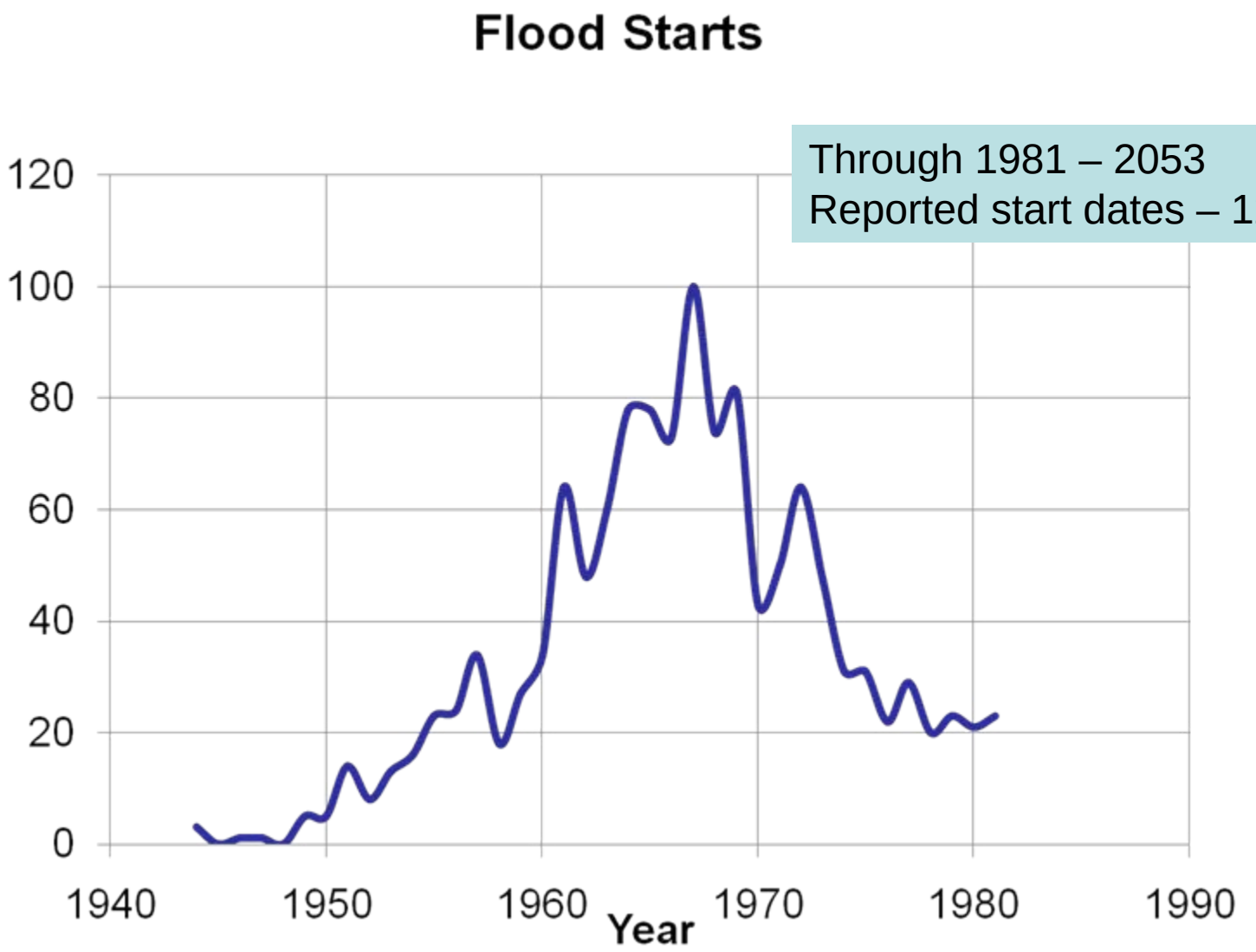
A History of Past Waterflood Operations in the Permian Basin

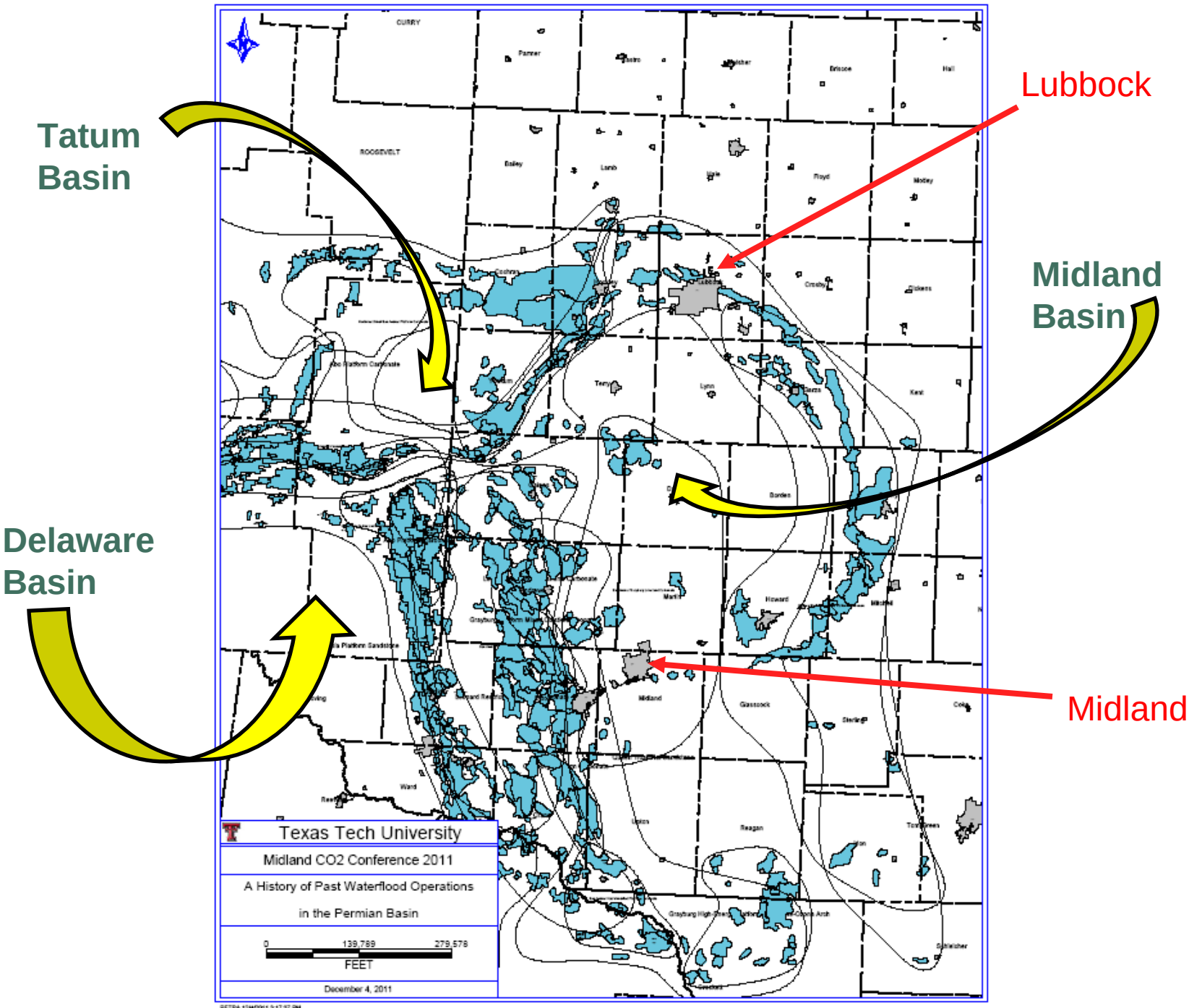
Marshall C. Watson, Ph.D., P.E.
Bob L. Herd Department of Petroleum Engineering
Texas Tech University

Presented at the 17th Annual CO_2 Flooding Conference

December 8-9, 2011

Midland, Texas

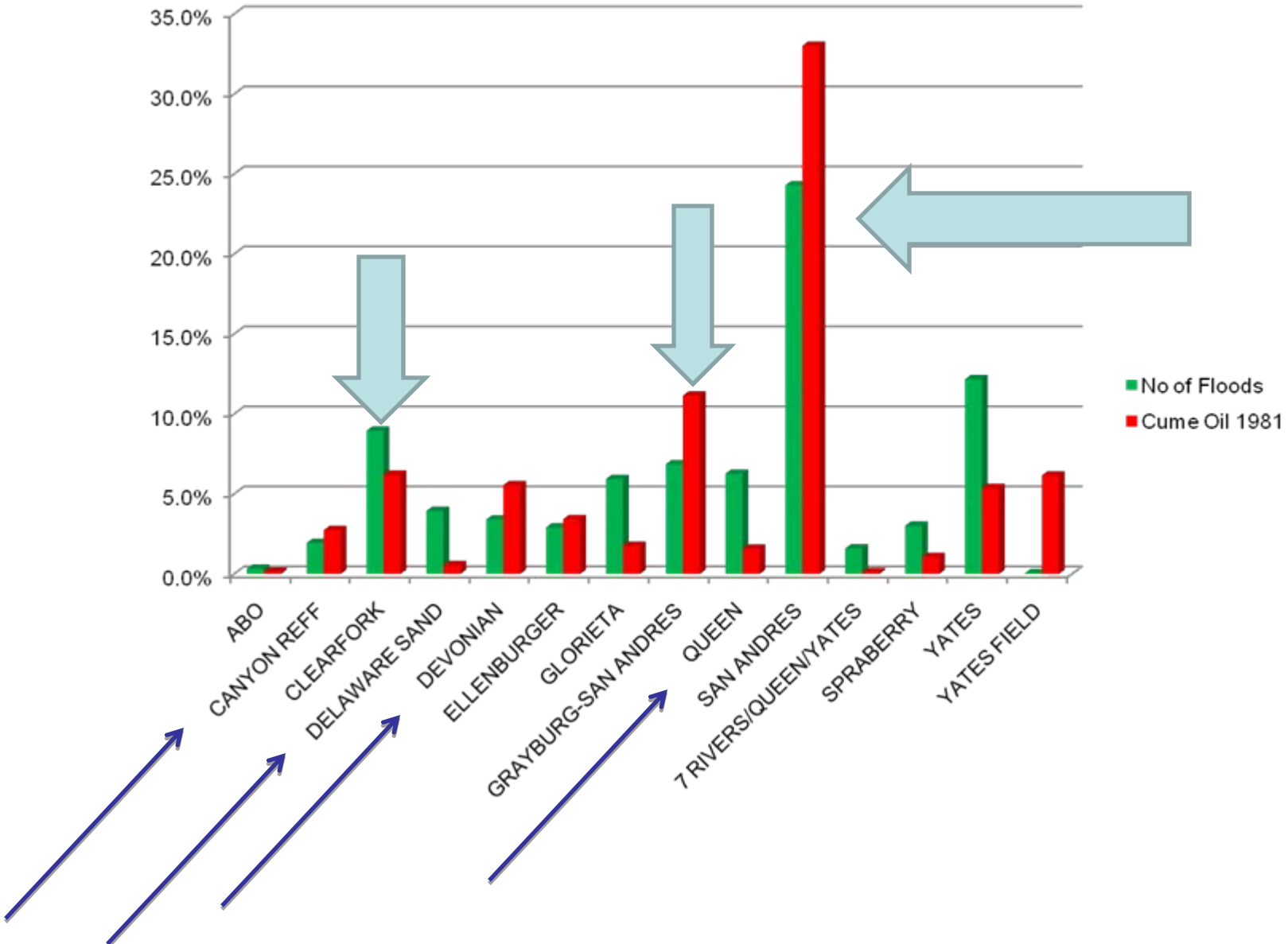

Flood Starts
Through 1981 – 2053
Reported start dates – 1286
120
100
80
60
40
20
0
1940
1950
1960
1970
1980
1990
Year


Tatum Basin
Lubbock
Midland Basin
Delaware Basin
Midland
Texas Tech University
Midland CO2 Conference 2011
A History of Past Waterflood Operations
in the Permian Basin
0
139,789
279,578
FEET
December 4, 2011

NW Shelf – Levelland Slaughter Statistics

- NW Shelf – 10% U.S. Reserves
- NW Shelf – Cume 4 BBO
- NW Shelf – Carbonate Reservoirs
- Levelland Slaughter – Cume 1.6 BBO
- Levelland Slaughter – 57 MBO/day
- Levelland Slaughter – 6% State's Production

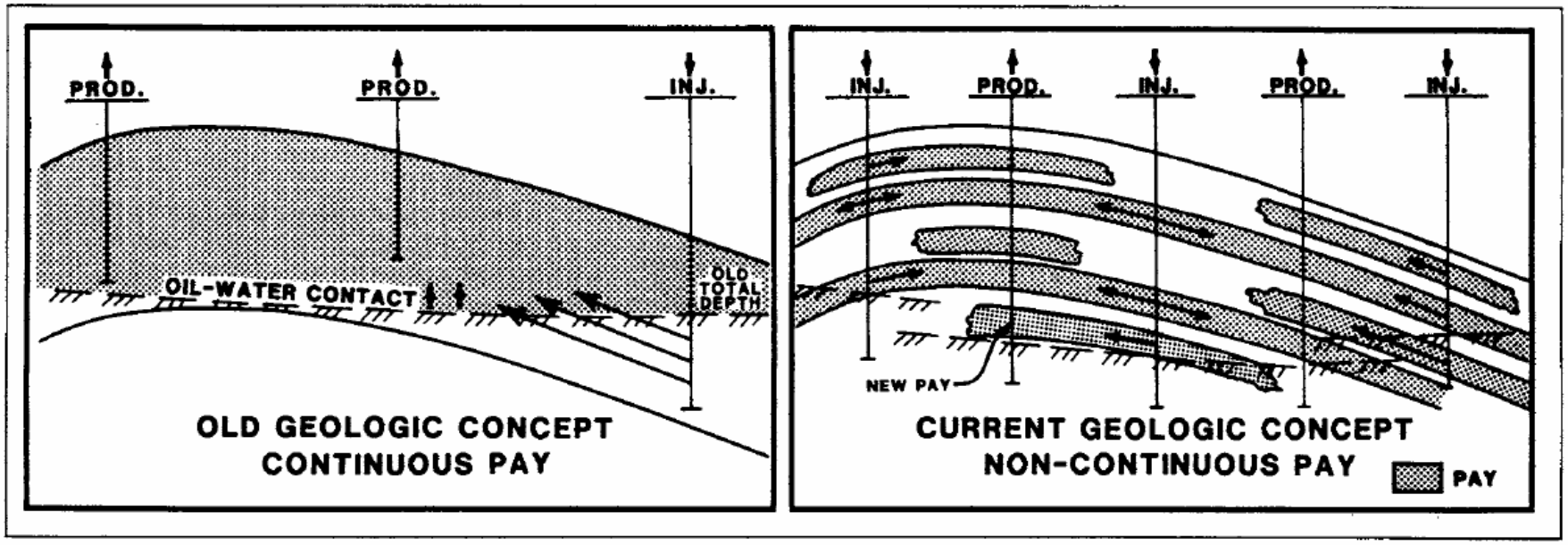
Permian Basin Waterfloods



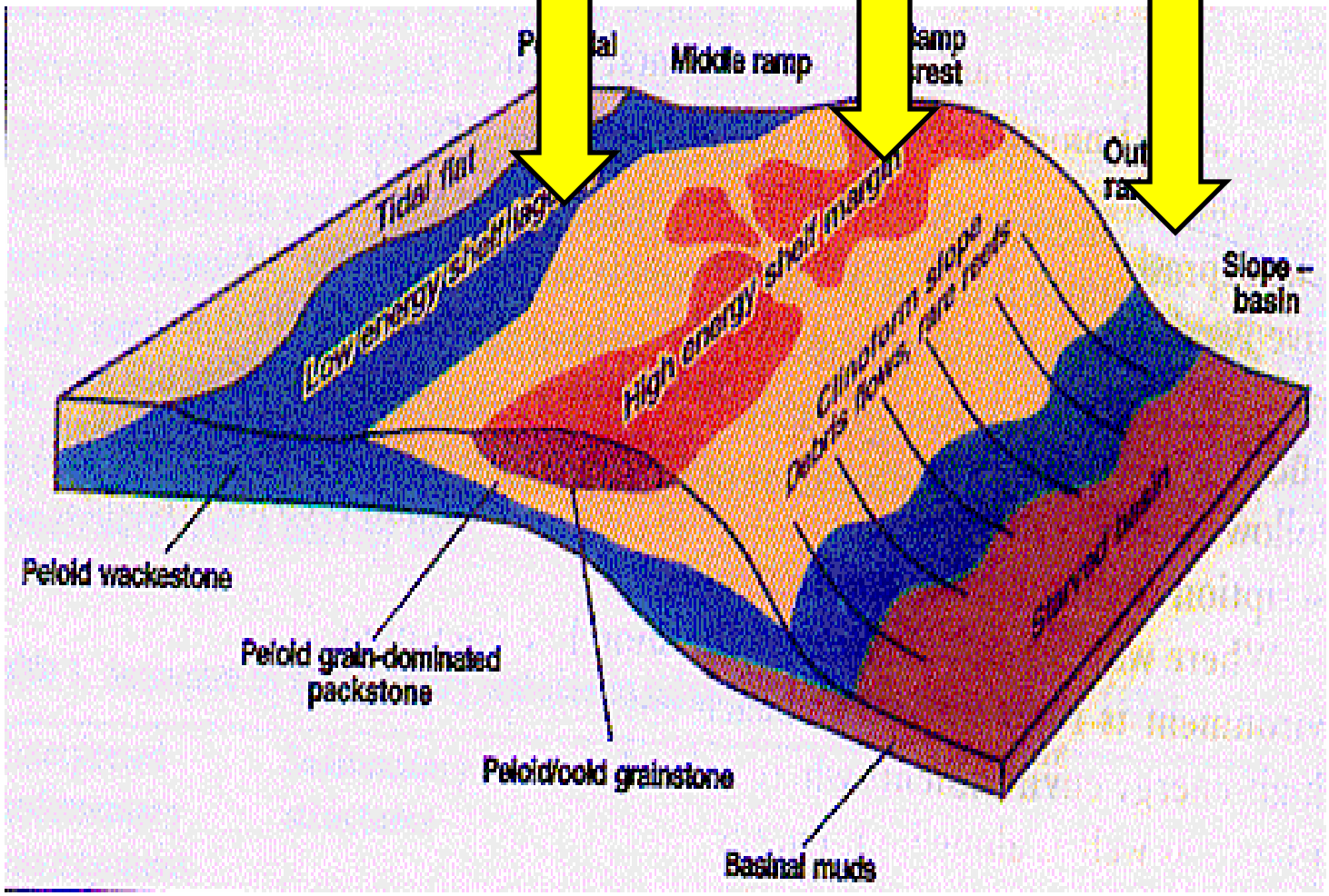
Evaluation

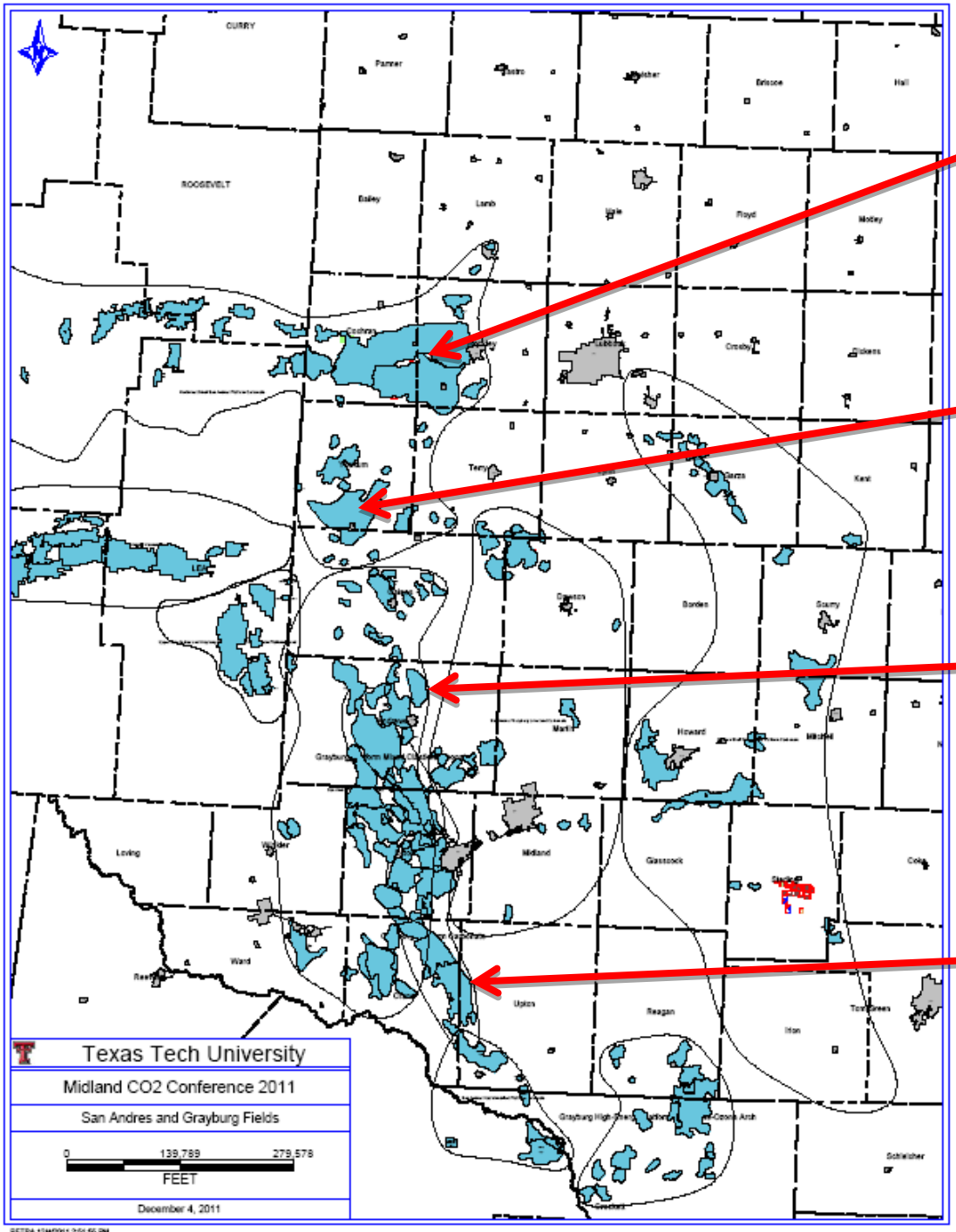
- Understand the Geology
- Understand the Petrophysics
- Understand the Reservoir Fluids
- Evaluate the Reservoir

Geologic Concepts are Important

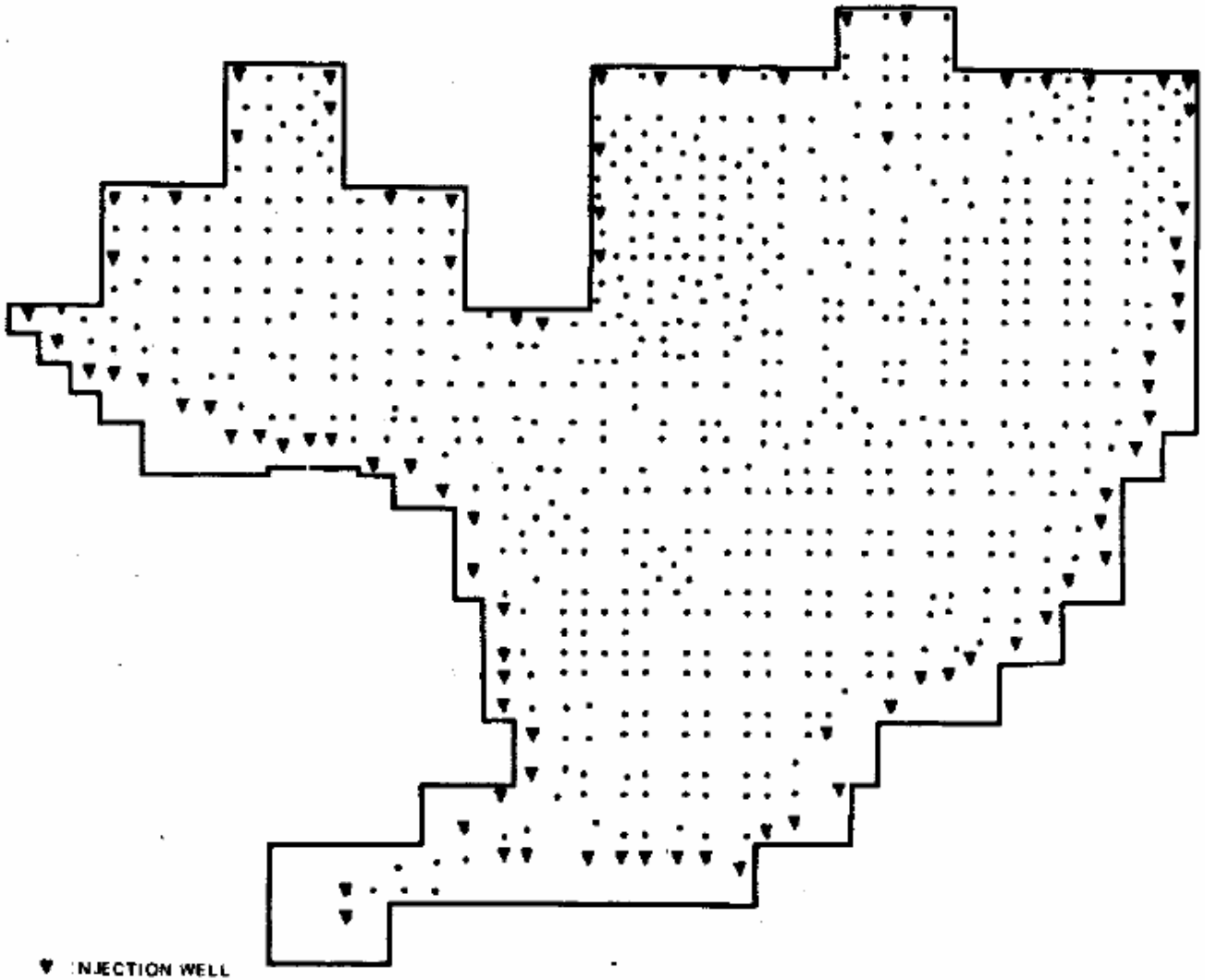


Carbonate Ramp Schematic

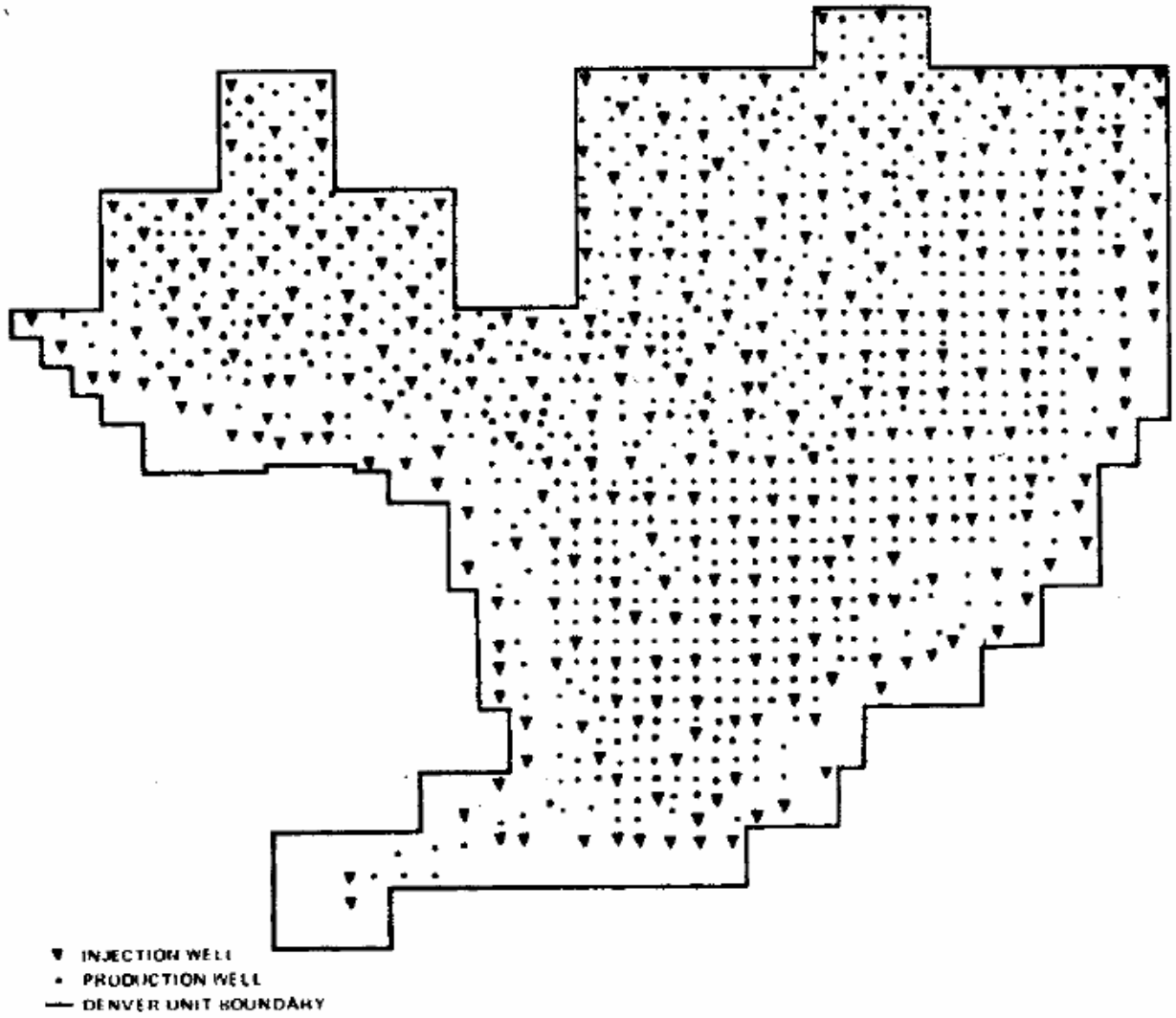


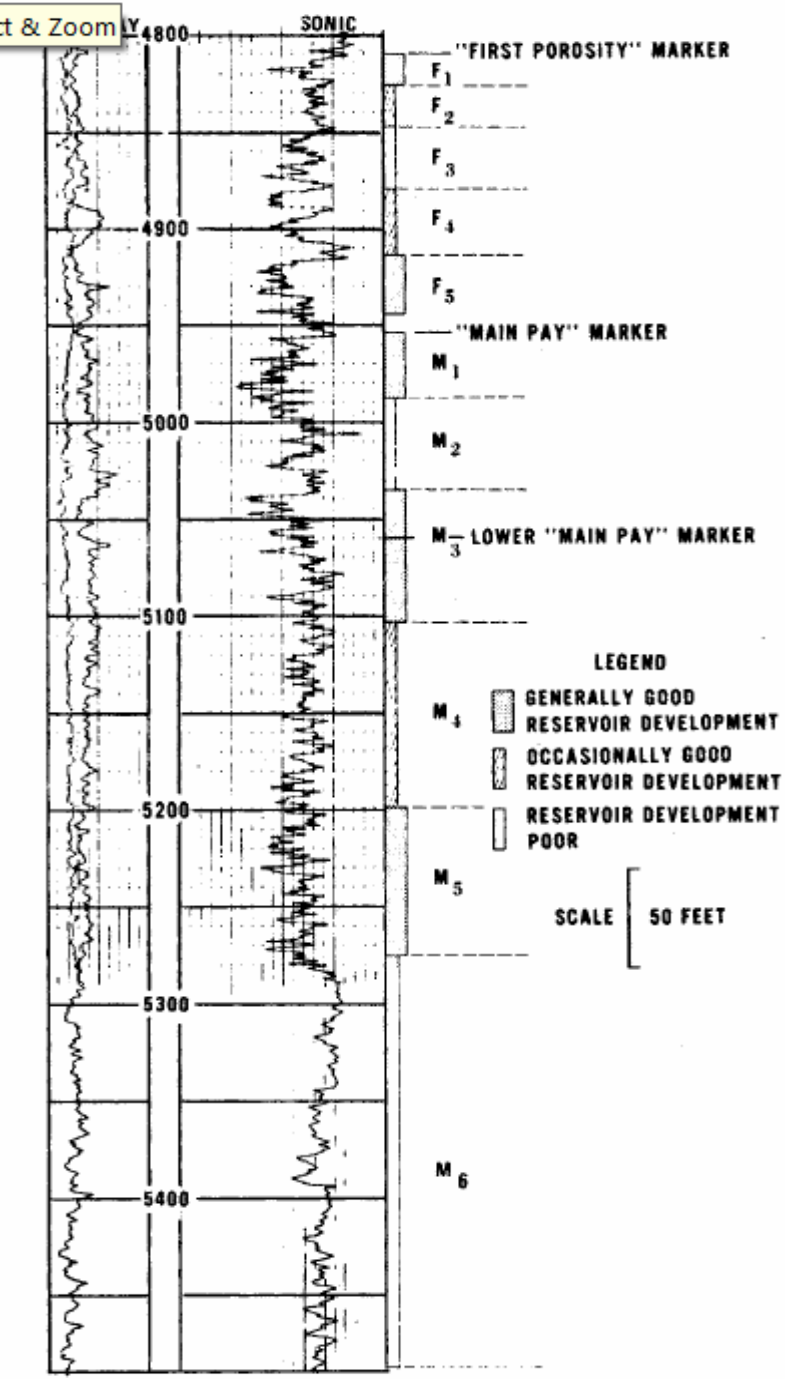

Levelland
Slaughter
Wasson
Means
McElroy
Texas Tech University
Midland CO2 Conference 2011
San Andres and Grayburg Fields
0
139,789
279,578
FEET
December 4, 2011

