APPENDIX 8-B. SEM Imaging Prepared by Juergen Schieber of Indiana University

1. API# 3700920034, Kerr-McGee No. 1 Schellsburg Unit, Bedford County, Pennsylvania Lexington/Trenton Formation, 7690 feet below surface

This sample has a tightly interlocking fabric, with good development of phyllosilicate framework pores, even some carbonate framework or carbonate dissolution pores, and pervasive small scale (foam type) porosity on the interstitial organic matter (OM). Interstial OM is more abundant, probably a rock with 1 percent or more overall total organic carbon (TOC). This sample, through combination of pervasive OM pores, more OM, and phyllosilicate framework pores may be a viable reservoir rock.

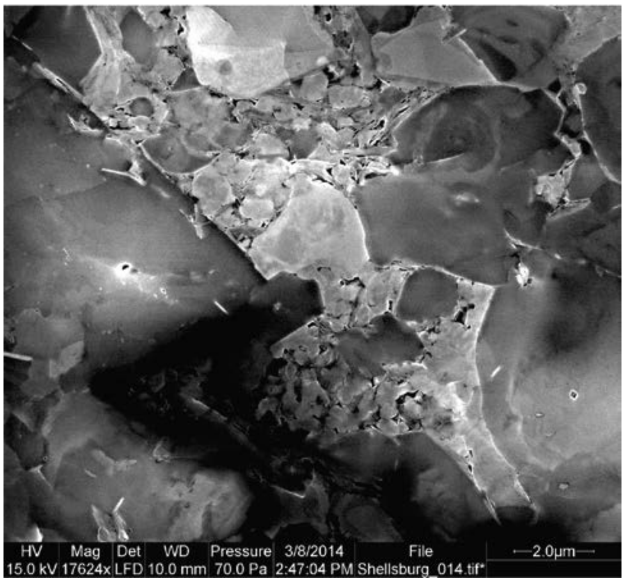


Figure 1. Typical view of shale fabric. Larger calcite grains (dark gray) with interstitial quartz (light gray) and clays (light to medium gray, felted appearance, with triangular phyllosilicate framework pores.

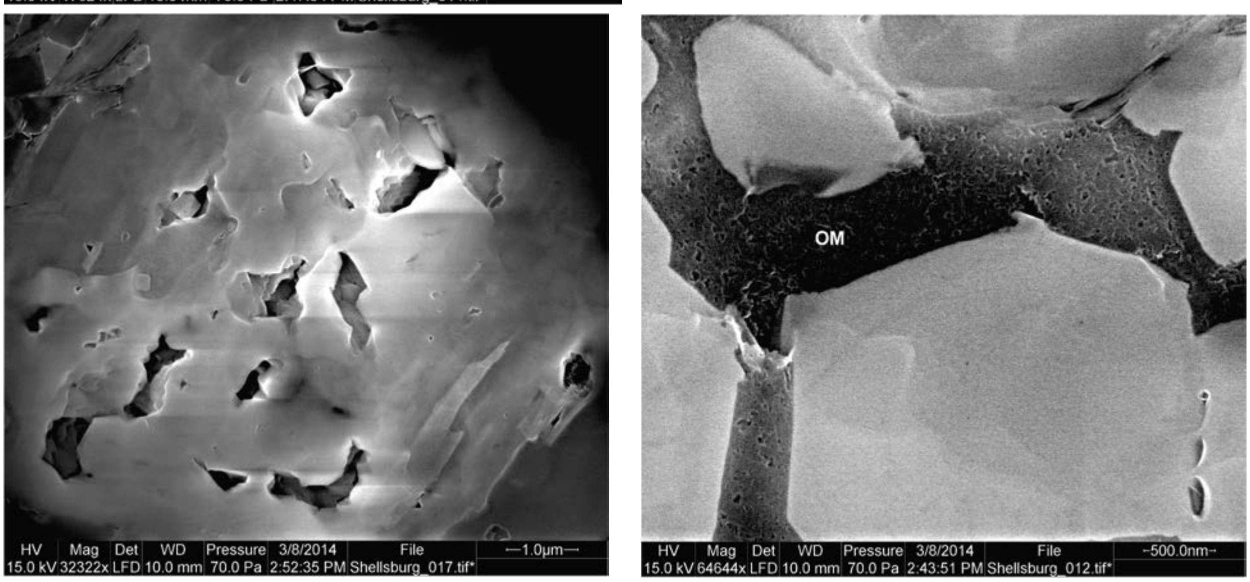


Figure 2. Left – Close-up of interstitial space with abundant phyllosilicate framework pores. This pore type is rather common in these chips. Right – Large pores in carbonate grain. They look like pores that are continuing into depth, and may be remains of carbonate framework pores (with the carbonate having recrystallized). These pores are comparatively rare.

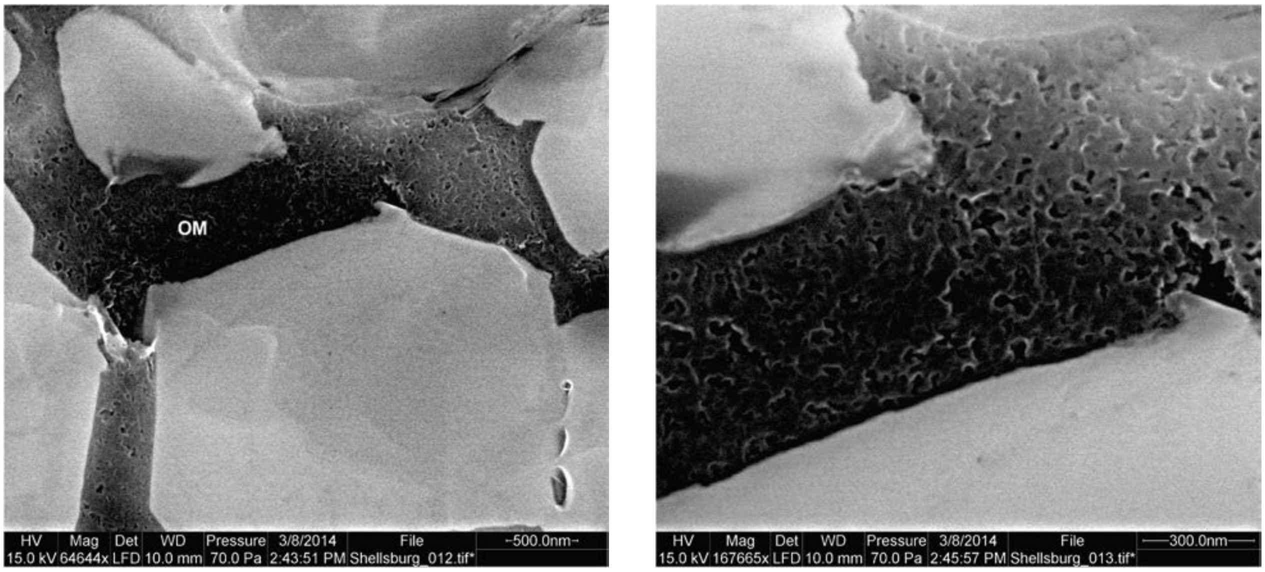


Figure 3. Left – View of interstitial OM between diagenetic quartz grains. The way the OM "invades" this space suggests that it came in as a fluid/hydrocarbon liquid. It is probably some sort of bitumen now. Right – Close-up of this OM that shows pervasive small pores of the "foam" type, ranging in size from 10-100 nm. This is the way the OM in this sample typically looks like.

2. API# 3703520276, Texaco No. 1 Commonwealth of PA Tract 285, Clinton County, Pennsylvania
Lexington/Trenton Formation at 14,480 feet below surface

This is a sample of rock characterized by a tight interlocking fabric of calcite grains and interstitial quartz, clay, and OM. There is very little OM visible in these chips (a few tenths of a percent at best). The occasional blob of interstitial OM can have porosity (both of the foam and bubble type).

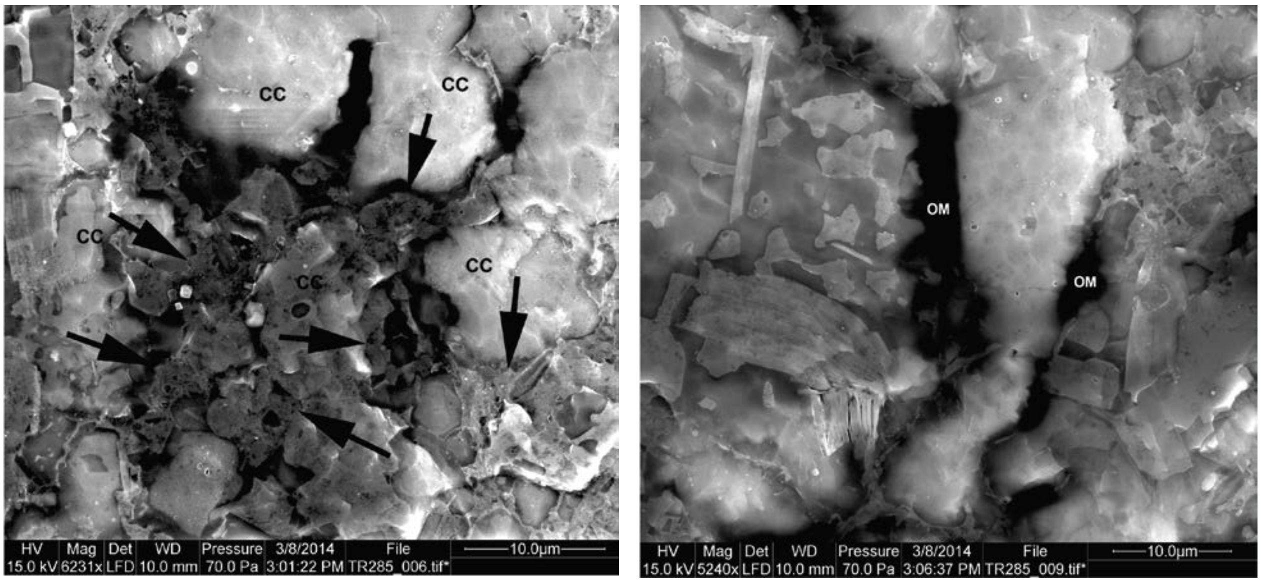


Figure 4. Left – A fabric overview. Large calcite grains (CC) have squeezed areas between them (arrows) where most of the quartz and clays and OM occur. Right – Closer view of tight interlocking fabric with amorphous OM in interstitial locations. These two OM spots did not show pore development.

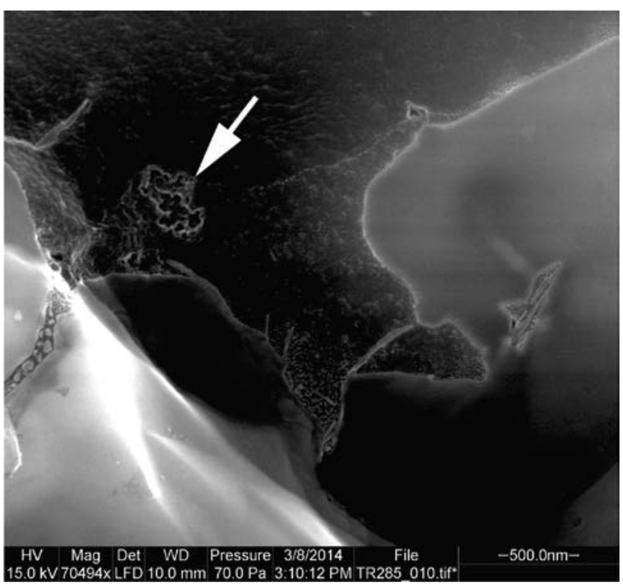


Figure 5. Close-up of another interstitial OM pocket. This one shows some pore development (arrow), but it is not pervasive. There is development of a “dimpled” texture on the OM, suggesting that it is still soft OM/bitumen, and that we are still within the oil window.

3. API# 3704920049, New York State Natural Gas No. 1 PA Forest & Waters Block 2, Erie County, Pennsylvania
Lexington/Trenton Formation, 4096 feet below surface

The cuttings from this well are rather large (~5 mm), so that only one was studied. The cuttings are carbonate dominated and gray looking; thus, TOC appears to be low, probably in the range of a few tenths of a percent. The overall fabric bears this out, consisting (as in every sample) of a tightly packed mixture of larger calcite grains (10-50 microns in size) that grew early in diagenesis (floating inclusions of clays [mainly] and other detrital minerals) and have squeezed between them quartz grains (detrital with overgrowths and diagenetic quartz) and clays, and pockets of interstitial organic matter. Amorphous OM has foam pores and is rather "soft" and easily destabilized by the ion beam (which can burn holes into it, and at high magnifications the OM surface will start to dimple and "retreat into the sample). The samples from this well appear to be the least mature thermally, probably right in the middle of the oil window (Ro 0.7-0.9?). Occasional bits of structured OM occur (also seen on other samples). Some nice examples of zoning in early diagenetic calcite grains, showing successive growth of dolomite, ankerite, and calcite.

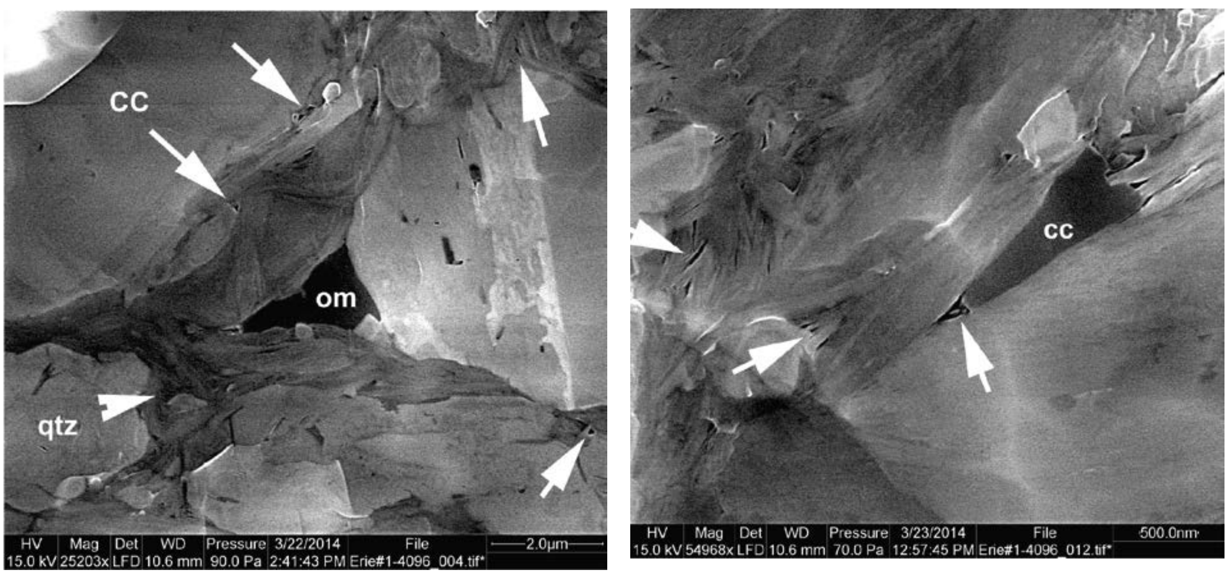


Figure 6. Left – View of the clay and quartz (qtz)-dominated interstitial areas between calcite (cc) grains, and one pocket of amorphous OM in the center. The arrows point to places with triangular shaped phyllosilicate framework pores. Right – Close-up view of a clay-rich portion that shows small phyllosilicate framework pores (arrows). In one place, diagenetic calcite (CC) propped open a pore and also "clamped" the ends of clay platelets in place. This kind of porosity seems to dominate the sample, but probably does not amount to much.

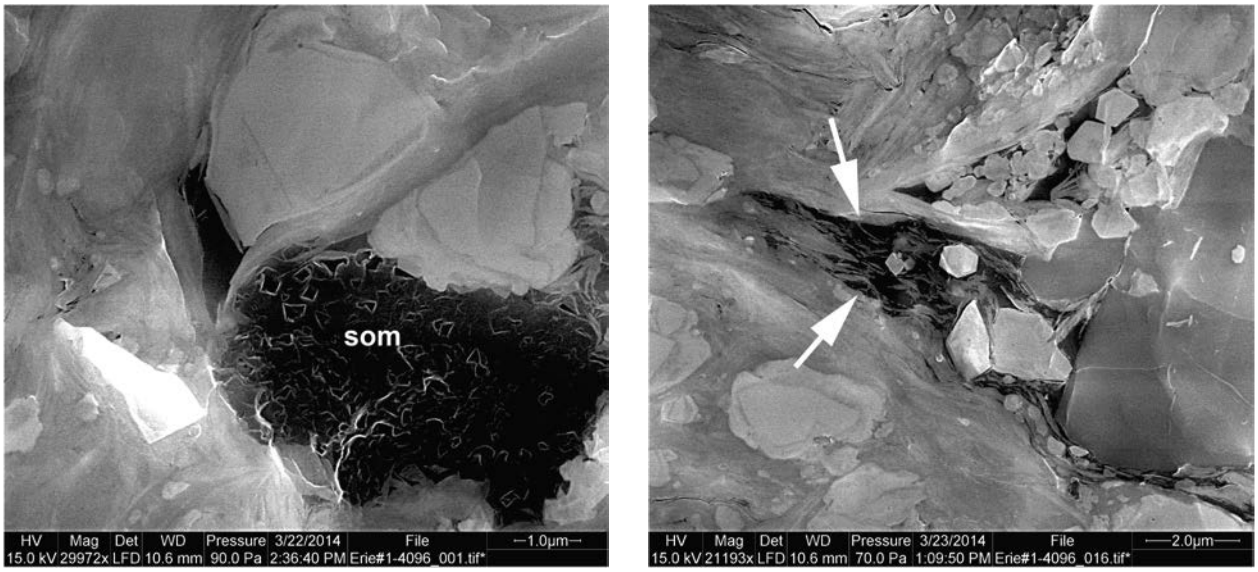


Figure 7. Left – Piece of likely structured OM (som) that seems to be resistant to compaction (may be some plant matter) and has strange triangular pores (not sure what that is). But it does not have pores in the matrix and is ion-beam "resistant". Right –Typical appearance of amorphous OM (dark, arrows) with intermingled clays.

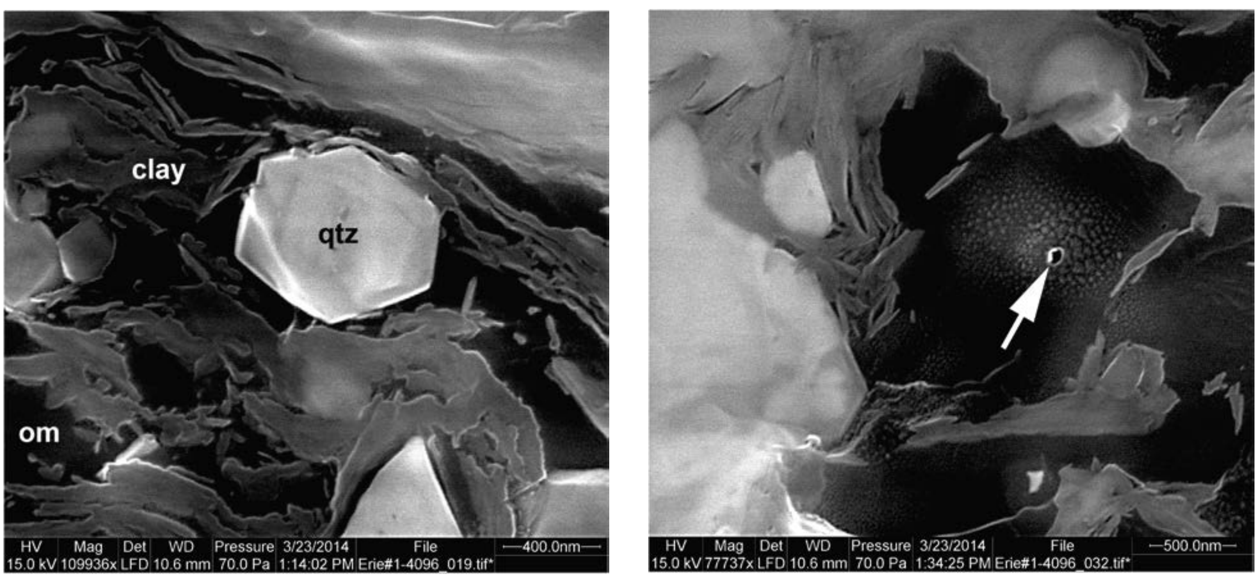
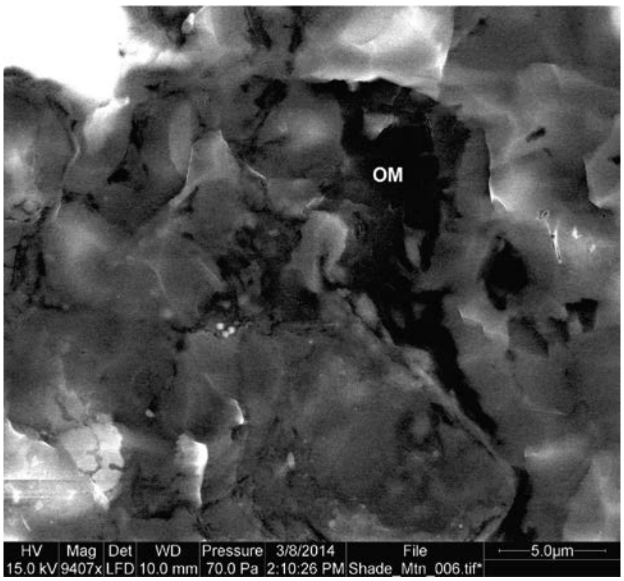


Figure 8. Left – Closer high magnification view of amorphous organic matter (OM) that is mingled with clays and diagenetic quartz (qtz). There is no porosity visible in the OM. Right – Another close-up view of amorphous OM. The ion beam burned a hole into the OM (arrow) and the surface of the OM has developed the characteristic dimpled appearance that occurs when the beam is vaporizing OM. This OM is probably "soft" hydrocarbons, probably bitumen.

4. API# 3706720001, Shell Oil Co. No. 1 Shade Mountain, Juniata County, Pennsylvania Point Pleasant Formation at 3750 feet below surface

Chips of this well have a tightly interlocking fabric as seen in other Utica/Point Pleasant samples, with clays, quartz, and OM in interstitial areas. There is more OM (may be a percent or a bit more), however, and OM pores are better developed. In addition to foam pores we also see well developed bubble pores, suggesting a higher maturity, maybe somewhere between Ro 1-2 (wet gas window?).



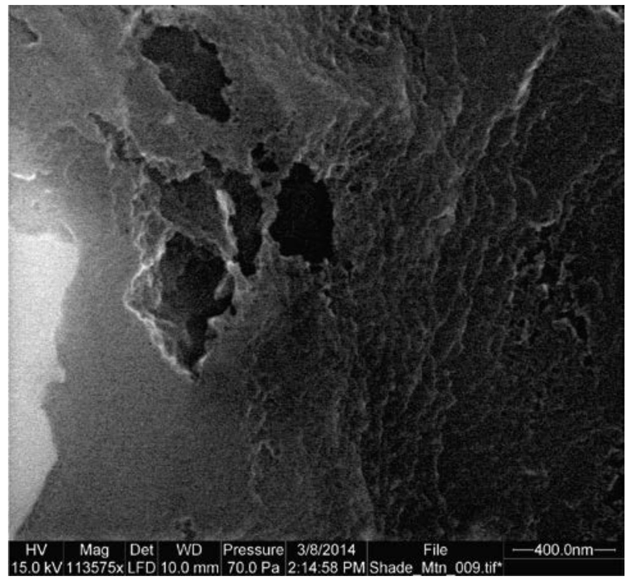


Figure 9. Left – Interstital OM within the overall tight fabric of these chips. Right – Detail of interstitial OM, showing tiny foam pores in the OM matrix, and large "bubble" pores in the 100's of nm size range. These formed probably as a consequence of liquid hydrocarbon migrating out of this source rock.

