The Giant Oil Field Evaporite Association: A Function of the Wilson Cycle, Climate, Basin Position and Sea Level*

Christopher G. St. C. Kendall¹, L.J. (Jim) Weber², and Abdulrahman S. Alsharhan³

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¹Geological Sciences, University of South Carolina, Columbia, SC (kendall@sc.edu)
²Qatar Subsurface, ExxonMobil Production Company, Houston, TX
³Middle East Geological Establishment, Al Ain, United Arab Emirates

Abstract

Over 50% of world's most easily accessible hydrocarbon reserves are trapped in carbonates; over 60% of these beneath evaporite seals. The seals are distinct widespread stratigraphic markers capping evaporite successions that accumulated during Wilsonian plate-motion cycles of extension and compression. Hydrocarbon-prone succession architecture is driven by base-level change during deposition; juxtaposing source, reservoir, and seals, and favoring hydrocarbon exploration and exploitation in Arabian Gulf, Central Asia, Atlantic, and the Cordilleran and Appalachian Mountains.

Critical to these settings are high rates of organic production, accumulation and preservation, a response to widespread enveloping continental plates windward of rain-shadowed lee shores of restricted anoxic and saline basins behind structural and/or depositional barriers. Internal drainage and/or limited access to open-ocean waters are products of linear belts of uplifted crust marginal to depressed crust, often below sea level, and so favoring evaporites and organic matter preservation. The upper bounding surface of updip, supratidal sabkha evaporite cycles is found in regressive coastlines, matching sea-level positions of late highstand system tracts while surfaces of downdip restricted playas and basin evaporites matches the sea-level position of lowstand system tracts.

Common updip shallow water carbonate platform play elements include sabkhas, salinas, and mudflats with nearshore and tidal-flat reservoirs sealed by lateral and top seal sabkha facies, and offshore bar and shoal complexes capped by tight peritidal carbonates. Examples include Central Basin Platform Permian San Andres, Arabian shelf Permian Khuff, and Devonian Dolomitized Wabamun ramp. Downdip carbonate-platform play elements include subaqueous salterns with platform-margin buildups; isolated buildups on
platform; and nearshore/tidal-flat plays. Examples include Eastern Arabian Basin Arab D and Eastern Siberian Basin Lower Cambrian Osa grainstone play.

Common basins play elements from shallow and/or deep basins include platform margin buildups, isolated buildups, and allochthonous mass-gravity deposits. With no structure, platform-margin buildups often lack top and lateral seal probability, but Iranian and Iraqi Asmari and Main Limestone plays have structure and potential. Smaller isolated buildups are the most successful play and include the Paradox Basin porous algal buildups, Western Canadian Middle Devonian Keg River play, and Michigan Basin Niagaran plays.

References


"The Giant Oil Field Evaporite Association" a function of the Wilson Cycle, Climate, Basin Position & Sea Level

CHRISTOPHER G. ST.C. KENDALL - University of S. Carolina
L. J. (Jim) WEBER – ExxonMobil Production Co.
ABDULRAHMAN ALSHARHAN - Middle East Geological Establishment
Acknowledgments

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for making the study reported in this presentation possible
Talk based on Proven Plays from Commercial Databases (e.g., C & C Reservoirs, IHS Energy, USGS Assessments)

Kendall, Weber & Alsharhan “Evaporite Plays”
Database captured 33% of total discovered reserves in carbonates
41% of plays exhibit an evaporite seal
64% of discovered reserves trapped under an evaporite seal
So evaporites are important?
Most are carbonate plays that accumulated beneath evaporite seals in inter-plate isolated restricted basins.

Location of Oil & Gas Fields of Arabian Gulf - Reservoirs are Younger to East
Evaporites - Tectonic Phase, & Source, Reservoir, & Seal, & Sea Level

- Major carbonate/evaporite successions accumulated in the arid tropics adjacent to continental plate margins at start of extensional & end of compressional Wilsonian phases of plate motion & to lee of structural & depositional barriers on trailing margins.

- These phases juxtaposed source, reservoir, & seal, favoring hydrocarbon exploration & exploitation.

- Geometries of hydrocarbon prone carbonate/evaporite successions are determined by position of base level change.

Evidence comes from plate motion cycles of Arabian Gulf, Central Asia, Atlantic, Cordilleran & Appalachian Mountains.

