Breakthroughs in the Use of Analogues for Geological Modeling – Examples from Holocene Sabkhas of Qatar*

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Abstract

The use of modern depositional systems as analogous, conditioning data in geological models is well established in the oil and gas industry. Most historical analogue work has been based on surface mapping and satellite imagery of facies patterns. These images are devoid of data on origin, thickness, age, time lines, sea-level history, and pore-water chemistry. Without such data it is difficult to determine how modern data should be applied to a geological or diagenetic model.

This paper presents the first results of a countrywide integration of surface sediments, ages, thicknesses, composition, and pore-water chemistry in an ArcGIS model. Industrial geotechnical data from boreholes, building excavations, and offshore dredging provided data on thickness and ages of the Holocene. This is the first integration of analogue data into a geo-referenced framework, examining modern analogue data in a format similar to that of ancient rock data.

The Holocene coastal systems of Qatar and Abu Dhabi have long been regarded as the most valid analogues for arid climate, carbonate ramp depositional systems. The coastlines vary in orientation to prevailing winds, sediment supply, and elevation profile. These factors create four major coastal, physiographic areas; each distinguished by variable facies types and facies proportions. Accordingly, windward, leeward, oblique and protected shoreline depositional profiles are recognized. All have a common sea-level history of a rapid rise over the last 10,000 years, followed by a highstand 4000-6000 years before present; approximately 2-4 meters above present-day sea level. Comparison of sabkha features between physiographic provinces provides an insight into the variability that might be expected in an ancient sabkha.

Comparisons of depositional and diagenetic histories along the different parts of the coast provide the basis for distinction of depositional models that can be incorporated into geological models. Facies types, 3-D shapes, ordering and internal structure are derivable conditioning parameters from modern data.

We propose that the use of modern depositional systems as analogues for ancient reservoir rocks should evolve in complexity, just as geological models have. Recent advances in geological modeling resolution call for equally high-resolution conditioning data, derived from Holocene sequence stratigraphic and diagenetic models.

Selected References

Jameson, J., D.D. Puls, and M.G. Kozar, 2010, Holocene Sabkha and Coastal Systems of Qatar: Process Models for the Interpretation of Ancient Arabian Plate Carbonate-Evaporite Reservoirs: International Petroleum Technology Conference, Doha, Qatar, Paper 13679-MS, 10 p.

Lambeck, K., 1996, Sea-level change and shore-line evolution in Aegean Greece since Upper Palaeolithic time: Antiquity, v. 70, p. 588-611.

Puls, D.D., J. Leblanc, M. Kozar, J. Jameson, and H. Al-Ansi, 2009, The Dukhan Sabkha: A Modern analog for the Arab C carbonate reservoir, Dukhan Field, Qatar: International Petroleum Technology Conference Proceedings, Doha, Qatar, 13 p.

Puls, D.D., M.G. Kozar, and J. Jameson, 2009, Holocene Sabkha and coastal systems of Qatar: Process models for the interpretation of ancient Arabian plate carbonate evaporite reservoirs: International Petroleum Technology Conference Proceedings, Doha, Qatar, 8 p.

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Aspects of modern, Qatar sabkhas that aid in modeling of ancient arid carbonates:

1. Recognition: Sabkhas are composed of marine sediments modified by a combination of evaporitic groundwater and pedogenic processes

   Gypsum is most common precipitate, minor anhydrite and salt

2. Ancient sabkhas

   - Recognition of a sabkha is largely based on the evaporite overprint
   - A sabkha is a diagenetic overprint- not a depositional facies
   - Comparable to dolomite as an alteration of a precursor

3. Variable composition and progradation patterns; regular facies order

4. Sub-regional deflation surfaces underlain by evaporites- important marker criterion

5. Facies offsets- form at sea level; little aggradation; overstepping progradation,

   Offsests can be incorporated in high-resolution models

6. Thickness of Holocene 4-8 meters: at scale captured in geological models
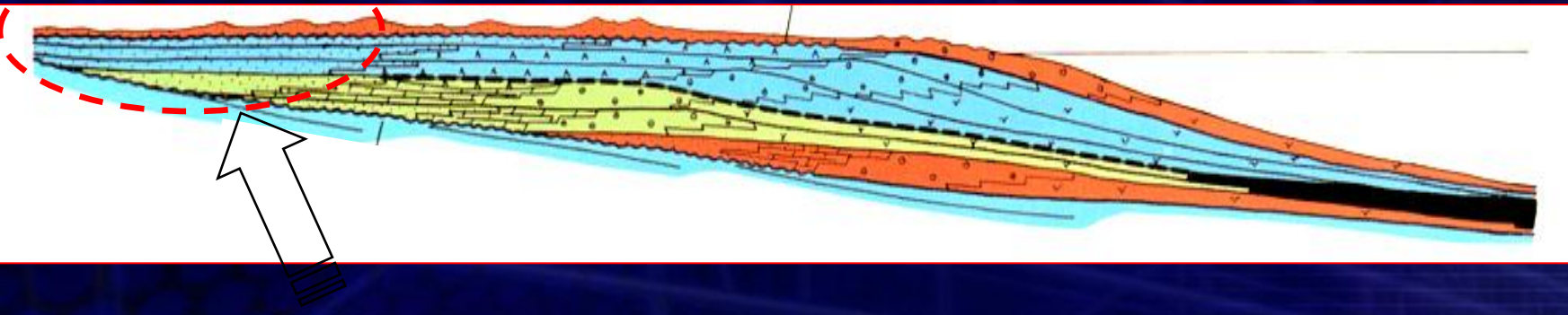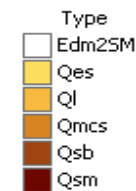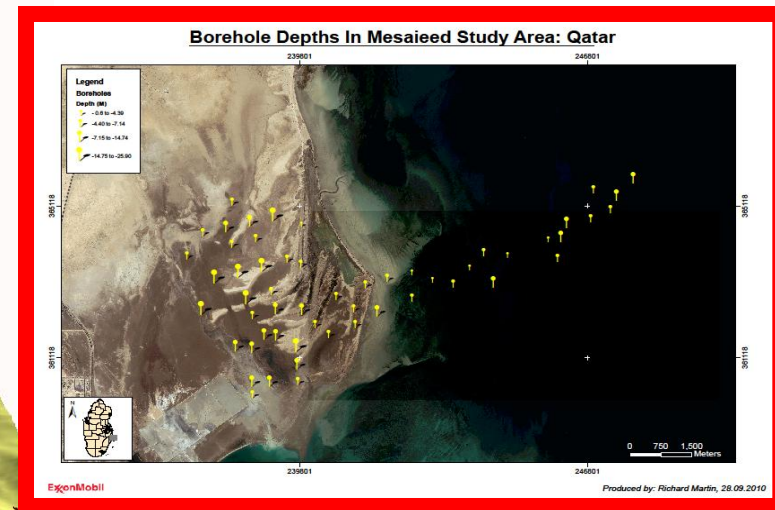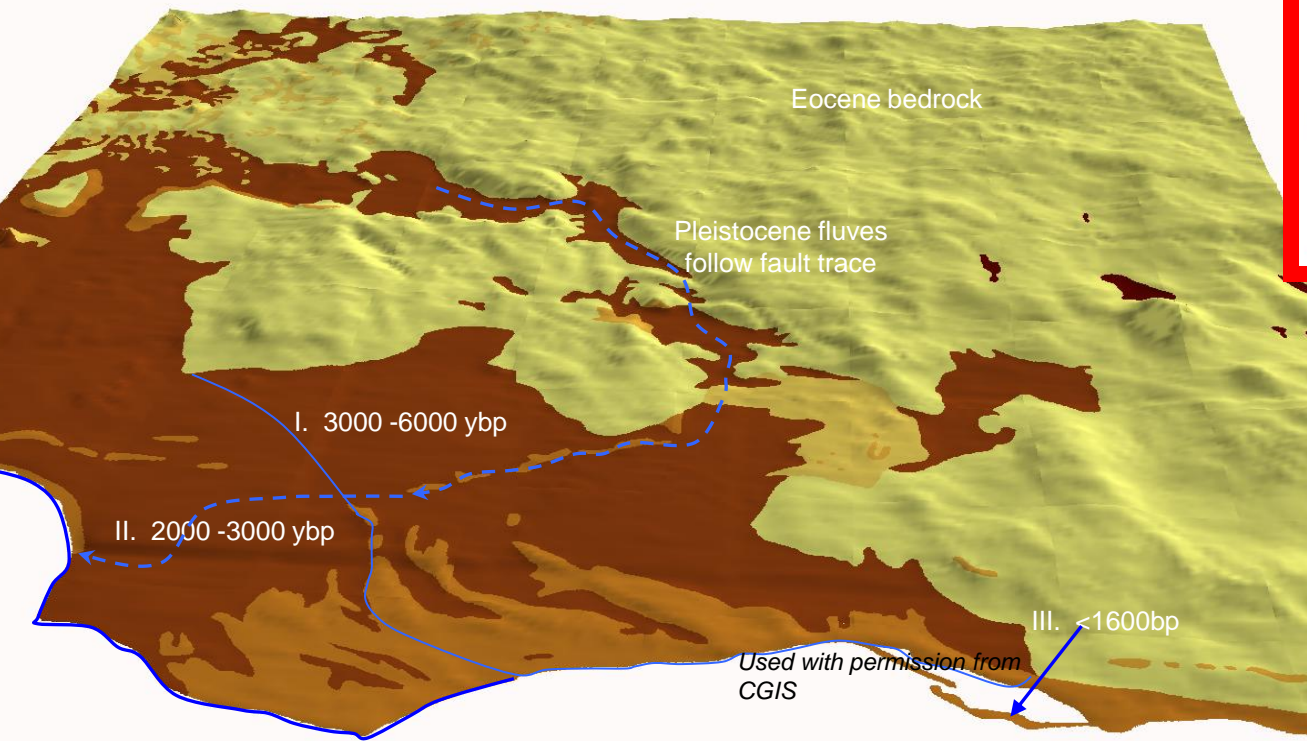
- Sabkhas are most landward facies tract in ramp profile

