Diagenetic Evolution of Porosity in Carbonates during Burial*

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Abstract

The diagenetic evolution of porosity and permeability in carbonates is complex and involves a number of independent factors. Carbonate sediments start with 40-80% porosity and generally lose porosity with time and burial (Schmoker and Halley, 1982); however, there are many factors that cause higher and lower porosity in carbonates of the same age and burial depth. Alteration of carbonate sediments during shallow burial is common and includes diagenesis in seawater shortly after deposition, freshwater diagenesis during subaerial exposure, and dolomitization in hypersaline waters. Marine (seawater) diagenesis varies with depth and carbonate saturation as is shown on Enewetak Atoll. Aragonite and Mg-calcite cementation dominate in shallow seawater; however, aragonite is dissolved, and radiaxial calcite precipitates in moderately deep seawater. In even deeper seawater, calcite dissolves and dolomite precipitates. Freshwater (meteoric) diagenesis and dolomitization commonly rearrange and decrease porosity, but they also impart strength to the rock that reduces porosity loss during deeper burial. Pennsylvanian limestones in west Texas show that prolonged subaerial exposure progressively decreases matrix porosity but increases conduit porosity (fractures and vugs), and hence, formation permeability. Reflux dolomitization is commonly associated with carbonates in arid climates, like the Permian of the Permian Basin. The porosity and permeability of reflux dolomites varies according to position in the dolomitizing system with less porosity and permeability in proximal parts of the dolomitizing system. Dolomitization decreases rate of porosity loss with burial (Schmoker and Halley, 1982), allowing some porous dolomite reservoirs like the Smackover of south Alabama at depths of 16,000-18,000 feet. Deep burial dissolution increasing porosity is the exception, rather than the rule. In summary, unlike quartzose sandstones, a complex array of diagenetic factors generally affect the ultimate porosity, permeability, and production of carbonate reservoirs.
References Cited


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Diagenetic Evolution of Porosity in Carbonates during Burial

Art Saller (arthur.saller@cobaltintl.com)
Controls on Carbonate Porosity

Depositional Sediments

Near Surface Diagenesis

Deep Burial Diagenesis

Reservoir Carbonate Porosity and Permeability
EVOLUTION OF POROSITY

• Modern carbonate sediments have porosities of 40% (grainstones) to 80% micritic carbonates (Enos & Swatsky, 1981)
• Carbonate reservoirs have 3-35% porosity
• Most nearsurface diagenetic processes decrease and/or rearrange porosity, but make more rigid
  – Submarine,
  – Subaerial exposure->meteoric diagenesis
  – Dolomitization
• Carbonates generally lose porosity during deeper burial
• Burial history- depth, temperature and time spent at those depths and temperatures determines rate of porosity loss
• Grainstones may lose porosity more slowly than wackestones and mudstone during early physical compaction
• Nearsurface diagenesis may impart a petrologic strength that reduces porosity loss during burial
• Dolomites lose porosity more slowly with burial than most limestones
POROSITY GENERALLY DECREASES WITH DEPTH
With much variation related to deposition & early diagenesis

SOUTH FLORIDA PLEISTOCENE TO JURASSIC CARBONATES

Diagenetic Evolution of Porosity in Carbonates during Burial

• Introduction
• **Marine Diagenesis - Enewetak**
• Freshwater Diagenesis – Pennsylvanian, West Texas
• Dolomitization – Permian, West Texas
• Deep Burial – Florida/ South Alabama
Deep Holocene Botryoidal Aragonite Cement

Calcitized Botryoidal Cement, Capitan Formation, Permian West Texas. Submarine cements precipitate where seawater pumps through reefs & grainstones.

Shallow marine to tidal flat cycles

Submarine Cementation can Substantially Reduce Depositional Porosity in Reefs

CAPITAN: PROGRADING SHELFL MARGIN SYSTEM

McKittrick Canyon

Toeset Mudstones
DEEP MARINE DIAGENESIS, ENEWETAK ATOLL

Carbonate Saturation decreases with depth in modern oceans because more CO₂ can be held in solution allowing more carbonate to be held in seawater.