Kendall, Weber & Alsharhan “Evaporite Plays”
Kendall, Weber & Alsharhan

Break Up - Mesozoic of Northern Atlantic

restricted entrances to sea

isolated linear belt of interior drainage

regional drainage away from margin

juxtaposed source, seal & reservoir

SWEET SPOT!

arid tropics air system

wide envelope of surrounding continents
Break Up Margins & Evaporites

- Mesozoic of northern Gulf of Mexico
- Mesozoic of North & South Atlantic margins
- Mesozoic of Yemen rift belt
- Mesozoic & Tertiary of Eritrea
- East African Rift
- Dead Sea
Collision Margin Evaporites

- Restricted entrance to sea
- Regional drainage into basin
- Isolated linear belt of interior drainage
- Juxtaposed source seal & reservoir
- Arid tropics air system
- Wide envelope of surrounding continents
Collision Margin & Evaporites

- Current Arabian Gulf & underlying Late Mesozoic to Tertiary
- Silurian of Michigan Basin & Western New York State
- Devonian of Western Canada & NW USA
- Permian of New Mexico & West Texas
- Permian of Zechstein Basin
- Mesozoic to Tertiary of southern South America
- Tertiary of Mediterranean
- Mesozoic & Tertiary in final phases of Tethys Sea

Kendall, Weber & Alsharhan “Evaporite Plays”
Restricted Basin Evaporites

restricted shallow shelf to lee of carbonate margin

- transgression lowers sediment input
- & evaporite accumulation dominates

restricted deep water rifted basin

- evaporation causes evaporite precipitation

Christopher Kendall, 2009
Example of Barred Basin Mesozoic - Arabian Gulf

- restricted entrance to sea
- juxtaposed source seal & reservoir
- structural & depositional barrier over Hercynian horst blocks
- wide shadow from adjacent continents

- upper Jurassic
- Saudi Arabia
- Kuwait, Iran
- & UAE

- arid tropical air system

(Rees et al. 2000)
Restricted Basins Isolated by Build Up Barriers Organic Rich Fill Arabian Gulf Jurassic

After Fox & Albrandt, 2002
Evaporites trapped by structural & depositional barrier

- Late Paleozoic to Early Mesozoic beneath Arabian Gulf
- Cretaceous Ferry Lake Anhydrite of Florida

Punctuated by limited access to sea & repeated arid climatic events
Carbonate/Evaporites Plays & Sequence Stratigraphy

- Downdip restricted playas, salinas & basin evaporites (upper surface coincides with sea level position of the lowstand (LST) & following transgressive (TST) system tracts
- Updip supratidal sabkha evaporite cycles (upper bounding surface preserved in regressive coastlines matching sea level position of late high stand (HST) system tract
Low Stand Evaporite Signals

arid carbonates/evaporites with deep basin, saltern, &/or flanking mudflat settings

exposed shelf & margin

karst

basin isolation & evaporation

no eustatic signal

basinwide aggrading evaporites

lowstand systems tract

sequence boundary

Christopher Kendall, 2009
Transgressive Evaporite Signals

arid carbonates/evaporites saltern with flanking mudflat settings

platform evaporites

saltern

mudflat

leaking exposed aggrading barrier

relative fall isolates depressions

transgressive systems tract

eustasy

time

earlier LST evaporites

SL

transgressive surface

Christopher Kendall, 2009

Kendall, Weber & Alsharhan “Evaporite Plays”
High Stand Evaporite Signals

Arid carbonates/evaporites dominated by ephemeral coastal sabkhas

Maximum flooding surface

Continental sabkha flats

Marine sabkha flats & salinas in small depressions

Highstand systems tract

Eustasy

Time

Progradation (keep up)

Christopher Kendall, 2009

Kendall, Weber & Alsharhan “Evaporite Plays”
Major Evaporite Settings

<table>
<thead>
<tr>
<th>Basin-Center Evaporites</th>
<th>Platform Evaporites</th>
<th>Continental Evaporites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow to Deep Basin</td>
<td>Subaqueous Saltern</td>
<td>Sabkha, Salina, Mudflat</td>
</tr>
<tr>
<td>Mean Sea Level</td>
<td></td>
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</tbody>
</table>

- **Basin-Center (Commonly product of LST & TST)**
  - Thick evaporites deposited across whole basin (>50 m thick evaporite intervals)
  - Shallow to deep water evaporites occur in many different settings (shelf, slope, basin)

- **Platform (Commonly product of LST & TST)**
  - < 50 m thick evaporite intervals, commonly < 5 m thick evaporite beds inter-bedded with thin to thick carbonate intervals
  - Shallow water (Saltern) & subaerial (Sabkha, Salina, Mudflat) evaporites landward of barrier or sill
  - Open marine sediments deposited seaward of sill

- **Continental (Playa Lakes) (not discussed here)**

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Discovered Reserves for Proven Carbonate Plays
Total = 490,000 MOEB

Discovered Reserves for Proven Evaporite Plays
Total = 485,884 MOEB

- 52% Basin Center
- 48% Platform
Evaporite Setting Plays & Basin Phase Evolution