    Form at sea level- modified above sea level

- Major source of diagenetic fluids for evaporite cementation; lots of microbial dolomite; no grainstone-replacement dolomite

- Analogues to major Middle East and US reservoirs: Khuff and Arab formations
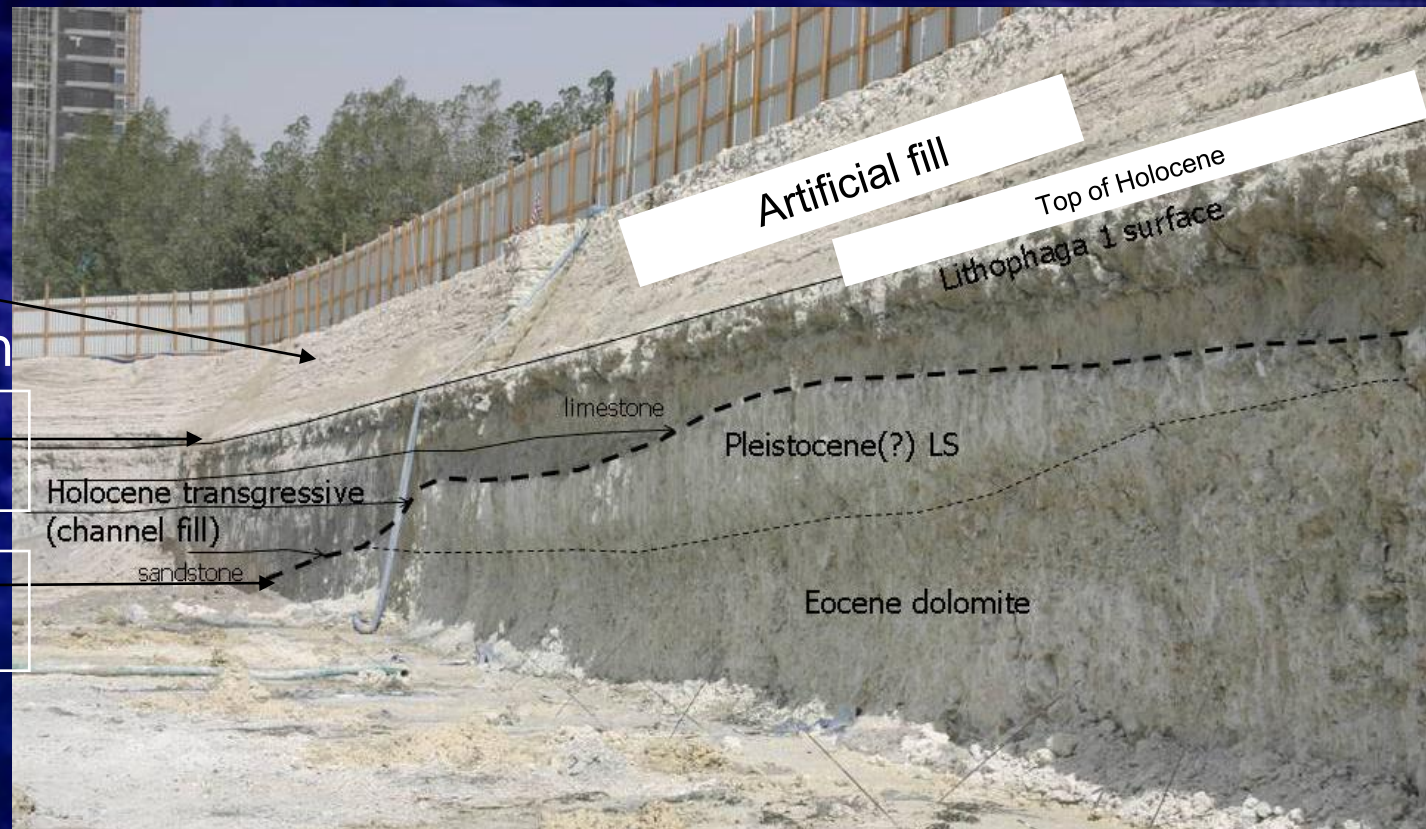
Perspective view of Dukhan sabkha
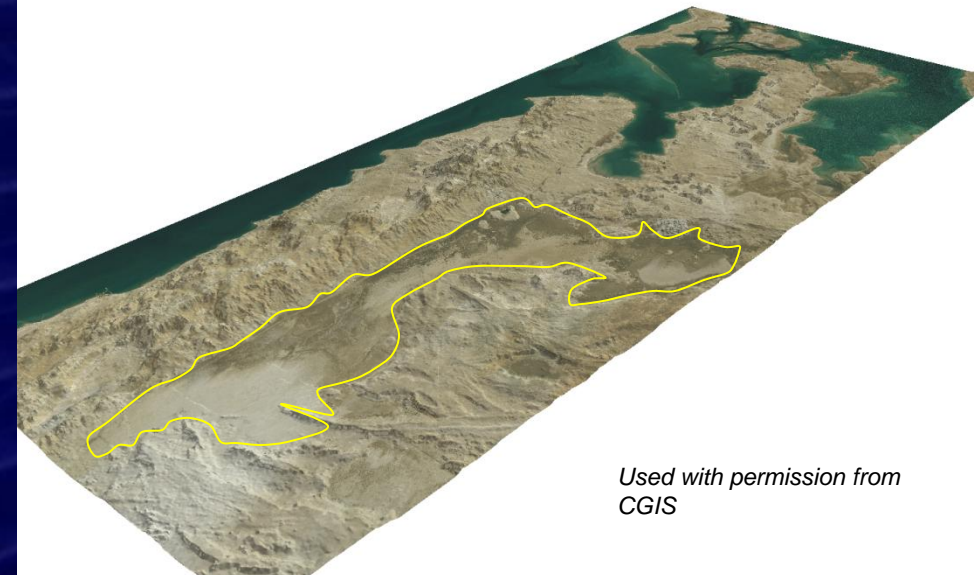
- Countrywide (+nearshore) digital databases: DEMs, surface geology, composition, water chemistry in ArcGIS

- 3-Dimensional- based on geotechnical studies (ports, airports, industrial and commercial projects, coring and 10 years of field mapping)

- Age control

- Building hydrological and geological models

Borehole Depths In Mesaieed Study Area: Qatar

Produced by: Richard Martin, 28.09.2010

ExxonMobil

Eocene bedrock

Pleistocene fluves follow fault trace

I. 3000 -6000 ybp

II. 2000 -3000 ybp

III. <1600bp

Used with permission from CGIS

Type
- Edm2SM
- Qes
- Ql
- Qmcs
- Qsb
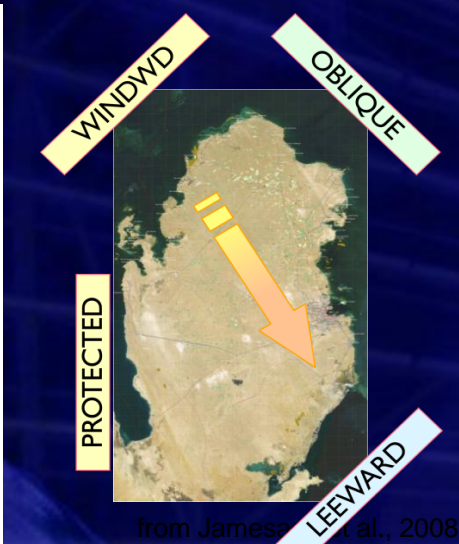- Qsm

