Origin and Characterization of Eagle Ford Pore Networks in the South Texas Upper Cretaceous Shelf*

Lucy Tingwei Ko¹², Robert G. Loucks², Stephen C. Ruppel², Tongwei Zhang², and Sheng Peng²

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Abstract

Recent studies have demonstrated that loss of primary pores and development of secondary pores in mudrocks are primarily controlled by burial diagenesis of the sediments and thermal maturation of organic matter. Lack of quantitative data on micro- to nanometer rock properties, however, limits the ability to understand and predict petrophysical properties and fluid flow in these fine-grained rocks. To upscale these rock properties requires detailed quantification of the pore types and distribution at multiple scales. Upper Cretaceous Eagle Ford mudstone samples were collected from continuous cores taken from two adjacent (∼6 km) oil-producing wells in Karnes County, Texas to investigate small-scale variations in mineralogy, diagenesis, and pore types. Backscattered and secondary electron images were collected at 5,000X, 15,000X, and 120,000X (instrument magnification) using a field-emission scanning electron microscope (FE-SEM) to capture a broad range of visible pore sizes and pore distribution. Consistent point-count methods were used to systematically quantify pore types. Pore-tracing methods were used to validate point-count methods as well as to provide size and shape information of the organic-matter (OM) pores and mineral pores. Eagle Ford facies in the studied include: (1) thin ash beds, (2) globigerinid-bearing, laminated, argillaceous wackestone-packstone (marl) with varying organic matter content, and (3) lime packstone with varying calcite, quartz, and clay mineral content. Samples from the two cores show similar thermal maturity histories. Pores include both secondary OM pores in migrated solid bitumen and primary interparticle pores between coccolith elements (with residual OM). The Eagle Ford mineral pore network consists of mineral pores originally saturated with formation water and partly cemented mineral pores containing migrated bitumen with OM pores. SEM-image-based point-count porosity data show that Eagle Ford pore network in both wells is dominated by primary mineral pores, but that secondary OM pores in migrated bitumen are also important. This study
concludes that the reservoir quality of Eagle Ford mudstones varies significantly at similar levels of thermal maturation. Pore morphology, TOC, and mineralogy all impact total porosity. A positive correlation was found between the amount of OM porosity and TOC, and between mineral porosity and volume percentage of quartz and feldspar.

References Cited


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Presentation date: June 20th, 2016
AAPG Annual Convention & Exhibition, Calgary, Canada
Sample Location and Depth

- K1 and K2 wells are about 4 miles apart
- K2 well is slightly deeper than K1 well

- Samples were selected based on lithofacies defined by core description and XRF
  - 9 samples from K1; 7 samples from K2
  - 13 marl samples; 3 limestone samples

- Division of UEF and LEF is based on U abundance from spectral GR, corresponding to changes in TOC and [Mo]
  - UEF: marls with less TOC, ash beds uncommon
  - LEF: marls with high TOC, ash beds common
Sample Location and Depth

Proximal Facies
- Fluvial-deltaic sandstone
- Organic-poor mudrock
- Organic-rich mudrock

Distal Facies

Texas Lower Cretaceous Shelf Margins
- Stuart City (Albian)
- Sligo (Aptian)

EIA Production Trend Map
- Oil
- Wet Gas/Condensate
- Dry Gas

Map showing sample locations and facies distribution.
Motivation and Research Question

- Lack of quantitative data on micron- to nanometer-scale rock properties has limited the ability to define and predict petrophysical properties and fluid transport mechanism.
- SEM image-based porosity and pore-size distribution vs. nitrogen adsorption vs. helium pycnometry
- Dominant pore type and pore network in the Eagle Ford?
- What controls pore types and their size distribution?
- In addition to thermal maturity, what else can impact pore type, abundance, and distribution?
**Research Objectives and Workflow**

**Qualitative**

- Define Pore Classification Scheme (Loucks et al., 2012)

  1. Interpret origins of pore types
  2. Identify pore types (Ko et al., 2016)

**Quantitative**

- Point count
- Manual Pore Tracing
- Total $\phi$, OM $\phi$
- Mineral $\phi$
- OM $\phi$
- N2 pore-size distribution, $\phi$
- Helium porosity

