Sixth Annual Conference on Carbon Capture & Sequestration

Geologic Storage - EOR

Economic Synergies for Combined EOR and Geological Sequestration : An example from the Michigan Basin

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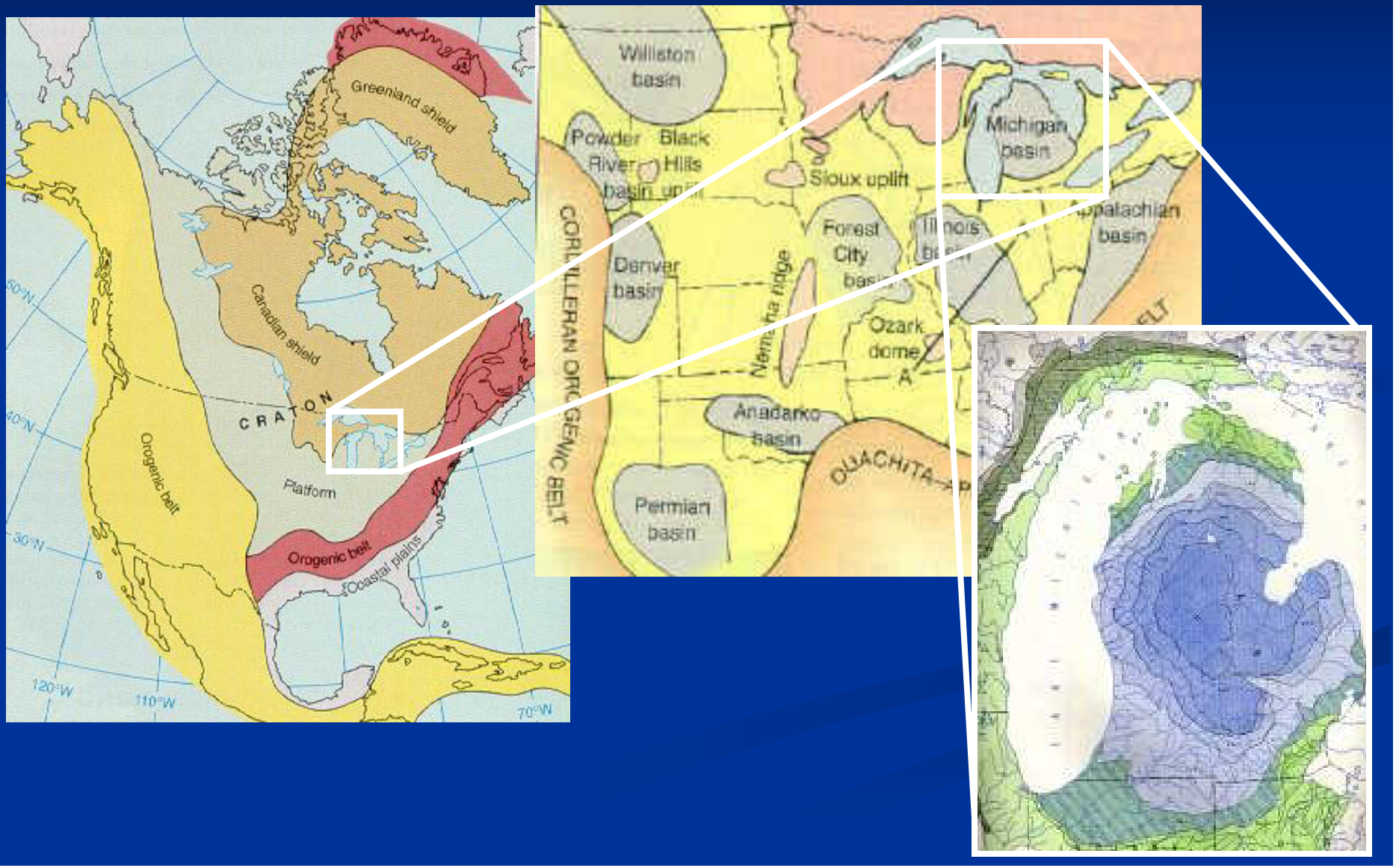
Geologic Setting of the Michigan Basin



Enhanced Oil Recovery in Michigan

- Historic oil production primarily from Ordovician, Silurian and Devonian carbonates
- Cumulative oil production exceeds 1.2 billion bbls
- Most fields produced through primary phase only
- A few dozen waterfloods have been mostly successful. Waterflood EOR production nearly equals primary production in some fields
- Gas storage in some oil fields has also enhanced oil recovery
- CO_2 flooding began in 1996. Only three fields to date.

