

Erosional Tidal Ridges in the Bakken Formation (Late Devonian-Early Mississippian), Southwestern Saskatchewan, Canada*

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Abstract

The Bakken Formation provides a rare opportunity to study an ancient tidal sand ridge system in the subsurface using a data set consisting of thousands of wells. Subsurface mapping and core examination show that the tidal ridge morphology is defined by a scour surface near the top of the Bakken Formation. This scour surface is part of a regional transgressive surface of erosion (TSE) that separates lowstand (LST) and transgressive (TST) systems tracts. In the study area, the LST consists of a progradational tide-dominated delta system. The overlying TST consists of a deepening-upward marine shale succession with shallow offshore deposits passing upwards into deeper anoxic shelf deposits.

The TSE is a sharp contact, or appears gradational due to modification by bioturbation. Cross-sections show the TSE has a ridge and swale morphology that truncates coarsening-upward successions in the LST. An isopach map of the LST shows a series of regularly spaced, linear, northeast-southwest oriented thick and thin sand trends. Ridges defined by the isopach map have vertical relief of 10 to 15 m (maximum 24 m) and crest-to-crest spacing of 3 to 7 km (maximum 10 km). These dimensions are comparable to those of modern shelf ridges. Bakken ridges are generally symmetrical which is typical of erosional Class I tidal ridges (Snedden and Dalrymple, 1999). Internally, Bakken ridges show no evidence of accretion deposits indicative of sand ridge migration. The ridge and swale morphology of the TSE played a major role in the migration and trapping of hydrocarbons.

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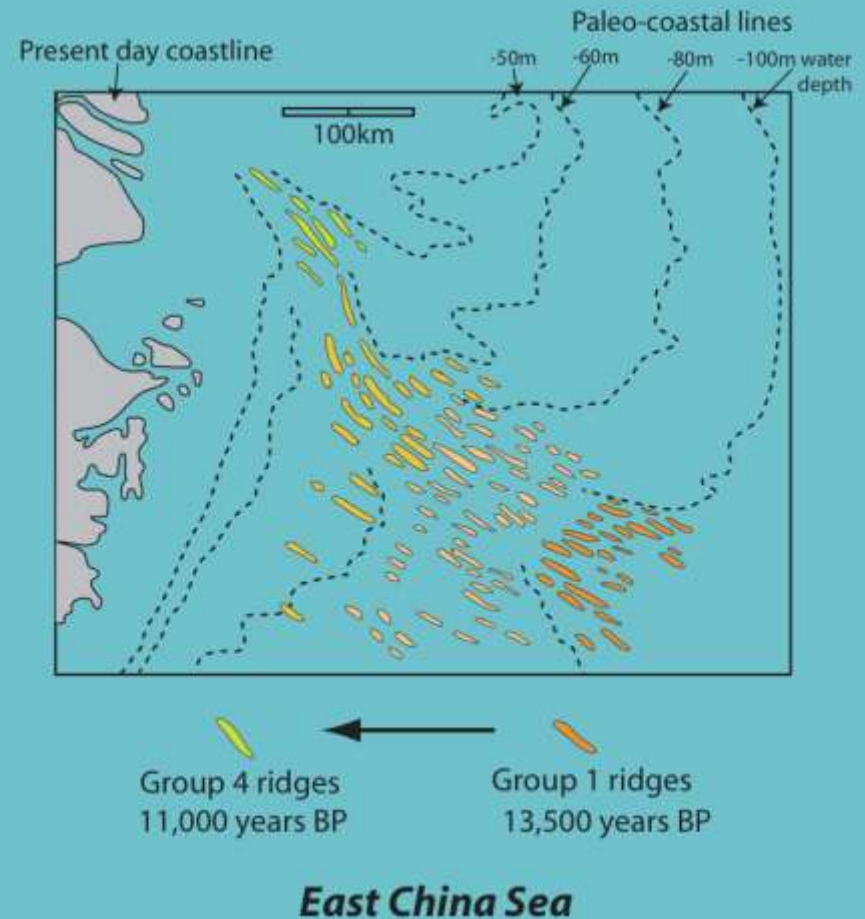
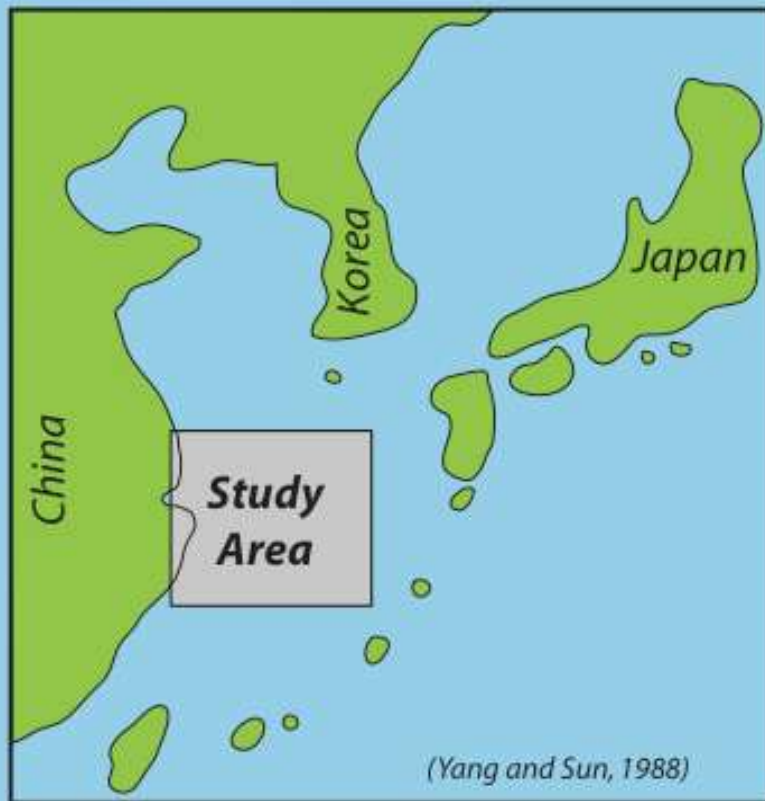
2005 AAPG Annual Convention



Introduction

- Tidal ridge systems are common on modern continental shelves, but rarely recognized in the stratigraphic record
- The Bakken Formation provides a unique opportunity to study an ancient tidal ridge system using thousands of wells and dozens of drill cores
- We will show that the Bakken tidal ridge system is defined by an erosional surface near the top of the formation
- The Bakken ridge system therefore does not reflect the depositional morphology of active tidal sand ridges as previously proposed

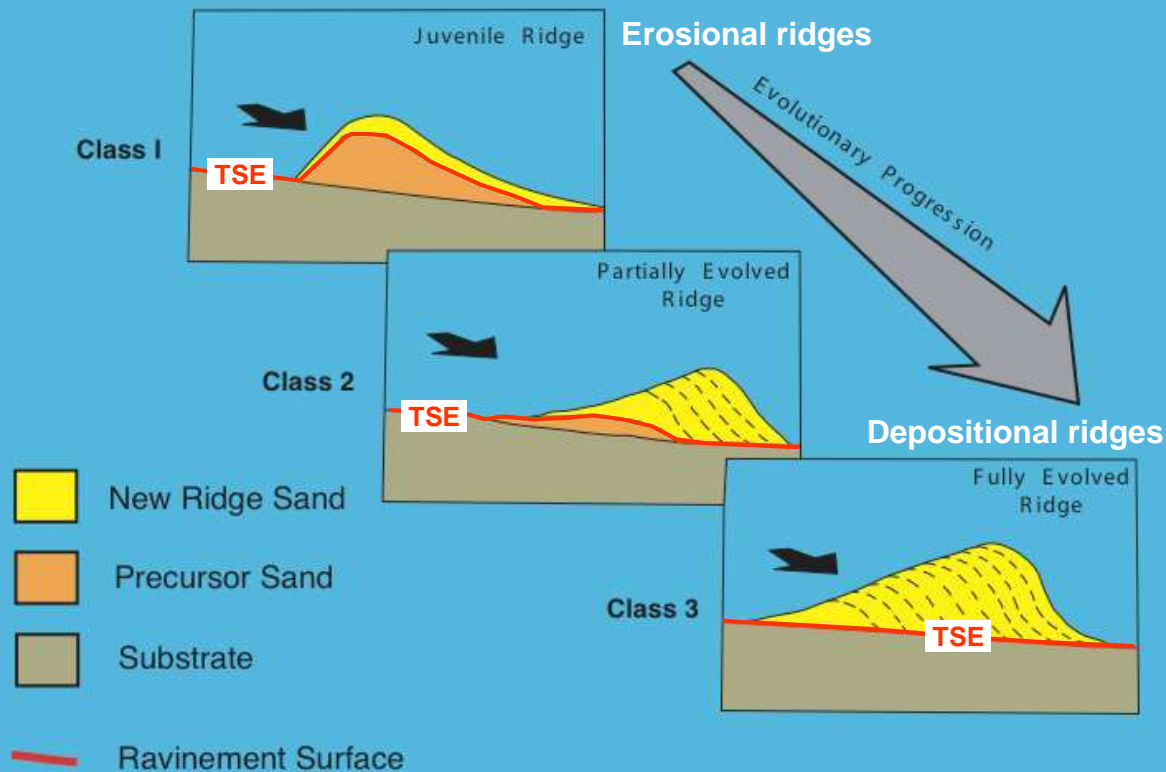
Modern Tidal Ridge Systems



Spectrum of Erosional to Depositional Tidal Ridges

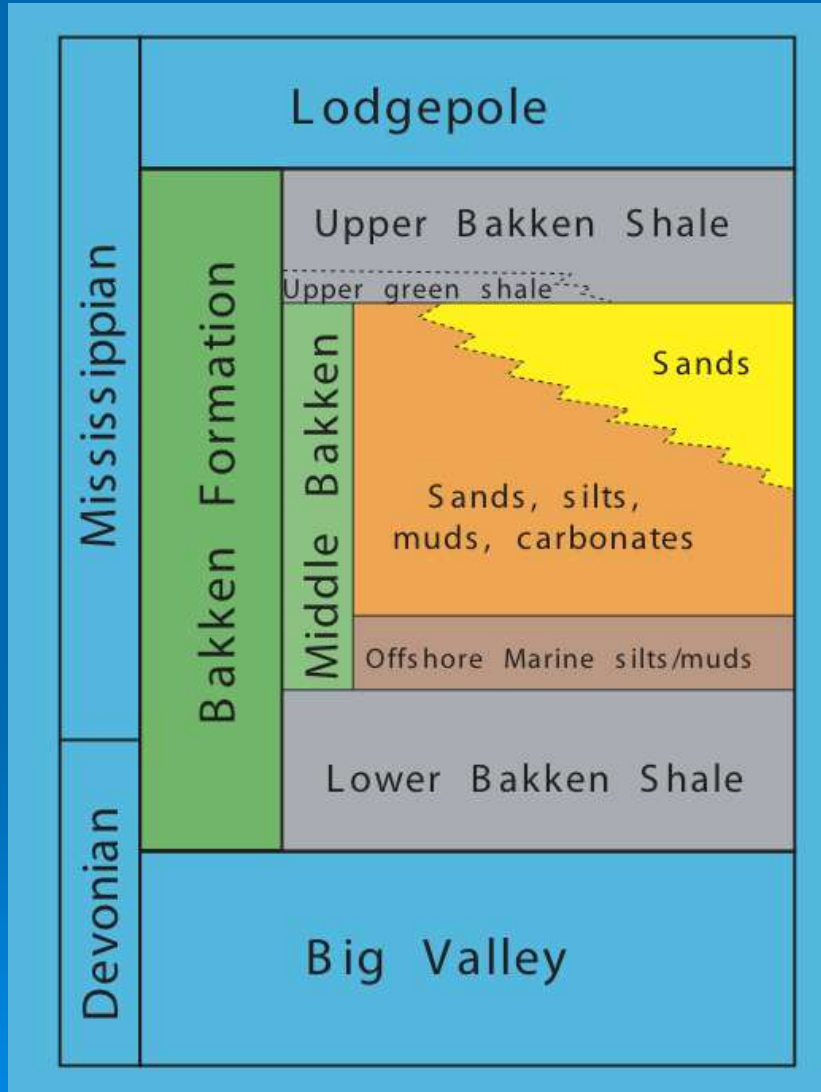
Three criteria can be used to determine the classification of ancient tidal ridges:

- Position of the TSE
- Ridge morphology (symmetrical vs asymmetrical)
- Nature of ridge facies (precursor deposits vs accreted ridge sand)



Modified from Snedden and Dalrymple (1999)

Bakken Stratigraphy



Distal Offshore Marine

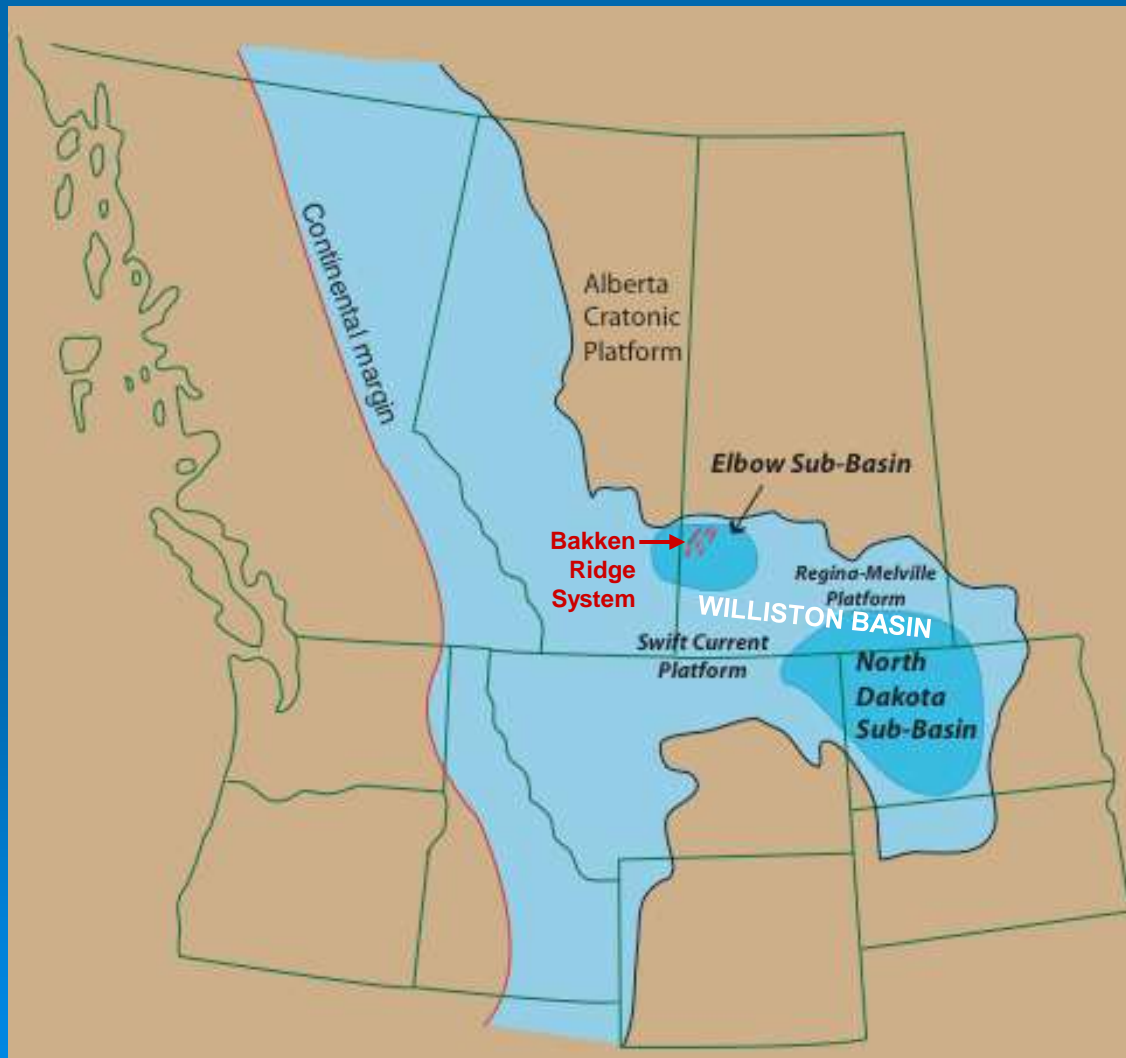
Offshore Marine

Tide-Dominated Deltaic

Offshore Marine

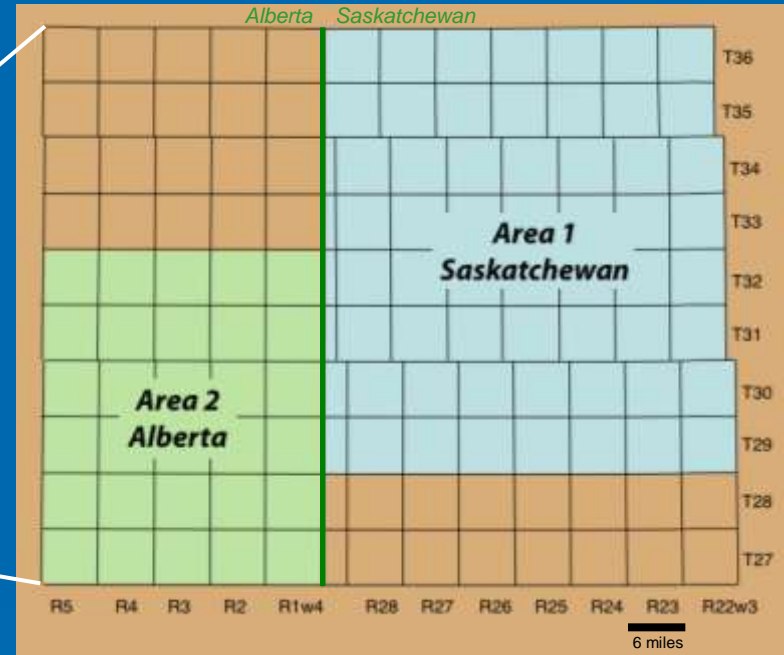
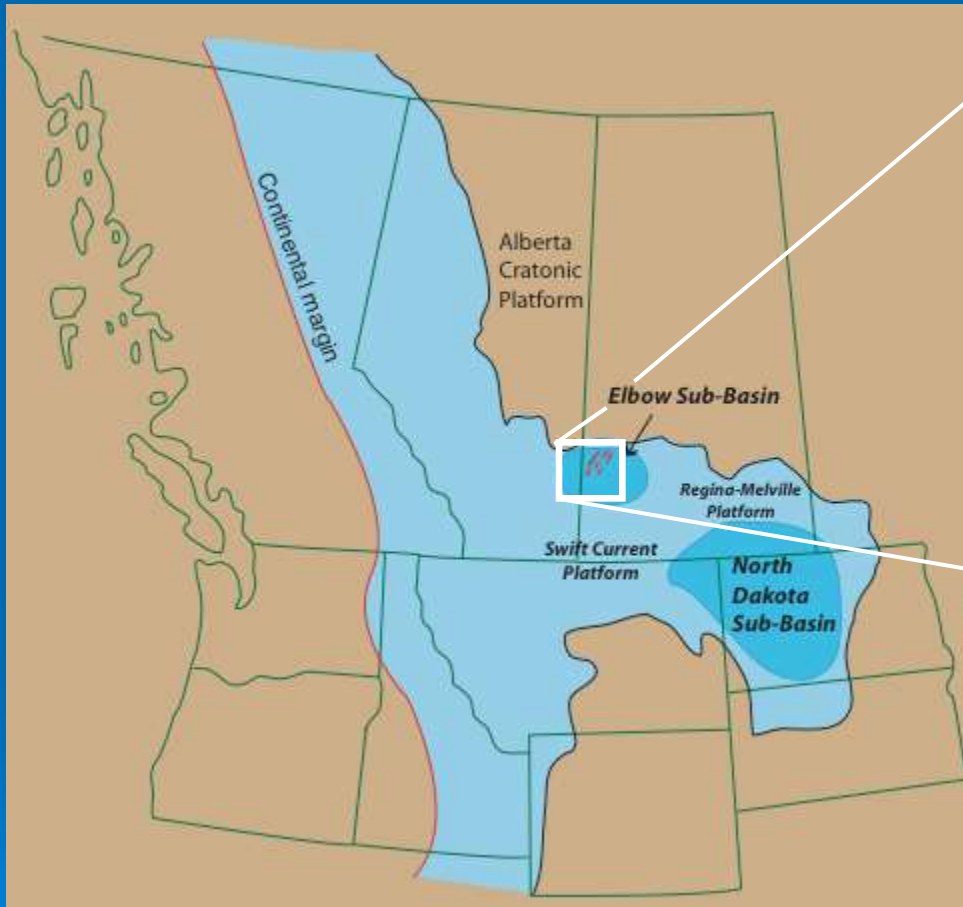
Distal Offshore Marine

Late Devonian Paleogeography



- The west coast of North America had an east-west oriented gulf that occupied most of the Williston Basin
- The Bakken Fm of the study area was deposited in a sub-basin on the northern side of the constricted gulf