5. API# 3708720002, Exxon No. 1 Commonwealth of PA Tract 377, Mifflin County, Pennsylvania
Trenton Limestone at 5230 feet below surface

The examined chips from this well show a tightly interlocking fabric, dominated by early diagenetic calcite with mineral inclusions (clays etc.) and quartz (diagenetic or detrital with diagenetic overgrowths) and clays squeezed into interstitial spaces. Together with interstitial quartz and clays we see pockets of amorphous OM. Small phyllosilicate framework pores (tens of nm to 100 nm) occur in the interstitial clay packings and interstitial pockets of organic matter (OM) show OM pore development. The OM pores are of the small “foam” type (tens of nm to 50 nm), none of the larger “bubble” pores were observed. Because there is not a lot of OM in these samples (probably no more than 1 percent, most likely less), OM porosity does not amount to much.

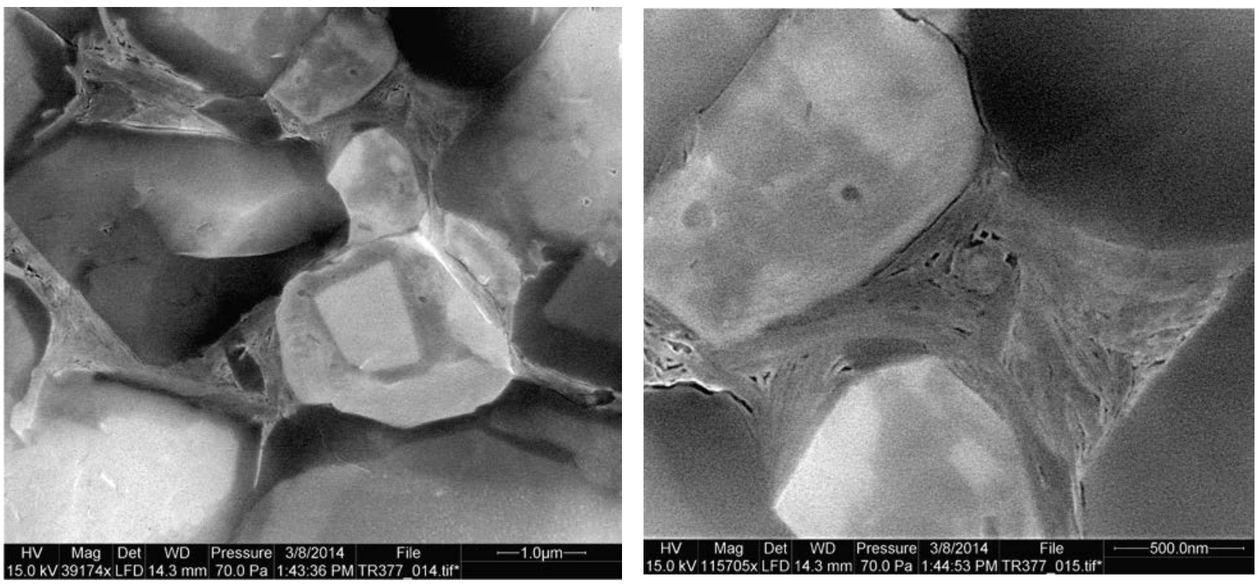


Figure 10. Left - Pretty typical fabric with large calcite grains (dark-med gray), and in between them we have quartz (light gray) of both detrital and overgrowth nature, and a felt of clay minerals with small pores. Right - Detail of interstitial clay packing with small triangular phyllosilicate framework pores. This type of porosity probably supplies the bulk of porosity in the examined chips.

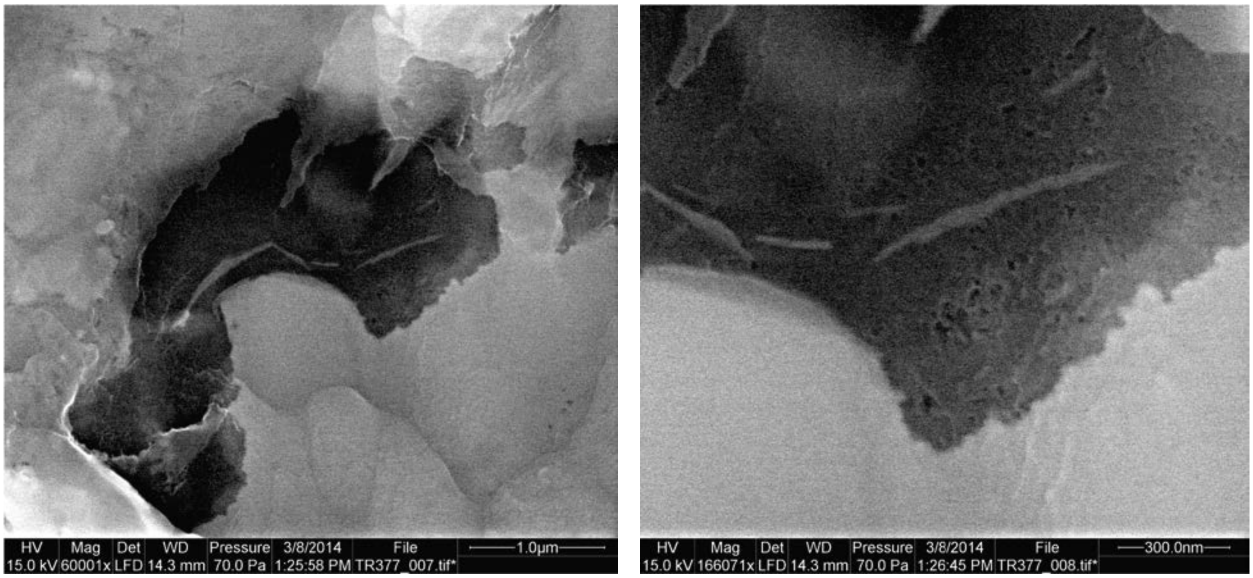
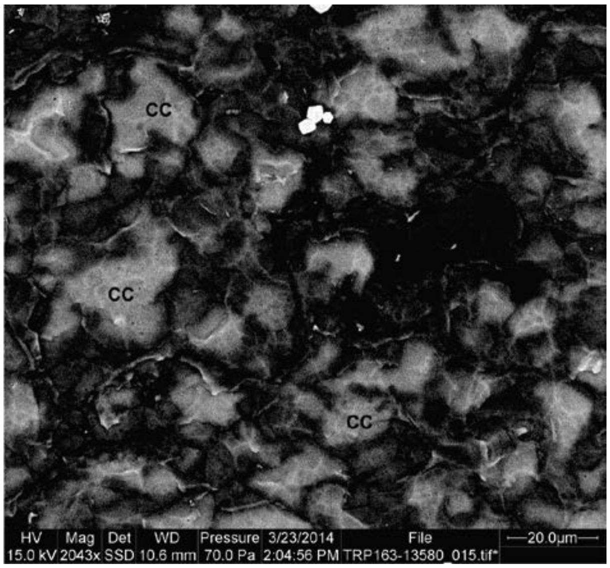


Figure 11. Left – Pocket of interstitial amorphous OM (dark gray – black) with inclusions of clay minerals. Right – Close-up of OM that shows small pores of the "foam" type. This sample probably could have been anywhere between Ro 0.7 and 0.9.

6. API# 3710320003, Texaco No. C-1 PA Dept. of Forests & Waters Tract 163, Pike County, Pennsylvania
Lexington/Trenton Formation, 13,580 feet below surface

There is lots of diagenetic silica in these chips, it ion mills very slowly, and surface is still a bit rough. The fabric is tightly packed and interlocking as before. OM has porosity (both foam and bubble type), but overall TOC appears to be low, so not much porosity overall (not much in the way of phyllosilicate framework pores, because too well silica cemented).



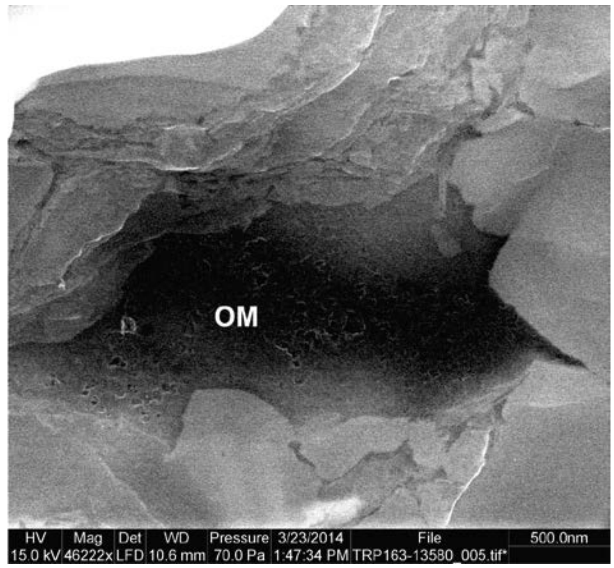


Figure 12. Left – Typical fabric (overview, backscatter image). The light gray grains are calcite (CC), and in between them are mainly diagenetic quartz (some detrital inclusions), clays, and some OM. Right – Pocket of amorphous OM in an interstitial area that shows development of mainly small "foam" pores (10-50 nm mostly), and a few larger pores that may mark the onset of bubble pore formation.

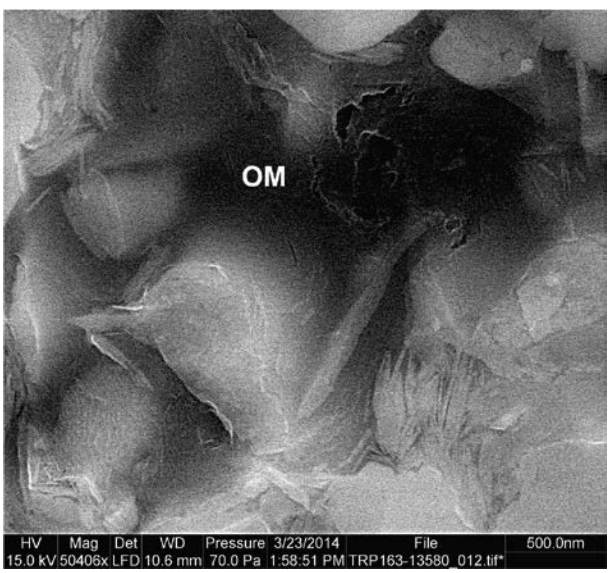


Figure 13. Another area with interstitial OM. In this sample, larger OM pores (bubble pores) are better developed.

7. API# 3712522278, Range Resources No. 1 Starvaggi, Washington County, Pennsylvania Kope Formation, 10,040 feet below surface

Samples from this well display a dense fabric, tightly packed, with clays squished into interstitial spaces. There is well developed phyllosilicate framework porosity. The interstitial OM does not show porosity development, however, probably because the unit never (or only barely) reached the oil window in this area. Not much of reservoir therefore. In a few places corrosion of pyrite grains was observed, but it is not a significant contributor to porosity.

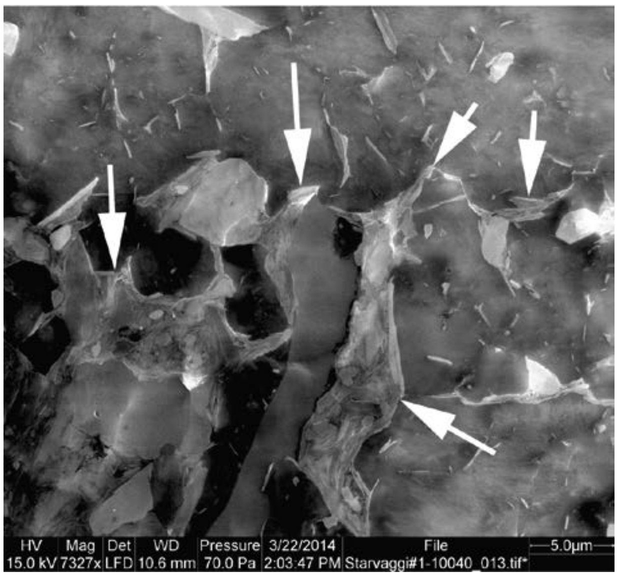


Figure 14. Typical fabric with large calcite crystals (with mineral inclusions) and interstitial quartz, clays (arrows), and OM pockets.

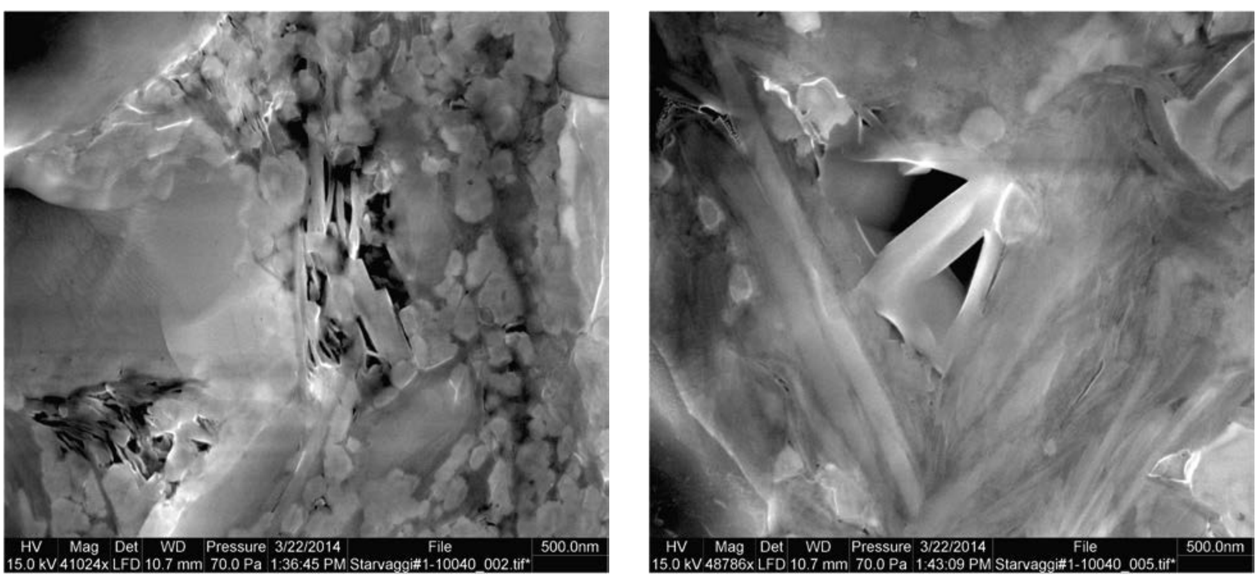


Figure 15. Examples of phyllosilicate framework pores can be seen in these chips. Left – Clay flakes have been "clamped" by diagenetic mineral growth. Right – Clay flakes make up a support framework with triangular pores.

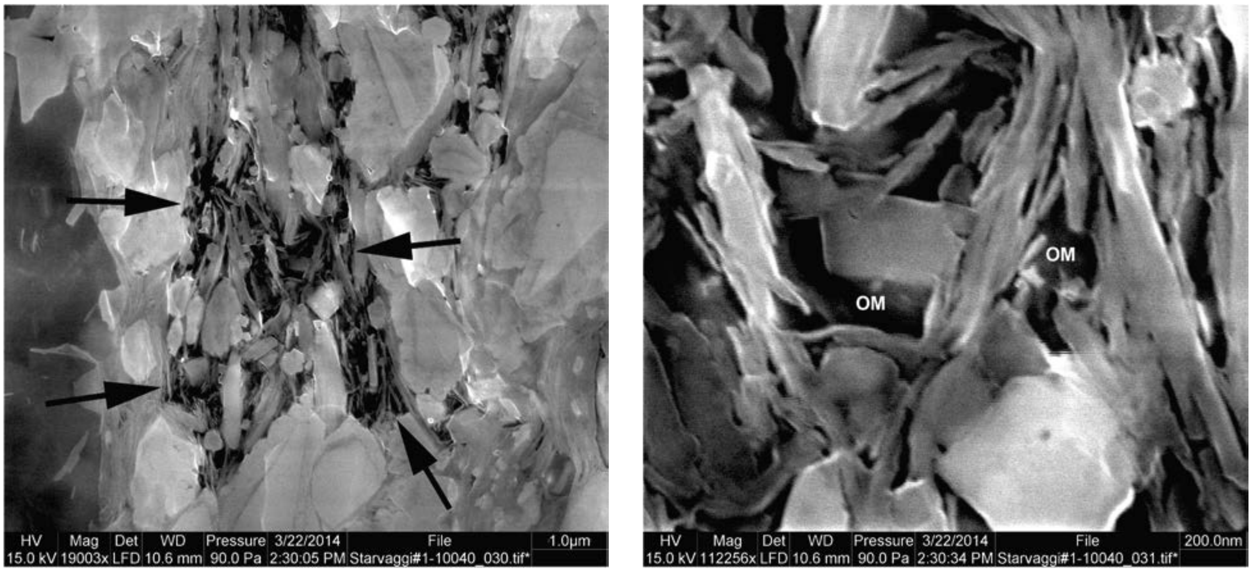
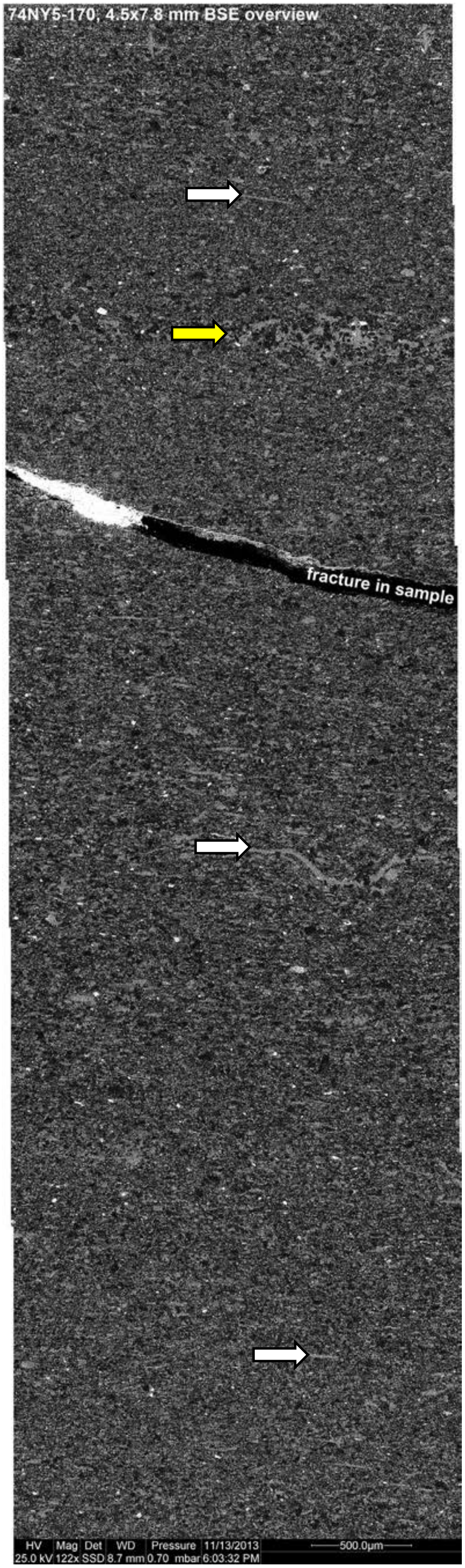


Figure 3._-_. Organic matter within interstitial spaces. Left – Darker area (arrows) marks an area where clays and OM are intermingled (OM "invaded" during hydrocarbon generation). Right – Close-up that shows OM between clay mineral flakes.



Core: 74NY5Depth: 170 feet

Figure 1: (left) a backscatter strip taken across the entire thickness of the sample for compositional and textural overview. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

There is faintly visible stratification at the mm to sub-mm scale, but no well defined layer boundries. There are a what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrows), and one partially preserved coarser silty lamina (yellow arrow). Overall it appears that primary physical stratification/lamination has been overprinted by burrowing organisms. No macroscopic burrows were seen in the provided sample though. This suggests that bioturbation occurred very early in depositional history, probably largely by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don't recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to low dysoxic bottom waters at the time of deposition. Medium gray colors dominate this rocks, so compositionally the sample should be dominated by clays, micas, and quartz (plus feldspar), probably a calcarous mudstone.

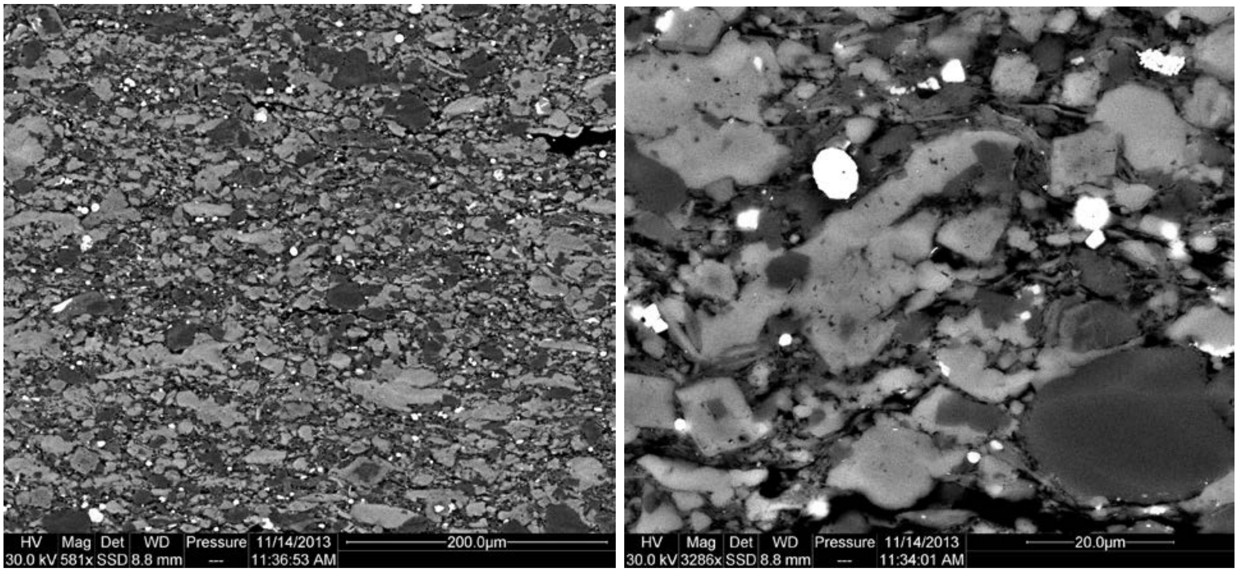


Figure 2: Closer view of shale fabric in BSE (backscatter). At left, lower magnification, basic fabric is a mixture of quartz (dark gray blebs), calcite grains (light gray) with some dolomitic cores (darker), and clays (slightly less dark gray than quartz). At right, close-up view. Calcite grains are either irregular (light gray) or euhedral (with occasional dolomite cores, darker gray). Clay minerals and organic matter are found in interstitial areas between quartz and carbonate grains. Very bright grains are pyrite.

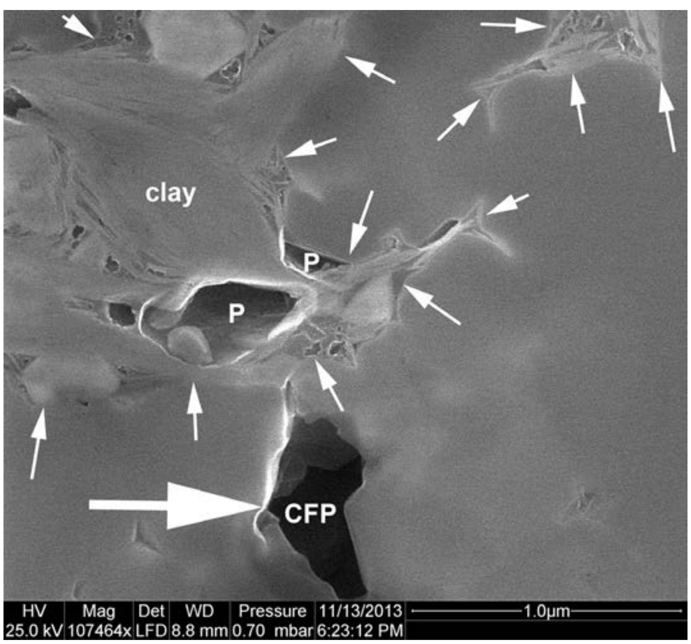


Figure 3: Large carbonate framework pore (CFP, white arrow), protected from collapse by surrounding carbonate grains. This pore type is not pervasive and from this sample at least it does not appear to significantly affect overall rock permeability. The overall rock fabric is rather tight, with clays and organic matter filling the interstitial space between detrital minerals and recrystallized carbonate grains. The areas outlined with small white arrows show this type interstitial component. The clay minerals have been squeezed to conform to the available space, and the majority of those clays is probably detrital. There are however patches in this general area that show a loose mixture of organic matter (likely bitumen) and small clay flakes, and that is probably material that came in during later diagenesis (clays first, followed by hydrocarbons). The organic matter is rather porous (see Fig. 4), and the

large pores marked P could be original OM pores that were completely emptied of hydrocarbons.