Silurian (Niagaran) Reef Trends

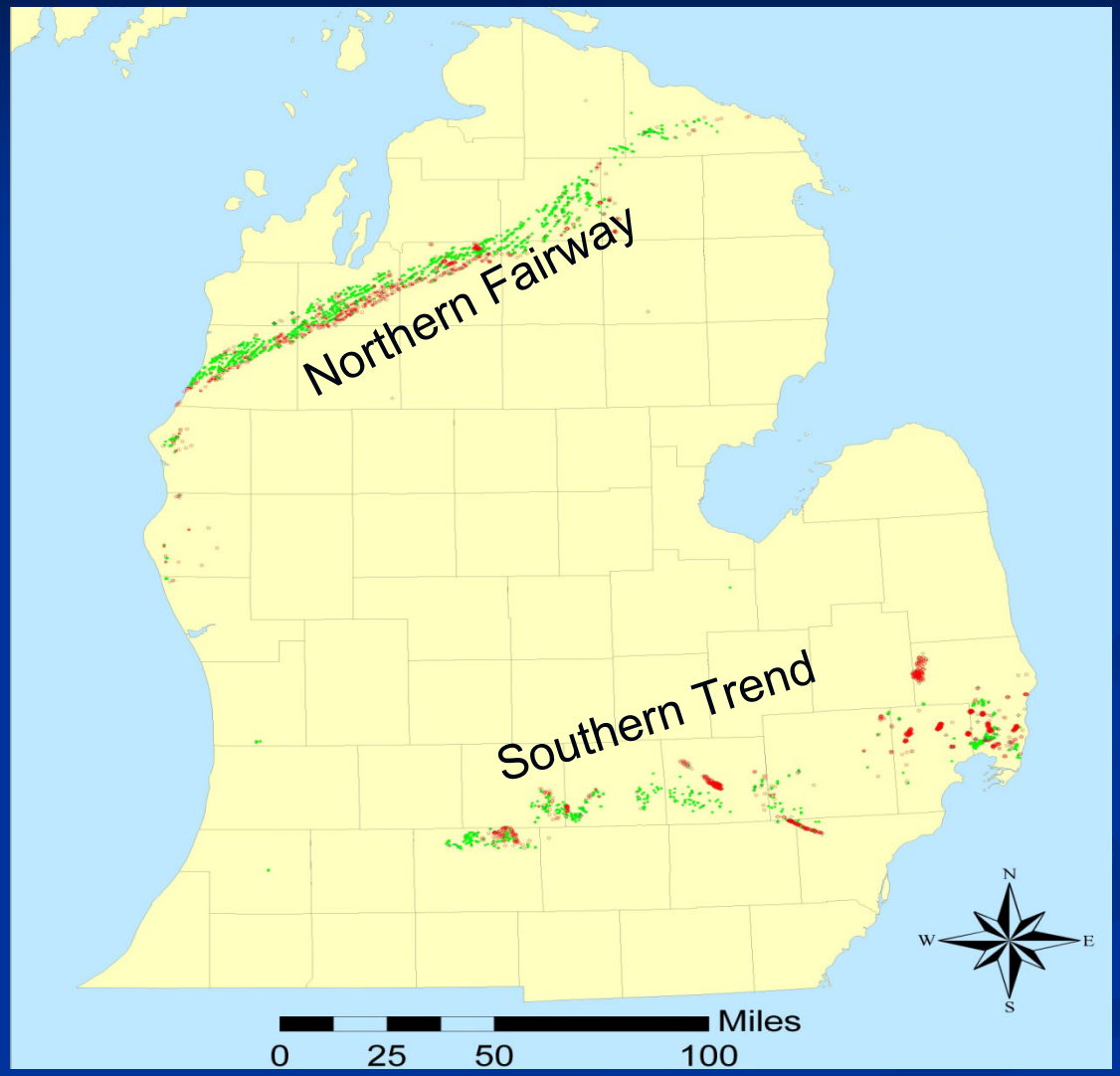
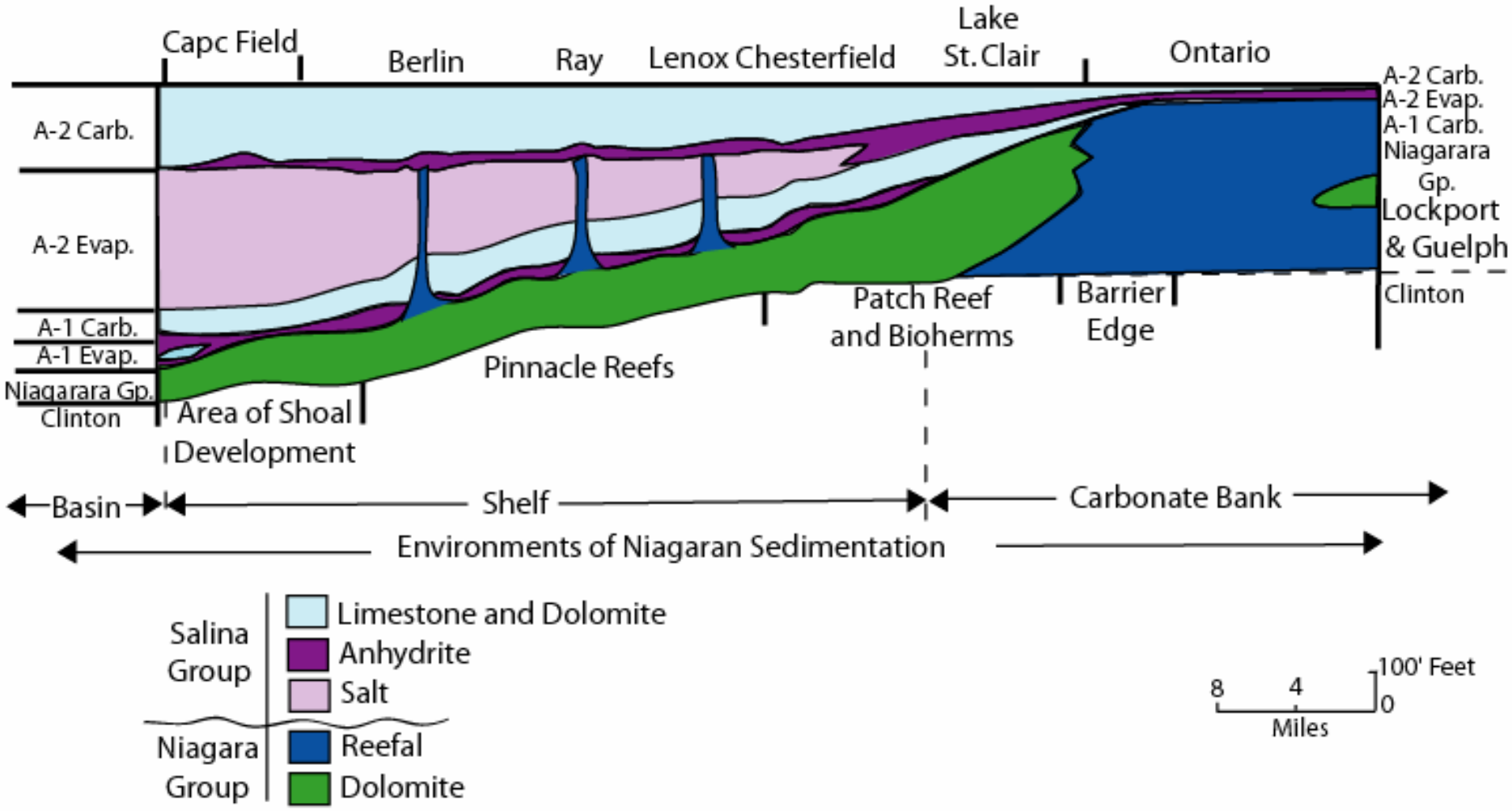


Image courtesy of Michigan DNR ESRI ArcMap online Database

Niagaran Reefs in Michigan Basin

- 1100+ reefs identified in northern and southern trends
- Depths of 3000 to 7000 ft
- Average height ~350 ft. (up to ~700ft.)
- Average diameter ~1000-4000 ft. (highly variable) Area ~ 40 to 400 acres
- Cumulative production:
  - > 450 MMBO > 2.5 TCF