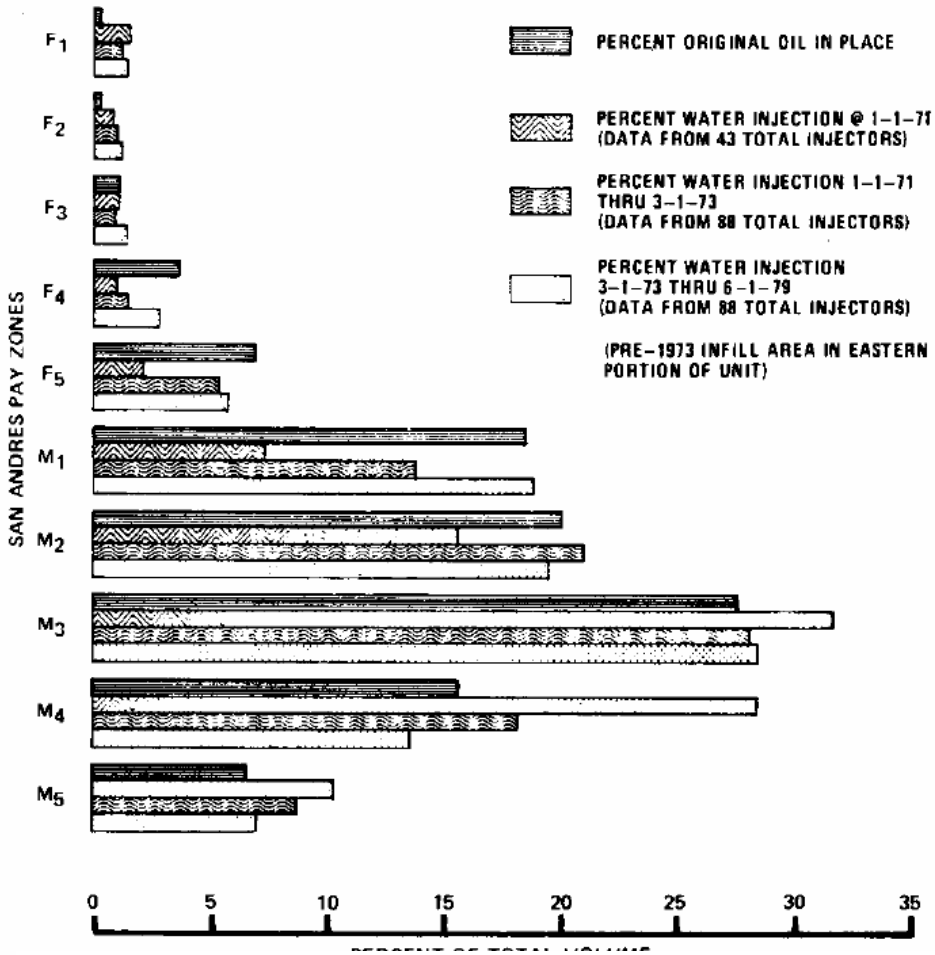
Denver Unit Peripheral Pattern



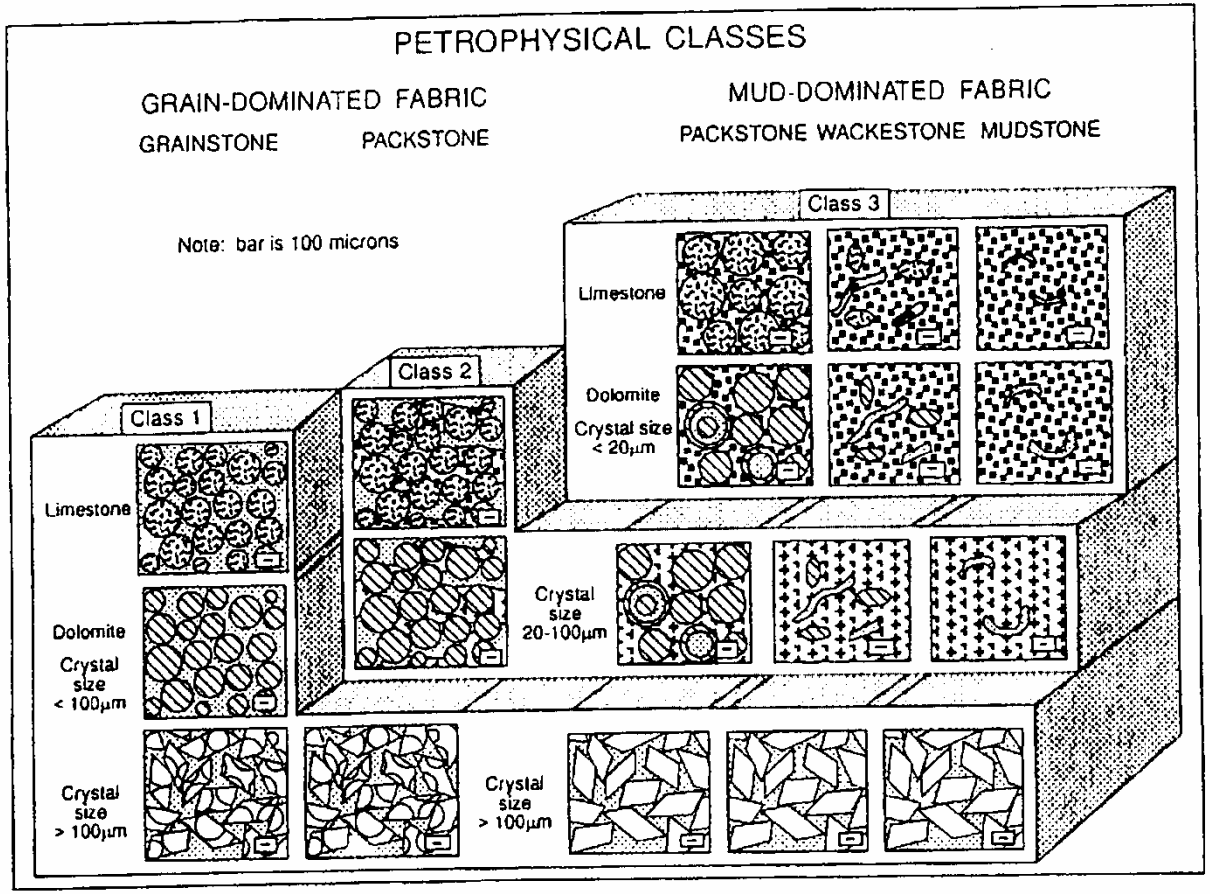
Denver Unit 9 Spot Plus Irregular Patterns



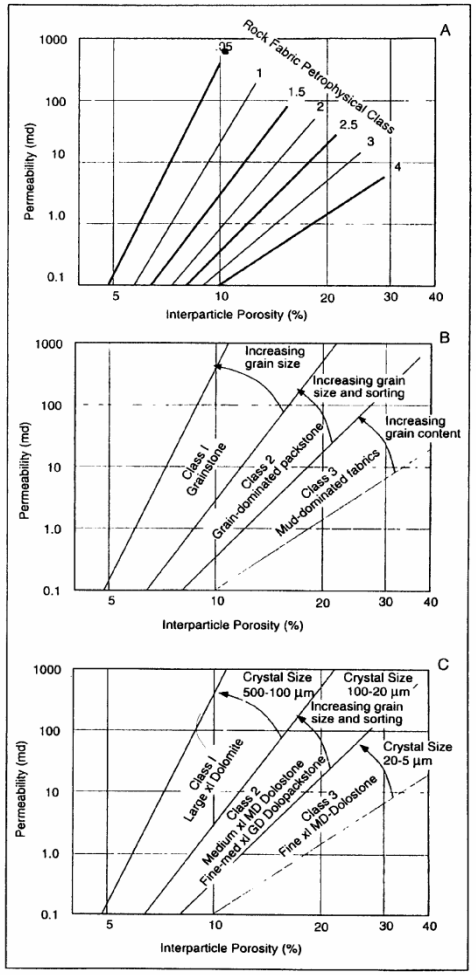

SONIC
4800
4900
5000
5100
5200
5300
5400
"FIRST POROSITY" MARKER
F1
F2
F3
F4
F5
"MAIN PAY" MARKER
M1
M2
M3 LOWER "MAIN PAY" MARKER
M4
M5
M6
LEGEND
GENERALLY GOOD RESERVOIR DEVELOPMENT
OCCASIONALLY GOOD RESERVOIR DEVELOPMENT
RESERVOIR DEVELOPMENT POOR
SCALE
50 FEET


SAN ANDRES PAY ZONES
F1
F2
F3
F4
F5
M1
M2
M3
M4
M5
PERCENT ORIGINAL OIL IN PLACE
PERCENT WATER INJECTION @ 1-1-71 (DATA FROM 43 TOTAL INJECTORS)
PERCENT WATER INJECTION 1-1-71 THRU 3-1-73 (DATA FROM 88 TOTAL INJECTORS)
PERCENT WATER INJECTION 3-1-73 THRU 6-1-79 (DATA FROM 88 TOTAL INJECTORS)
(PRE-1973 INFILL AREA IN EASTERN PORTION OF UNIT)
0
5
10
15
20
25
30
35

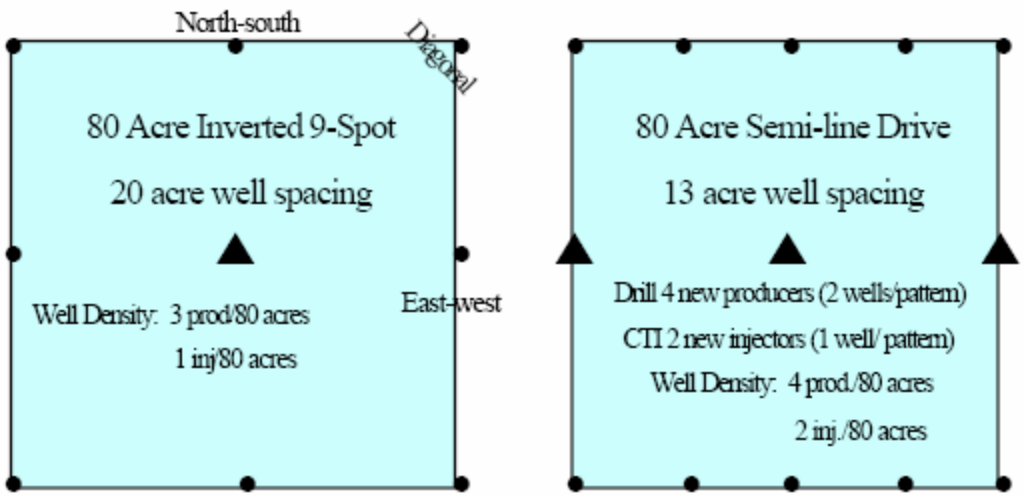
Lucia Rock Classification



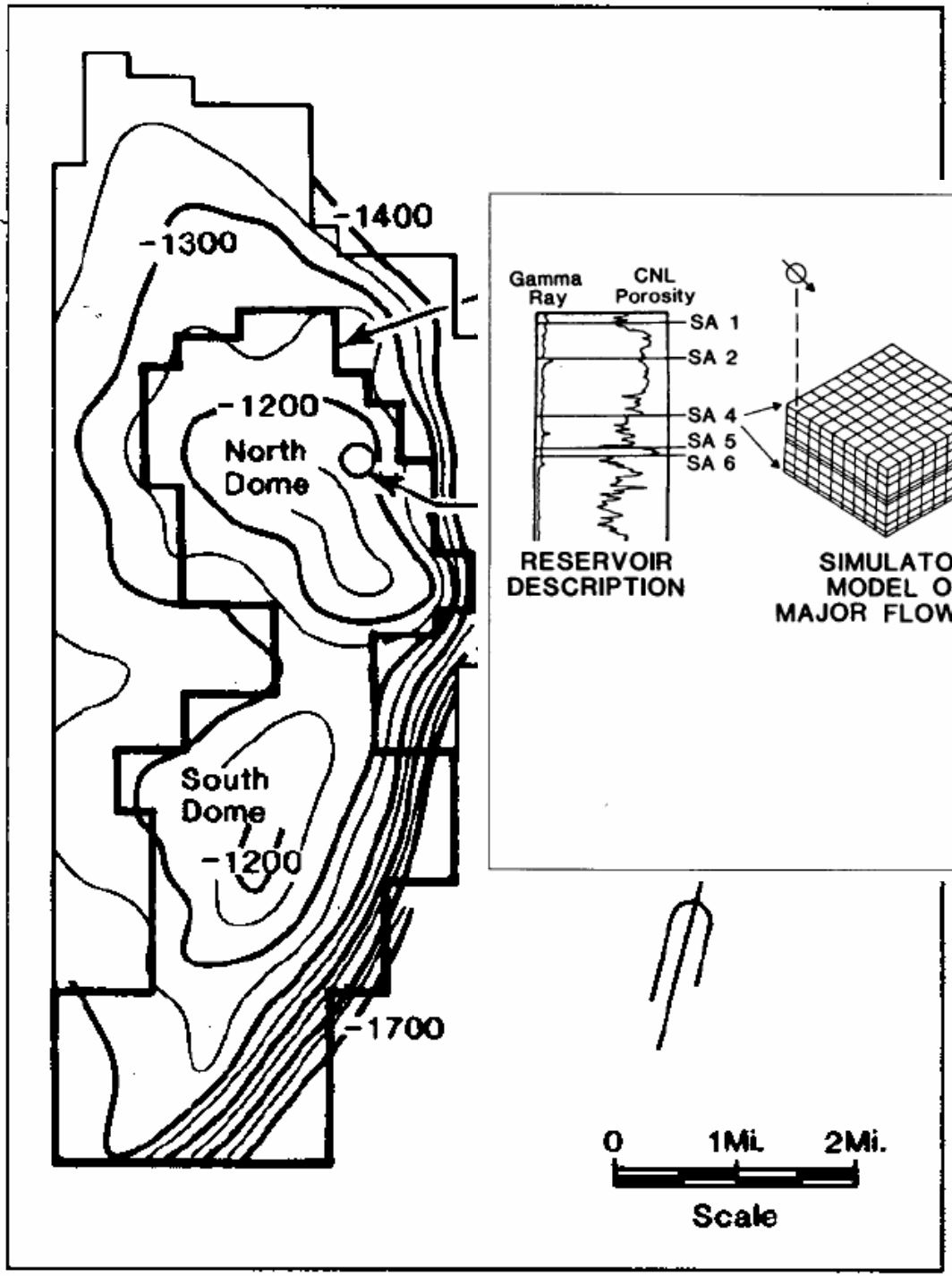
Lucia Porosity – Permeability Transforms

