Complex Feed Back Loops Controlling Heterozoan Reef Development on Salt Diapirs, La Popa Basin, Mexico*

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Abstract

In the distal part of the Hidalgoan foreland basin in NE Mexico three, isolated carbonate platforms nucleated on seafloor topography created by vertically rising passive diapirs. The platforms developed in both the Late Cretaceous (Maastrichtian) and early Paleocene and are composed of heterozoan fauna dominated by coralline red algae, benthic foraminifera, sponges, and bivalves.

Carbonate facies type and architecture of each platform was distinctly influenced by the complex interplay of both short-term local conditions surrounding individual diapirs and by long-term regional conditions that affected the entire shelf. Local conditions included windward-leeward platform geomorphology, possible cold seeps at the salt-sediment interface, and halokinesis. Regional conditions included eustatic sea-level fluctuations, foreland basin tectonism, and siliciclastic sediment supply to the outer shelf via hyperpycnal flows. No single factor dominates the system, but each plays a recognizable role in the final outcome of facies type, geometry, and initiation and demise of the platform.

Platform facies are distributed asymmetrically across individual diapirs, reflecting windward versus leeward margin paleogeographic setting and differential minibasin subsidence related to salt withdrawal. Carbonate facies form the base of angular unconformity-bounded carbonate/siliciclastic cycles called “halokinetic sequences.” The cycles reflect local variations in net diapiric-rise rates versus local sediment accumulation rates and vary in number and character between the different diapirs and between the windward and leeward margins of each diapir.

The presence of heterozoan faunal assemblages forming the platforms may be in response to high nutrient levels from local methane seeps forming at the salt-sediment interface and from continental runoff. The platforms form in the upper parts of parasequence sets developed within the transgressive systems tract (TST) of 3rd-order distal-deltaic siliciclastic depositional sequences. Hidalgoan shortening of La Popa
basin formed large wavelength salt-cored detachment folds. Diapirs that lie in the hinges of folds were shortened or “squeezed” significantly more than diapirs that lie on the limbs of folds. Squeezed diapirs generated much higher and broader topographic relief and are dominated by extensive, thick, shallow water (<15m deep) sponge, red algal reef and grainstone bank facies, whereas limb diapirs contain thin, deeper water (>30m deep) silty, red algal packstone facies reflecting lower carbonate production rates in a deeper water setting.

References


**Websites**

Controls on Heterozoan Reefs Developed on Salt Diapirs, La Popa Basin, Mexico

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Regional Location of La Popa Basin
Satellite Image of La Popa Basin

- La Popa salt basin
- Coahuila Platform
- Burgos salt basin
Geologic Map of La Popa basin

Explanation:

- **Tc**: Carroza Formation
- **Tv**: Viento Formation
- **Adjuntas Formation**
- **Tped**: Upper Potrerillos Formation
- **Tped**: La Popa lentil
- **Tped**: Upper Gordo lentil
- **Tped**: North Chivos lentil
- **Tsd**: Delgado Sandstone Member
- **Kp**: Lower Potrerillos Formation
- **Kp**: San Jose lentil
- **Kc**: Lower Gordo lentil
- **Kc**: Cuchilla Sandstone Tongue
- **Km**: Muerto Formation
- **Kp**: Parras Shale
- **Ki**: Indurada Formation
- **Kc**: Lower Cretaceous lentils
- **Kc**: Lower Cretaceous limestone
- **Jm**: Jurassic evaporite

Map Symbols:

- Strike and dip of bedding
- Photogeologic bed
- Anticline
- Syncline, showing plunge
- Fault
- Reverse fault, teeth on hanging wall

Legend:

- **La Popa diapir**
- **La Popa weld**
- **El Papalote diapir**

Geographic Features:

- **Parras Basin**: Location of the basin
- **La Gavia**: Geologic formation
- **El Gordo diapir**: Geologic feature
- **San Jose de la Popa**: Location of the location
- **Carriozos**: Location of the location

Scale:

- **km**: Distance scale on the map
Cross Section Across La Popa Basin

Parras basin

La Gavia anticline

Delgado syncline

El Gordo diapir

El Papalote diapir

La Popa weld

NNE | WSW

NE  | SSW

N  | SW

Km

Secondary Detachment

Kpa

Ju-Kl

Jm

Km

Kpa

Ju-Kl

Ju-Kl

Jm

Kpa

Kpd

Km

Kpa

Km

Kpa

Km

Ke

T v

T p l

P p s j

K m

K p l

K p l

K p l

K p l

K p a

0

1 2 3 4 km

Meters

0 1000

-1000

-2000

-3000

-4000

-5000

-6000

-7000

-8000

A' ENE
Outcrop of El Gordo Diapir
Local Controls:
Windward-Leeward Facies
El Gordo Depofacies Cross Section
Windward Facies
Outcrop of massive reef

Delgado Sandstone Tongue

Upper Gordo lentil
Windward Facies
Forereef Calciturbidities
Windward Facies
Heterozoan Fauna: Red Algal & Sponge Reef
Leeward Facies
Outcrop of Grainstone Clinoforms in Paleocene La Popa Lentil

Photo by Bob Goldhammer
Leeward Facies
Heterozoan Fauna: Benthic foram, echinoderm, red algal grainstone
Great Barrier Reef Satellite Image
Windward-Leeward Facies

(Harris and Kowalik, AAPG Methods of Exploration. No 11 1994.)
Heterozoan Fauna vs. Photozoan Fauna

- Red algae
- Sponges
- Echinoderms
- Bivalves
- Bryozoans
- Brachiopods
- Benthic forams

- Hermatypic coral
- Green algae
- Rudistid clams
Controls on Heterozoan Faunal Distribution

1. Cool water temperatures
   - Latitude
   - Upwelling

2. High nutrient levels
   - Upwelling
   - Continental runoff
   - Methane/cold seeps
# Cold Water Controls: Latitudinal Belts

<table>
<thead>
<tr>
<th></th>
<th>TROPICAL &gt;22°C</th>
<th>SUBTROPICAL 22-18°C</th>
<th>TEMPERATE 18-10°C</th>
<th>COLD 10-5°C</th>
<th>POLAR &lt;5°C</th>
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<td>Chlorozoon</td>
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<td>Nelson (1988)</td>
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<td>Non-tropical</td>
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<td>Betzler et al. (1997)</td>
<td></td>
<td></td>
<td>Warm temperate 20-11°C</td>
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<tr>
<td>James (1997)</td>
<td>Photozoan</td>
<td></td>
<td>Heterozoan</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cold Water Controls: Upwelling

Strong offshore winds cause low pressures near shore.

Upwelling of deep, colder water.

Effects of upwelling.

Normal temperatures.

Continental slope.
High Nutrient Control

**NUTRIENT GRADIENT** (mg Chlα/m³)

- **OLIGOTROPHIC**
  - DOMINANT BENTHOS: CORAL
  - PRIMARY CONTROL: NUTRIENT LIMITATION
  - REGION: CARIBBEAN SEA
  - MODERN: OCEANIC REEFS

- **MESOTROPHIC**
  - DOMINANT BENTHOS: CORAL-ALGAE, MACROALGAE
  - PRIMARY CONTROL: COMPETITION
  - REGION: GULF OF MEXICO
  - MODERN: SUBTROPICAL, EQUATORIAL

- **EUTROPHIC**
  - DOMINANT BENTHOS: HETEROTROPHS
  - PRIMARY CONTROL: LIGHT
  - REGION: RIVER DELTAS
  - MODERN: MERIDIONAL

- **HYPERTROPHIC**
  - DOMINANT BENTHOS: BACTERIA
  - PRIMARY CONTROL: OXYGEN
  - REGION: SEWAGE OUTFALLS
  - MODERN: CORAL REEF TURN-ON/TURNOFF ZONE
Ways to Increase Nutrient Levels

1. Upwelling
2. Continental runoff
3. Methane/cold seeps
Increased Nutrient Levels: Continental Runoff

Modified from Goldhammer (1999)
Geologic Map of El Papalote Diapir

El Papalote lentils
silty oyster packstone
El Papalote Lentil Facies Silty Oyster Bank
Outcrop of Lentil Geometry
Lentils and Hyperpycnal Flows/Deposits
Basinal Black Shales and Hyperpycnal Flows/Deposits
Outcrop of Hyperpycnal Flow Deposits