New Exposures

Palm Tower Pit Exposure: Incised Valley filled with carbonates and clastics during Holocene sea level rise

Doha Corniche Reclamation

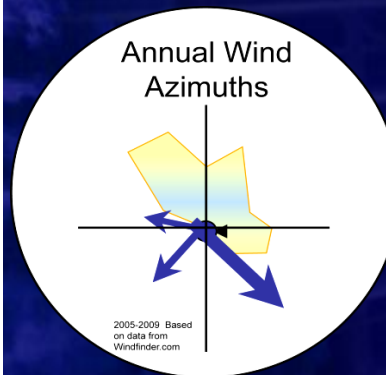Open Marine Coralgal sands
2300 bp

Transgressive Stromatolite 8000 bp
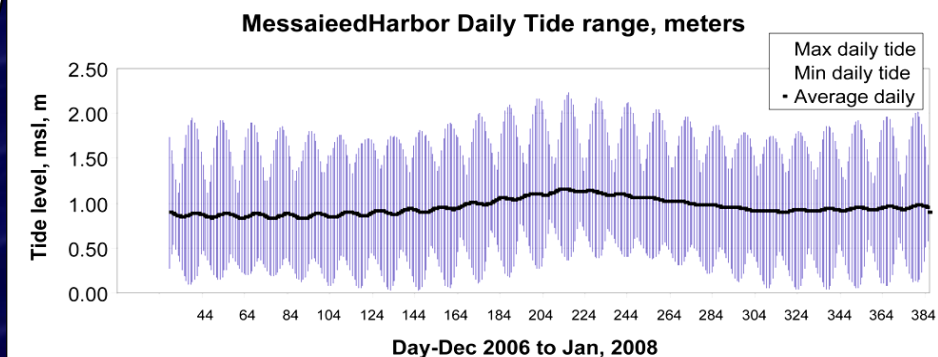
Artificial fill

Top of Holocene

Lithophaga 1 surface

limestone

Pleistocene(?) LS

Holocene transgressive (channel fill)

sandstone

Eocene dolomite

Surface Geology of Qatar
Technical Services Department Data Center EED
Scale: 1:500,000

WINDWD
OBLIQUE
PROTECTED
LEEWARD

from Jameson et al., 2008

Used with permission from CGIS-from Jameson et al. 2006

Annual Wind Azimuths

2005-2009 Based on data from Windfinder.com

Used with permission of QP GIS (UPDA) from Jameson et al. 2010

Coastal deposits comprise 18% land surface of Qatar

- Mean annual temperature 26C range 19-43

- Hot tropical dry climate (7.5 cm rain/yr avg)

- High negative water balance (difference between precipitation and evaporation 0 - ~1700 along coast.

- Strong seasonal winds from northwest drive marine circulation
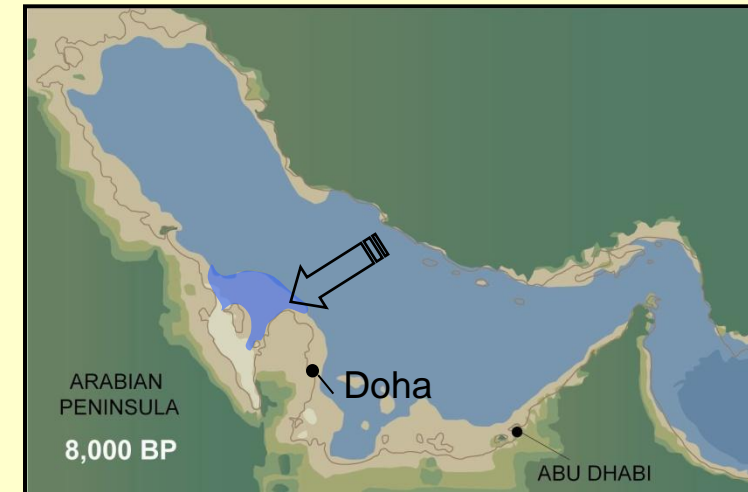
- Micro-tidal range ~1.6 m average

MessaieedHarbor Daily Tide range, meters

Max daily tide
Min daily tide
Average daily

Tide level, msl, m

Day-Dec 2006 to Jan, 2008

Pleistocene sea level history

18,000 BP

Last glacial maximum: arid, alluvial valley

10,000 BP

Gulf floods very rapidly- ~ 1m/100 years

12,000 BP

Straits of Hormuz flood

8,000 BP

Salwa floods, Qatar forms peninsula

After Lambeck, 1996

Holocene sea level

Years before present ka

- Rapid rise

- Highstand above present day + 2-4 m

- Marked oscillations, stillstands

- <3000 yrs drop to present day

Relative sea level m

Unit 3

Unit 4

Doha Hg hiatus

Beaches offset

C wide Hardgnd

Literature
Strom
Hardground
Beach
KSA
Borehole
Inter-subtidal
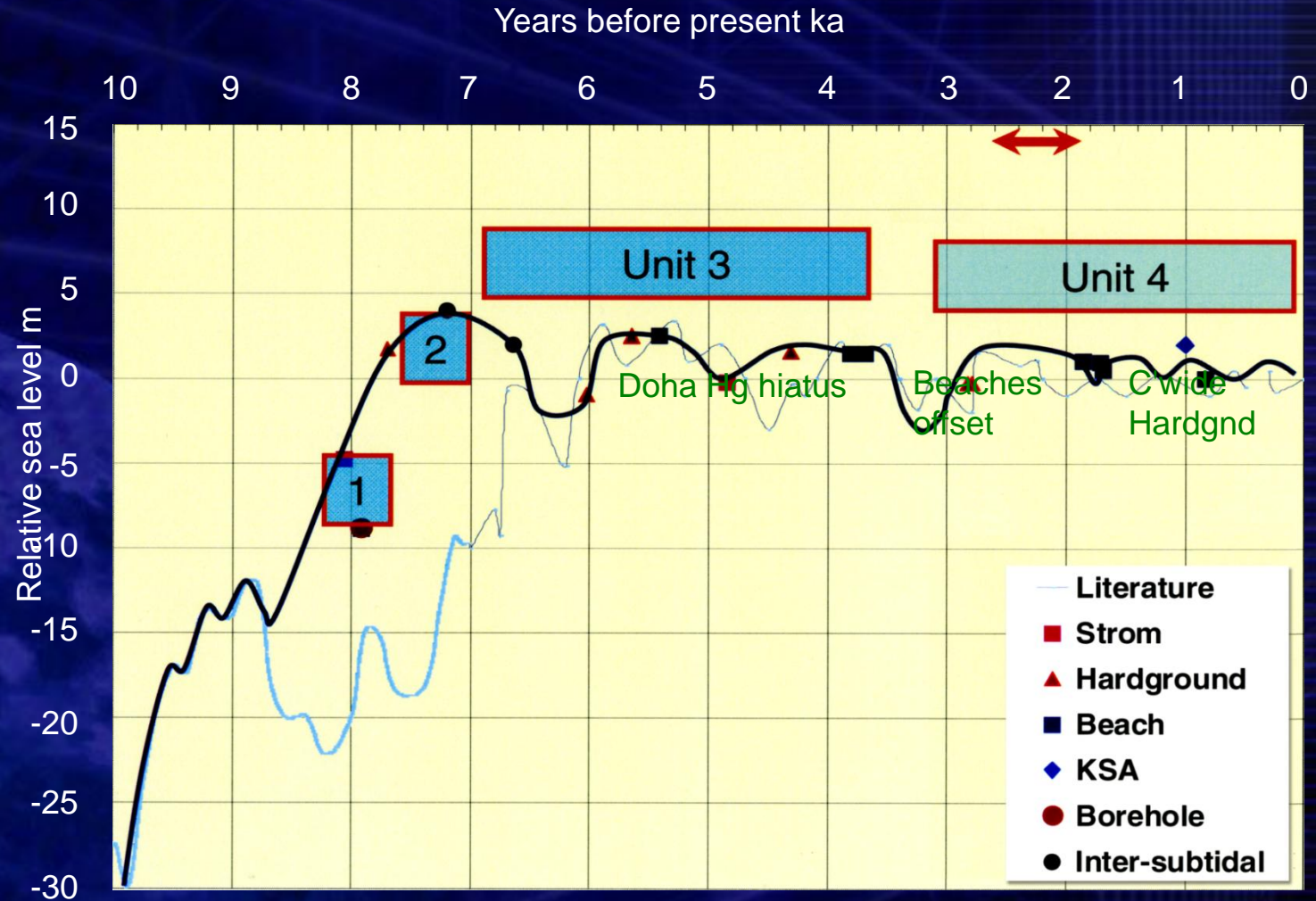
Jameson et al., 2010