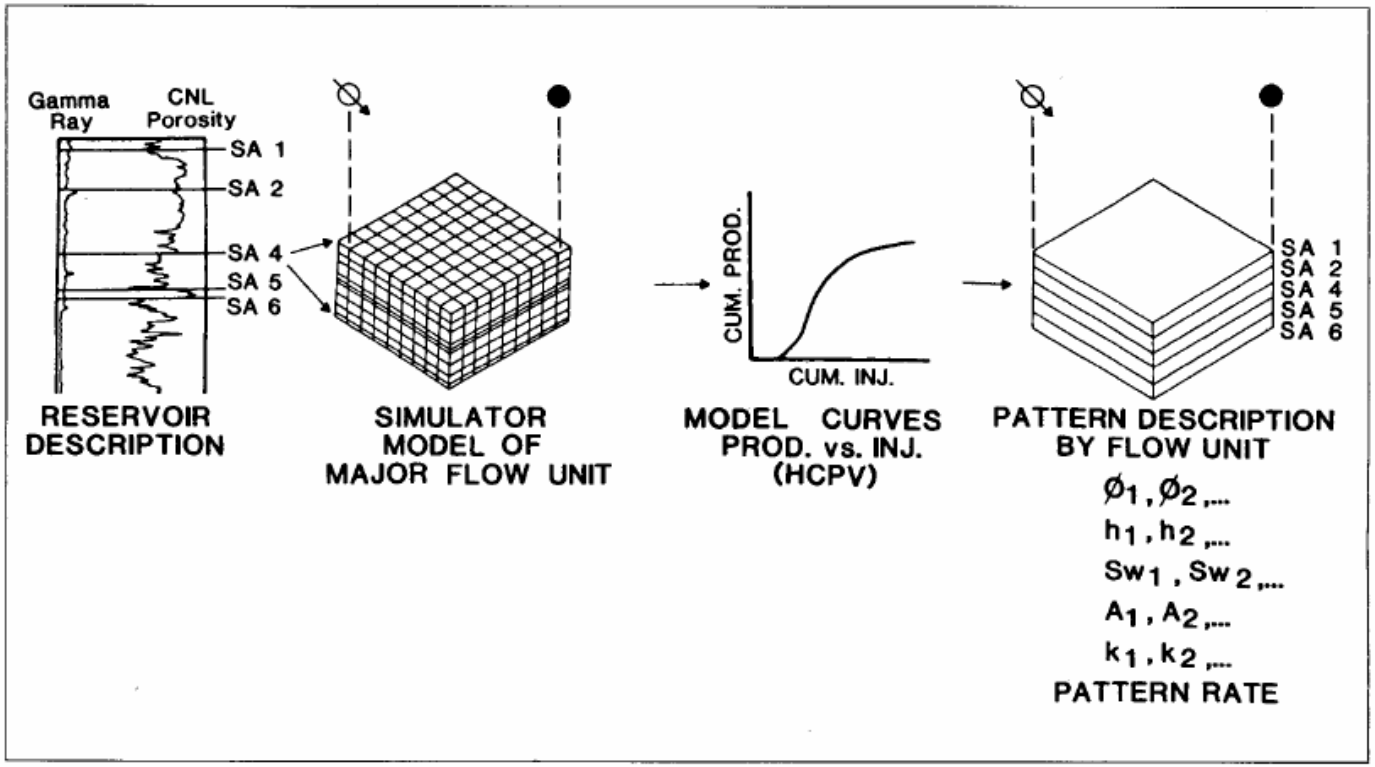


Denver Unit Patterns Modifications

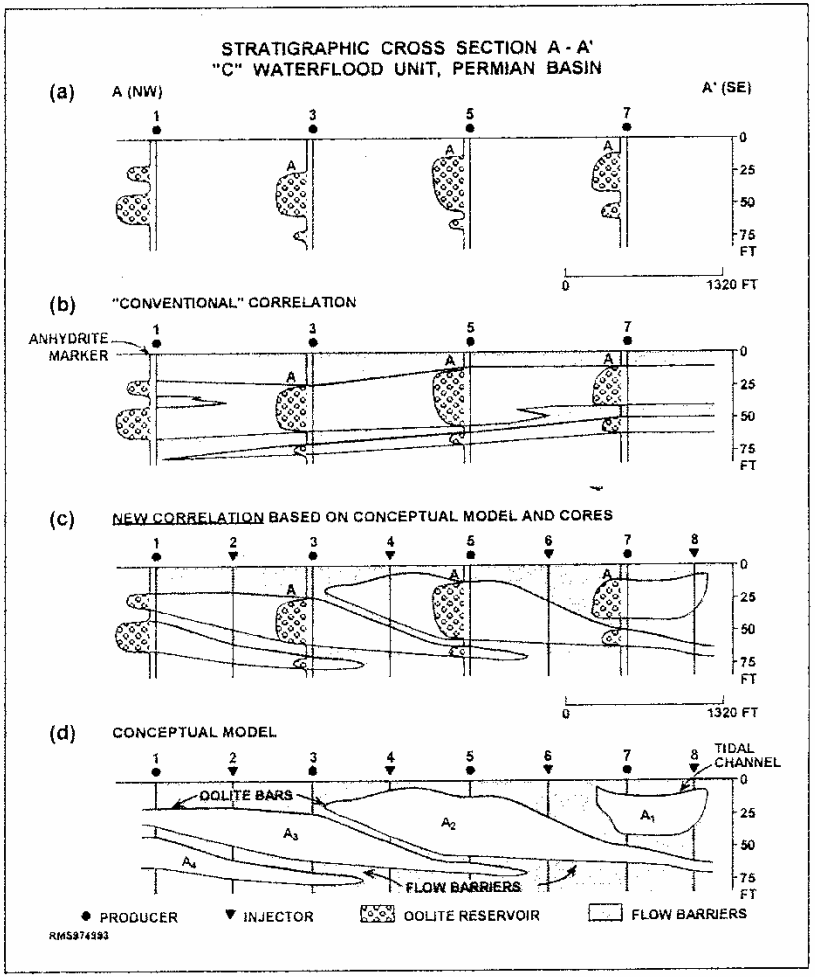


Means San Andres

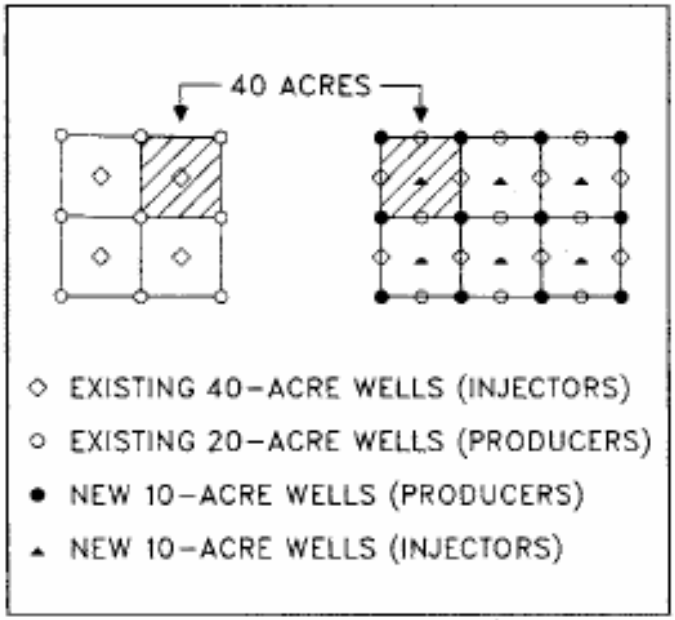


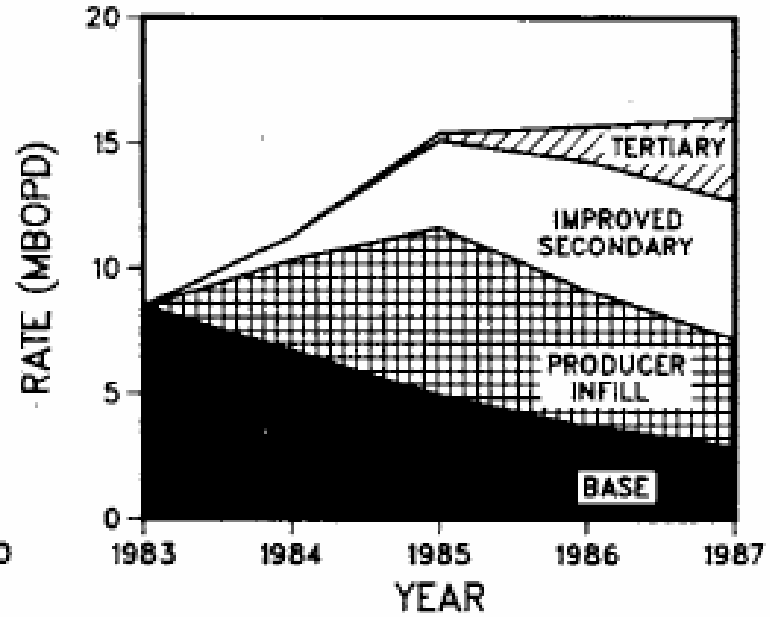


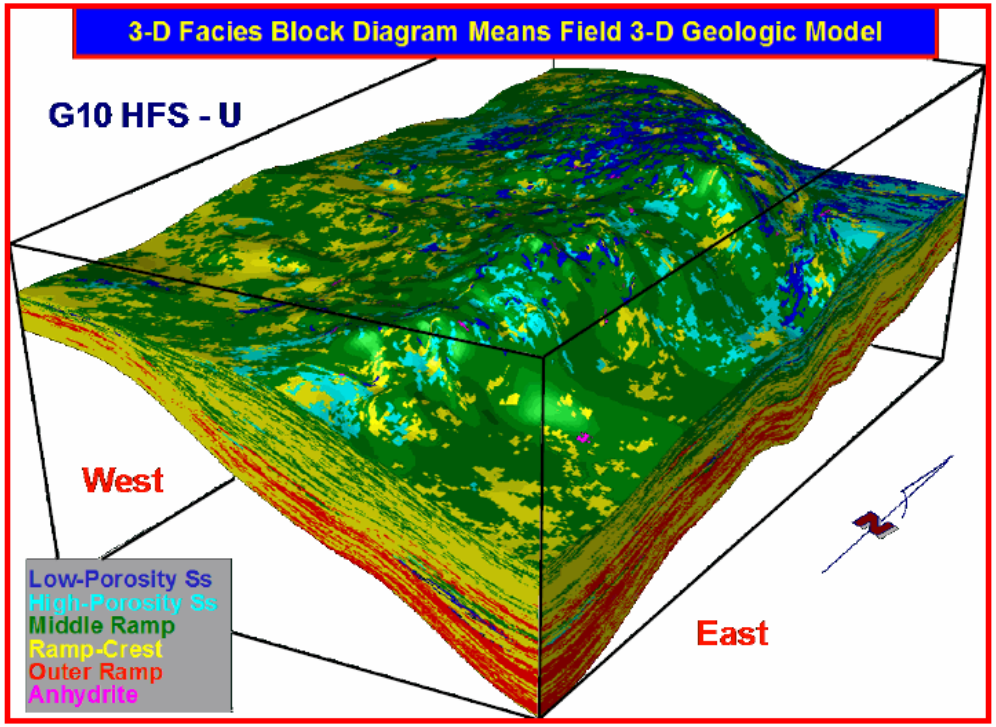
Shoal – Correlation and Discontinuity



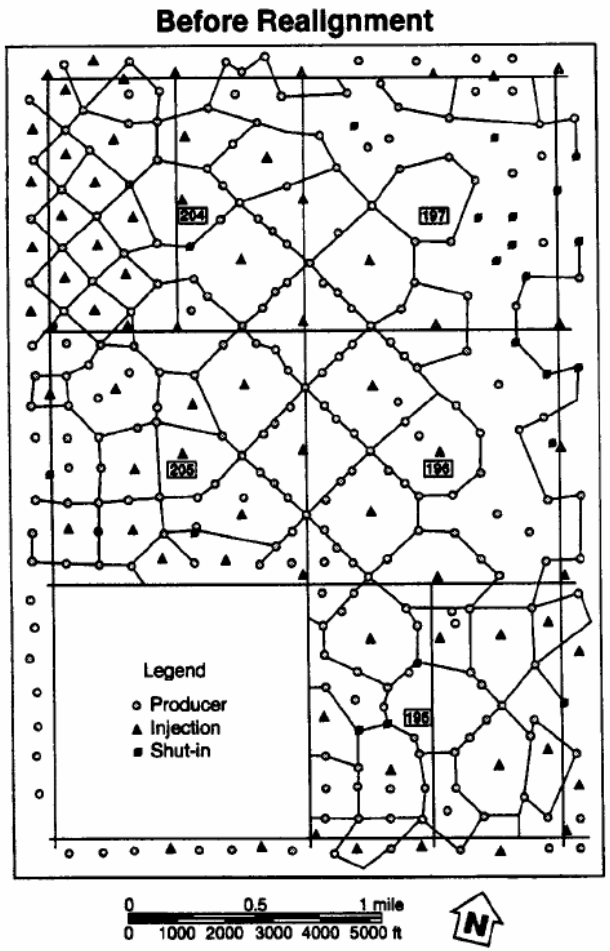
Means San Andres

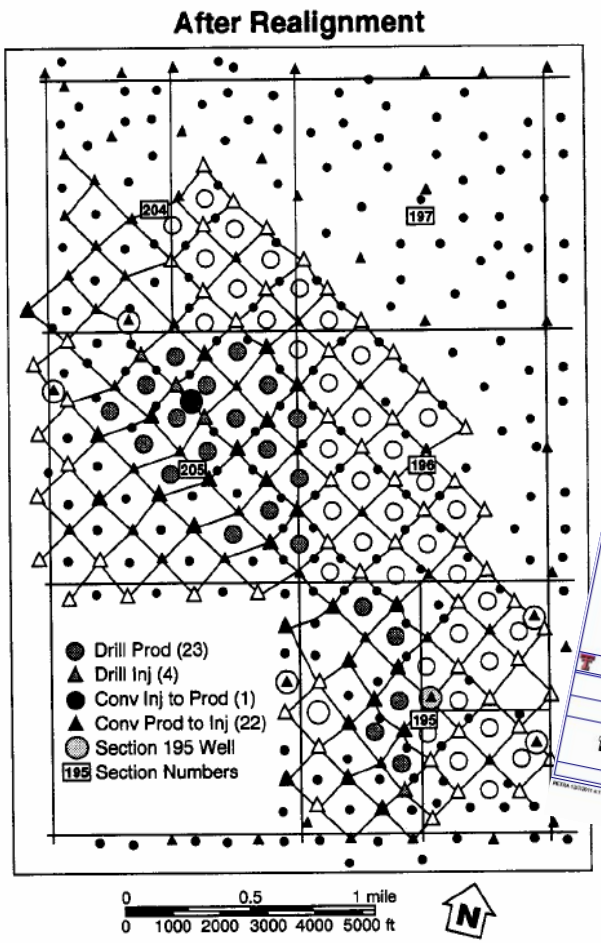


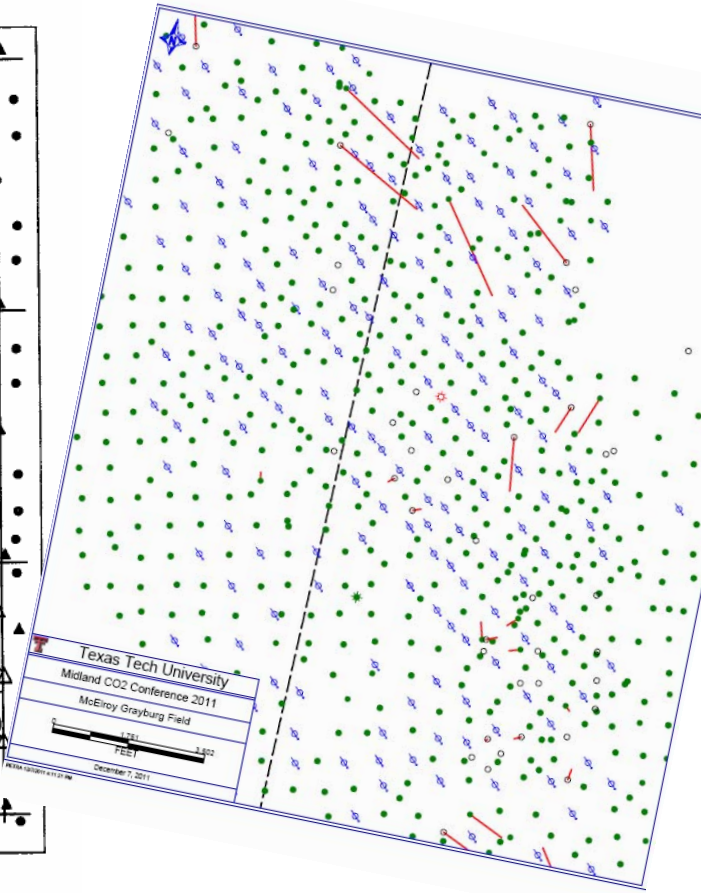




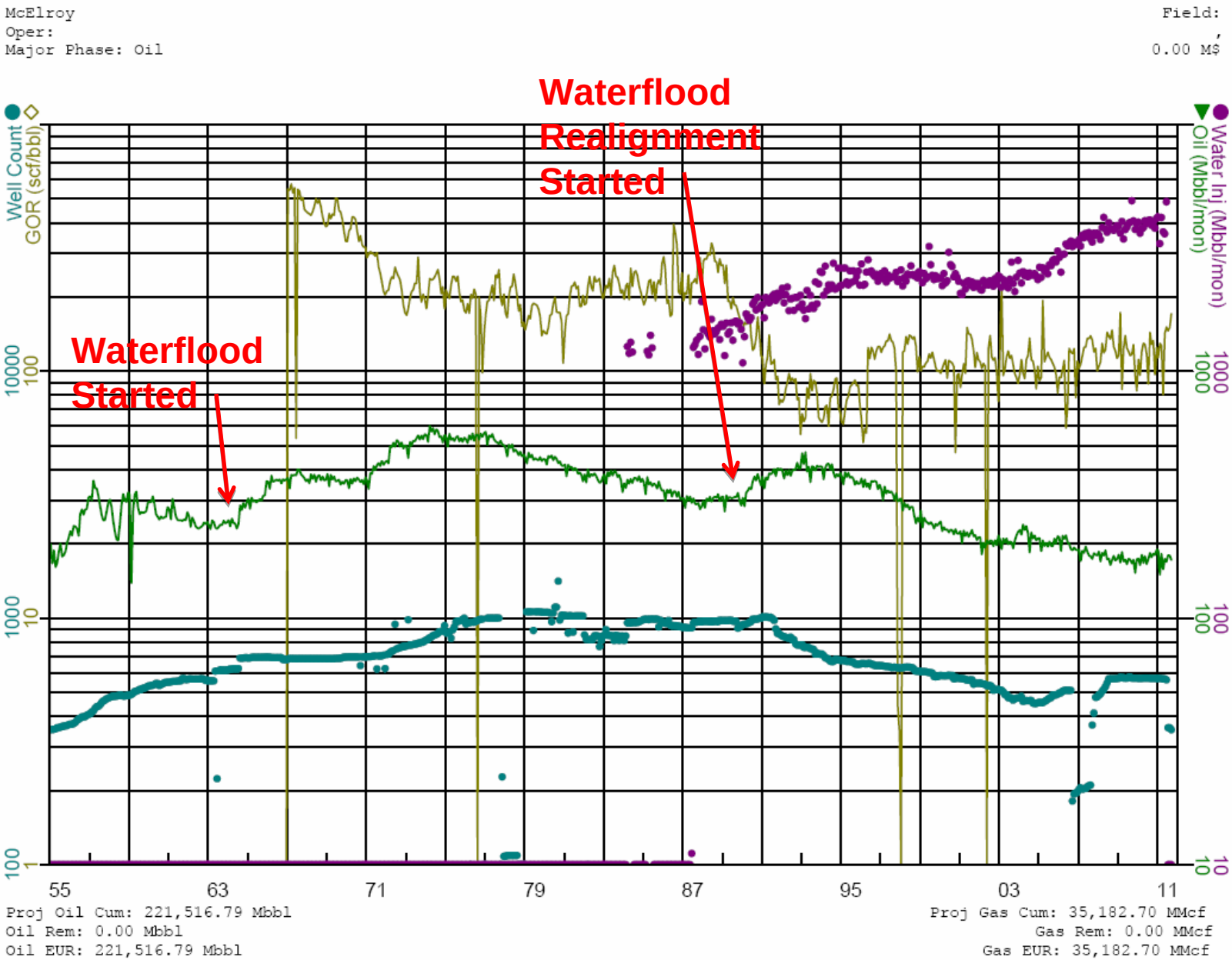
McElroy Grayburg Field



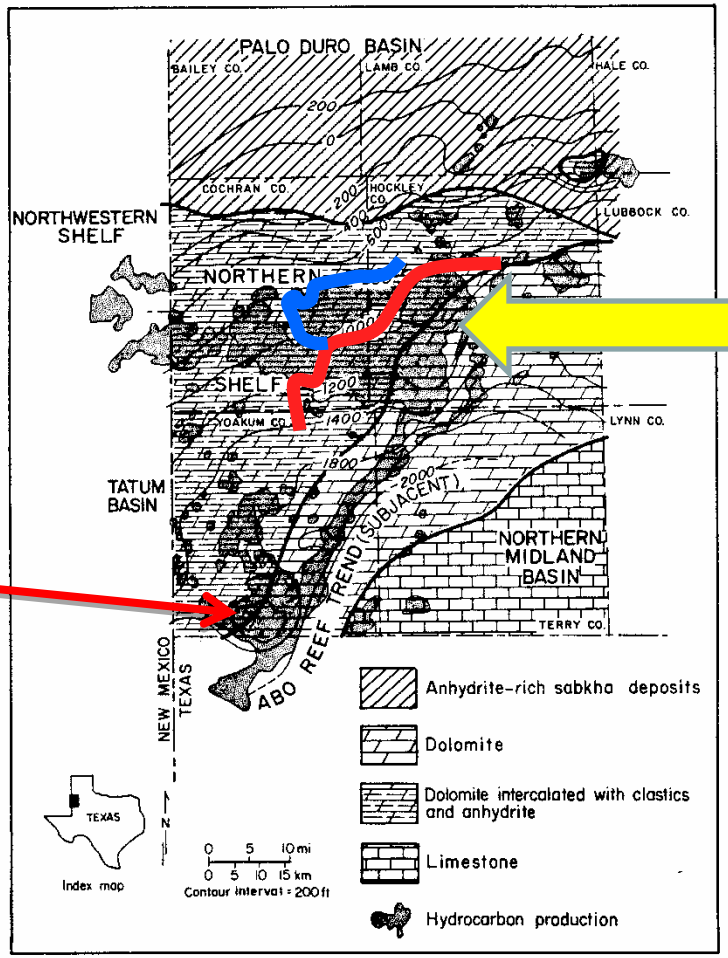




McElroy Field



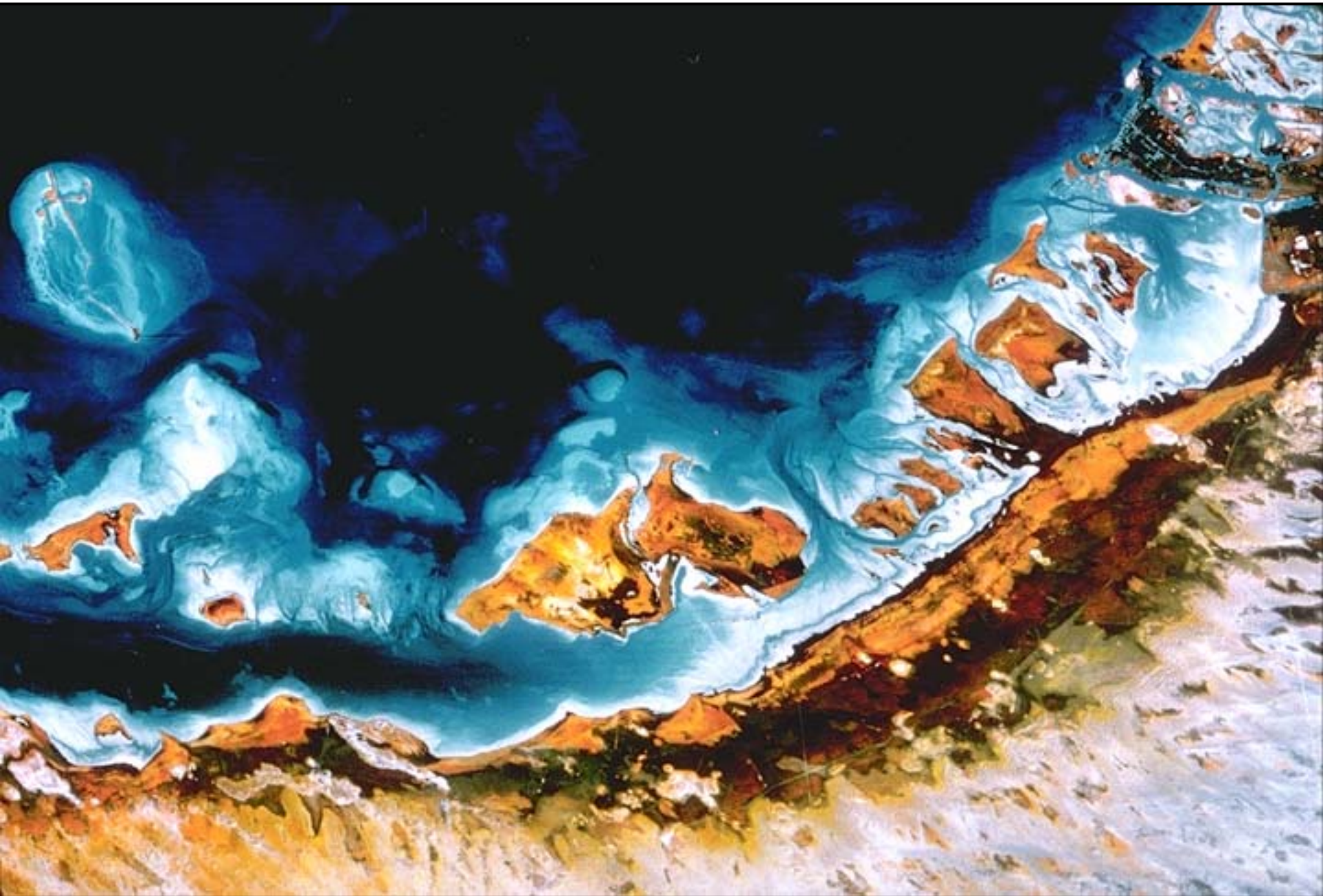
Depositional Environment - Partitioning Levelland Slaughter



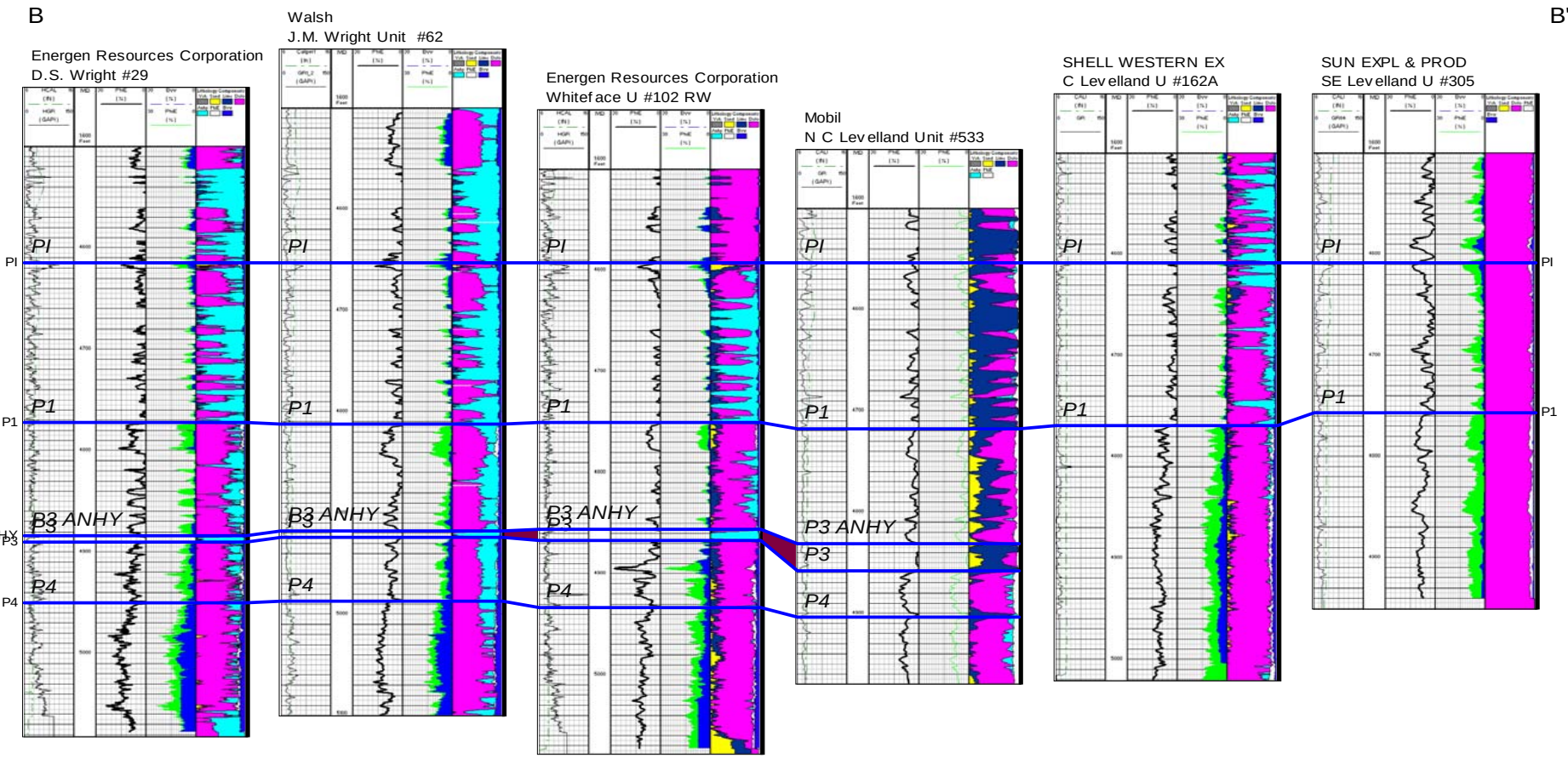
Wasson


BULGARIA
Black Sea
Varna
Sokhumi
Groznyy
CAUCASUS MOUNTAINS
Caspian Sea
(lowest point in Europe, -28 m)
(Aktau)
Nukus
UZBEKISTAN
Dasoguz
Thessaloniki
Istanbul
Bosporus
Samsun
Bat'umi
GEORGIA
Tbilisi
Sumqayit
Türkmenbaşy
TURKMENISTAN
Buxoro
Aegean Sea
GREECE
Bursa
Ankara
Trabzon
ARMENIA
Erzurum
Yerevan
AZERBAIJAN
Baku
Balkanabat
Türkmenabat
GARAGUM
Athens
Izmir
TURKEY
Kayseri
Denizli
Konya
Van
Diyarbakır
Tabriz
Ashgabat
Mary
KOPPEH DAGH
Antalya
TAURUS MOUNTAINS
Adana
Gaziantep
Rasht
Zanjān
Qazvin
Mashhad
Crete
Nicosia
Aleppo
Latakia
Mosul
Arbil
Kirkuk
Tehran
Herāt
CYPRUS
SYRIA
Ḥimṣ
Qom
Mediterranean Sea
Beirut
LEBANON
Damascus
Golan Heights
Kermānshāh
Arāk
AFG.
Haifa
ISRAEL
Baghdad
IRAQ
Esfahān
IRAN
DASHT-E LŪT
Alexandria
Port Said
Jerusalem
West Bank
Amman
Dead Sea
(lowest point in Asia, -408 m)
Ahvāz
Cairo
Al Jīzah
Suez
Gaza Strip
JORDAN
Al 'Aqabah
An Nāṣirīyah
Al Baṣrah
Abādān
Zāhedān
PAK.
Kuwait
KUWAIT
Shīrāz
Būshehr
Tabūk
Ḥafr al Bāṭin
Bandar 'Abbās
WESTERN DESERT
Asyūt
EGYPT
Ḥā'il
Persian Gulf
Al Jubayl
Ad Dammām
Dhahran
BAHRAIN
Manama
QATAR
Doha
Abu Dhabi
Dubai
OMAN
Luxor
Buraydah
Riyadh
Muscat
Aswān
Tropic of Cancer
HEJAZ
Medina
SAUDI ARABIA
Yanbu' al-Baḥr
UNITED ARAB EMIRATES
Ḥalā'ib
Jiddah
Mecca
NUBIAN DESERT
Red Sea
RUB' AL KHALI
Port Sudan
ASIR
Abhā
Ṣalālah
SUDAN
Jīzān
Omdurman
Khartoum
Wad Madanī
ERITREA
Massawa
Asmara
Sanaa
YEMEN
Al Ḥudaydah
Al Ghaydah
Arabian Sea
Al Mukallā
Aden
Gulf of Aden
Socotra (YEMEN)
DJIBOUTI
Djibouti
Desē
Lac 'Assal
(lowest point in Africa, -155 m)
Berbera
Scale 1:21,000,000
Lambert Conformal Conic Projection, standard parallels 12°N and 38°N
0 300 Kilometers
0 300 Miles
Addis Ababa
Hargeysa
SOMALIA
ETHIOPIA

Potential Reservoir-Forming Settings



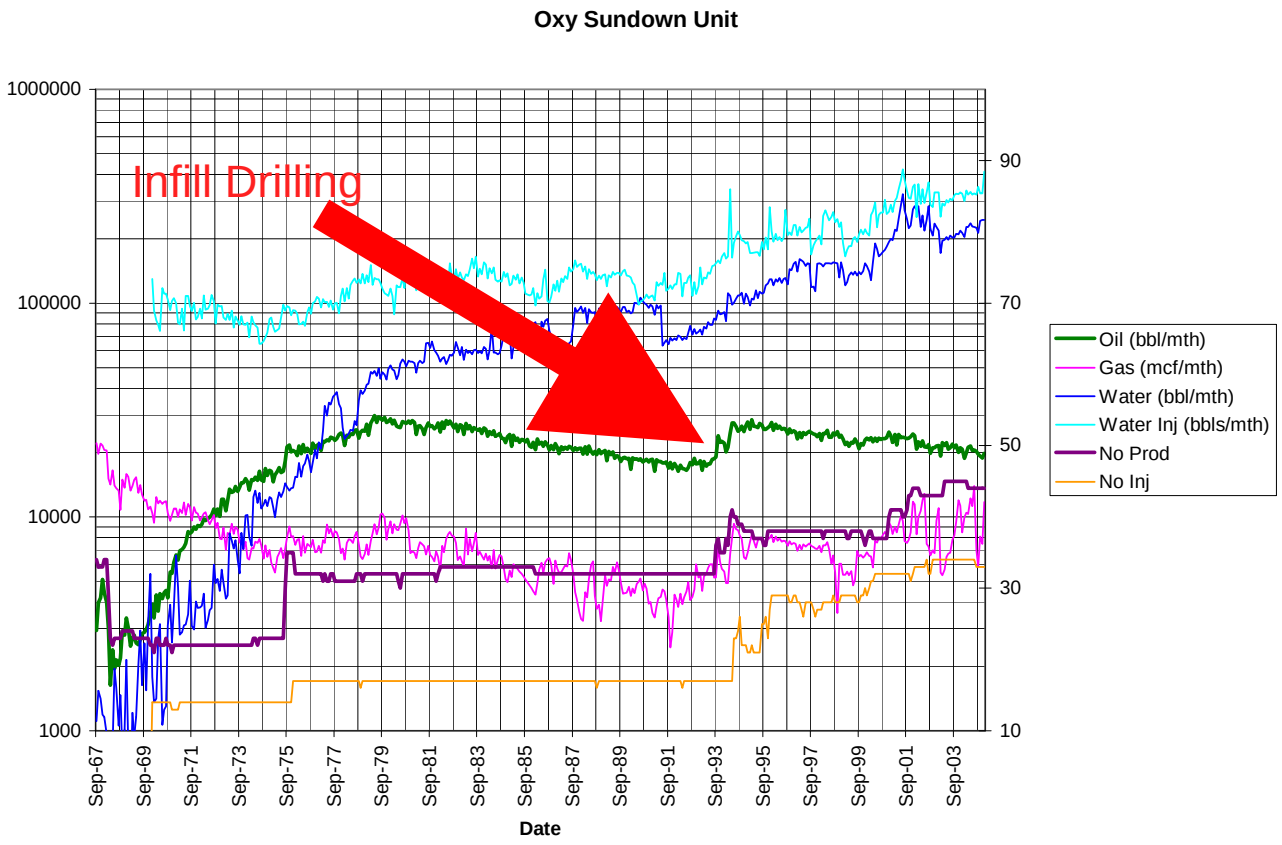
East West Cross Section Through the Levelland Field



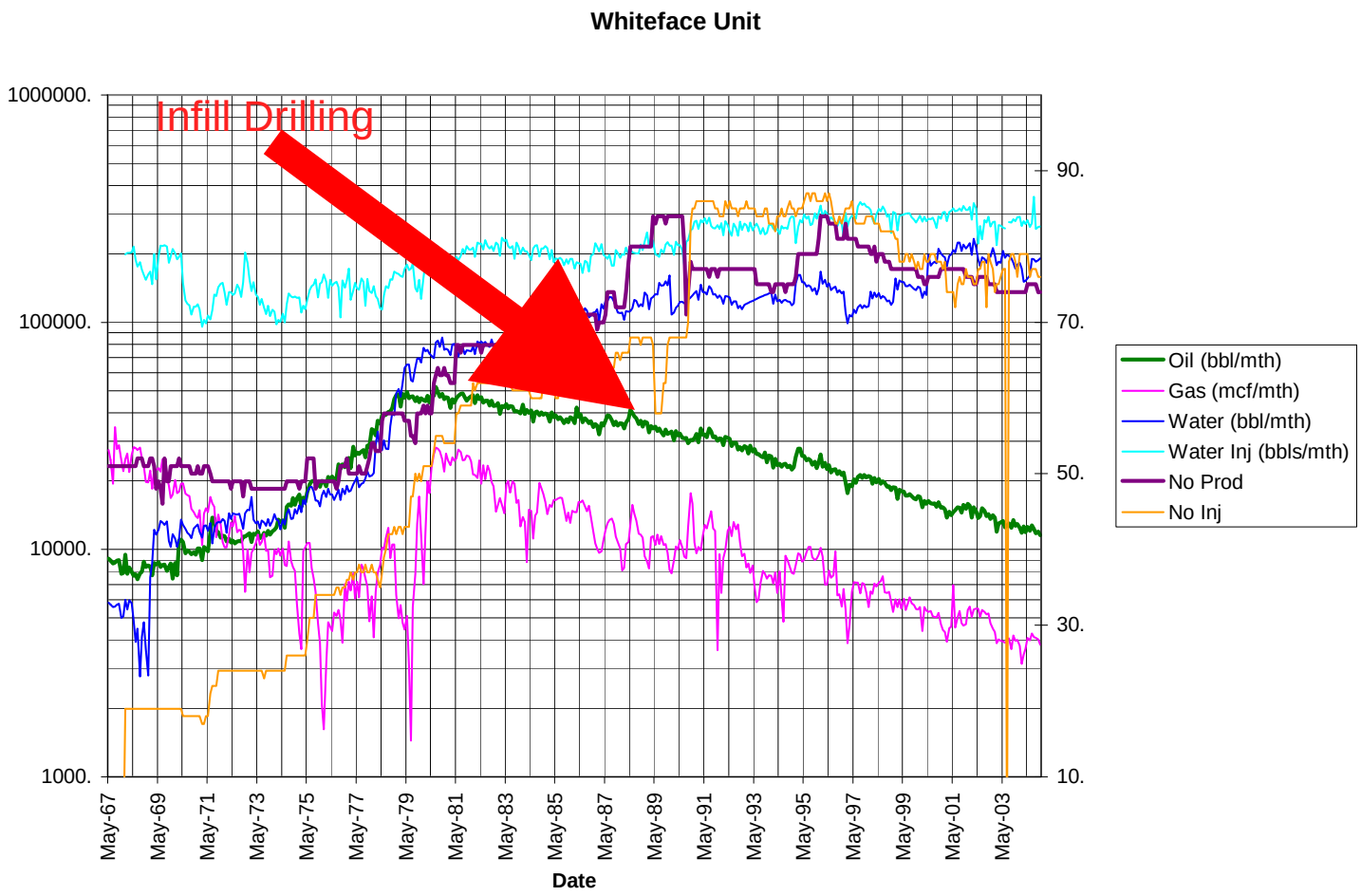
Reservoir Petrophysical Properties
Ramp Type
San Andres Carbonate

Area	Shoal	Lagoon (Levelland)	Near Shore Intertidal
Depth	4900	4900	4900
Net Pay Primary (feet)	70	30	25
Net Pay Secondary (feet)	70	30	17
Gross Pay (feet)	120	60	60
Porosity Range (fraction)	0.08 – 0.18	0.08 – 0.16	0.08 – 0.11
Average Porosity (fraction)	0.12	0.11	0.09
Water saturation – Initial (frac)	0.28	0.20	0.30
Permeability – Range (md)	1.0 – 40	0.1 - 30	0.1 - 30
Permeability Geo Mean (md)	2.5	1.5	0.5
k_{ro} @ Swi (frac)	0.57	0.57	0.57
S_{ro} (frac)	0.28	0.28	0.28
k_{rw} @ Sor (mD)	0.21	0.21	0.21
S_{wi} (frac)	0.21	0.25	0.35
Oil Saturation – At start of flood (frac)	0.6	0.6	0.6
Gas Saturation – At start of flood (frac)	0.08	0.08	0.08