Image of outcrop with indication of Cl, fs, ms, cs, fsa, msa and 1 m scale.
Hyperpycnal Flows Indicate Increased Continental Runoff

‘Density outflows from a river mouth with a density greater than the ambient fluid into which they flow’ (Bates, 1953)

• Form bottom-riding density flows resulting from extreme river flooding events.
Increased Nutrient Levels: Methane Cold Seeps

http://www.ifremer.fr/serpentine/fiches/fiche4-img1-web.jpg
East Flower Garden Banks as Modern Analog

Water temperature: 20°C-30°C tropical

Water depth ranges: 20m-136m

www.gulfbase.org
Geologic Map of El Papalote Diapir
Cross Section of El Papalote Diapir

- Halokinetic breccia
- Overturned depositional syncline
- Lentil 1
- Lentil
- Lentil 2
- Lentil 3
- Lentil 4
- Lentil 5
- Lentil 6
- Delgado ss. tongue?
- Evaporite debris flow
- Black shale

HALOKINETIC SEQUENCE I II III IV V VI
Model of Type A Halokinetic Sequences

**PHASE 1**
Diapir rise rate greatly exceeds local sediment accumulation rate. Results in diapir inflation.

**PHASE 2**
Failure of inflated diapir margin. Results in generation of angular unconformity and overlying debris flow.

**PHASE 3**
Sediment accumulation rate greatly exceeds diapir rise rate. Results in sediment onlap and overlap of diapir.

**PHASE 4**
Diapir rise rate greatly exceeds local sediment accumulation rate. Results in generation of next halokinetic sequence boundary.
Local Control- Shadow Zone

From Kneller and McCaffrey (GCSSEPM, 1995)
Type A Shadow Zone

El Papalote Diapir

Sediment influx

Cretaceous Sand-rich oyster banks

Tertiary Sand-rich oyster banks

Sand-poor Bryozoan bioherm
Normal Lentil Facies
Silty Mollusc Packstone
Shadow Zone Lentil Facies
Sponge, Bryozoan, Brachiopod
Shadow Zone Lentil Facies: Brachiopod Bioherm

Klosterman et al., 2007, J. Paleont
Regional Control Relative Sea Level

HALOKINETIC SEQUENCES
ON THE NORTH SIDE OF LA POPA SALT WELD

LA POPA SALT WALL

HALOKINETIC SEQUENCES
Axis of La Popa Syncline

THIRD-ORDER COMPOSITE HALOKINETIC SEQUENCES

THIRD-ORDER DEPOSITIONAL SEQUENCE STRATIGRAPHY

SEQUENCE BOUNDARY
HIGHSTAND SYSTEMS TRACT

LARGE SALT CUSP

COMPOSITE SEQUENCE III

TYPE B

TRANSGRESSION SYSTEMS TRACT

LARGE SALT CUSP

COMPOSITE SEQUENCE III

TYPE A

HIGHSTAND SYSTEMS TRACT

DEPTH OF OUTCROP EXPOSURE

2 km

200 m

100 m

KT Boundary
Regional Structural Control
Seismic of “Squeezed” Diapir

Data courtesy of WesternGeco and Shell
Regional Structural Control

Paleocene Paleogeographic Map

- San Jose lentils 1 and 2
- Leeward
- La Popa syncline
- Carroza syncline
- El Gordo anticline
- La Popa diapir
- Delgado syncline
- Lower Gordo lentil
- El Papalote diapir
- El Papalote lentil 1
- siliciclastic sediment influx
- approx. 26° N
- lowermost shoreface
- prevailing winds
- slope break
- outer shelf facies
- HIDALGOAN FORELAND BASIN

North

7 km
Controls on Maastrichtian and Paleogene Carbonate Platforms

1. Passive salt diapirs created bathymetric highs for platform development
2. Windward –leeward asymmetric facies distribution on platform
3. Heterozoan fauna due to raised nutrient levels from detrital influx and cold seeps?
4. Brachiopod reefs in shadow zone of diapir
5. Platforms confined to TST of 3rd-order depositional sequences
6. Thickest, most widespread, shallow water platforms on shortened diapirs