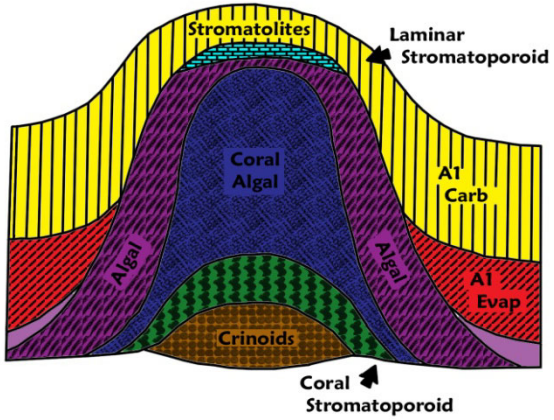
Niagaran Reefs



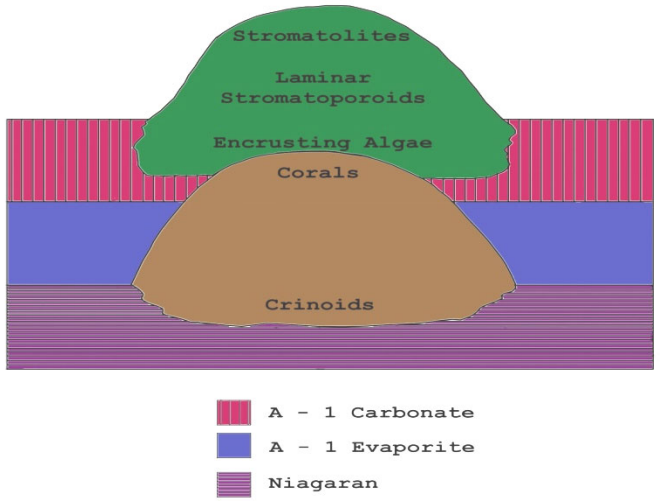
Modified from Burgess and Benson, 1969

Models for Niagaran Pinnacle Reefs

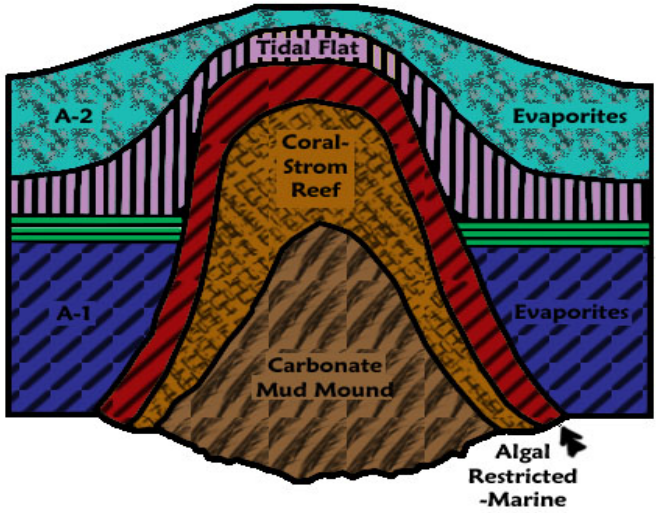
Mantek 1973



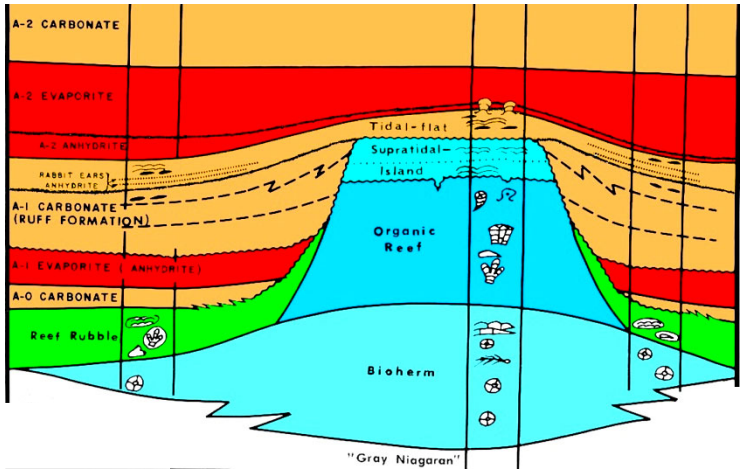
Mesolella 1974



Sears and Lucia 1979



Huh 1973



EOR in Niagaran Reefs

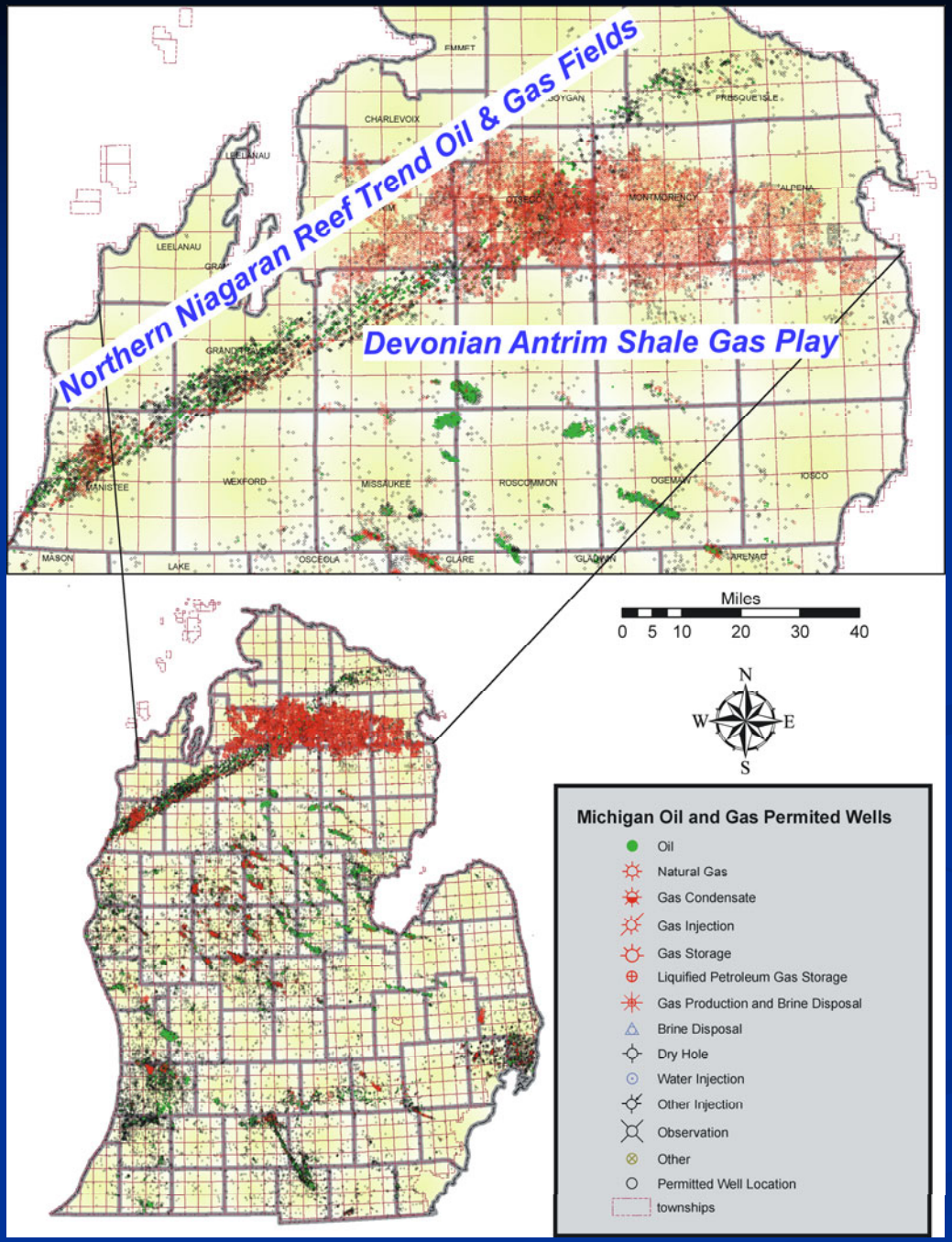
- Secondary recovery programs started in early 1970's (gas re-injection and water injection for pressure maintenance)
- Positive factors:
  - High K (good injectivity and productivity)
  - High gravity oil (35-45^0 API)
- Negative factors:
  - Heterogeneous Reservoir with layered K
  - Limited aerial distribution/size
  - Irregular development pattern

Brock et al. (1995)

EOR Potential for Niagaran Reefs

- Primary Oil Recovery
  - Northern trend (25-35%)
  - Southern trend (15-20%)
- Secondary Oil Recovery
  - Northern trend (10-15%)
  - Southern trend (~20%)
- Primary plus Secondary
  - Northern trend (35-45%)
  - Southern trend (35-45%)

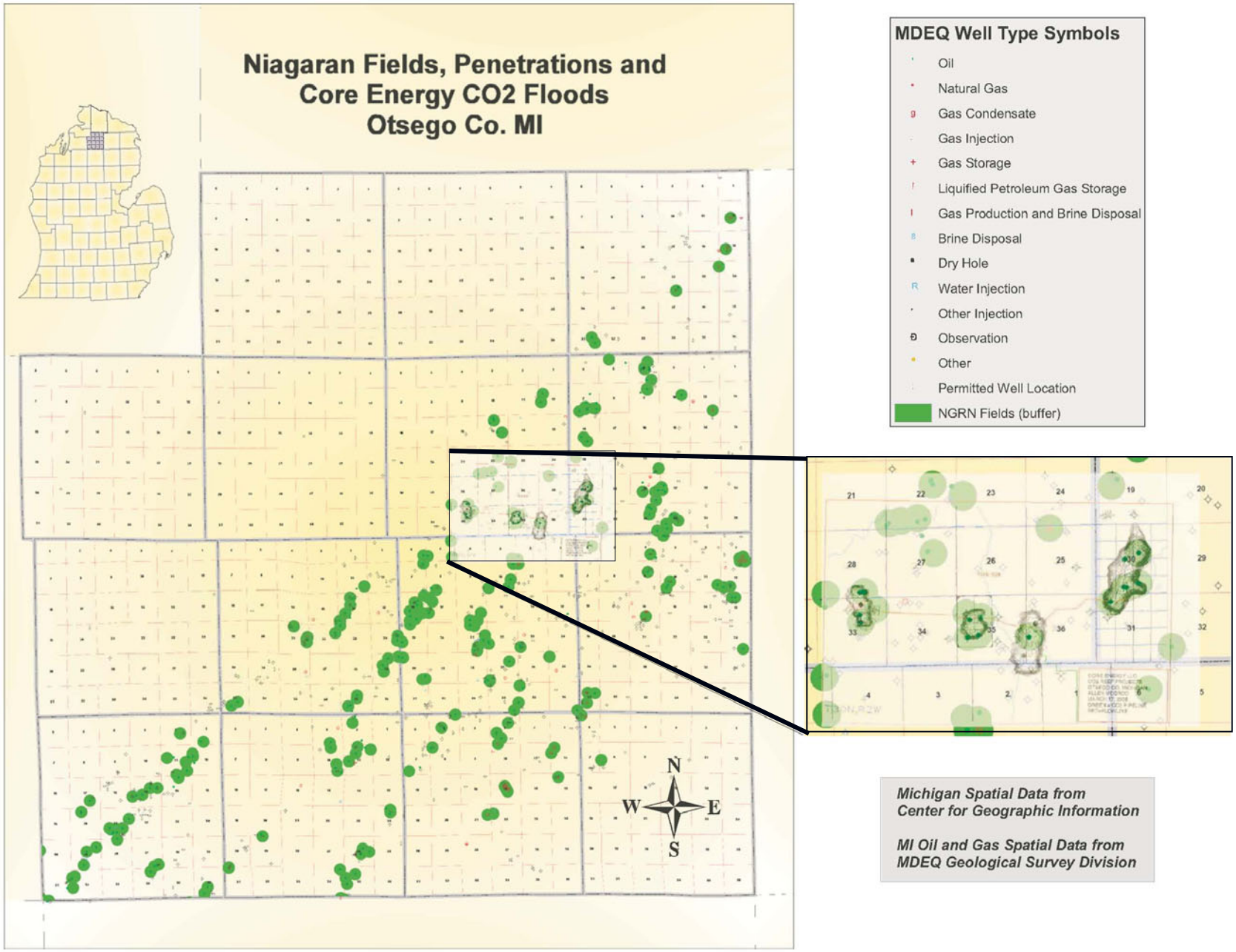
Brock et al. (1995)