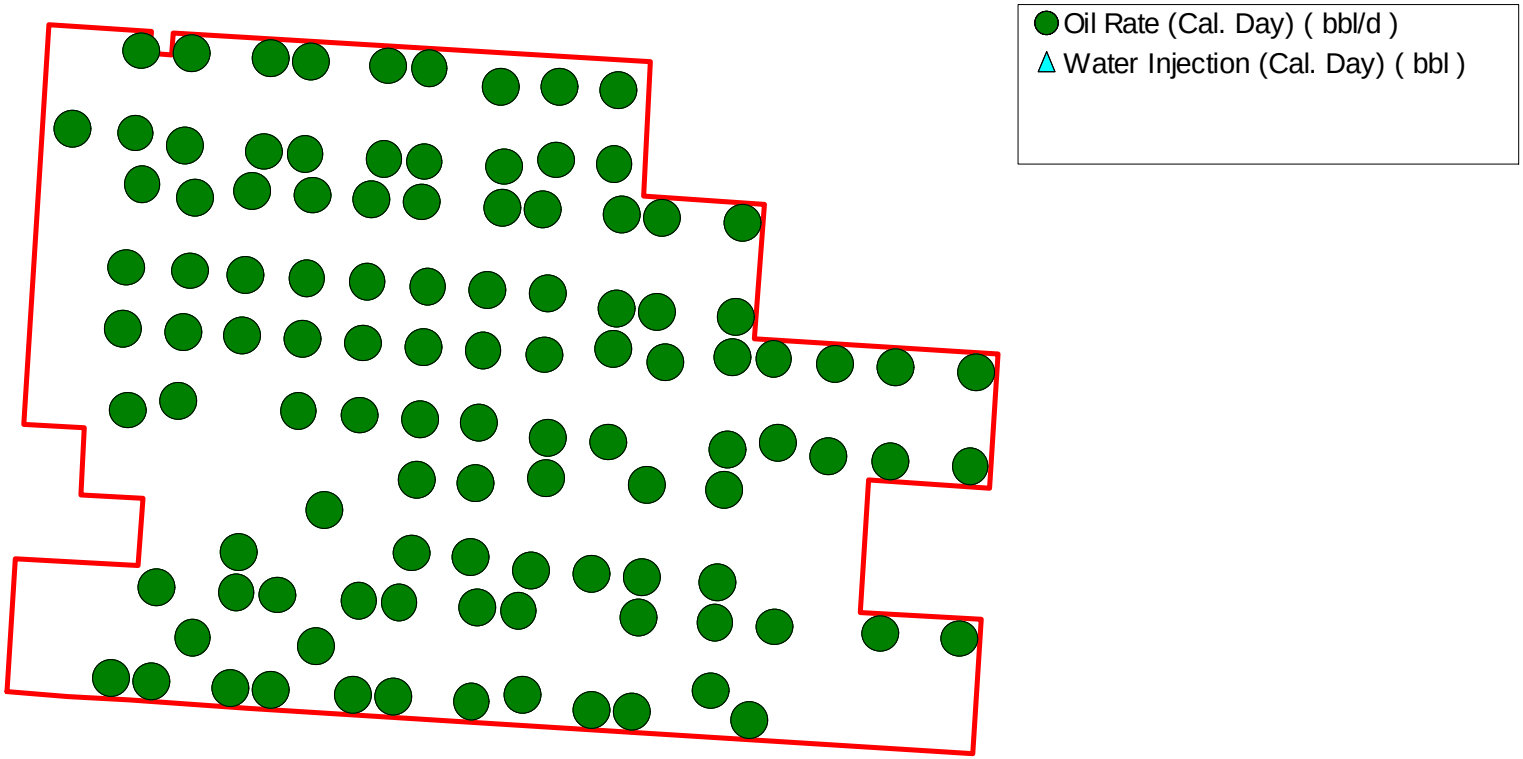
Infill Drilling - Shoal



Infill Drilling – Lagoon & Near Shore

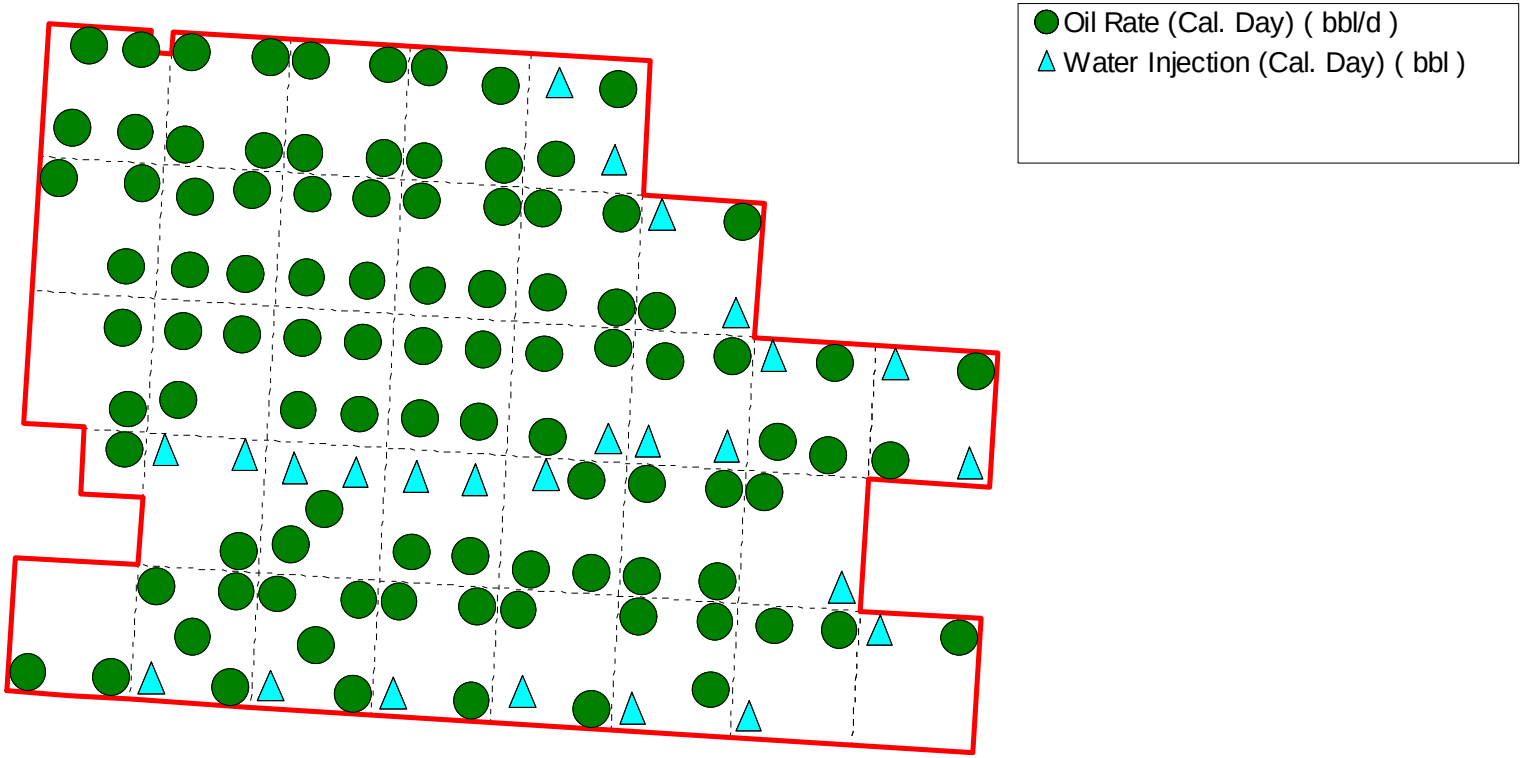


SOUTHEAST LEVELLAND UNIT
At unitization

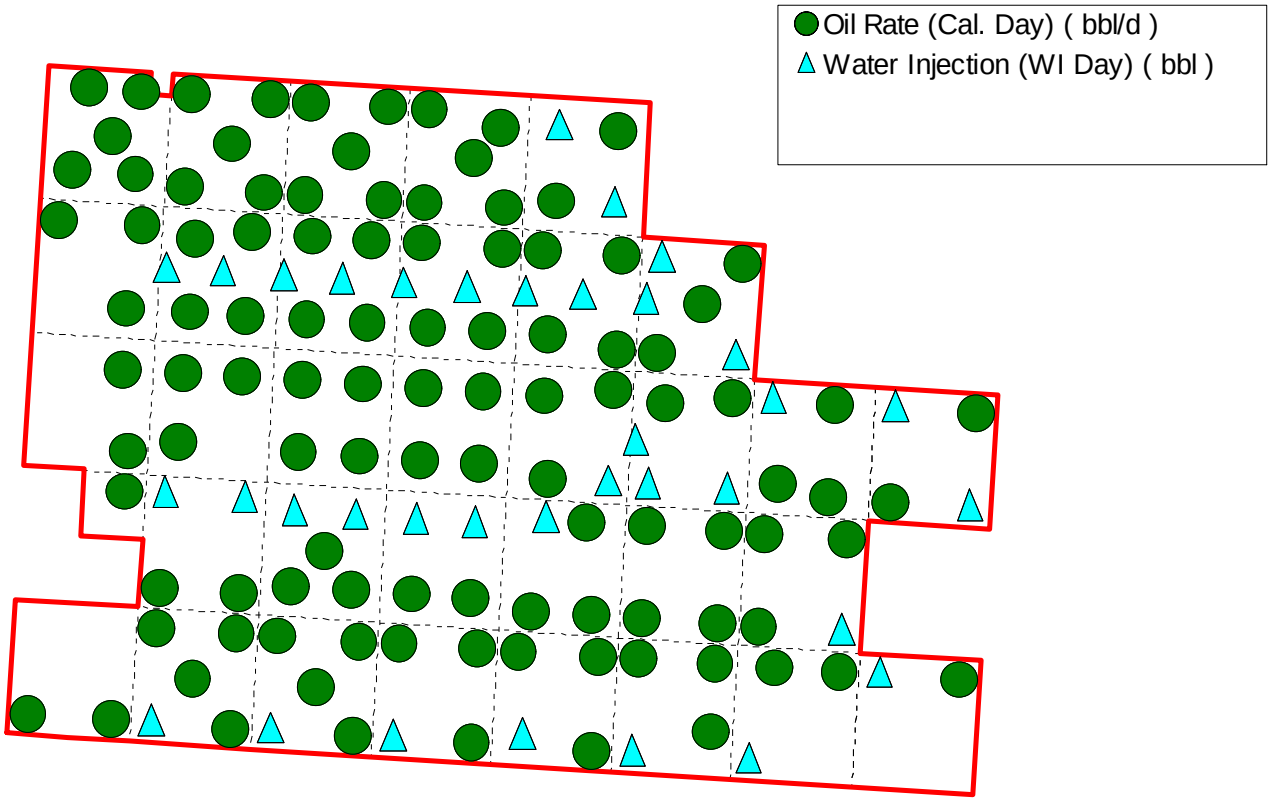


Start of WF project -December 1964

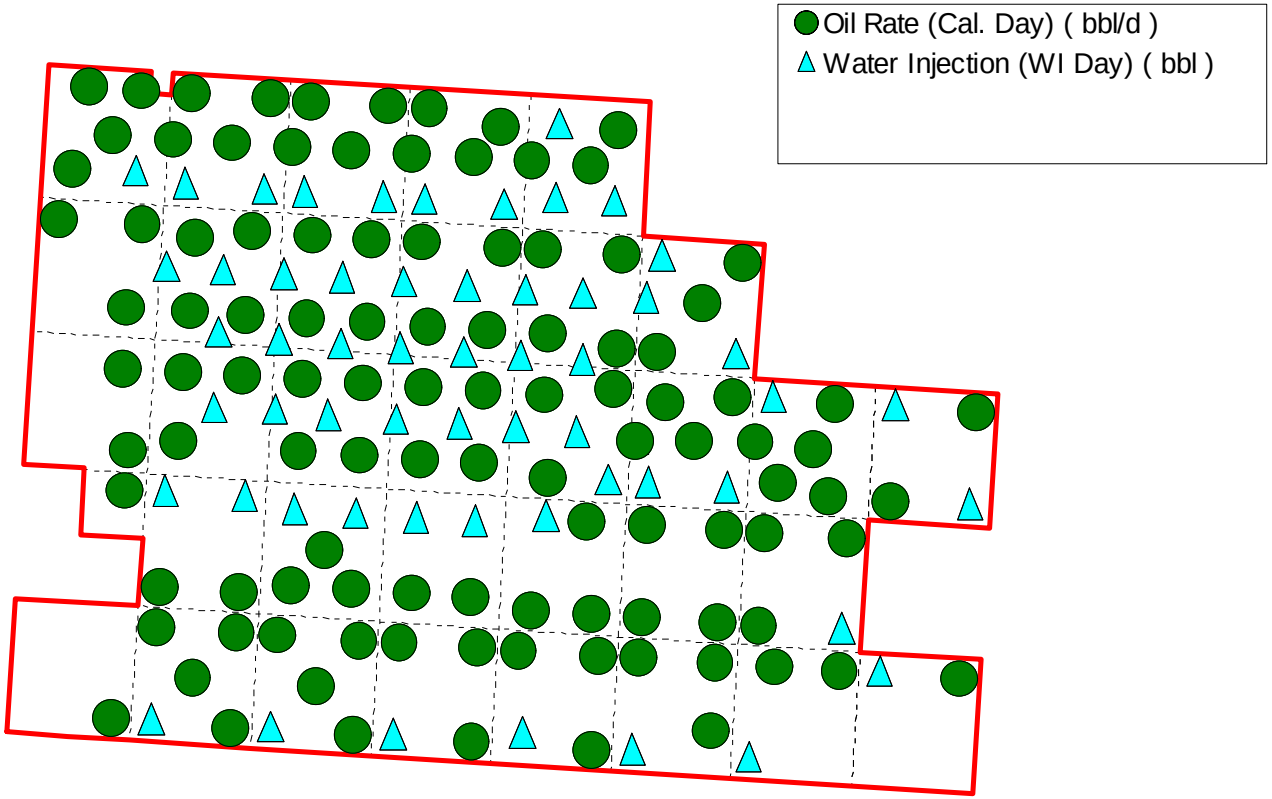
FEB 1967



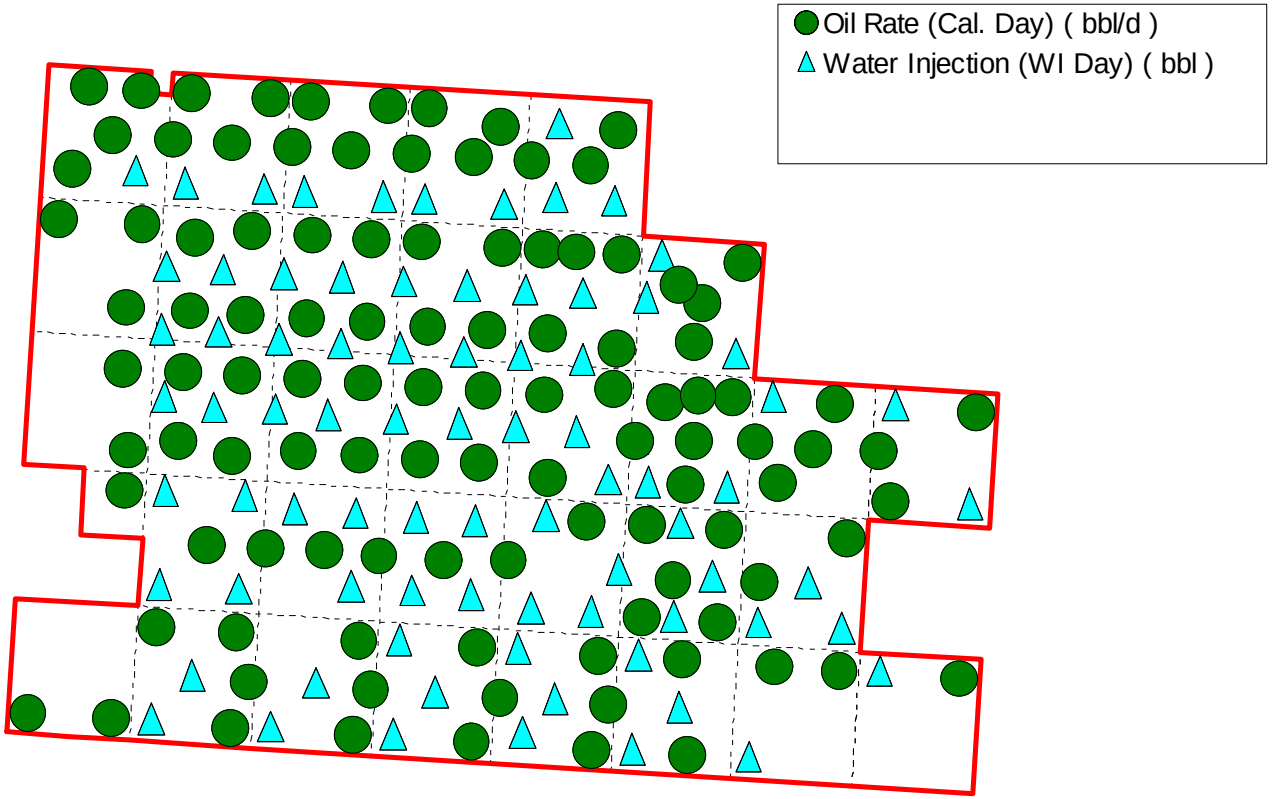
JULY 1969



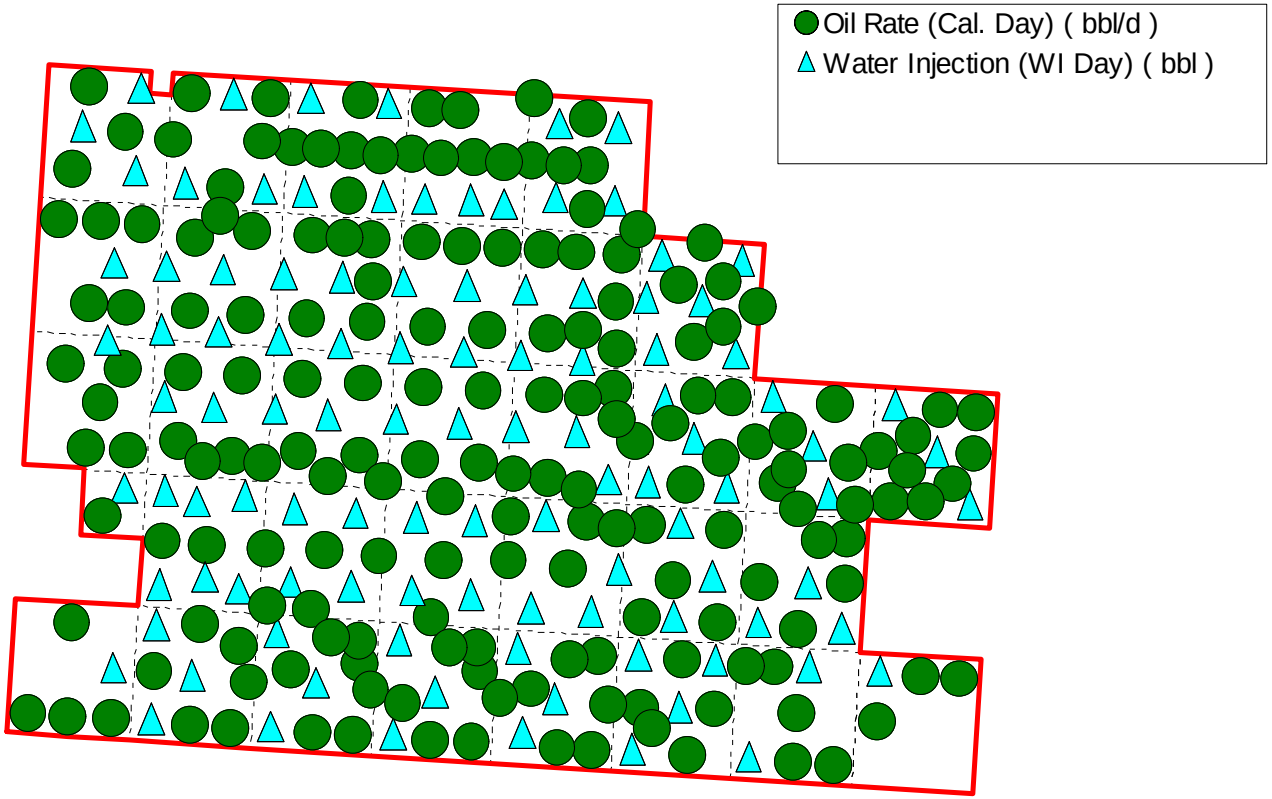
Dec 1971



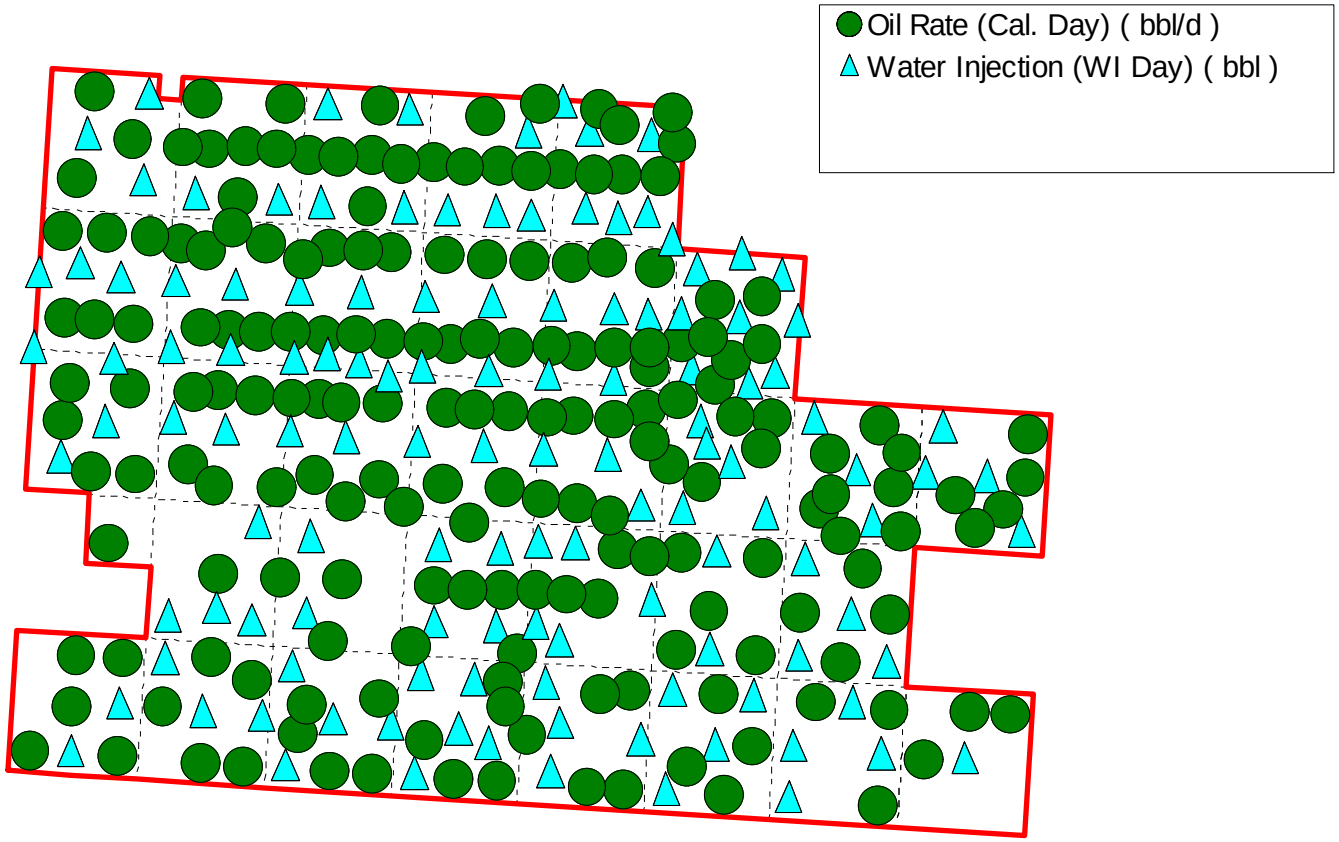
Oct 1973



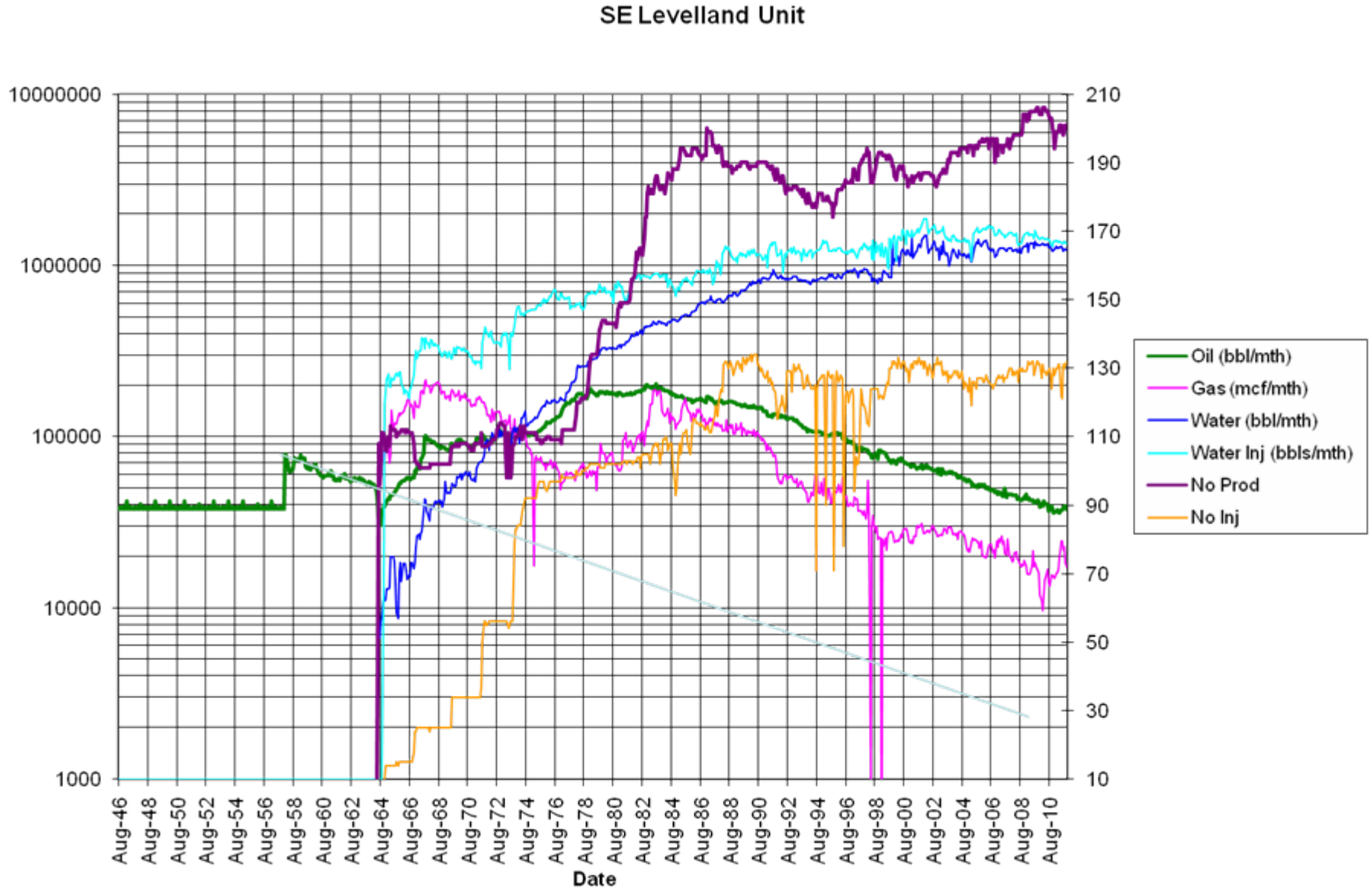
Dec 1982



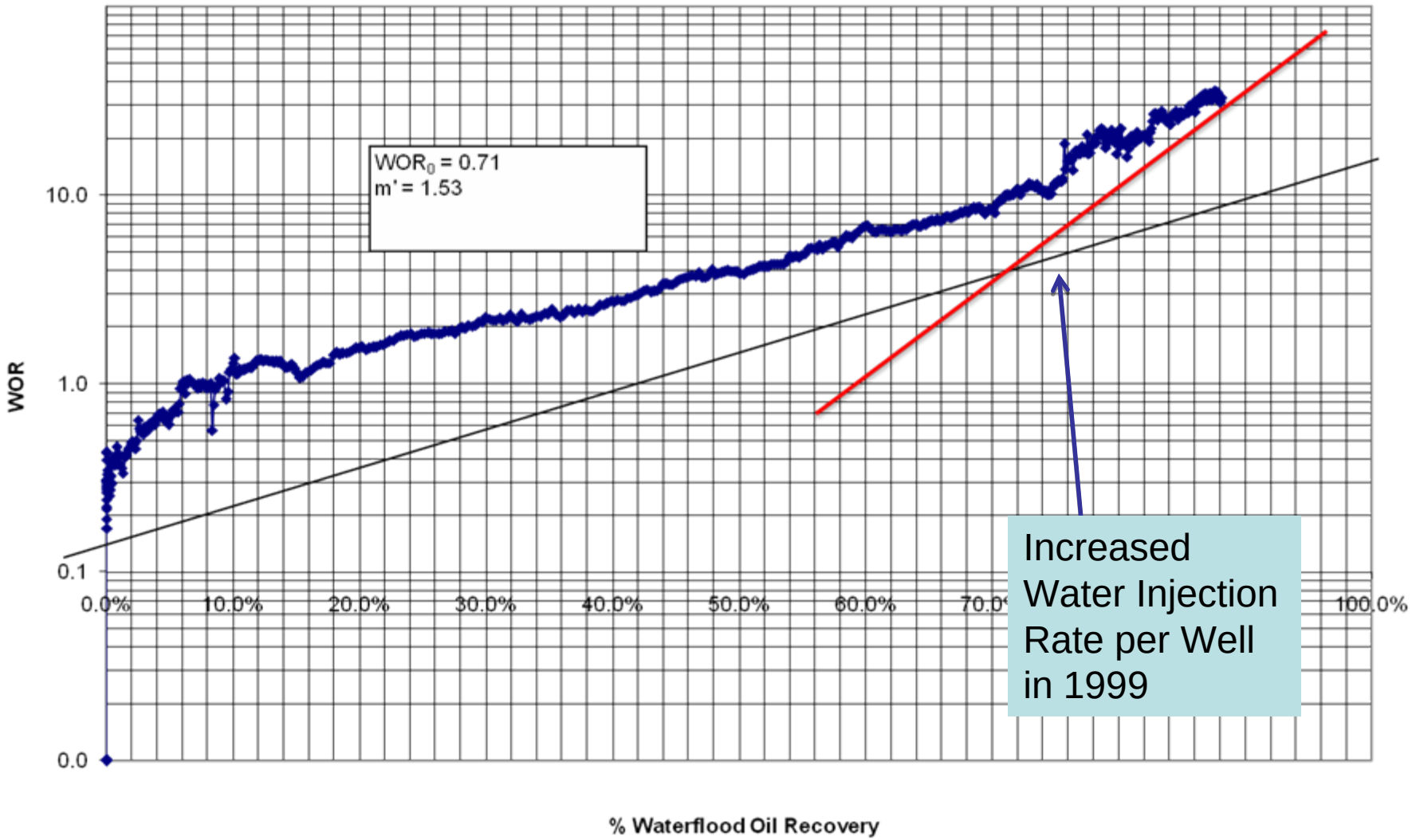
Jan 1997

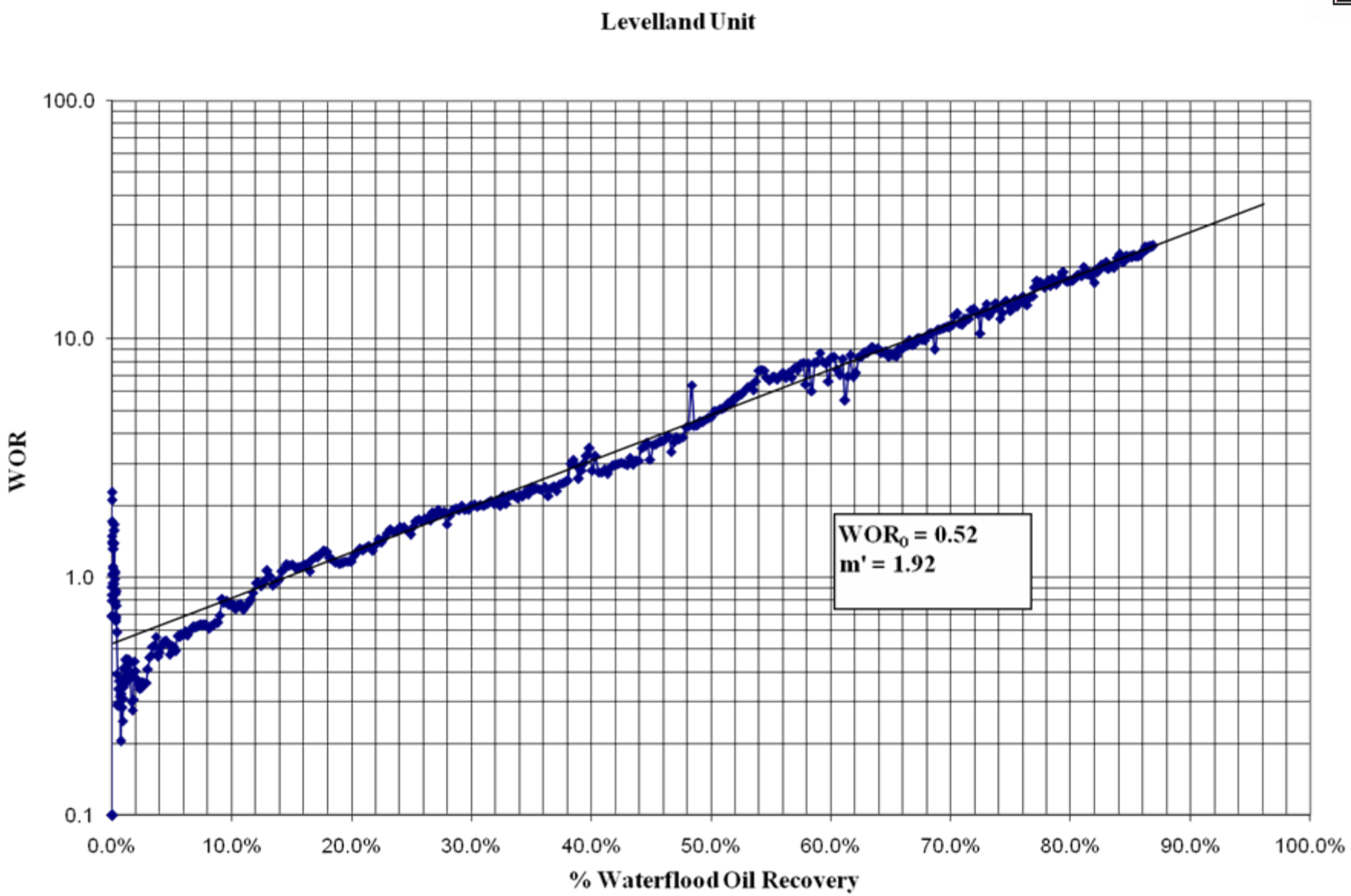


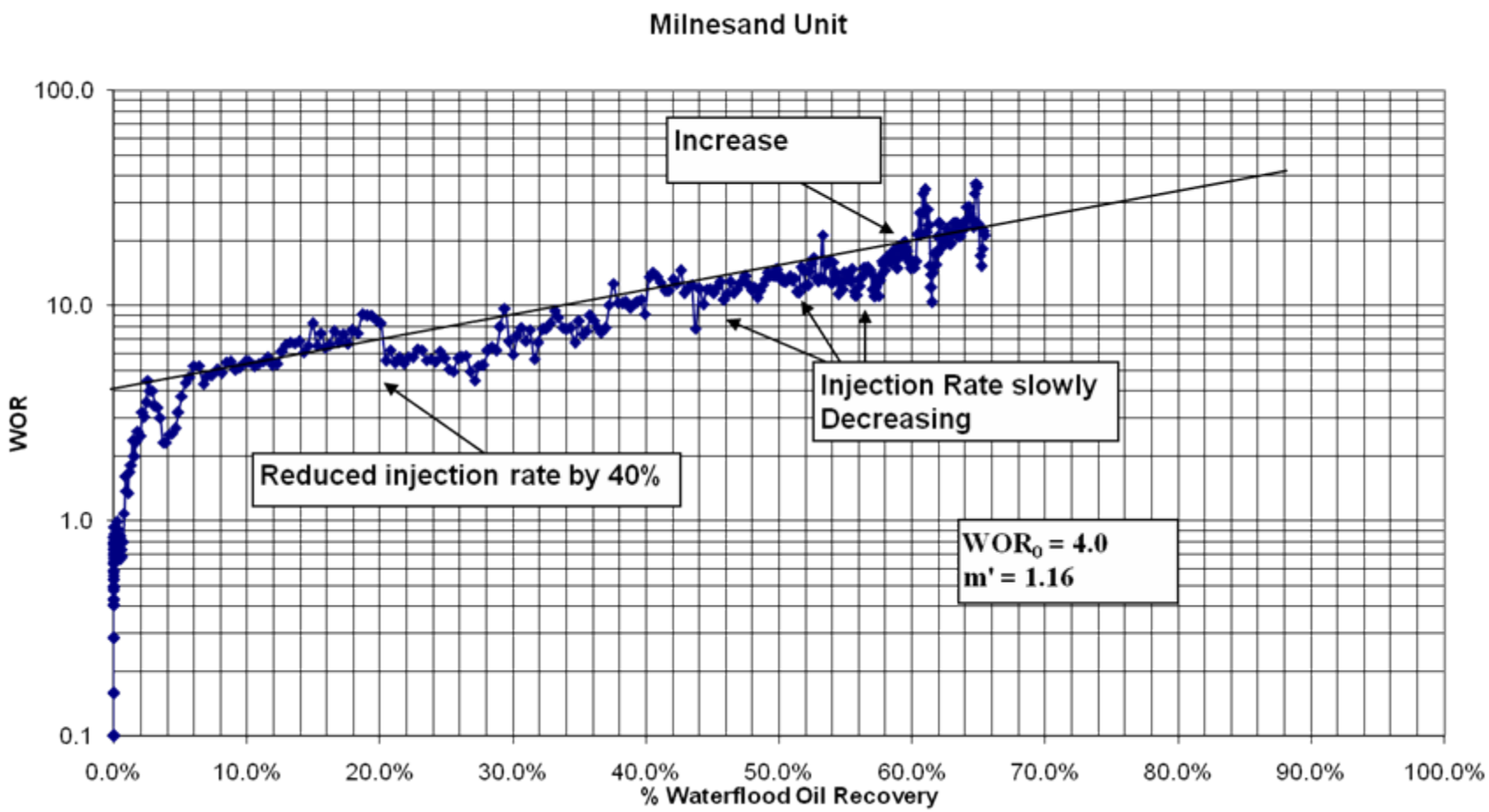
SOUTHEAST LEVELLAND UNIT



SE Levelland Unit




Levelland Unit
100.0
10.0
1.0
0.1
WOR
0.0%
10.0%
20.0%
30.0%
40.0%
50.0%
60.0%
70.0%
80.0%
90.0%
100.0%
% Waterflood Oil Recovery
WOR0 = 0.52
m' = 1.92


Milnesand Unit
100.0
10.0
1.0
0.1
WOR
0.0%
10.0%
20.0%
30.0%
40.0%
50.0%
60.0%
70.0%
80.0%
90.0%
100.0%
% Waterflood Oil Recovery
Increase
Injection Rate slowly Decreasing
Reduced injection rate by 40%
WOR0 = 4.0
m' = 1.16

Vertical Heterogeneity

Dykstra and Parsons' coefficient of permeability variation" (*V*)

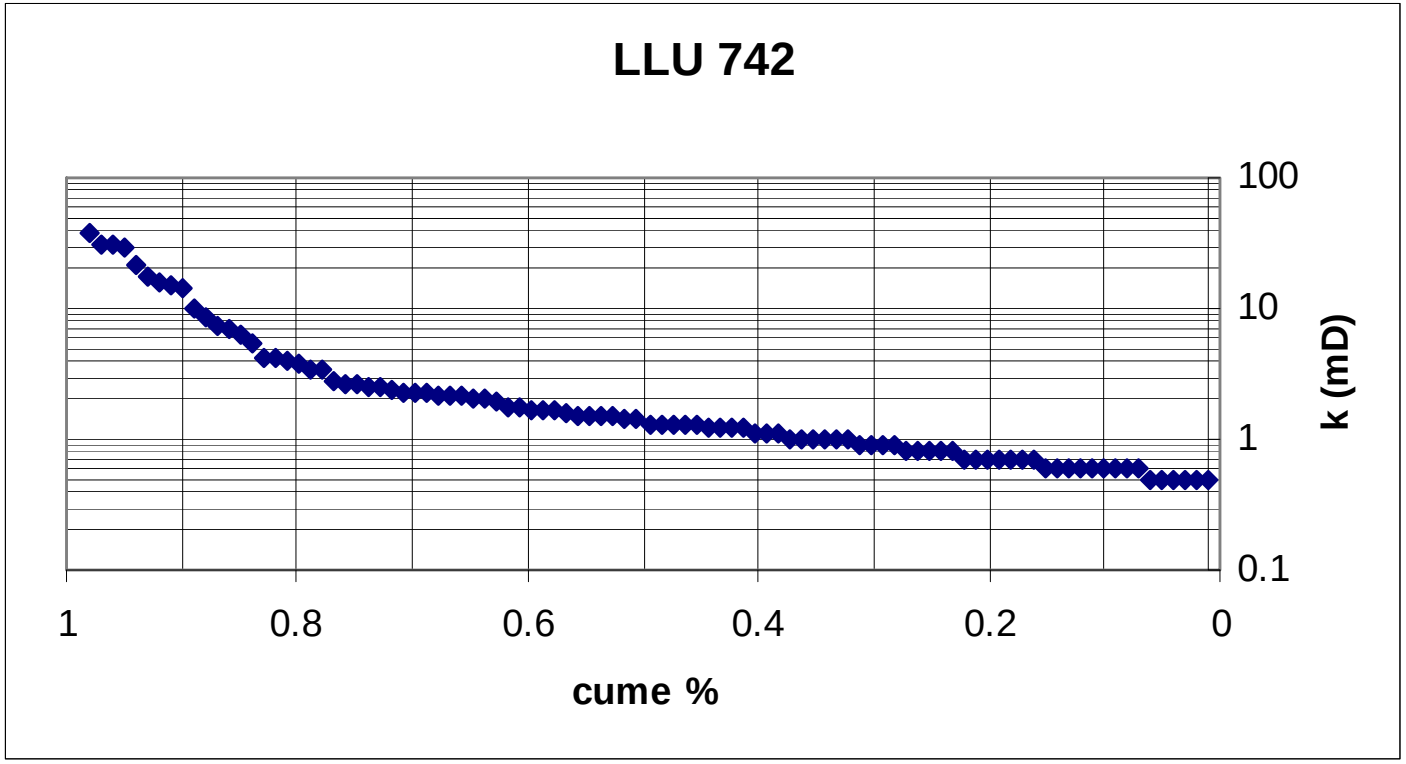
$$V = \frac{\bar{k} - k_\sigma}{\bar{k}}$$

Where $\bar{k} =$ permeability at the 50th percentile of the cumulative sample and

$k_\sigma =$ Permeability at 84.1 percent of the cumulative sample.