Evidence of Holocene Highstand

Eolian Deflation
surface

40-60 cm

- Intertidal sand 4000 ypb

- 1.7 m above sea level

- Erosional top; ~ 1 to 1.5m removed

Marcia flammea 3990 bp

Jameson et al., 2010

Decimeter plates of gypsum originally formed above water table at top of erosional remnant indicate ~ 150-100 cm erosion

Stillstands marked by regional marine hardgrounds

With permission

QP Centre GIS (UPDA)

Lithophaga bored hardground

Borer: 4310 bp

1430 yr hiatus

Rock: 5650 bp

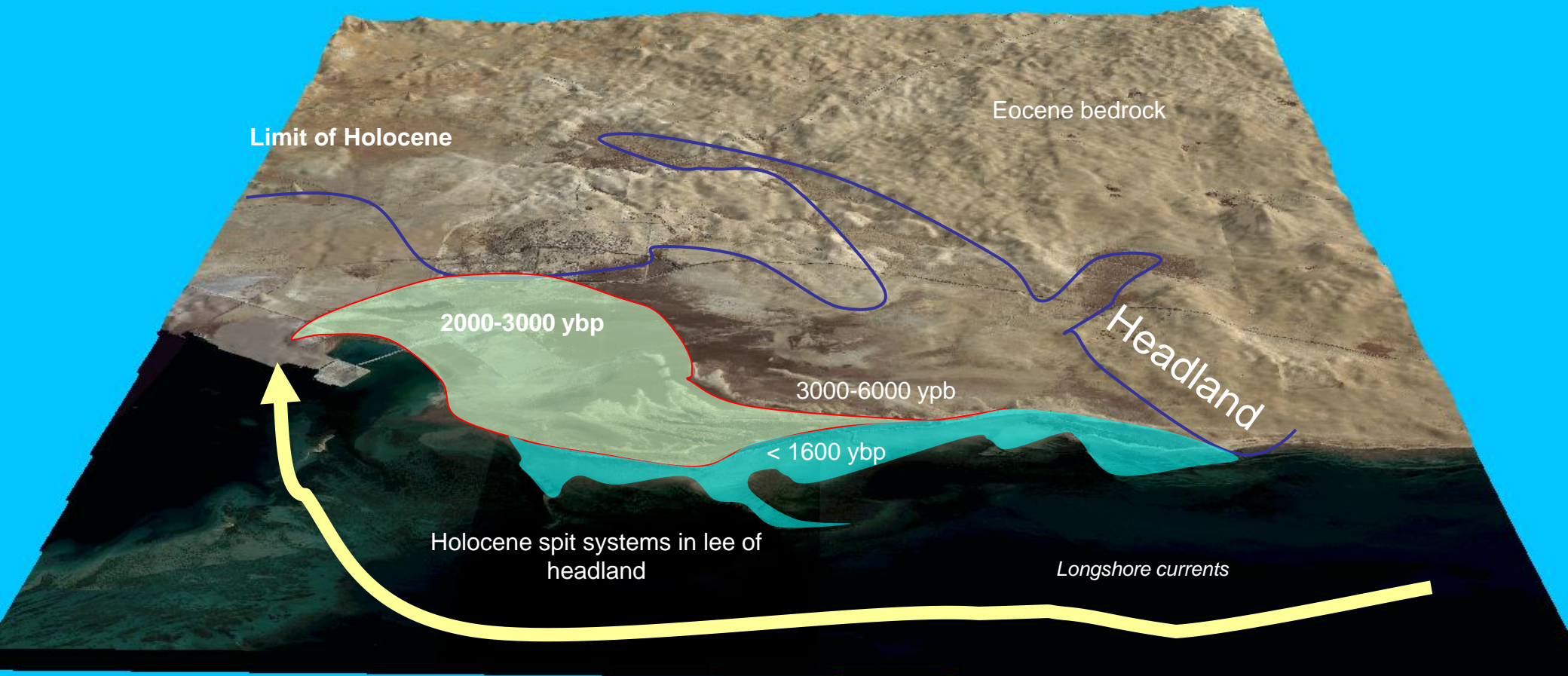Sea level drops marked by offsets in coastal spits

>4000 bp

1

< 2000 bp

2
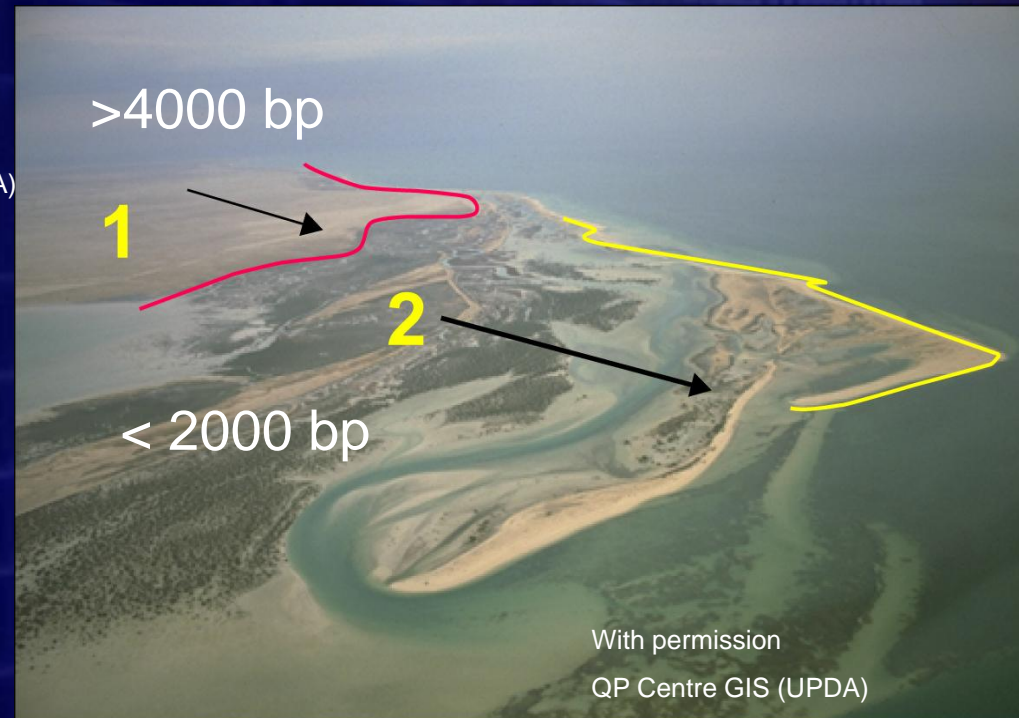
With permission

QP Centre GIS (UPDA)

Al Thakhira view from south, showing facies offsets coincident with sea level changes

Origin and Depositional pattern: rapid aggradation followed by episodic seaward progradation