Study Area and Data Set

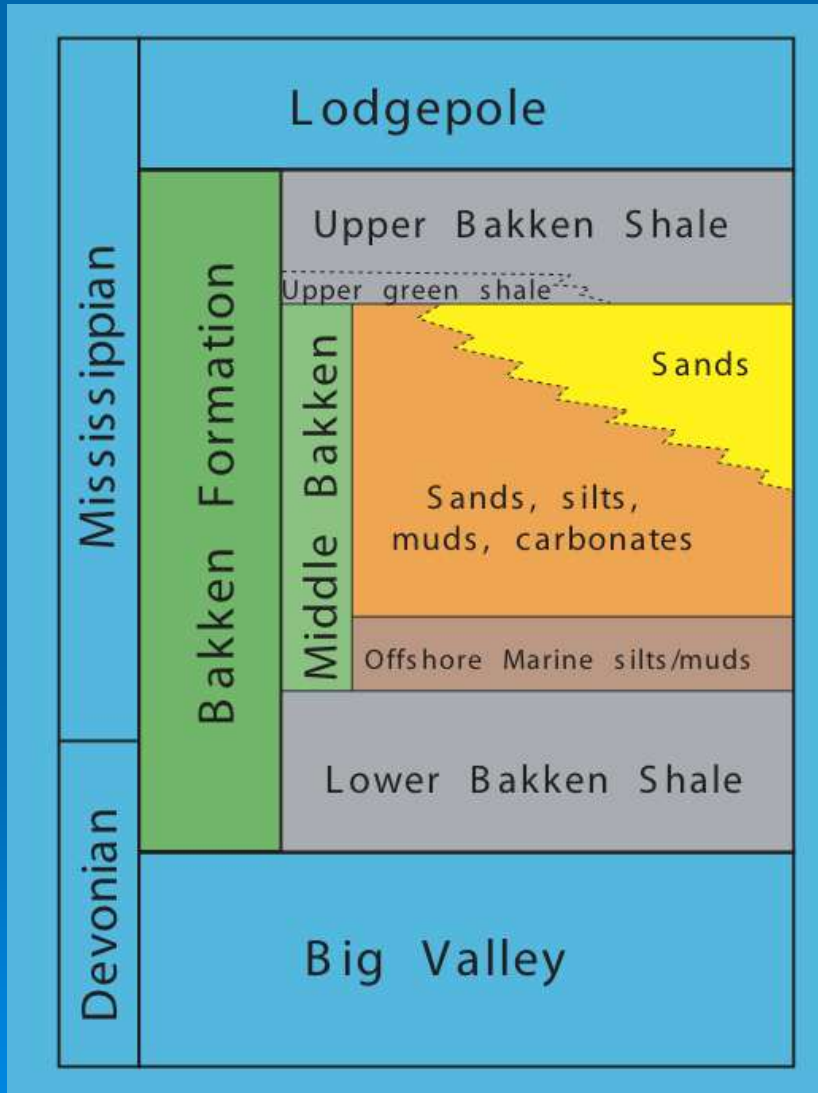


Area 1:
~ 5200 km² (2000 sq miles)
~ 4000 wells*
20 cores examined

Area 2:
~ 2800 km² (1100 sq miles)
~ 700 wells*
37 cores examined

* All pre-2001 wells with Bakken penetration

Sequence Stratigraphy



HST

MFS

TST

TSE

LST

SB

TST

SB/TSE

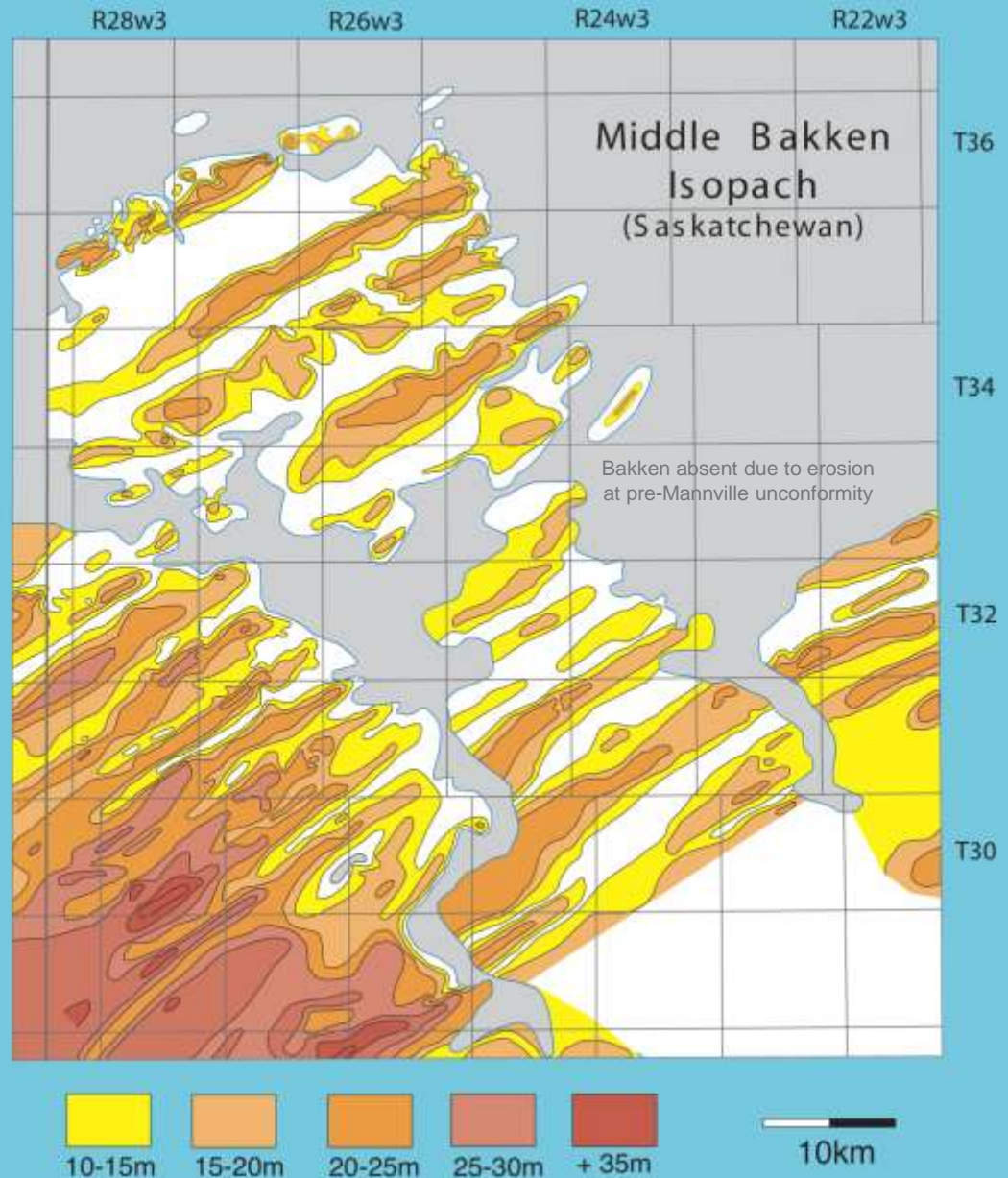
Regional sequence stratigraphic framework of Smith and Bustin (2000)

Isopach map

LST = lowstand systems tract
 TST = transgressive systems tract
 HST = highstand systems tract
 SB = sequence boundary
 TSE = transgressive surface of erosion
 MFS = maximum flooding surface

Isopach Map

- overall thickening to SW
- regularly spaced, linear NE-SW oriented thick and thin trends
- thick trends are generally symmetrical



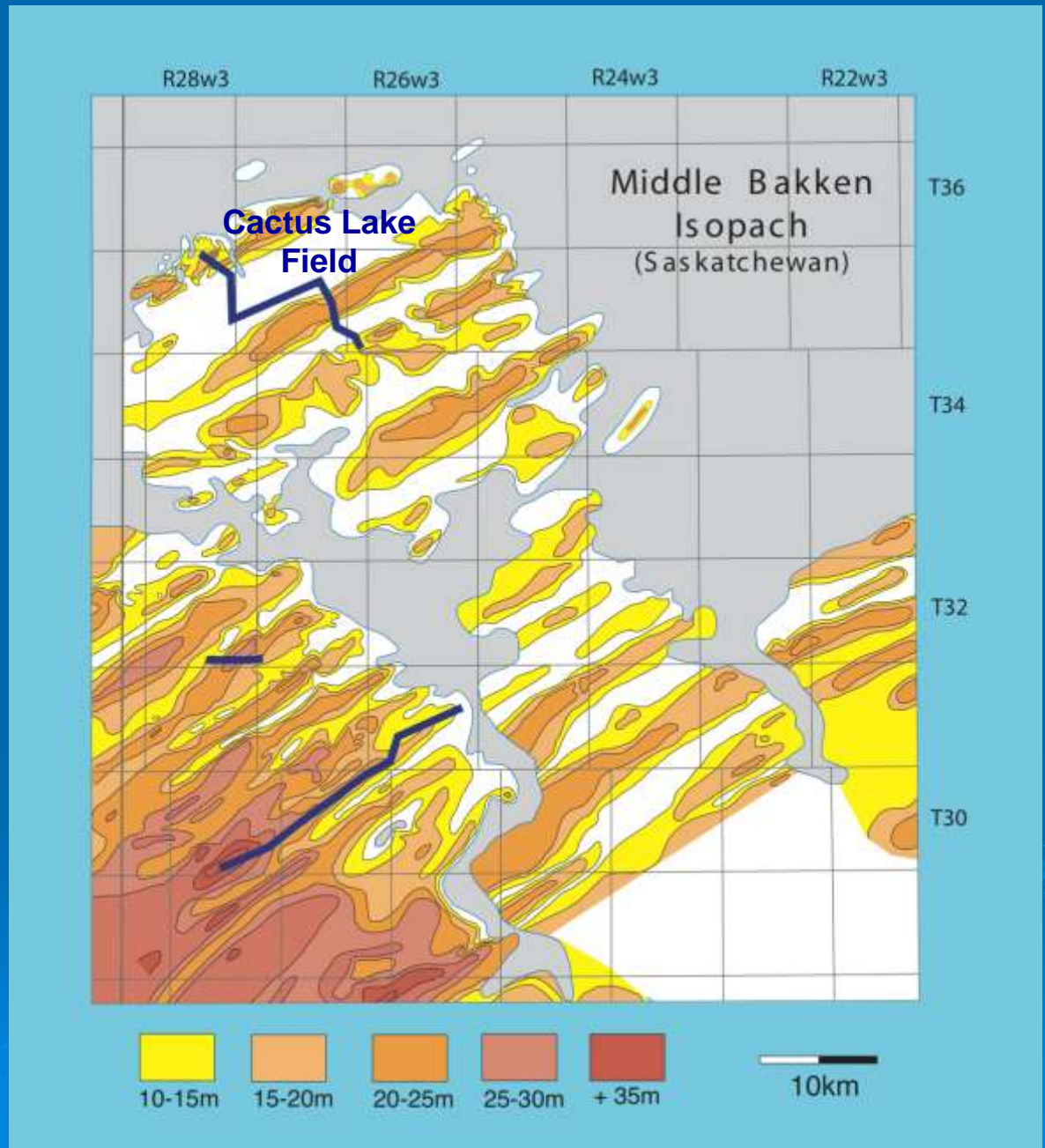
Dimensions of Tidal Ridges in the Middle Bakken Member

	Typical Range	Maximum
Vertical Relief	10 – 15 m	24 m
Crest-to-Crest Spacing	3 – 7 km	10 km
Length*	13 – 40 km	80 km