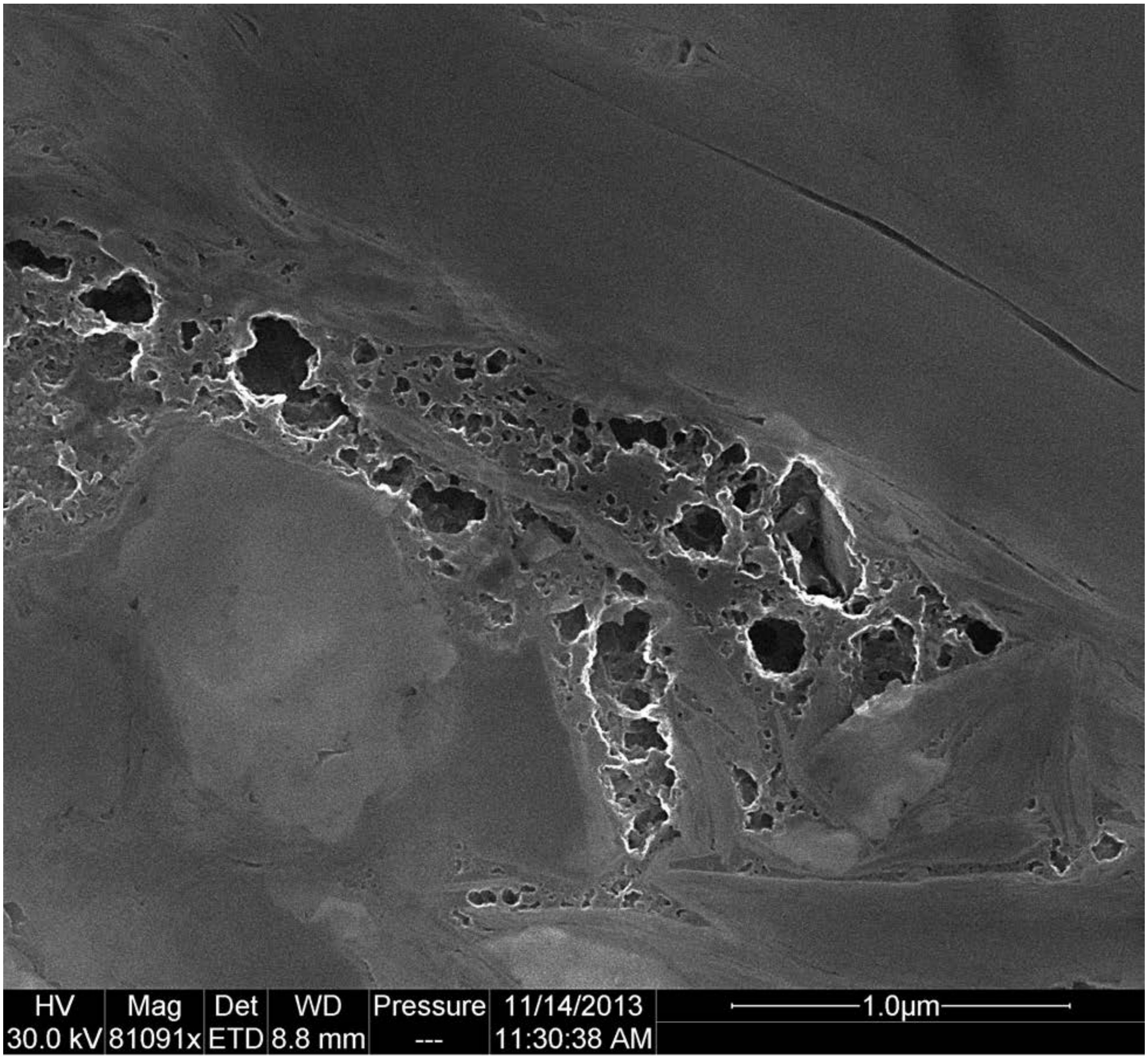


Figure 4: Shows porosity in these hydrocarbons (Fig. 3) in more detail. The most commonly observed porosity is found in these portions of interstitial areas (Fig. 2) that are filled with kerogen, most likely bitumen. The bitumen typically contains admixed clay mineral flakes, the latter probably in part a result of late diagenetic mineral formation. The OM pores consist of two categories, small “foam” pores (tens of nm to 50 nm) that permeate the OM matrix, and larger “bubble” pores that measure up to ¾ microns and even 1 micron in diameter. Pore throats at the depth of bubble pores strongly suggest that these form a 3D interconnected pore network.

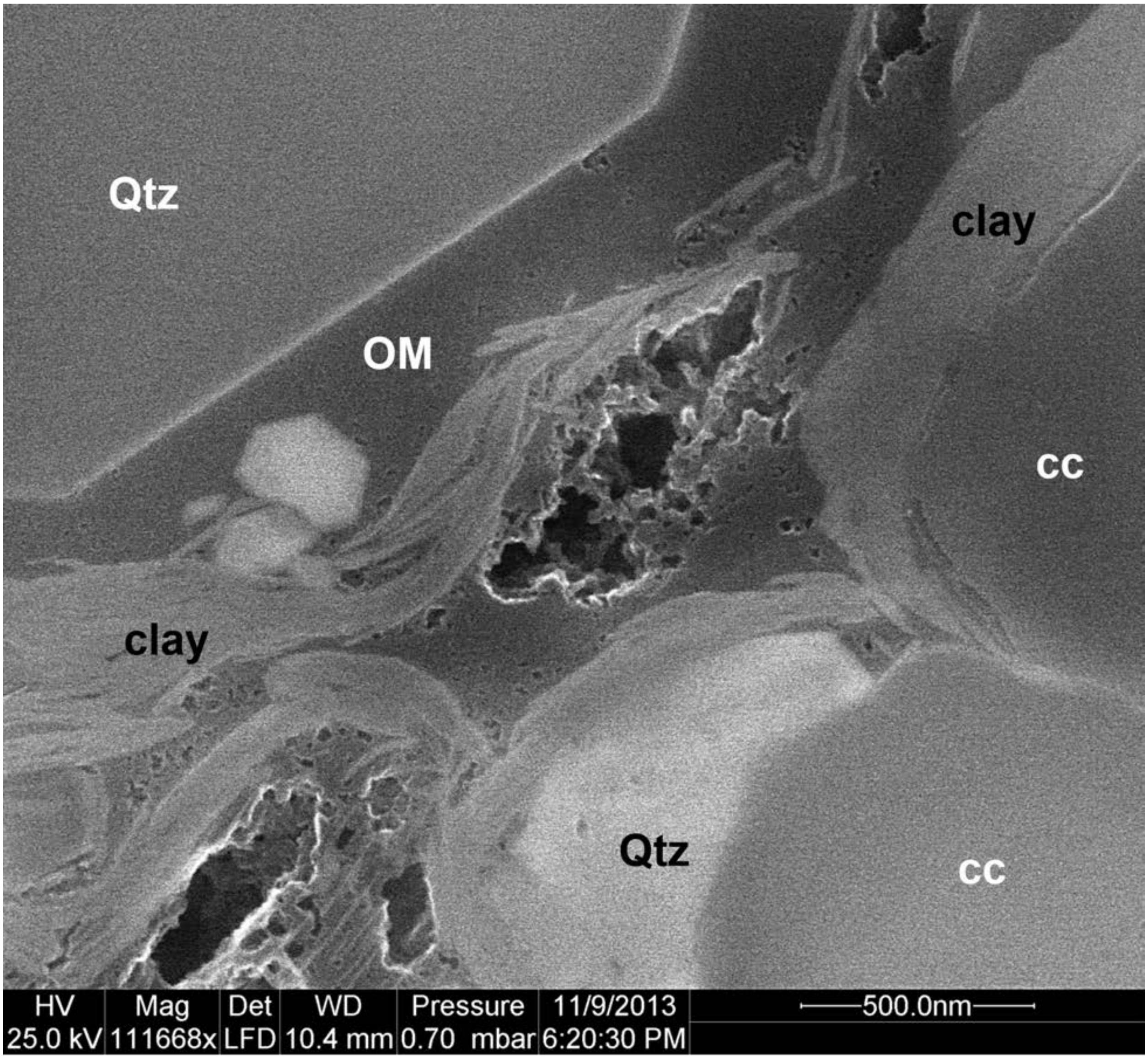


Figure 5: Paragenetic detail of a bitumen invaded pore space. Quartz and calcite form the primary rock fabric, and probably grew into an open pore/interstitial space (euhedral x-tal faces). Diagenetic clays formed next, and at the end the remaining pore space was filled with organic matter /bitumen. Once heated further, the bitumen “cracked”, released liquid and gaseous hydrocarbons, and pores were generated.

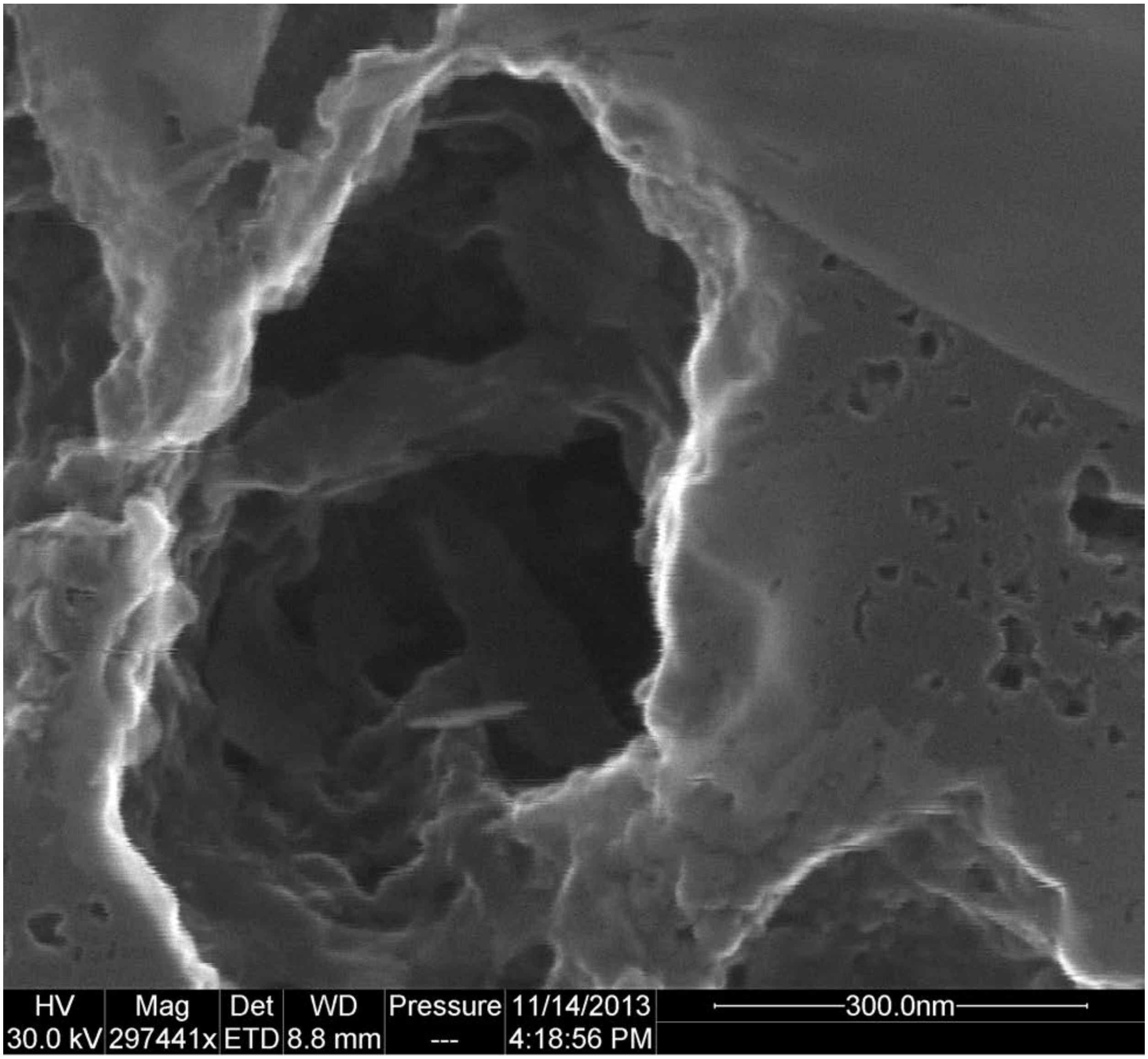


Figure 6: Closeup of pores in OM. Shows in depth pore throats that are probably interconnected. These pores most likely are critical to reservoir performance.

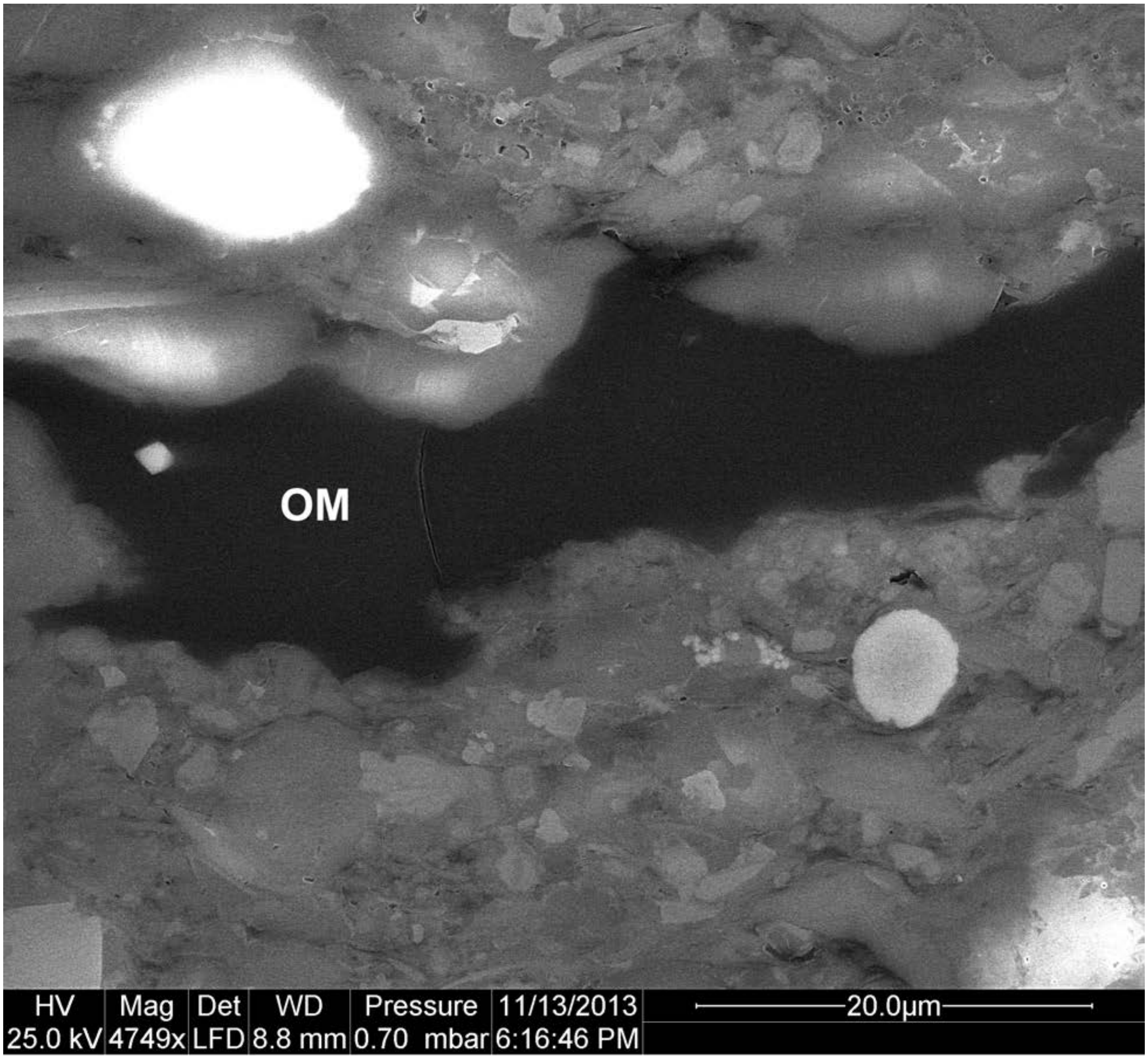


Figure 7: A piece of organic matter (probably plant derived) within the silicate bearing shale matrix. This structured OM (cross linked) does not show pore development, even at high maturity levels There is not too much of this type of OM visible (in relative terms), and its presence most likely does not have a serious negative effect on overall porosity and permeability.

If we consider (for argument sake) that this rock has say 3% TOC, that makes ~6% TOC by volume, and assume from above images that this volume may be occupied by pores to ~50%, then the organically hosted porosity may be as much as 3%, and with a bit of other porosity, the rock might be at about 4%. That puts it in the ballpark with other well producing shale gas reservoirs (e.g. Eagleford, Haynesville), at least from a petrographic perspective.

Core: 74NY5Depth: 240 feet

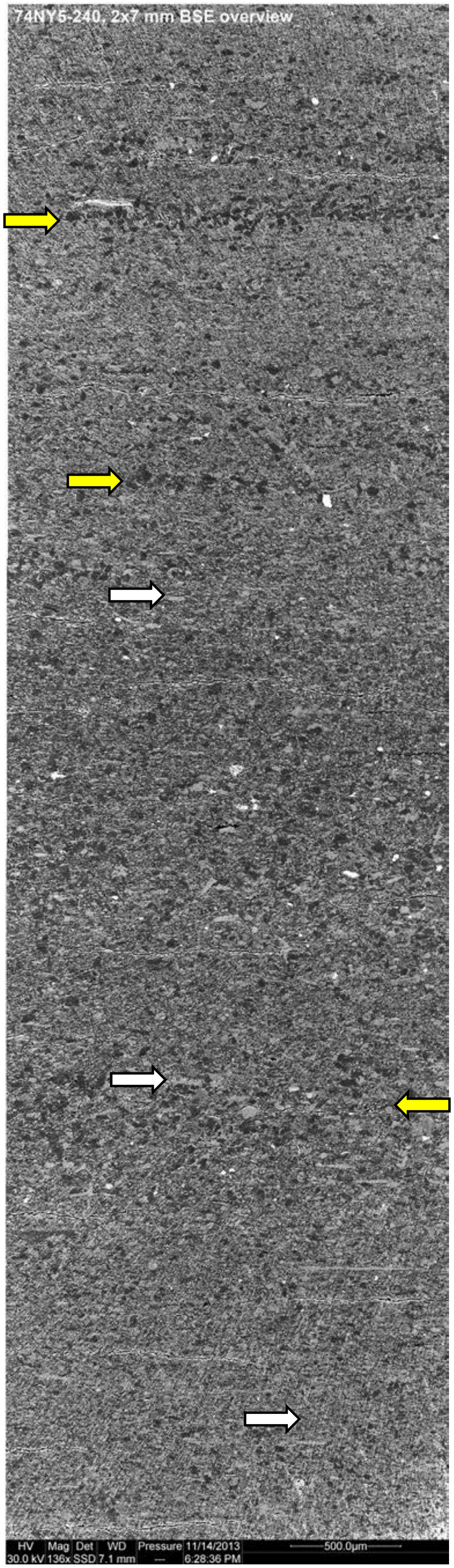


Figure 1: (left) a backscatter strip taken across the entire thickness of the sample. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

There is faintly visible stratification at the mm to sub-mm scale, but no well defined layer boundries. There are a what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrows), and some partially preserved coarser silty lamina (yellow arrows). Overall it appears that primary physical stratification/lamination has been overprinted by burrowing organisms. No macroscopic burrows were seen in the provided sample though. This suggests that bioturbation occurred very early in depositional history, probably largely by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don't recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to low dysoxic bottom waters at the time of deposition. The lighter gray colors are more prominent in this sample and suggest a higher carbonate content when compared to the sample from 170 feet depth. So compositionally the sample is either a very calcarous mudstone (40-50% calcium carbonate) or even a very clay & silt-rich mudstone. If you have some geochemical data on this core you could check that.

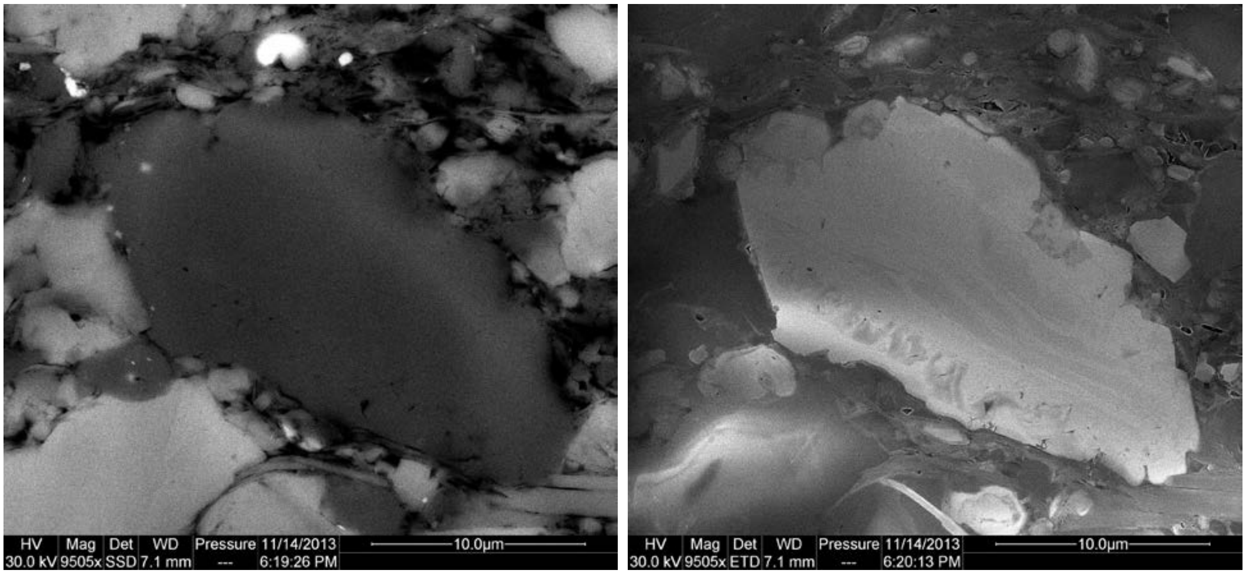


Figure 2: The shale matrix in close-up. At left BSE image that shows a dark gray quartz grain in the center, surrounded by light gray calcite grains, and a mixture of smaller particles that are mingled with organic matter (black). At right a secondary image in charge contrast mode that that shows that the quartz grain has substantial diagenetic overgrowth, and that the dark-black areas from the left image show visible pores. These are typically in interstitial areas filled with bitumen.