AAPG 2011

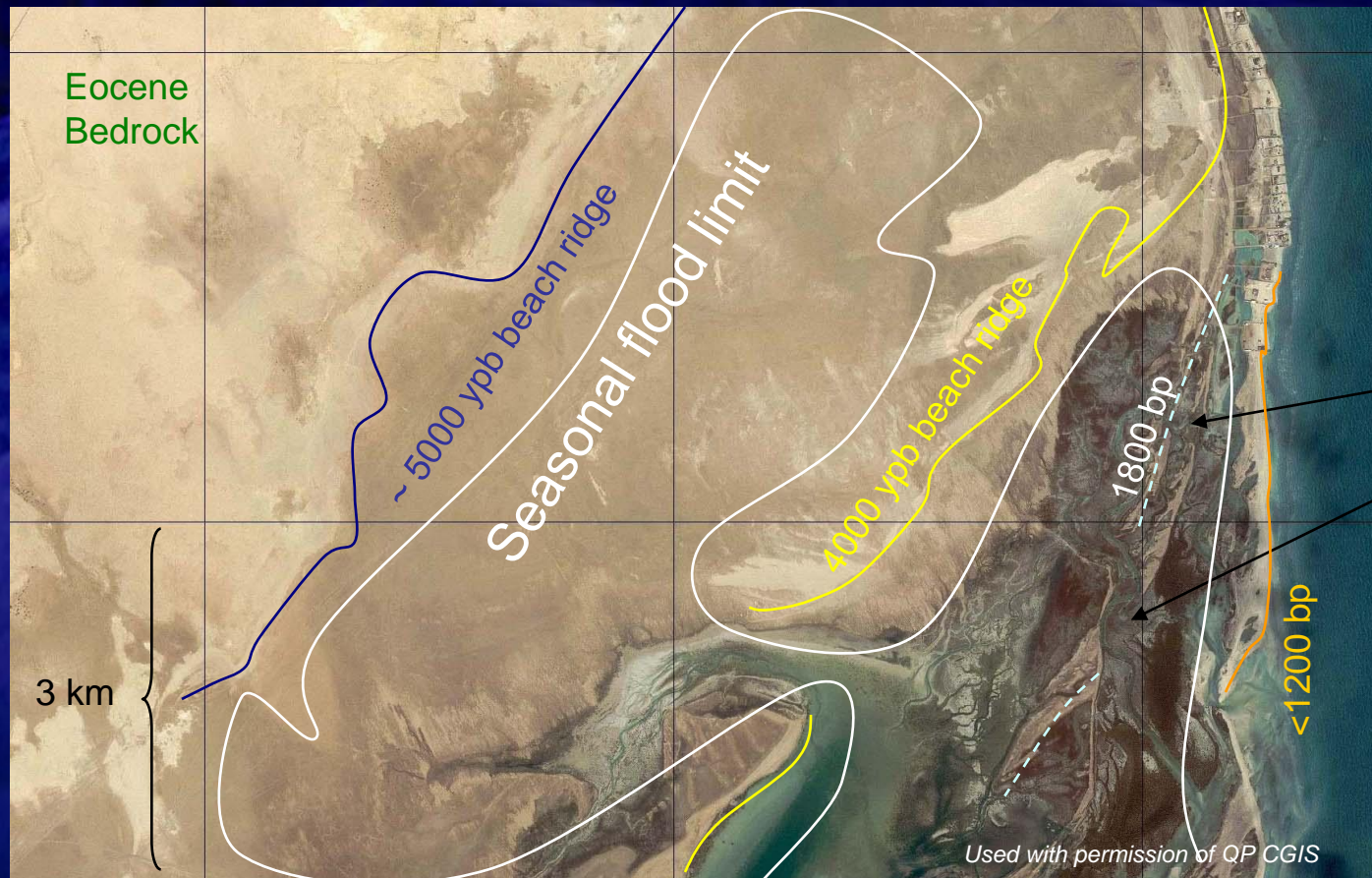Leeward accretion of spit systems around headland

Eocene bedrock

Limit of Holocene

2000-3000 ybp

3000-6000 ypb

< 1600 ybp

Headland

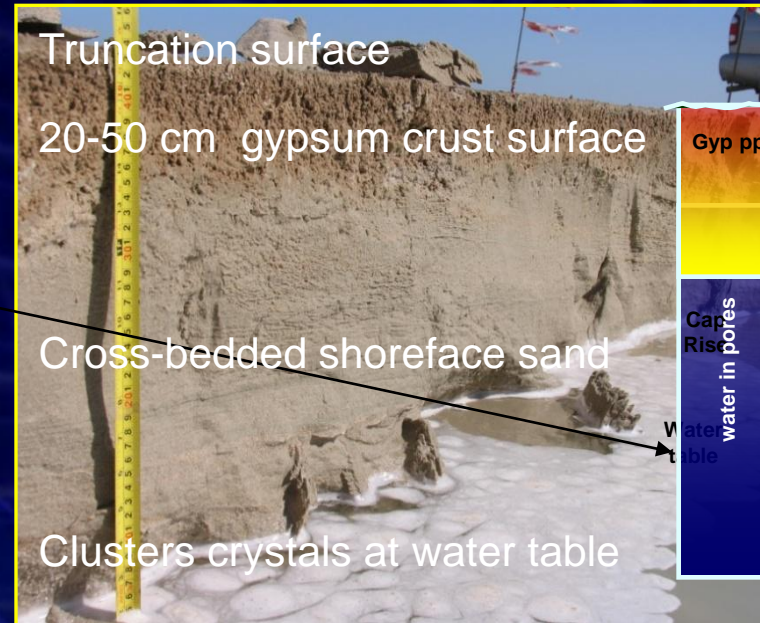Holocene spit systems in lee of headland

Longshore currents

Imagery used with permission CGIS

Back-barrier areas are characterized by both tidal erosion and Stokes deflation. They are often marked by evaporites

Eocene Bedrock

~ 5000 ypb beach ridge

Seasonal flood limit

4000 ypb beach ridge

1800 bp

<1200 bp

3 km

Tidal drainage redistribution of beach ridges

Imagery by DigitalGlobe

Used with permission of QP CGIS

Regional erosion surfaces marked by evaporites

Example of erosion and gypsum precipitation at a deflation surface

Truncation surface

20-50 cm gypsum crust surface

Cross-bedded shoreface sand

Clusters crystals at water table

Gyp ppt

Cap Rise

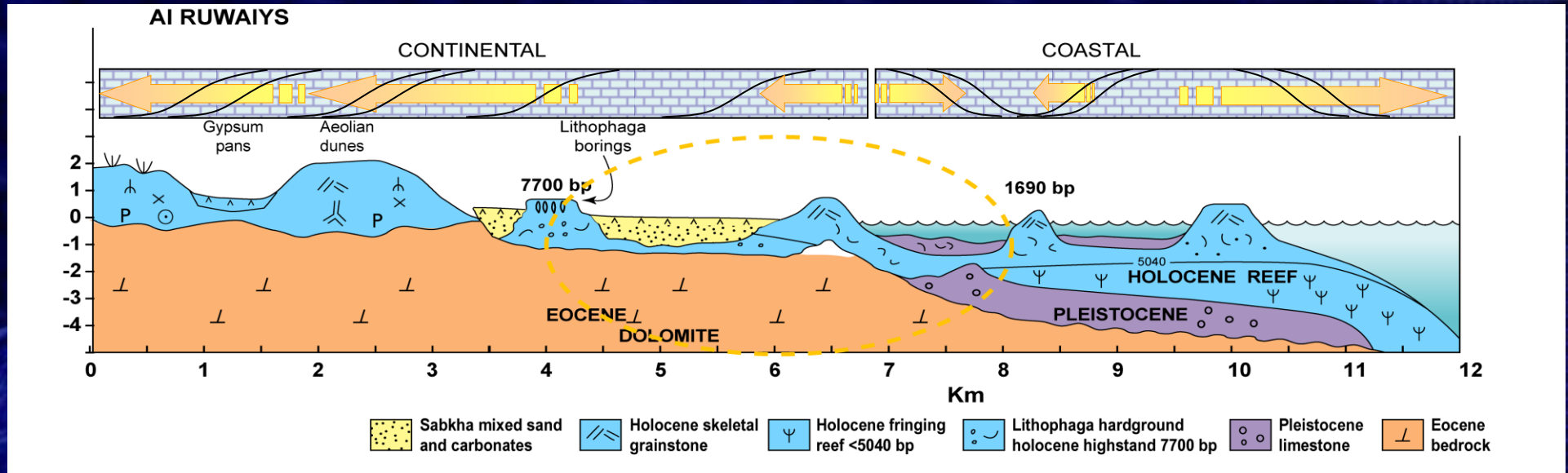water in pores

Water table

Eolian Deflation surface

40-60 cm

Used with permission from CGIS- from Jameson et al., 2010

25 km

Evaporation

Meters | Mud | Silt | Fine | Med | Low | Crse | VCrs | Grvl | Evap

Sand

Lam gyp crust

Skel sand lam and ebb oriented troughs

Creamy micrite with whole

Laminated skeletal sand

Burrowed skeletal mollusc sand

Cemented coarse skeleltal sand

AI RUWAIYS

CONTINENTAL — COASTAL

Gypsum pans · Aeolian dunes · Lithophaga borings

7700 bp · 1690 bp

EOCENE DOLOMITE · HOLOCENE REEF · PLEISTOCENE · 5040

Legend:
- Sabkha mixed sand and carbonates
- Holocene skeletal grainstone
- Holocene fringing reef <5040 bp
- Lithophaga hardground holocene highstand 7700 bp
- Pleistocene limestone
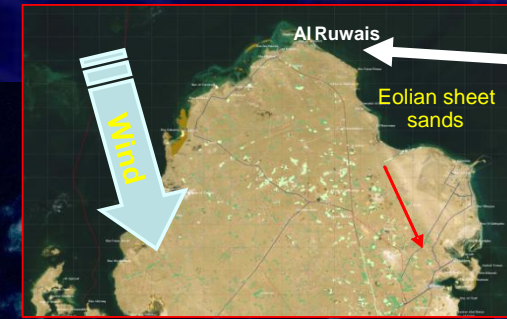- Eocene bedrock