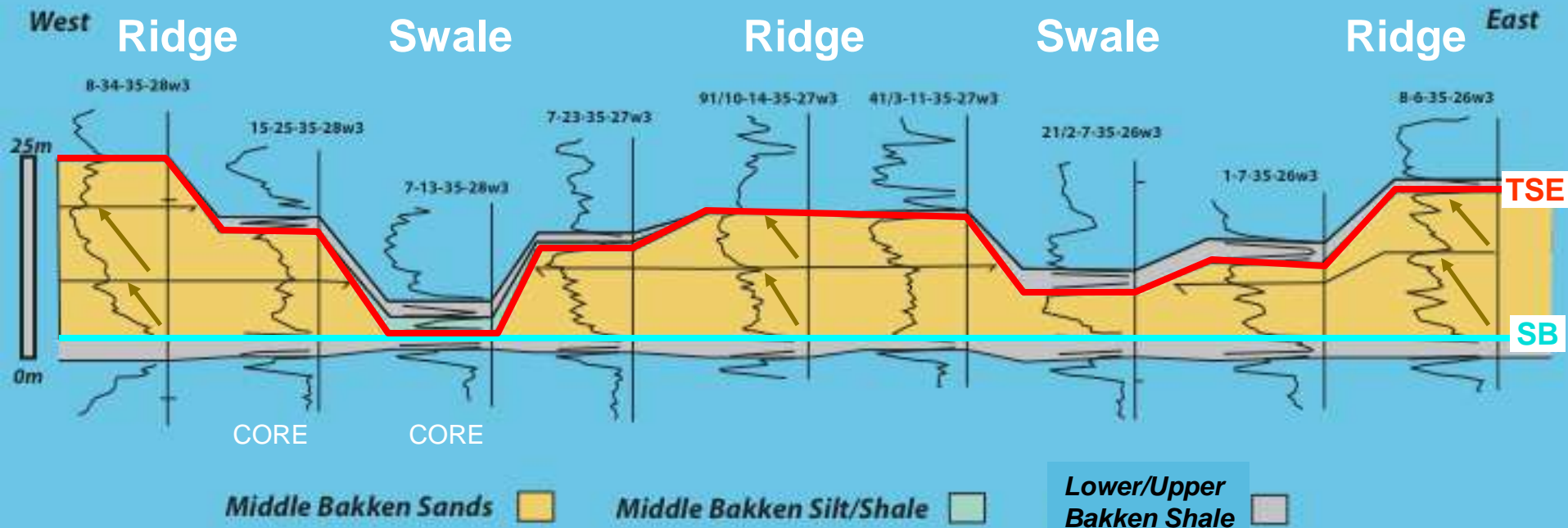
The Bakken ridge dimensions are comparable to those of modern tidal ridge systems

*Range for contiguous non-eroded ridge segments. Maximum estimated by extrapolating ridge trend across areas where Bakken Formation is absent due to erosion

Cross-Section Location

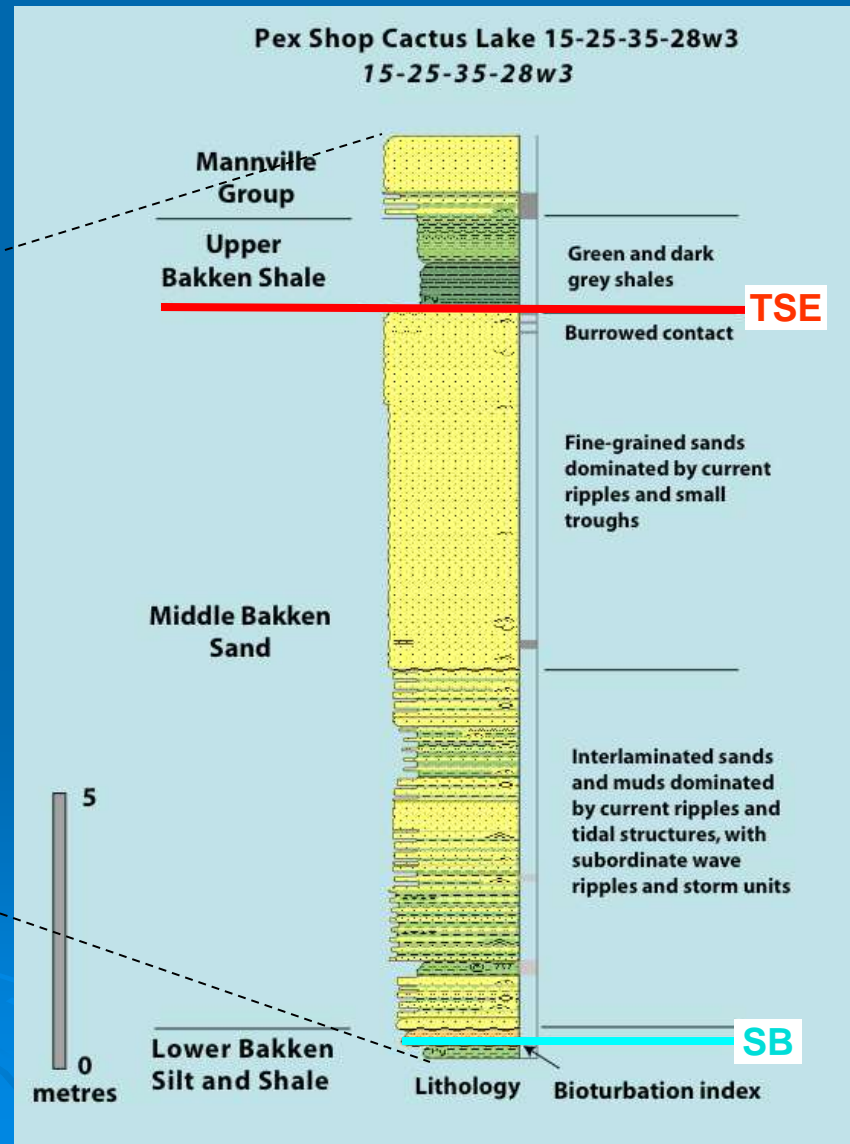
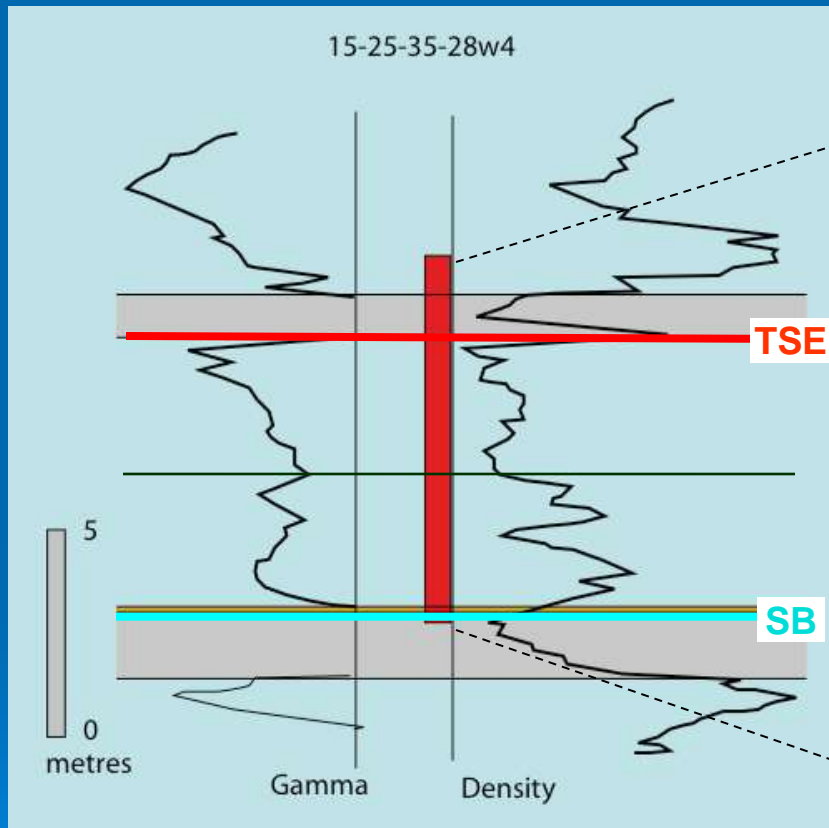


Cactus Lake Cross-Section

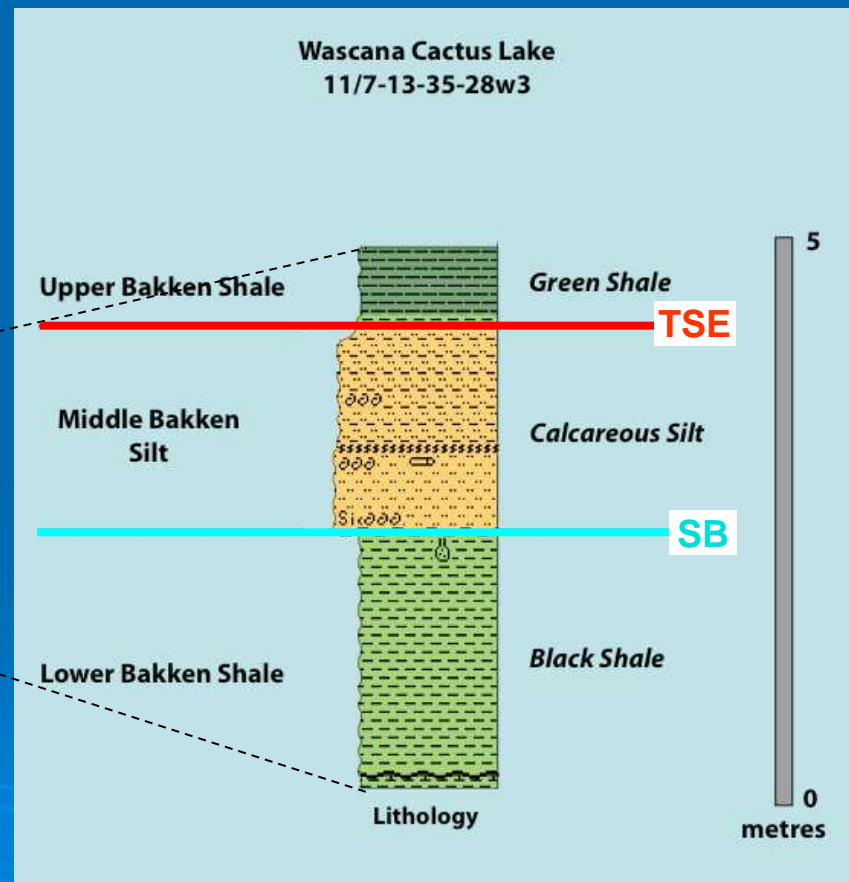
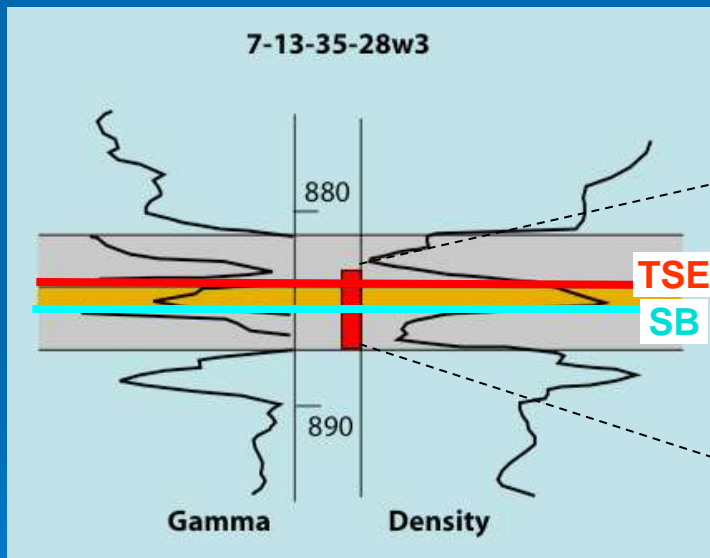


Note TSE has ridge and swale morphology and truncates progradational cycles in the Middle Bakken