N = 9 Plays

<table>
<thead>
<tr>
<th>TECTONIC PHASE FOR PLATFORM-SUBAQUEOUS SALTERN EVAPORITE SETTINGS</th>
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</thead>
<tbody>
<tr>
<td>Rift</td>
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<tr>
<td>Post-Seal</td>
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<tr>
<td>Seal</td>
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<tr>
<td>Reservoir</td>
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<tr>
<td>Source</td>
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</tbody>
</table>

Passive Margin

- Seal: 
  - Peten
  - Arabian Platform
  - Timan-Pechora
  - Angara-Lena
  - Gulf Basin
- Source: Pelagian

Continental Interior

- Seal: Pelagian

Back-Arc

- Seal: Pelagian

Pathway for Passive Margin Settings

- 25% of Plays Do Not Evolve to Foreland Phase
- Stratigraphic Traps are Important
- Source, Reservoir, Seal Likely in Drift Phase
- >90% Source Rocks Carbonate in Origin
- Source Rocks in Close Proximity to Reservoir

Plays Occur in Passive Margin Settings

Source Reservoir Seal

Dominant Occurrence Minor Occurrence
# Evaporite Play Settings & Basin Phase Evolution

**N = 13 Plays**

## Tectonic Phase for Basin Center-Shallow Marine Shallow Basin Evaporite Settings

<table>
<thead>
<tr>
<th></th>
<th>Rift</th>
<th>Sag</th>
<th>Drift</th>
<th>Foreland</th>
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<tr>
<td>Post-Seal</td>
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<tr>
<td>Reservoir</td>
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<td>Source</td>
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<td>Reservoir</td>
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<tr>
<td>Source</td>
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</tbody>
</table>

**Passive Margin**

- Gulf Suez
- Michigan
- Oman Salt
- European Permain
- Williston
- Dnepr/Donets
- Pripyat
- Paradox

**Continental Interior**

- Amu Darya
- Western Canada

**Back-Arc**

- Zagros Fold Belt

### Play Elements & Tectonic Evolution

Pathway for Continental Interior Settings

- **Rift**
- **Sag**
- **Foreland**

**Plays in Continental Interior Settings**

- 40% of Plays Do Not Evolve to Foreland Phase
- Stratigraphic Traps Important
- Source, Reservoir, Seal Possible in ALL Phases
- >90% Source Rocks Carbonate in Origin
- Source Rocks in Close Proximity to Reservoir
Summary & Conclusions

- One can predict Carbonate Play Opportunities in Evaporite Basins from an understanding of Basin Phase Evolution and Evaporite Setting.

- The opportunities occur in:
  - Land Detached Isolated Platforms in Basin-Center Evaporite Settings in Arc-Related and Passive Margin Settings that Evolve to the Foreland Basin Phase.
  - Isolated buildups in Platform Evaporite Settings in Passive Margin Settings that May or May Not Evolve to the Foreland Basin Phase.

- The Exploration potential of Carbonate Plays in Evaporite Basin is good. However where the “prospects” are located is the ever evolving objectives tied to access to prospective acreage and a drilling program!
Conclusions

Now let’s find oil!
Arid Climates Common to Earth History

Evidence comes from:

- Evaporites of Mesozoic to Tertiary of Middle East; Paleozoic & Mesozoic the USA, Europe & Middle East
- Eolian sediments of Late Paleozoic & Mesozoic section of Western USA, Permian-Triassic of Western Europe & Middle East, Precambrian of India & NW Africa

All these evaporite basins have oil reserves

Kendall, Weber & Alsharhan “Evaporite Plays”
### Current Reserves for Middle East

<table>
<thead>
<tr>
<th>Country</th>
<th>Crude Oil (BB)</th>
<th>Natural Gas (TCF)</th>
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<tbody>
<tr>
<td>Saudi Arabia</td>
<td>263.5 bbls</td>
<td>204.5 Tcf</td>
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<tr>
<td>Iraq</td>
<td>112.0 bbls</td>
<td>109.0 Tcf</td>
</tr>
<tr>
<td>UAE</td>
<td>97.8 bbls</td>
<td>212.0 Tcf</td>
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<tr>
<td>Kuwait</td>
<td>96.5 bbls</td>
<td>52.7 Tcf</td>
</tr>
<tr>
<td>Iran</td>
<td>89.7 bbls</td>
<td>812.3 Tcf</td>
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<tr>
<td>Oman</td>
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<tr>
<td>Bahrain</td>
<td>0.1 bbls</td>
<td>3.9 Tcf</td>
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</table>