- Little or no sabkha
- Broad coarse, mollusc-red algal intertidal sands
- Broad eolian sheet sands
- Marked facies offsets
- Early Holocene fringing reef platform
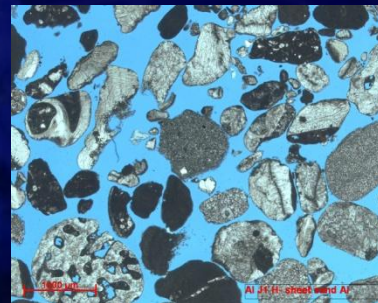
Back-barrier carbonate sheet sands 100 km^2

Al Ruwais

Wind

Eolian sheet sands

Used with permission QP Centre for GIS

Limit of platform

Limit of platform

Ras Ra Kha

5 km

Subtidal

Subtidal

Intertidal

Umm Taiys

Shoreline

Sabkha with inliers of Holo Highstand and Eocene

Sabkha with inliers

Broad intertidal, shifting sand platform with

Beachrock stabilized islands

Built on early Holocene fringing reef

From Jameson et al, 2010, Imagery used with permission of CGIS

Surface Geology of Qatar

Used with permission of QP GIS
(UPDA) from Jameson et al., 2010

Variable progradation
directions Bir Zekreet

Used with permission QP Centre for GIS- from Puls et al., 2009

Foram peloid
sands

Peneroplis planatus

• Indented coastline, low energy, fine grain size, low-relief beaches
• Foram, peloid sands- up to 90% forams
• Elevated salinity
• Continental sabkhas below sea level
• Variable progradation directions: leeward accretion from highs

Interior Protected Coast

Concentric facies distribution Dukhan Sabkha

- Higher salinity= anhydrite
- Evaporite pans in interior areas
- Deflation below sea level
- Variable progradation directions
- Concentric pan fills

Legend:
- E - Eocene Undifferentiated
- Er - Eocene Rubble
- H af - Cryptalgal mat - blistered
- H br - Holocene extensive beach rock
- H cc - Holocene beach-shoreface course carbonate
- H ds - Holocene Aeolian dune sand
- H gcm - Holocene Salina gypsum crystal mush
- H itc - Holocene Intertidal carbonate sand
- H pc - Holocene pustulose gypsum crust
- H pct - Holocene thin gypsum crust
- H pds - Holocene pebble deflation surface
- H sf - Holocene salt flat
- H sfc - Holocene beach-shoreface carbonate
- H ss - Holocene carbonate sand
- H taf - Holocene thin algal laminite
- H td - Holocene channels
- H vss - Holocene sand flat
- HH br - Holocene beach
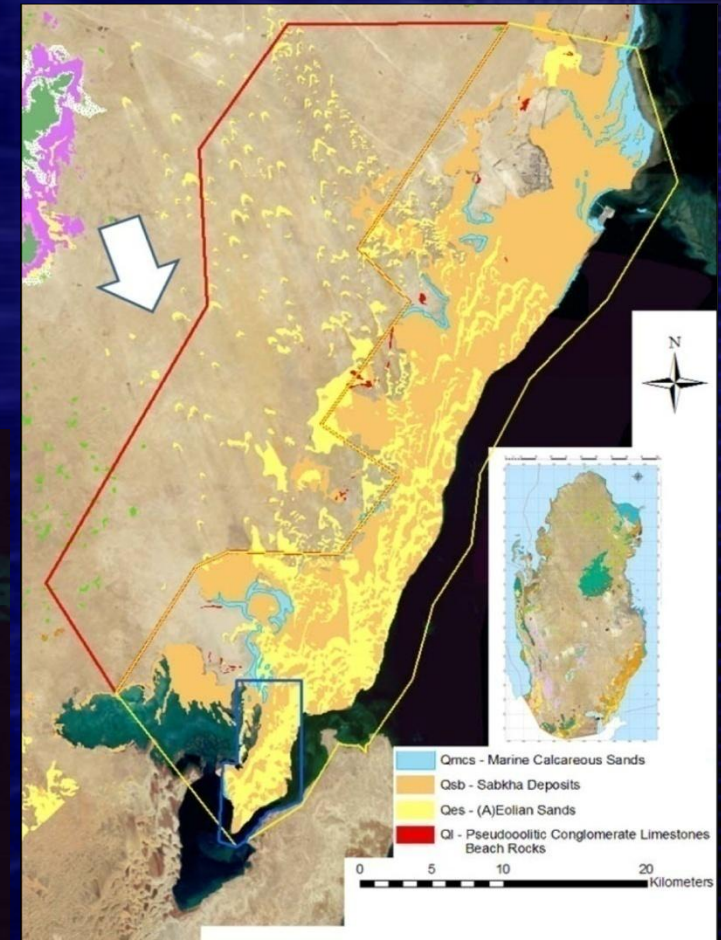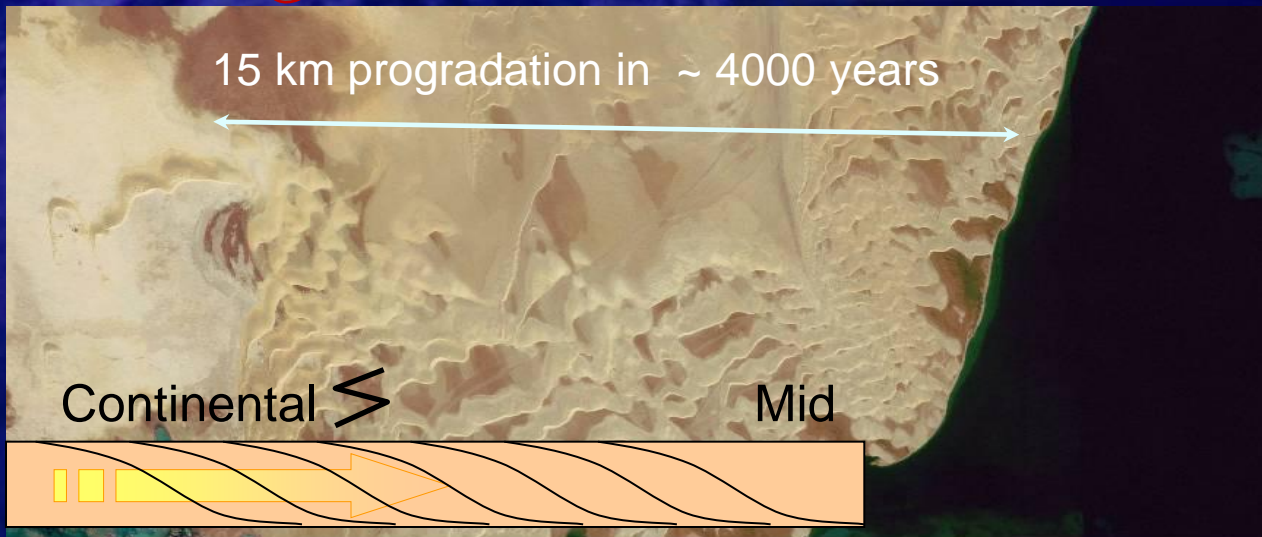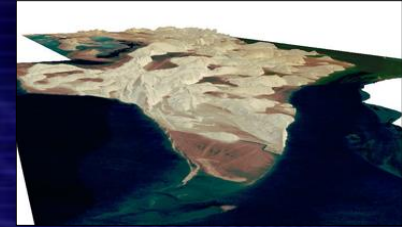- P - Pleistocene outcrop undifferentiated
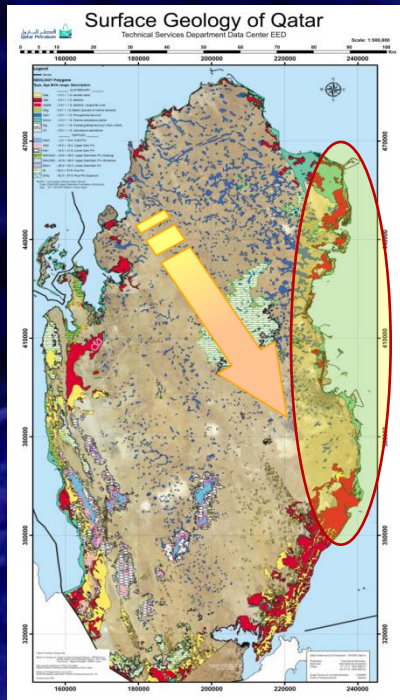- Pb - Pleistocene beach