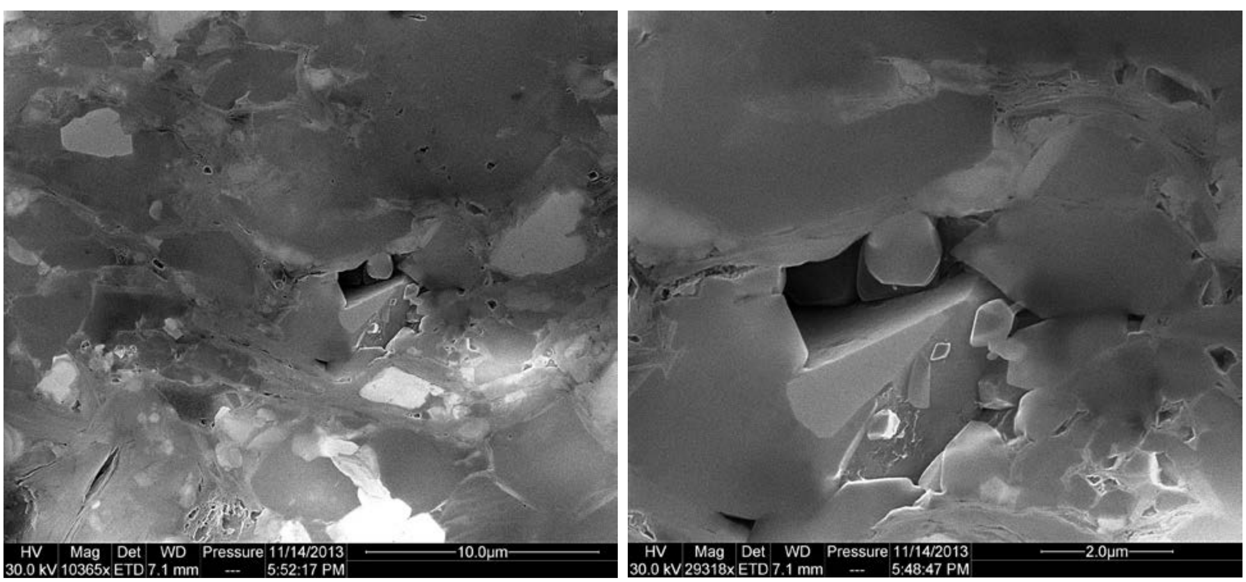


Figure 3: But there are in addition framework pores preserved through the support of surrounding calcite and quartz grains. The left image shows one such pore in the center, and the right image shows a close-up. In the close-up, the framework support comes largely from calcite grains, but lighter gray quartz (charge contrast imaging) is also involved.

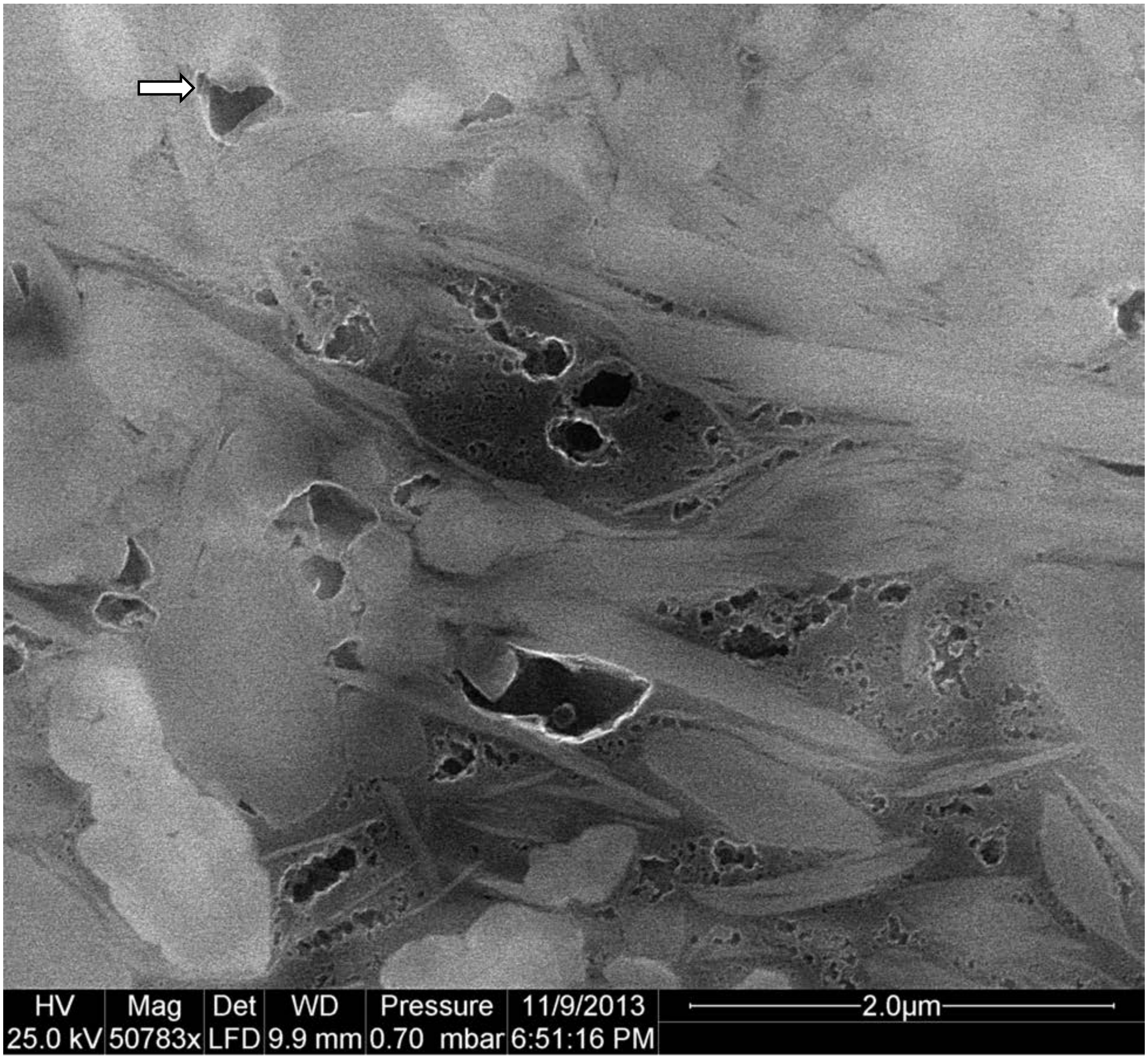
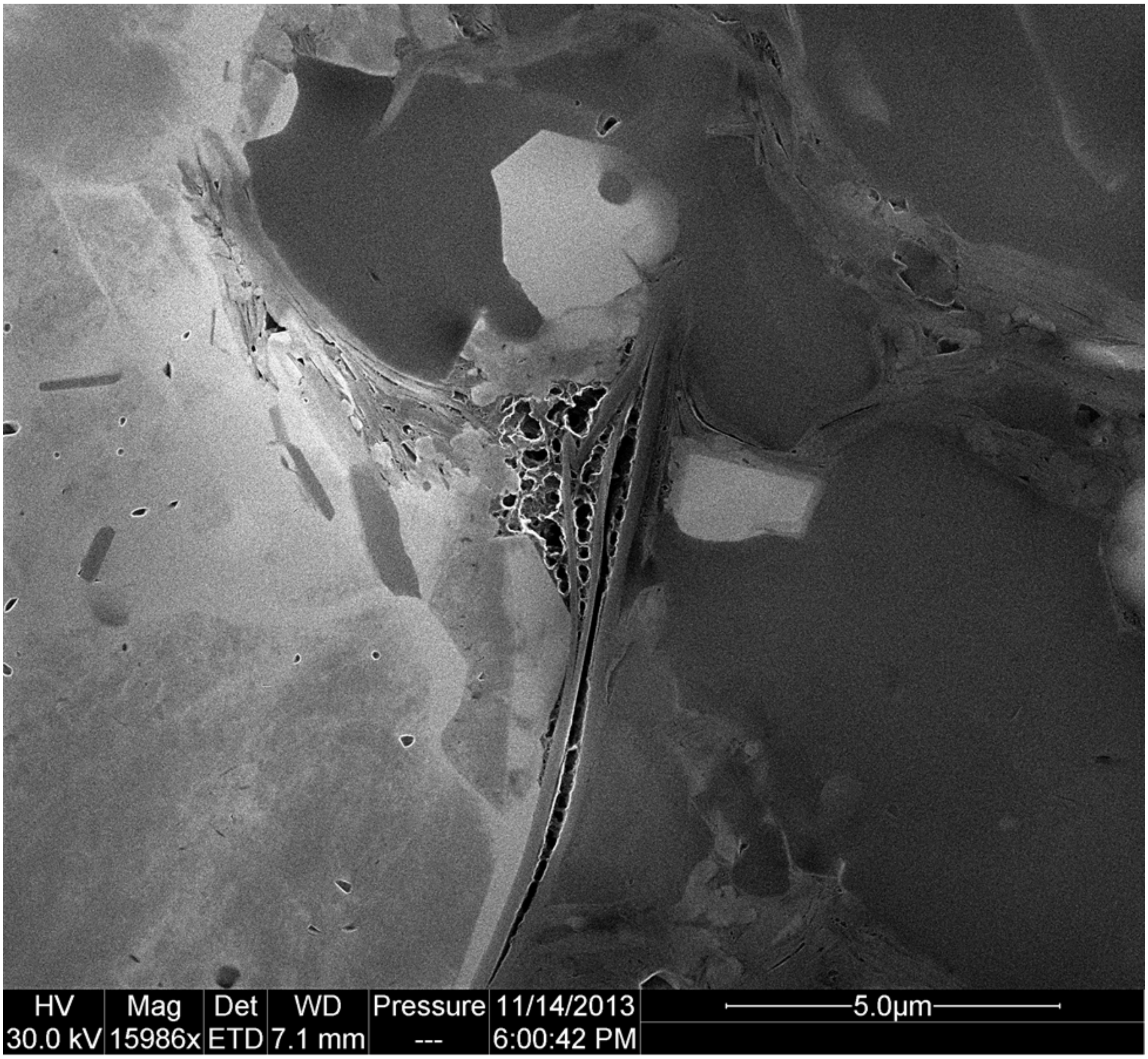


Figure 4: A nice shot of one of these interstitial spaces between quartz and calcite grains that is filled with larger (more than 1 micron) clay flakes that show deformation and were probably detrital. Remaining pore spaces within this framework of detrital clays are filled with porous organic matter (likely bitumen) and small, probably diagenetic clay flakes. Most Phyllosilicate Framework Pores are filled with OM, but some of them are empty (see for example white arrow) and probably were drained completely (thus they are all pore, instead of OM plus pores). The margins of larger pores are typically white rimmed, which is due to charge buildup during imaging (we run in low-vacuum mode with water as a quench gas). I could reduce/eliminate that effect, but would sacrifice finer scale resolution elsewhere.



<u>Figure 5:</u> Another example of interstitial Om with very well developed OM pores. Here the OM infilled between sheets of a mica grain that splayed open in an existing pore space prior to hydrocarbon formation and infilling of the space with (likely) bitumen. The next image shows details of the OM porosity.

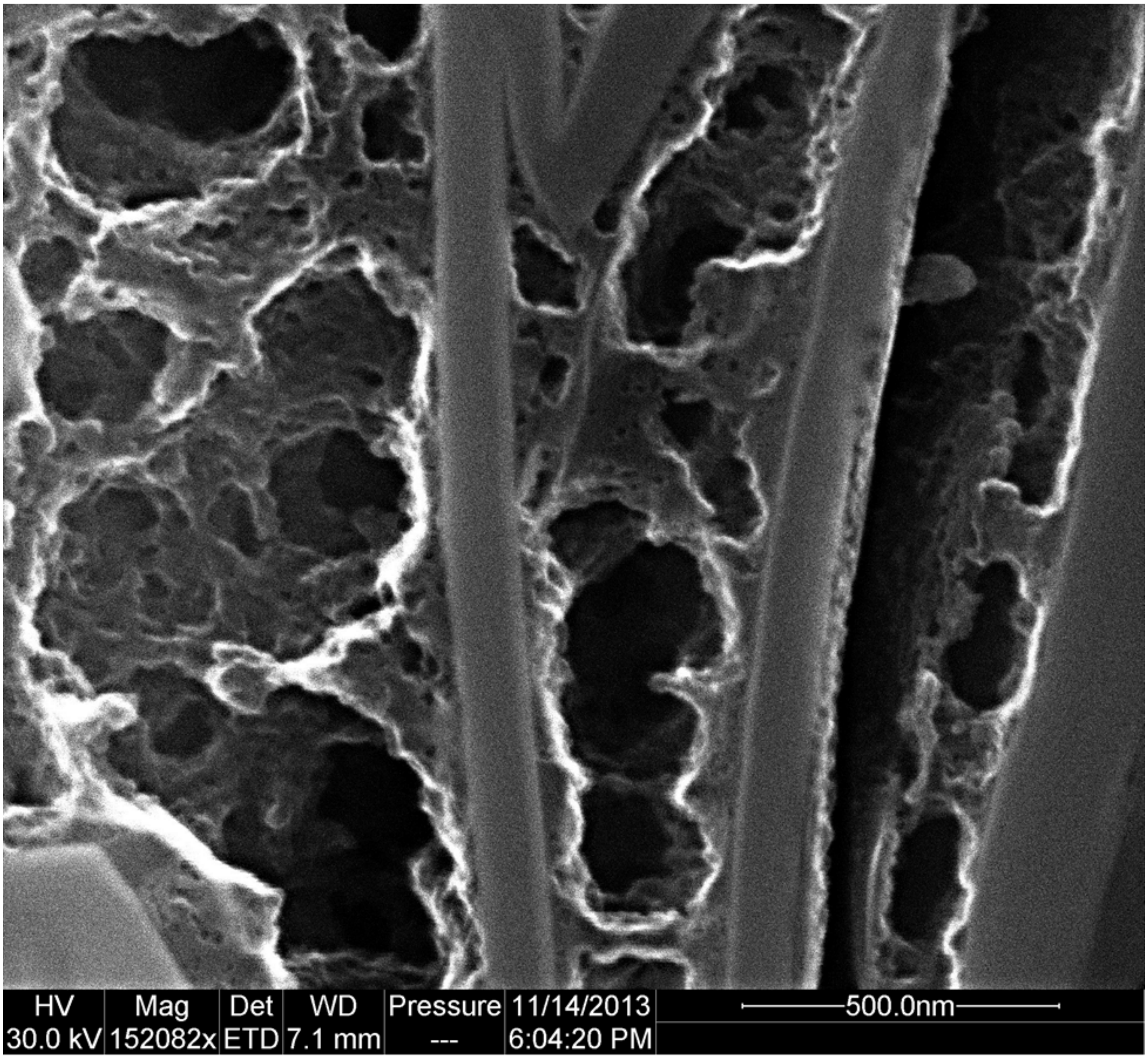


Figure 6: Detail from Fig. 5. Subvertical sheets of mica are separated by highly porous OM, probably pyrobitumen. The pores show pore throats and pore connectivity at depth.

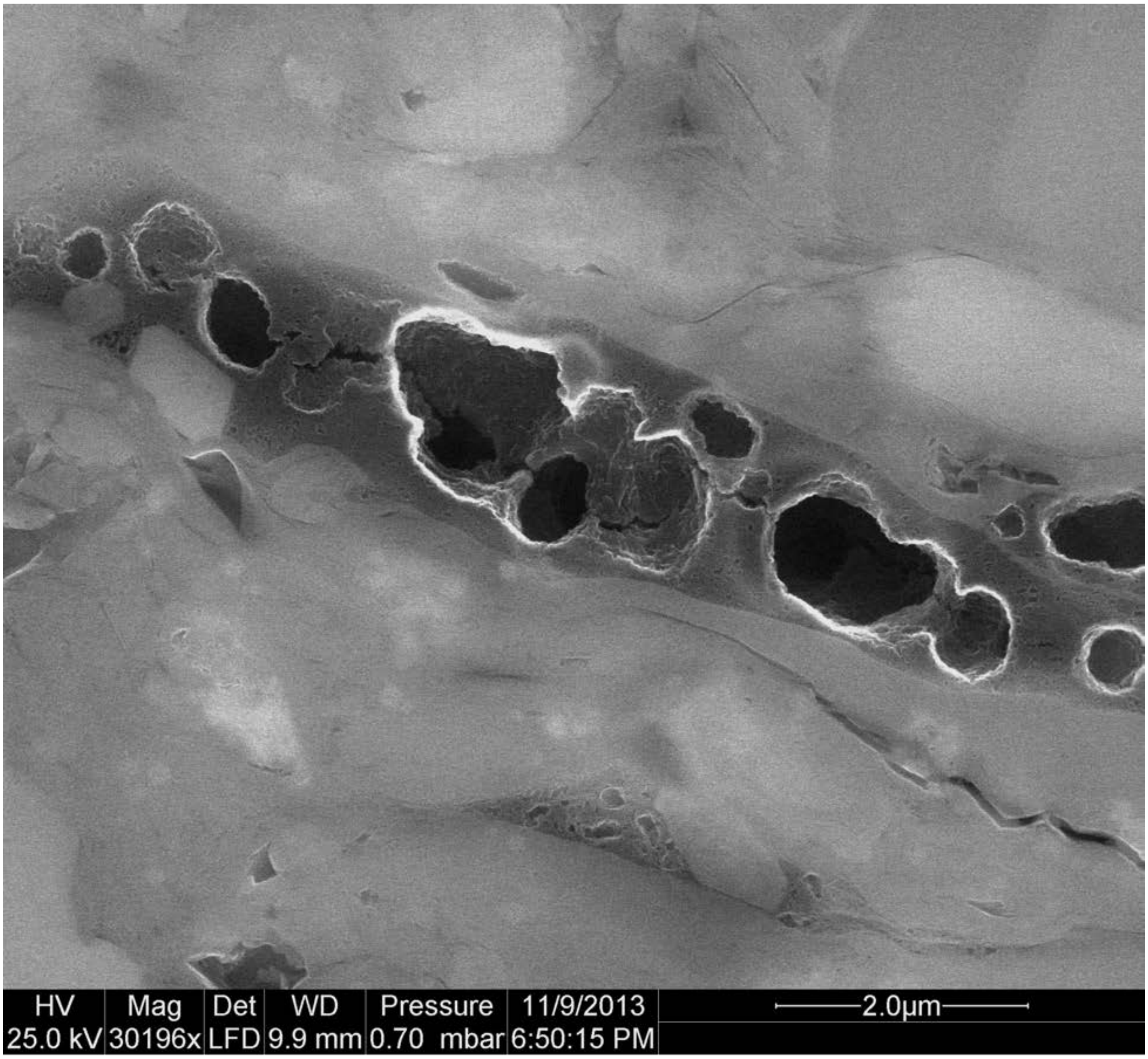


Figure 7: An elongate space filled with porous OM/bitumen, very well developed large (multi-micron) bubble pores. These show pore throats at depth and are most likely interconnected throughout the sample. White rims of large pores are again a charging artifact (avoidable, but harmless, allows better image quality elsewhere). OM porosity like this is typical for good reservoir facies in the Eagleford and Haynesville shales.

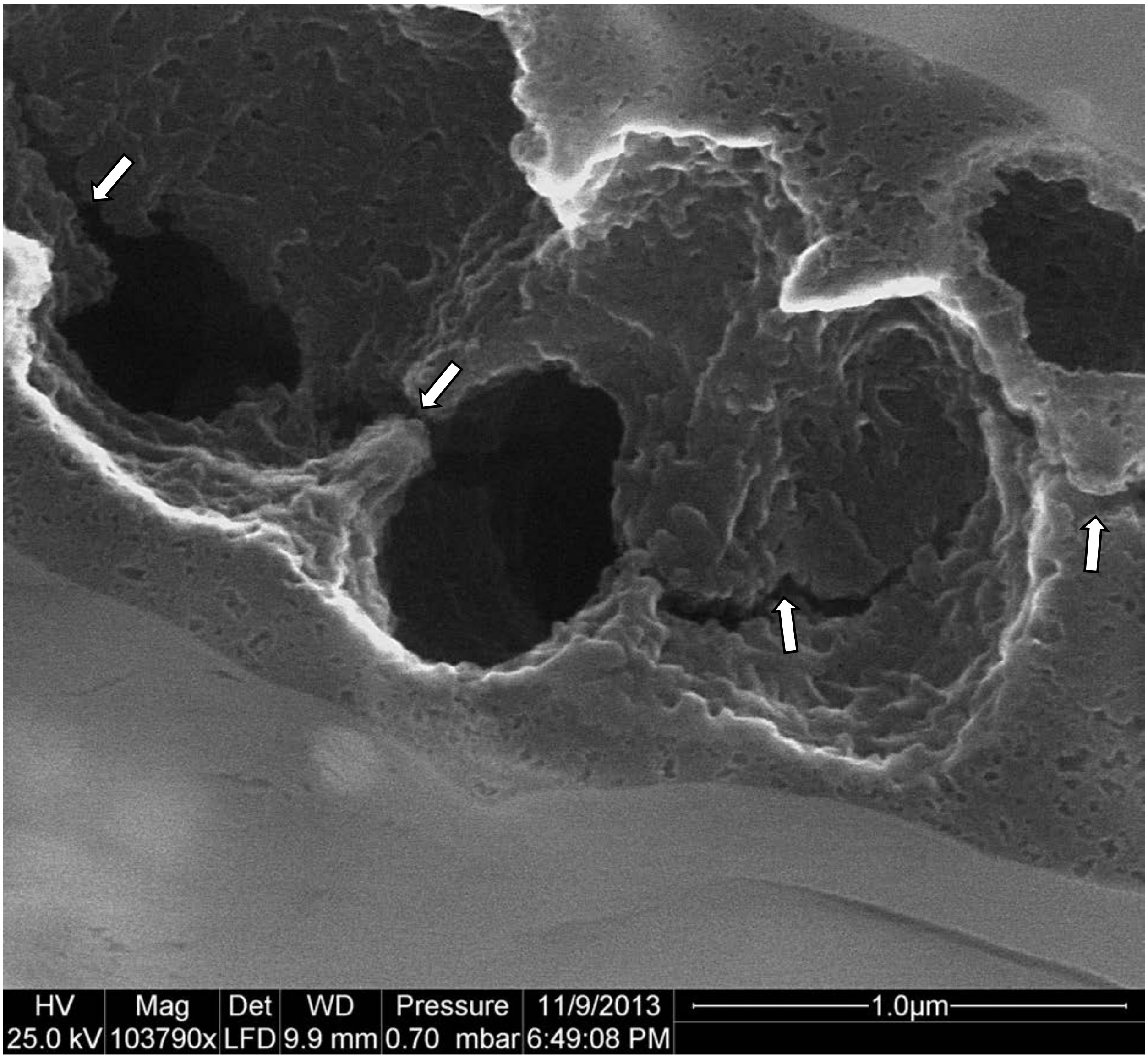
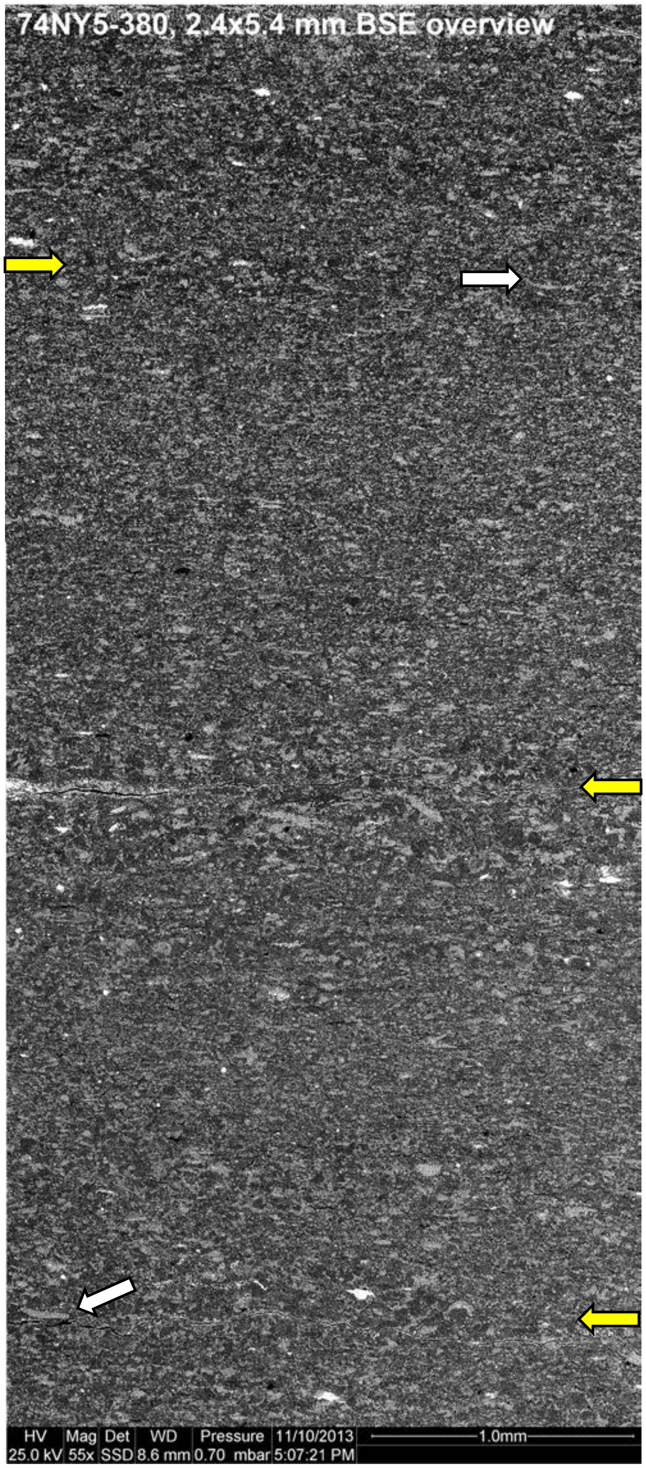


Figure 8: Close-up from Fig. 7. Shows the foam pores (gas storage) in the bitumen matrix that contains the larger bubble pores (gas transport). At this magnification we can identify an abundance of foam pores in the 10 nm or larger size range. The white arrows point to a fracture that roughly parallels the OM in this area, most likely a result of sample expansion due to removal of confining pressure.