**Petrography Description**

**Texture** (grain size, shape, & sorting)

**Fabric** (spatial & geometric configuration)

Relationship among pore, mineral, & OM

Determine diagenesis and paragenesis

1. Define scales of heterogeneity
2. Determine parameters that affect the heterogeneity of pores

- Mineralogy
- Maturity
- TOC, OM type
Methods: Three Scales of Investigation

Step 1:
Four SEM photomicrographs: 5,000X randomly selected, across bedding

Step 2:
Two SEM photomicrographs: 15,000X Across bedding planes

Step 3:
1 SEM photomicrographs: 120,000X
Focus on OM pores
One inside foram
Another one in the matrix

- Random selection but avoid anomalously large sizes of grains or forams
- Each sample:
  - Four 5,000X SEM photos
  - Eight 15,000X SEM photos
  - Eight 120,000X SEM photos
Methods – Point Count vs. Pore Tracing

Five categories: Mineral, OM, OM pore, interP pore, intraP pore

Total counted points: 1,000 points; *JMicrovision* (Roduit, 2008)
1. Skeletal-debris, globigerinid-bearing, laminated wackestone-packstone

2. Globigerinid-bearing, laminated packstone

3. Globigerinid-bearing, laminated wackestone-packstone

4. Globigerinid-bearing, laminated mudstone-wackestone
Increasing amount of kaolinite and chlorite from upper to lower EF.
Bulk Mineralogy – UEF & LEF Marl, Limestone

- Calcite
- Dolomite
- Pyrite
- Marcasite
- Apatite
- Illite&Mica
- Kaolinite
- Chlorite

Pie charts showing the mineral composition of K1 11,778 UEF and K2 12,174 UEF.
Increasing amount of kaolinite and chlorite from upper to lower EF.
EF samples have reached late oil to condensate and gas window
EF samples have reached late oil to condensate and gas window

K2 cores slightly more mature than K1 cores
EF samples have reached late oil to condensate and gas window
- K2 cores slightly more mature than K1 cores
### Eagle Ford Pore Evolution Model

<table>
<thead>
<tr>
<th>Petroleum generation stage</th>
<th>Organic matter</th>
<th>Minerals and pore types of Eagle Ford marine mudrocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerogen</td>
<td></td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Bitumen + gas</td>
<td></td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Oil + gas</td>
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</tr>
<tr>
<td>Gas</td>
<td>decrease in volume of kerogen</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
</tbody>
</table>

(Ko et al., 2016, in press)
Define and Categorize EF Pore Types

- **Mineral pores**
  - Primary mineral pore
    - Interparticle pore
    - Intraparticle pore
  - Modified mineral pore

- **OM pores**
  - Primary OM pore
  - Secondary OM pore
    - OM bubble pore
    - OM spongy pore

(Loucks et al., 2012; Ko et al., 2016, in press)
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Examples of Dominant Mineral Pores

- SEM photomicrographs showing
  1. Modified mineral pores
  2. Primary mineral pores

Modified mineral pores with relic OM

Primary mineral pores

- calcite
- dolomite
- clay minerals
- quartz

K1 well 11901 (LEF)

K1 well 11939 (LEF)
Examples of Dominant OM Pores

- SEM photomicrographs showing
  1. OM bubble pores
  2. OM spongy pores
Visible point-count porosity increases towards higher magnification images because smaller pores are best resolved at 120,000X.

However, areas at highest magnification are the least representative.
Sample Depth vs. Total Porosity (5,000X)

- Extent of spreading of the data points implies the heterogeneity of rocks
- Average visible porosity in marls marked in black
- Average visible porosity increases towards LEF
Mineral Pores Dominate EF Pore Network

K1
- Total Porosity
- OM Porosity
- Mineral Porosity
- Limestone facies

K2
- Total Porosity
- OM Porosity
- Mineral Porosity
- Limestone facies

Point-count porosity (%): @5,000X

Depth (ft):
- K1: 11,760 to 11,960
- K2: 12,160 to 12,320

Point-count porosity (%): @15,000X

Depth (ft):
- K1: 11,760 to 11,960
- K2: 12,160 to 12,320
Pore Shape, Pore-Size Distribution

\[ G = \frac{A}{P^*L_c} \]