Ridge Core



Swale Core



Core Photos of TSE



Sharp contact on
ridge crest



Bioturbated contact
on ridge crest

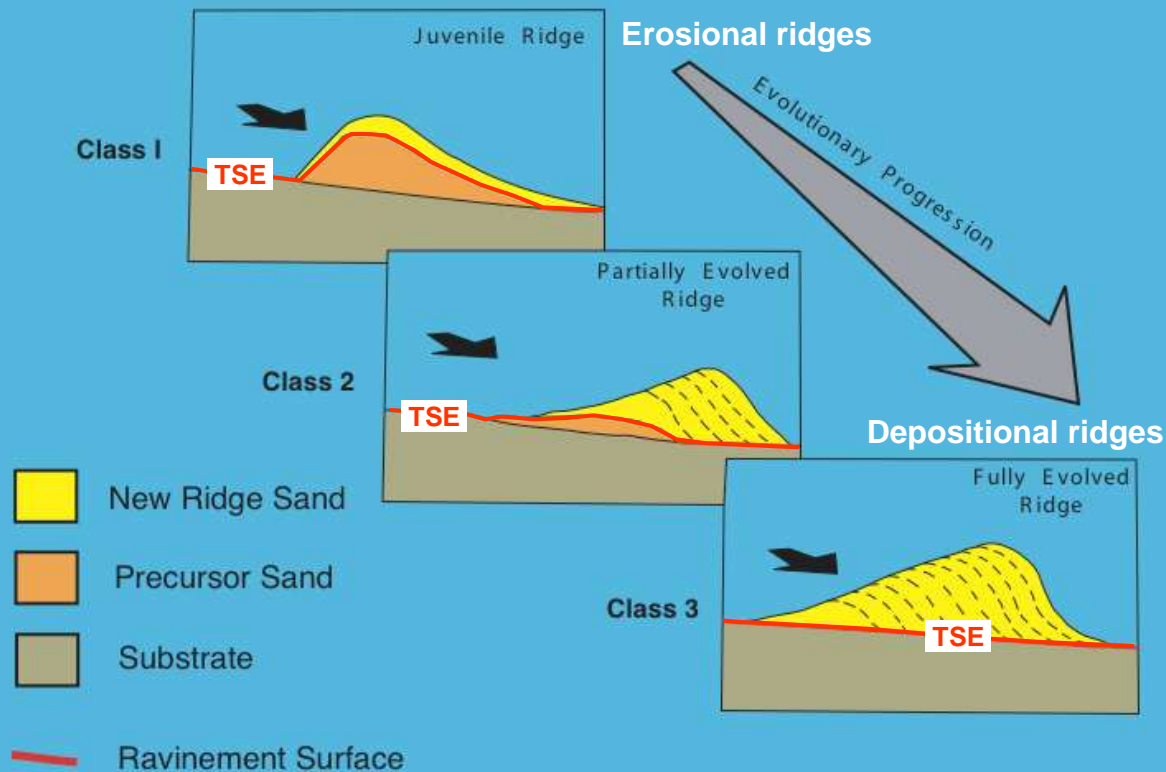


Bioturbated
contact in swale

Spectrum of Erosional to Depositional Ridge Types

Three criteria can be used to determine the classification of ancient tidal ridges:

- Position of the TSE ☒
- Ridge morphology (symmetrical vs asymmetrical) ☒
- Nature of ridge facies (precursor deposits vs accreted ridge sand)



Modified from Snedden and Dalrymple (1999)

Current Ripples & Herringbone Structures



Interlaminated Sandstone and Shale



Tidal Structures



Double mud
drapes and
sigmoidal
bedding



Tidal Structures



Flaser forks

Double mud
drapes



Neap-spring
cycles

Tidal Channel Facies



Wave Ripples and Storm Beds



Bioturbation

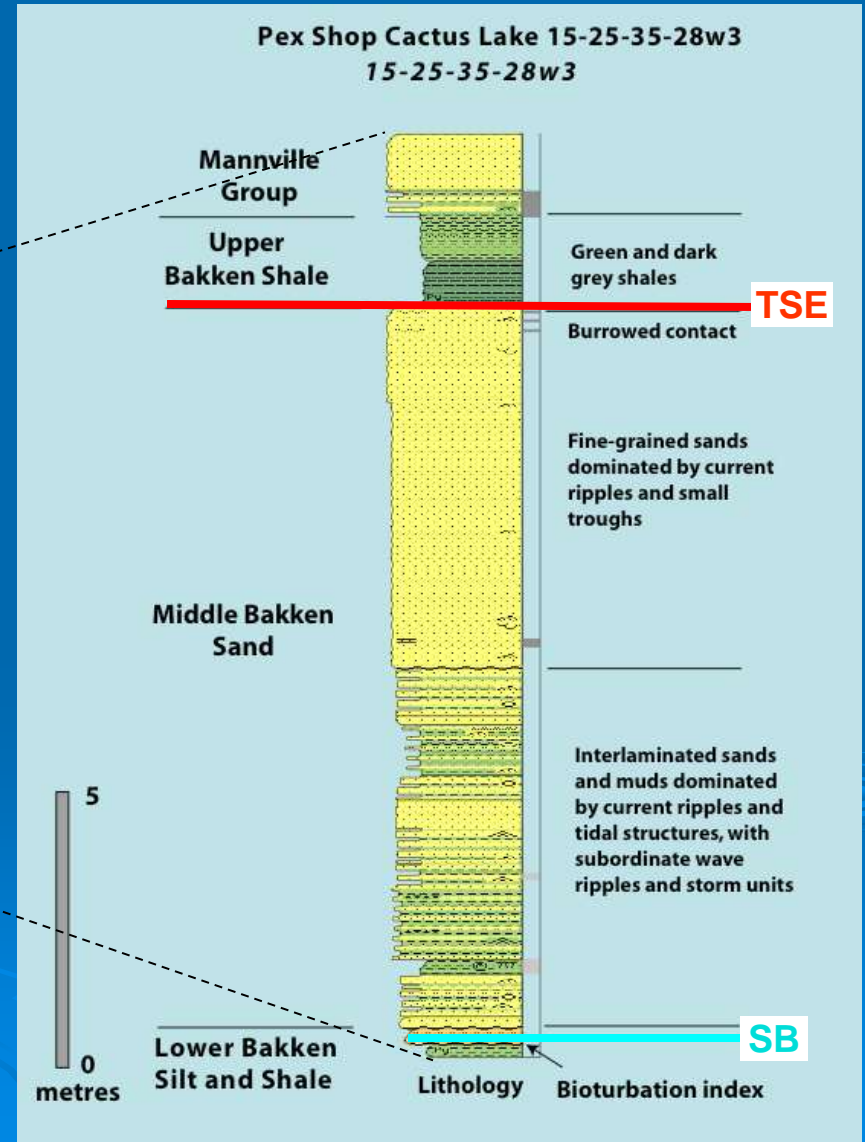
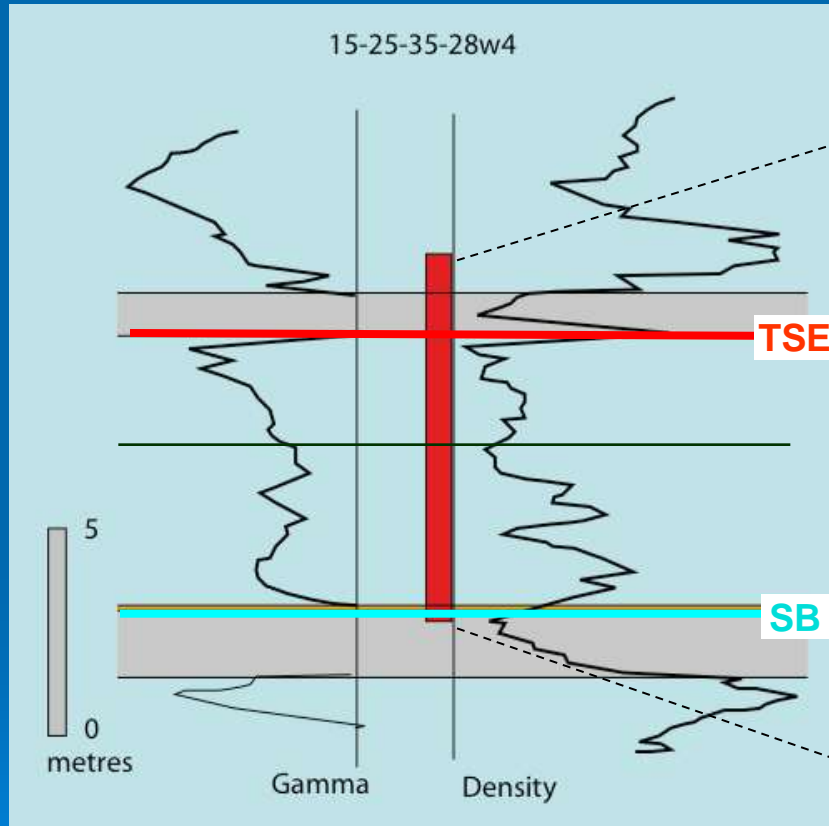


