Pore Structure of Opal-CT and Quartz Phase Porcelanites, Monterey Formation, California*

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Abstract

We identify and quantify significant differences in pore size, shape, and complexity between opal-CT and quartz-phase porcelanites, but also between rocks of the same silica phase with distinct silica content or sedimentary fabric using secondary and backscattered electron scanning electron microscopy of argon-ion polished or focused-ion beams' cut surfaces. Porcelanites are important reservoir rocks that demonstrate great differences in producability despite similar bulk physical characteristics. Previous studies have measured an order-of-magnitude lower permeability in opal-CT compared with quartz phase porcelanites, presumably due to difference in pore-throat size. In quartz-phase, we identify three porosity microfabrics. Silica-rich porcelanite (> 80% silica) has patchy/speckled and laminated microfabrics. The first displays low porosity matrix and high porosity lenticular patches. We measured 17-20% bulk porosity of (pore-diameter 0.05-3.00 microns). In contrast, a laminated silica-rich porcelanite (26% bulk porosity) has ~100 μm-thick layers that alternate between highly porous (35% and pore size 0.01-3.7 microns) with good interconnectivity and low porosity layers (19%) with isolated pores (0.01-0.7 microns). The massive silica-poor porcelanites have porosity of 10% with (0.02- 0.03 microns) and poor connectivity. Our range of bulk porosities for quartz-phase porcelanite (10-26%) measured by microanalysis is similar to that determined by standard methods. Opal-CT porcelanite also reveals three different microfabrics: two in high-silica (> 75%) and one low silica (< 60%). One high-silica porcelanite with 30% bulk porosity has a pervasive lepispheric fabric in which lepispheric cores and interlepisphere porosity each comprise ~ 1/2 of the total porosity (3-138 nm size). Lepisphere cores are formed of highly porous granular opal-CT, but this porosity is mostly isolated by a virtually pore-free, surrounding impermeable mantle. The larger and better-connected interlepisphere pores are formed by larger, crosscutting and radiating bladed crystals. The second silica-rich, opal-CT porcelanite is characterized by extraordinarily large and connected vuggy pores with bulk porosity of 60%. This unique pore structure is associated with silica mobility during stalled burial or tectonic uplift of the opal-CT to quartz transition zone. The last fabric is in silica-poor opal-CT porcelanite that has 18% bulk porosity with poorly connected pores (0.001-0.09 microns).

References Cited

Chaika, C., and J. Dvorkin, 2000, Porosity Reduction during Diagenesis of Diatomaceous Rocks: AAPG Bulletin, v. 84/8, p. 1173-1184.

Isaacs, C.M., 1980, Diagenesis in the Monterey Formation Examined Laterally along the Coast near Santa Barbara, California: USGS Open-File Report 80-606, 343 p.

Loucks, R.G., R.M. Reed, S.C. Ruppel, and U. Hammes, 2012, Spectrum of Pore Types and Networks in Mudrocks and a Descriptive Classification for Matrix Related Mudrock Pores: AAPG Bulletin, v. 96/6, p. 1071–1098.

Schwalbach, J.R., S.A. Gordon, C.P. O'Brien, D.F. Lockman, W.C. Benmore, and C.A. Huggins, 2007, Reservoir Characterization of Monterey Formation Siliceous Shales: Tools and Applications, *in* L. Knauer (ed.), Contributions to the Geology of the San Joaquin Basin, California: Pacific Section, AAPG Miscellaneous Publication 48, p. 119-146.

Pore structures of opal-CT and quartz phase porcelanites, Monterey Formation, California

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Objectives and Hypothesis

Objectives

- Characterize the shape, size and distribution of pores in porcelanites of different silica phases and compositions
- Assess % of porosity that is isolated and ineffective
- Develop best petrographic methods for high-resolution, high-quality imaging

Hypothesis

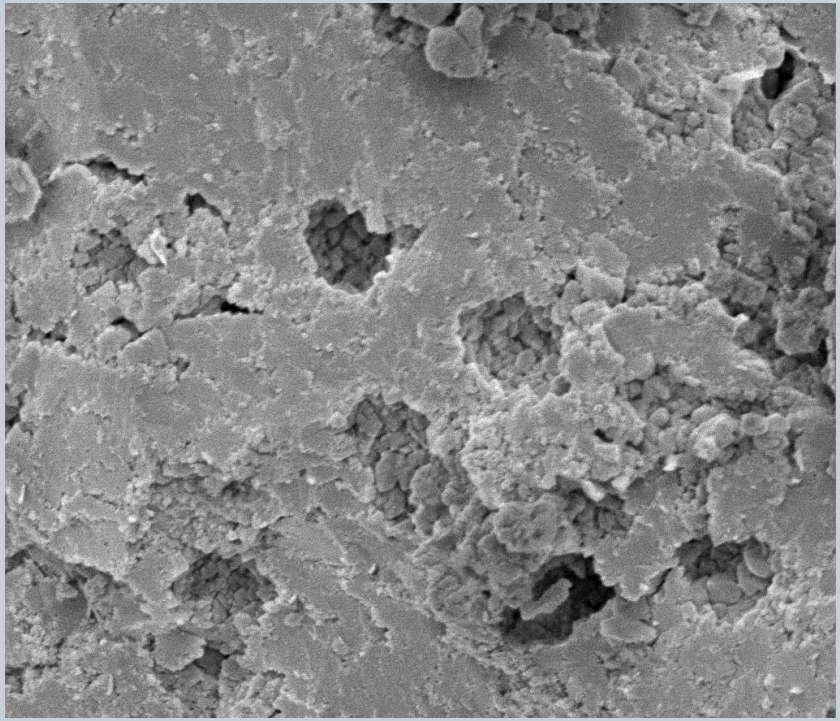
- Variable of permeability between silica phases indicated by mercury injection capillary pressure may be due:
  - Pore-throat size distribution (Schwalbach et al., 2007)
  - The pore-structure (size, shape and connectivity)

Materials and Methodology

- Silica phase and mineralogy
  - X-ray diffraction (XRD)
- Chemical composition
  - Energy Dispersive X-Ray Spectroscopy (EDS)
  - X-Ray Fluorescence Spectroscopy (XRF)
- Imaging
  - Scanning Electron Microscope (SEM)
    - Secondary Electron Imaging
    - Backscattered Electron Imaging
- Cross-section polishing
  - MultiBeam Focused Ion Beam micro milling (FIB-SEM)
  - Cross Section Polisher-Argon Ion milling (CP)
- Image processing and analysis
  - ImageJ and Photoshop

Surface Preparation Assessment

- Traditional broken surface SEM poor for quantitative analysis

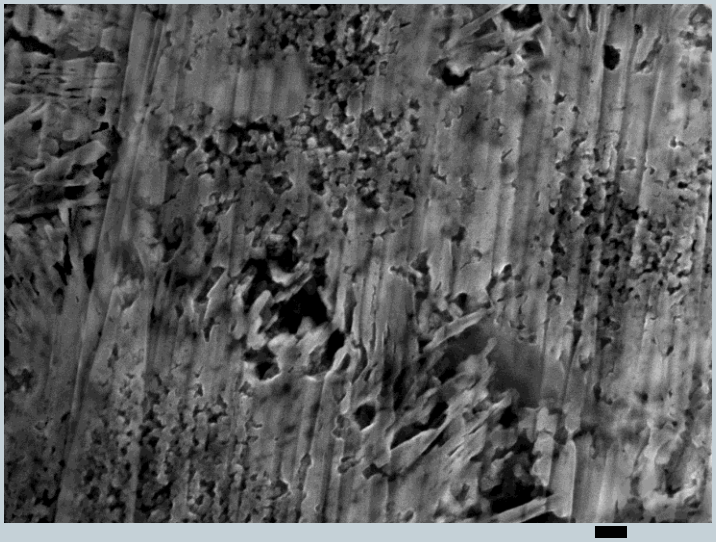


5 μm

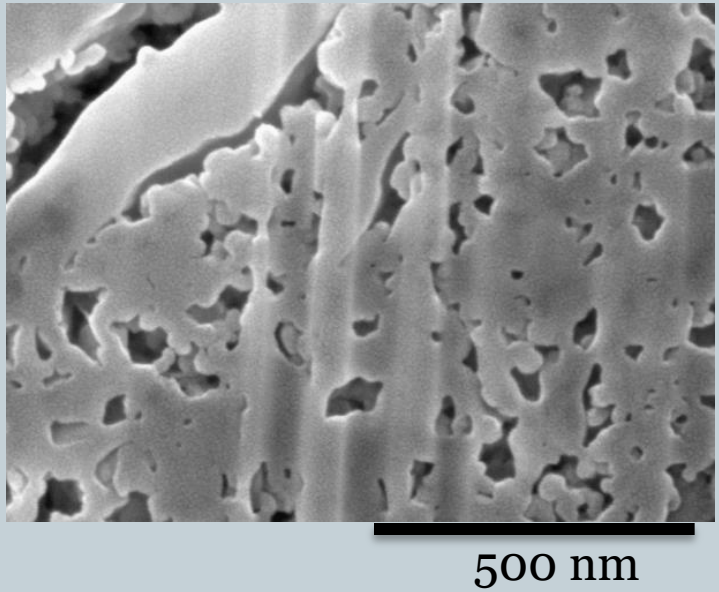
Surface Preparation Assessment
Focused Ion Beam (FIB) System

- A Focused Ion Beam (FIB) System:
  - Good data for specific area
    - Curtain effect due to uneven topography & density variation
  - Small area without spatial context

JIB-4500 Multi-Beam FIB-SEM FEI



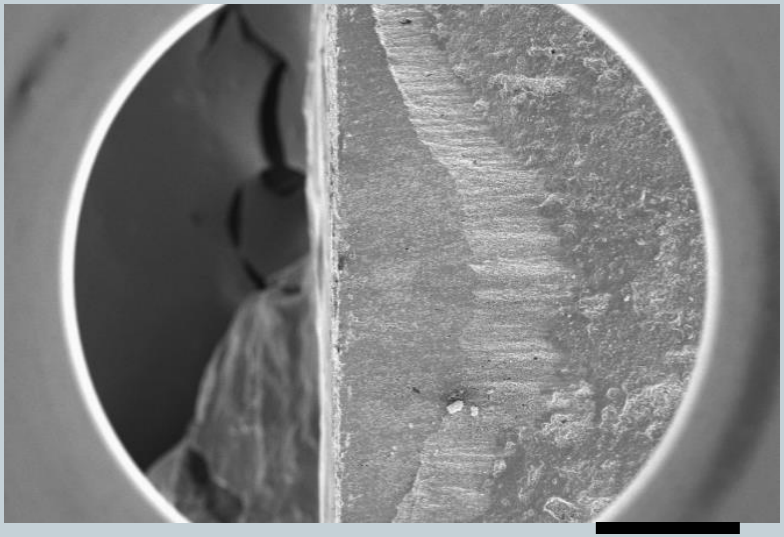
Quanta 3D FEG Dual-Beam FIB-SEM

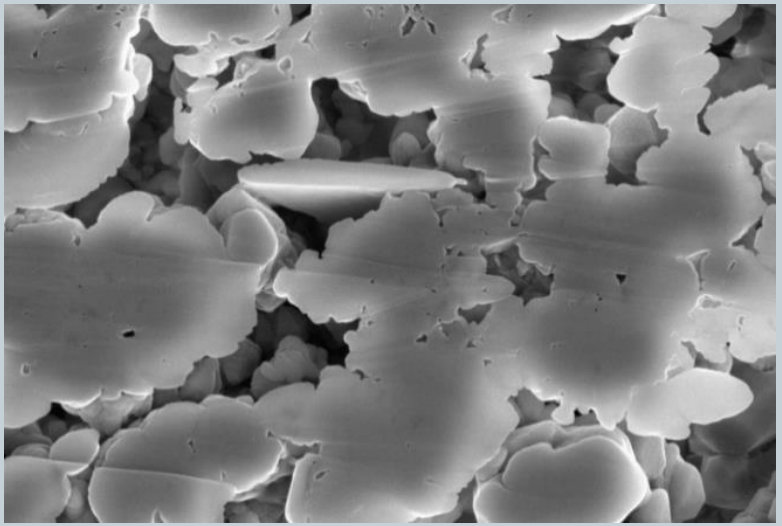


Cross-section Polisher

- An argon ion mill cross-section polisher
  - Large (mm-scale) representative x-section free from artifacts and distortion providing good spatial context