- **A**: area
- **P**: perimeter
- **L_c**: characteristic length

(Afsharpoor and Javadpour, 2016)
Pore Shape, Pore-Size Distribution

**upper Eagle Ford**

![Bar chart showing pore size distribution for upper Eagle Ford](image)

**lower Eagle Ford**

![Bar chart showing pore size distribution for lower Eagle Ford](image)
Pore Shape, Pore-Size Distribution

**Upper Eagle Ford**

- K1 11,778
- K1 11,818
- K2 12,169
- K2 12,174
- K2 12,185

Normalized frequency distribution (%)

<table>
<thead>
<tr>
<th>Pore-size range ECD (nm)</th>
<th>250-500 nm</th>
<th>500-1000 nm</th>
<th>1000-2000 nm</th>
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<td>0%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
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</table>

**Lower Eagle Ford**

- K1 11,838
- K1 11,878
- K1 11,901
- K1 11,918
- K1 11,939
- K1 11,943
- K2 12,246
- K2 12,308

Normalized frequency distribution (%)

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Pore Shape, Pore-Size Distribution

**Increased % of silt grains**

**K2 12,169**

**K2 12,174**

**K2 12,185**

**upper Eagle Ford**

Normalized frequency distribution (%)

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**lower Eagle Ford**

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Impacts of TOC on OM Porosity

Average visible OM porosity vs. TOC

- **R² = 0.2844**
- **R² = 0.2006**

- **5,000X**
- **15,000X**

![Graph showing the relationship between Leco TOC (wt%) and Avg visible OM porosity (%) for different magnifications.](image-url)
Impacts of TOC on OM Porosity

Average visible OM porosity vs. TOC

- **OM bubble + spongy pores + primary OM pores**
- **limestone**
- **OM spongy pores**

- **R² = 0.1208**
- **R² = 0.8066**

![Graph showing the relationship between average visible OM porosity and Leco TOC (wt%)](image)
Impacts of TOC on OM Porosity

- Positive correlation for total OM spongy porosity with TOC
- Likely multiple factors determine distribution of OM porosity, not just TOC
No correlation for mineral porosity vs. calcite and total clay minerals vol.\%

Although concentrated areas of fecal pellets (composed of coccolith hash) and broken foraminifera bodies are major allochems that host interparticle pores -> calcite is also cement
(Quartz + Feldspar) vs. Mineral Porosity

- Weak positive correlation for mineral porosity vs. quartz + feldspars vol.%
- Interpreted to be related to the rigidity of the mineral framework that inhibits compaction of mineral pores and later allowed petroleum to migrate within the intergranular pore networks.
Compare Pore-Size Distribution

- PSD derived from SEM imaging and N2 adsorption is straightforward in comparison
- Pores > 250 nm is approximately 25% of the total pore volume (SEM)
Some inconsistency for pores in the 30- to 70-nm size range
Data raises some concerns regarding the reliability of either method
Compare image-based and He porosity

- SEM image-based porosity underestimates the bulk porosity because pores less than 5 nm are not included (cannot be resolved).
- However, SEM provides pore type and network information that other methods cannot provide.
Conclusions

- Mineral pores and their pore networks are main contributor to total porosity and total pore network in the EF strata

- Pore development is primarily controlled by depositional and diagenetically modified processes (first order) and thermal maturation of organic matter (second order): compaction & cementation are two important processes in the EF

- Bulk mineralogy of UEF marls is similar; however, LEF marls demonstrate much more variations: increase abundance of kaolinite and chlorite and significant diagenetic alteration observed in LEF
Conclusions

- OM pore morphology affects OM porosity. Only OM spongy pore volume relates to TOC.

- Strong nm- and μm- scale heterogeneity of rock components and properties (texture, fabric, mineralogy, and TOC) affects pore types, abundance, and distribution – without complication of thermal maturity.
Implication and Future Works

- Texture and fabric impact pore-size distribution. Quantification of grain size, shape, and sorting is needed.

- Quantification of diagenesis in mudstones. Relationship of compaction and cementation of mudstone is not clear.

- Identification of kerogen and pyrobitumen using synchrotron-based scanning transmission X-ray microscopy (STXM) or other advanced techniques.

- Can we connect these quantitative results to petrophysics? If so, what will be the representative elemental area (REA)?
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