Skolithos in current rippled sandstone

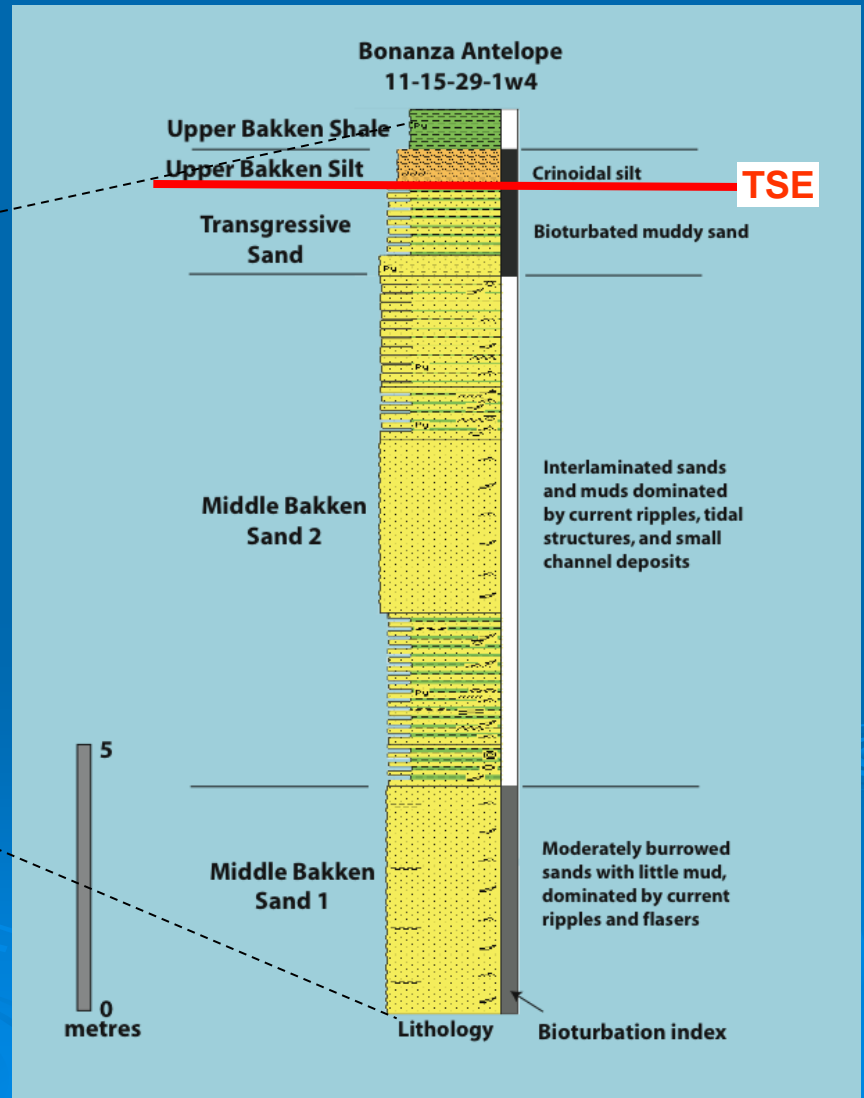
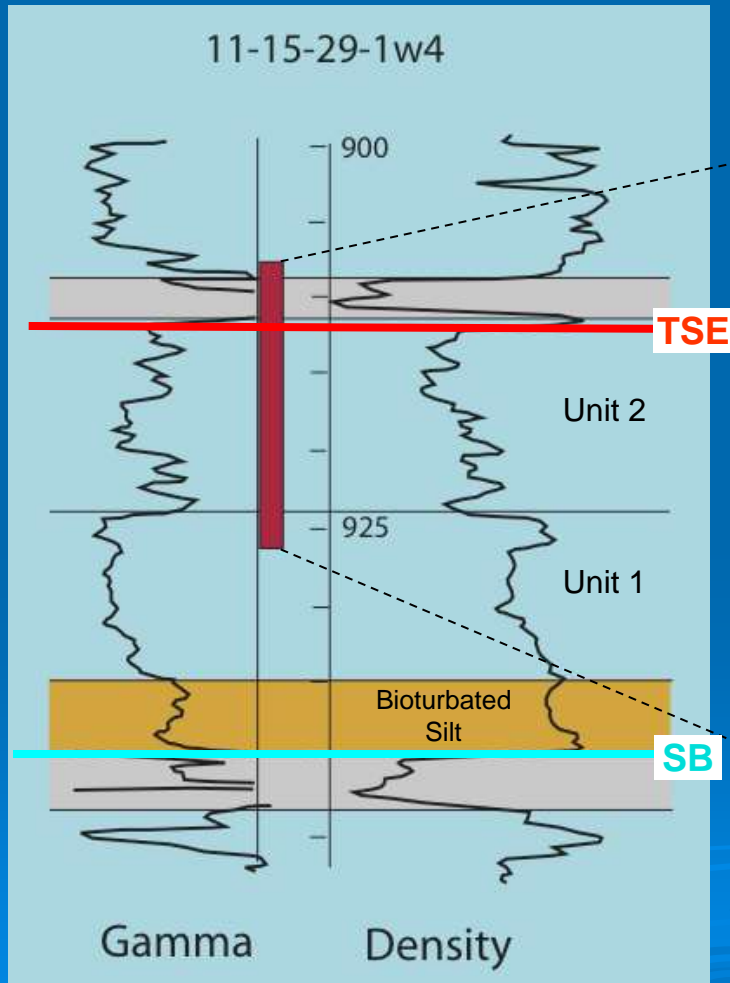


Chondrites and Helminthopsis in siltstone

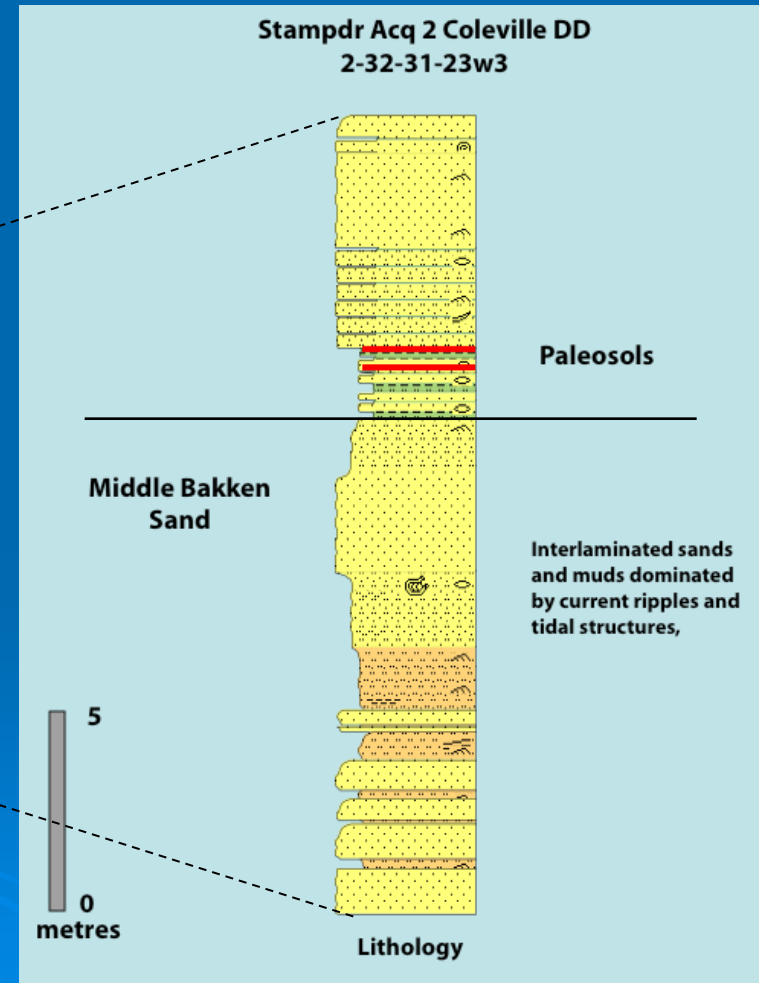
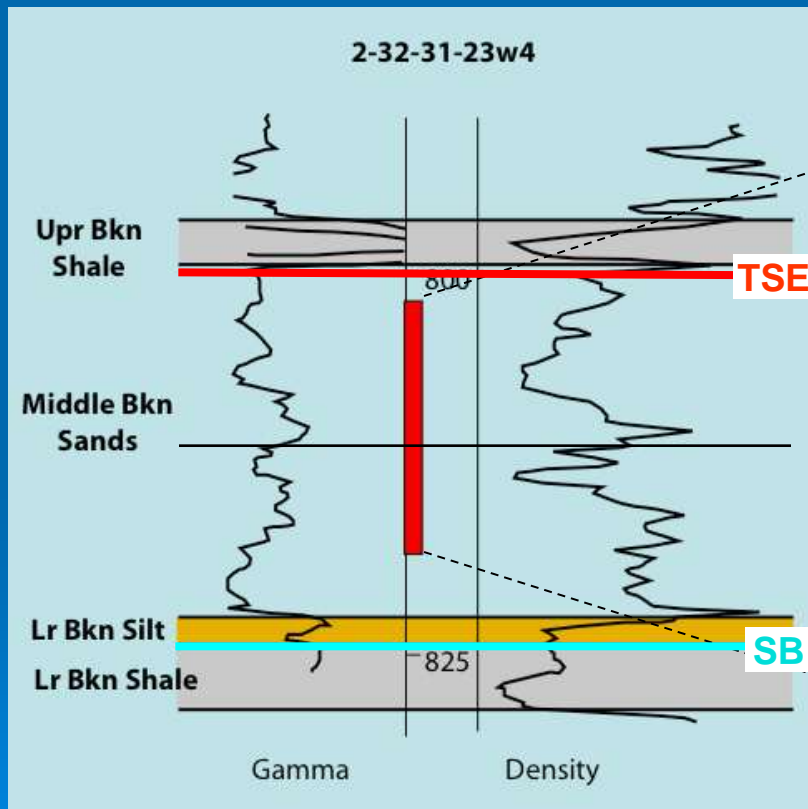
Ridge Facies Core