JEOL CP





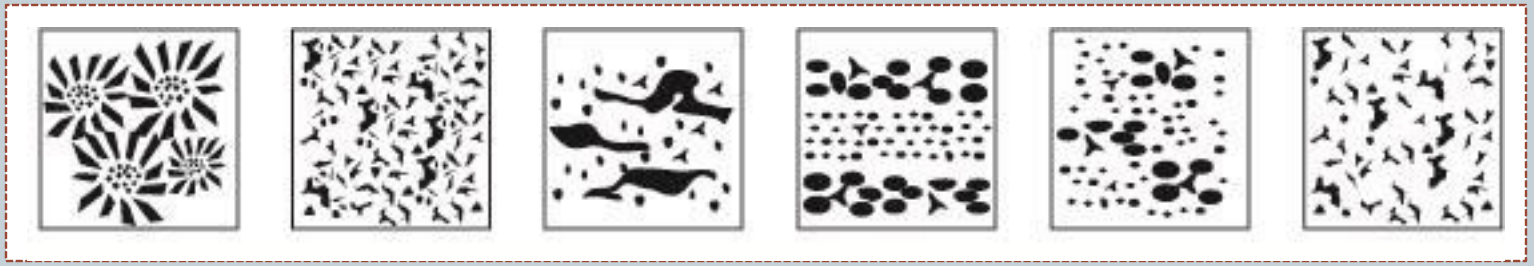
Types of porosity

Porosity microstructure varies with lithology

- Opal-CT phase porcelanites
  - Silica-rich opal-CT porcelanite (Lepispheric with three layers)
  - Transition-zone silica-rich opal-CT porcelanite
  - Silica-poor opal-CT porcelanite
- Quartz phase porcelanites
  - Silica-rich quartz porcelanite (laminated)
    - Highly porous and interconnected
    - Low porosity with poor connectivity
  - Silica-rich quartz porcelanite
    - Patchy to indistinct laminations of detritus
    - Heterogeneous microstructure and porosity
  - Silica-poor quartz porcelanite
    - Moderate porosity with poor connectivity

Types of porosity

Microstructure porosity by lithology



Opal-CT Silica-rich | Opal-CT Silica-poor | Opal-CT Silica-rich Transition-zone | Quartz Silica-rich | Quartz Silica-rich | Quartz Silica-poor

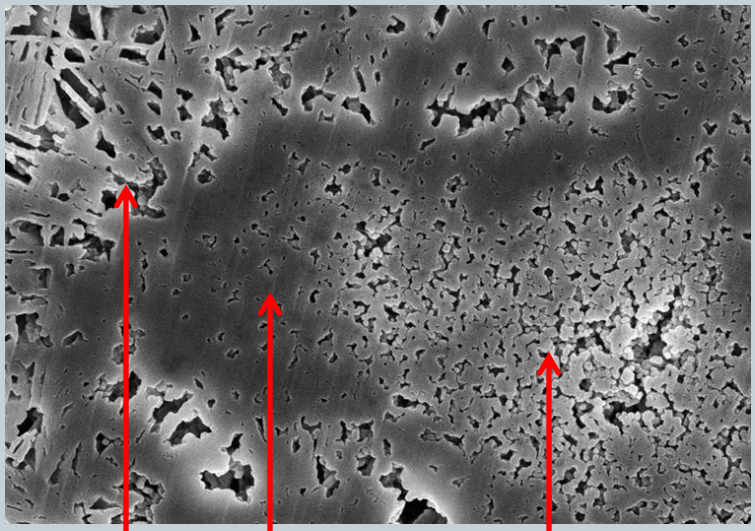
We recognized two types of pore size:

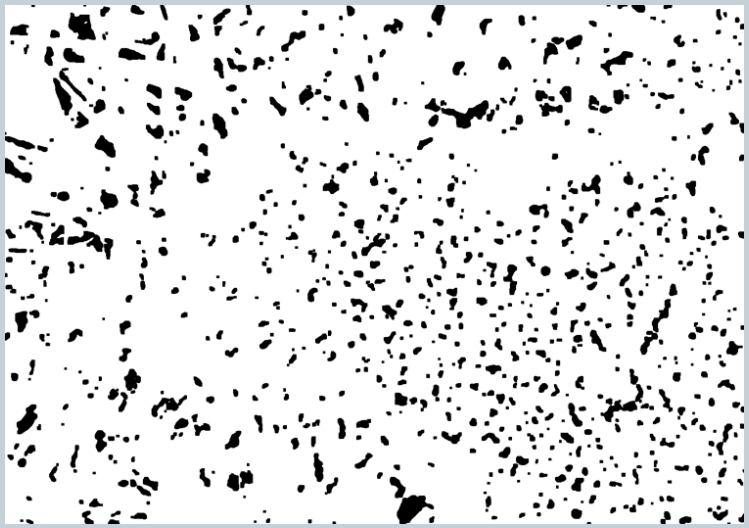
Nanopores	≤1 nm and < 1 μm
Micropores	≤ 1 μm and < 62.5 μm

Loucks et al. (2012) classification is used in this study.

1. Opal-CT Porcelanite
1.a. Silica-rich

- Lepisheres with three distinct layers of pore structure





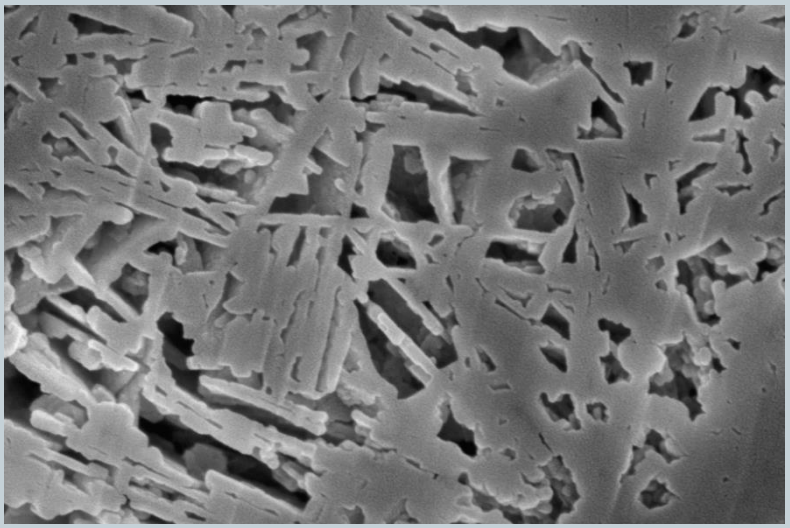
Interlepisphere

Core

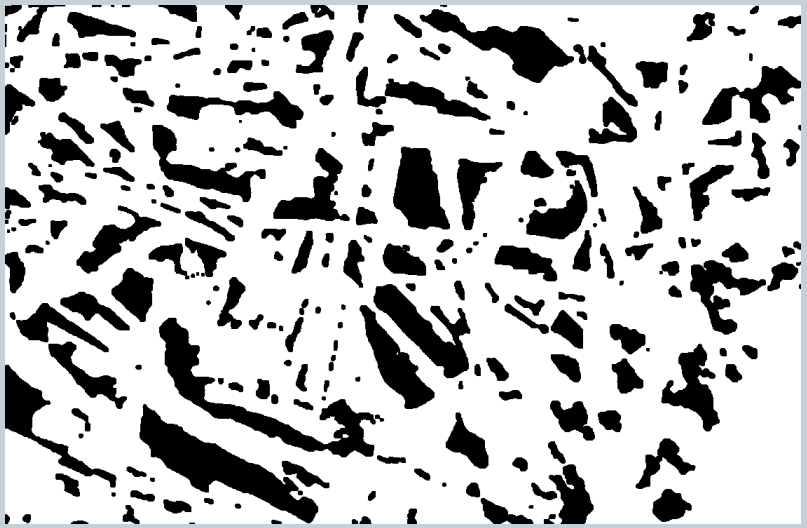
Mantle: Impermeable layer isolating the core

Interlepisphere porosity

- Very porous, nanopores
- Bladed and elongated



500 nm

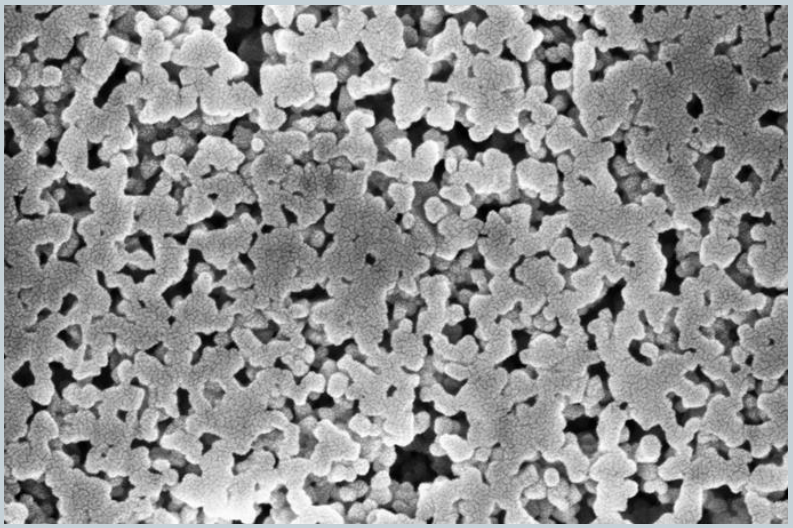


500 nm

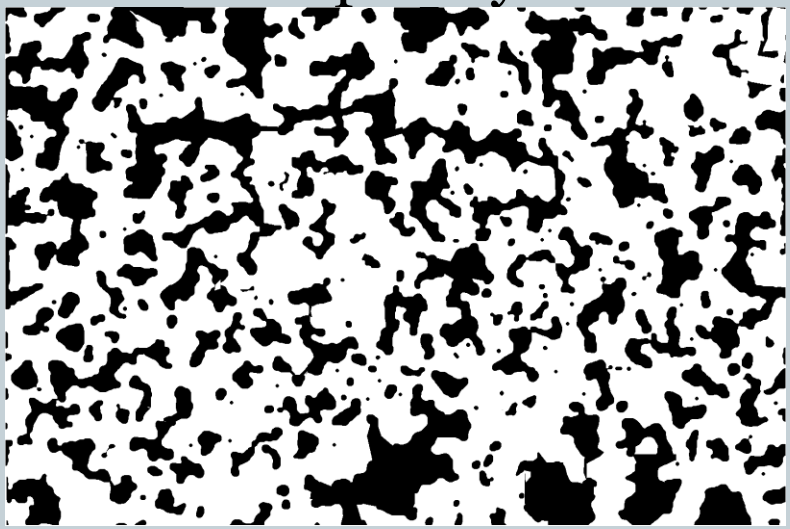
Pore Area %	AR-Aspect Ratio	Roundness
25.19	1.53	0.65

Lepisphere core porosity

- Highly porous, nanopores
- Granular and connected, but…almost completely isolated