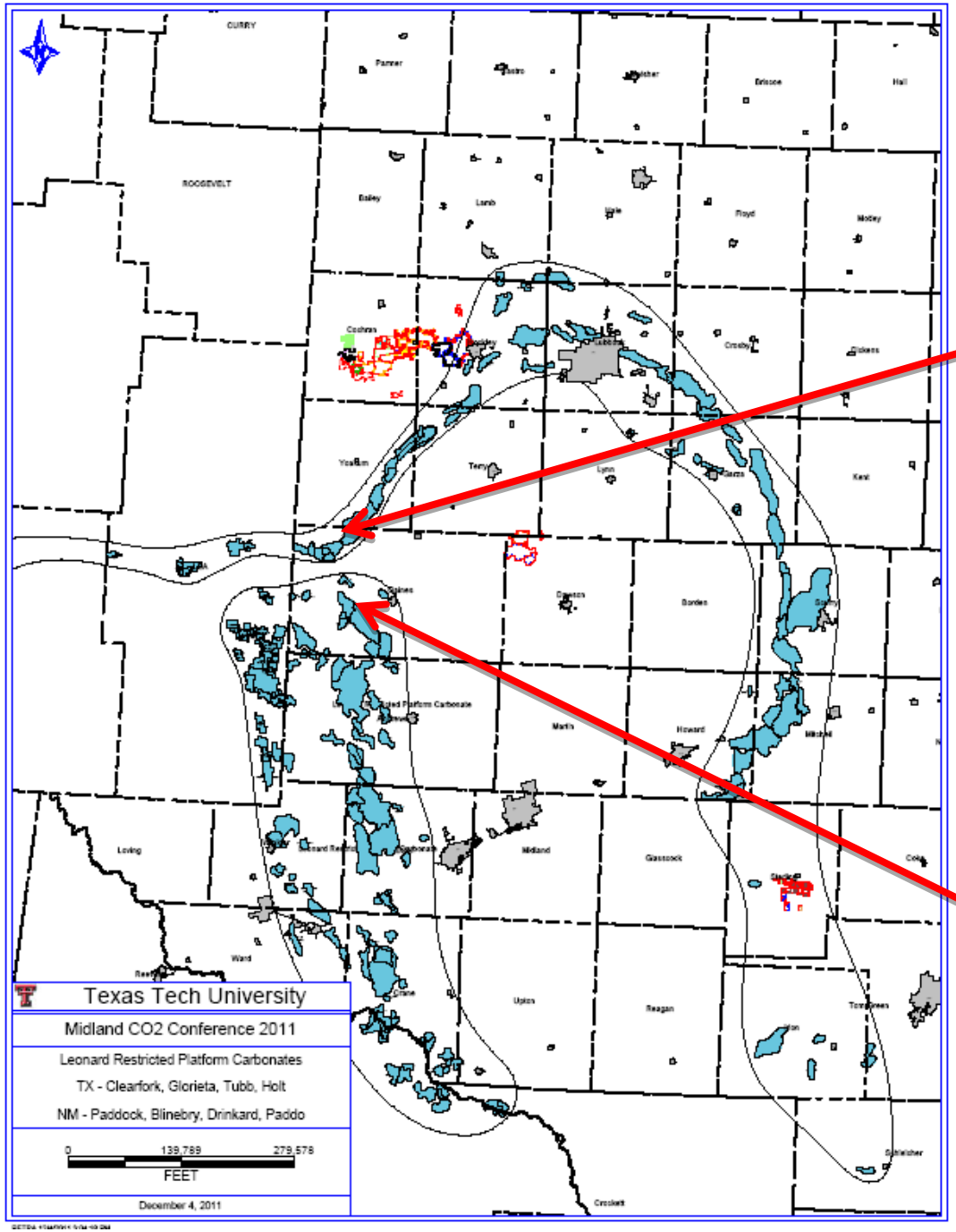
<u>Assumes a log normal distribution</u>

Shoal Permeability Distribution



Summary of Flood Evaluation by Area

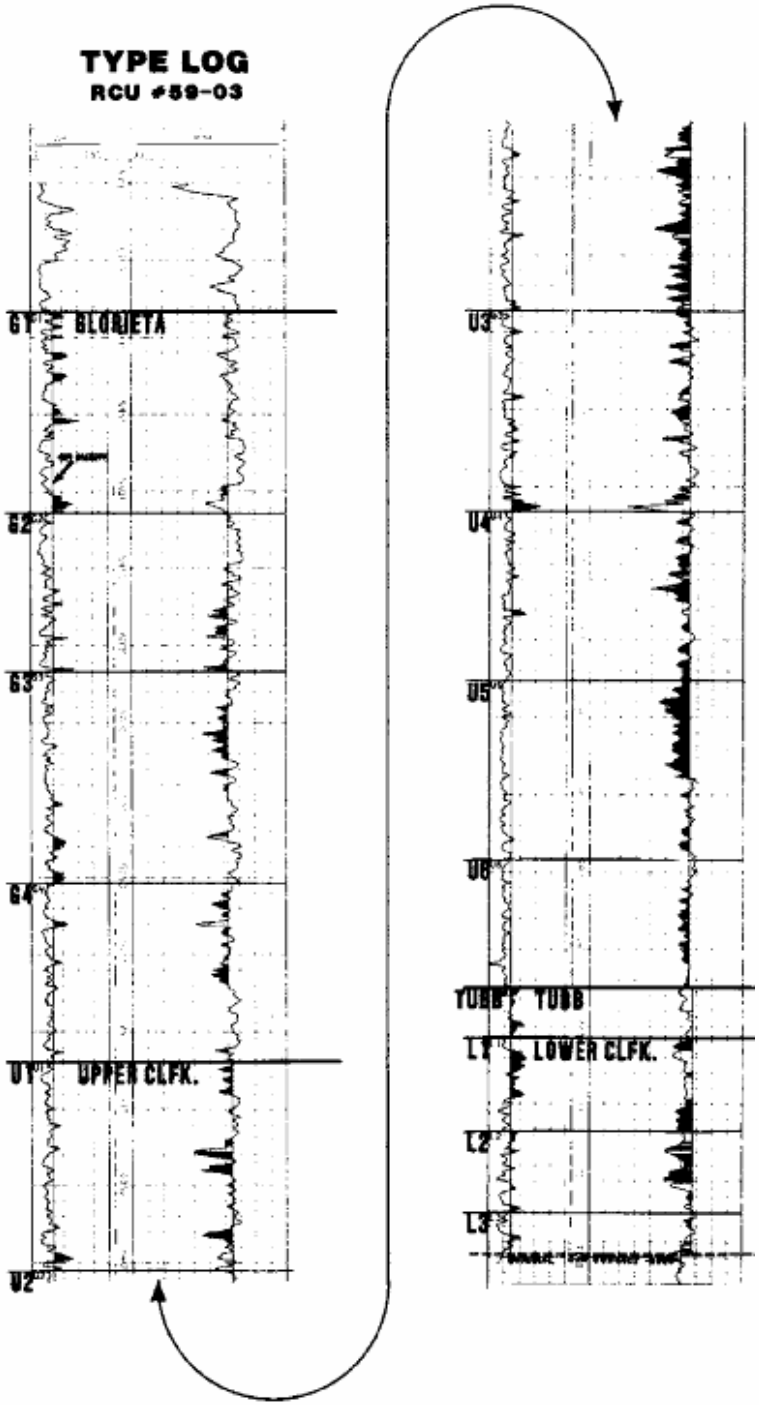
UNIT/LEASE NAME	AREA	WOR AT START OF FLOOD	PEAK OIL:INJ RATIO	VOIDAGE RATIO	S:P	WOR_0	m'	V
Oxy West RKM	Shoal	0.25	0.26	1.2	2.5	0.5	1.79	
Oxy Sundown	Shoal	0.40	0.23	1.3	4.8	0.9	1.85	0.77
Oxy Levelland	Shoal	0.35	0.26	1.1	2.3	0.5	1.92	0.73
Energen Whiteface	Lagoonal	0.60	0.27	1.4	2.8	0.8	1.22	0.88
Oxy Southeast Levelland	Shoal	0.25	0.30/0.23	1.2	3.6	0.7	1.53	
Walsh Starnes	Intertidal – Near Shore	0.35	0.21	2.5	0.8	1.0	1.11	0.88
Devon M.G. Gordon	Shoal	0.15	0.47	1.1	1.5	0.2	2.22	0.90
North Central Levelland	Lagoonal	1.00	0.30	1.9	2.4	0.5	1.72	
Milnesand	Shoal and Intertidal	0.70	0.09	1.6	0.7	4.0	1.16	0.46