Surface Geology of Qatar
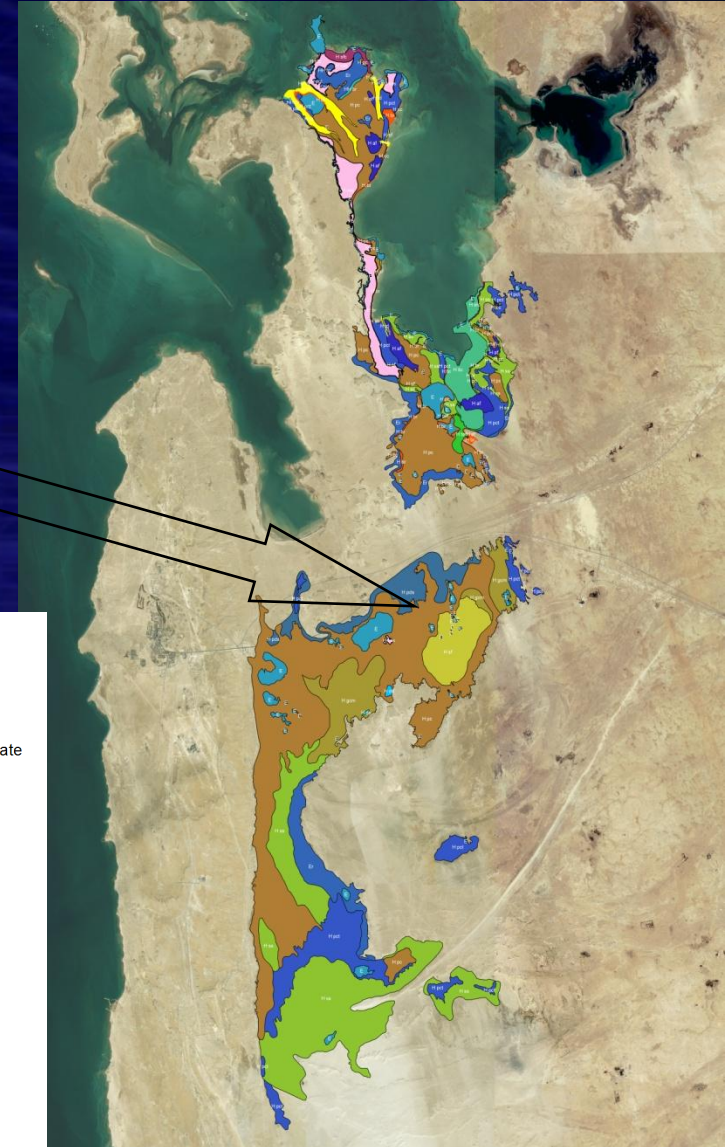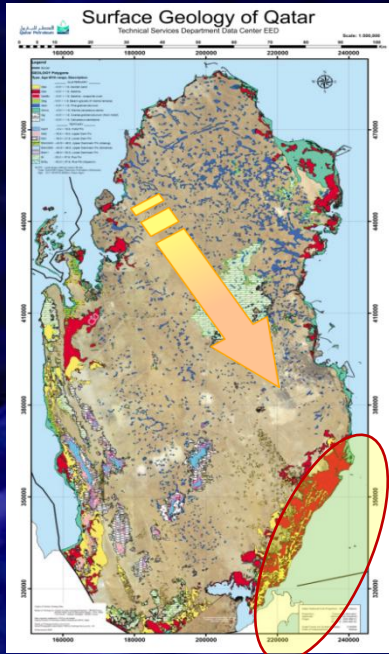
- Unusual setting: dune field empty into sea
- Fine siliciclastic sediments from land trapped at shoreline
- Unidirectional shoreline-parallel progradation
- Extensive evaporite precipitation at surface and water table

All figures used with permission of QP GIS (UPDA)

15 km progradation in ~ 4000 years

Continental ⟩   Mid

Qmcs - Marine Calcareous Sands
Qsb - Sabkha Deposits
Qes - (A)Eolian Sands
Ql - Pseudooolitic Conglomerate Limestones Beach Rocks

0   5   10   20
Kilometers
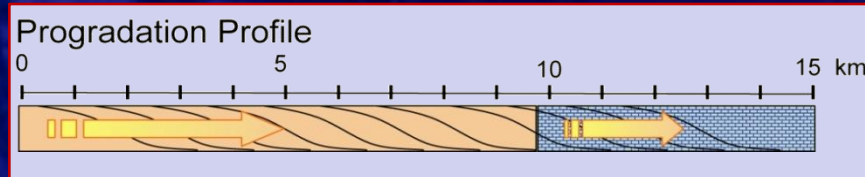
Used with permission of QP GIS (UPDA)

from Jameson et al., 2006

Oblique Coast:
- Beach and spit systems built in lee of headlands
- Major spit offsets due to sea level changes
- Ebb-dominated sabkha systems in lee of beaches
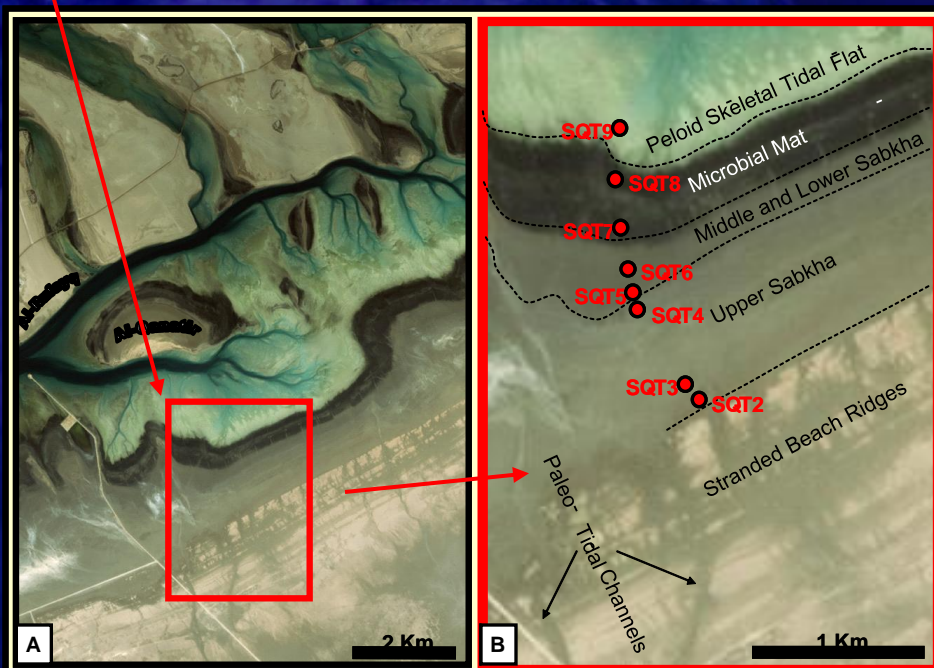- Extensive gypsum precipitation at water table and surface

Al Qanatir,Abu Dabhi

Illustration of facies ordering

1. Evaporite flat

2. Beach

3. Microbial mat

4. Lagoon (laminated sand, mangrove mud, burrowed sand and mud)

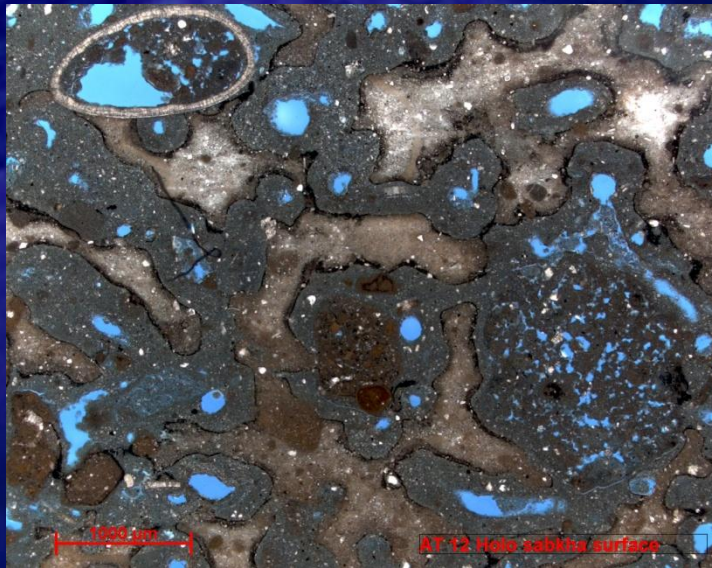Fixed order related to exposure, tides, wave energy