Local source of CO_2 as byproduct of Antrim Shale production along northern trend

CO_2 Enhanced Oil Recovery in Michigan

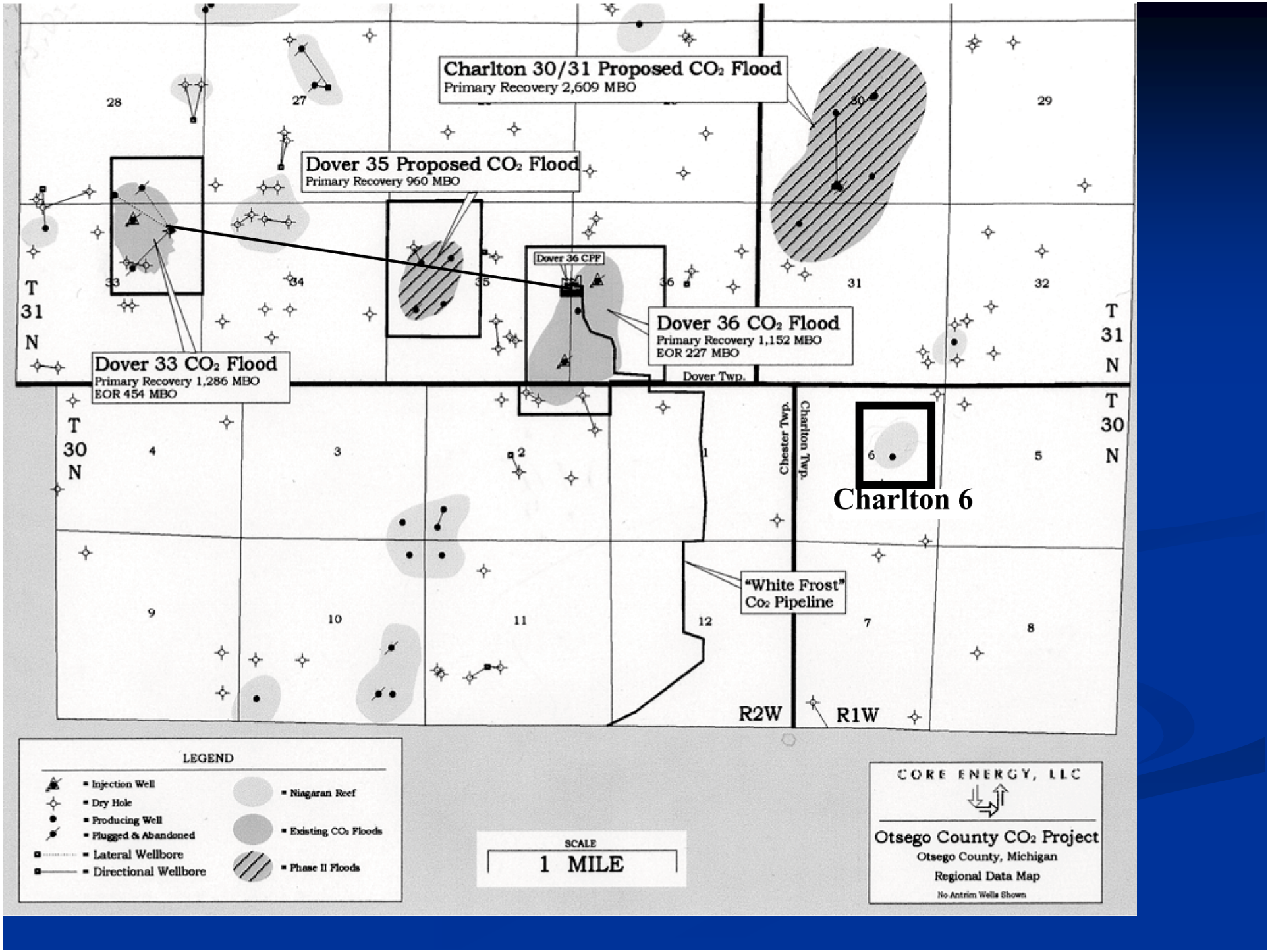
- Three Niagaran reef reservoirs in Otsego County have been converted to EOR CO_2 injection floods (Dover 33, Dover 35 and Dover 36 fields).
- Dover 33 and 36 were developed in 1996 with continuing operations to date.
- The Dover 35 reef EOR project was initiated in early 2004.
- Local source of CO_2 as byproduct of Antrim Shale gas production


Niagaran Fields, Penetrations and
Core Energy CO2 Floods
Otsego Co. MI
MDEQ Well Type Symbols
Oil
Natural Gas
Gas Condensate
Gas Injection
Gas Storage
Liquified Petroleum Gas Storage
Gas Production and Brine Disposal
Brine Disposal
Dry Hole
Water Injection
Other Injection
Observation
Other
Permitted Well Location
NGRN Fields (buffer)
N
W
E
S
Michigan Spatial Data from
Center for Geographic Information
MI Oil and Gas Spatial Data from
MDEQ Geological Survey Division