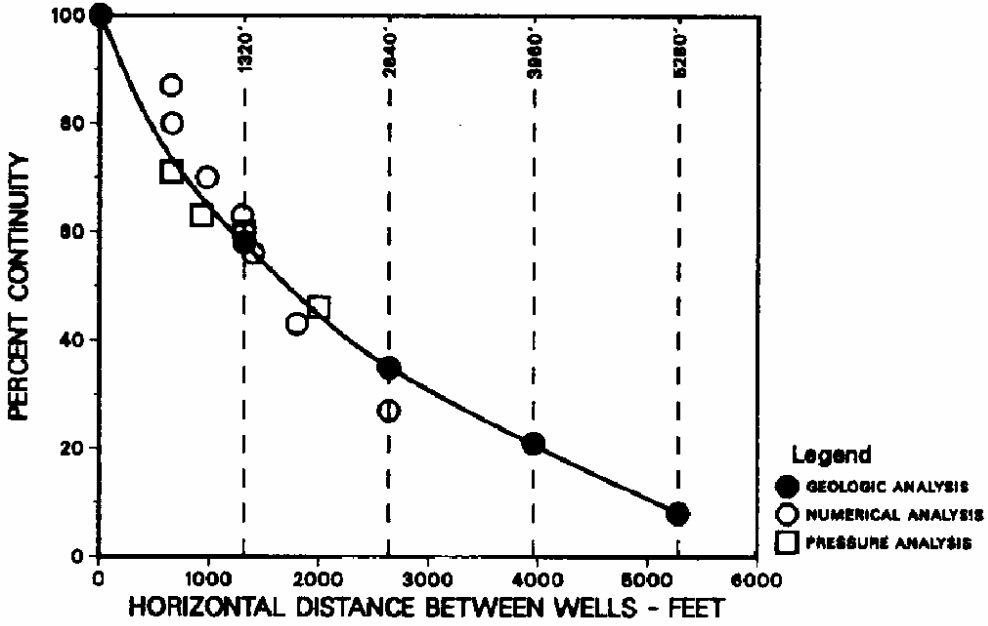


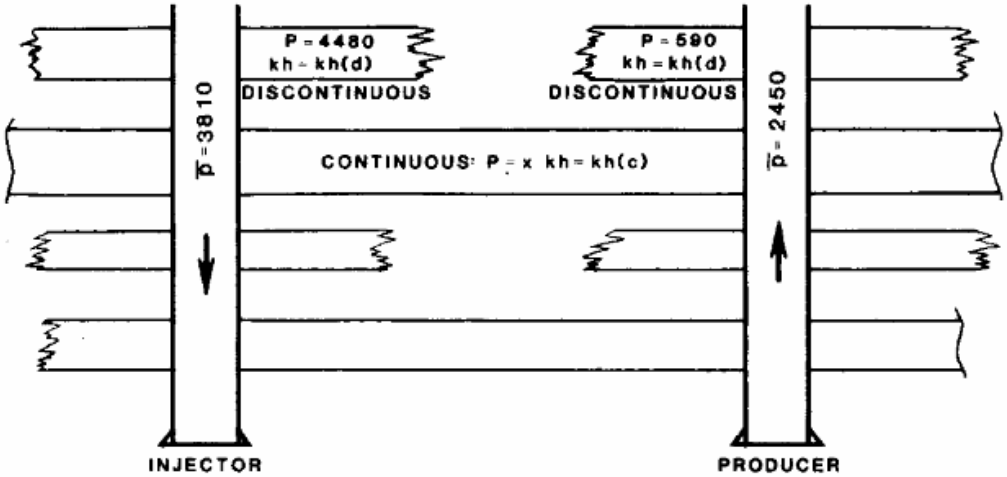
South Wasson Clearfork

Robertson Clearfork

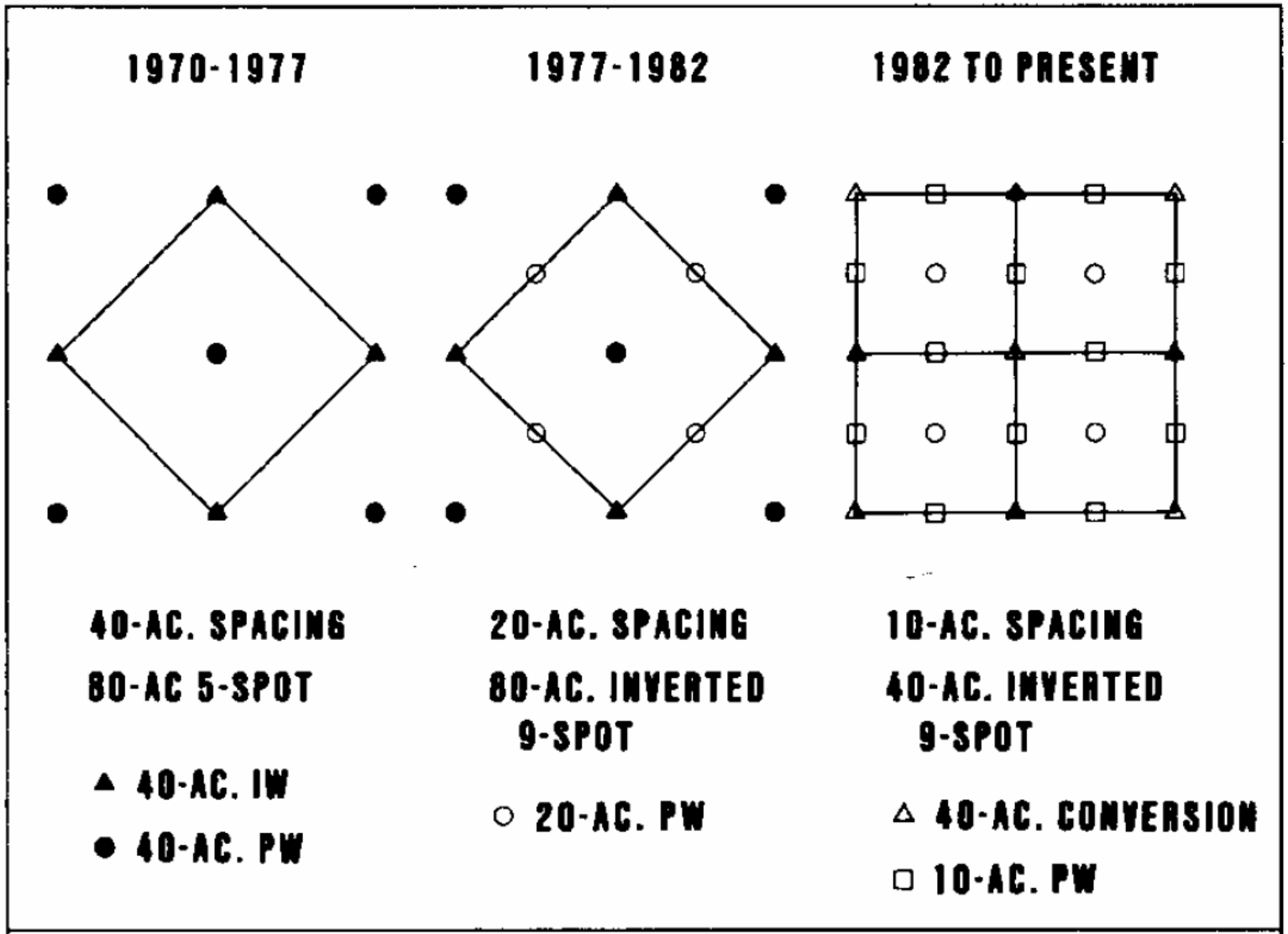
Robertson Clearfork Unit



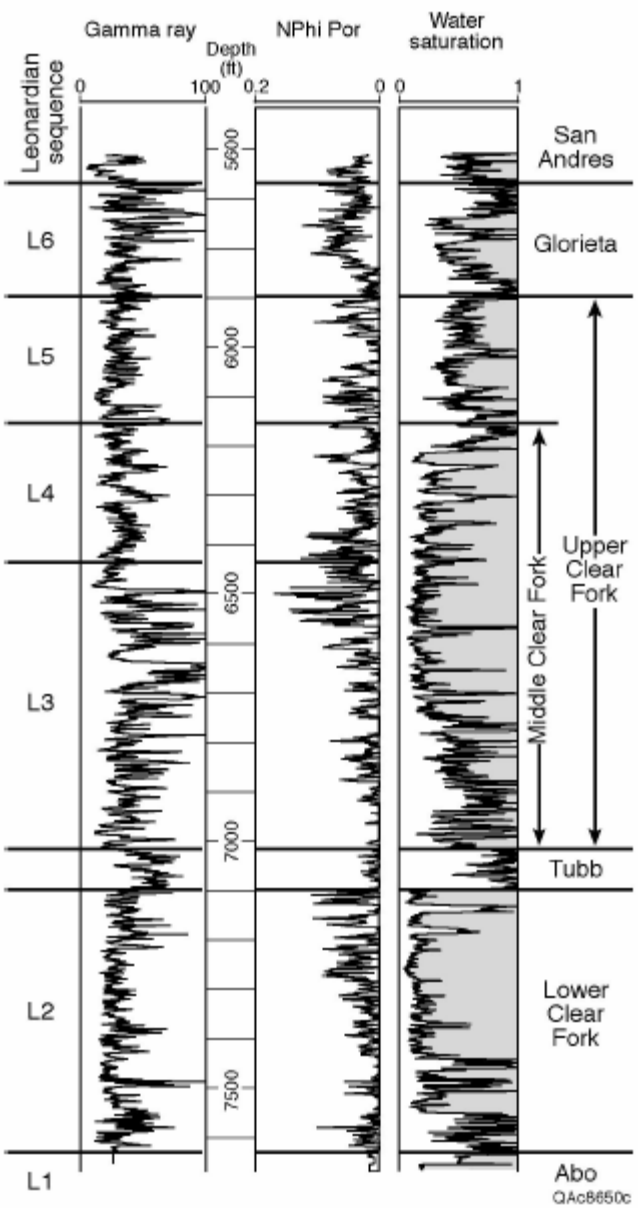


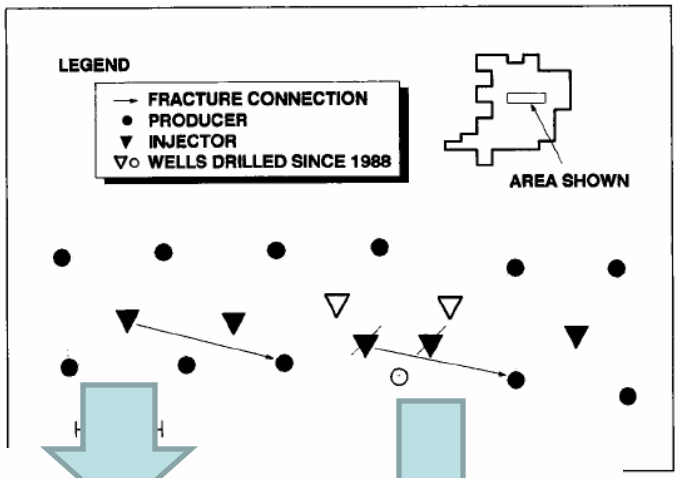


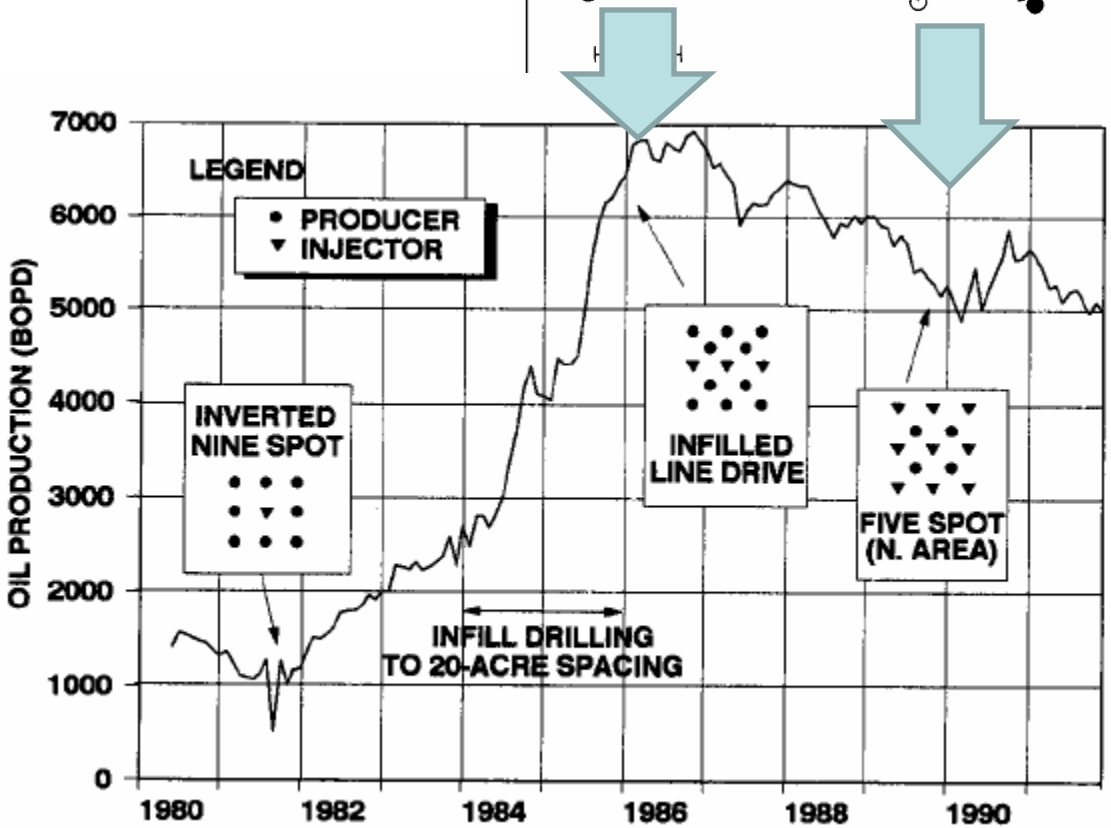
RCU Evolution of Waterflood Patterns



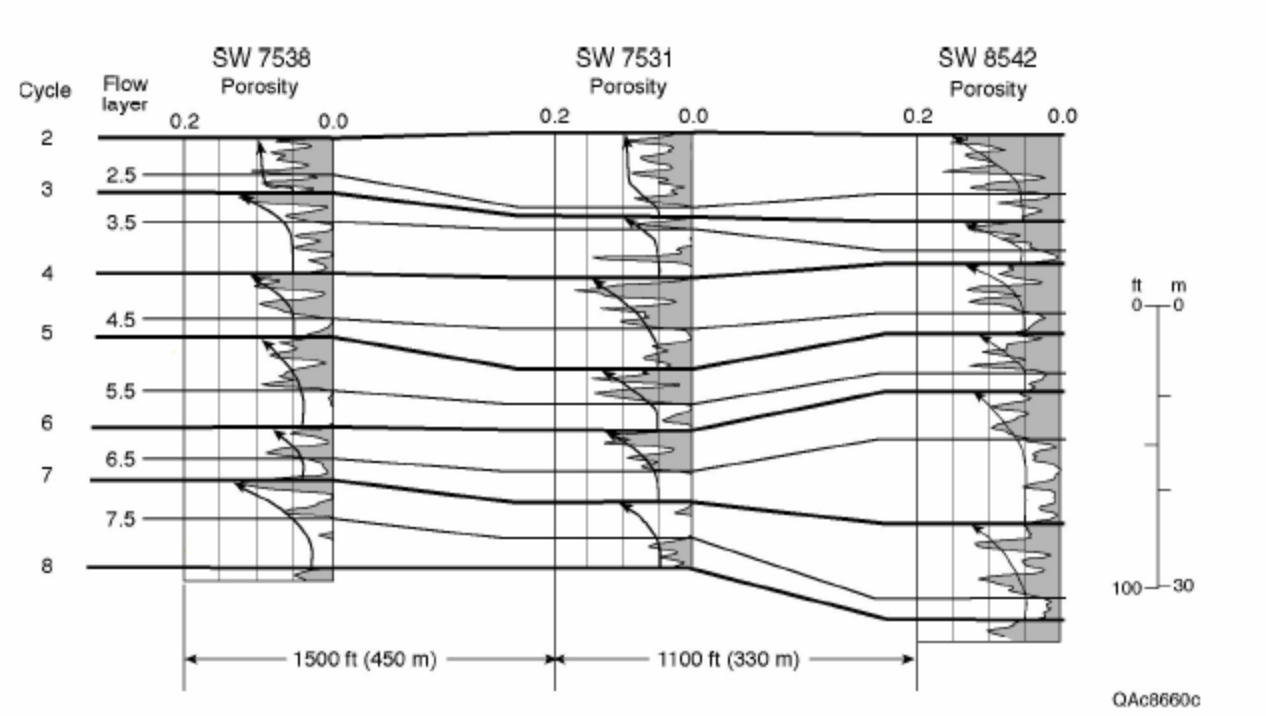
South Wasson Clearfork Unit

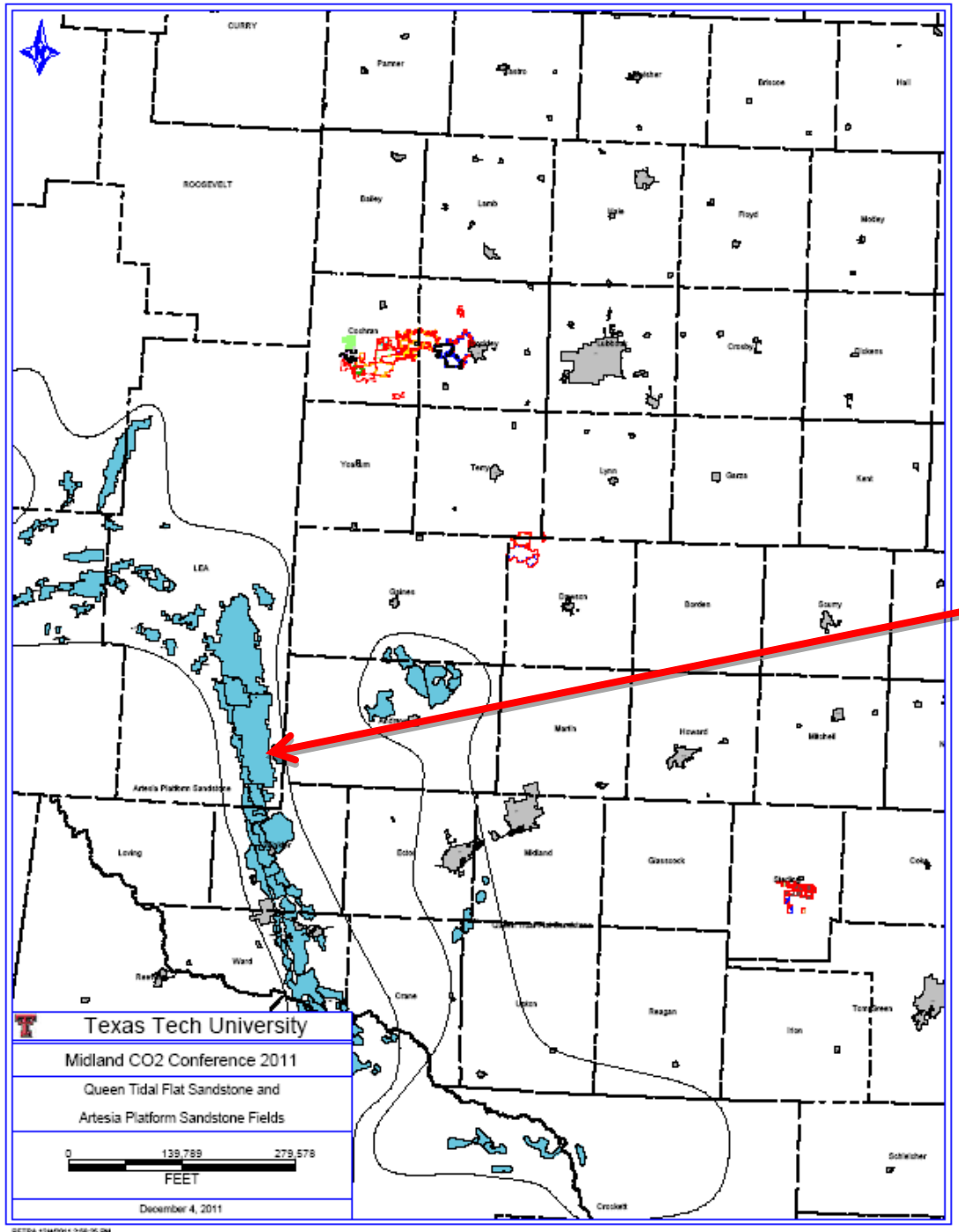






South Wasson Clearfork Sequence Stratigraphy Defines Flow Layers





West Dollarhide Queen Sand

West Dollarhide Queen Sand Unit Lea Co, NM

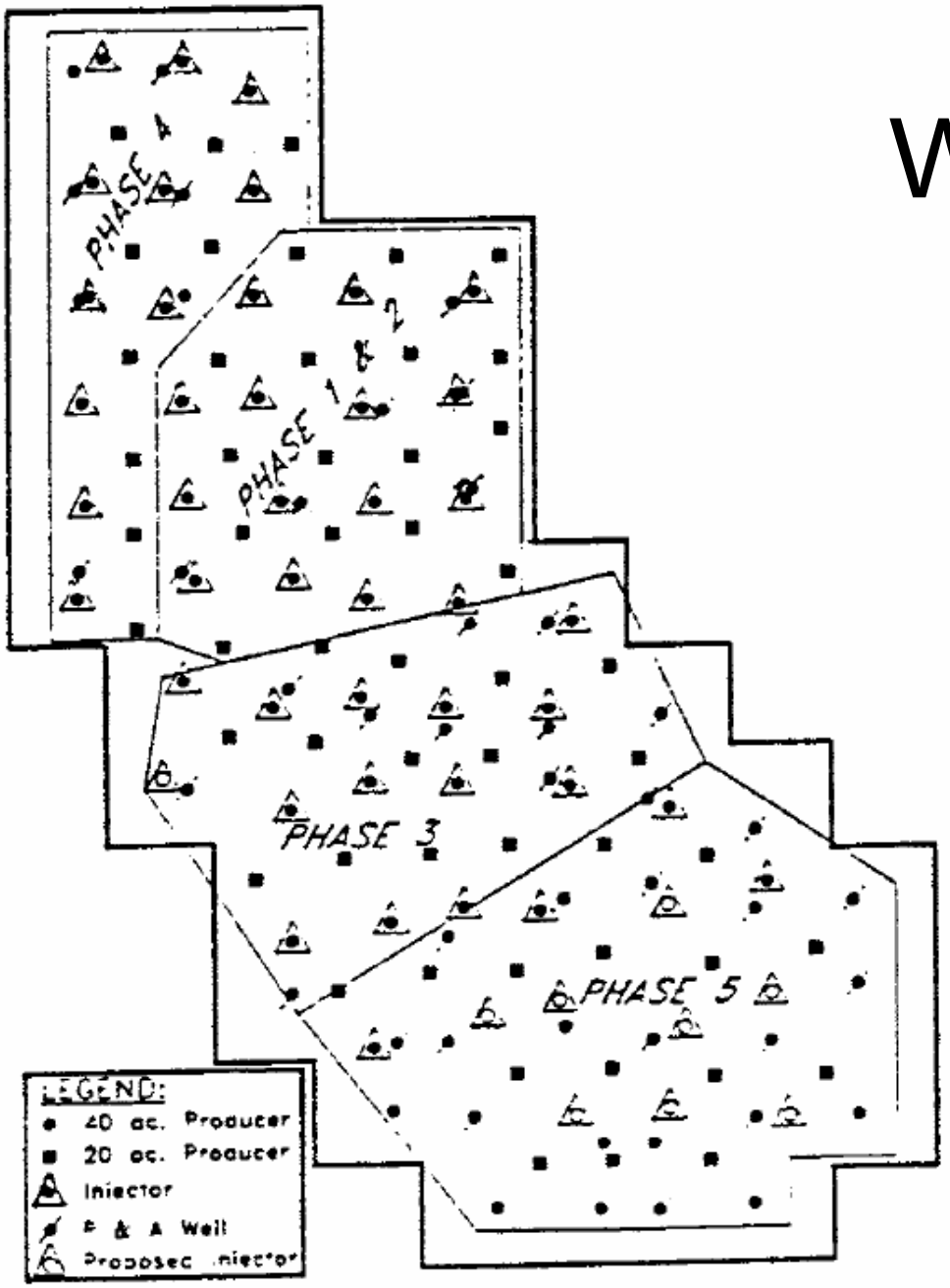
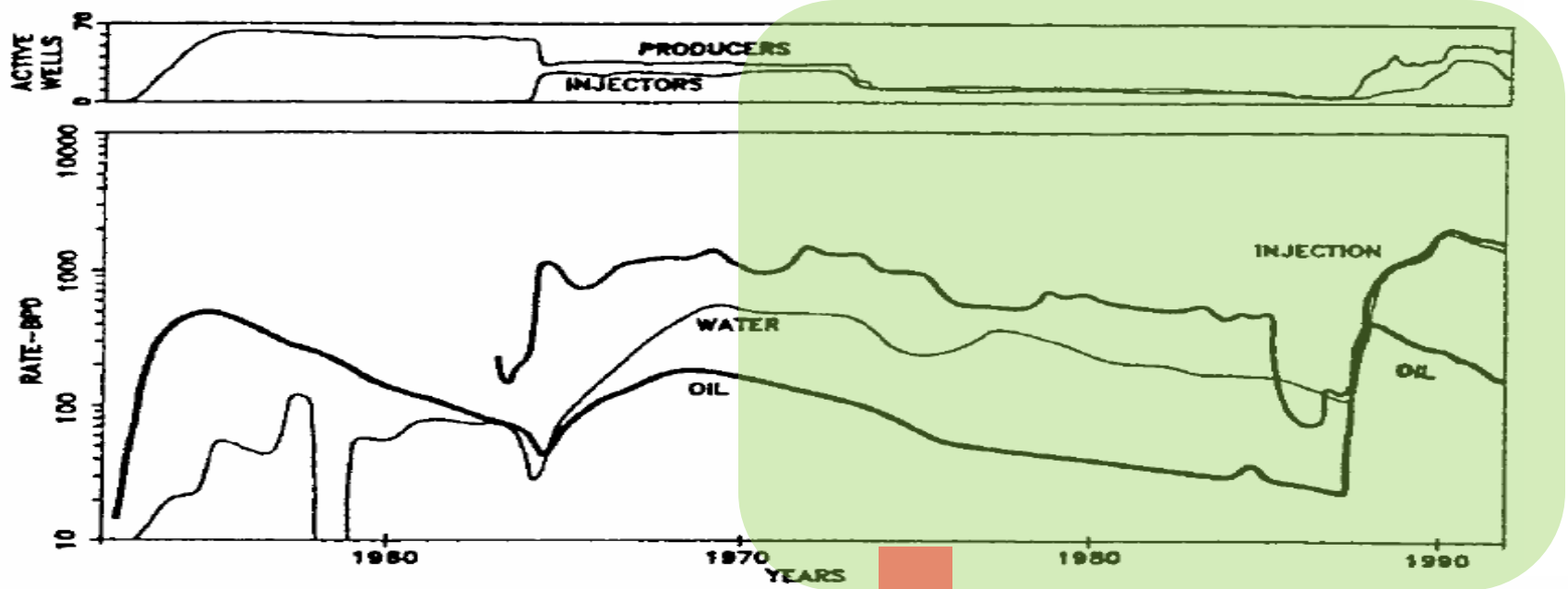
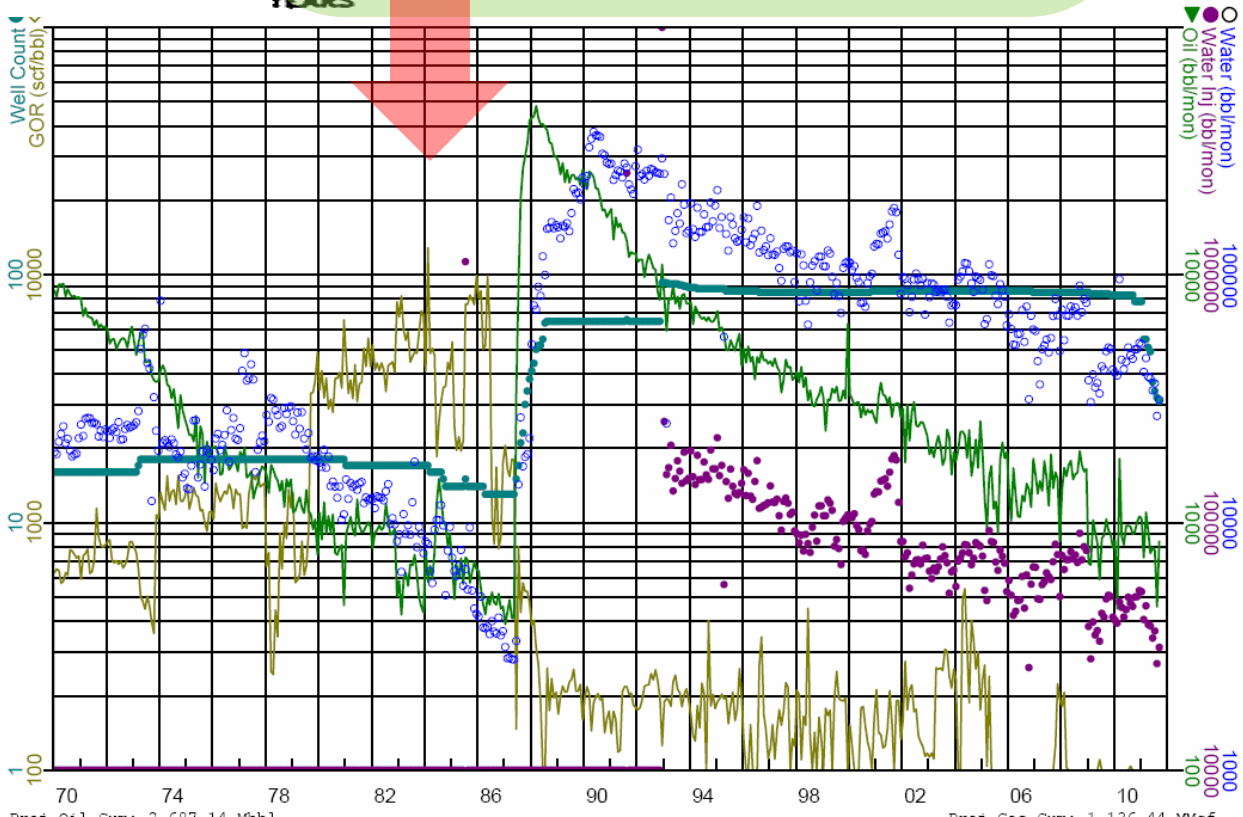
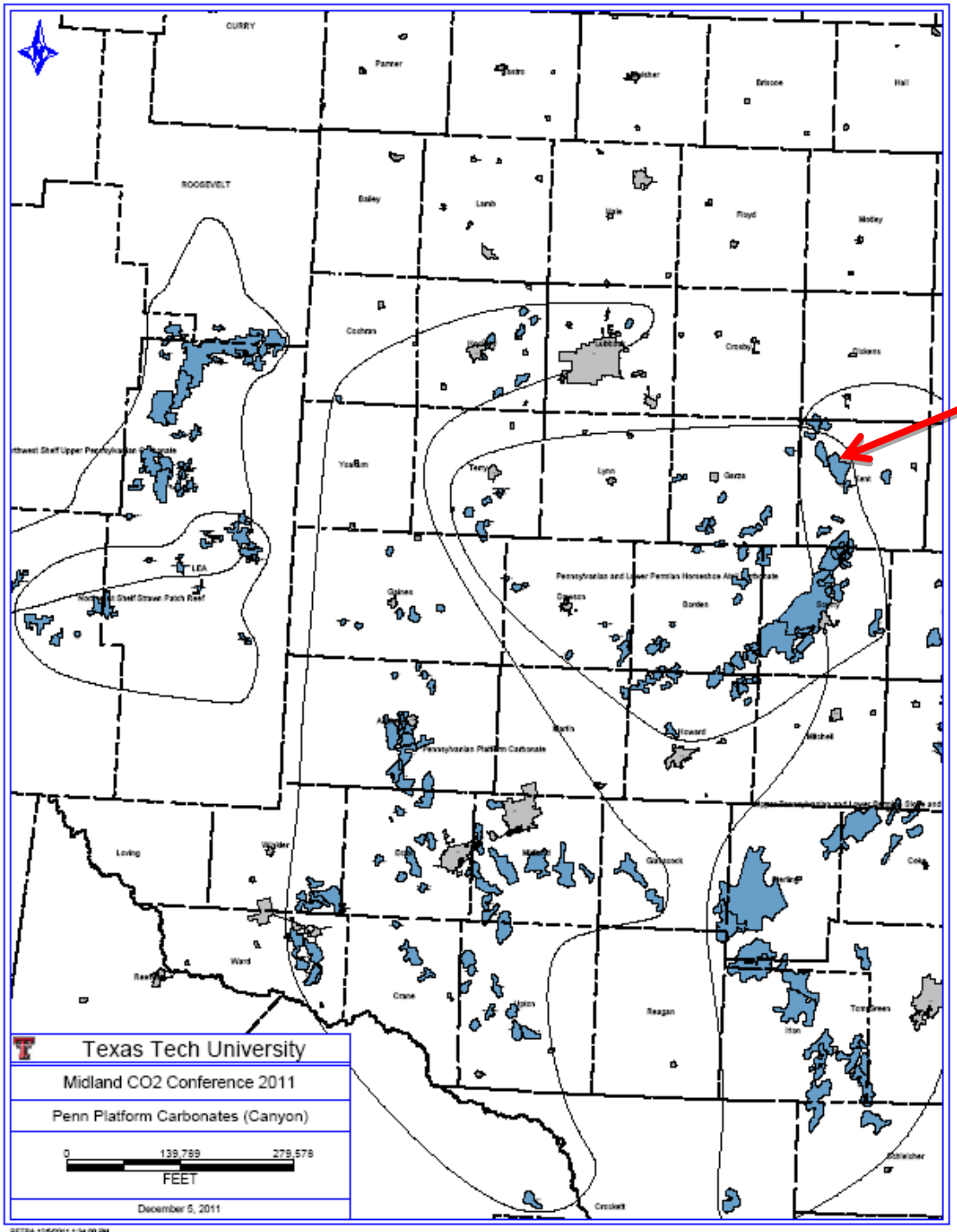


Figure 17 – Redevelopment Phase Areas
Sirgo–West Dollarhide Queen Sand Unit



Dollarhide Queen Sand Unit Infill Drilling and Re-Development



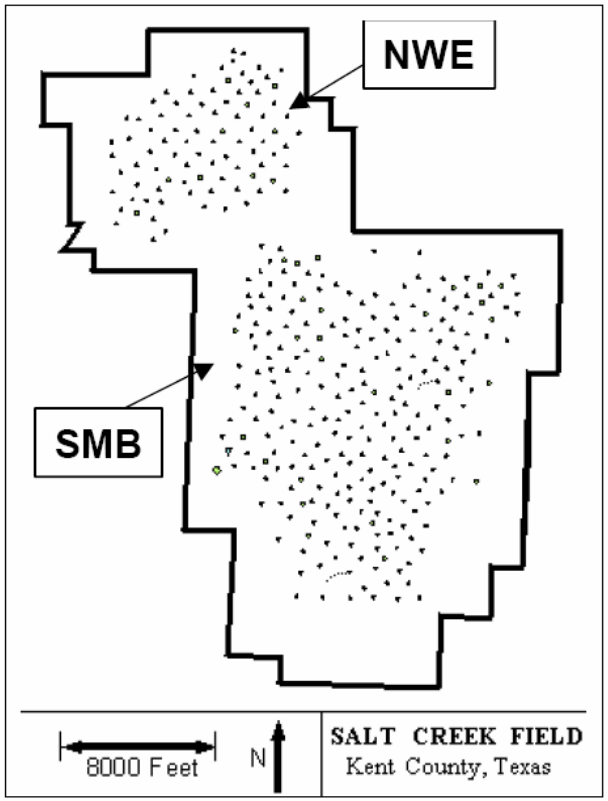

CURRY
Parmer
Briscoe
Hall
ROOSEVELT
Bailey
Lamb
Floyd
Motley
Cochran
Crosby
Dickens
Yoakum
Terry
Lynn
Garza
LEA
Gaines
Dawson
Borden
Howard
Mitchell
Loving
Winkler
Ector
Midland
Glasscock
Coke
Ward
Crane
Upton
Reagan
Irion
Tom Green
Crockett
Texas Tech University
Midland CO2 Conference 2011
Penn Platform Carbonates (Canyon)
0
139,789
279,578
FEET
December 5, 2011

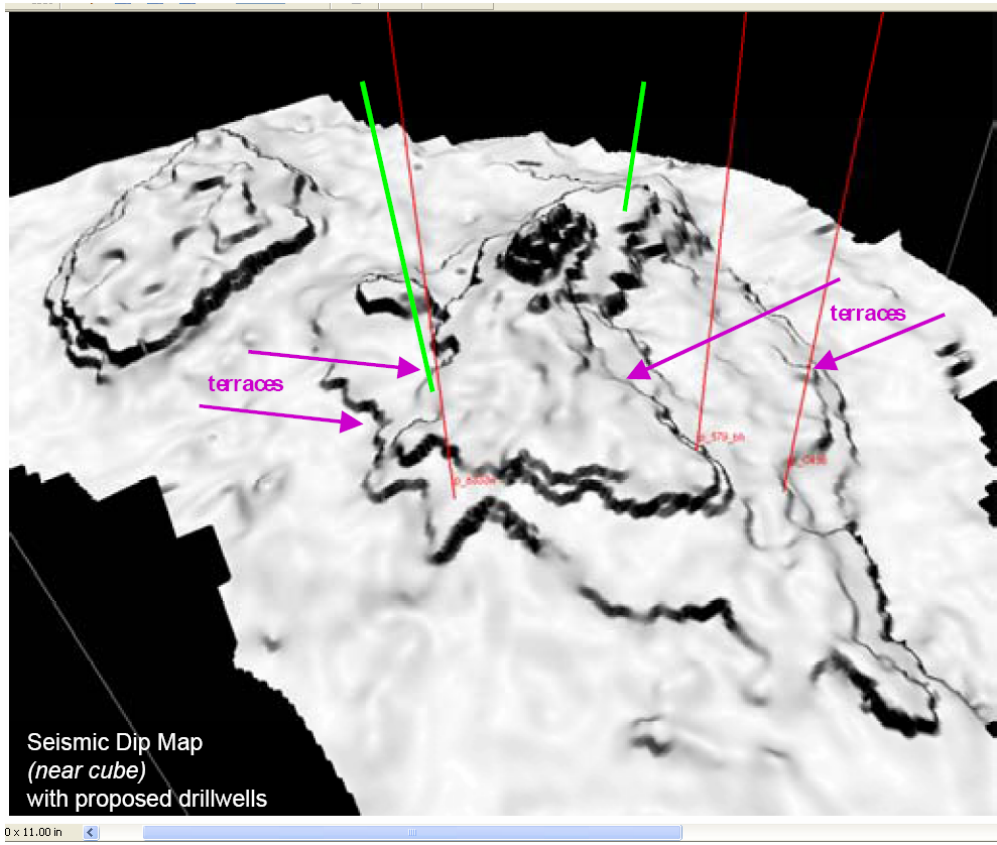
Salt Creek

Salt Creek Canyon

Snapshot Tool

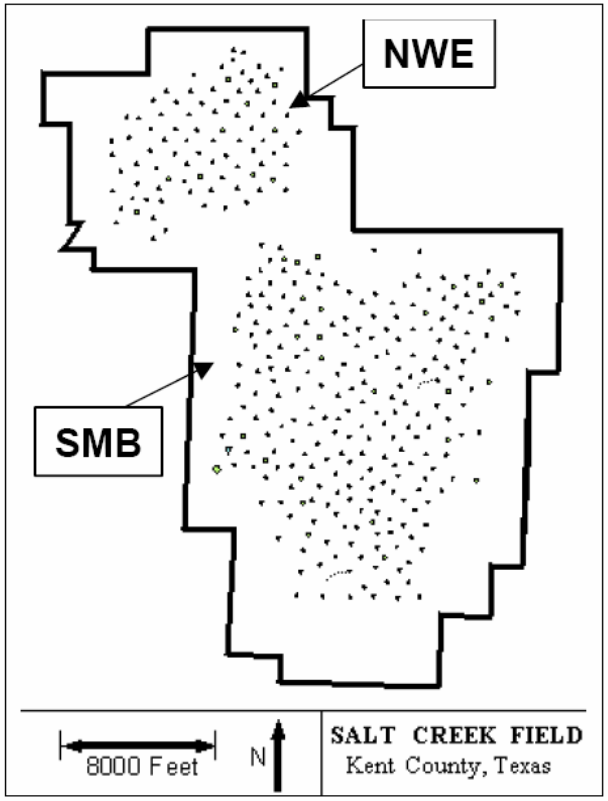
Figure 1. Salt Creek Field Unit location map.

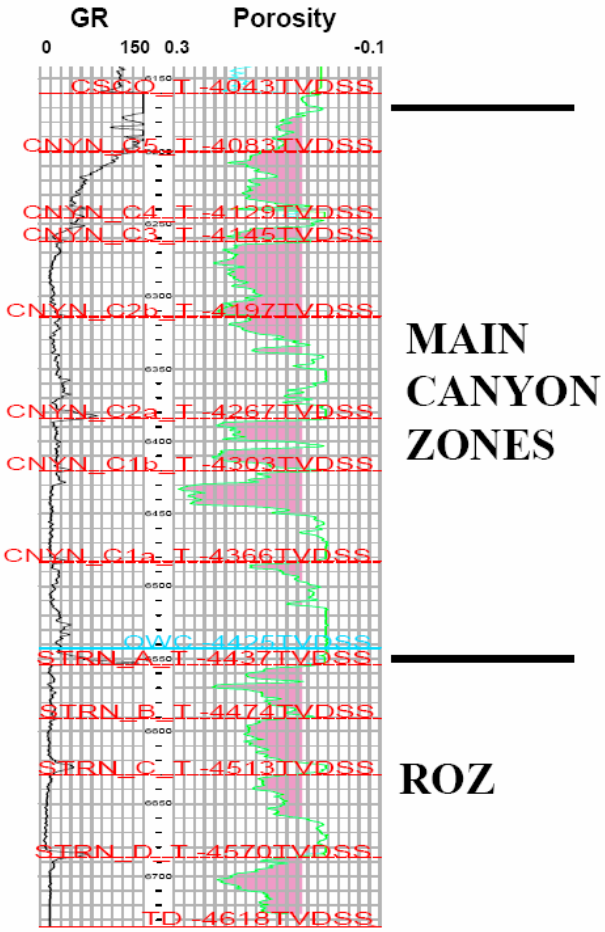




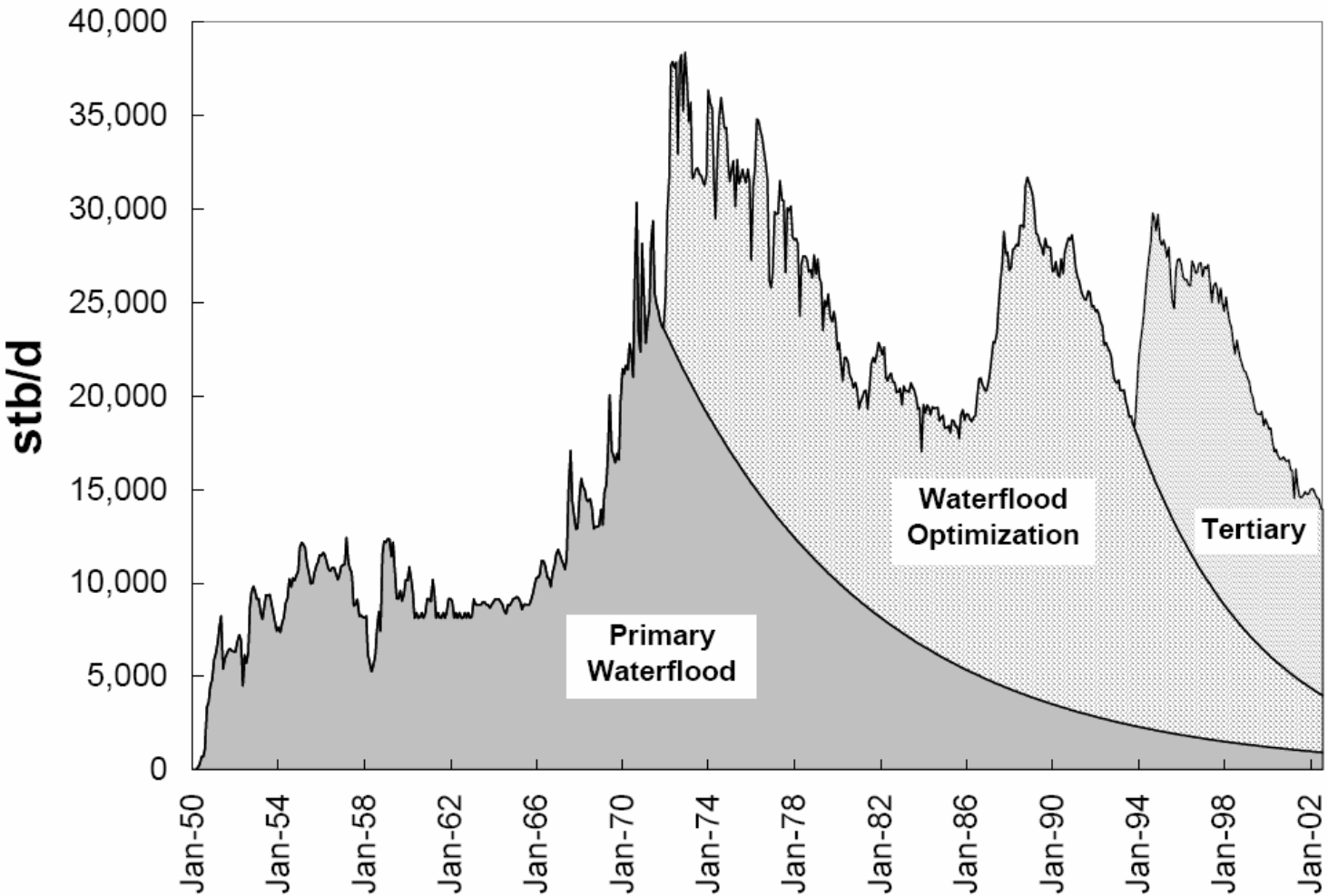
Snapshot Tool

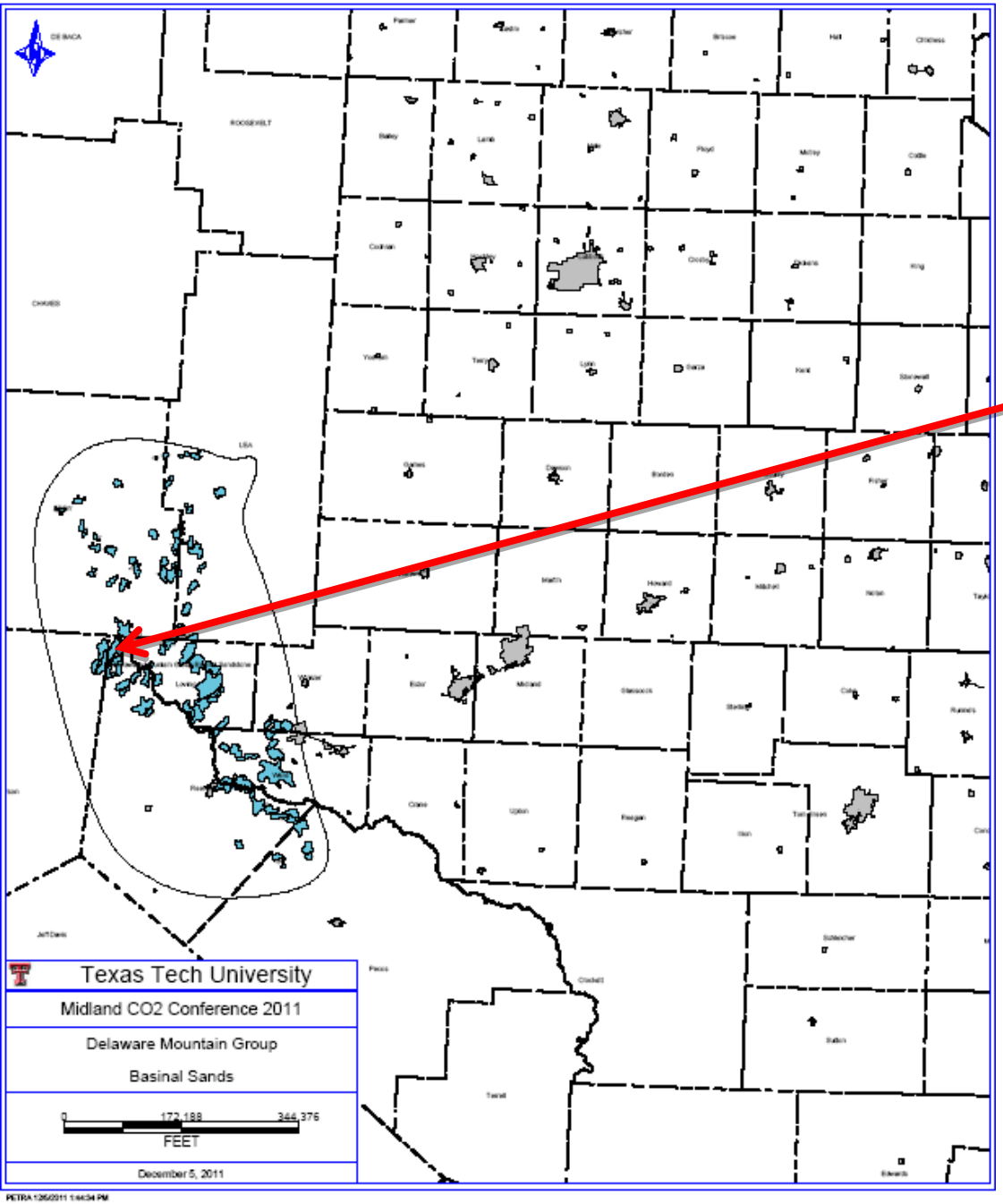
Figure 1. Salt Creek Field Unit location map.