500 nm

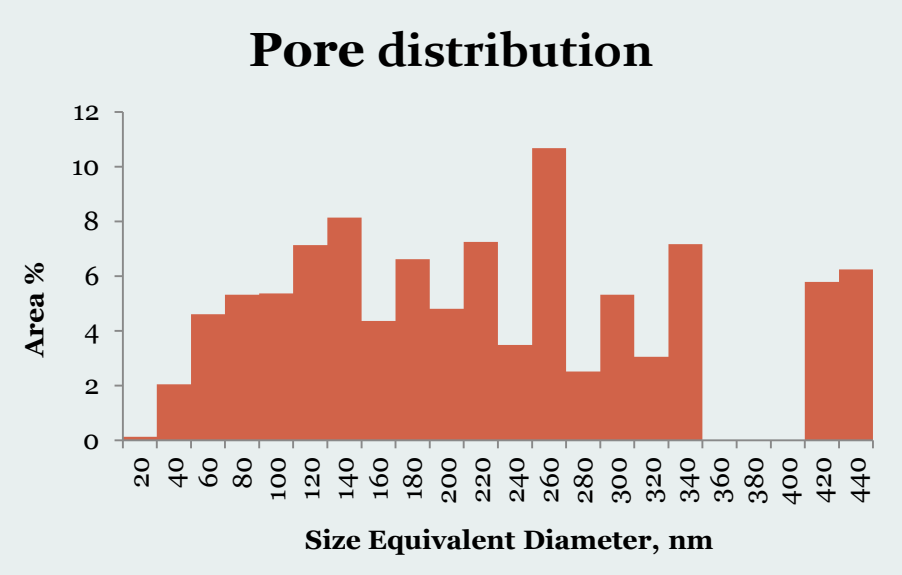


500 nm

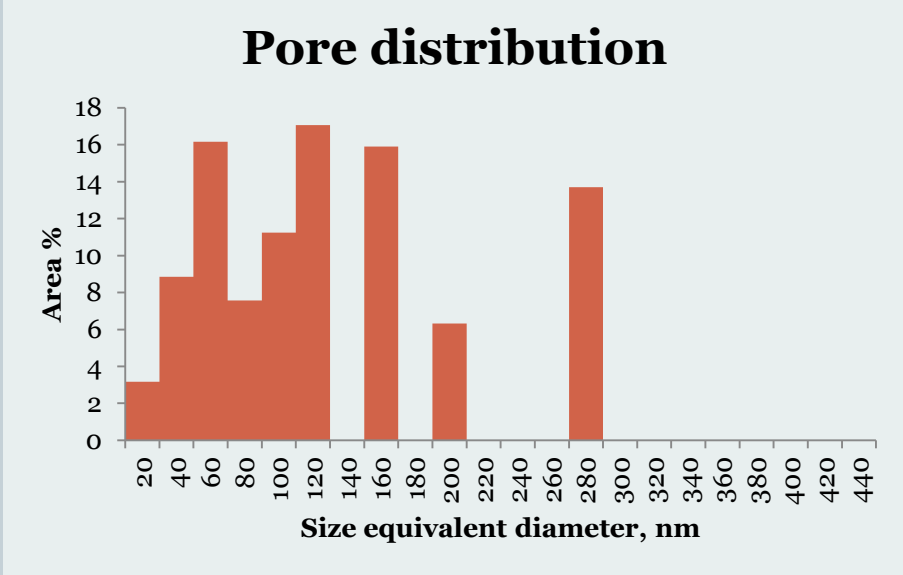
Pore Area %	AR-Aspect Ratio	Roundness
34.38	1.49	0.66

Pore distribution

Interlepisphere

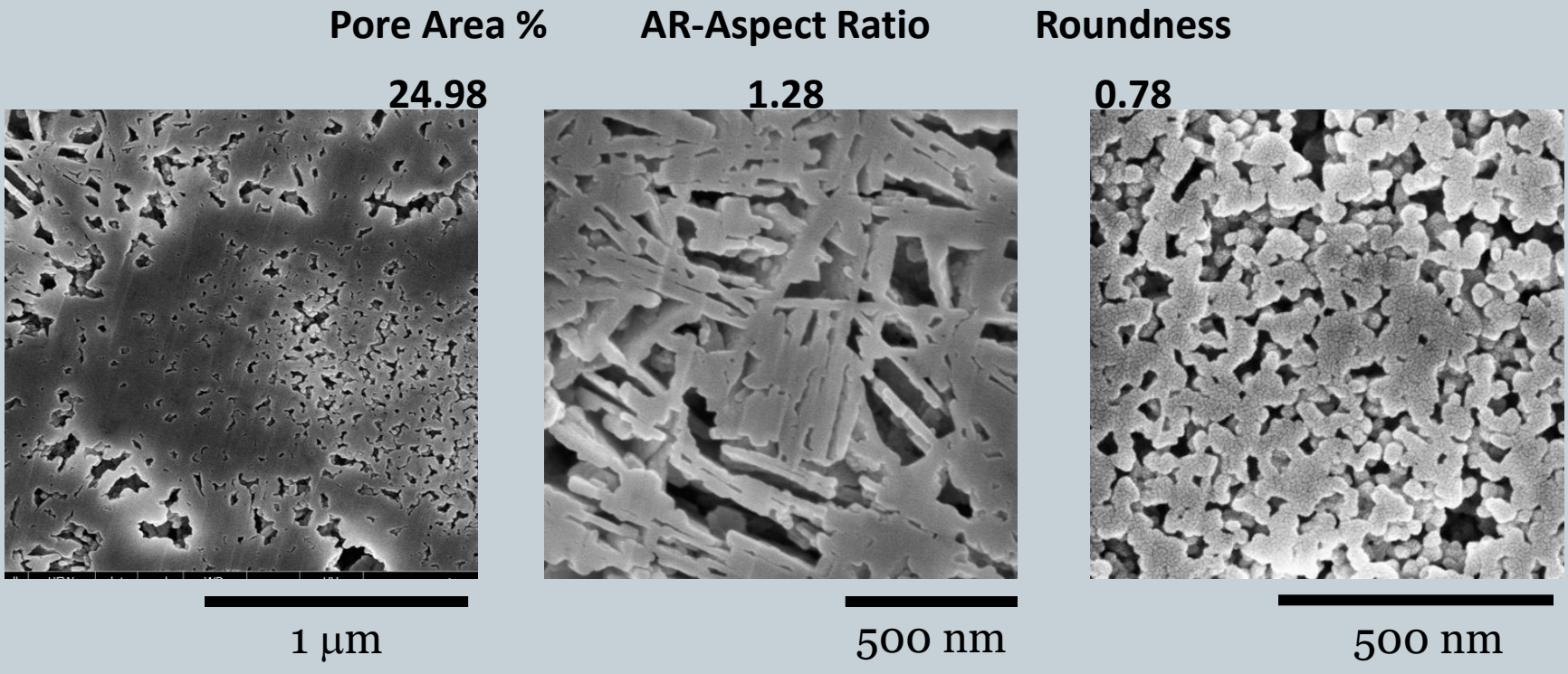


Core of the lepisphere

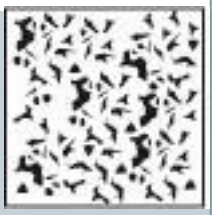


Lepisphere pore structure

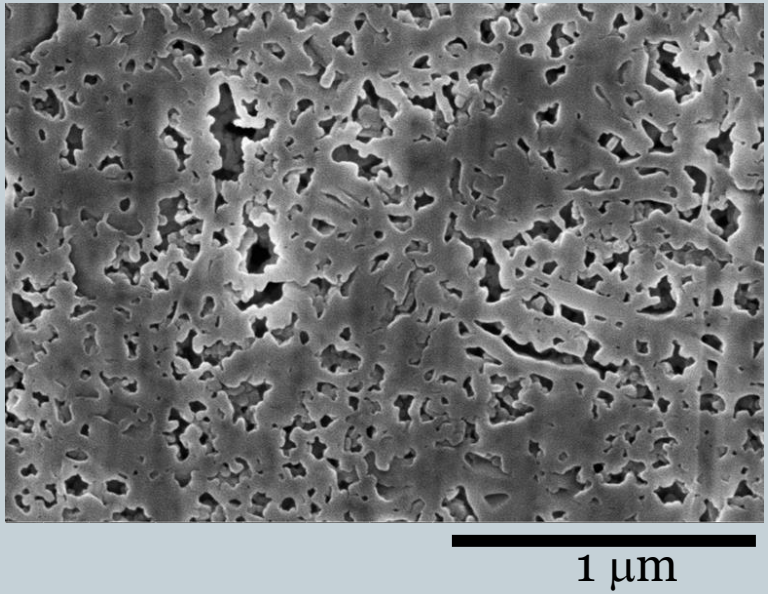
- Consists of lepispheres with three layers
  - Core: highly porous and connected; nanopores (3-280 nm).
  - Mantle: virtually impermeable
    - Resulting in isolation of cores—ineffective porosity.
  - Interlepisphere: Very porous; nanopores (10-440 nm)

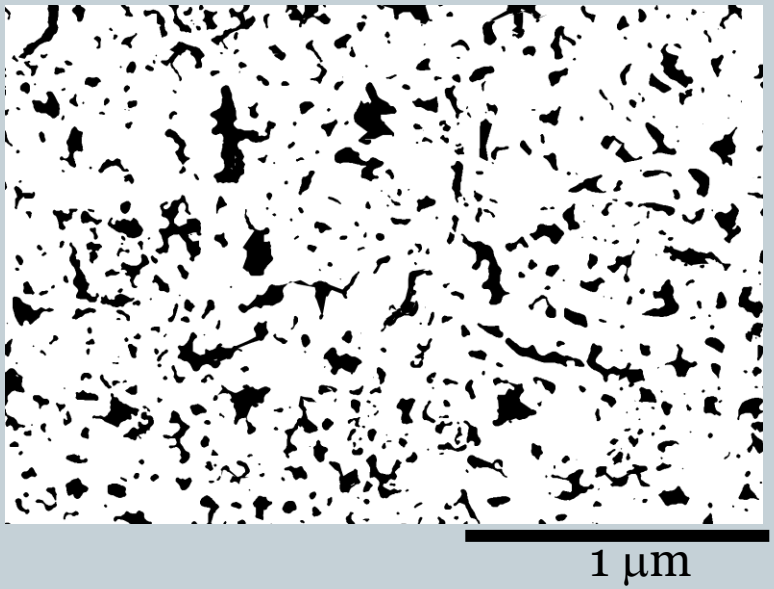


1. b. Silica-poor opal-CT



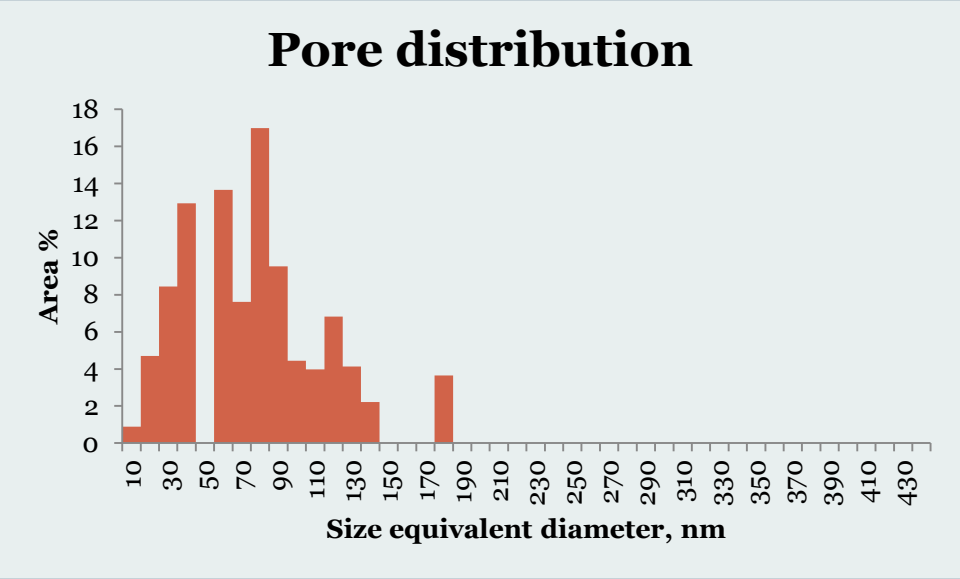
- Nanopores (3-180 nm)
- Low porosity, small size with poor connectivity