Ridge Facies Core



Ridge Facies Core with Paleosols

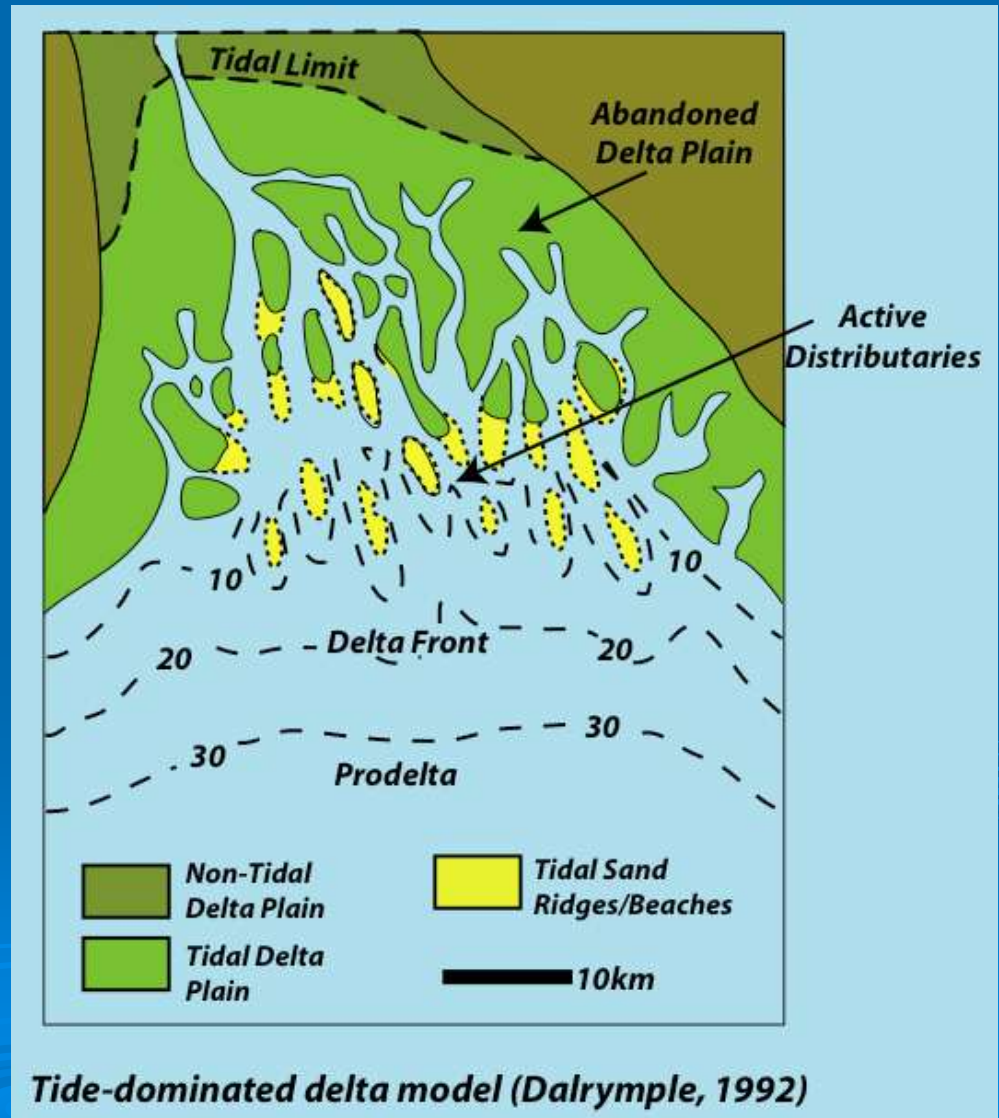


Paleosols

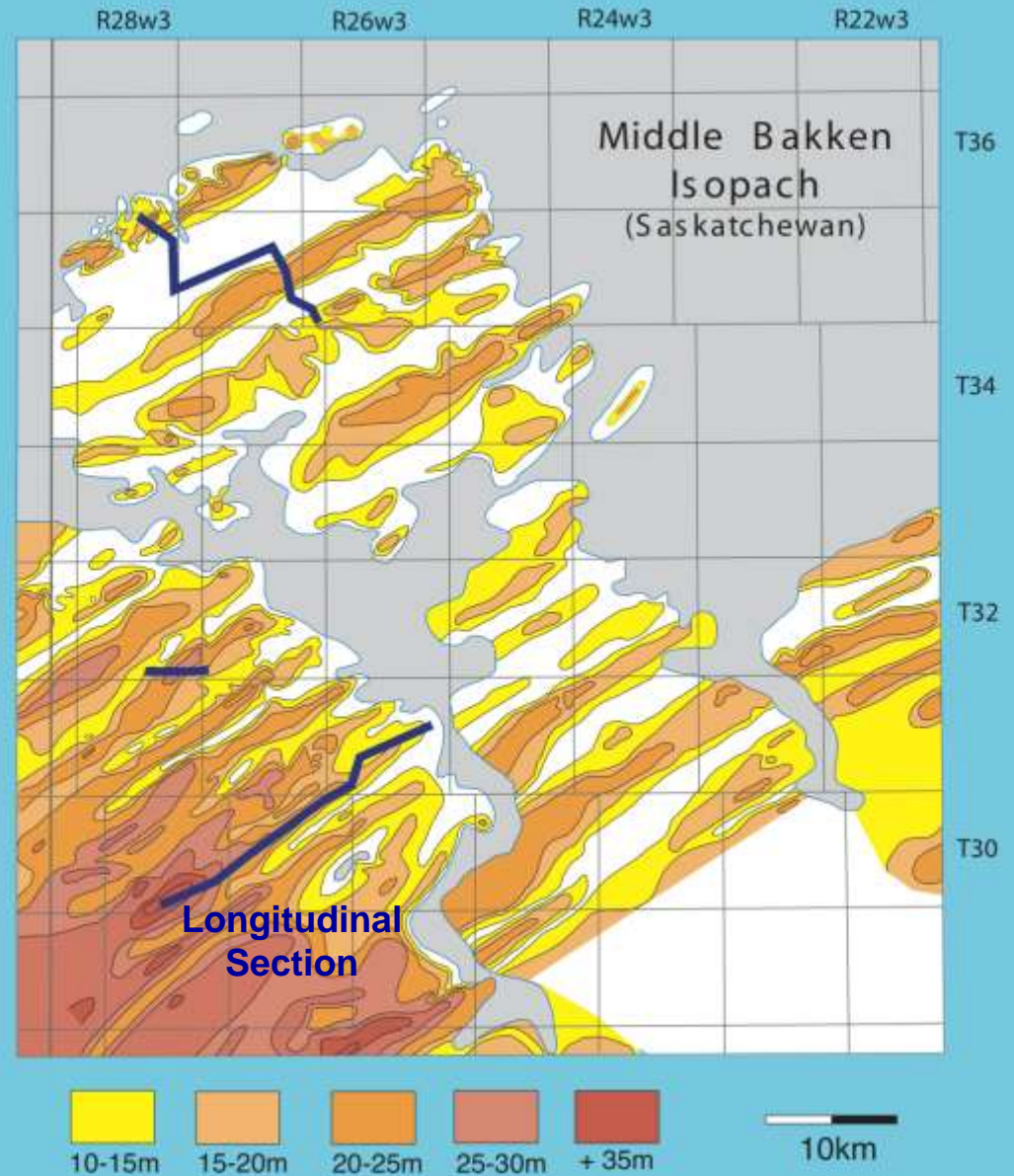


Bakken Facies Model

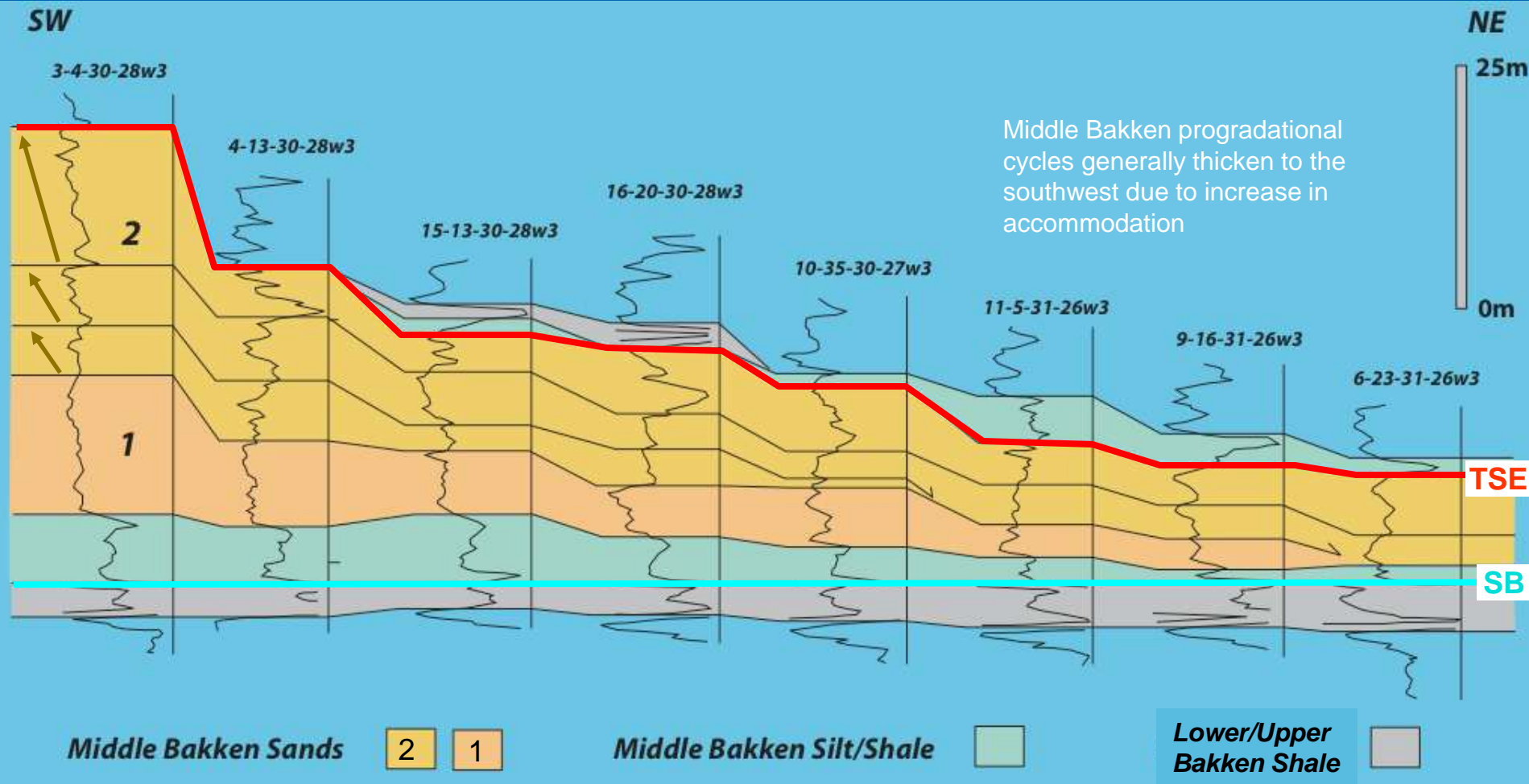
- Middle Bakken sands and muds were deposited in a progradational, current- and tide-dominated setting with subordinate wave and storm influences, and lateral abandonment facies. A likely setting is a series of large flood tidal deltas.



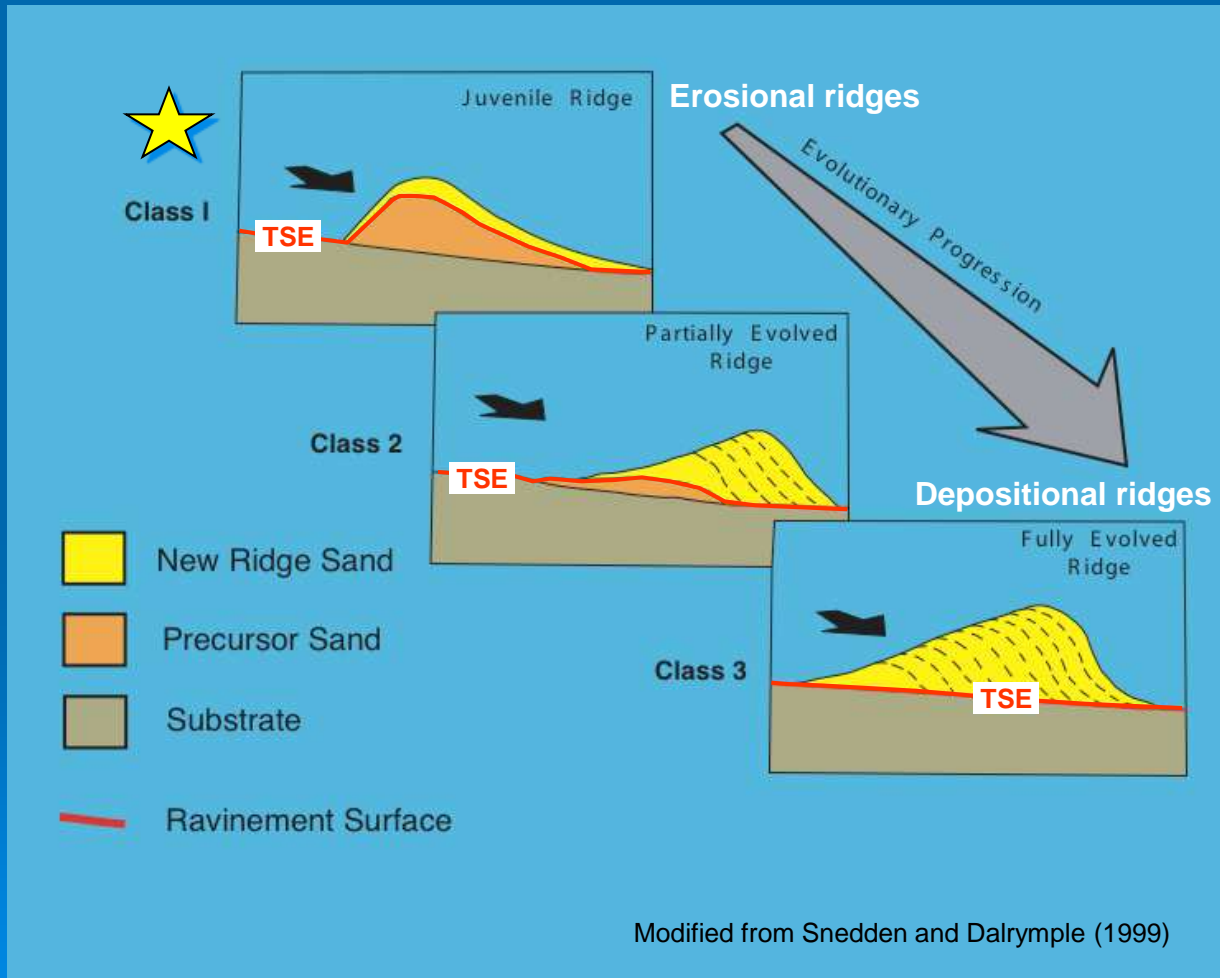
Cross-Section Location



Longitudinal Section Along Ridge Crest



Spectrum of Erosional to Depositional Ridge Types



Three criteria can be used to determine the classification of ancient tidal ridges:

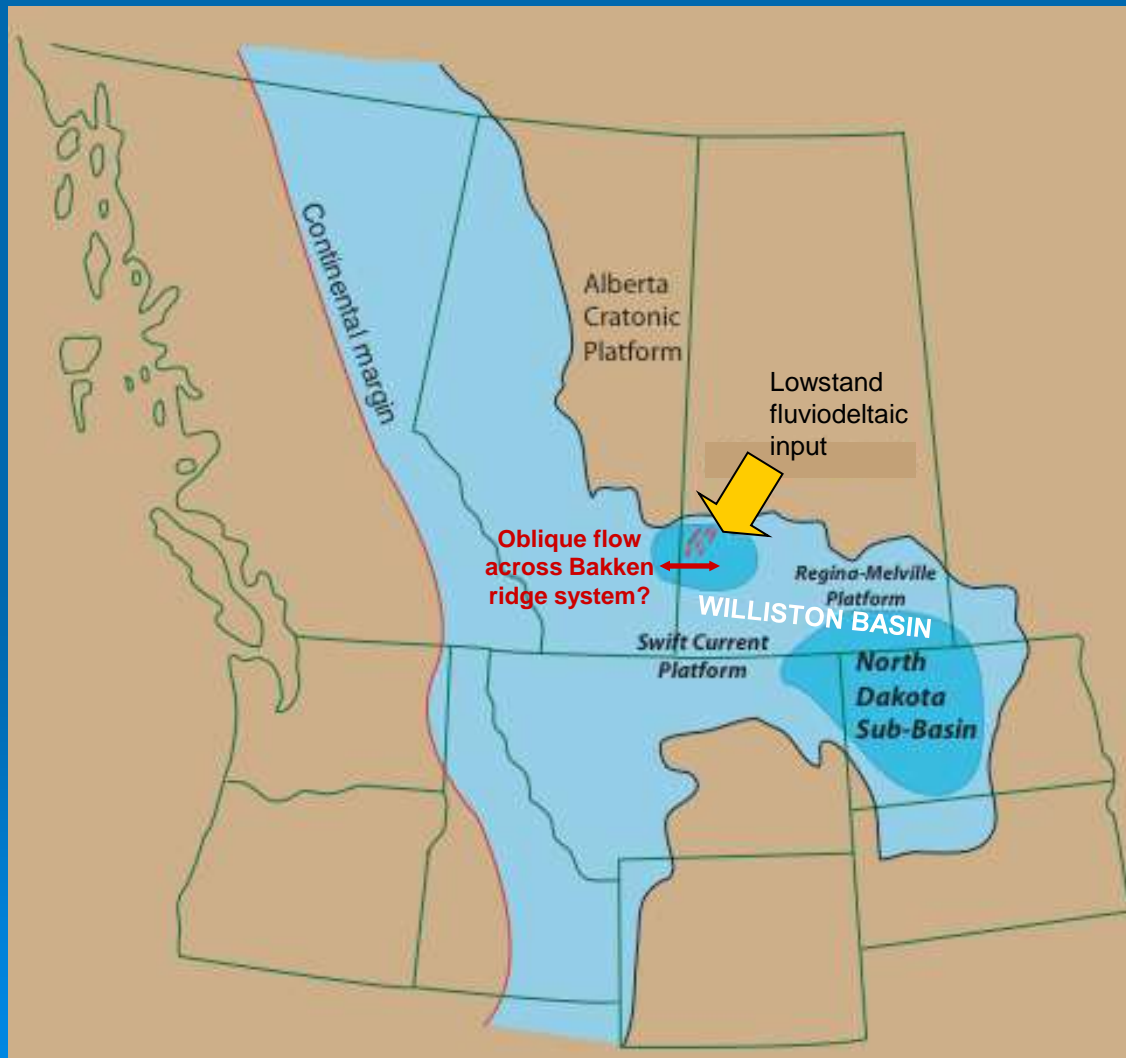
- Position of the TSE ✓
- Ridge morphology (symmetrical vs asymmetrical) ✓
- Nature of ridge facies (precursor deposits vs accreted ridge sand) ✓

All three criteria indicate Bakken ridges are erosional ridges (Class 1)

Expected Features of Depositional Ridges

- x TSE at base of ridge facies
- x Asymmetric ridges
- x Ridge facies consists almost wholly of sand
- x Inclined bedding that dip in a consistent direction with respect to ridge orientation
- x Coarsest grain size and best reservoir quality consistently on higher-energy flanks

Late Devonian Paleogeography



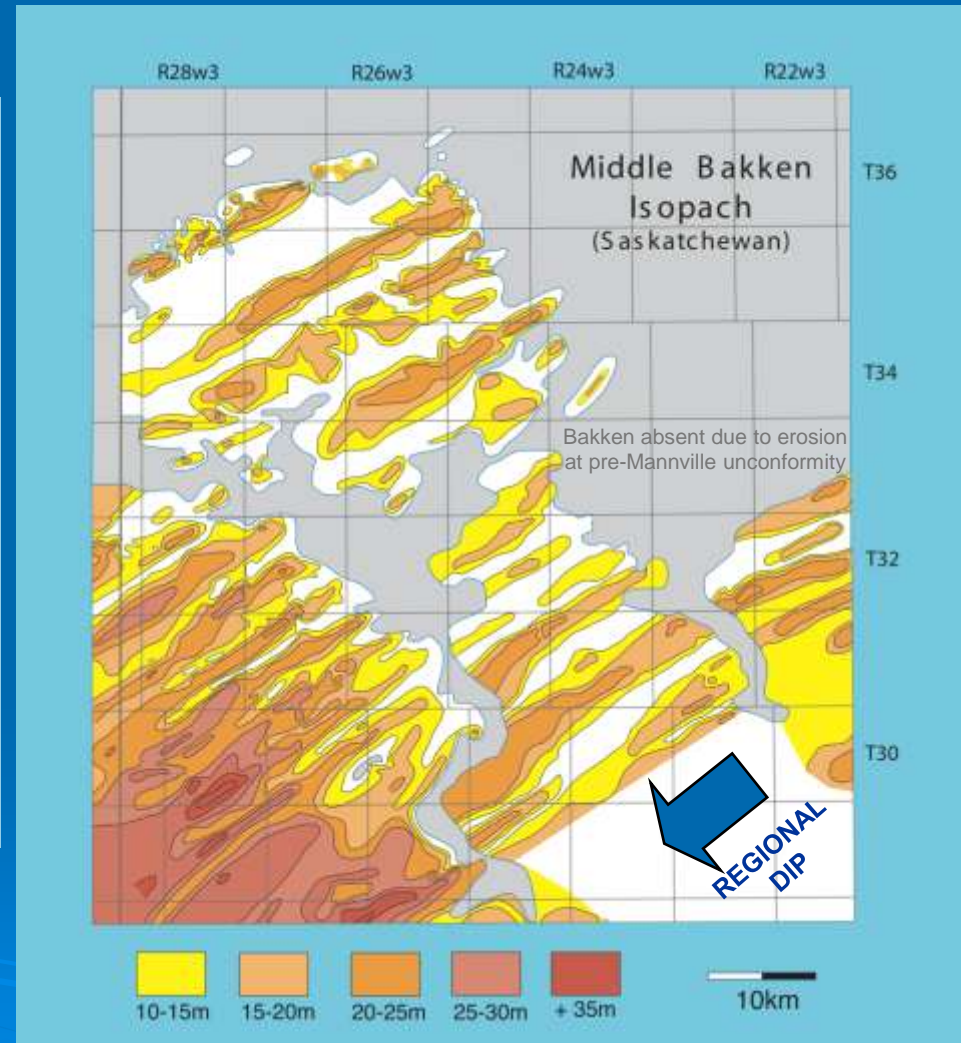
- Sediment supplied to tide-dominated deltas during lowstand
- Ridge and swale morphology of TSE generated net erosion of sea floor during rising sea level
- Ridge orientation was oblique to flow generated by tidal exchange through constricted gulf

Hydrocarbon Trapping



The Middle Bakken Member is a major heavy oil resource in SW Saskatchewan with 2015 million barrels OOIP and 242 million barrels ultimate recoverable reserves*

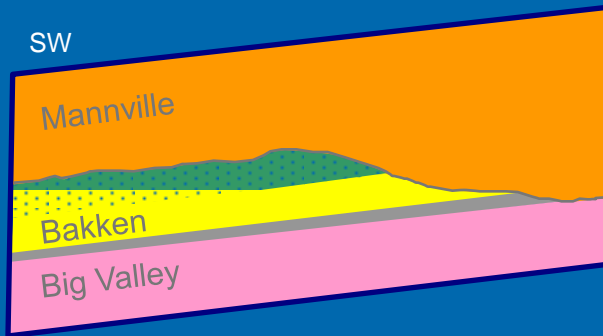
The tidal ridge morphology of the TSE near the top of the Bakken Formation played a major role in the migration and trapping of hydrocarbons



* Saskatchewan Industry and Resources data at <http://www.public-knowledge.com>

Hydrocarbon Trapping

SUBCROP

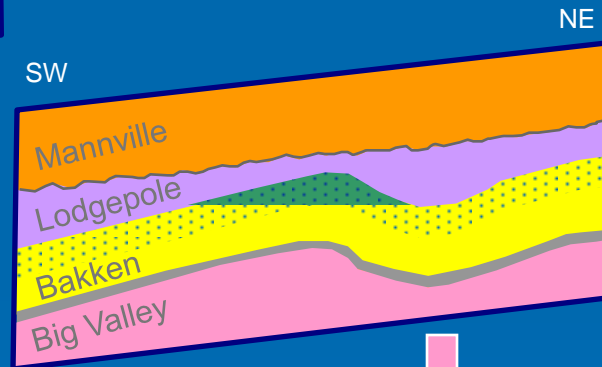


NE

SW

Longitudinal profiles along ridge crest

STRUCTURAL HIGH



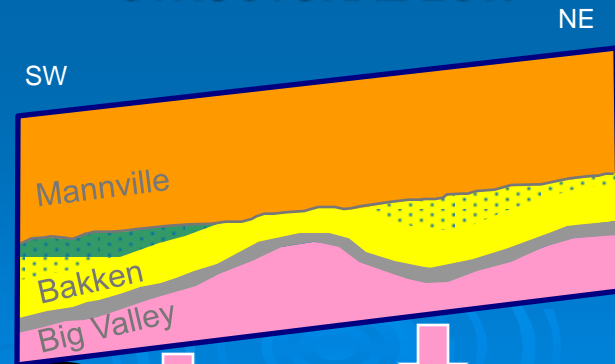
NE

SW

Salt
Collapse

Distribution of reservoir quality facies within ridges adds to the complexity of hydrocarbon pooling and reservoir heterogeneity

STRUCTURAL LOW



NE

SW

Salt
Collapse

Salt
Collapse

Conclusions

- A tidal ridge system in the Bakken Formation is defined by a transgressive surface of erosion (TSE) near the top of the formation
- Ridge facies beneath the TSE are older precursor deposits - they are lowstand deposits that were laid down in tide-dominated deltas and related environments
- The Bakken ridge system was not generated by the accretion of active tidal ridge sands
- The ridge and swale morphology of the TSE played a major role in the migration and trapping of hydrocarbons

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