Overall, this rock will be a good producing reservoir as long as there is enough OM to provide enough pore space, because OM porosity is what will carry the day.



Core: 74NY5 Depth: 380 feet

Figure 1: (left) a backscatter strip taken across the entire thickness of the sample. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

There is faintly visible stratification at the mm to sub-mm scale, but no well defined layer boundries. There are a what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrows), and some partially preserved coarser silty lamina (yellow arrows). Overall it appears that primary physical stratification/lamination has been overprinted by burrowing organisms. No macroscopic burrows were seen in the provided sample though. This suggests that bioturbation occurred very early in depositional history, probably largely by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don't recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to low dysoxic bottom waters at the time of deposition. The lighter gray colors (carbonate) are in between the 170 and 210 feet samples, suggesting a somewhat lower carbonate content that in the 210 feet sample. So compositionally the sample is probably a calcarous mudstone (30-40% calcium carbonate). If you have some geochemical data on this core you could check that.

Figure 2: Shale fabric with abundant diagenetic quartz that supports framework pores (white arrows). In places these quartz framework pores are filled with organic matter and diagenetic clays (black arrows). Diagenetic silica varies across the sample, but the association between diagenetic silica, organic matter, and clays is pervasive. CC=calcite, Qtz-o = overgrowth and diagenetic quartz, Qtz-d = detrital quartz.

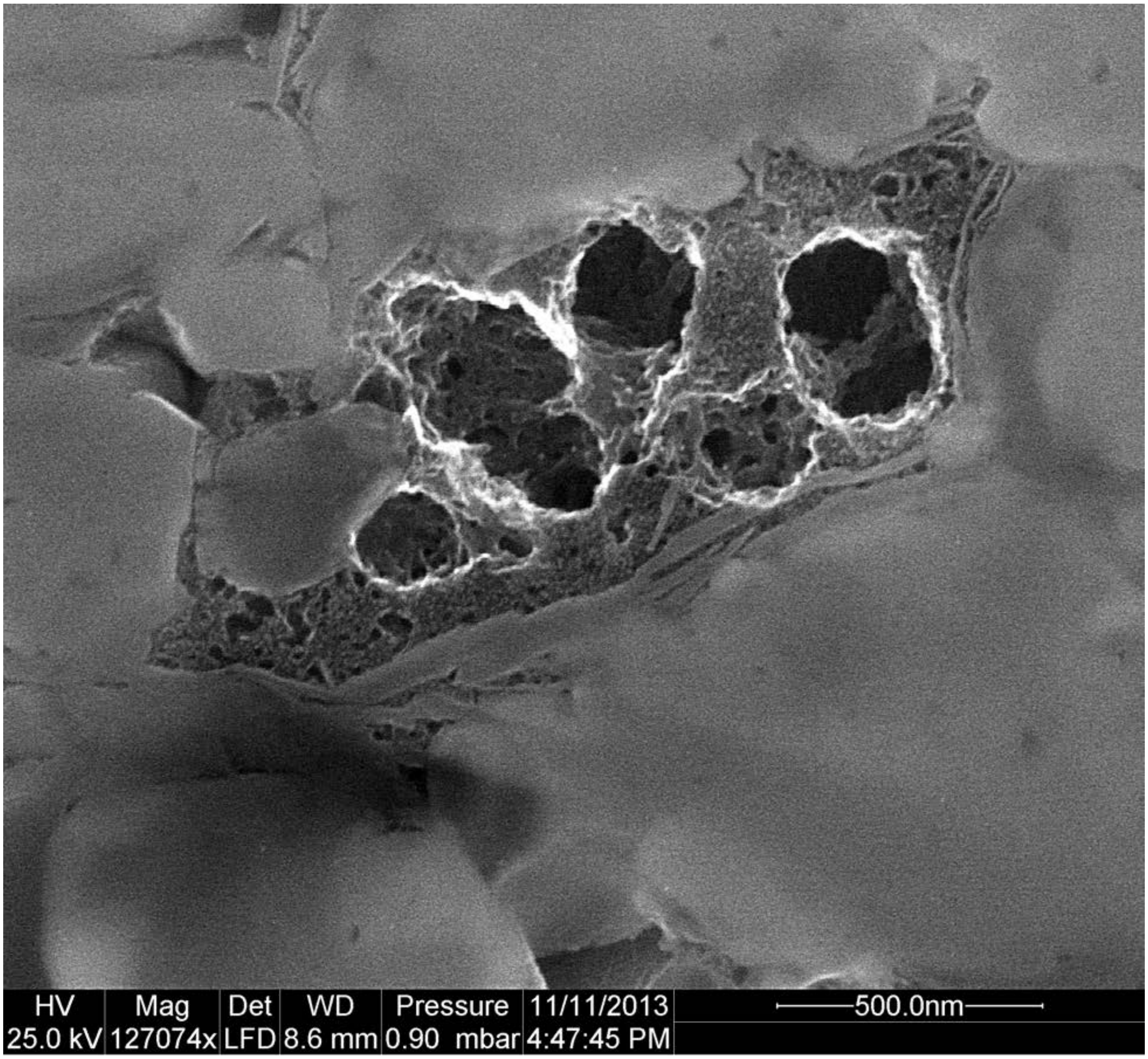


Figure 3: Close-up of organic matter pore fill from Fig. 2. Note large bubble pores with at depth pore throats and connectivity, and abundant foam pores in OM matrix. OM most likely bitumen infill of originally open pores.

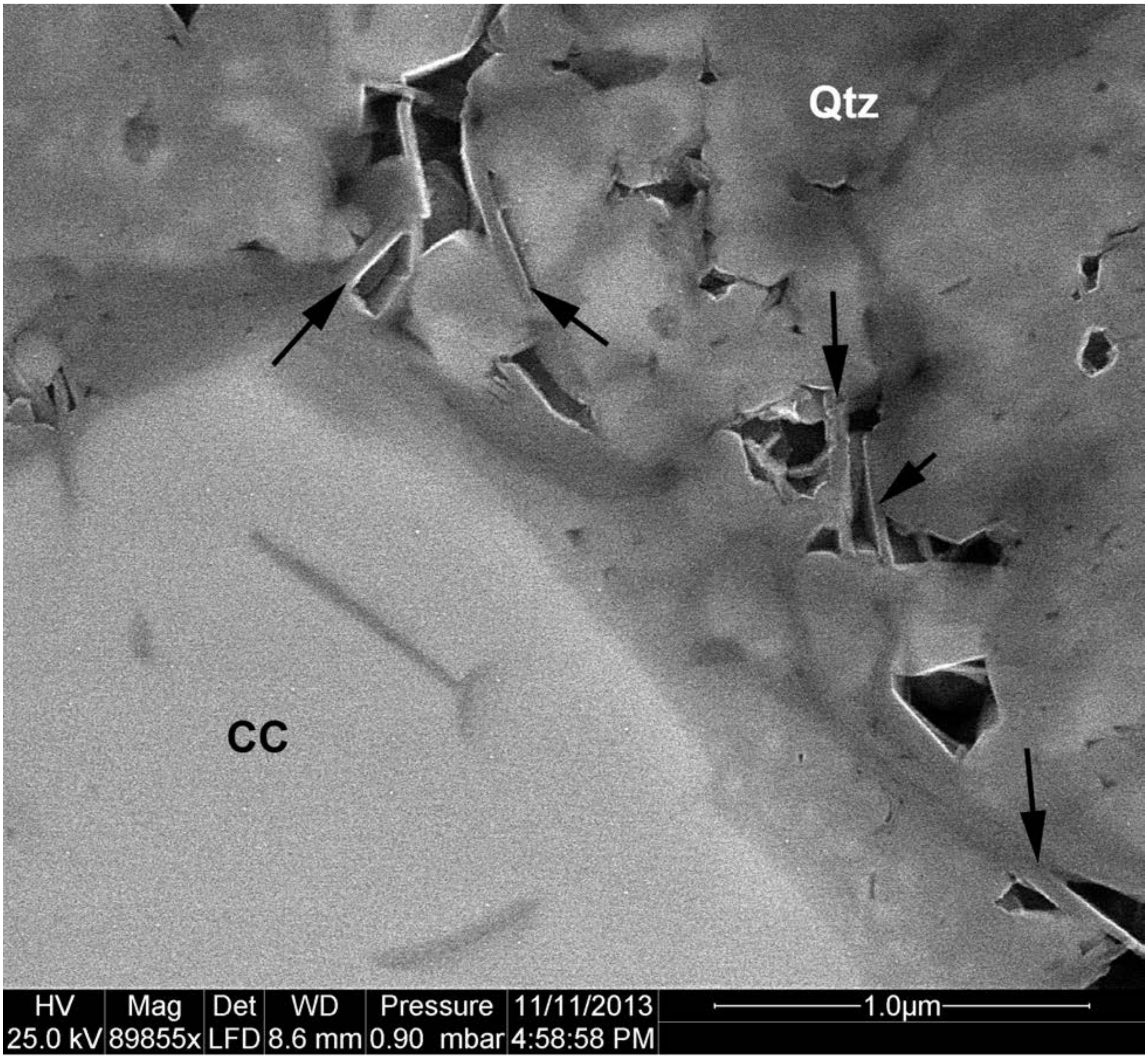


Figure 4: Framework pores between diagenetic quartz grains (Qtz), partly also defined by (most likely diagenetic) clay flakes (black arrows). CC=calcite. In this sample these kinds of framework pores are common, but OM porosity still dominates overall porosity.

In this sample there is a clear spatial association of diagenetic silica cementation (sets up pore network for late diagenetic fluid movement) with the formation of diagenetic clays, bitumen infilling of pores, and later diagenetic formation of OM pores.

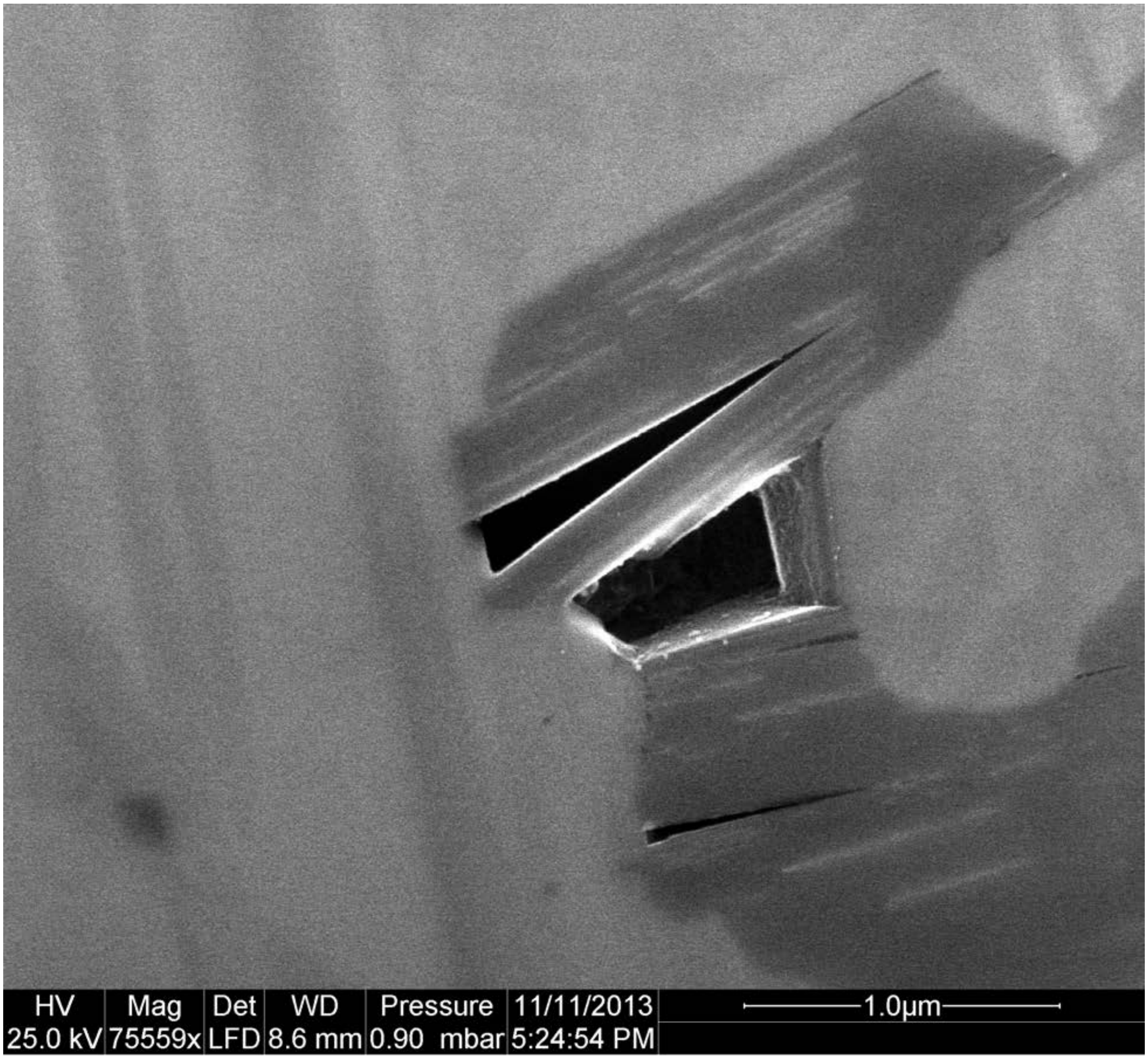
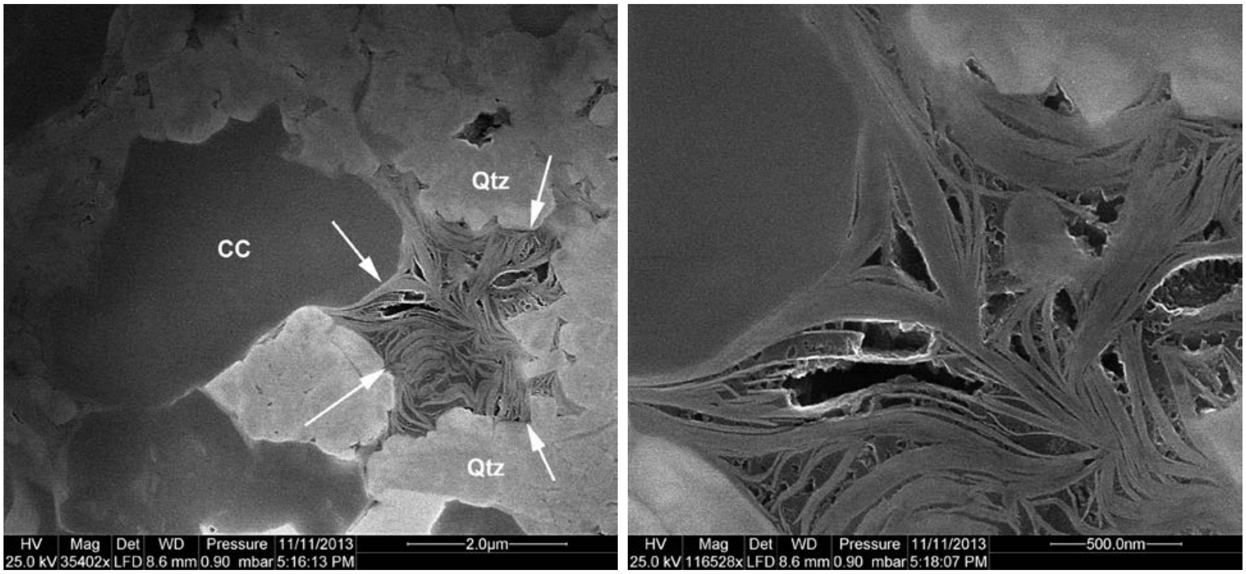
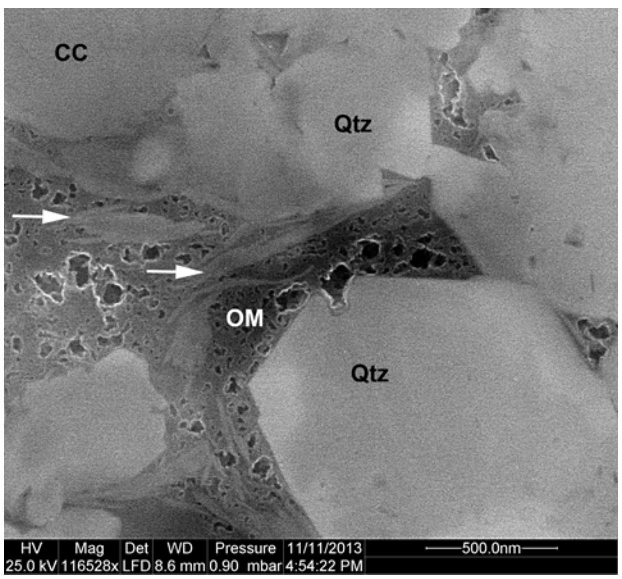


Figure 5: Example where diagenetic clay flakes have grown in a space between diagenetic quartz grains and define triangular and polygonal phyllosilicate framework pores. These are usually associated with areas of diagenetic silica cementation.



<u>Figure 6:</u> Example where a late diagenetic pore defined by calcite (cc) and diagenetic quartz grains (Qtz) is filled by clays (probably diagenetic) that form an open framework whose pores were subsequently filled by organic matter (bitumen). Heating of the bitumen produced the observed OM pores in the bitumen fill.



<u>Figure 7:</u> Another example of pore spaces defined by diagenetic quartz, and infilled with diagenetic clays and bitumen with OM bubble and foam pores.

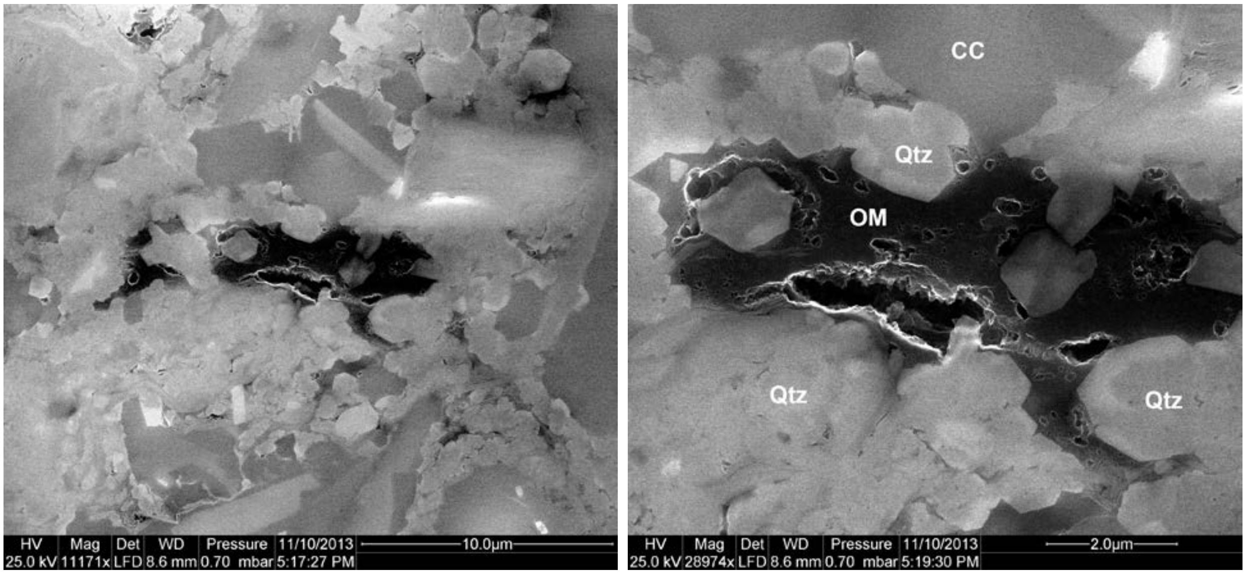


Figure 8: OM pore fill (dark-gray to black, in center) in the context of the overall fabric. Low mag at left, high mag at right that shows the well developed OM pores in the bitumen fill. These pores, protected from collapse by diagenetic silica cement, were most likely the travel routes of hydrocarbons when this rock produced oil.

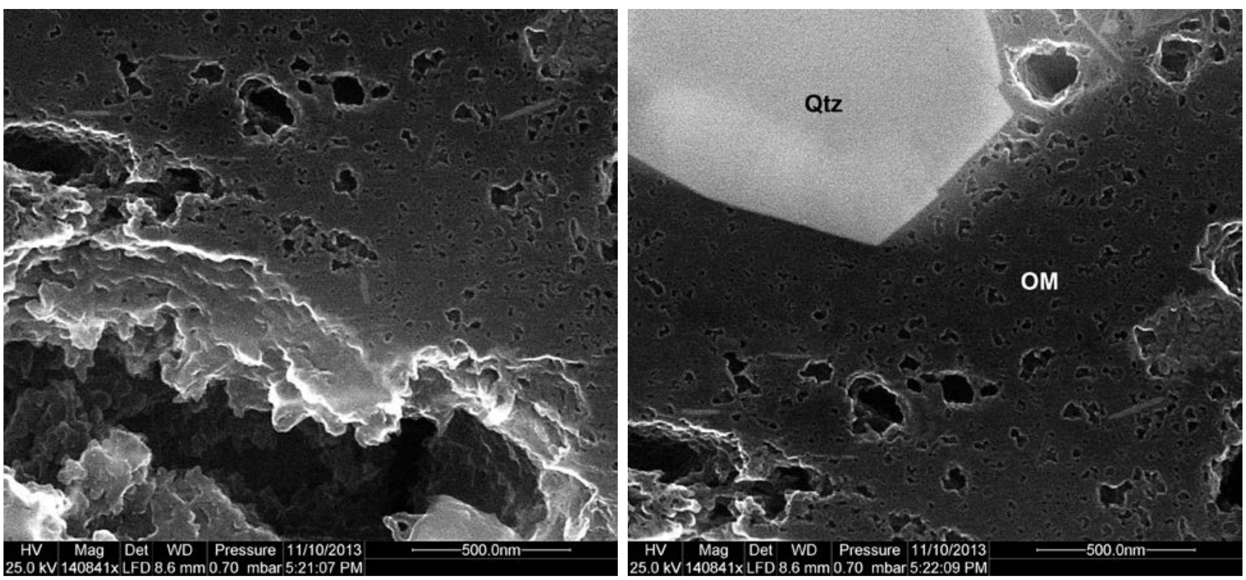
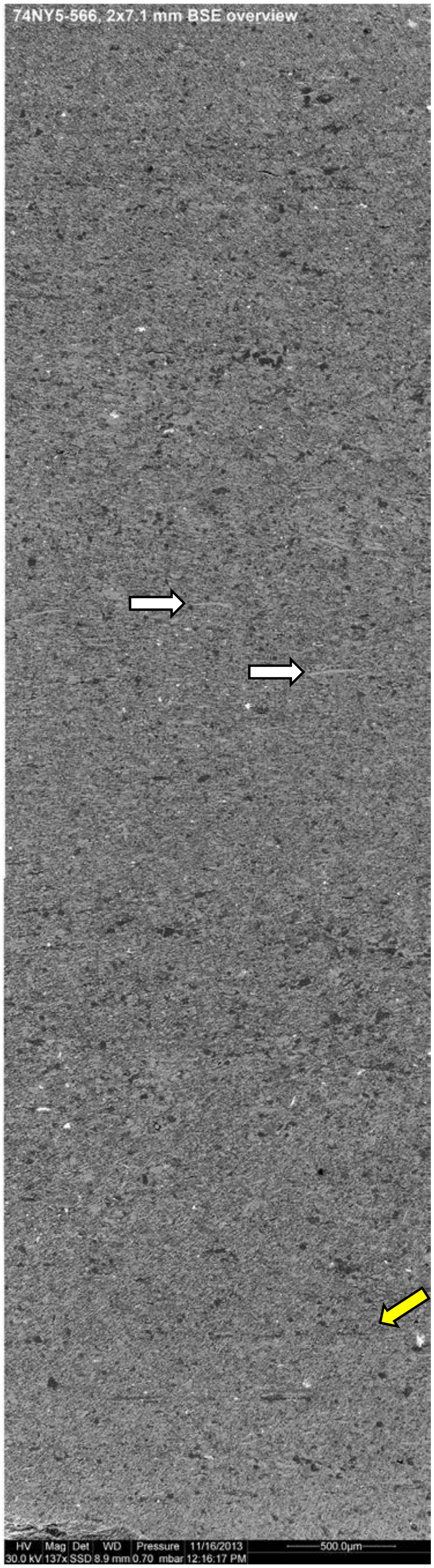


Figure 9: OM pore development in the bitumen fill seen in Fig. 8. Shows well developed bubble pores and abundant foam pores in the 10-50 nm size range.