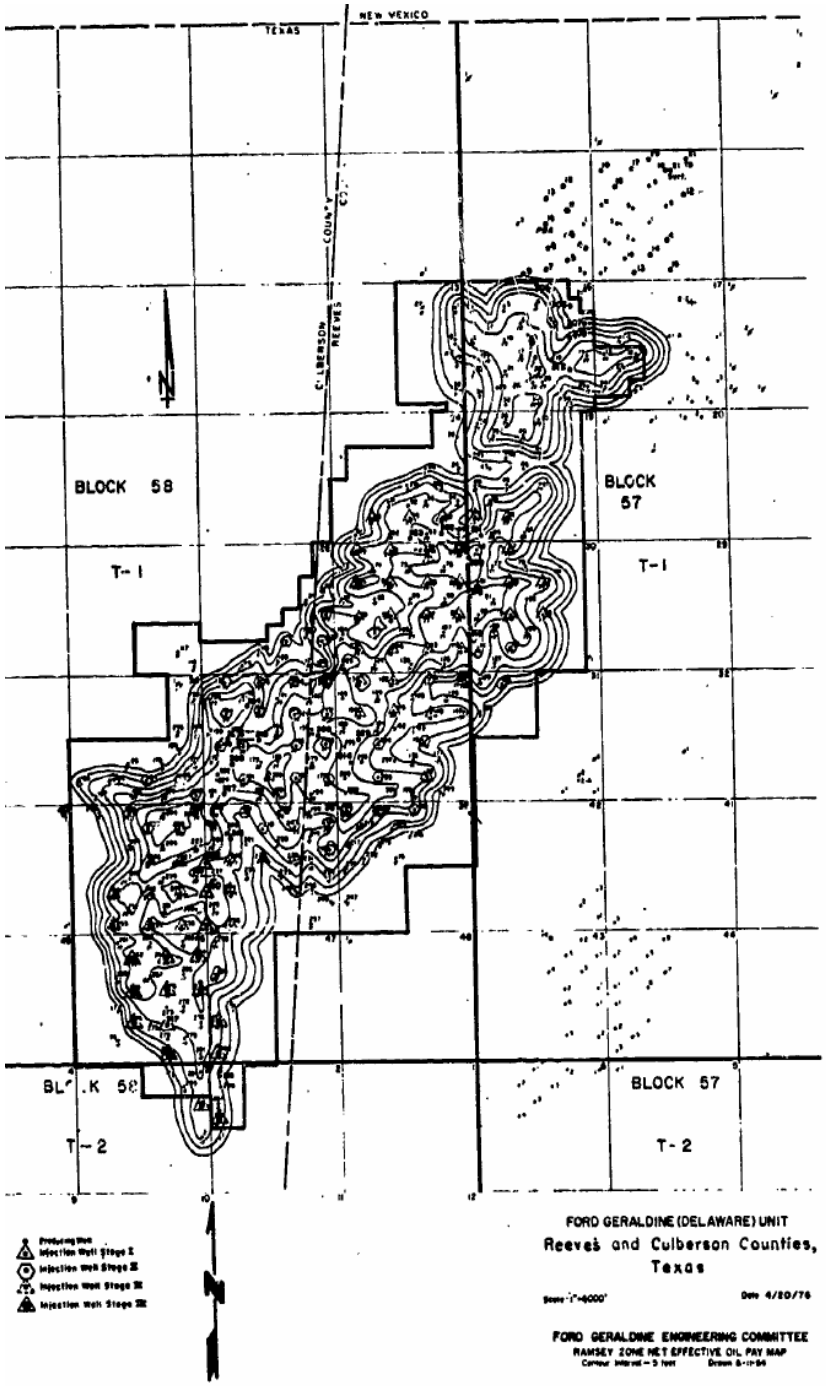
Salt Creek Canyon

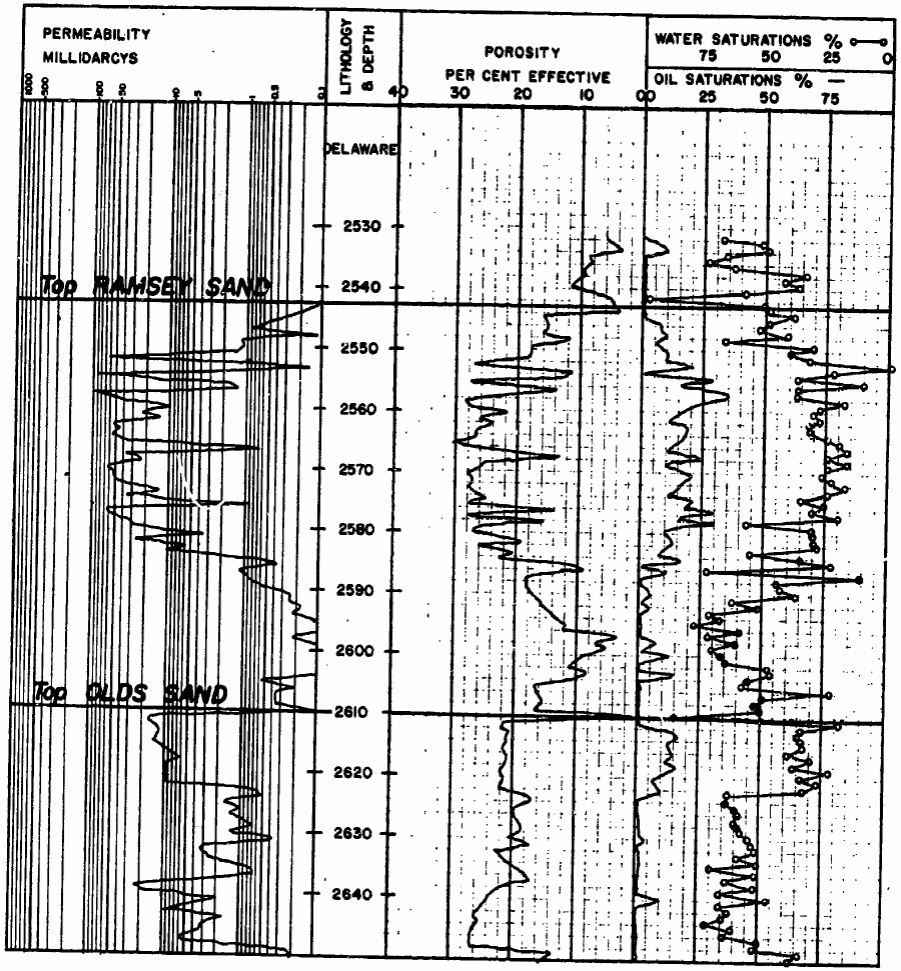




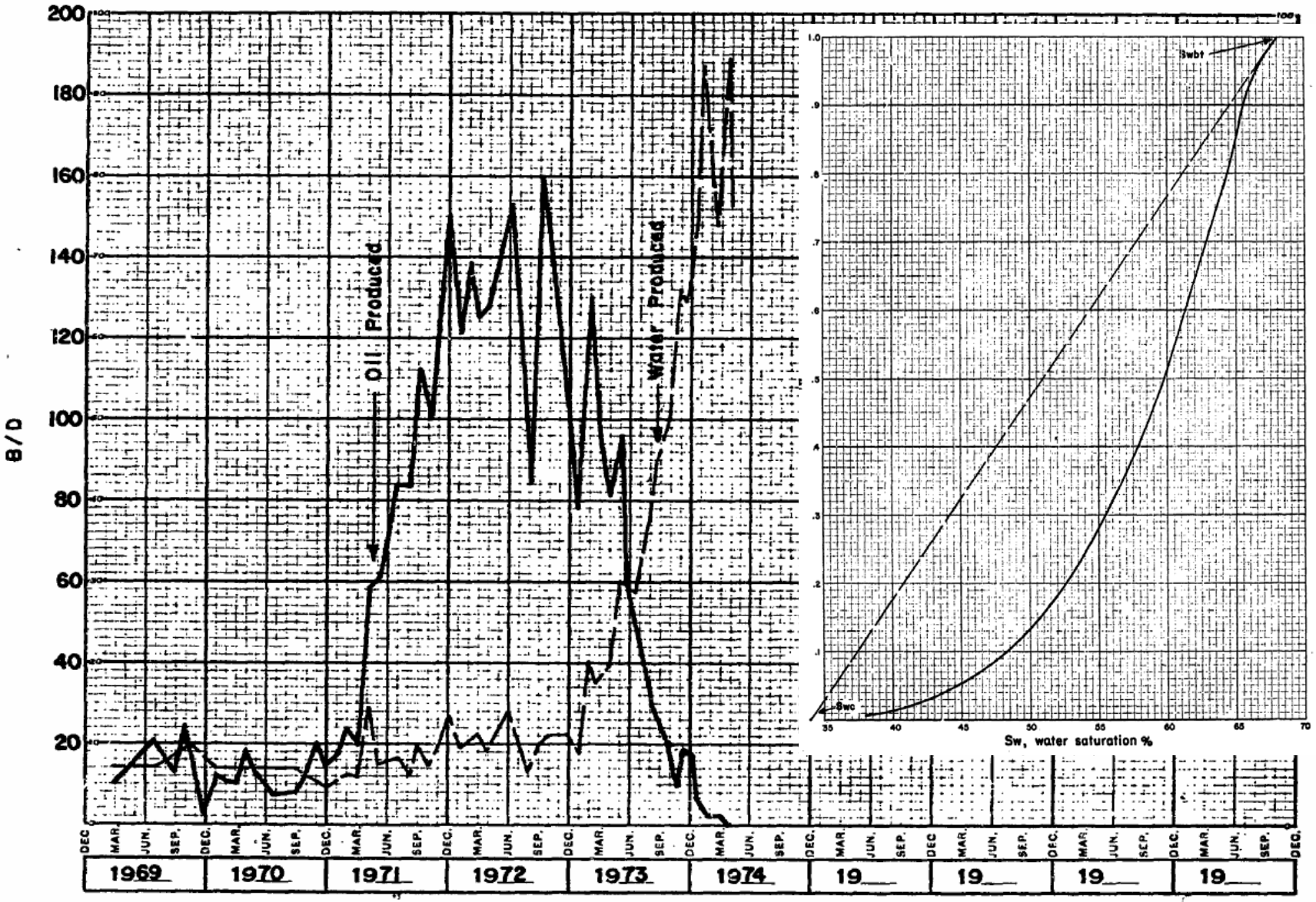
Ford Geraldine
(Delaware Sand)

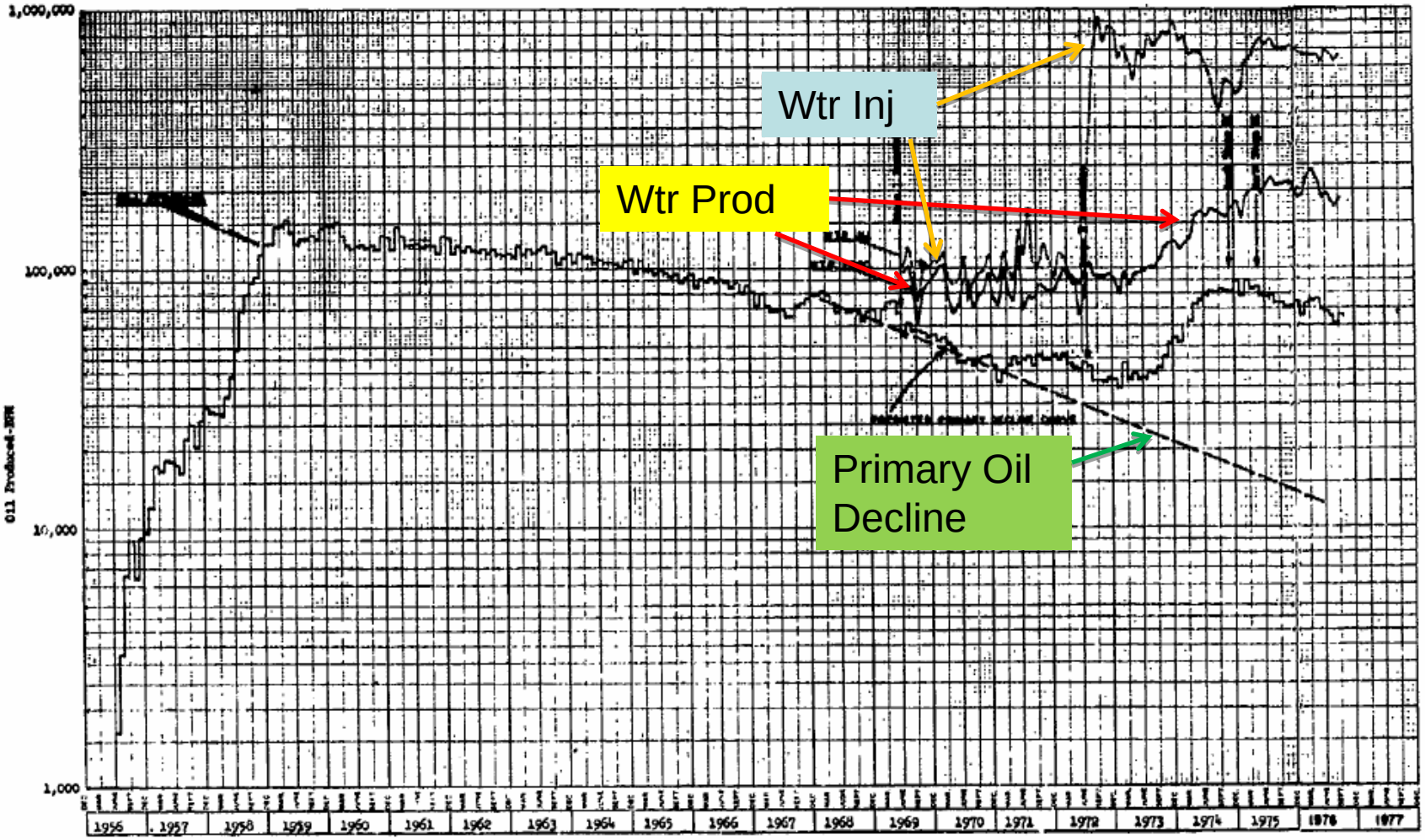
Ford Geraldine (Delaware Sand)

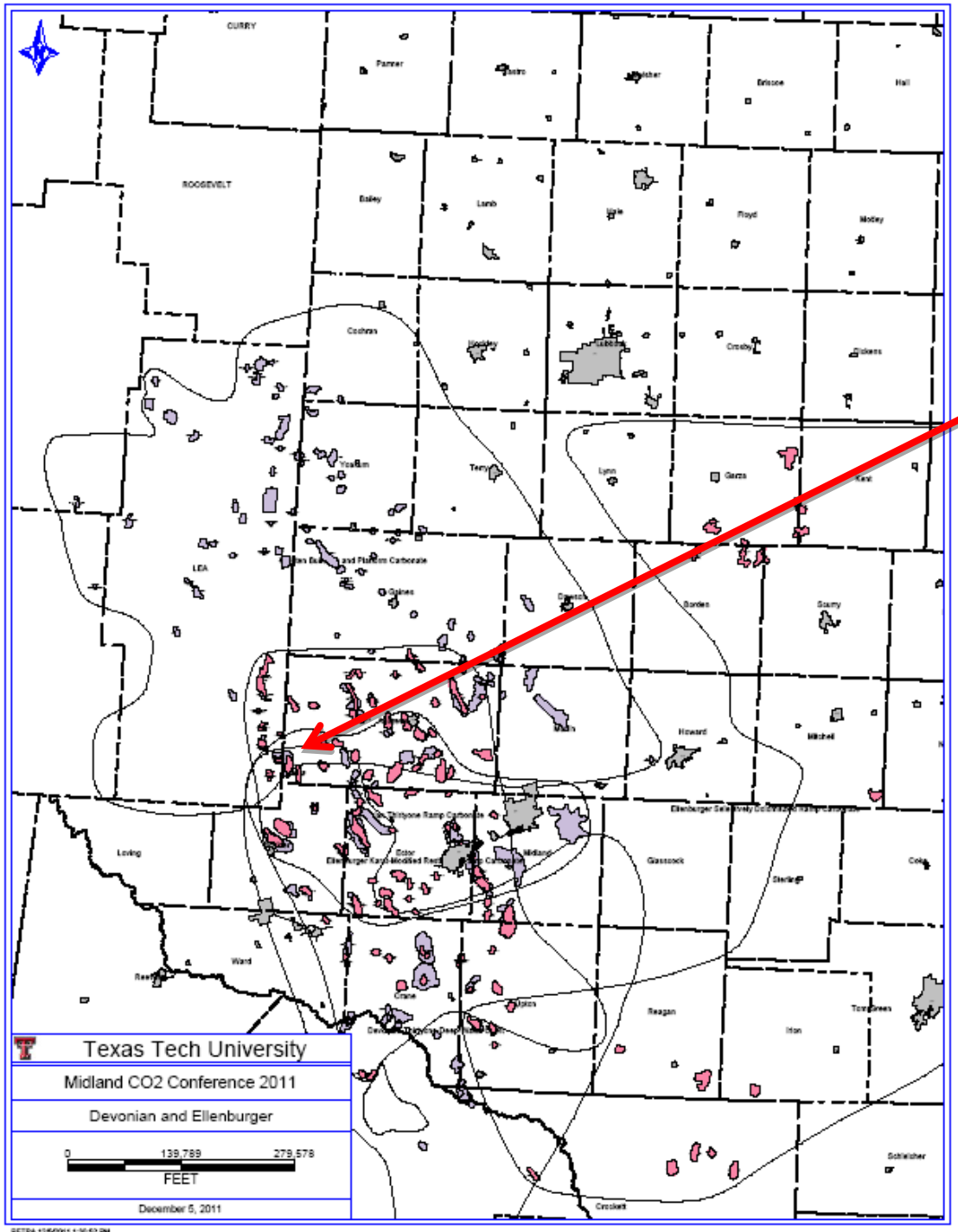




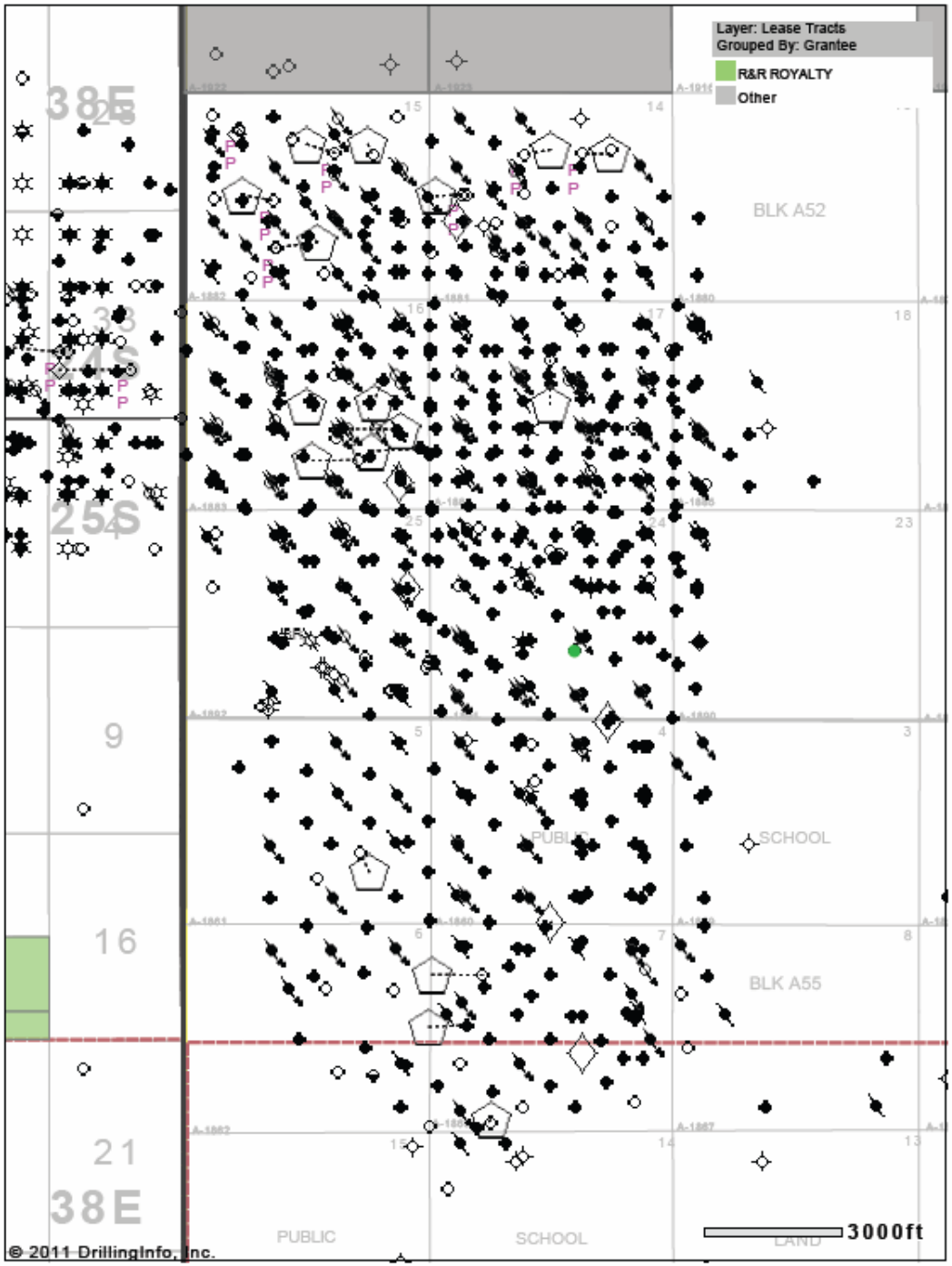
Ford Geraldine – Type Well Flood Response




Wtr Inj
Wtr Prod
Primary Oil Decline
1,000,000
100,000
10,000
1,000
Oil Produced-BBL
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977

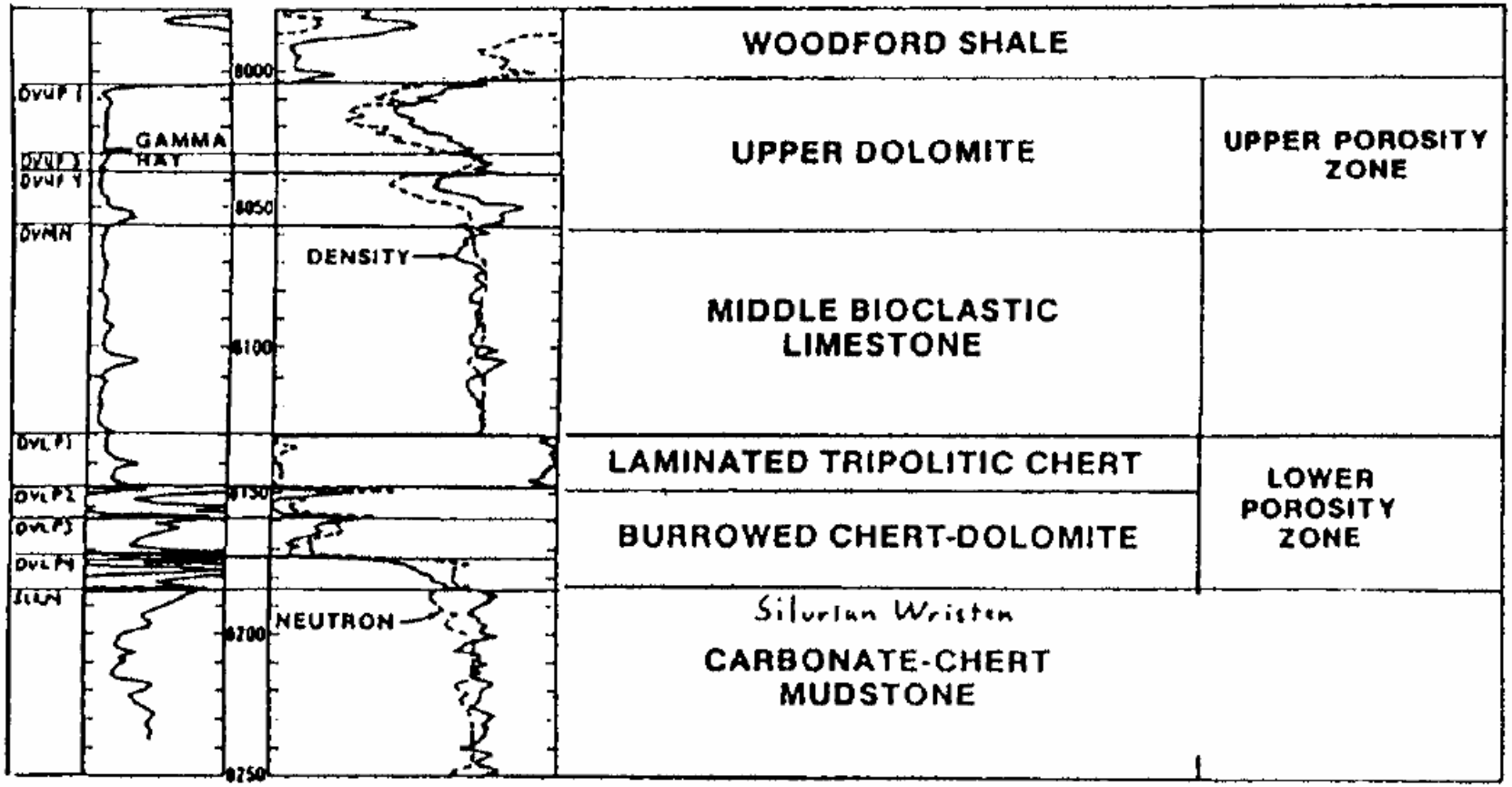


Dollarhide Devonian Unit



Dollarhide Devonian Unit

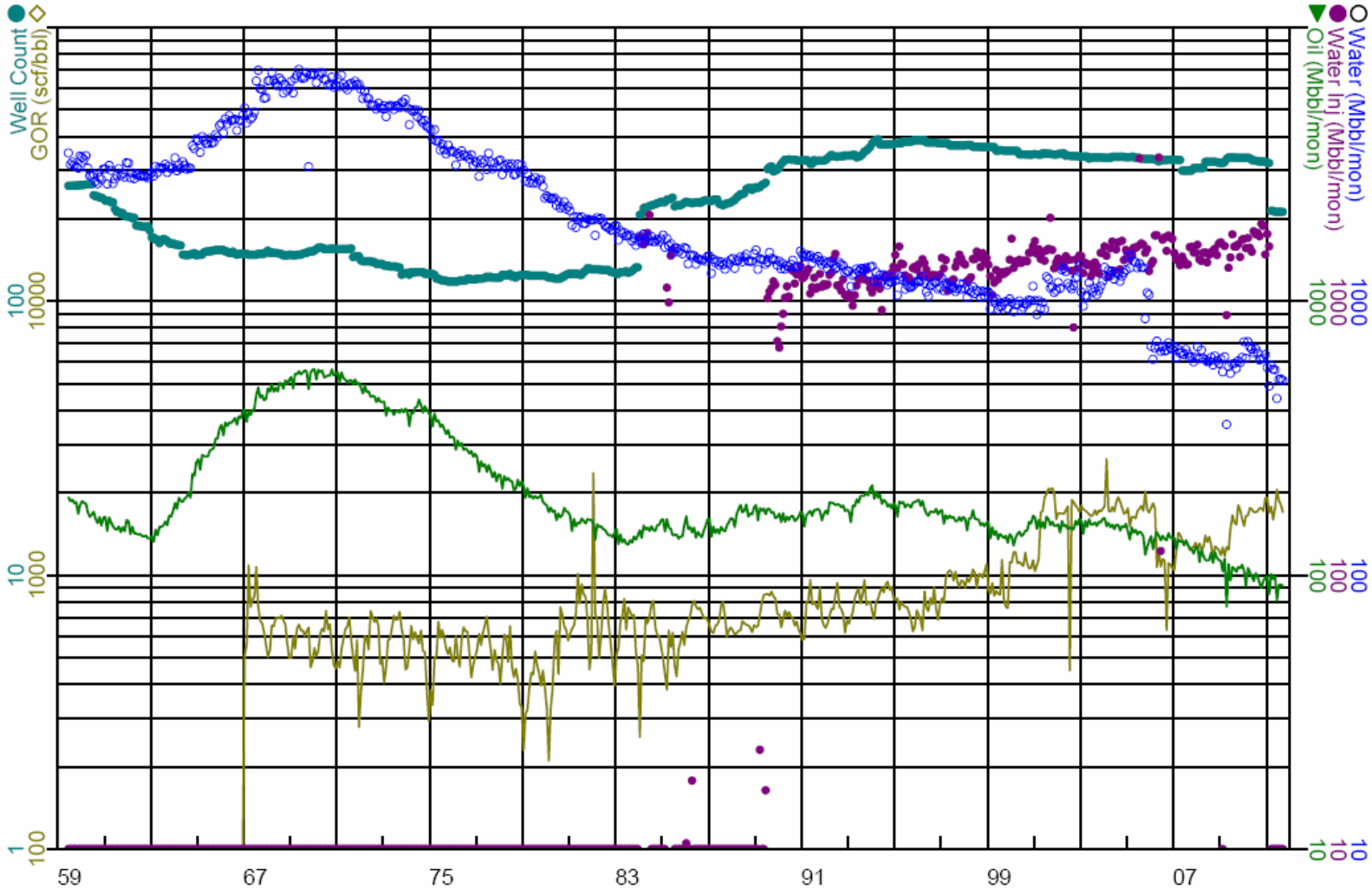
DOLLARHIDE 46 - 5D



Dollarhide Devonian Unit

Dollarhide Devonian Unit
Oper:
Major Phase: Oil

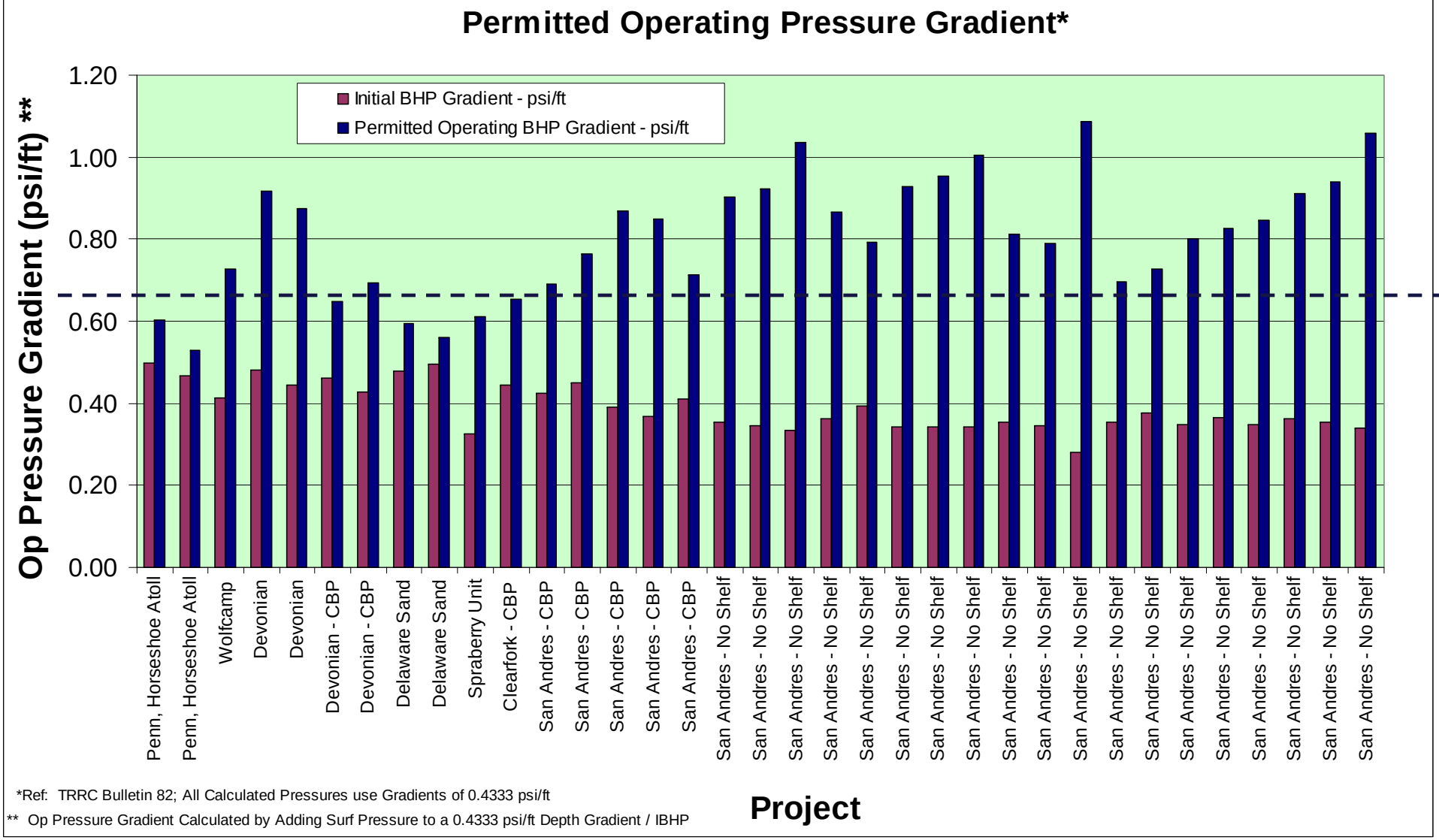
Field:
0.00 M$



Proj Oil Cum: 137,047.41 Mbbl
Oil Rem: 0.00 Mbbl
Oil EUR: 137,047.41 Mbbl

Proj Gas Cum: 92,268.21 MMcf
Gas Rem: 0.00 MMcf
Gas EUR: 92,268.21 MMcf

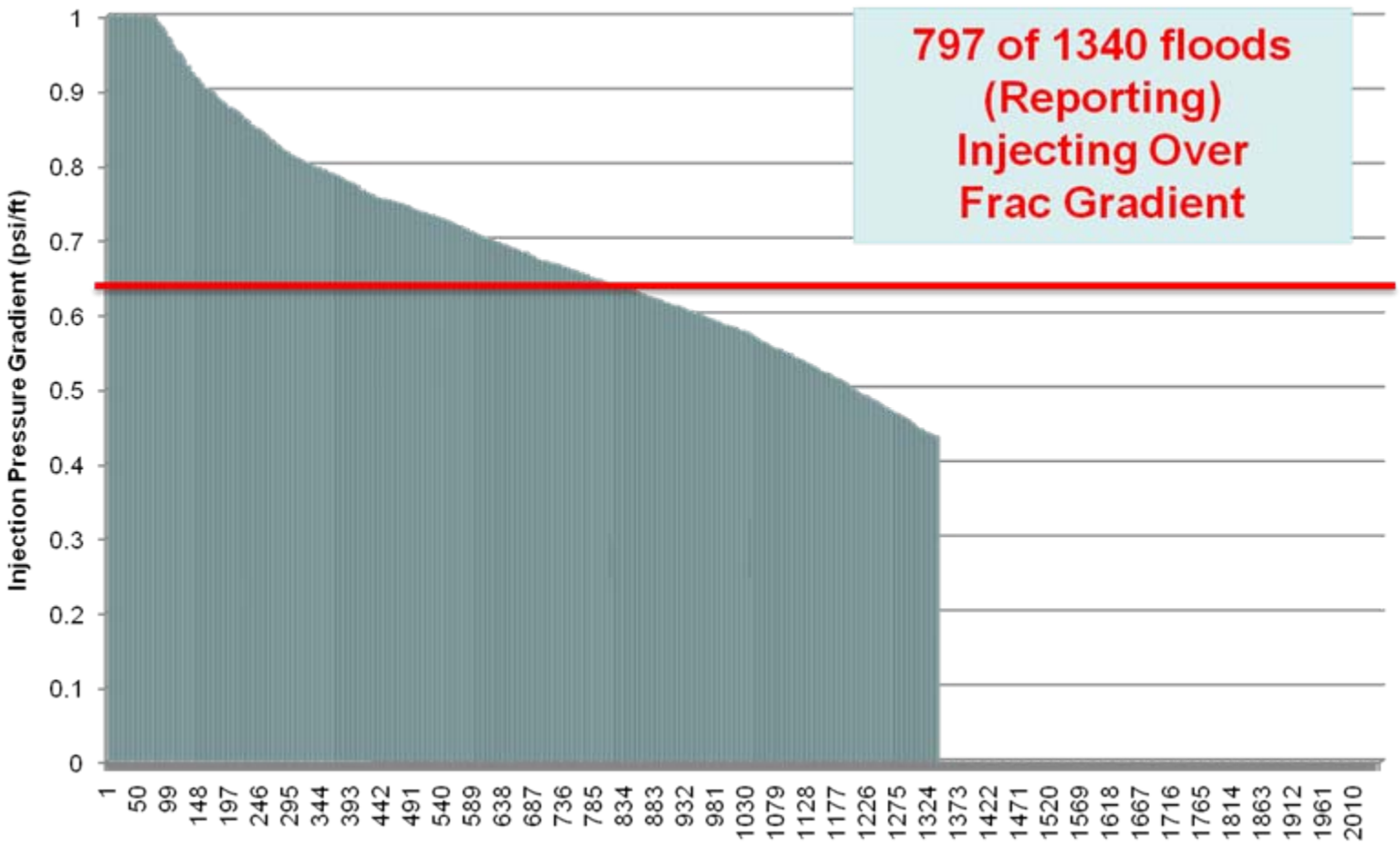
Generic Version of
CO_2 Project (Waterflood Phase) Permitted BHP Injection Pressures