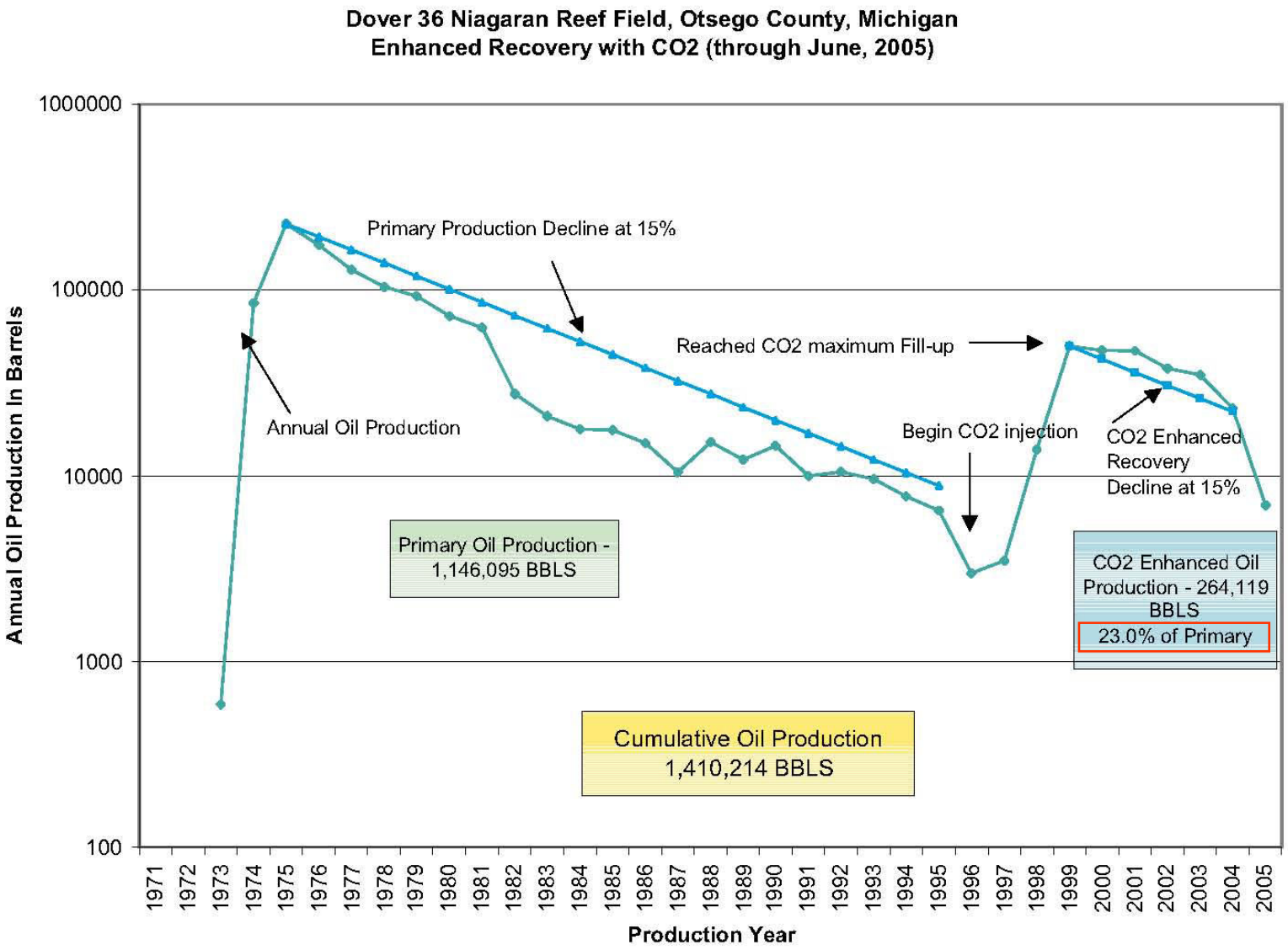
CO_2 Enhanced Oil Recovery in Michigan

- High purity CO_2 is byproduct from gas processing of Devonian Antrim Shale production
- Injected over 300,000 tons of CO_2 into three Niagaran Reef reservoirs
- Enhanced oil recovery of >750,000 bbls in nine years

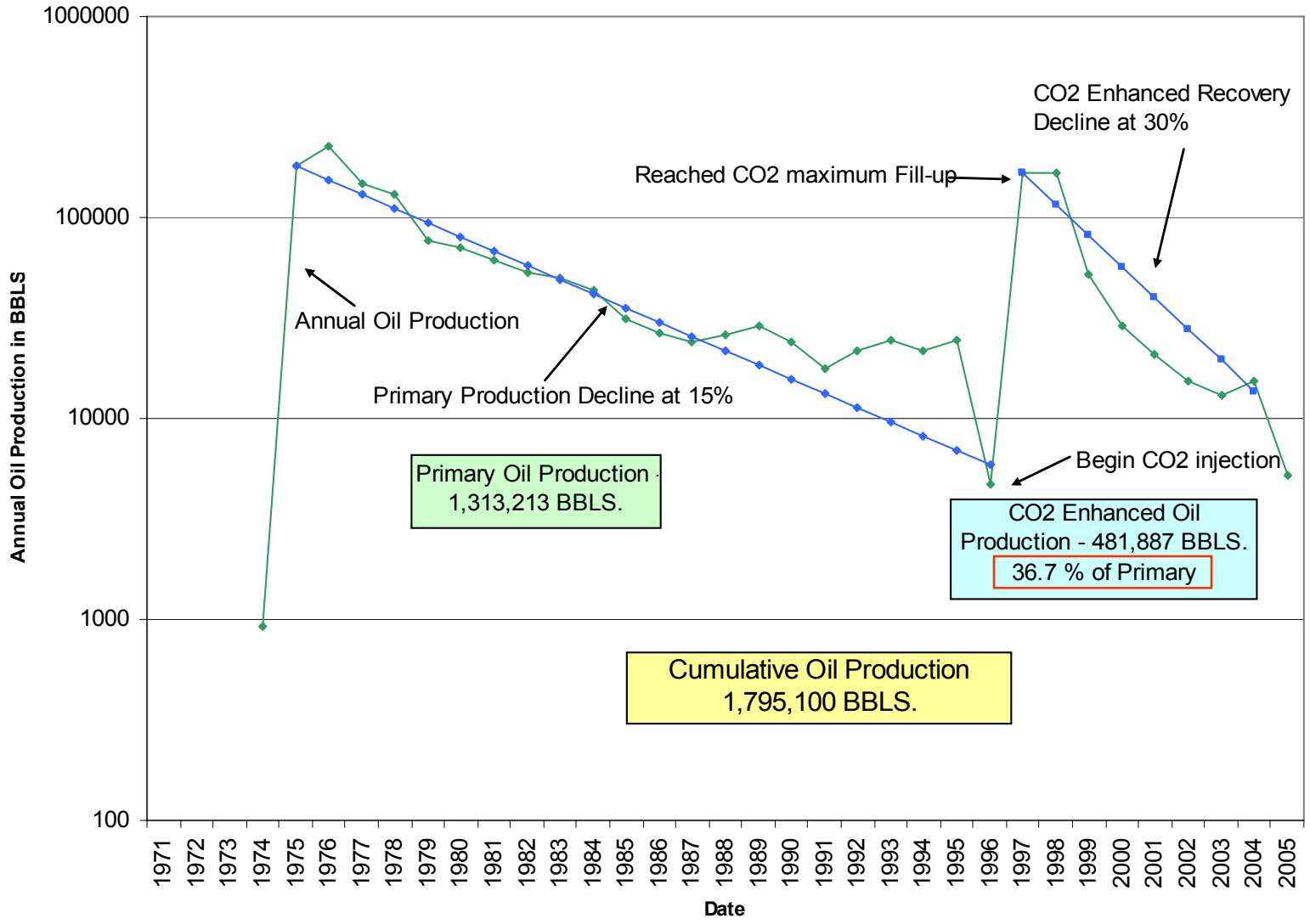
Antrim Surface Production and Processing Facilities