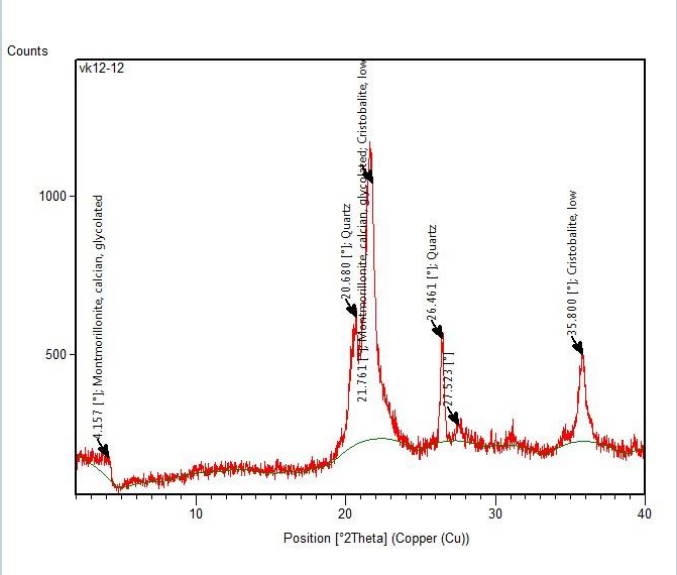




Pore distribution

Silica-poor opal-CT porcelanite

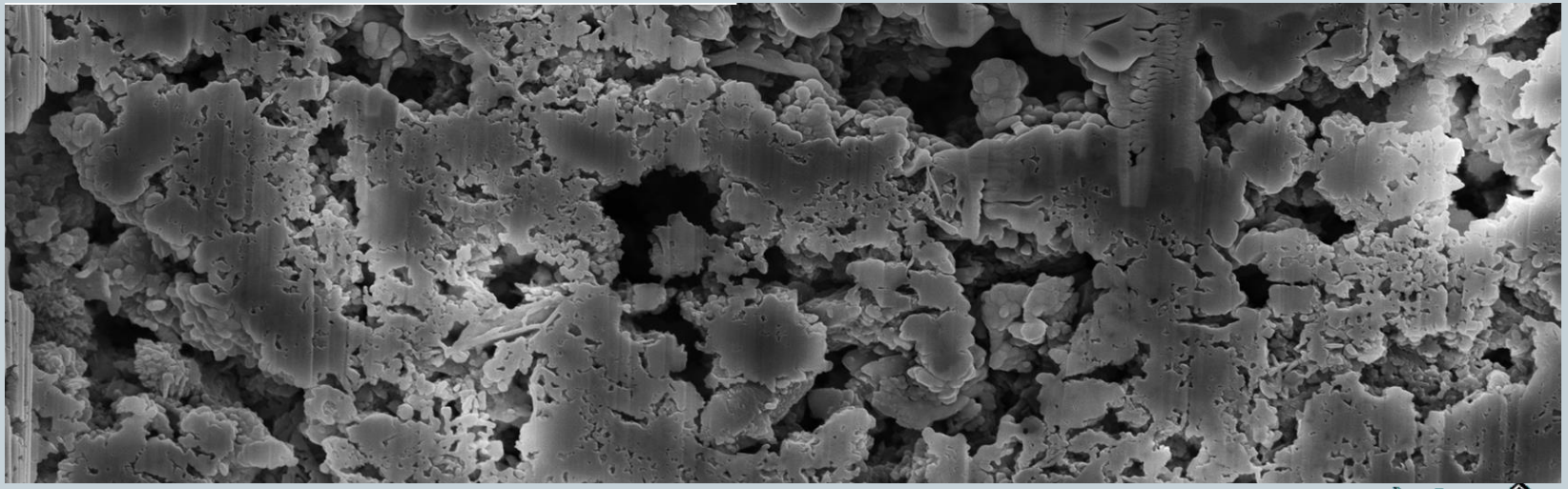




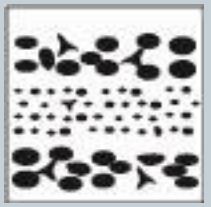
Pore Area %	AR-Aspect Ratio	Roundness
18.82	1.48	0.67

1. c. Transition-zone opal-CT

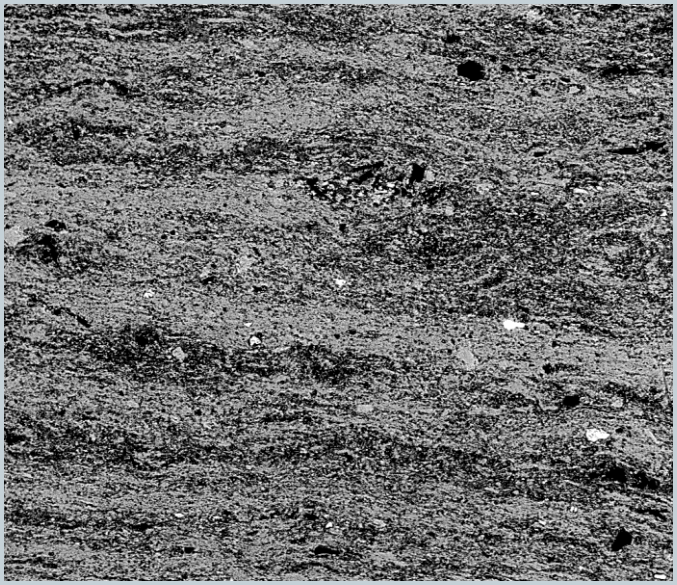
- Porcelanite with porosity as high as common diatomites (~65%)
  - Large, interconnected vuggy pores.
    - Associated with <u>dissolution</u> related to late quartz chert formation at cessation of burial



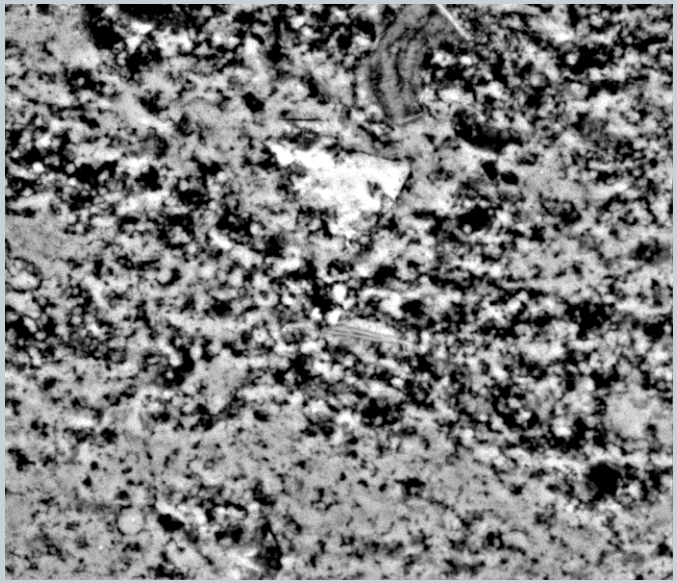
2. Quartz phase porcelanites
2. a Silica-rich (Laminated)



- Laminated bed: ~100 µm-thick laminations
- Laminations are defined by marked difference in porosity.
- Heterogeneous with layered porosity
  - Backscattered image of epoxy impregnated porcelanite



400 µm

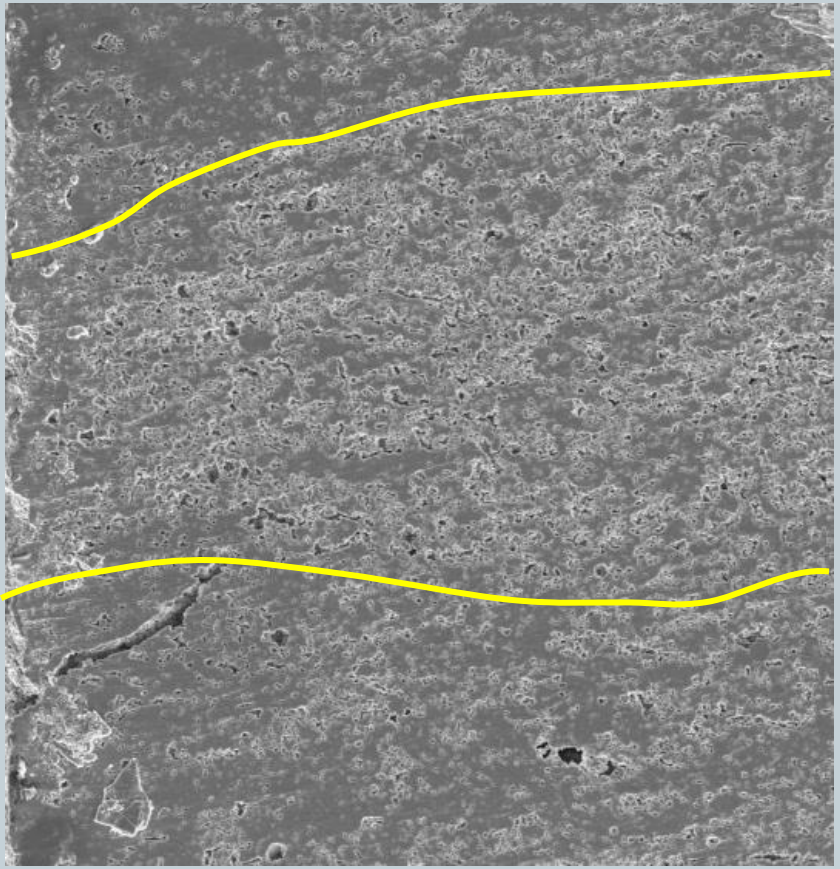


20 µm

Silica-rich (Laminated)

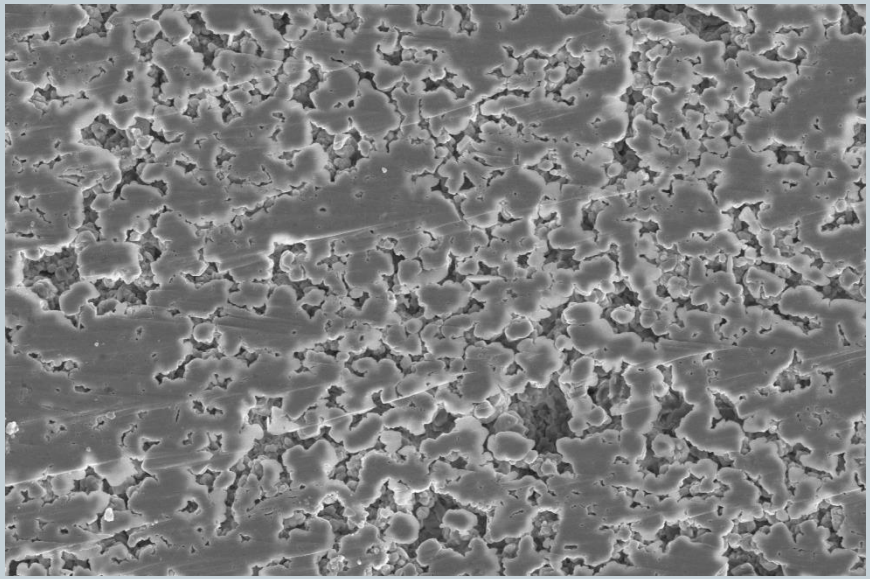
SEM image

- Low porosity with less interconnection
- Highly porous and interconnected
- Low porosity with less interconnection

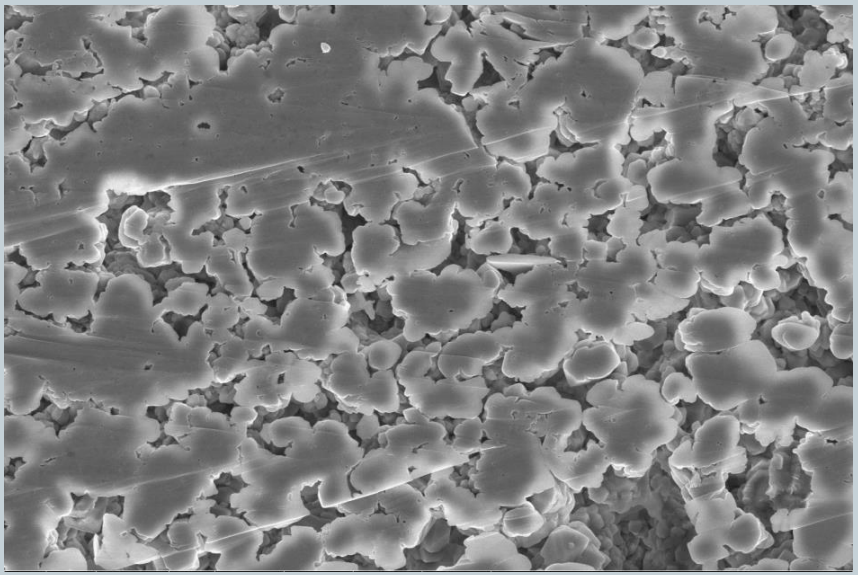


Silica-rich (Laminated)