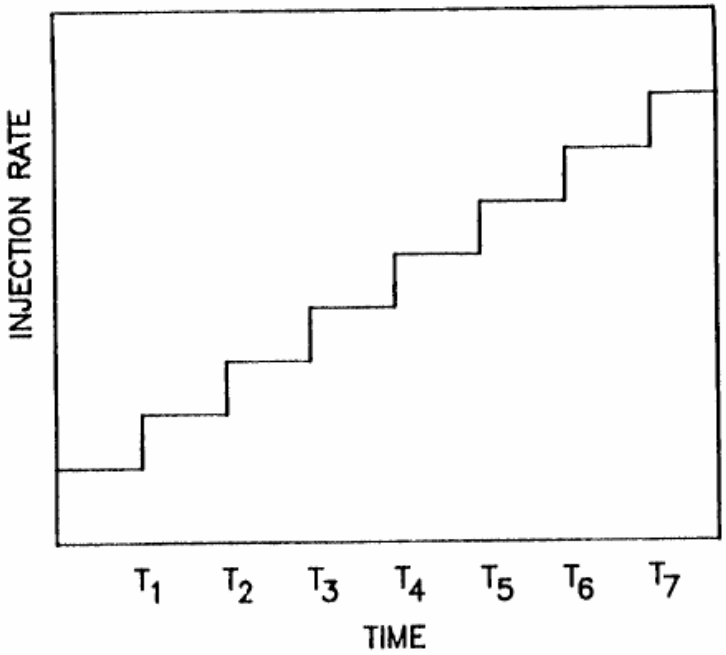
*Ref: TRRC Bulletin 82; All Calculated Pressures use Gradients of 0.4333 psi/ft

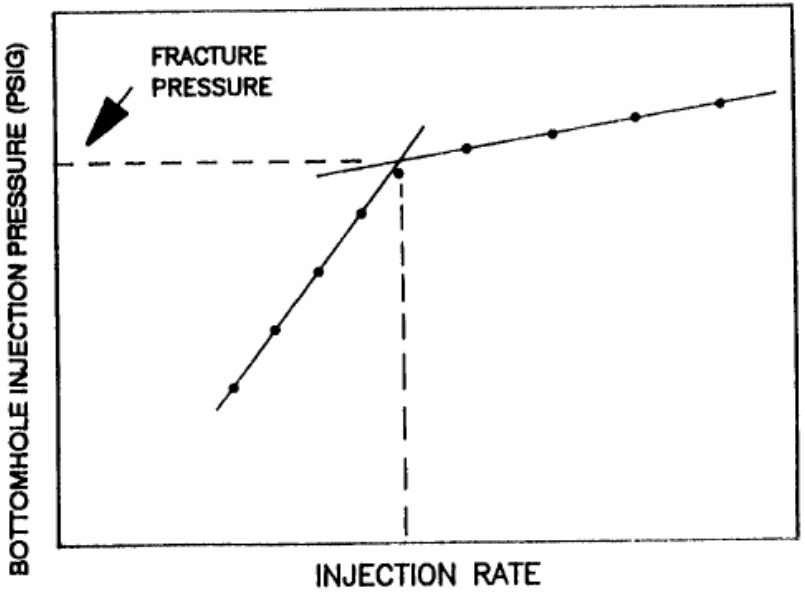
** Op Pressure Gradient Calculated by Adding Surf Pressure to a 0.4333 psi/ft Depth Gradient / IBHP

Injection Pressure 1982



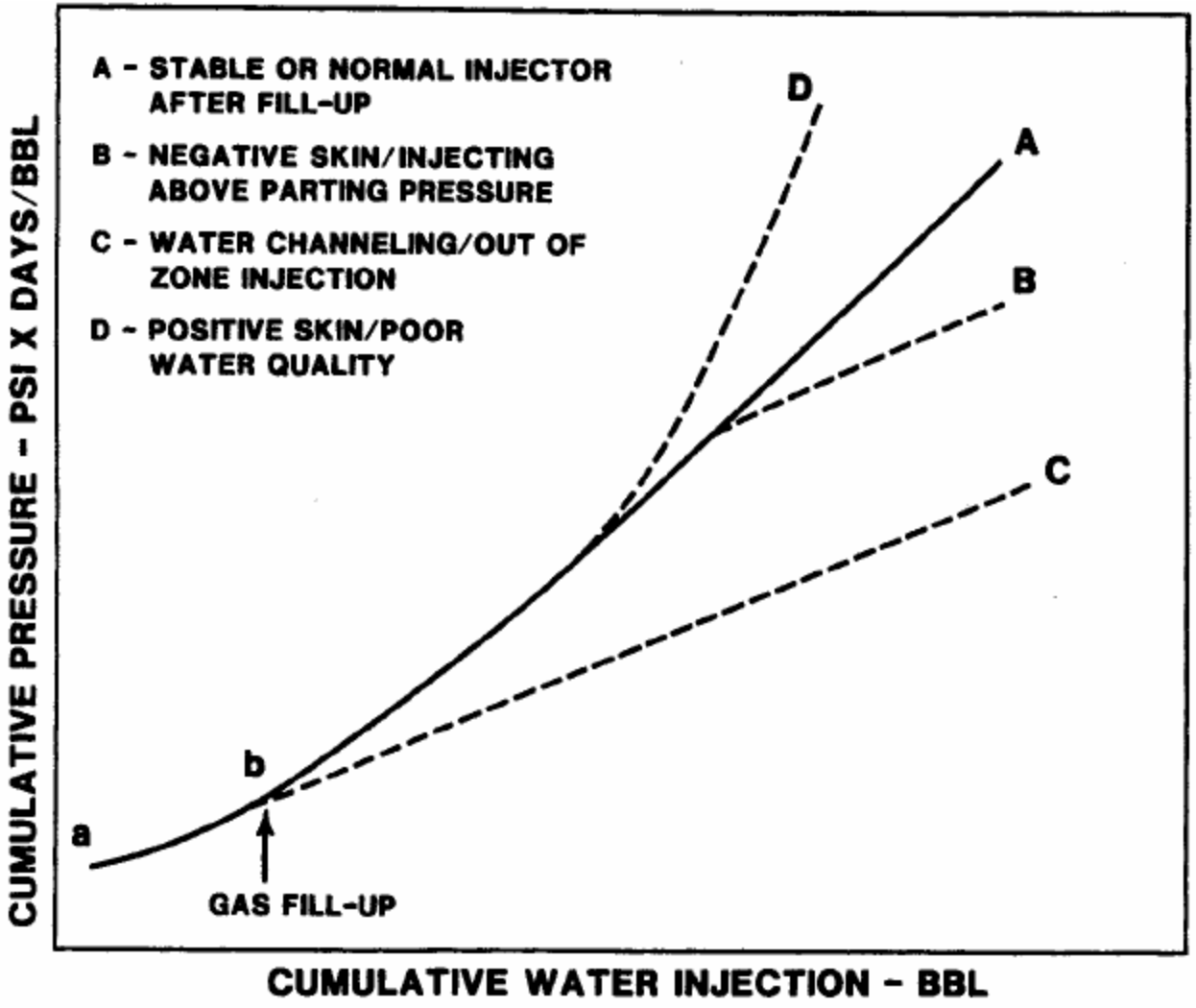
Step Rate Test





Is there a difference after shut in and while on injection?

Hall Plot


A - STABLE OR NORMAL INJECTOR AFTER FILL-UP
B - NEGATIVE SKIN/INJECTING ABOVE PARTING PRESSURE
C - WATER CHANNELING/OUT OF ZONE INJECTION
D - POSITIVE SKIN/POOR WATER QUALITY
D
A
B
C
a
b
GAS FILL-UP
CUMULATIVE PRESSURE - PSI X DAYS/BBL
CUMULATIVE WATER INJECTION - BBL

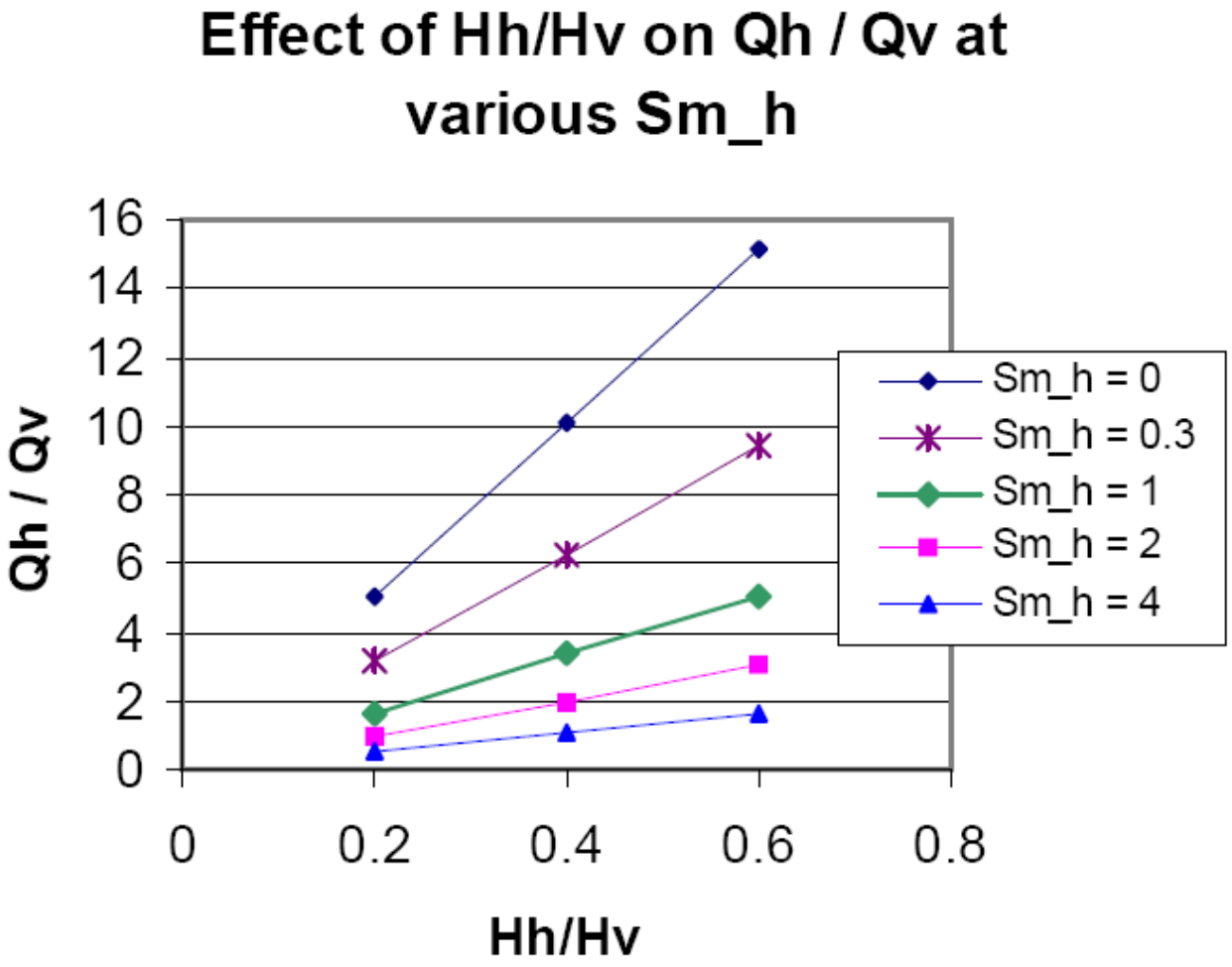
Vertical or Horizontal?

$$\frac{Q_h}{Q_v} = k_{anisot}\frac{H_h}{H_v}\frac{ln\left(\frac{2r_e}{r_w} - 0.75 + S\right)}{ln\left(\frac{2r_e}{r_w}\right) - 0.75 + S_{m_h} + S_h + S_{ca_h} - 1.386}$$

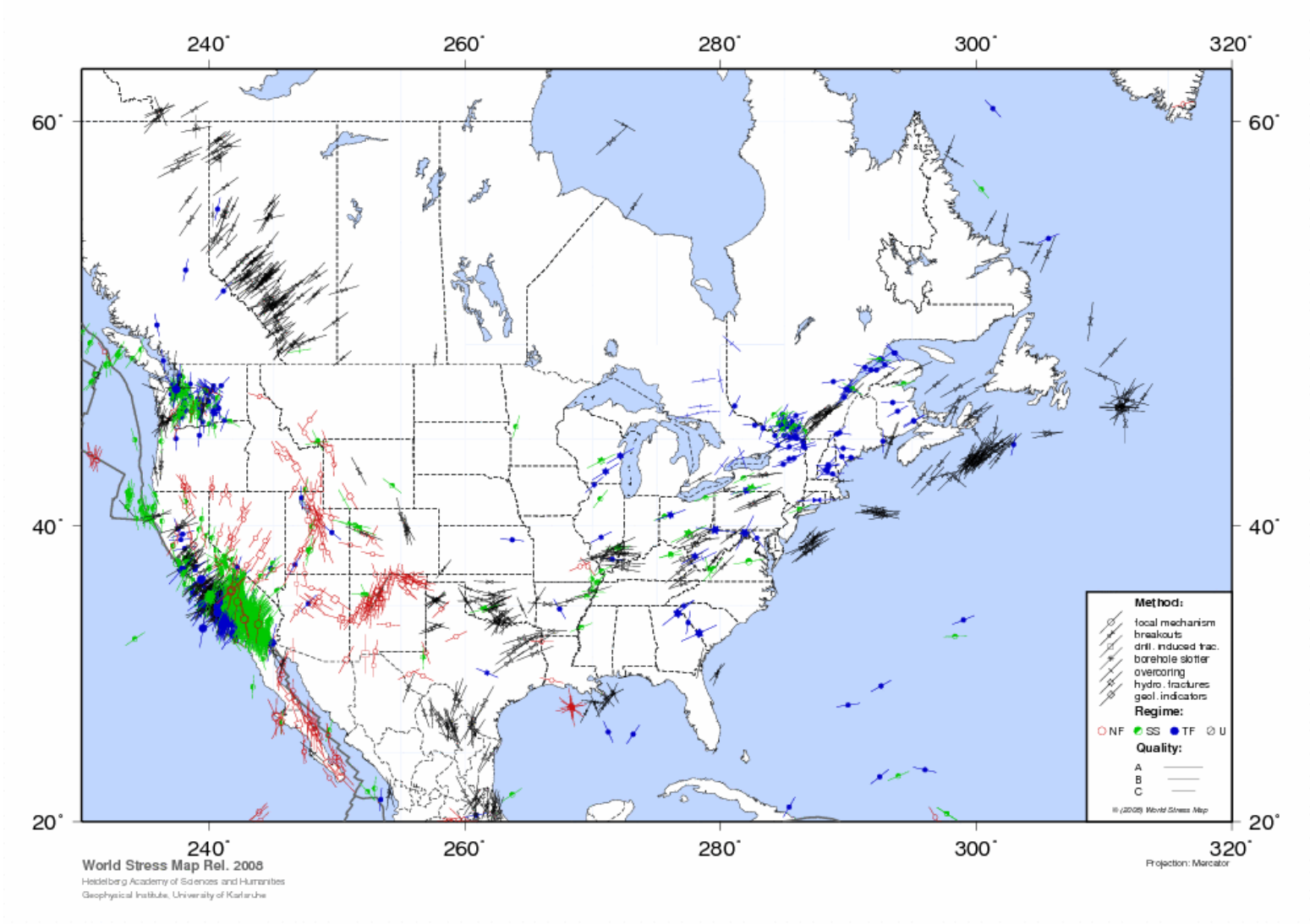
Where:

k_{anisot}	= permeability anisotropy (k_{max}/k_{min})
H_h	= thickness of layer containing the horizontal wellbore
H_v	= sum of all completed layers in a vertical well
r_e	= drainage radius
r_w	= wellbore radius
S	= negative vertical – well skin factor due to stimulation
S_{mh}	= the mechanical well skin damage to a horizontal well
S_h	= the negative skin factor due to the horizontal well = $-\ln(L/4r_w)$
S_{cah}	= the shape related skin factor (function of drainage shape, well length, H_h, and k_v/k_h) given by a correlation derived from charts
L	= horizontal wellbore length

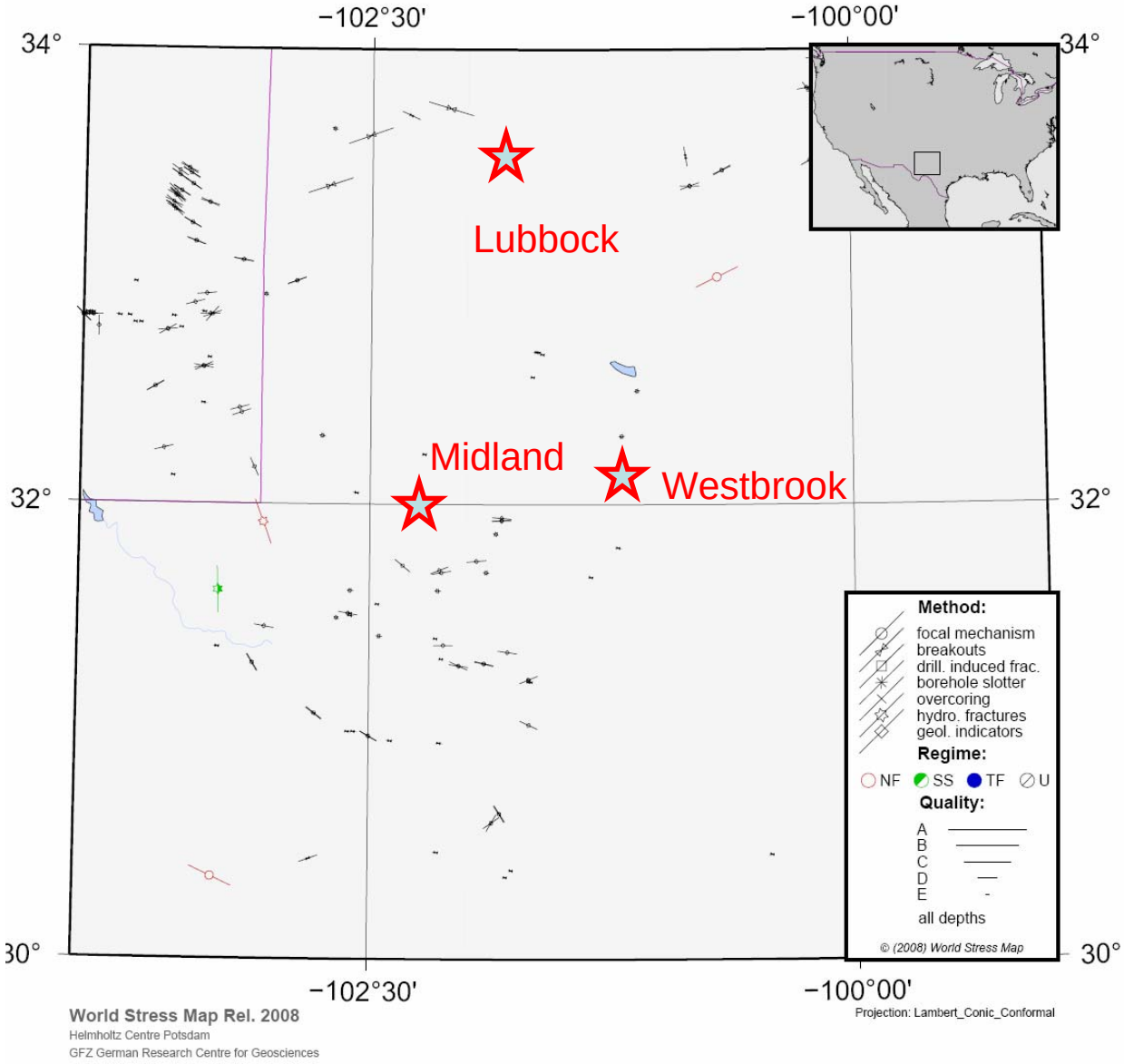
Vertical or Horizontal?



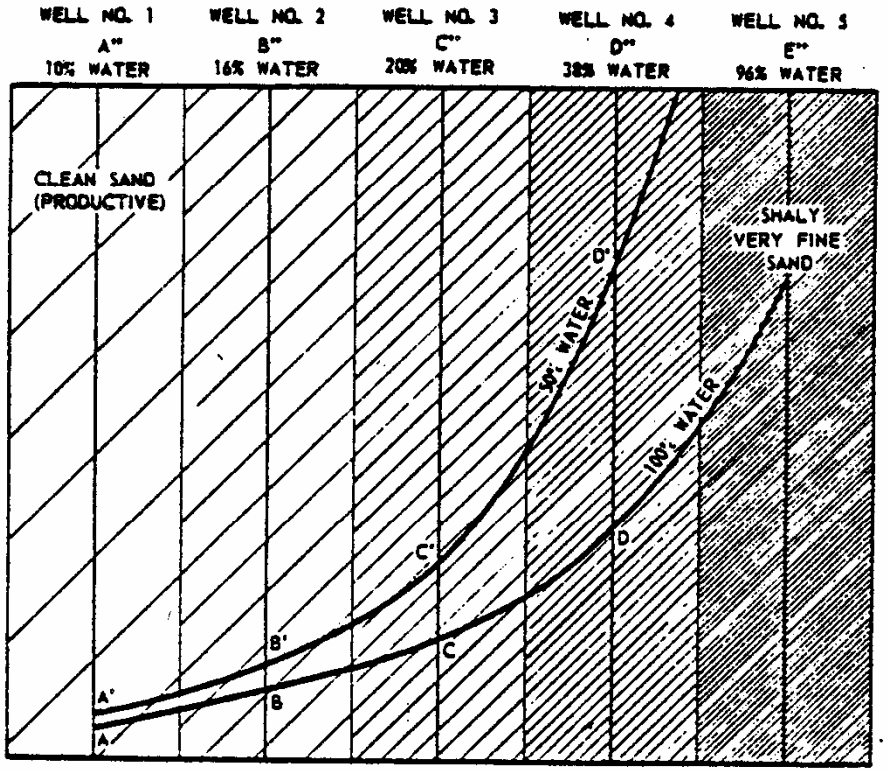
Stress Map of North America



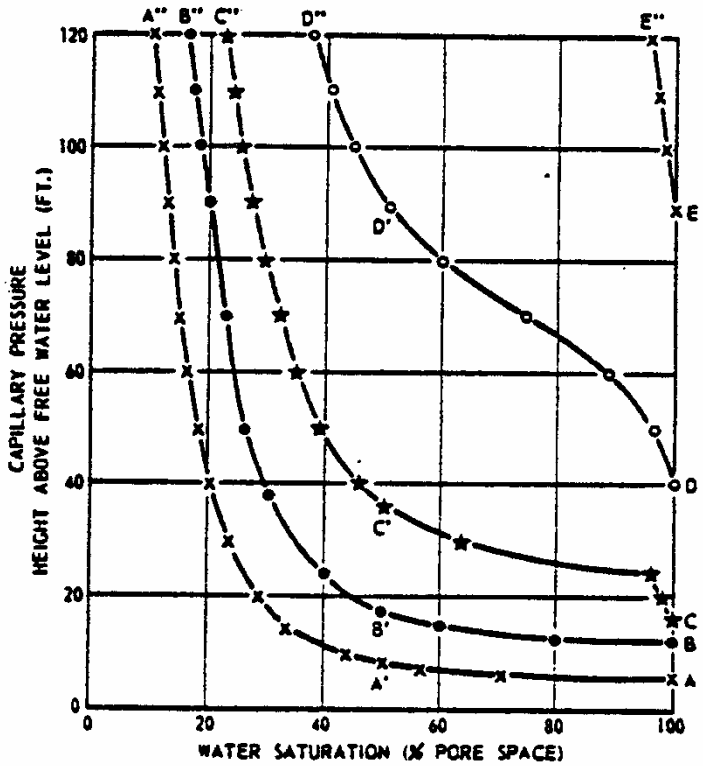
Permian Basin Stress Map



Capillary Pressure Curves

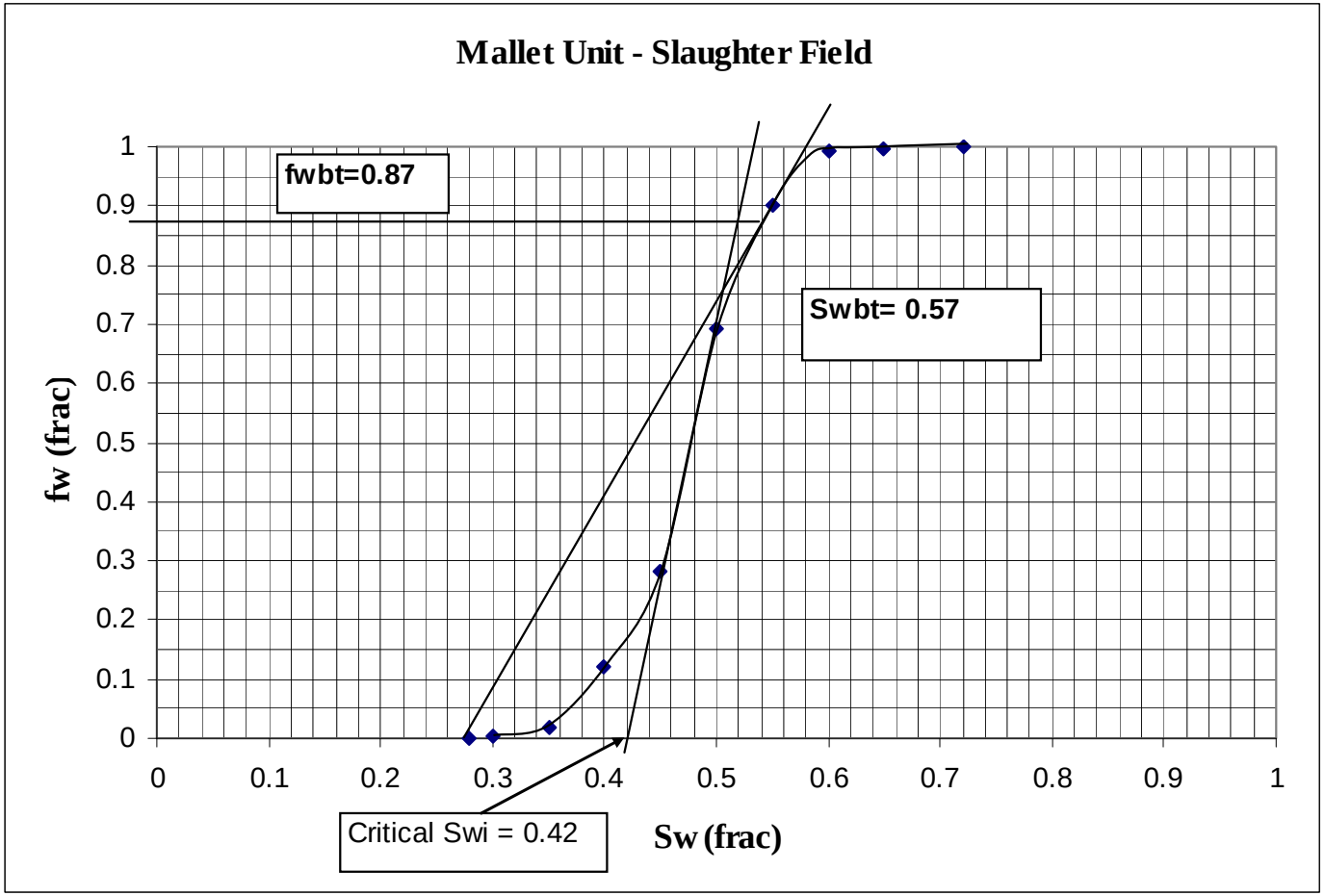


SAMPLE NUMBER	POROSITY (%)	PERM. (MD)
A	21.1	430.0
B	18.8	116.0
C	13.9	13.4
D	12.2	1.2
E	4.6	0.3



FLUID DISTRIBUTION IN A HETEROGENOUS RESERVOIR

Net Pay - Fractional Flow Curve



Texas Tech Christmas Wish List

- West Texas Consortium – TTU's Backyard
  - Study Brownfields of the Permian Basin
  - Catalog and organize data
  - Group waterfloods by geology/reservoir characteristics
  - Collect and catalog stress data
  - Look at failed waterfloods for solutions
- Specific Field Studies
  - Fields studies include all SCA and PVT work
  - MRI tools available
  - Miscibility lab work
- Operational studies
  - Horizontal Drilling, completion, cementing, etc
- A winning football team…….aka BCS Bowl Appearance


BOB L. HERD DEPARTMENT
OF PETROLEUM ENGINEERING