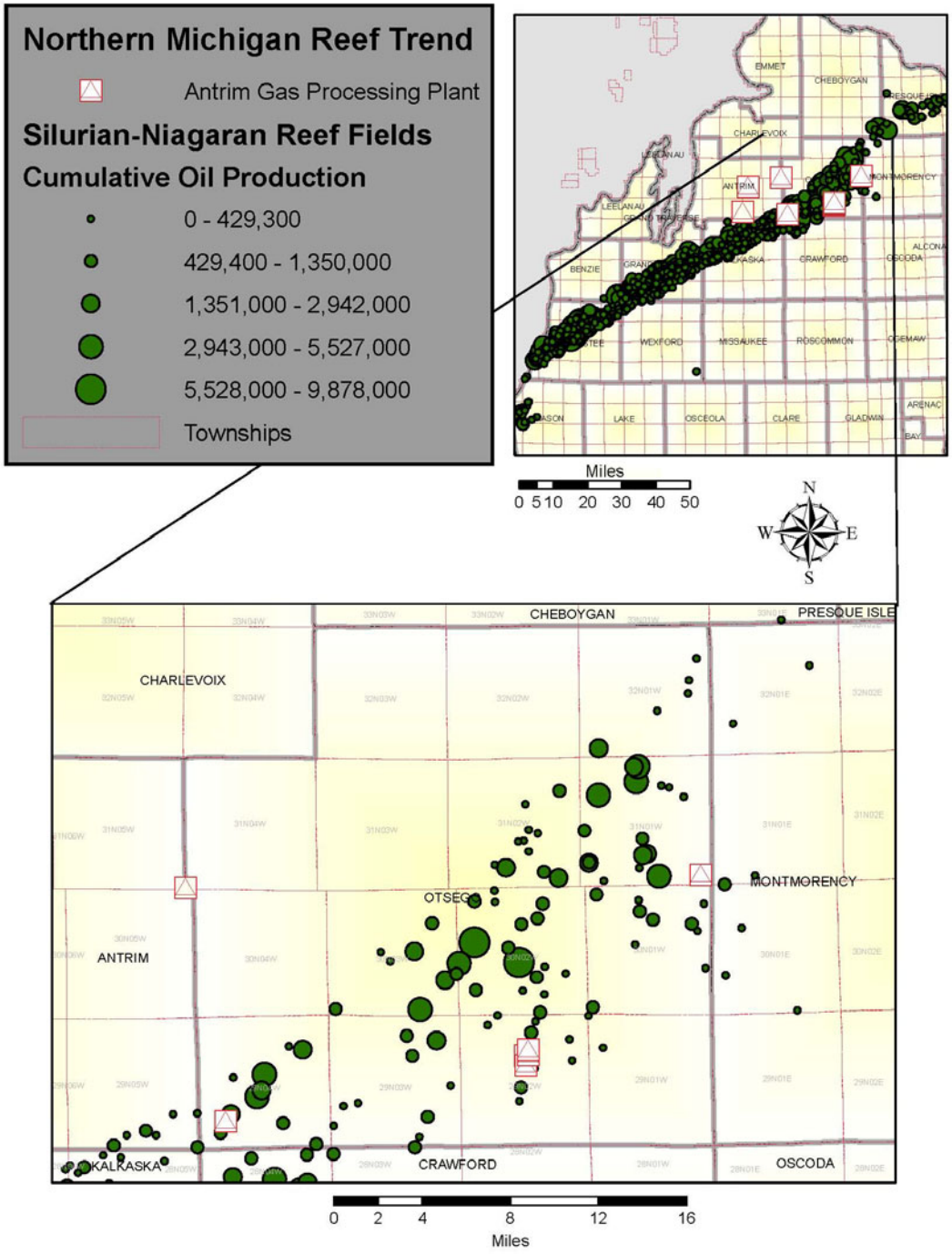

Charlton 30/31 Proposed CO₂ Flood
Primary Recovery 2,609 MBO
Dover 35 Proposed CO₂ Flood
Primary Recovery 960 MBO
Dover 36 CPF
Dover 36 CO₂ Flood
Primary Recovery 1,152 MBO
EOR 227 MBO
Dover 33 CO₂ Flood
Primary Recovery 1,286 MBO
EOR 454 MBO
Dover Twp.
Chester Twp.
Charlton Twp.
Charlton 6
"White Frost"
Co₂ Pipeline
T 31 N
T 30 N
R2W
R1W
LEGEND
Injection Well
Dry Hole
Producing Well
Plugged & Abandoned
Lateral Wellbore
Directional Wellbore
Niagaran Reef
Existing CO₂ Floods
Phase II Floods
SCALE
1 MILE
CORE ENERGY, LLC
Otsego County CO₂ Project
Otsego County, Michigan
Regional Data Map
No Antrim Wells Shown

CO_2 Injection Facilities for EOR Otsego County, Michigan


Dover 36 Niagaran Reef Field, Otsego County, Michigan
Enhanced Recovery with CO2 (through June, 2005)
Annual Oil Production In Barrels
1000000
100000
10000
1000
100
Primary Production Decline at 15%
Reached CO2 maximum Fill-up
Annual Oil Production
Begin CO2 injection
CO2 Enhanced Recovery Decline at 15%
Primary Oil Production - 1,146,095 BBLS
CO2 Enhanced Oil Production - 264,119 BBLS
23.0% of Primary
Cumulative Oil Production
1,410,214 BBLS
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Production Year

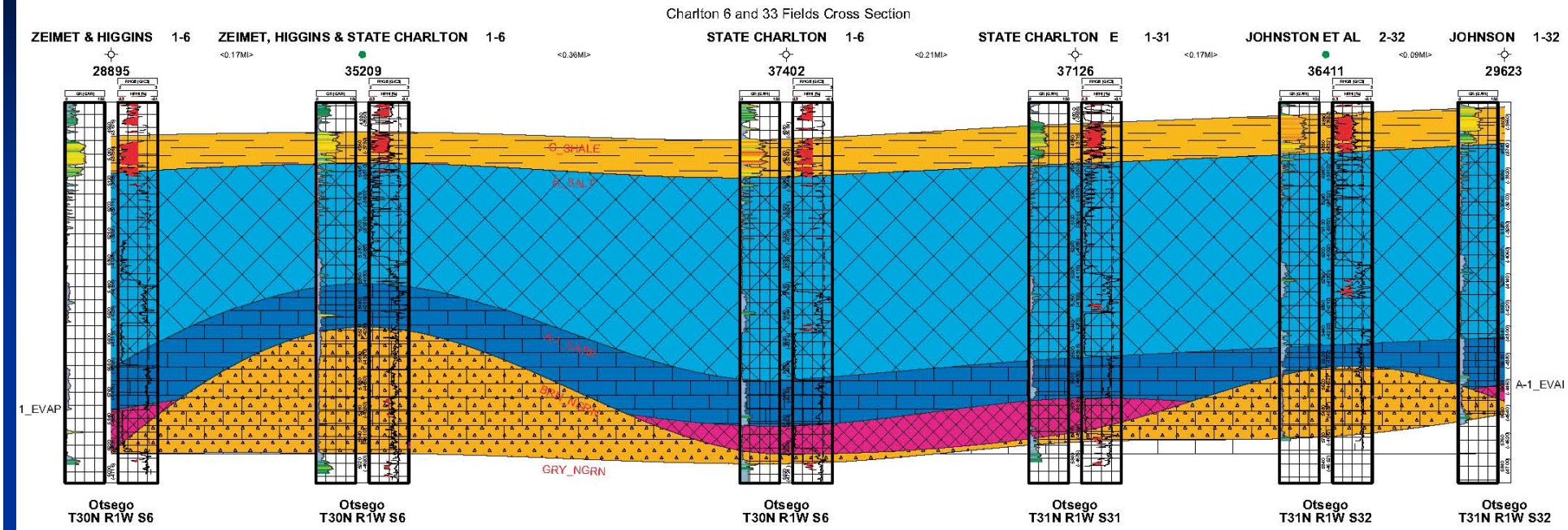
Dover 33 Niagaran Reef Field, Otsego County, Michigan
Enhanced Recovery with CO2 (through June, 2005)