Core: 74NY5   Depth: 566 feet

Figure 1: (left) a backscatter strip taken across the entire thickness of the sample. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

Any original primary stratification/lamination has been pretty much erased in this sample. There are a what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrows), and some zones of somewhat higher carbonate content (yellow arrows). Overall it appears that primary physical stratification/lamination has been completely destroyed by burrowing organisms. No macroscopic burrows were seen in the provided sample, suggesting that essentially all bioturbation occurred very early in depositional history, probably largely by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don’t recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to dysoxic bottom waters at the time of deposition. Lighter gray colors are prominent in this sample and suggest a carbonate content similar to the 240 feet sample, or somewhat higher. Technicallly this is probably a fine grained lime mudstone with a terrigenous clastic component in the 30-40% range). If you have some geochemical data on this core you could check that.

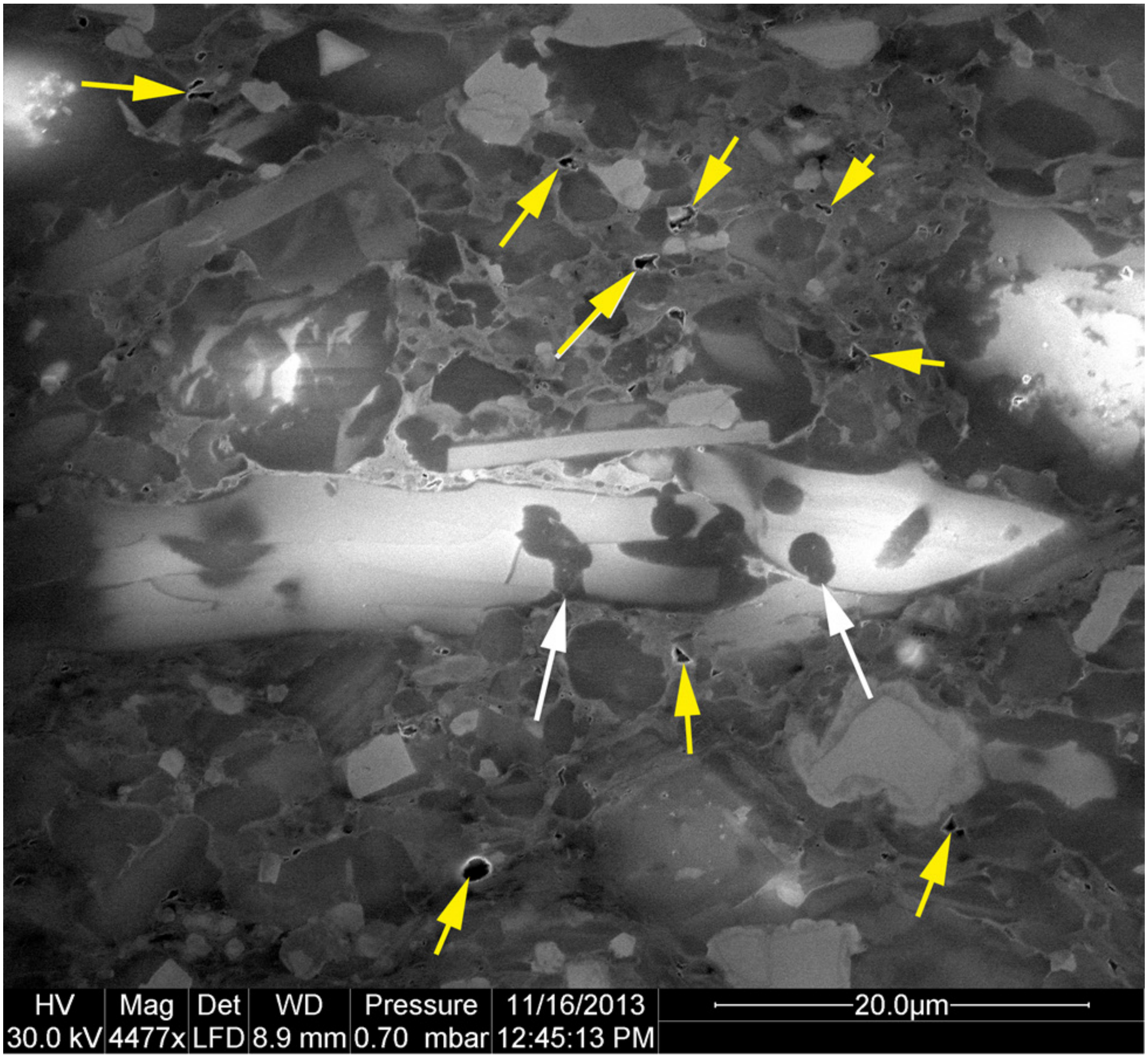


Figure 2: Overview of a (at first) pretty tight appearing shale fabric. The shell fragment in the center of the image (bright) consists of calcite, and has borings filled with dolomite (darker gray, white arrows; formed very early in diagenesis). The yellow arrows point to open framework pores (calcite and quartz defined). In addition, many interstitial spaces between larger mineral grains contain pore filling bitumen that has developed OM-pores.

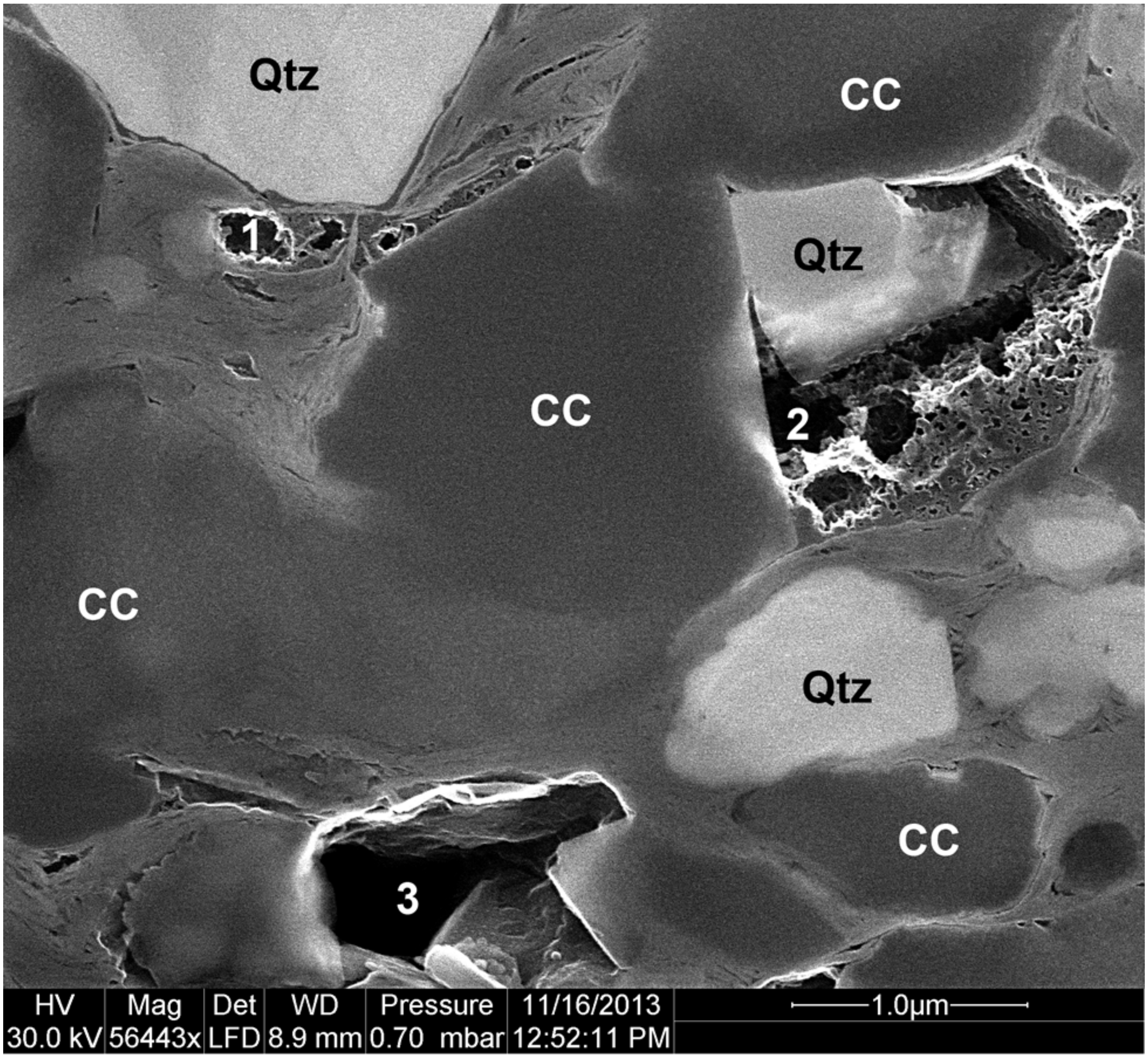


Figure 3: Closer view of shale fabric from Fig. 2. Shows the typical clay plus OM (bitumen) fill of interstitial spaces, and the development of pores in the OM fill. Qtz=quartz, CC=calcite. Spot 1 shows development of large bubble pores in OM, Spot 2 shows development bubble pores into very deep connected channels/tubes, and Spot 3 shows a completely open framework pore (defined by calcite grains). One could envision progressive development of OM pores from foam to bubbles to tubes in OM, and finally completely emptying of framework pore spaces due to out-migration of liquid hydrocarbons.

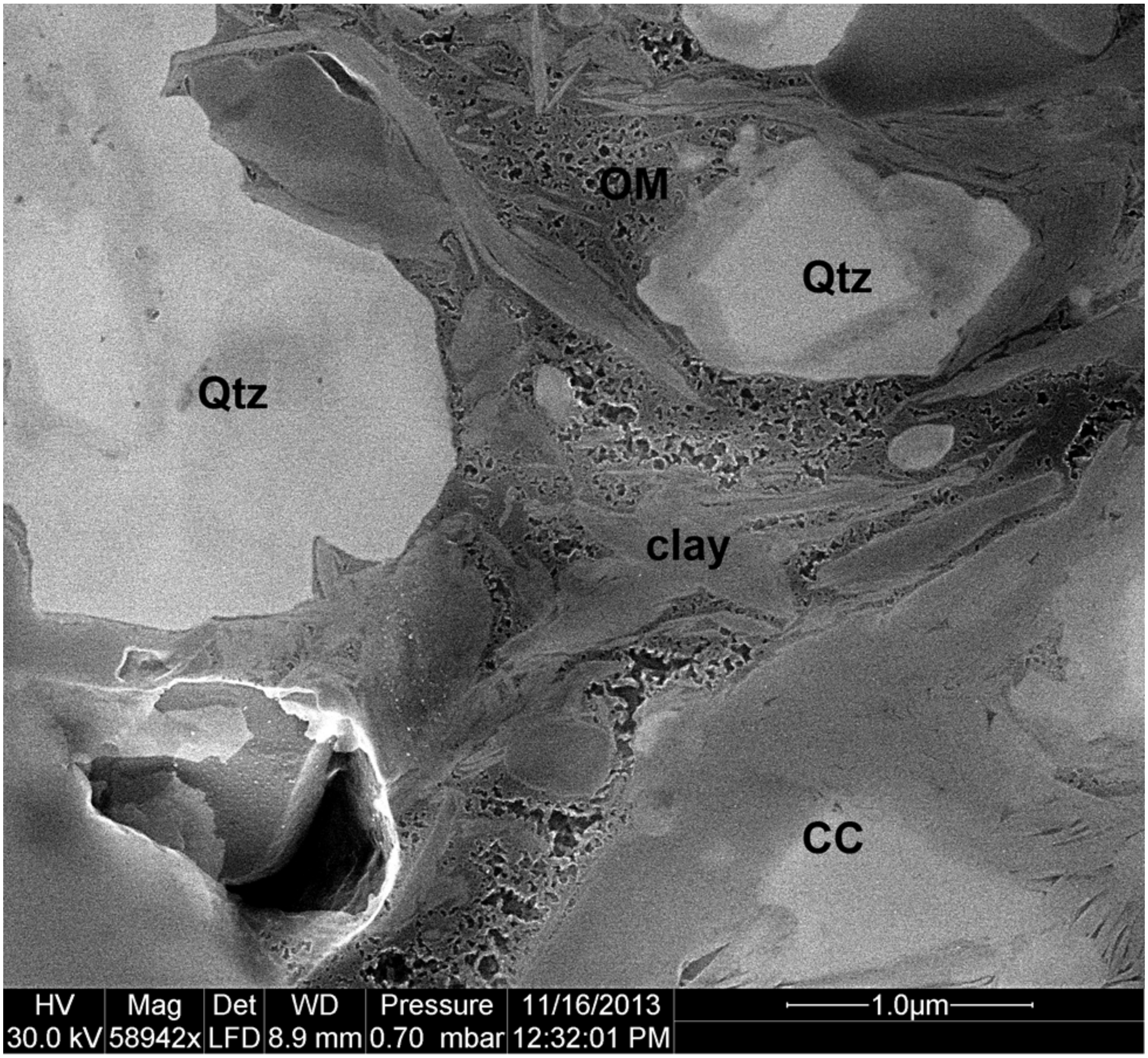


Figure 4: Another typical shale fabric close-up. Qtz=quartz, CC=calcite, OM=bitumen. With OM that shows very good OM pore development in bitumen fills and a completely open large framework pore in the lower left corner of the image.

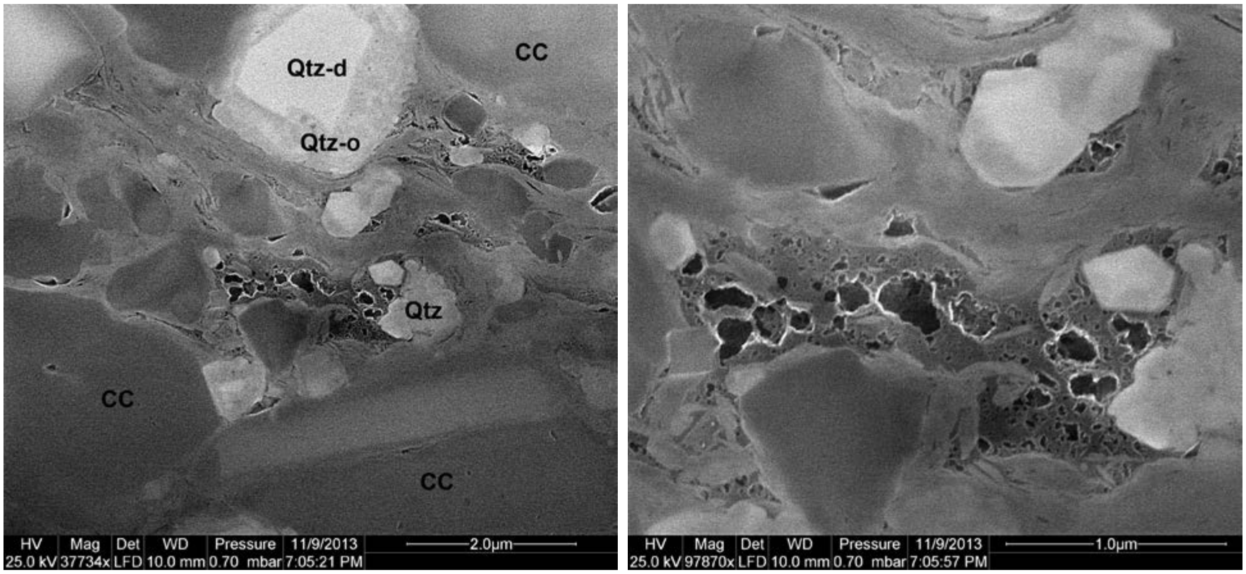


Figure 5: Anotehr nice example of interstitial organic matter with good development of OM pores (foam and bubble). And in left image clear development of abundant diagenetic overgrowth quartz (Qtz-o) on detrital quartz. Qtz=quartz, CC=calcite.

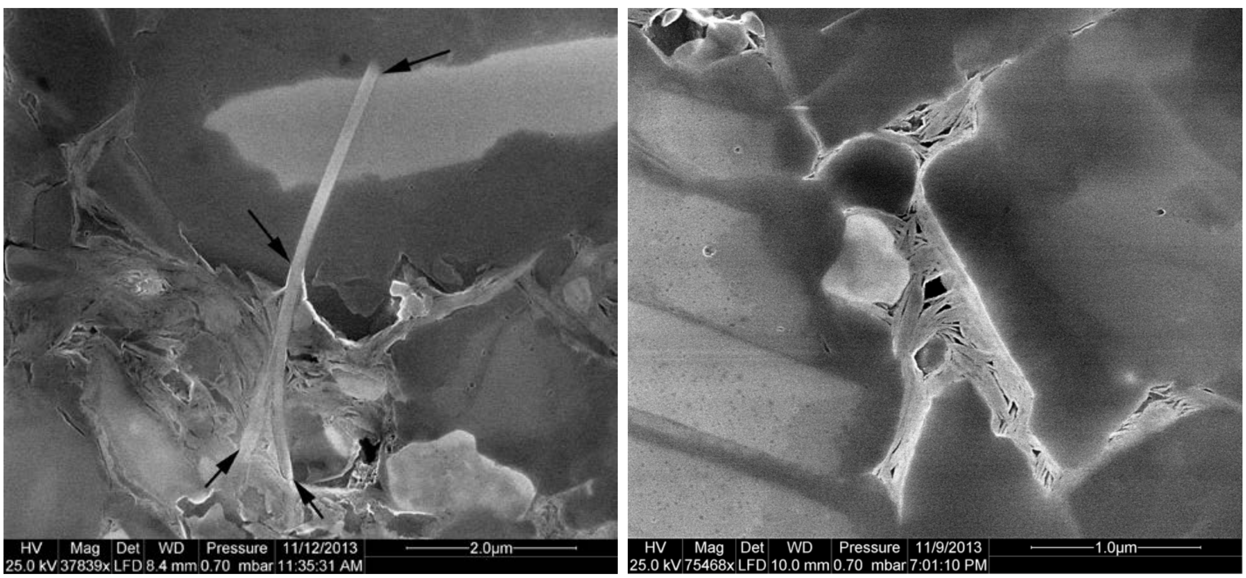
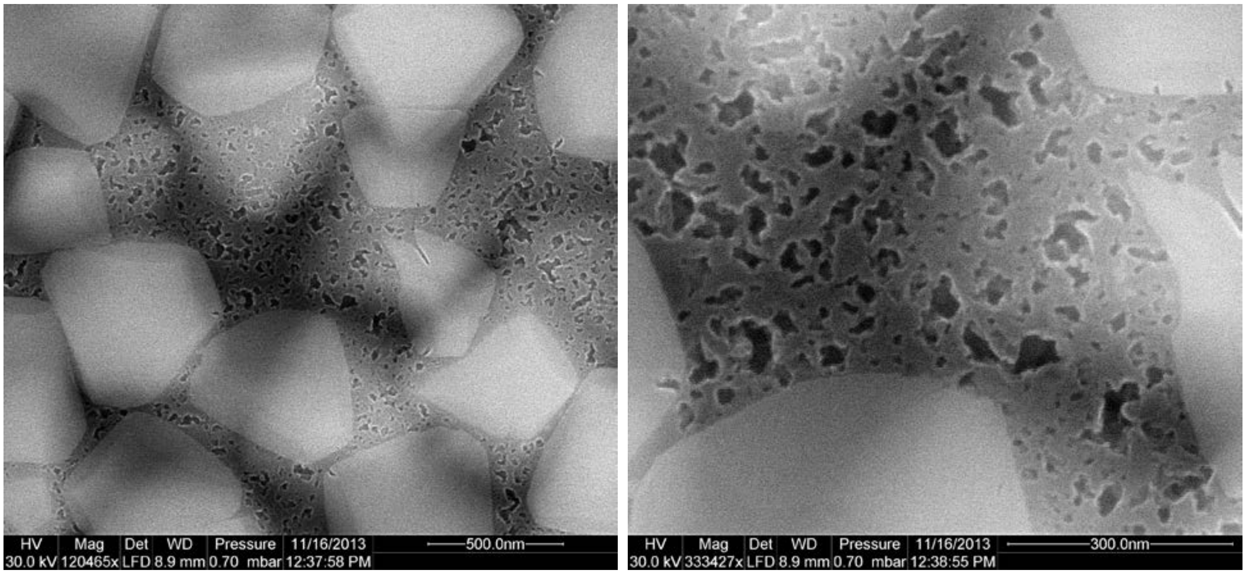
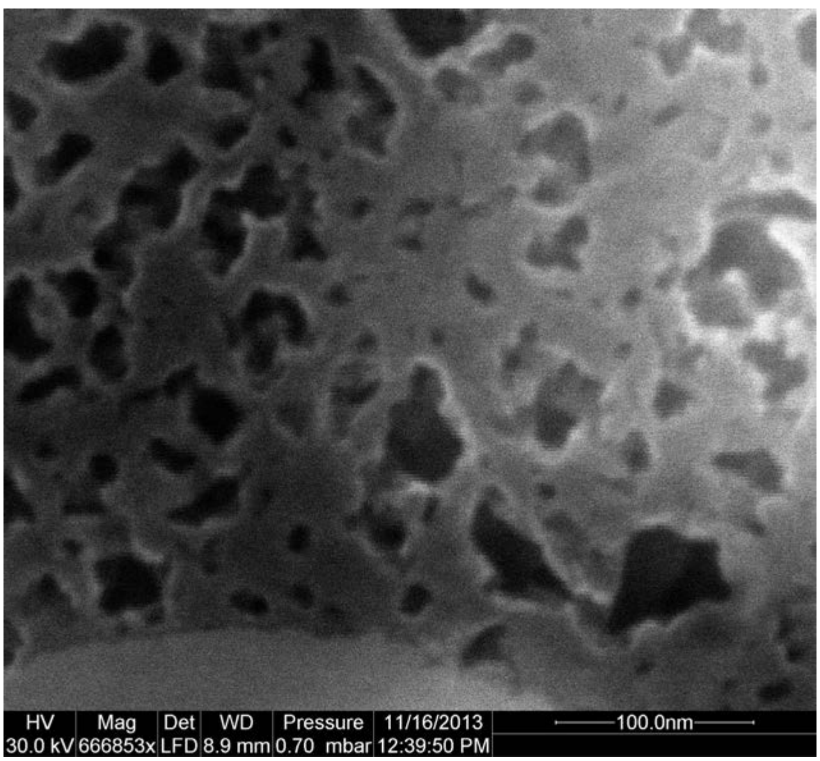


Figure 6: At left a clay or mica flake that stands near vertical (black arrows) and is split open at the bottom and embedded in diagenetic calcite at the top. This positioning of phyllosilicate flakes retards compaction and helps to preserve original pore spaces. The calcite embedding also suggests abundant precipitation of diagenetic calcite before the onset of any substantial compaction. Early formed diagenetic calcite is likely an important factor in the preservation of carbonate framework porosity. At right clay flakes define triangular Phyllosilicate Framework Pores. Clay minerals, even though not dominating the fabric, still add “value” to the overall porosity picture.