(from Saller and Koepnick, 1990)
TEMPERATURE PROFILES FROM ENEWETAK WELLS INDICATE CIRCULATION OF SEAWATER THROUGH THE ATOLL

Wells are cool because cool sea water is circulating through atoll.

Warming due to geothermal heat flow near the basement.

(from Saller and Koepnick, 1990)
Beachrock on Enewetak is Marine Cemented Grainstones that has Cemented WW II Artifacts (from C.H. Moore, 1970s)

(from Saller and Moore, 1989)
**Dissolved, cemented Coral**

**ARAGONITE ZONE:**
1. Aragonite Cement
2. HMC Cement

**CALCITE ZONE:**
1. HMC to LMC
2. Aragonite Dissolution
3. Calcite (LMC) Cement

**DOLOMITE ZONE:**
1. Calcite Dissolution
2. Dolomitization

(Saller and Koepnick, 1990)

**Oligocene, Enewatak ~2000 feet**

**Equant, Marine Calcite Cement**

**Dissolved, cemented Coral**
Calcite Dissolution & Dolomitization by deep seawater, Eocene, Enewetak ~ 4200’ Deep

Strontium isotopes (87/86) in marine carbonates vary though time & can be used for dating & as a tracer.

Strontium Isotopes in Seawater through Time

Eocene strata with depositional $^{87}\text{Sr}/^{86}\text{Sr} = 0.70767-0.70777$

(from Saller and Koepnick, 1990)

From Burke et al. 1982
Marine Calcite Cements & Dolomites have distinctly younger Sr indicating precipitation after substantial burial by seawater circulating through the margin of the atoll.

(from Saller and Koepnick, 1990)

(from Halley et al., 1986)
Radial Marine Cement Circulate into the Platform Margin after Substantial Burial

Common Marine Cement

(from Saller and Koepnick, 1990)
Dolomitization by Deep Seawater after Substantial Burial

Dolomite $^{87}\text{Sr}/^{86}\text{Sr} = 0.70855-0.70901$
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Pennsylvanian Carbonate Cycles in Southwest Andrews Area in West Texas show the Effect of Duration of Exposure on Porosity in Carbonates

Central Basin Platform

SOUTHWEST ANDREWS AREA

Midland Basin

Alternate between deposition & subaerial exposure

**A) INITIAL FLOODING OF SHELF**

- **Subaerial exposure surface**
  - Shale - reddish-green; unfossiliferous
  - Grainstone - root motting and brecciation
  - Grainstone - ooids, peloids and/or fossil fragments; current-laminated
  - Burrowed packstone
  - Fossiliferous wackestone/packstone - burrowed; mollusks, phylloid algae
  - Argillaceous wackestone - brachiopods, crinoids, tubular forams, fusulinids
  - Tubular foram packstone

- **Interpretation of depositional environment**
  - FLUVIO-DELTAIC
  - HIGH-ENERGY SHOAL
  - LOW-ENERGY SUBTIDAL (3-20 m deep)
  - DEEPENING

~90 cycles: Frequency ~110 ky

**B) DEVELOPMENT OF SHOALS**

**C) SEA LEVEL DROP & EXPOSURE**

EVOLUTION OF POROSITY DURING SUBAERIAL EXPOSURE

• Total porosity generally decreases with duration of subaerial exposure
• Dissolution at the surface lowers the surface, & that CaCO$_3$ moves down and can precipitate calcite in the shallow subsurface decreasing porosity
• Systematic changes in porosity, pore types & permeability occur during exposure
• Initially primary pores are filled as secondary pores (esp. moldic porosity) are created during early diagenesis
• Later, moldic pores are filled as vugs and fractures are created (Φ less, K more)
• Prolonged exposure results in fractures & cavernous porosity with high K, but low Φ
Stage 1. Very Brief or No Exposure

Much Primary Porosity

Stage 2. Brief to Moderate Exposure

Much Moldic Porosity

Stage 4. Prolonged Exposure

Minor Vuggy & Fracture Porosity

Stage 3. Moderate Exposure

Moldic, Vuggy & Fracture Porosity

Compaction reduces porosity in initially porous micritic sediment with no early lithification.
Brief subaerial exposure (10-30K years?) in grainstones causes dissolution that creates pores (mainly moldic), and cementation that fills pores and lithifies the rock.
Moderate subaerial exposure (30-60K years?) causes dissolution of some conduit pores and more cementation resulting in decreased porosity, but increased permeability.

