Integration of sequence stratigraphy, diagenesis, and geochemistry provides a comprehensive understanding of the nature, distribution, and connectivity of pores in the hydrocarbon-productive Cretaceous Eagle Ford Formation, South Texas. For this study, samples were gathered from two wells that contain 1) foraminiferal mudstones with high (up to 8 wt%) total organic carbon (TOC) contents, deposited in the transgressive system tract (TST) or near the maximum flooding surface (MFS), and 2) limestones with relatively low TOC (<1 to 2 wt%) contents, deposited during highstands (HST). The Eagle Ford differs in thermal maturity between the wells, with the formation at ‘low’ maturity (Ro ~0.7%) in one and at higher maturity (Ro ~1.2%) in the other.

Early diagenesis in TST/MFS mudstones resulted in precipitation of euhedral pyrite, quartz, and kaolinite, which filled foraminifera tests (intraparticle pores) and partially filled interparticle pores between detrital grains. In HST limestones, euhedral microsparry calcite precipitated from recrystallization of abundant foraminifera and coccoliths; interparticle pores remained between calcite crystals. In both lithologies, bitumen coats all precipitated minerals. Bitumen occludes pores in mudstones, whereas it lines pores and only locally occludes them in limestones. Subsequent porosity development in the bitumen (limited connectivity) was observed only in the high-maturity well and principally in mudstones. Based on laboratory measurements and inferred from focused-ion-beam scanning electron microscopy, good connectivity exists between interparticle pores in limestones, which is consistent with higher hydrocarbon yield (S1 peak in RockEval analyses) from limestones relative to mudstones, and indicates that hydrocarbon storage is significant in limestones.
References Cited


Linking diagenesis with depositional environments as it bears on pore types and hydrocarbon storage—an example from the Cretaceous Eagle Ford Formation, South Texas

Neil Fishman
January 6, 2015
Tulsa Geological Society
Paleogeographic setting, Eagle Ford

Study well locations

Eagle Ford Shale Play,
Western Gulf Basin,
South Texas

Ro ~0.7%
Ro ~1.2%
Sequence stratigraphic framework

Eagle Ford, near Del Rio, TX

'upper' Eagle Ford

'lower' Eagle Ford
Broadly, two lithologies of interest

Org-rich mudst, TST-MFS, up to 8% TOC, $\Phi = 8-9\%$, $k_{\text{eff}} = 50$ nD

Limestones, HST, <1 locally up to 3% TOC, $\Phi = 6-7\%$, $k_{\text{eff}} = 300$ nD
Broadly two lithologies of interest

- Recrystallized limestone
- Foraminiferal mudstone

**organic lean** (<2 wt% TOC)

**organic rich** (up to 8 wt% TOC)

From Ritz et al., 2014
**Petrologic goals for porosity studies**

Place inorganic & organic porosity development within a temporal and thermal framework for lithologies of interest (org-rich mudst & ls)

<table>
<thead>
<tr>
<th>A</th>
<th>Mineral Matrix Pores</th>
<th>Organic-Matter Pores</th>
<th>Fracture Pores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pores between or within mineral particles</td>
<td>Pores within organic matter</td>
<td>Pores not controlled by individual particles</td>
</tr>
<tr>
<td>Interparticle Pores</td>
<td>Interparticle Pores</td>
<td>Organic-Matter Pores</td>
<td>Fracture Pores</td>
</tr>
<tr>
<td>Pores between grains</td>
<td>Intercrystalline pores within pyrite laminae</td>
<td>Intraparticle pores within clay aggregates</td>
<td></td>
</tr>
<tr>
<td>Pores between crystals</td>
<td>Pores within pellets or pellets</td>
<td>Dissolution-pseudo pores</td>
<td></td>
</tr>
<tr>
<td>Pores between clay platelets</td>
<td>Pores within fossil bodies</td>
<td>Moldic pores after a crystal</td>
<td></td>
</tr>
<tr>
<td>Pores at the edge of rigid grains</td>
<td>Moldic pores after a fossil</td>
<td>Primary porosity (original, modified by diagenesis)</td>
<td></td>
</tr>
<tr>
<td>Secondary porosity (through diagenesis &amp; catagenesis)</td>
<td>Pore types, focus herein</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure modified from Loucks et al., 2012; AAPG Bulletin*
Nature of pores, mudstone & limestone

**MUDSTONE:**
- Both intra- & interparticle pores
- Organic pores abundant, in some samples
- Fractures filled with calcite and/or organic material

**LIMESTONE:**
- Most pores are interparticle between authigenic calcite (C) or pyrite (P)
- Fractures filled with calcite and/or organic material
- Organic pores observed, in some samples

Organic porosity in some samples...
Organic porosity, function of thermal maturity

Eagle Ford Ro ~0.7%:
Organic pores minimal or lacking entirely

Eagle Ford Ro ~1.2%:
Organic pores very well developed
Nature of the pore-filling organic material

Organic material in limestones:
- Coats early diagenetic minerals
- Locally occludes remaining pores
- Can line interparticle pores

Organic material in mudstones:
- Coats early diagenetic minerals
- Occludes pore (intra- & interxtalline)

Organic material post-dates early, diagenetic minerals, was mobile (fills pores), & abundant in mudstones but less so in limestones = migrated bitumen, now, in part, 'pyrobitumen'
Timing of events, org-rich TST/MFS mudstones

Kaolinite (K), pyrite (P), calcite (C), & abundant 'bitumen' as intra/inter-particle cements

Minimal compaction of forams prior to authigenic mineral ppt — authigenic minerals early
Similar diagenetic history in both cores