- Highly porous and interconnected



20 μm

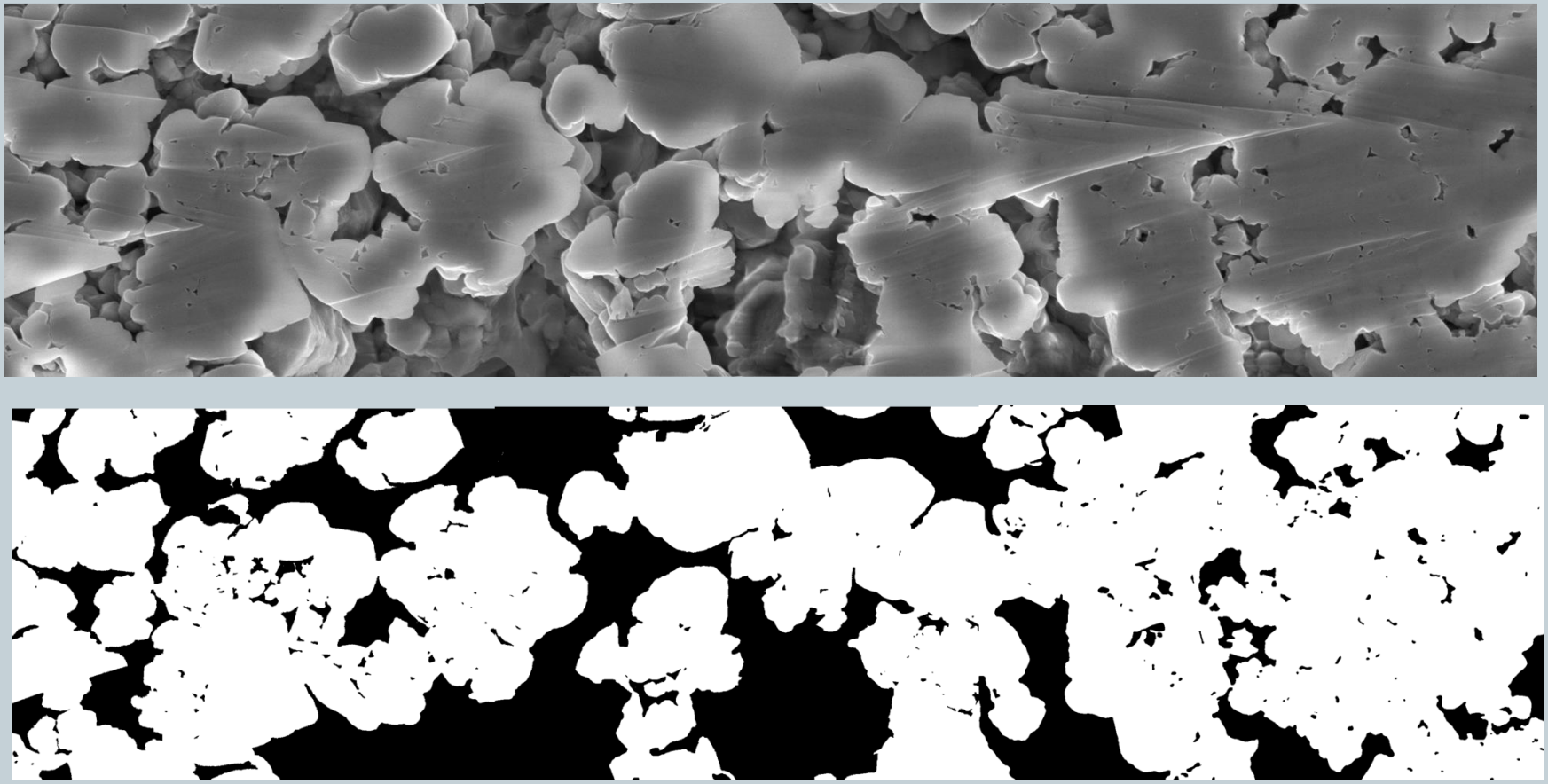


10 μm

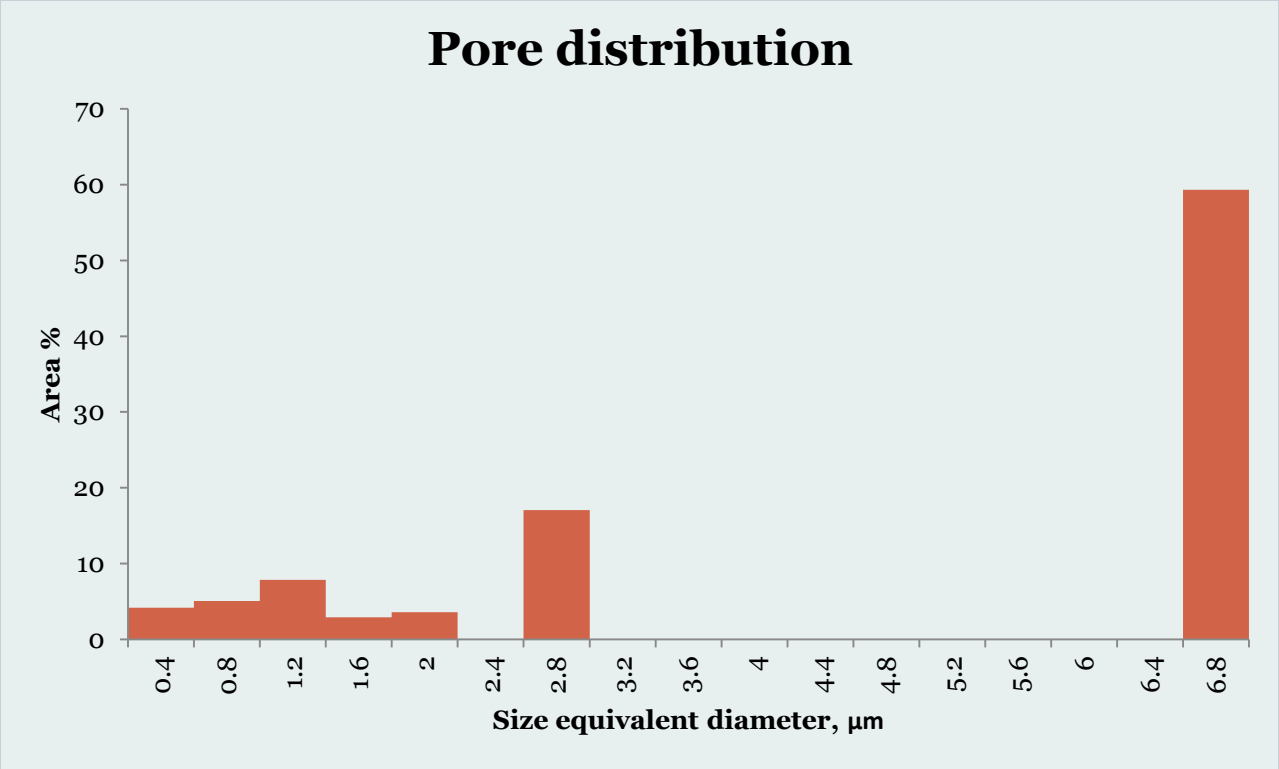
Silica-rich (Laminated)

An argon ion mill cross-section polished

- Extremely large and highly connected pores (Micropores)



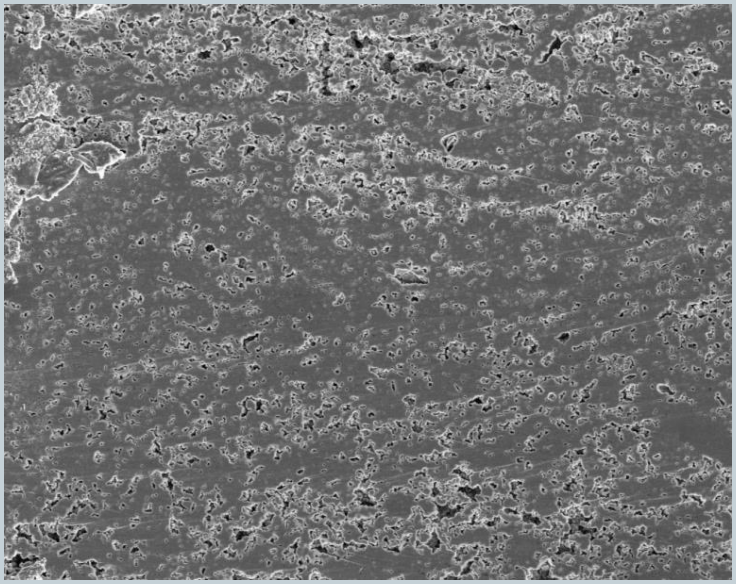
Pore distribution



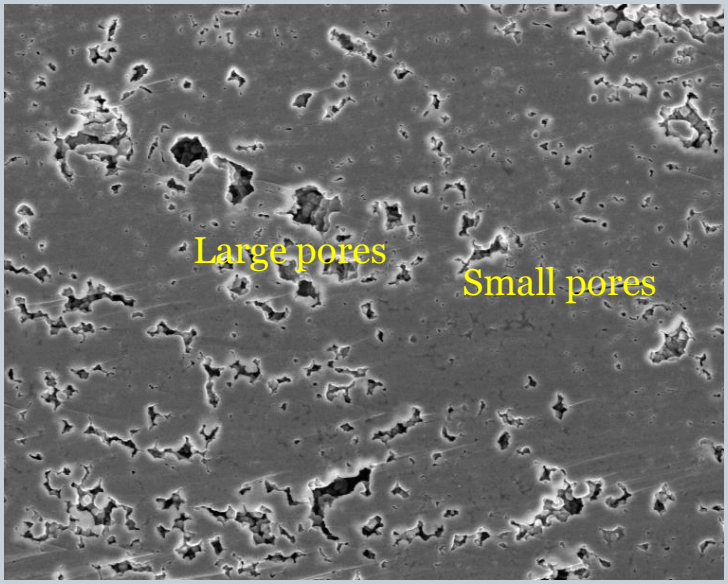
Pore Area %	AR-Aspect Ratio	Roundness
28.50	3.00	0.33

Silica-rich (Laminated)

- Low porosity with less interconnection



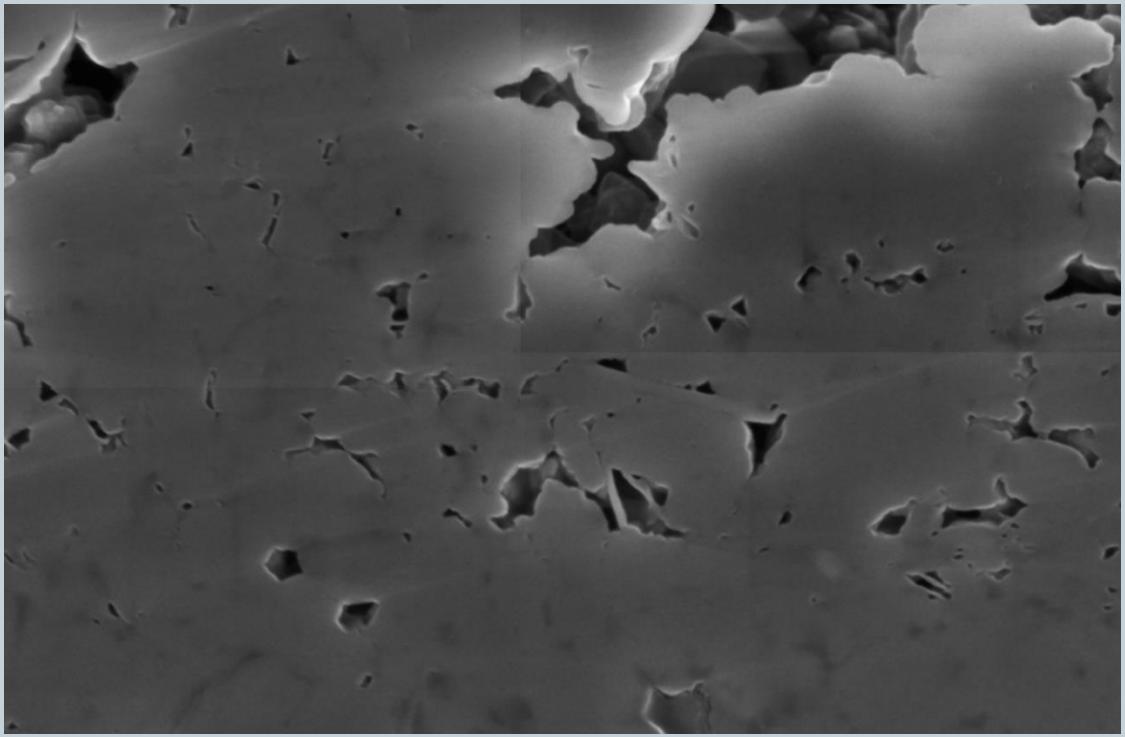
50 μm



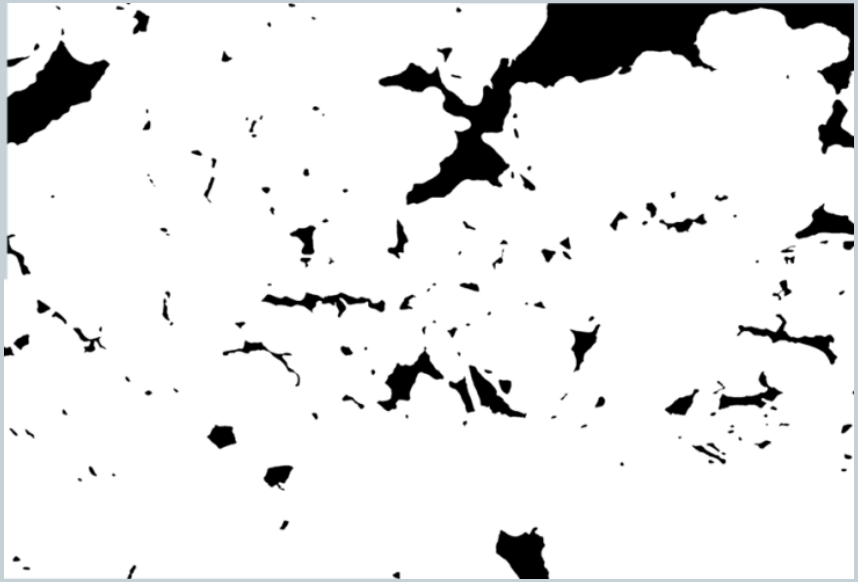
20 μm

Silica-rich (Laminated)