Porosity ~10%; Permeability ~10 mD
SW ANDREWS: PROLONGED EXPOSURE IN/NEAR SOIL ZONE

Shaley material (s) fills between breccia clasts. Iron-rich burial cements fill other pores.
POROSITY:

UPPER PENN. SW ANDREWS

Thinner cycle = Longer Exposure

Prolonged exposure fills most matrix pores, but creates caves that continually form and collapse. Total Porosity in Mature Karst Areas is commonly <3%. 

Sediment around collapse cave clasts
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EFFECT OF DOLOMITIZATION ON POROSITY DEPENDS ON:

(A) Input of Ions,
(B) Position in System/Saturation
(C) Volume of Brines Flowing Through

(1) \[ 2\text{CaCO}_3 + \text{Mg}^{2+} \rightarrow \text{CaMg(CO}_3\text{)}_2 + \text{Ca}^{2+} \]
Solid volume decreases by 12%
Dolomitization creates porosity

(2) Except when it doesn’t
\[ \text{CaCO}_3 + \text{Mg}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaMg(CO}_3\text{)}_2 \]
Solid volume increases by 75%
Dolomitization is common in platform interiors in arid climates. Permian of west Texas is a classic example. Most of this dolomitization is probably related to evaporated seawater formed in lagoons. That evaporated seawater is dense, moves down and dolomitizes. (REFLUX DOLOMITE)
Preferential Dolomitization of Platform/ Shelf Tops of Middle-Upper Permian Carbonates (Arid Climate)

Porosity varies within Dolomitizing Systems

MUCH PRECIPITATION OF DOLOMITE OCCLUDING POROSITY

Porosity in dolomite increases from Platform Interior toward Margin, but is not controlled by facies.

From Saller & Henderson, 1998
STAGE/DURATION OF DOLOMITIZATION AFFECTS POROSITY

Overdolomite

Platform Interior

Basin

Time 3. Continued Flow of Dolomitizing Brine Precipitates Additional Dolomite in Previously Dolomitized Areas ( Zones 1 and 2 ) and Dolomite Replaces Limestones in Zone 3

Highest Oil Production occurred where high porosity platform margin dolomites are above the oil/water contact.

From Saller & Henderson, 1998
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LOSS OF POROSITY WITH DEEPER BURIAL

- Physical (plastic) compaction
- Chemical compaction (pressure solution)
- Cementation
• Physical (plastic) compaction
  – Carbonate muds start with ~80% porosity (Enos & Swatsky, 1981)
  – Without early lithification, they will compact until they have no effective porosity

Note flattening of burrow-fills due to compaction of carbonate mud

Ooid Grainstone; Jurassic Smackover Fm; ~10,000 feet deep; Plastic Deformation & Grain-to-Grain Pressure Solution

Grainstone will also compact, but more slowly
LOSS OF POROSITY WITH BURIAL

- Physical (plastic) compaction
- Chemical compaction (pressure solution)
- Cementation

Burial cements are commonly derived from pressure solution of adjacent strata

Burial Cement; Smackover ~10,000 feet (from C.H. Moore)
Upper Jurassic Smackover dolomite with 10-15% porosity, west Florida.

Rate of Porosity Loss Depends on Pressure, Temperature & Time.

MORE THAN 75% LIMESTONE
MORE THAN 75% DOLOMITE

From Schmoker & Halley, 1982

Early dolomitization causes lithification that decreases porosity loss with burial.
Carbonate dissolution during deep burial can create porosity.
- Acidic waters can be expelled from organic-rich shale
- Dissolution is commonly associated with “hydrothermal dolomite”

Reddish drilling mud fills vugs created during dissolution during deep burial at the margins of an Oligocene platform

POROSITY GENERALLY DECREASES WITH DEPTH
With much variation related to deposition & early diagenesis, temperature, pressure, & time

SOUTH FLORIDA PLEISTOCENE TO JURASSIC CARBONATES

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