, J7-8). A rare possible intercrystalline nanopore is present at LM5-9 in Photograph K. Pore diameters were measured at 839.1 nanometers (Photograph I: FG4-2) and 148.2 nanometers (Photograph K: CD2-6).

Magnification: I: 10000X J: 10000X K: 12000X L: 12000X

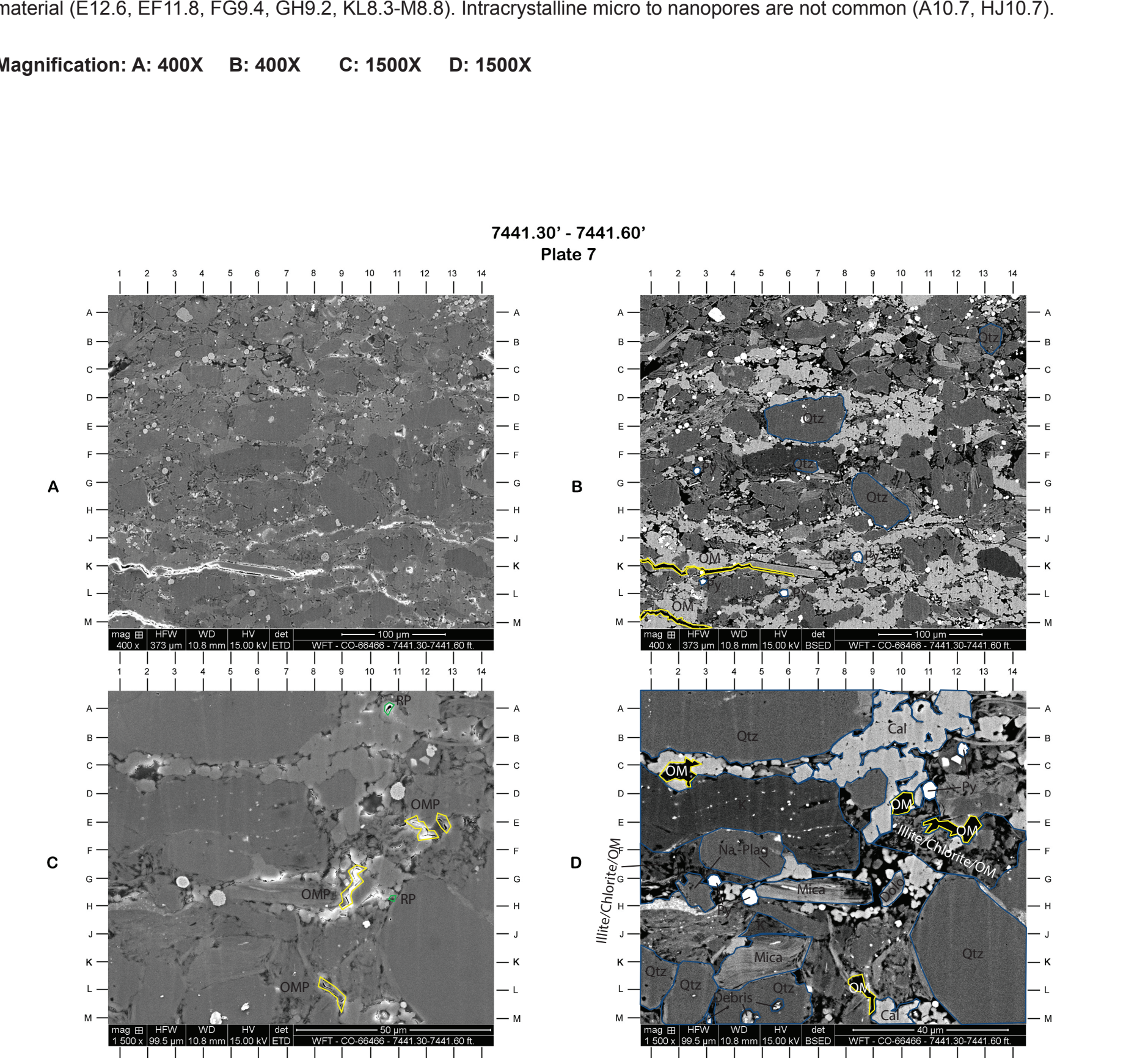


Low magnification photomicrographs (Photographs A and B) provide an overview of the fabric of the argon-ion milled (AIM) surface. This sample consists of a silty limestone (based on the core description). Quartz grains (DE7, GH4, F05-6, AB1-3) are the primary detrital grain identified by EDS. Pyrite is identified by the white color (F02-8, KL2-9, JK4-8, L5-8). Organic material is somewhat common (K12-4, M1-3, J12-JK13-8).

Photographs C and D represent a high magnification view of Photographs A and B at F7. Detrital grains include quartz (AB5-8, HM12-14, KL1-KM2-3, LM7-9), sodium plagioclase feldspar (FG3-6, GH2-3), and mica (GH5-8, K13-4, JK6-4). Mottite has likely been replaced by very fine sparry calcite (AB9-12, C1-2, C5-8, LM6-12) is the primary authigenic mineral in this sample. Authigenic kaolinite is also present (H45). Kaolinite has been identified at E11-3 to DE7-7 by EDS. It is possible that this is a dissolved leighite that is being altered to kaolinite. Pyrite (G3-2, GH4-6, BC12-2, D11) partially replaces organic material (CD2, D10, EF12-5, L8-3-M9). A dolomite rhomb (GH9-10) shows a variable shade of gray due to the higher amount of iron in the outer rim. The matrix (FG1-2, FG12-14, EF10) contains intermixed illite and chlorite as well as organic material. Debris occurs as a result of sampling (LM2-4, M4-4, LM5-5).

The presence of pores can be evaluated by using the SE image (Photograph C) to identify the white "edge effect" that commonly occurs around sharp edges of pore boundaries. Both pores and organic material appear black in BSE images; however, organics lack the white "edge effect" associated with pores in the SE images. The micro to nanopores in these photographs appear to be associated with organic material (E12-6, EF11-8, F05-4, GH2-2, KL3-4-M8-8). Intracrystalline micro to nanopores are not common (A10-7, H10-7).

Magnification: A: 400X B: 400X C: 1500X D: 1500X



Field Emission Scanning Electron Microscopy

Additional features of this limestone are shown in Photographs E-H. Secondary images (SE) are shown in Photographs E and G, and backscattered electron images (BSE) are shown in Photographs F and H. Quartz is the primary detrital grain in this sample (Photographs E and F: EG10-12, KL5-8, JM1-LM5; Photographs G and H: BE1-2, EG1-2) with less common mica (Photographs E and F: F3-AB10, G14-K6). Very fine sparry calcite is common (Photographs E and F: A07-AB14, F05-7, GH4-4, JK4-5; Photographs G and H: GH1-7, D5-6, C13, FM13-14, HM1-M7, KM9-11). Pyrite (Photographs E and F: CD13-14, FQ8-9, FQ13-5; Photographs G and H: DE14, BC6-7, GH2-4, HK8-9, K17) partially replaces organic material. Organic material (Photographs E and F: E2, AB12, CD10-12, GH10-11, KL4-8; Photographs G and H