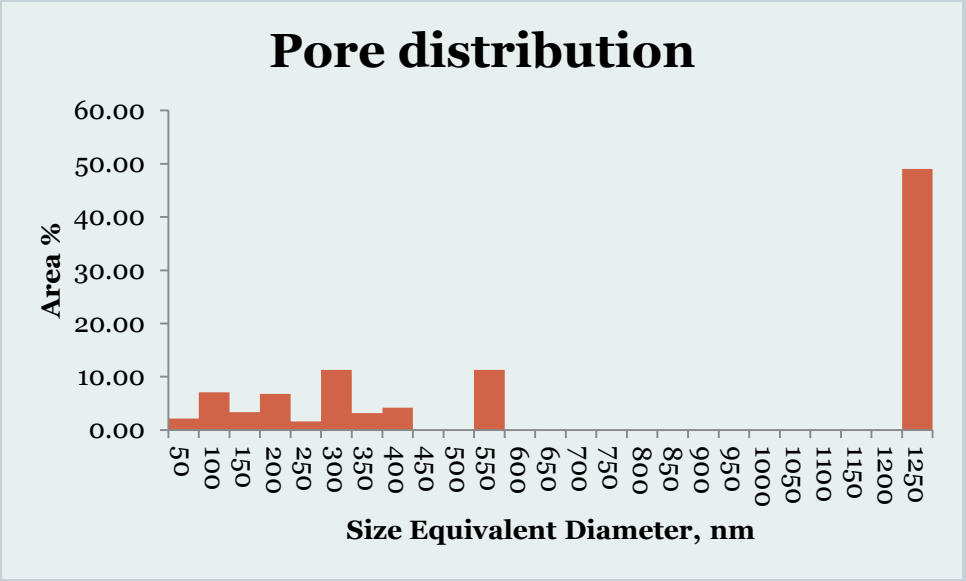
- Small pores- nanopores (3-600 nm)
- Low porosity and poor interconnection



Pore distribution



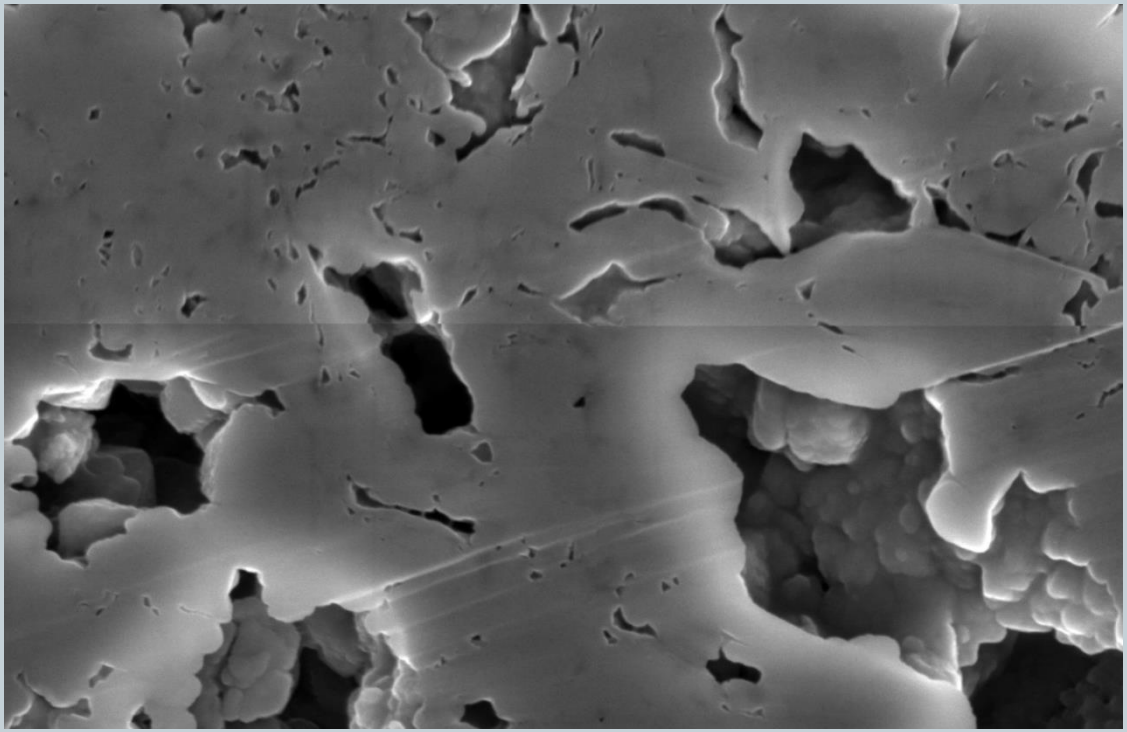
1 μm



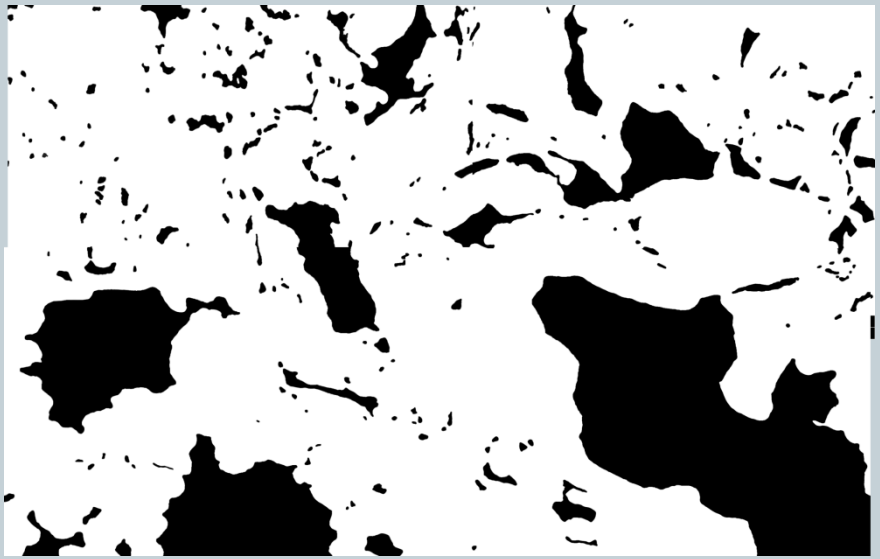
Pore Area %	AR-Aspect Ratio	Roundness
8.89	1.526	0.655

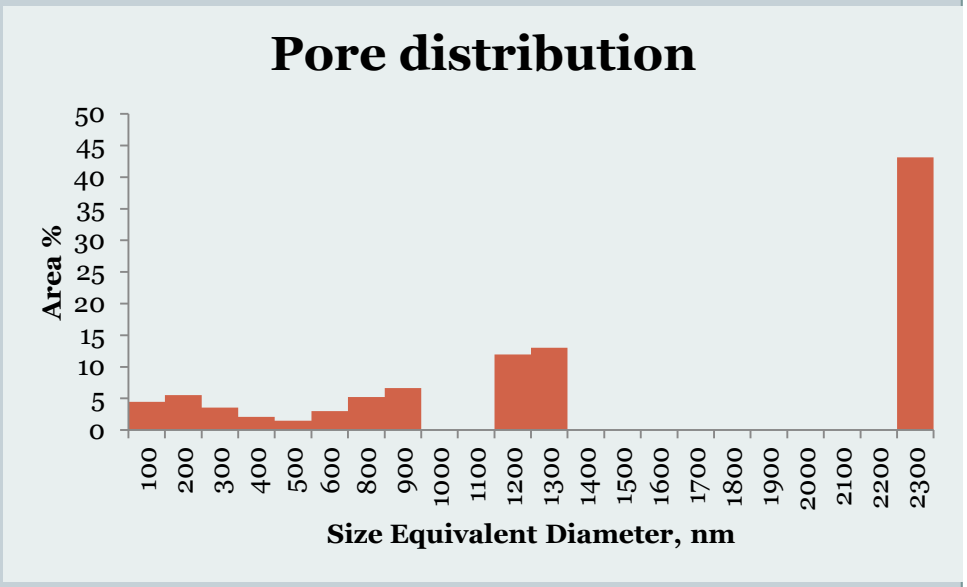
Silica-rich (Laminated)

- Large pores - nanopores to micropores
- Moderate porosity and poor interconnection



Pore distribution

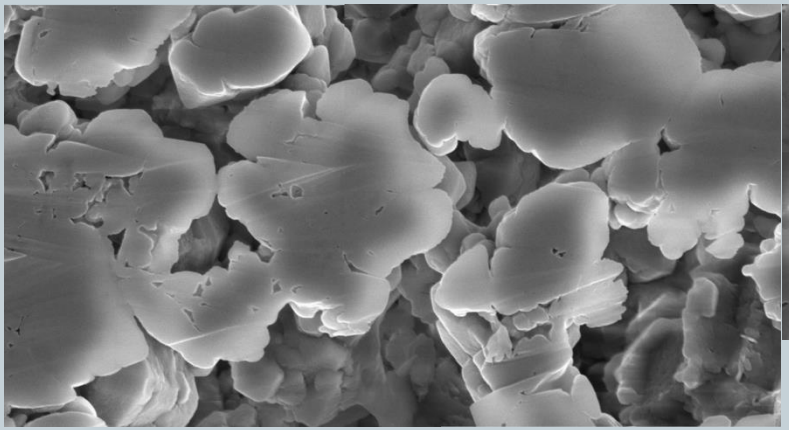


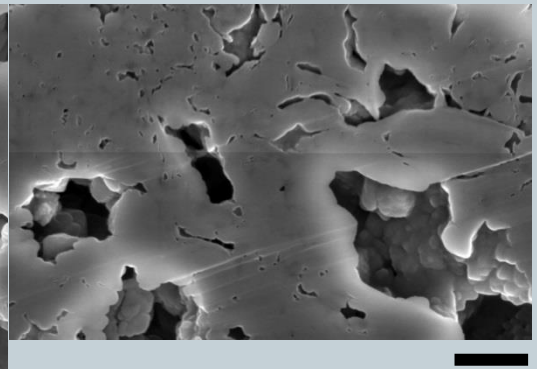


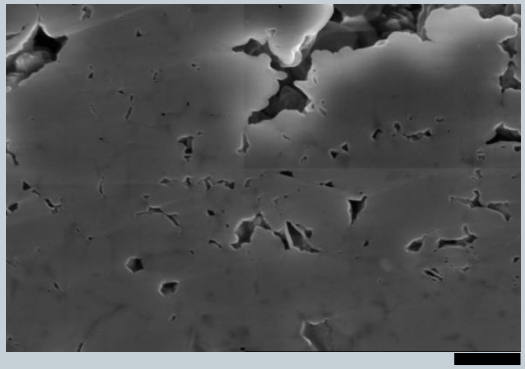
Pore Area %	AR-Aspect Ratio	Roundness
24.82	1.781	0.562

Silica-rich (Laminated)

- > 80% Silica and bulk porosity 19.86%
- Heterogeneous porosity between laminations
- Relatively consistent porosity along laminations that differ by being:
  - Highly porous with well interconnected Micropores
  - Low to moderately porous with irregular distribution of isolated Micro to nanopores (3-2300 nm)



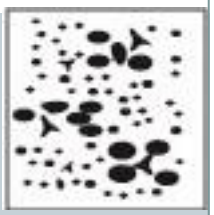




2. b. Silica-rich quartz phase (Massive)