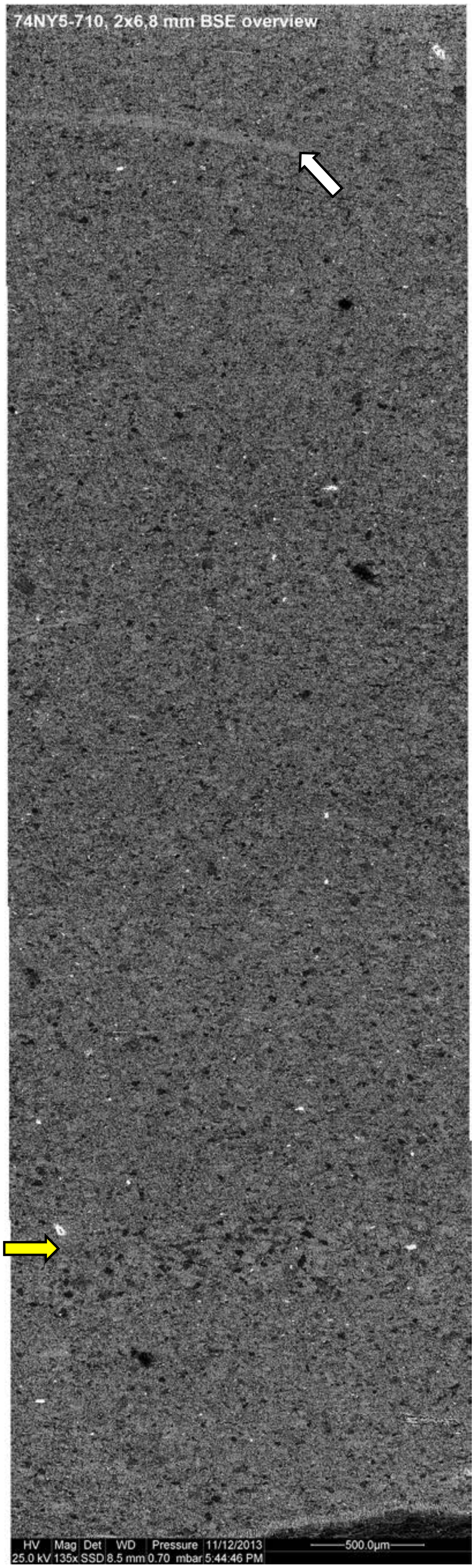


<u>Figure 7:</u> The space between the sub-crystallites of pyrite framboids very typically is infilled with kerogen (left) and that kerogen (bitumen?) also shows well developed OM pores (right). Not a significant component in the overall pore picture, but it contributes.



<u>Figure 8:</u> Very high magnification image of OM from Fig. 7. Pores as small as 5 nm in size can still be recognized.

Overall, a shale with a combination of framework and OM porosity. The latter dominates, but there is enough of the former to benefit gas flow/transmission. A promising reservoir rock, comparable with good Eagle Ford and Haynesville reservoir shales/mudstones.



Core: 74NY5 Depth: 710 feet

Figure 1: (left) a backscatter strip taken across the entire thickness of the sample. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

Any original primary stratification/lamination has been pretty much erased in this sample. There are what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrow), and some zones of higher coarse silt content (yellow arrow). Overall it appears that primary physical stratification/lamination has been largely destroyed by burrowing organisms. No macroscopic burrows were seen in the provided sample, suggesting that essentially all bioturbation occurred very early in depositional history, probably by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don't recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to dysoxic bottom waters at the time of deposition. Lighter gray colors are prominent in this sample and suggest a content similar to the 240 feet sample. Technically this is probably a fine grained lime mudstone with a terrigenous clastic component in the 30-40% range). If you have some geochemical data on this core you could check that.

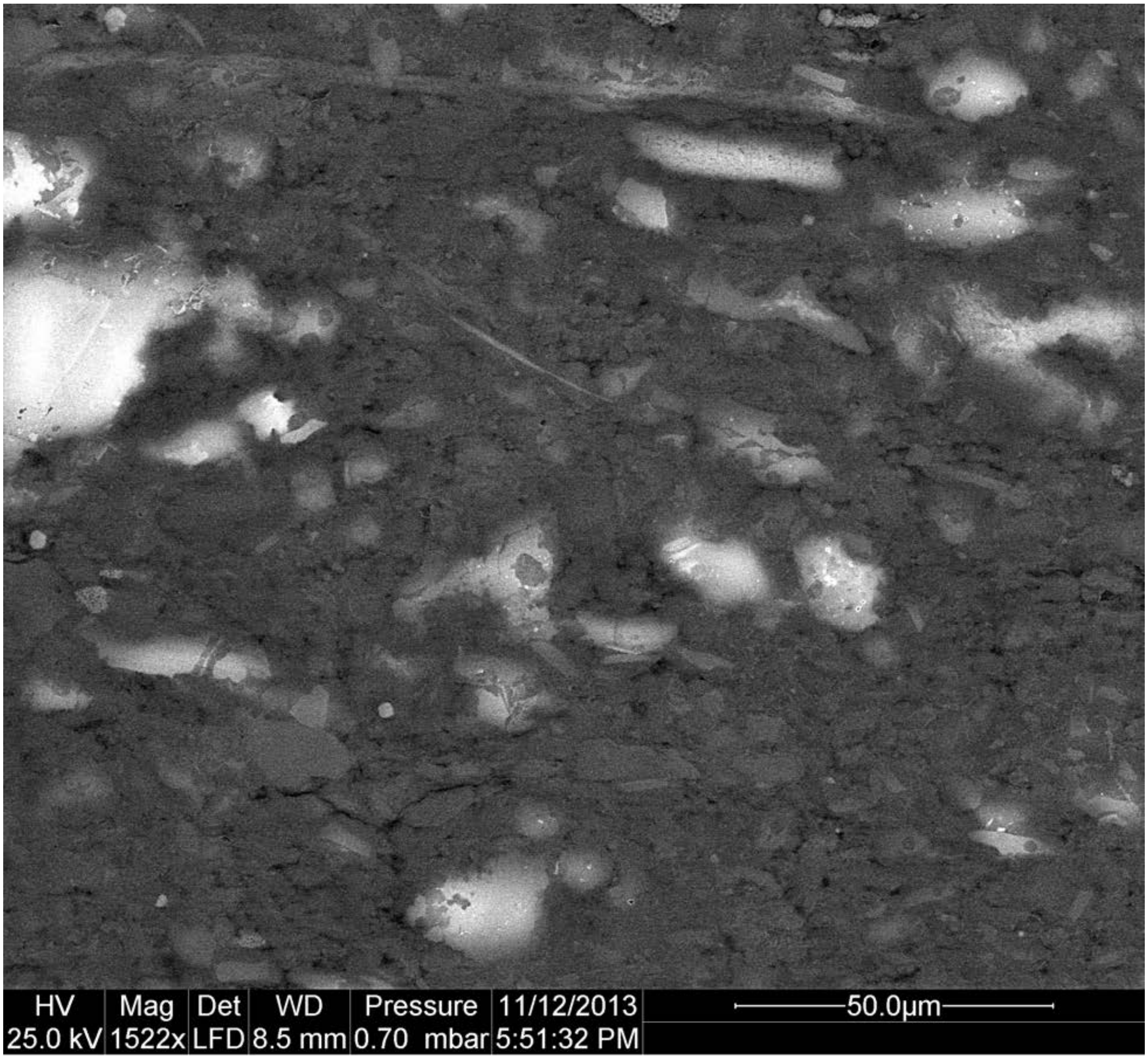


Figure 2: Mid-level overview of shale fabric (SEM image). Bright areas are characterized by continuous calcite cement (brightness due to charging). The fabric consists largely of a mingling of calcite grains, quartz grains, and clays and organic matter (dark-black areas) that are crowded together in interstitial areas. A few thin calcareous slivers (light gray) are fossil shell material.

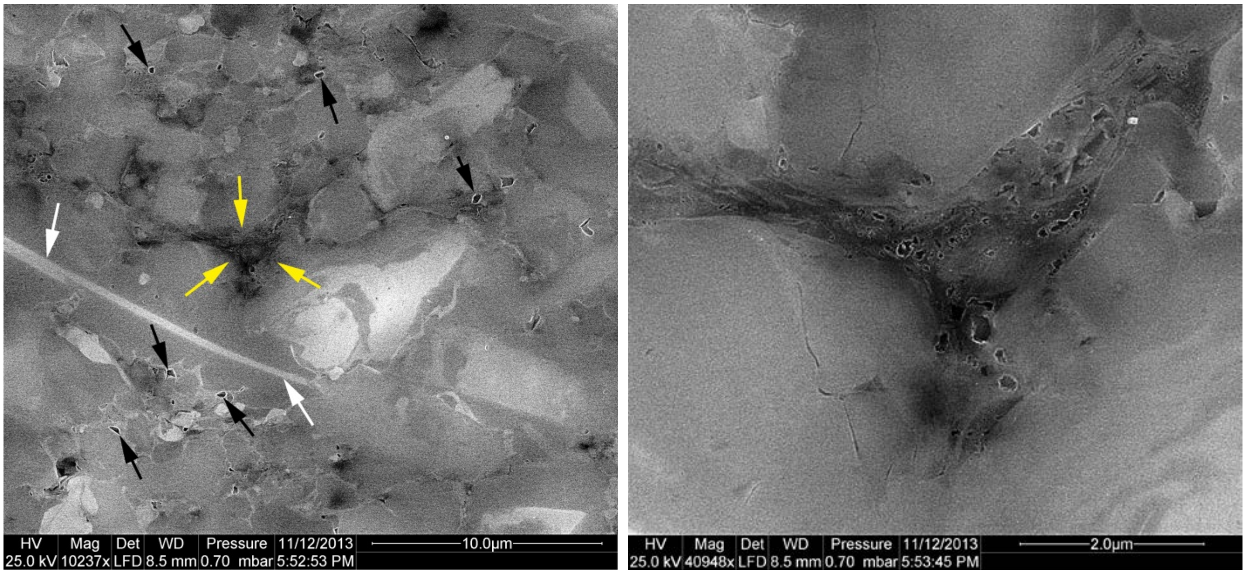


Figure 3: Closer view of shale fabric. Left image: White arrows point to calcite shell fragment. Black arrows point to open framework pores between calcite grains and (in places) quartz grains. However, due to the comparatively high carbonate content, the calcite defined framework pores dominate. The yellow arrows point to an interstitial area with abundant organic matter. Right image: Close-up of this organic-rich area. Visible are the larger bubble pores within the OM.

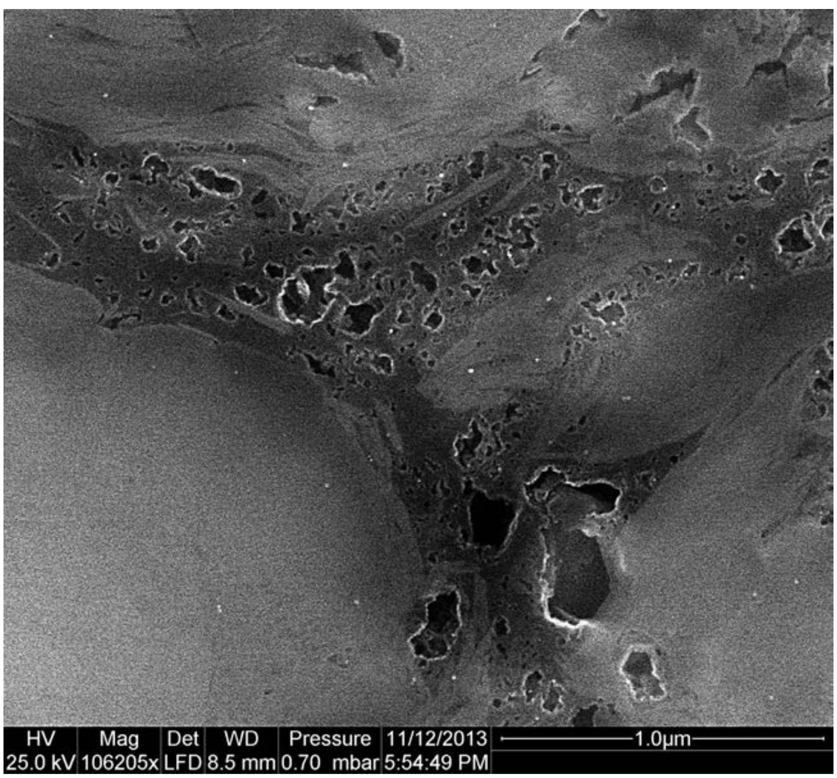


Figure 4: Close-up of OM pores from Fig. 3. The larger bubble pores are bright rimmed because of charging in low vacuum imaging mode. This the same mode of OM and OM-pore occurrence as in all previous samples (170-566 feet).

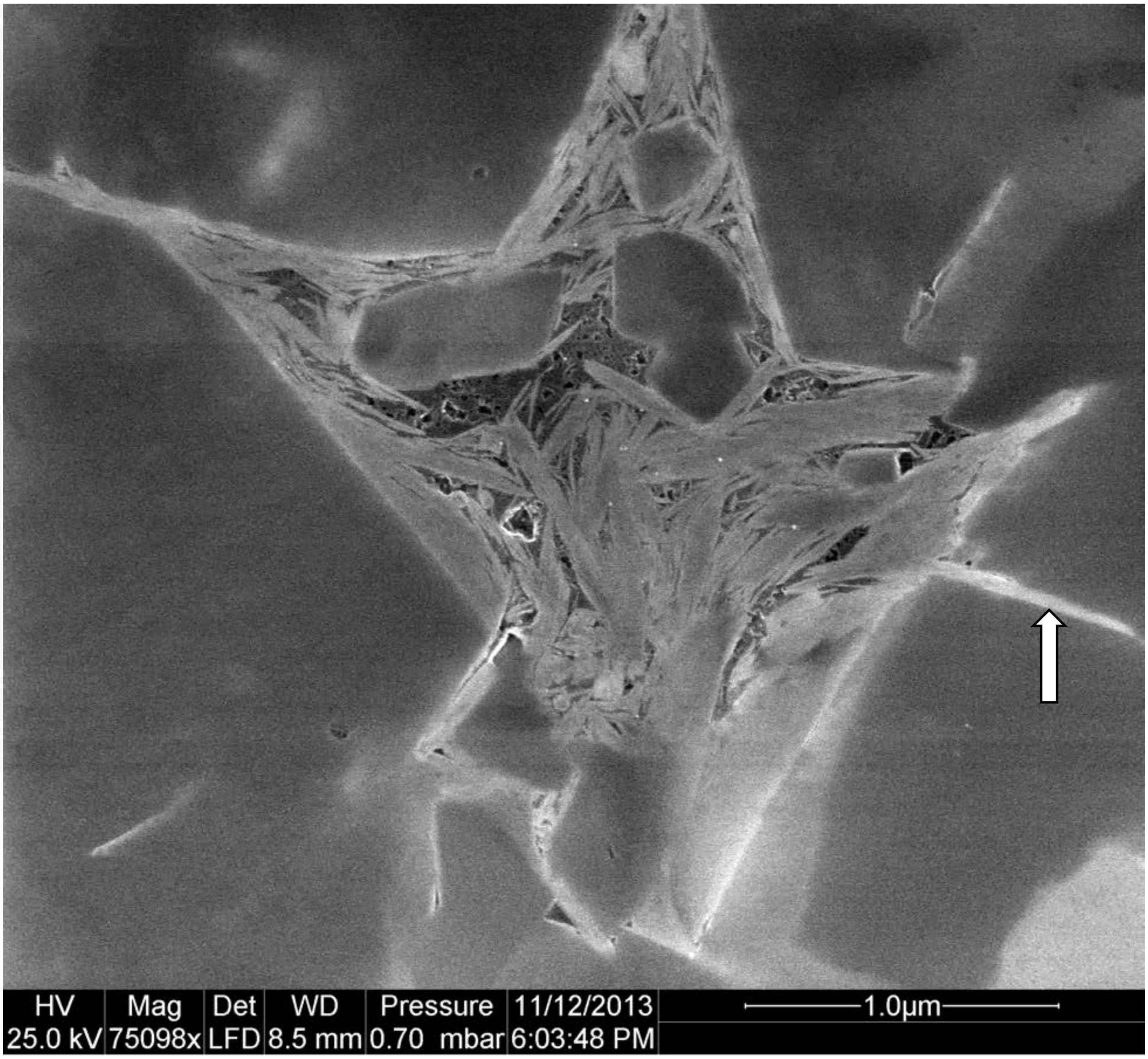


Figure 5: Another view of an interstitial area with a framework of clay minerals (the larger ones, >1 micron are likely detrital in origin) and an infill of organic matter between these. Later heating produced pores in the OM. Abundant early diagenetic carbonate cementation (preserves porosity by preventing compactional collapse of early pores) is indicated by the “deep” inclusion of clay platelets in carbonate/calcite grains (white arrow).

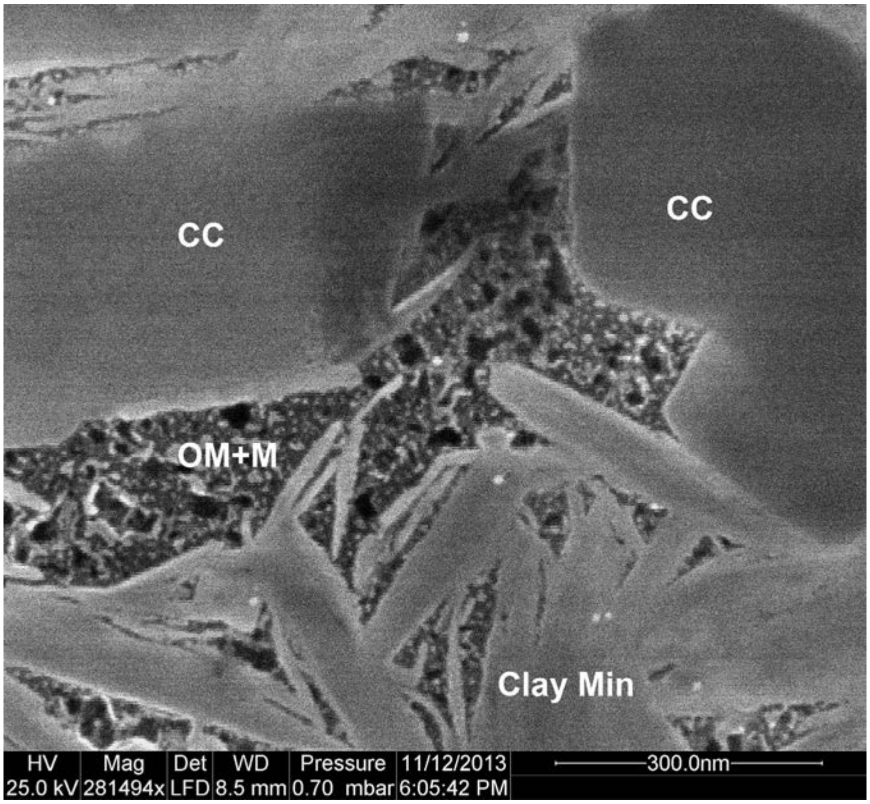


Figure 6: Close-up of Fig. 5. Shows that in this instant the OM filled areas are not simply OM plus pores, but OM that is finely mingled with mineral matter (brighter gray spots) and also contains pores (dark gray to black spots). These mineral grains were probably carried with the hydrocarbon liquids (now bitumen) that entered the original pore spaces.

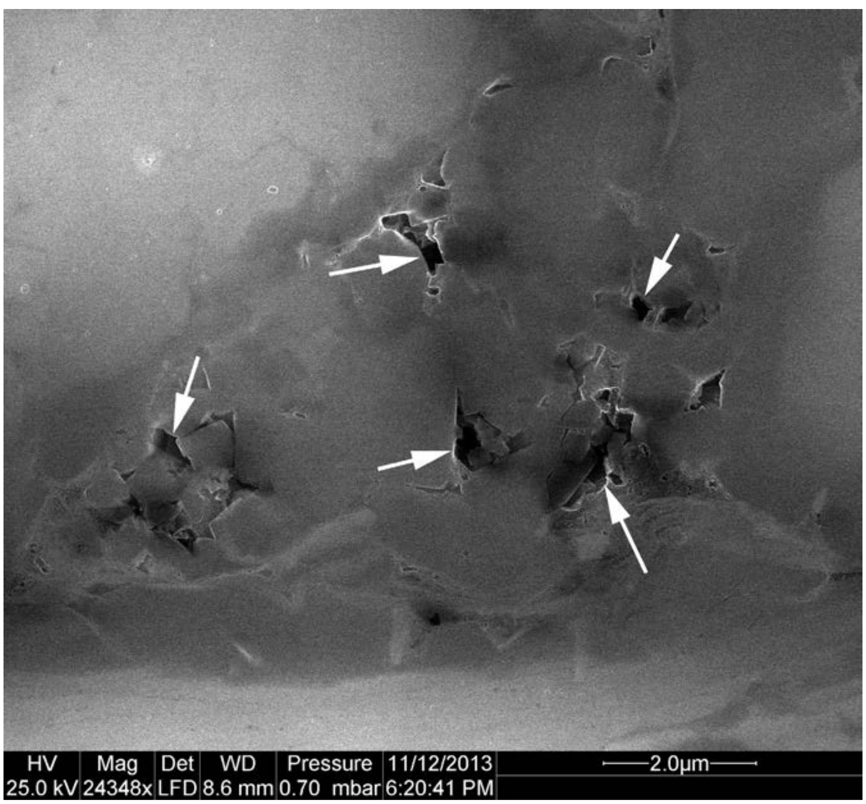
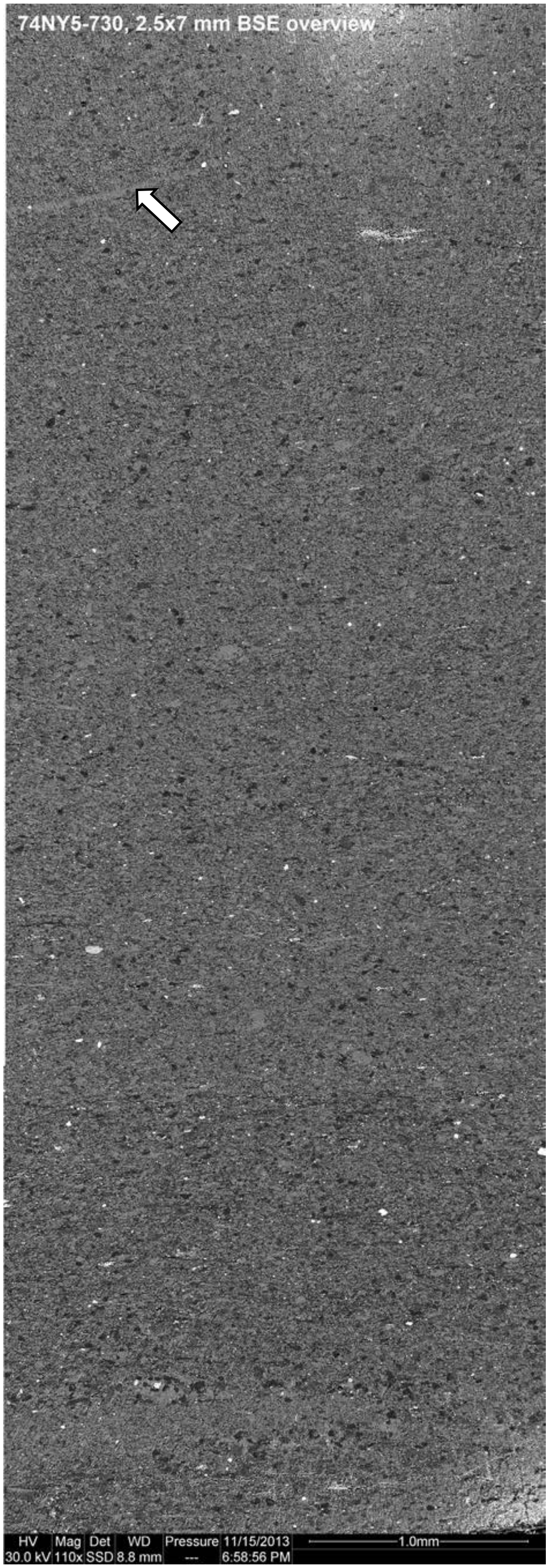


Figure 7: White arrows point to open framework pores defined by carbonate grains. Because of abundant early diagenetic carbonate growth and the high carbonate content of the rock, Carbonate Framework Pores appear to be more abundant in this sample when compared to previous samples (170-655 feet).