Most in carbonate plays beneath evaporite seals

*Kendall, Weber & Alsharhan “Evaporite Plays”*
Late Paleozoic - Arabian Gulf

Restricted Entrance To Sea

Juxtaposed Source Seal & Reservoir

Structural & Depositional Barrier over Hercynian Horst Blocks

Permian Khuff Saudi Arabia Oman & UAE

Arid Tropical Air System

Wide Shadow from Adjacent Continents

SWEET SPOT!
**Plays & Basin-Center Evaporites (BDMDB)**

**Possible Carbonate Plays**

1. **Platform (Margin) Buildup**
2. **Isolated Buildup Attached to Shelf/Ramp**
3. **Isolated Platform (Isolated Buildup Detached from Shelf/Ramp)**
4. **Allochthonous Deposit**
   - A. Megabreccia
   - B. Turbidites/Grain Flow

**Basin Examples:**
- Volga-Urals
- Amu Darya
- Caspian North
- Tadzhik

N = 6; 100,116 MOEB

Kendall, Weber & Alsharhan “Evaporite Plays”
Platform Evaporite Plays (PMM)

Platform Examples:

- Caspian Middle Tarim
- W. Canada Plains Neuquen
- Caucasus North
- Midland Basin
- Central Basin Platform

Possible Carbonate Plays:

1. Nearshore/Tidal Flat
2. Offshore Bar/Shoal Complex

Weber & Sarg, 2005

N = 7; 31,205 MOEB

99% > 90%

Kendall, Weber & Alsharhan "Evaporite Plays"
### Proven Plays & Known Opportunities

<table>
<thead>
<tr>
<th><strong>EVOLUTION TYPE</strong></th>
<th><strong>EXTENSION</strong></th>
<th><strong>THERMAL (SAG)</strong></th>
<th><strong>THERMAL (PASSIVE MARGIN)</strong></th>
<th><strong>CONVERGENCE</strong></th>
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<tr>
<td><strong>PASSIVE MARGIN</strong></td>
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</tr>
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Kendall, Weber & Alsharhan “Evaporite Plays”
Conclusions Hydrocarbon Potential

Successions of carbonate & evaporite sediments associated with:

- High rates of organic production
- Arid rain shadow of lee shores
- Restricted basins confined behind structural and/or depositional barriers
Conclusions – Arid Climate Thru’ Time

- Common through earth history
- Signaled by thick sections of evaporites from lacustrian & marine settings adjacent to margins of
  - Pulled apart continental plates
  - Compressional terrains of colliding margins
- Evaporites also common through earth history forming great marker horizons
Plate Phase & Restricted Basins

- break up
- collision
- lee of barrier
- arid setting

*Kendall, Weber & Alsharhan “Evaporite Plays”*
Hydrocarbon Play Settings

- Global platform subaqueous shallow shelf basins and saltern settings favor evaporite accumulation within:
  - Lowstand systems tracts *(Common)*
  - Transgressive systems tracts *(Common)*
  - Highstand systems tracts *(Uncommon)*

- Carbonates interbedded in evaporites often limestone from TST & early HST

- Decreased rate of relative sea level rise during late HST forms aggraded carbonate sills that favor percolation & so evaporite formation

Kendall, Weber & Alsharhan “Evaporite Plays”
Evaporite Conditions & Impact on Play Elements

- **Source Rocks**
  - Source & reservoir juxtaposed (90% same basin phase; >80% same super-sequence)
  - Silici-clastic source rocks not necessary (75% source rocks = carbonates)
  - Arid rain shadow of lee shores with low rainfall and low siliciclastic influx
  - High rates of organic production; algae & bacteria proliferate; limited in-fauna

- **Reservoir Rocks**
  - Exposed carbonate terrains less likely to experience pervasive pore-occluding meteoric diagenesis

- **Seal Rocks**
  - Reservoir and seal (successions of carbonate & evaporite sediments) juxtaposed (81% same basin phase; ~60% same super-sequence)
  - Evaporites form regional seals

Requisite Conditions = Restriction & Aridity

Abu Dhabi Arid Carbonate Coastline
Photo courtesy of NASA
Plays & Basin-Center Evaporites

SHALLOW MARINE SHALLOW BASIN

POSSIBLE CARBONATE PLAYS
1. PLATFORM (MARGIN) BUILDUP
2. ISOLATED BUILDUP
3. ALLOCHTHONOUS DEPOSIT (MEGA BRECCIA, TURBIDITE, GRAIN FLOW)

Examples:
- Gulf of Suez
- Michigan Paradox
- Oman Salt Basin
- Zagros Fold Belt
- W. Canada Plains
- Pripyat
- Dnepr/Donets
- Amu Darya
- Williston
- Central Iran

Kendall, Weber & Alsharhan “Evaporite Plays”
Platform Evaporite Saltern Plays

PLATFORM - SUBAQUEOUS SALTERN

Examples:
Arabian Platform
Timan-Pechora
Angara-Lena
Pelagian Platform
Gulf Basin
Peten Basin

Possible Carbonate Plays
1. Platform (Margin) Buildup
2. Isolated Buildup
3. Nearshore/Tidal Flat

N = 9; 200,920 MOEB

Weber & Sarg, 2005