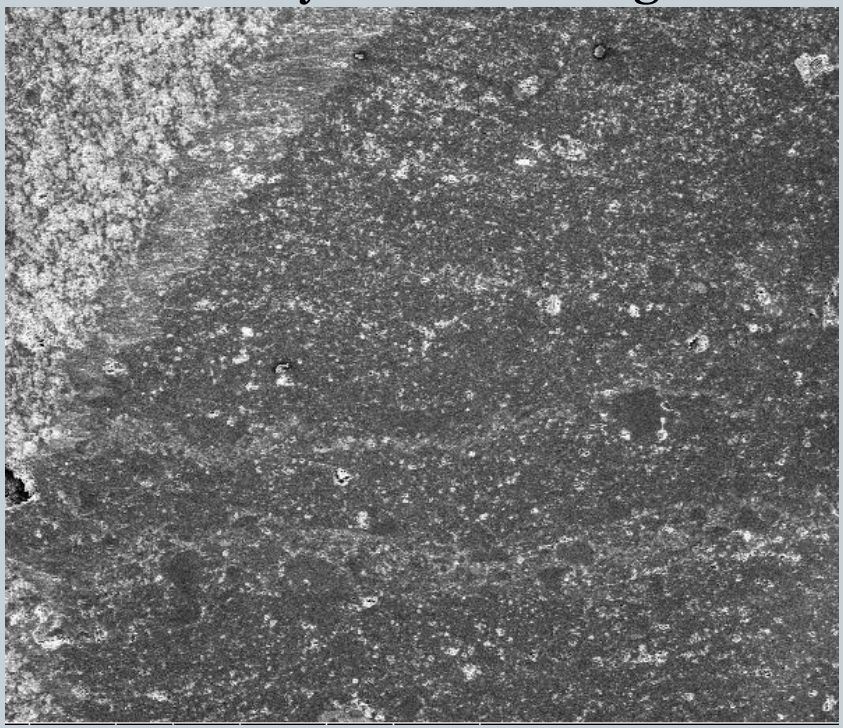
- High silica > 80%
- Massive beds
- Microstructure
  - Patchy to indistinct laminations of detritus
  - Heterogeneous microstructure and porosity
    - Micropores with some authigenic clays
    - Nanopores with some primary and authigenic clay
  - Poor connectivity

Silica-rich (Massive)



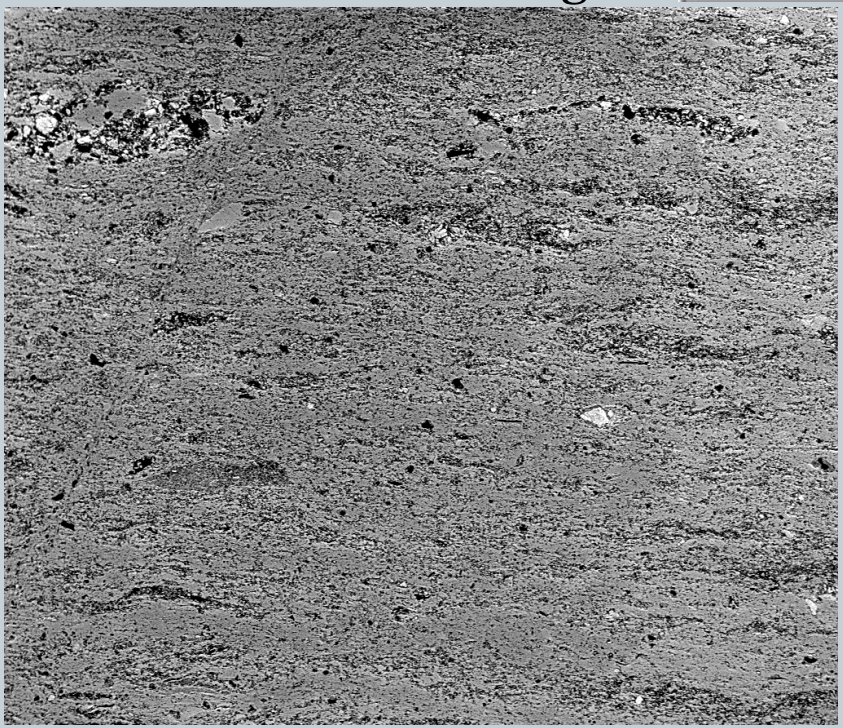
- Patchy to indistinct laminations of detritus

Secondary electron image



300 μm

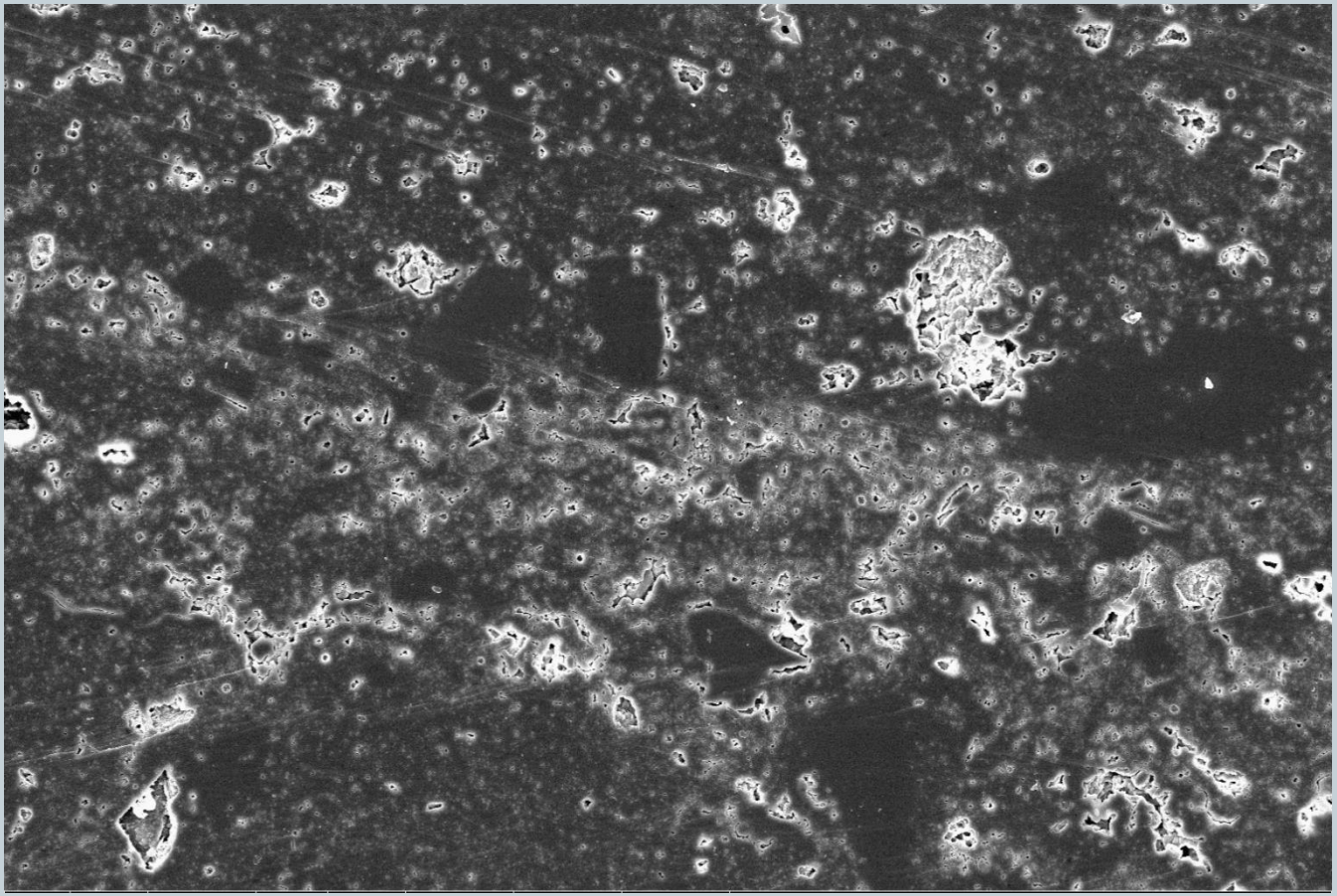
Backscattered image



500 μm

Silica-rich (Massive)

- Heterogeneous microstructure and porosity

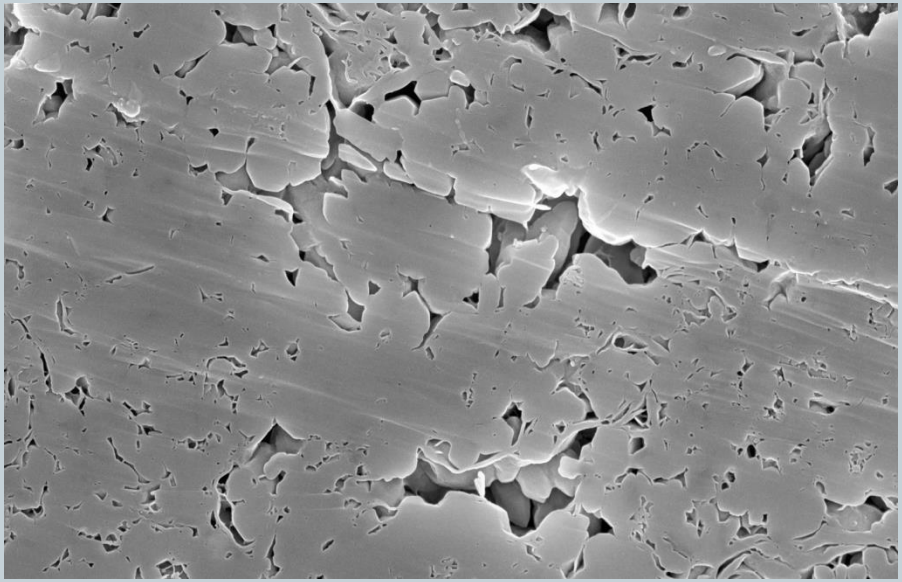


Silica-rich (Massive)

Nanopores (poor connectivity)

Some primary and authigenic clays

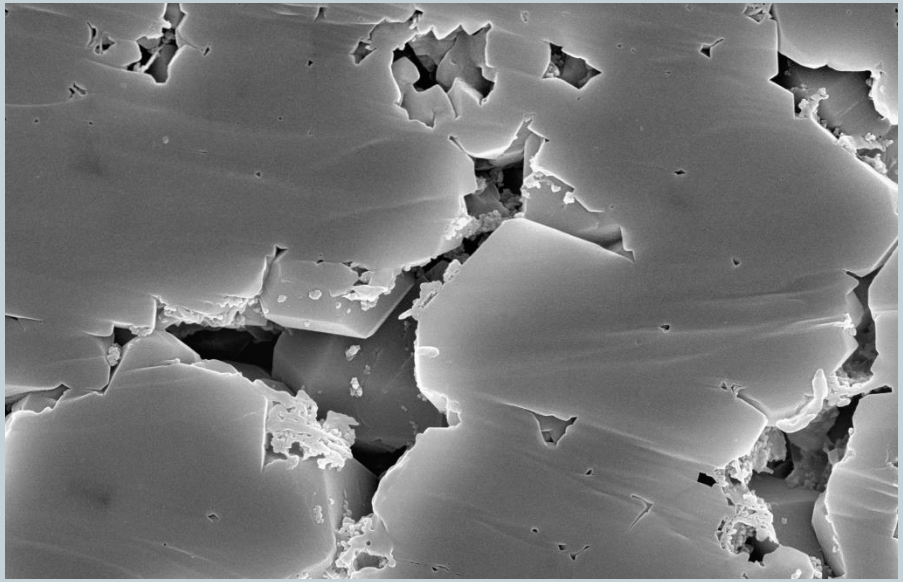
Detrital rich patches



1 μm

Micropores (poor connectivity)