Paragenetic sequence

- Pyrite
- Calcite
- Quartz
- Kaolinite
- Bitumen/pyrobitumen
- Fracture
- Organic porosity

'Bitumen/pyrobitumen' filled remaining interparticle pores
Organic pores, 'late' diagenesis (secondary $\phi$), EF high maturity
Timing of events, HST recrystallized limestones

Authigenic pyrite (P), quartz (Q), calcite (C), Kaolinite (K), & 'bitumen'—interparticle cements but bitumen less common in Is than mudst

Calcite recrystallized from biological components

Paragenetic sequence

Pyrite — — —
Calcite — — —
Quartz — —
Kaolinite —
Bitumen/pyrobitumen \( \square \) — —
Fracture —
Organic porosity —

'Bitumen/pyrobitumen' filled remaining interparticle pores

Organic pores, 'late' diagenesis (secondary \( \phi \)), EF high maturity
Eagle Ford diagenesis summary

- Early diagenesis similar in TST/MFS organic-rich mudstones, both cores
- Early diagenesis similar in HST limestones, both core
- 'Bitumen/pyrobitumen' present in limestones and mudstones—abundant in mudstones
- Organic porosity development minimal or absent in low maturity (0.7% Ro) but abundant in high maturity (1.2% Ro)
- Organic porosity (secondary $\phi$) developed in 'bitumen' (now largely pyrobitumen) that fills pores remaining after ppt of early-formed minerals (e.g., kaolinite, calcite, pyrite, etc.)
- Organic-rich mudstones = organic porosity & associated storage best developed and dominates pore types (minor intercrystalline porosity)
- Recrystallized limestones = intercrystalline porosity & associated storage best developed and dominates pore types (minor organic porosity)
Pore type & connectivity a function of lithology

TST/MFS organic-rich mudst, has some pore connectivity, largely organic porosity/storage: a function of thermal maturity. Lower calcite contents result in more ductile framework. (50 nD)

HST limestone has good pore connectivity, largely interparticle porosity/storage: not as dependent on thermal maturity. Rigid framework due to diagenetic calcite. (300 nD)

EXPLANATION
Green = organic material
Blue = interconnected porosity
Red = unconnected porosity
Eagle Ford, summary of pore types by lithology

- Pore types varies by lithology
  - OM pores dominate in org-rich mudstones, higher maturities
  - Interparticle pores largely in limestones
  - Interparticle pores provide best connected porosity/storage

Organic-rich mudstone

Recrystallized limestone
Pairing diagenesis with catagenesis

Original organic macerals

Kerogen

‘Bitumen/pyrobit’

Oil-cond/Wet gas

Dry gas

Original detrital grains + inorganic biological material

diagenesis

‘dead’ carbon*

*after Hunt, 1996, Jarvie and Tobey, 1999

Time, burial, heat

Ro ~ 0.6%

Ro ~ 1.0%

Ro >1.5%
Porosity & storage related to sequence strat

Lithologic (sequence strat) controls on pore types
Interparticle in limestones vs organic in mudstones

<table>
<thead>
<tr>
<th>Interval</th>
<th>TOC</th>
<th>Sw</th>
<th>k_eff</th>
<th>Pore Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>5-8%</td>
<td>20%</td>
<td>50 nD</td>
<td>Abundant organic</td>
</tr>
<tr>
<td>Upper</td>
<td>8-9%</td>
<td>40%</td>
<td>300 nD</td>
<td>Interparticle</td>
</tr>
</tbody>
</table>

From John Guthrie and Randy Mitchell

Storage (geochem) then linked to both sequence strat & diagenesis
Broadly two lithologies of interest

- Recrystallized limestone
- Foraminiferal mudstone

Organic lean
Organic rich

Hardness linked sequence stratigraphy (diagenesis)

Ritz et al., 2014
Influence of lithology on ‘brittleness’ & production

Lithologic (sequence strat) controls on TOC & mineralogy
Limestones harder, mudstones more ductile

<table>
<thead>
<tr>
<th>Lithology</th>
<th>TOC</th>
<th>( \Phi )</th>
<th>( S_w )</th>
<th>( k_{\text{eff}} )</th>
<th>Calcite Rigid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>&lt;2%</td>
<td>6-7%</td>
<td>40-50%</td>
<td>300 nD</td>
<td>More</td>
</tr>
<tr>
<td>Foraminiferal mudstone</td>
<td>5-8%</td>
<td>8-9%</td>
<td>20%</td>
<td>50 nD</td>
<td>Less</td>
</tr>
</tbody>
</table>

Interparticle pores; more calcite = more rigid. Zone of fracability & moveable HC

From John Guthrie and Randy Mitchell

Limestones more ‘fracable’ & provide HC storage
Conclusions

• Porosity development—diagenesis (inorganic) & catagenesis (organic)
  ◦ both important for HC storage & production
• Pore types related to original lithology, function of depo environment
• Inorganic (interparticle) pores in HST (interbedded) limestones
  ◦ Early diagenesis (calcite recrystallization) led to interparticle porosity
  ◦ Overall ‘higher’ perm in Is due to diagenesis
• Organic pores in organic-rich TST/MFS mudstones, thermally mature
  ◦ Early diagenesis resulted in authigenic mineral precipitation
  ◦ Early catagenesis resulted in occlusion of remaining pores with bitumen
• Organic pores developed the pore-filling bitumen (now pyrobitumen)
  ◦ Organic porosity (secondary $\phi$) probably began at $>$Ro $\sim$1.0%
• Moveable HC in both mudstones & limestones
  ◦ Both lithologies contribute to production
• Reservoir characterization, function of diagenesis & sequence strat
Acknowledgments

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