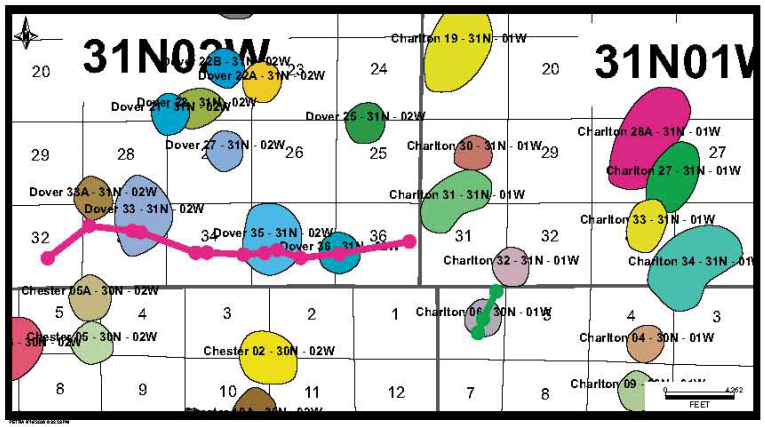


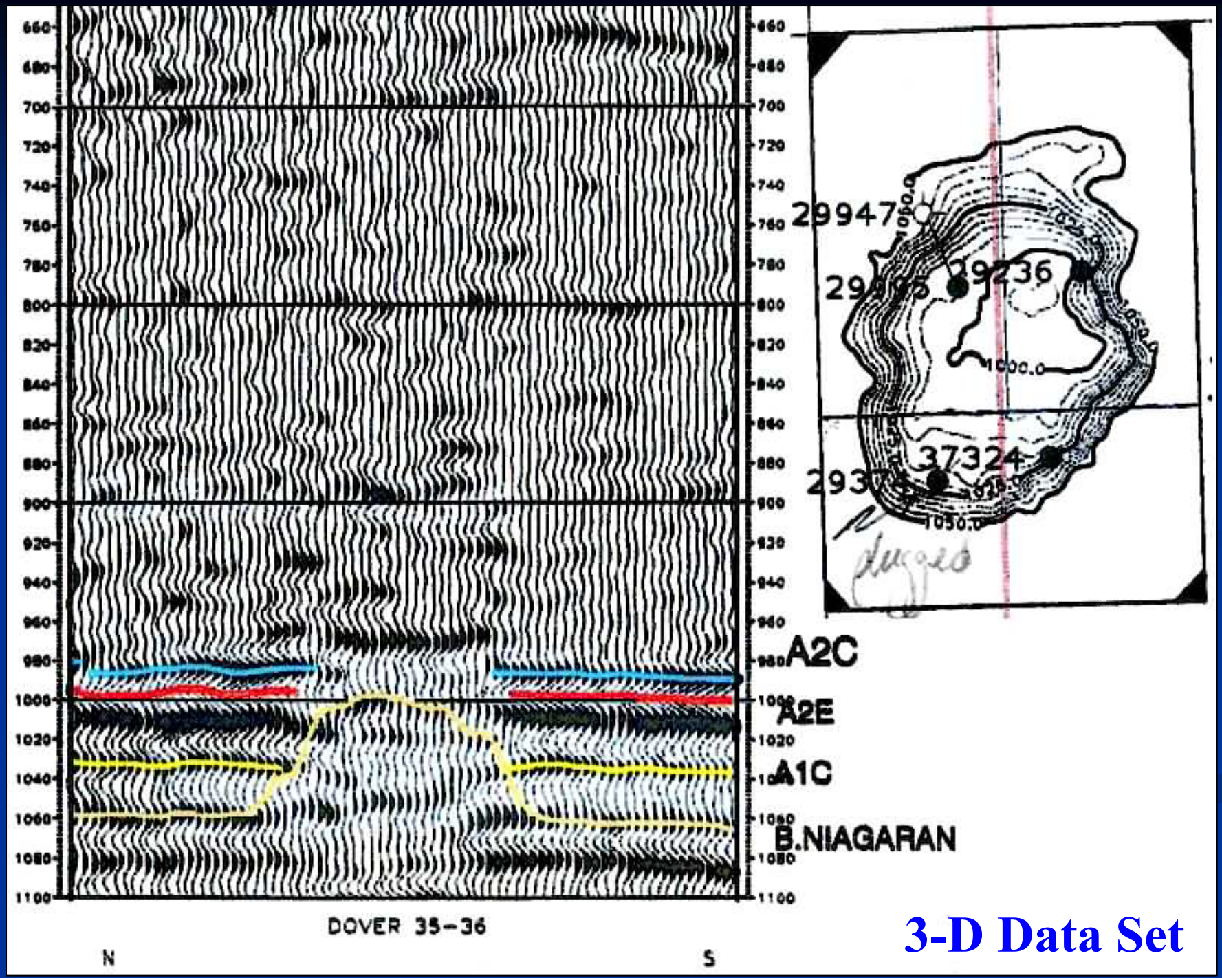


Abundant EOR Targets

Only three reefs out of more than 700 in Northern Michigan, have been developed using CO_2 EOR methods

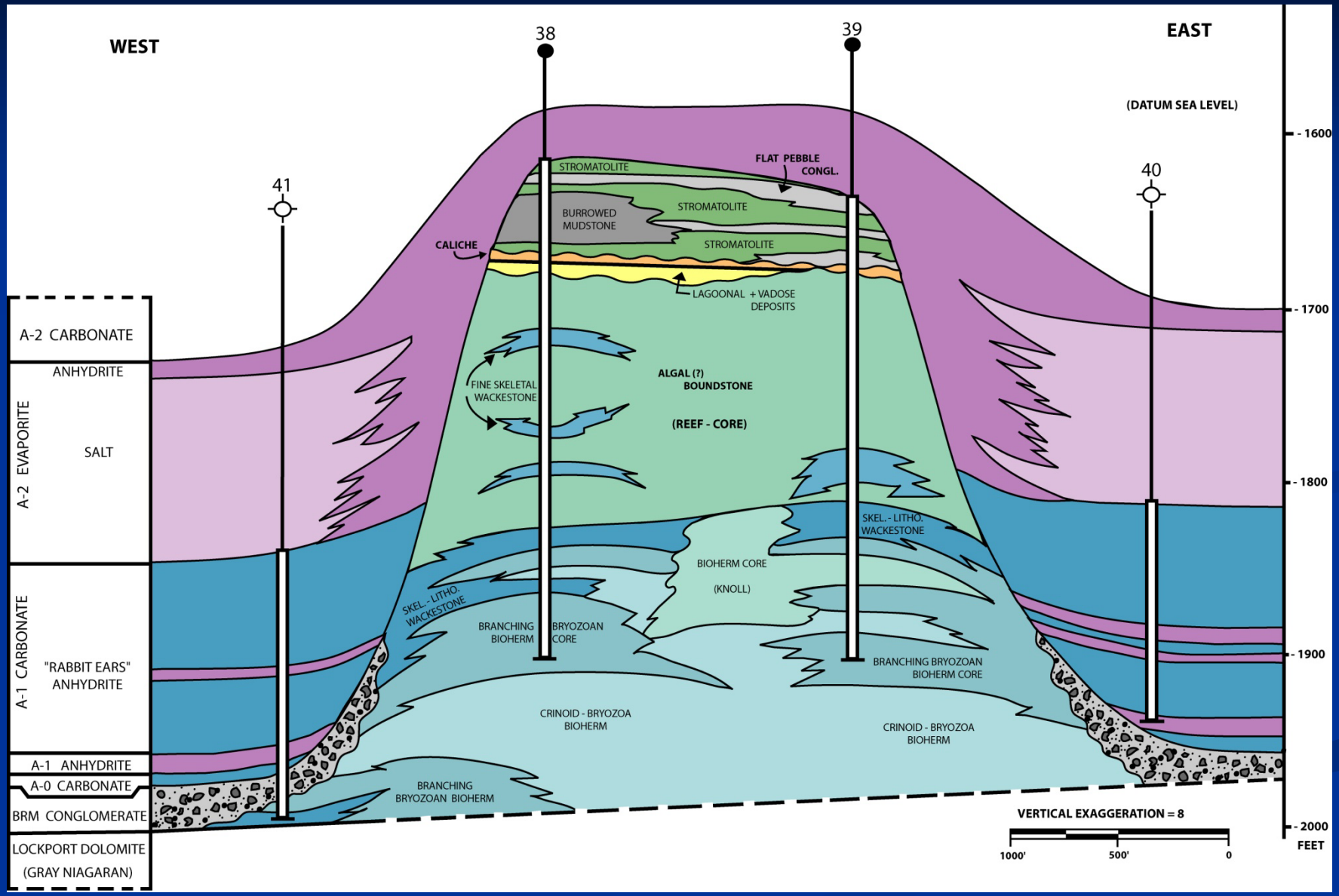

Charlton 6 and 33 Fields Cross Section
ZEIMET & HIGGINS 1-6
ZEIMET, HIGGINS & STATE CHARLTON 1-6
STATE CHARLTON 1-6
STATE CHARLTON E 1-31
JOHNSTON ET AL 2-32
JOHNSON 1-32
28895
35209
37402
37126
36411
29623
<0.17MI>
<0.36MI>
<0.21MI>
<0.17MI>
<0.09MI>
G_SHALE
B_SALT
A-1_CARB
SHALE
GRY_NGRN
1_EVAP
A-1_EVAI
Otsego T30N R1W S6
Otsego T30N R1W S6
Otsego T30N R1W S6
Otsego T31N R1W S31
Otsego T31N R1W S32
Otsego T31N R1W S32