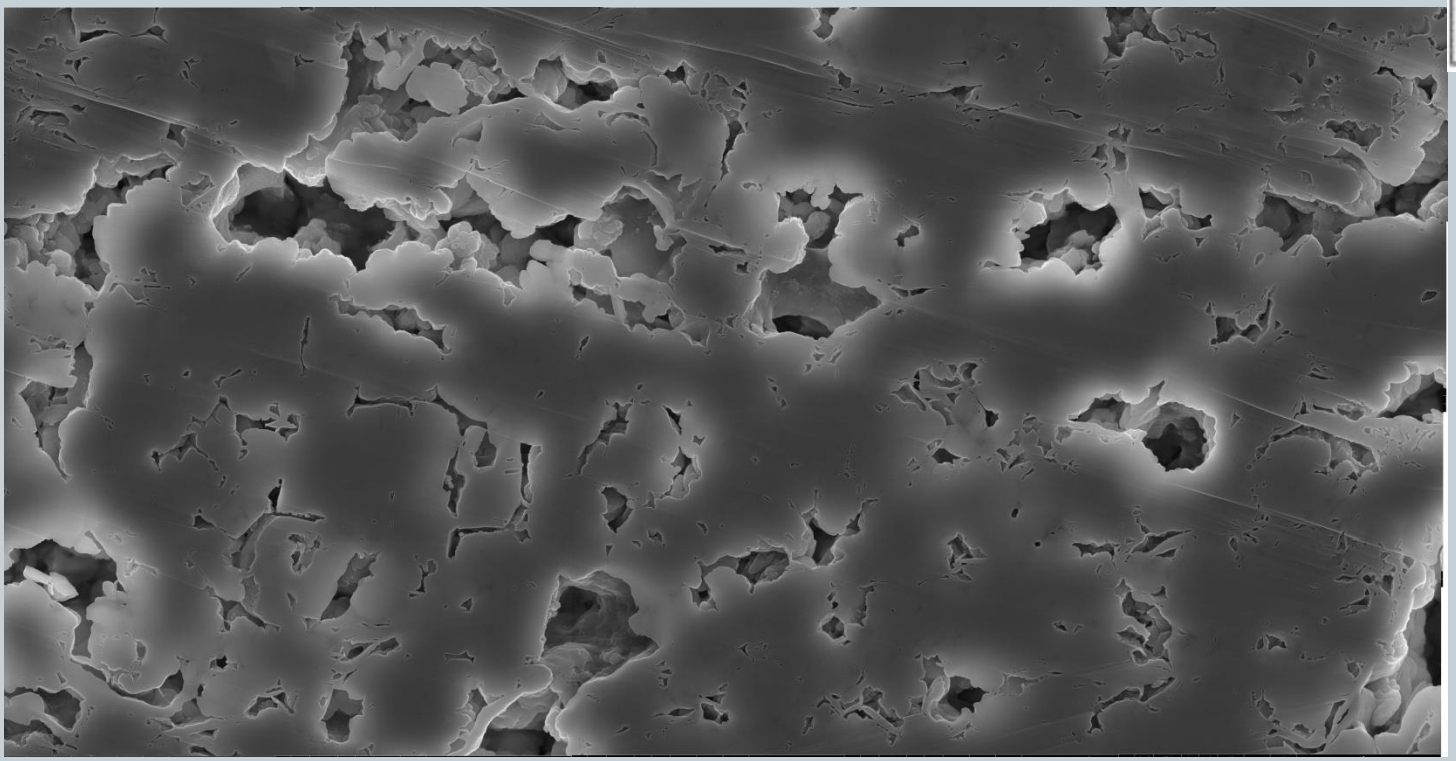
Some authigenic clays



1 μm

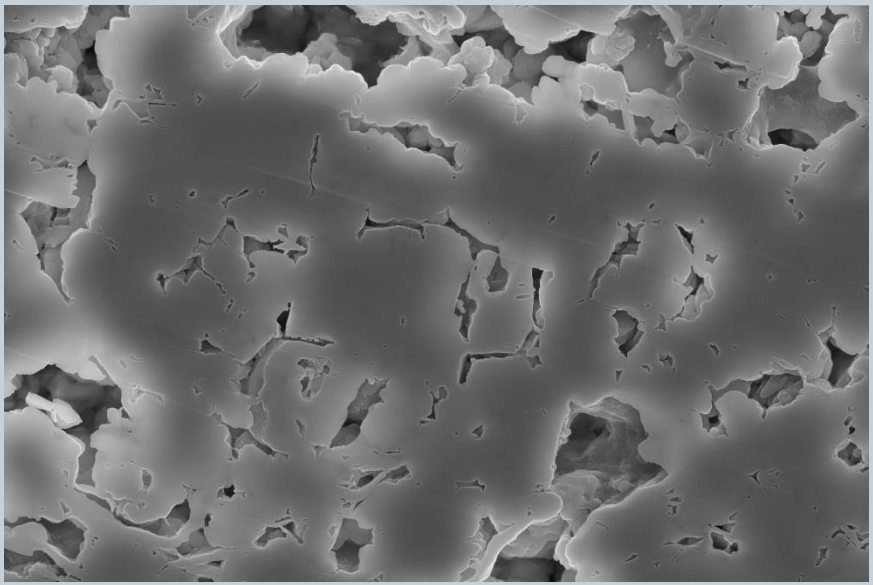
2. c. Silica-poor quartz phase

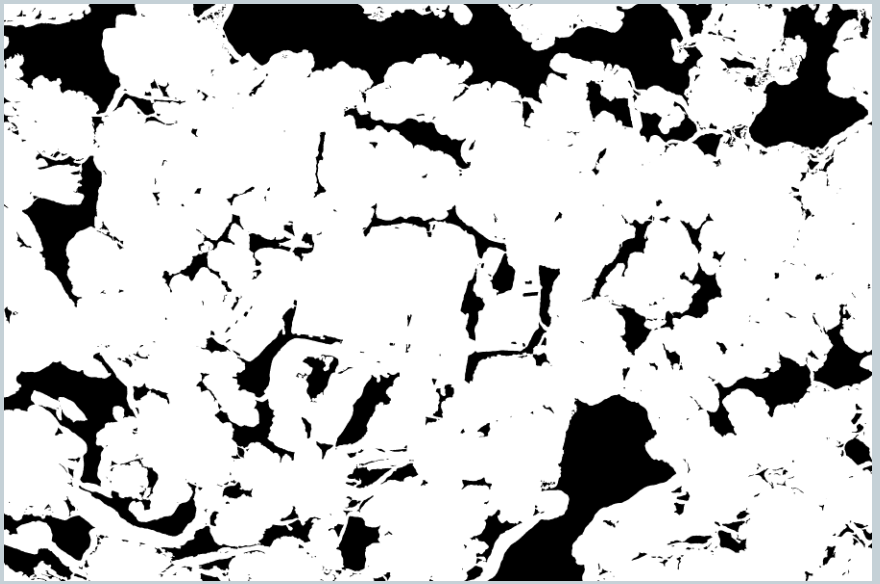
- Moderate porosity and poor connectivity



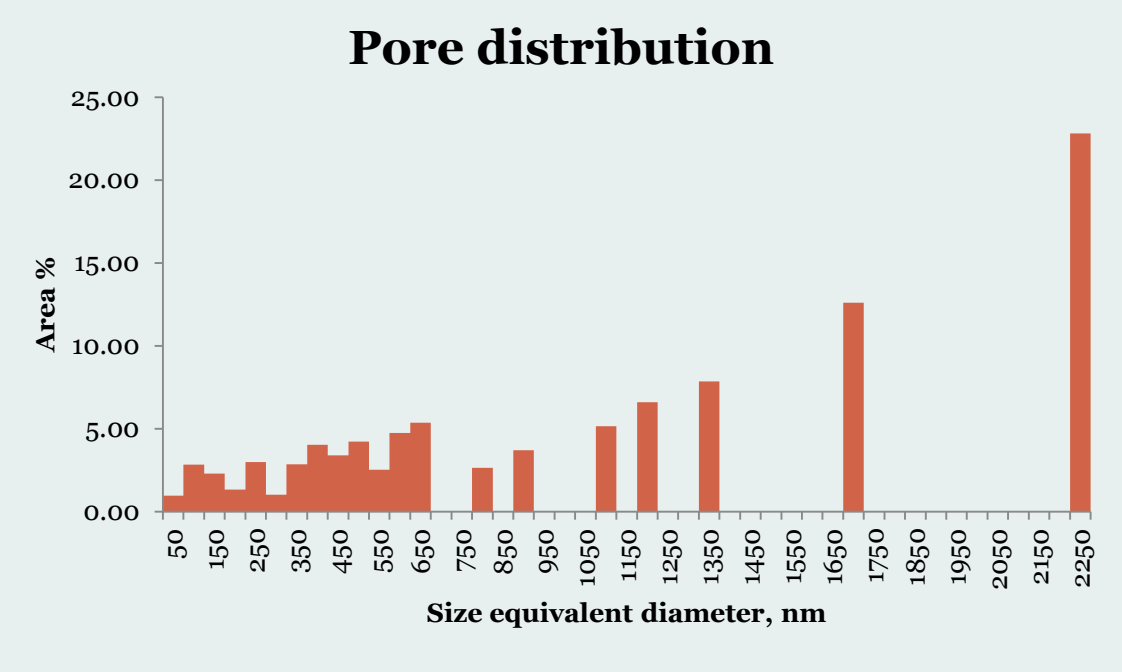
Silica-poor quartz-phase

- Moderate porosity and poor connectivity





Pore distribution



Pore Area %	AR-Aspect Ratio	Roundness
21.62	1.32	0.76

Porosity Results from Previous Studies

1. Isaacs, 1980

Quartz porosity 9-22 %

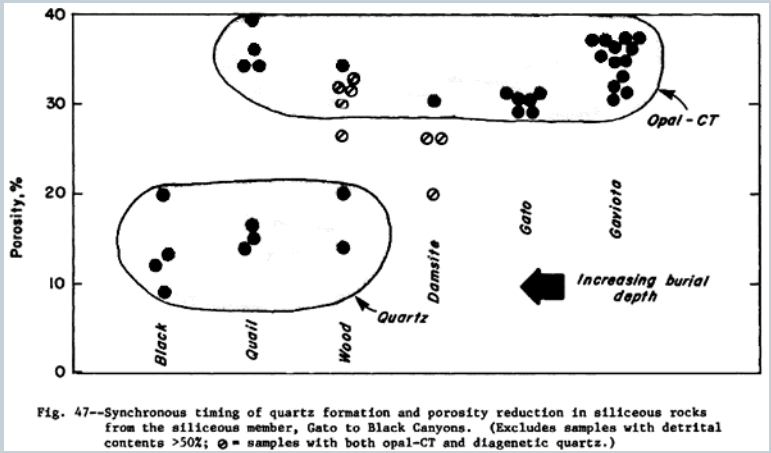


Fig. 47--Synchronous timing of quartz formation and porosity reduction in siliceous rocks from the siliceous member, Gato to Black Canyons. (Excludes samples with detrital contents >50%; ⊘ = samples with both opal-CT and diagenetic quartz.)

2. Schwalbach et al., 2007

Quartz porosity 15-30%

	Typical Porosity (%)	Grain Density (g/cc)	Permeability (air, md)	Pore-throat diameter (microns)	Oil Saturation (%)
Opal CT	**25-40**	**2.25-2.35**	**0.01 – 0.1's**	**0.01 – 0.1**	**0 - 30**
Quartz	**15-30**	**2.55-2.65**	**0.1 – 1.0's**	**0.1 – 1.0**	**30 - 60**

Typical reservoir parameters of opal CT and quartz porcelanites.

3. Chaika and Dvorkin, 2000

Quartz porosity 12-26%

THIS STUDY

Bulk Porosity 9-26%;
Locally to 35%

Summary: Opal-CT

1. Opal-CT phase porcelanites display three types of microstructure porosity
   - High-silica opal-CT porcelanite:
     - Consists of lepispheres with three layers
       - Core: highly porous and connected
       - Mantle: virtually impermeable
         - Resulting in isolation of cores—ineffective porosity.
       - Interlepisphere: very porous, bladed, nanopore and connected.
   - Low-silica opal-CT porcelanite:
     - Low porosity, nanopore, and poor connectivity
   - Transition-zone silica opal-CT porcelanite:
     - Extremely porous, with large connected, vuggy pores
     - Micropore

Summary: Quartz phase

2. Quartz phase porcelanites display the following microstructure porosity
   - Silica-rich quartz porcelanite- Laminated
     - Highly porous and interconnected micropores
     - Low porosity of poor connectivity with nanopores to micropores size
   - Silica-rich quartz porcelanite
     - Massive beds
       - Patchy to indistinct laminations of detritus
       - Heterogeneous microstructure and porosity
         - Micropores with some authigenic clays
         - Nanopores with some primary and authigenic clay
     - Poor connectivity
   - Silica-poor quartz porcelanite
     - Moderate porosity
     - Poor connectivity

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Thank you

Question?