Extensive cementation of interior sabkhas

Gypsum lined fractures

Insect pelletization and micritization

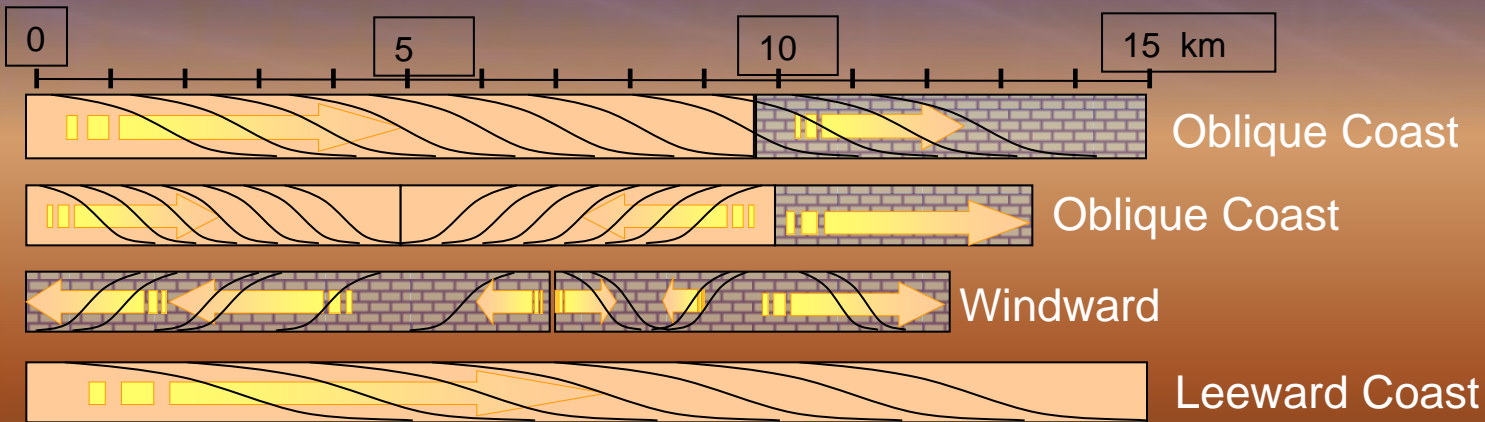Rigid

sediment

behavior

due to

cementation

Water table collapse features

Gypsum mega-polygons

Modern lessons for ancient interpretation

0   5   10   15 km

Oblique Coast

Oblique Coast

Windward

Leeward Coast

Protected Coast

Variable progradation patterns- in normal coastal sediments

Lagoon

Beach

Intertidal

New insights into building blocks for models:
sabkha recognition, correlation tools, cyclicity

With permission of QP CGIS

EXPOSED OLDER CARBONATES

OLDER BEACH

HIGH ENERGY BEACH

INNER RAMP

RAMP CREST

OUTER RAMP

LAGOON

SABKHA AND SALINAS

INTERTIDAL SAND FLAT ISLAND

SHOALS

SHALLOW SUBTIDAL

DEEPER SUBTIDAL

TIDAL DELTA

WASH-OVER FANS

PROGRADATION DIRECTION

Parasequence Boundary

PSB
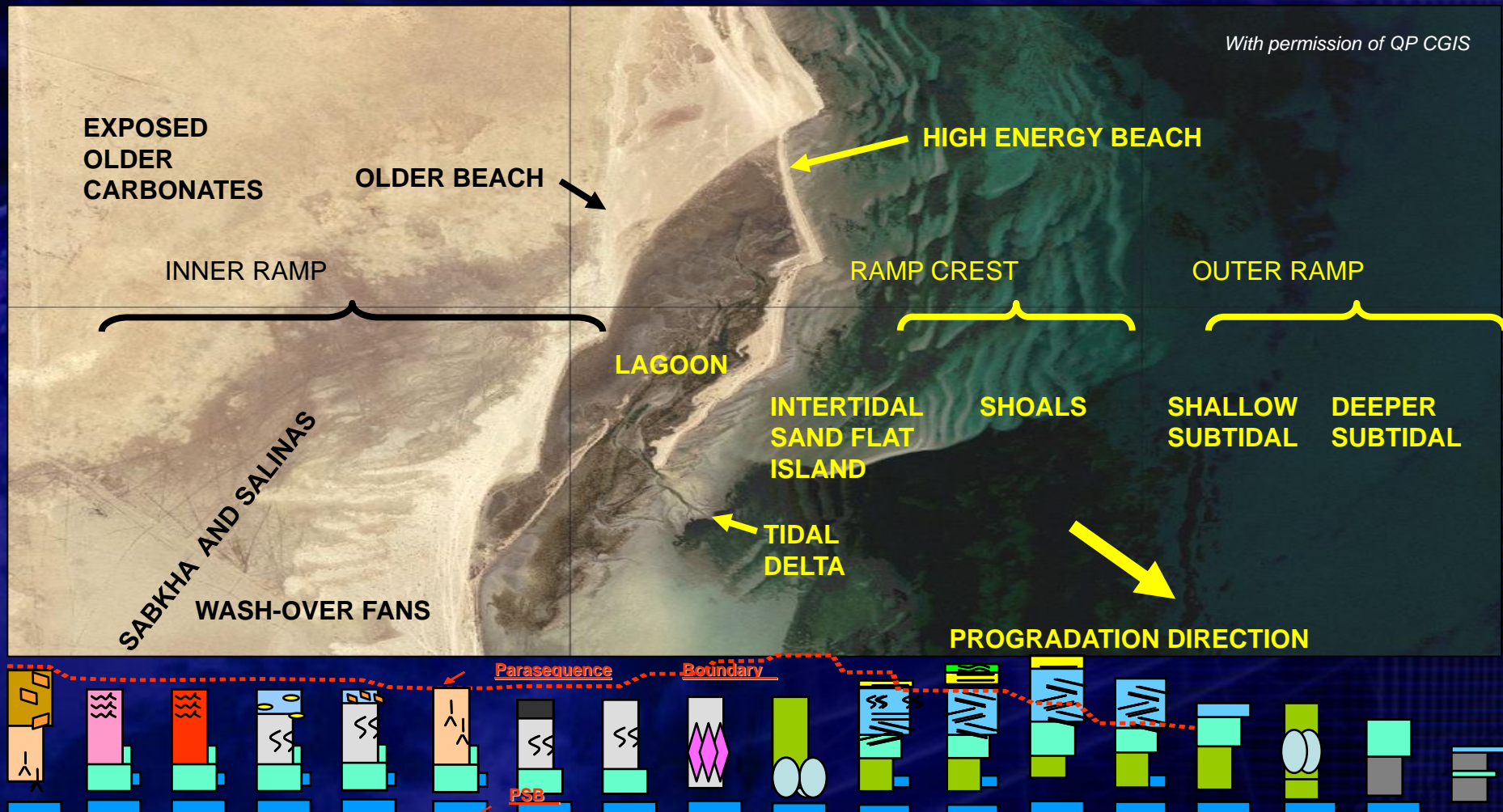
Depositional Processes

Due to high-frequency sea level changes, slope, and environmental variations

Diagenetic Processes

Surface and water-table precipitation of gypsum, with minor amounts of anhydrite, halite, calcite, and dolomite.

Insights for Modeling Sabkha Systems

- Recognition- normal marine sediments modified by evaporites: sabkhas consist of beaches, tidal deltas, sand sheets, intertidal flats variably modified by meteoric and marine pore waters, gypsum precipitation dominates

- Facies distribution-
  1. Regular profile of facies, like other coastal sediments
  2. Variable progradation directions and rates
  3. Variable sediment composition

- Facies offsets- seaward shifts of 4-6 km predictable from facies offsets at unconformities and amount of erosion