31N02W
31N01W
Charlton 19 - 31N - 01W
Dover 32B - 31N - 02W
Dover 32A - 31N - 02W
Dover 26 - 31N - 02W
Dover 27 - 31N - 02W
Charlton 30 - 31N - 01W
Charlton 28A - 31N - 01W
Charlton 27 - 31N - 01W
Dover 33A - 31N - 02W
Dover 33 - 31N - 02W
Charlton 31 - 31N - 01W
Charlton 33 - 31N - 01W
Dover 35 - 31N - 02W
Charlton 32 - 31N - 01W
Charlton 34 - 31N - 01W
Chester 05A - 30N - 02W
Chester 05 - 30N - 02W
Chester 02 - 30N - 02W
Charlton 04 - 30N - 01W
Charlton 09
FEET

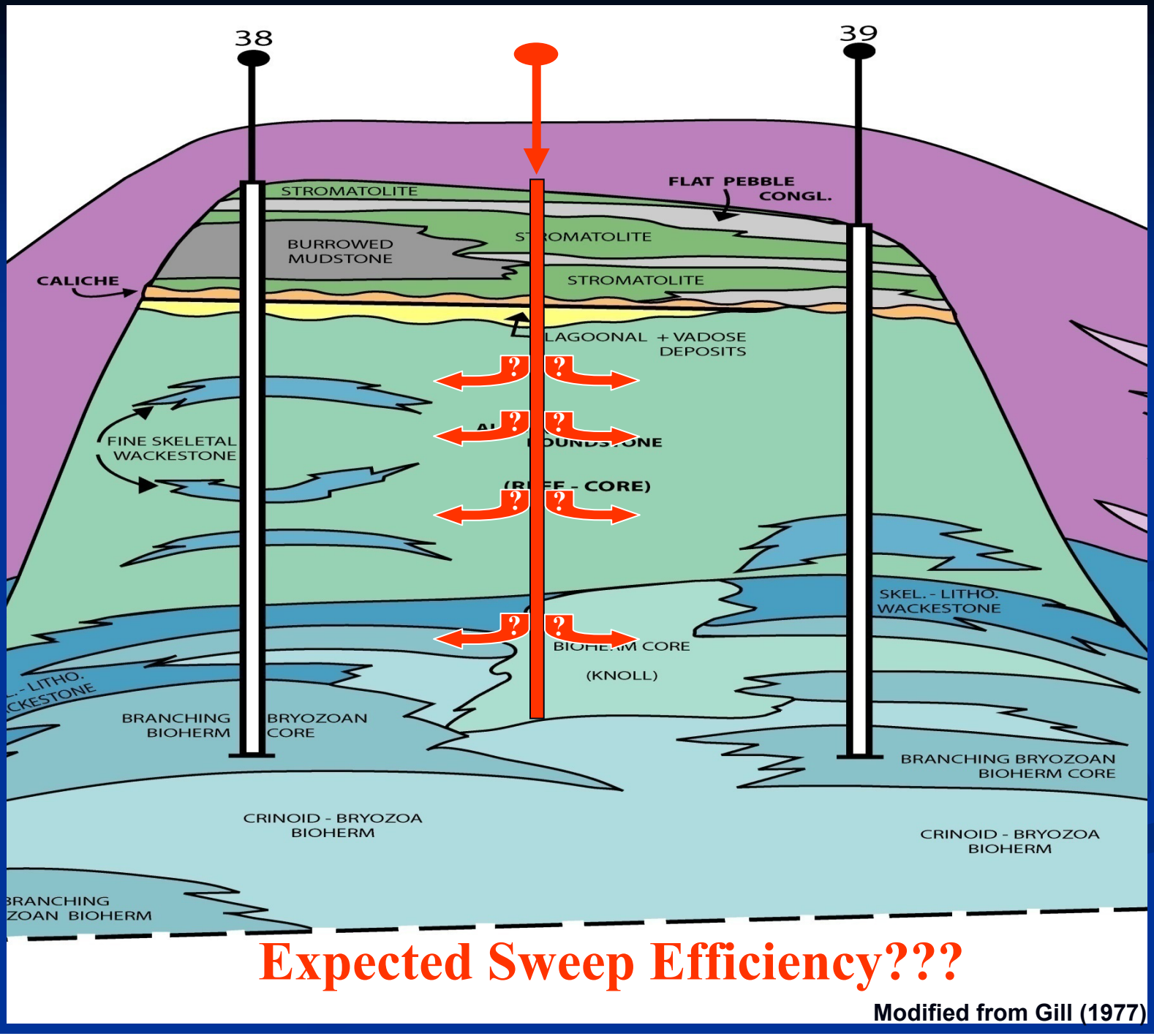

660
680
700
720
740
760
780
800
820
840
860
880
900
920
940
960
980
1000
1020
1040
1060
1080
1100
29947
29236
37324
1000.0
1050.0
A2C
A2E
A1C
B.NIAGARAN
DOVER 35-36
N
S

3-D Data Set

Belle River Mills Field (southern trend)

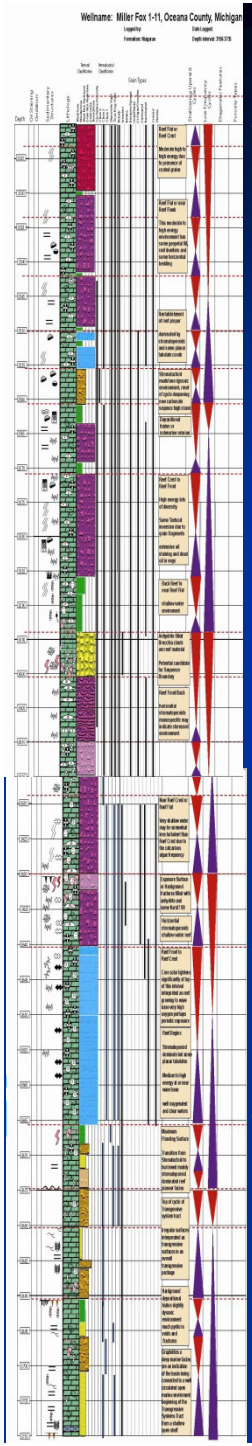


Re-drafted from Gill, 1977



Expected Sweep Efficiency???

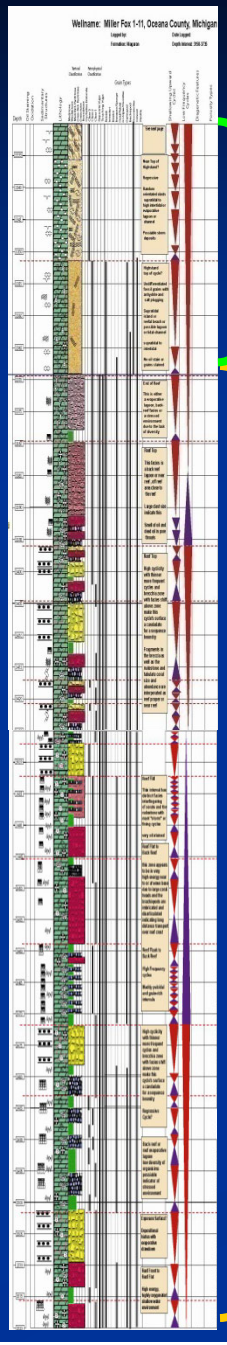
Modified from Gill (1977)



Reef

Mud Mound

Sandomierski (2006)



Supratidal/
Intertidal

Reef

Niagaran Reefs are Complex and Heterogeneous

Sequence Stratigraphic framework may enhance predictability of reservoir facies!

Conclusions

1. Silurian pinnacle reefs have significant promise as CO_2 injection targets for EOR and sequestration
2. Three reefs have been successfully flooded during the past ten years
3. Over 750,000 bbls of oil have been recovered, which is about 30% of the total primary production
4. Although some CO_2 is moved from reef to reef, over 300,000 tons of CO_2 have been sequestered

Conclusions

1. Michigan Niagaran Reef EOR potential is High

But:

2. Niagaran pinnacle reefs are vertically complex – predictable?
3. There is a distinct correlation between detailed facies type and reservoir quality (f, K)
4. Original depositional facies and cycle framework may be responsible for controlling reservoir compartmentalization (baffles and barriers)