So, the rock should perform similarly as previous samples.



Core: 74NY5   Depth: 730 feet

Figure 1: (left) a backscatter strip taken across the entire thickness of the sample. Very bright = pyrite; dark gray = quartz, feldspar and clays; medium gray = calcite; black = organic matter and pores.

Any original primary stratification/lamination has been pretty much erased in this sample. There are what appears to be a few remnants of small, thin fossil calcareous shell fragments (white arrow). Overall it appears that primary physical stratification/lamination has been largely destroyed by burrowing organisms. No macroscopic burrows were seen in the provided sample, suggesting that essentially all bioturbation occurred very early in depositional history, probably by small (mm-sized) polychaetes and /or nematodes. The fossils shells are unidentified, but their paucity (I don't recall there being calcareous plankton in the Ordovician) might suggest sparse thin shelled benthos. But you are the carbonate expert, so you may have your own, and hopefully better, ideas on that matter. Overall, I would infer suboxic to dysoxic bottom waters at the time of deposition. Lighter gray colors are prominent in this sample and suggest a carbonate content somewhat lower than the 240 feet sample (probably in the 40-50% range). Technically this is probably a borderline fine grained lime mudstone or a highly calcarous mudstone. If you have some geochemical data on this core you could check that.

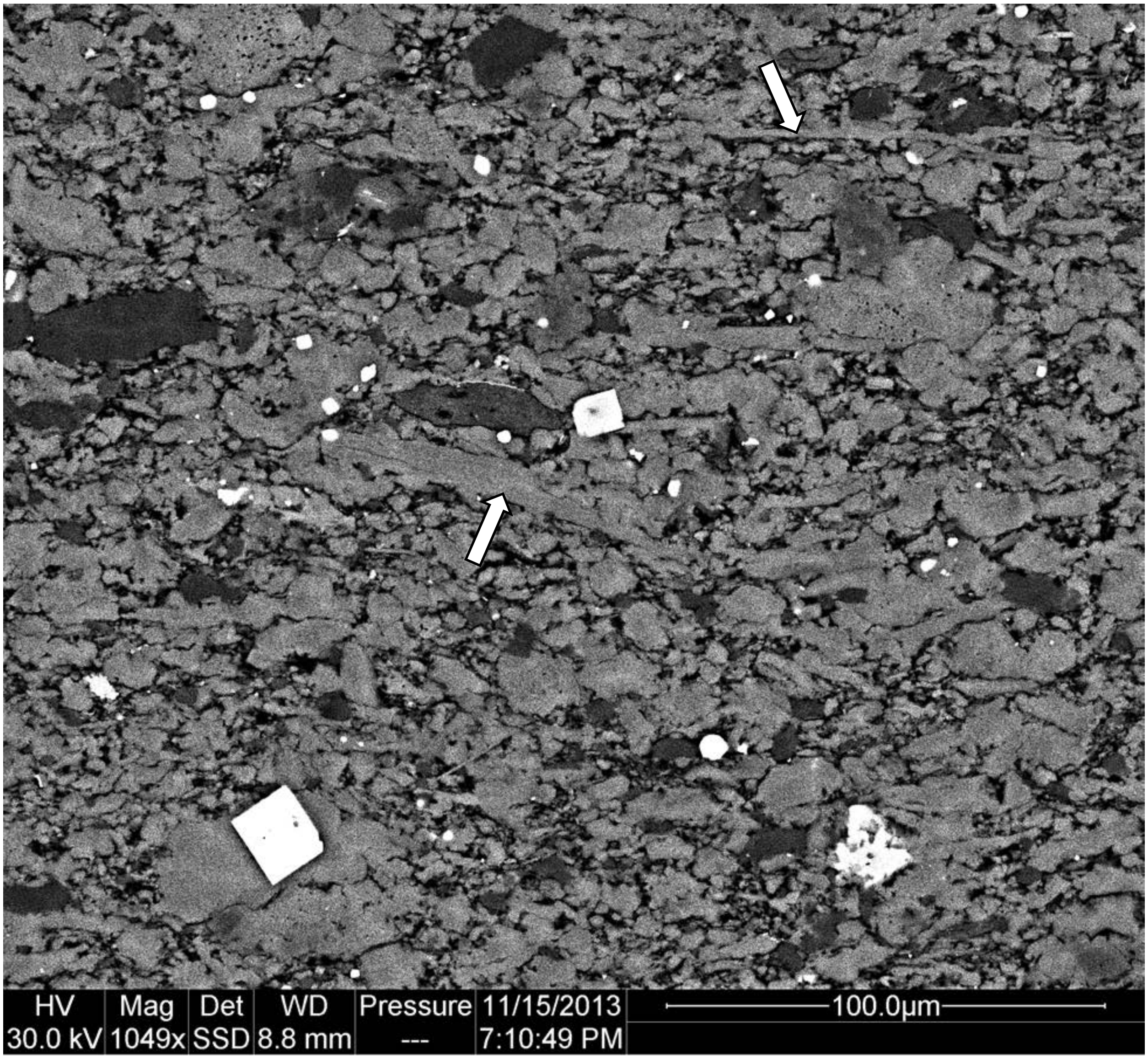


Figure 2: Shale fabric at higher magnification (backscatter image). The dominant color is light gray, due to calcite (this field of view suggests dominance of carbonate over terrigenous components). The dark grey blebs in the tens of micron size range are quartz grains, the clay minerals and organic matter are squeezed in the interstitial areas between larger mineral grains. White arrows point to fragments of thin fossil shells. Most likely thin shelled benthos. Very bright grains are pyrite.

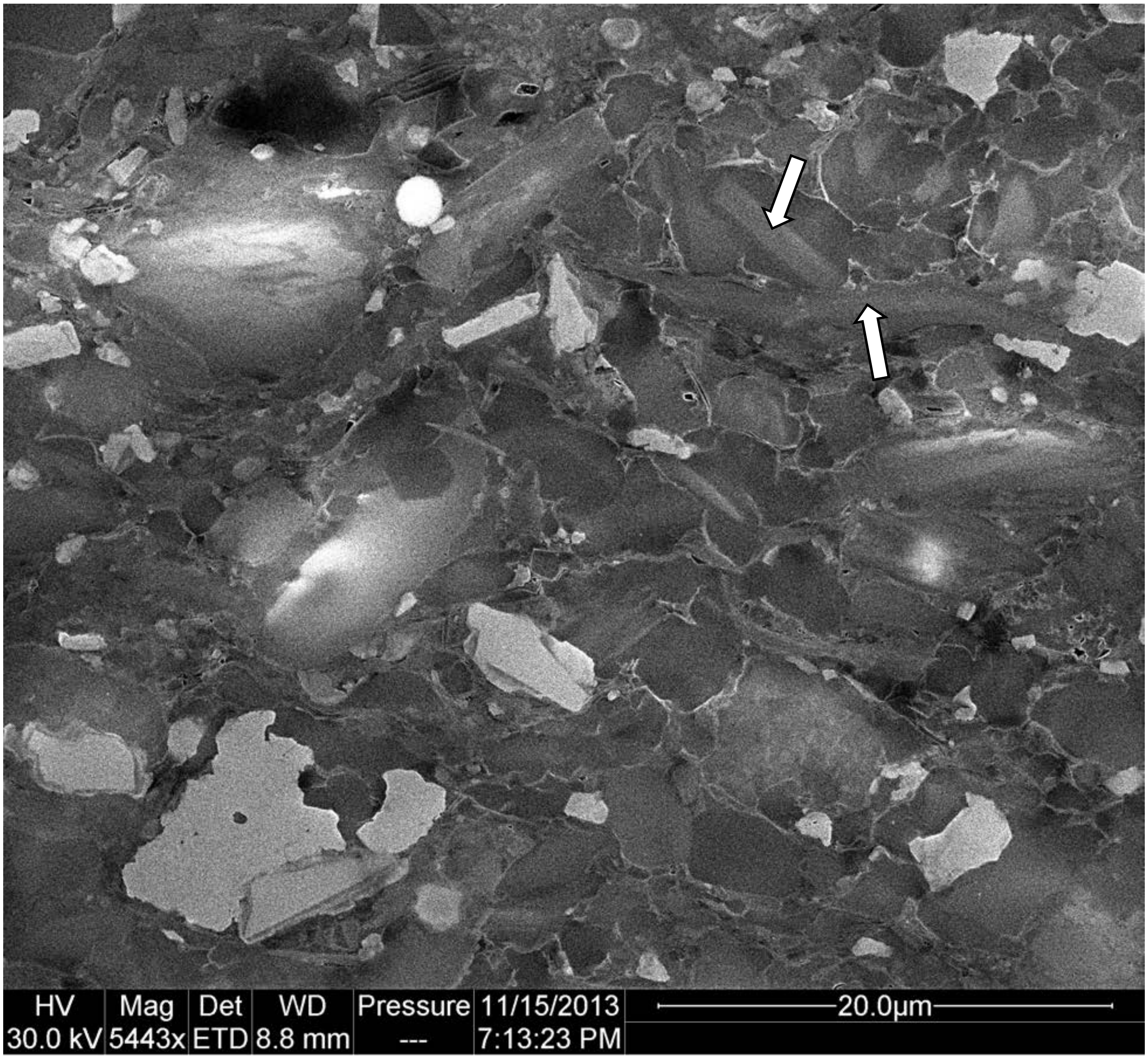


Figure 3: Shale fabric at even higher magnification (SEM mode, charge contrast image). The light gray grains are quartz (detrital with overgrowth, and also all diagenetic). Most of the medium to darker gray grains are carbonate/calcite. Some of these contain slightly lighter lath-shaped cores (white arrows) which are probably fossil debris with diagenetic overgrowth. So, its possible that there is more fossil debris in here than meets the eye in a standard thin section.

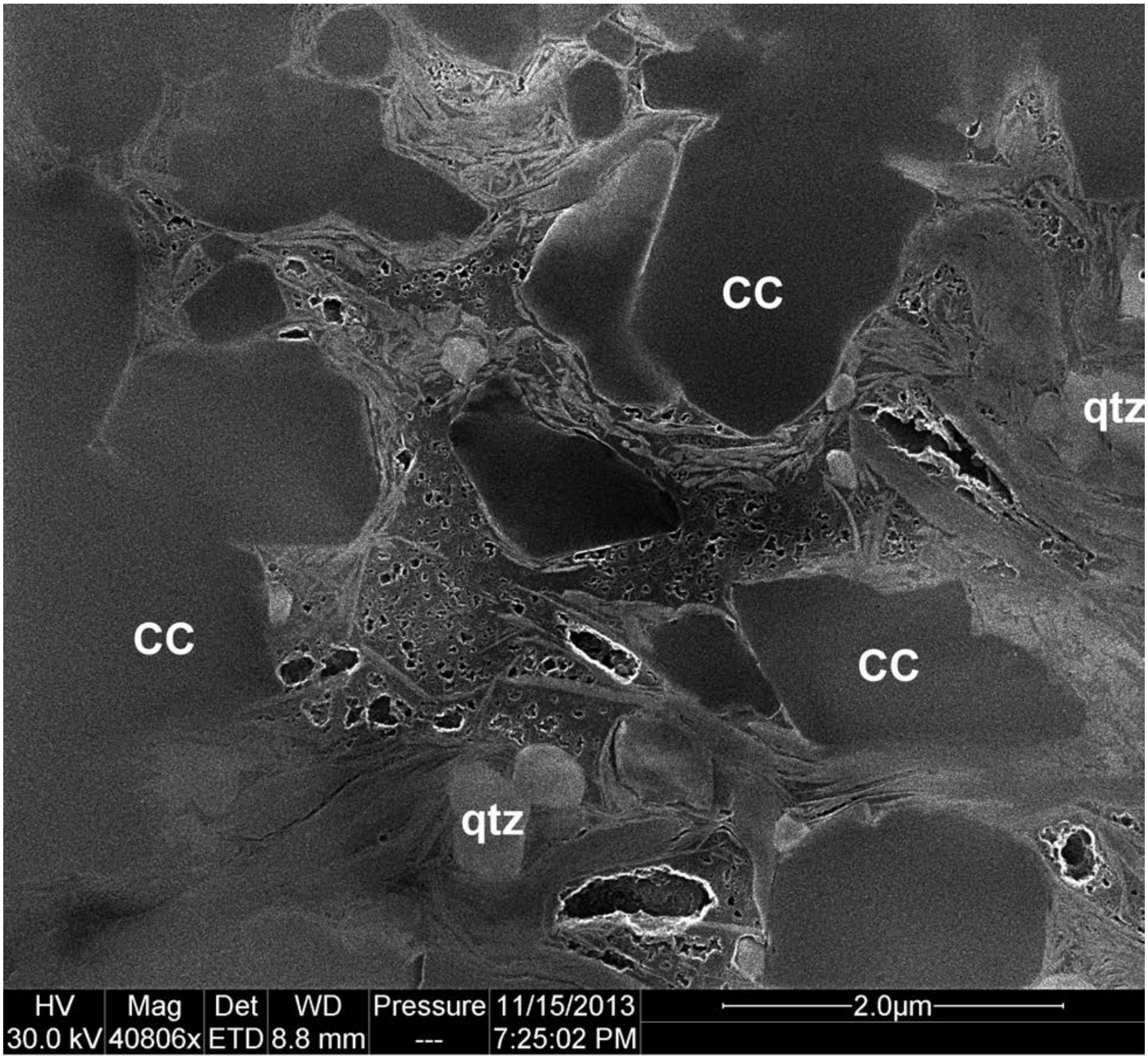


Figure 4: The interstitial OM and clays assembly looks pretty much the same as in all previous samples. The mineral grain framework is dominated by calcite (cc) grains, most of the quartz (qtz) in this view is diagenetic in origin (grew prior to clays and bitumen introduction). Large bubble pores with pore throats visible at depth (interconnectivity). The white line around the large pore openings is due to charging (low vacuum imaging, no coating). The OM porosity is definitely well developed in this, as well as in all the other samples.

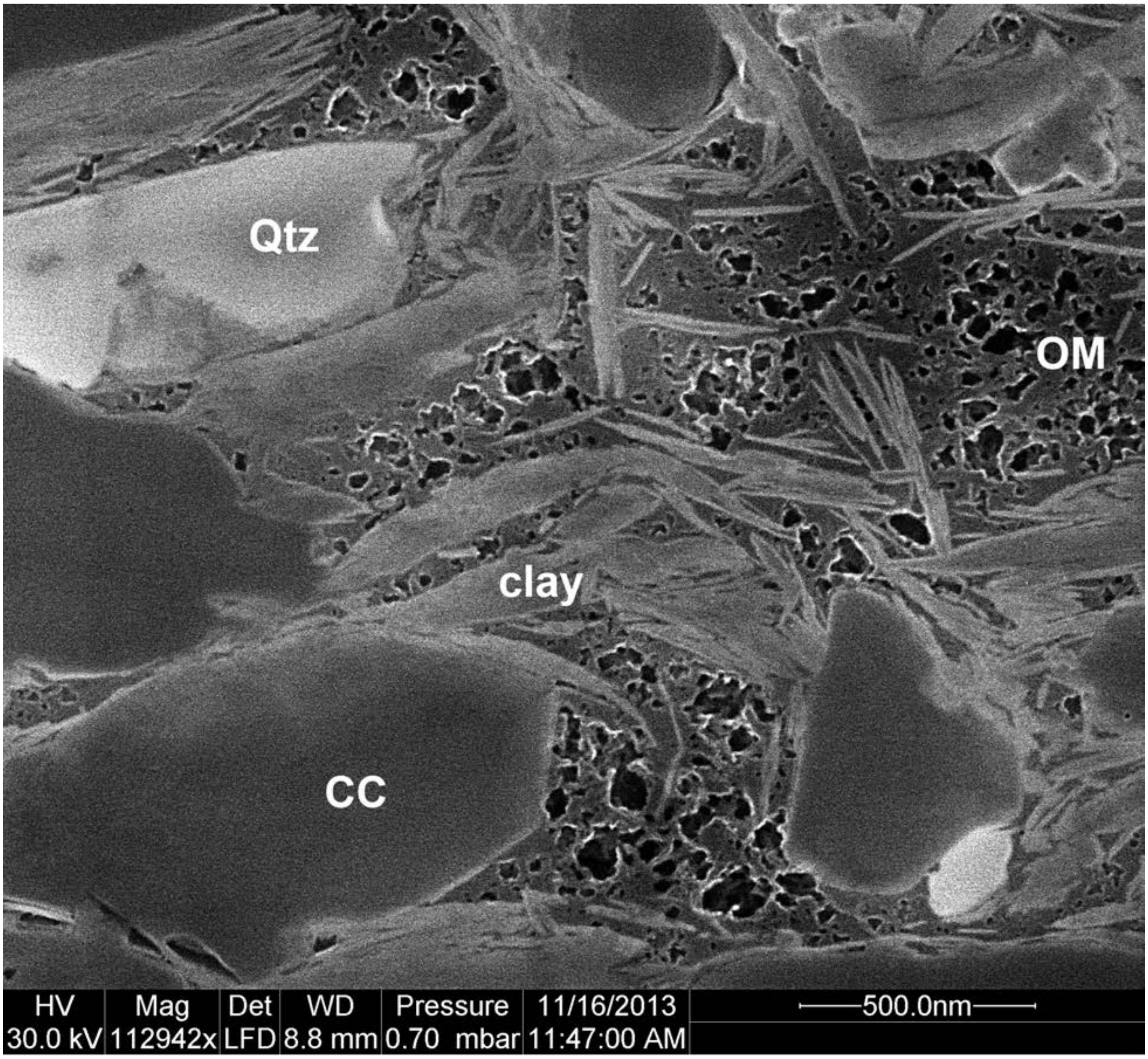


Figure 5: Detail view of the interstitial OM/clay assemblage. CC=calcite; Qtz=quartz. Shows well developed OM porosity with a mixture of larger bubble pores (connectivity/conduction) and smaller foam pores (storage).

Figure 6: The black feature in the center of the image is a piece of organic (probably plant related) debris, and is an example of structured organic matter (cross-linked etc.). Structured OM does not show visible pores, even at high levels of thermal maturity. That latter statement applies to all samples examined.

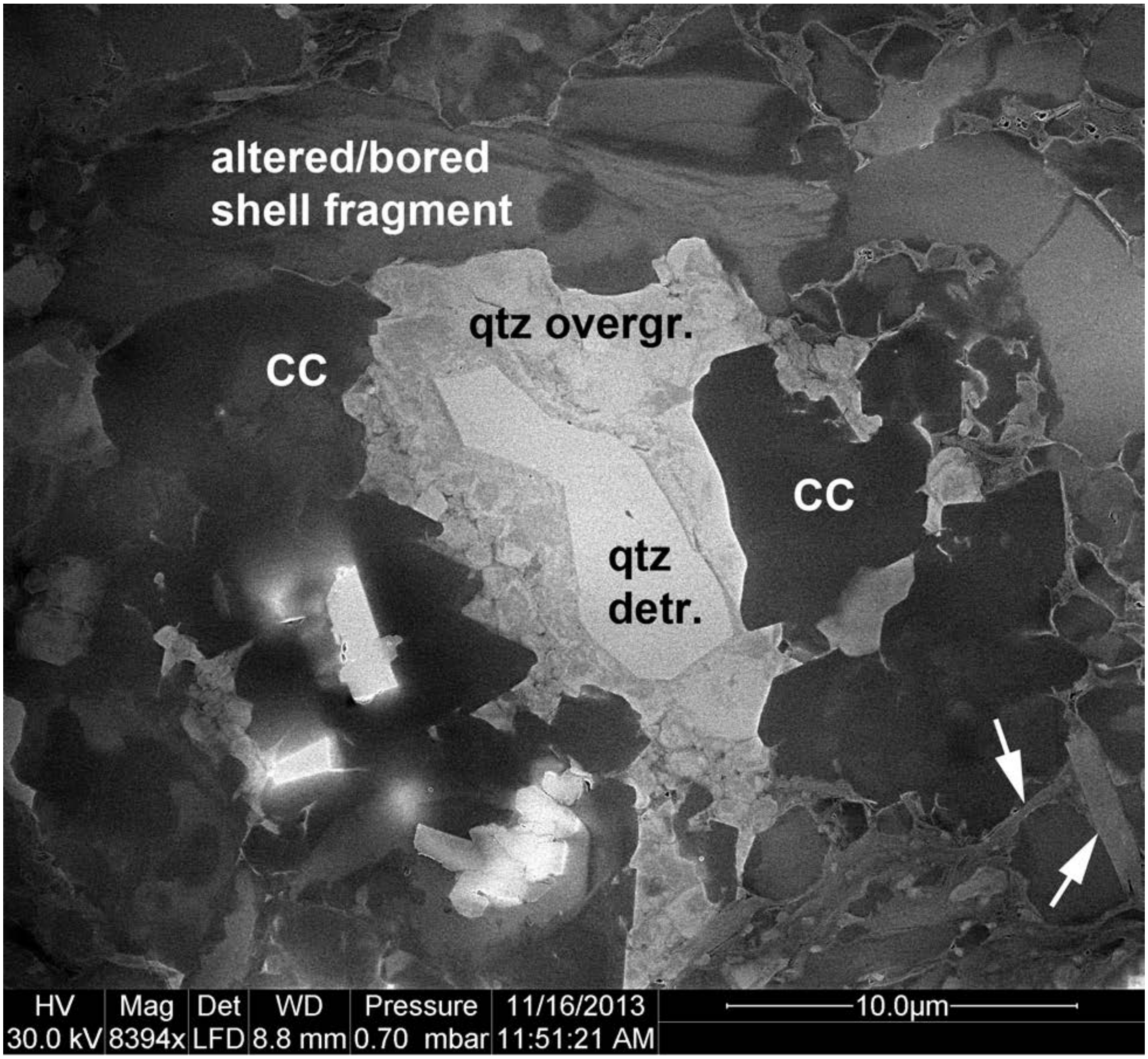


Figure 7: Detrital quartz grain in center, with a wide rim of quartz overgrowth, may have formed/grown prior to substantial compaction. Dark gray grains are typically calcite (CC). There are also fossil shell fragments (some with borings) and lath shaped mica flakes (white arrows) squeezed in between other grains. Quite heterogeneous fabric, varying from carbonate to detrital dominated over a distance of a few ten microns. Not enough diagenetic quartz to have a strong impact on overall porosity development and preservation.

So, all samples have in common a very well developed OM porosity hosted in bitumen. The majority of samples (though not this one) also have a subordinate proportion of open framework pores (between carbonate, quartz, and phyllosilicate grains). Overall the porosity looks good, even though it would help to have a larger proportion of open framework pores for better gas conduction.