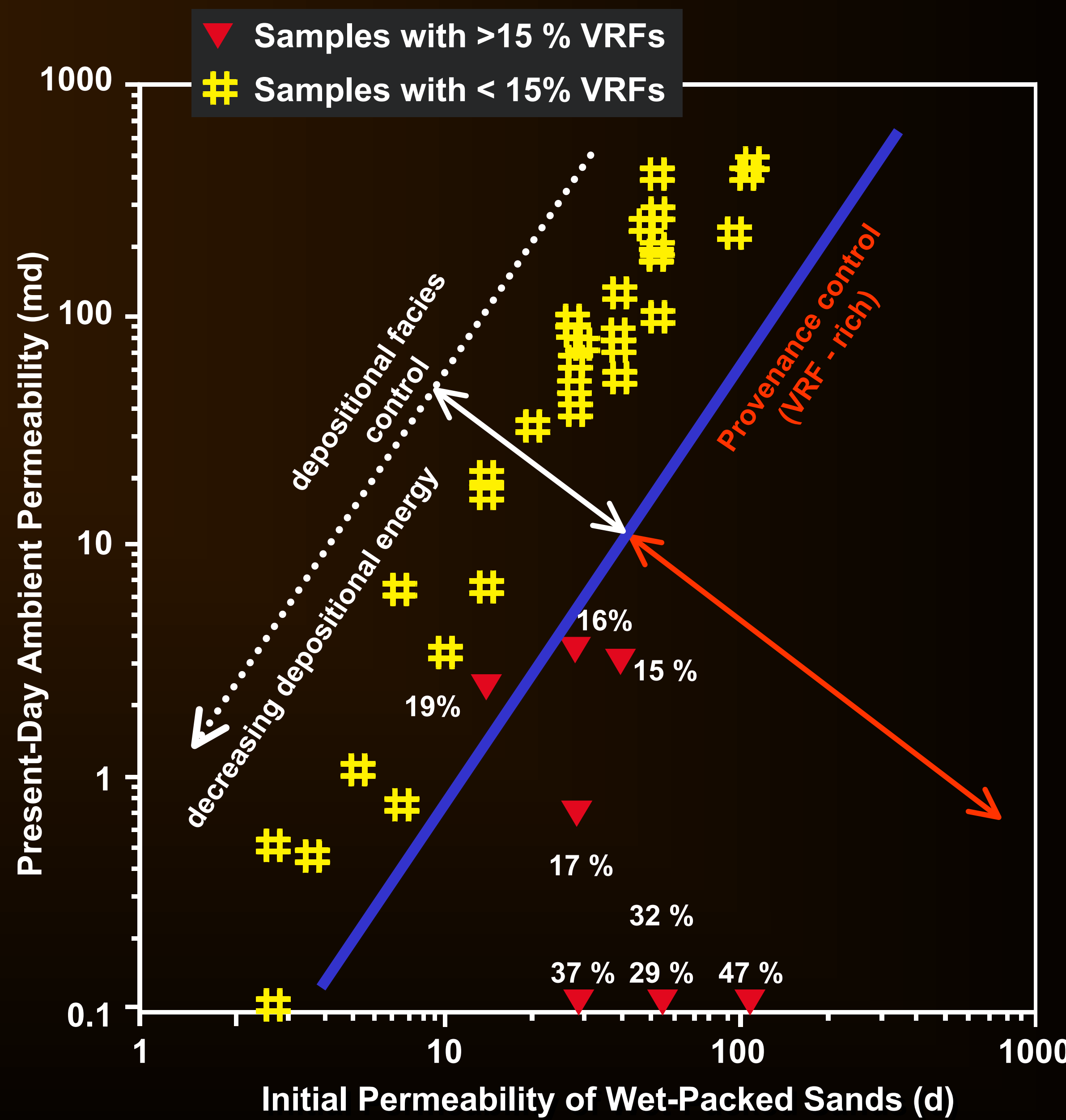
Predrill Assessment of p&p in Frontier and Mature Areas

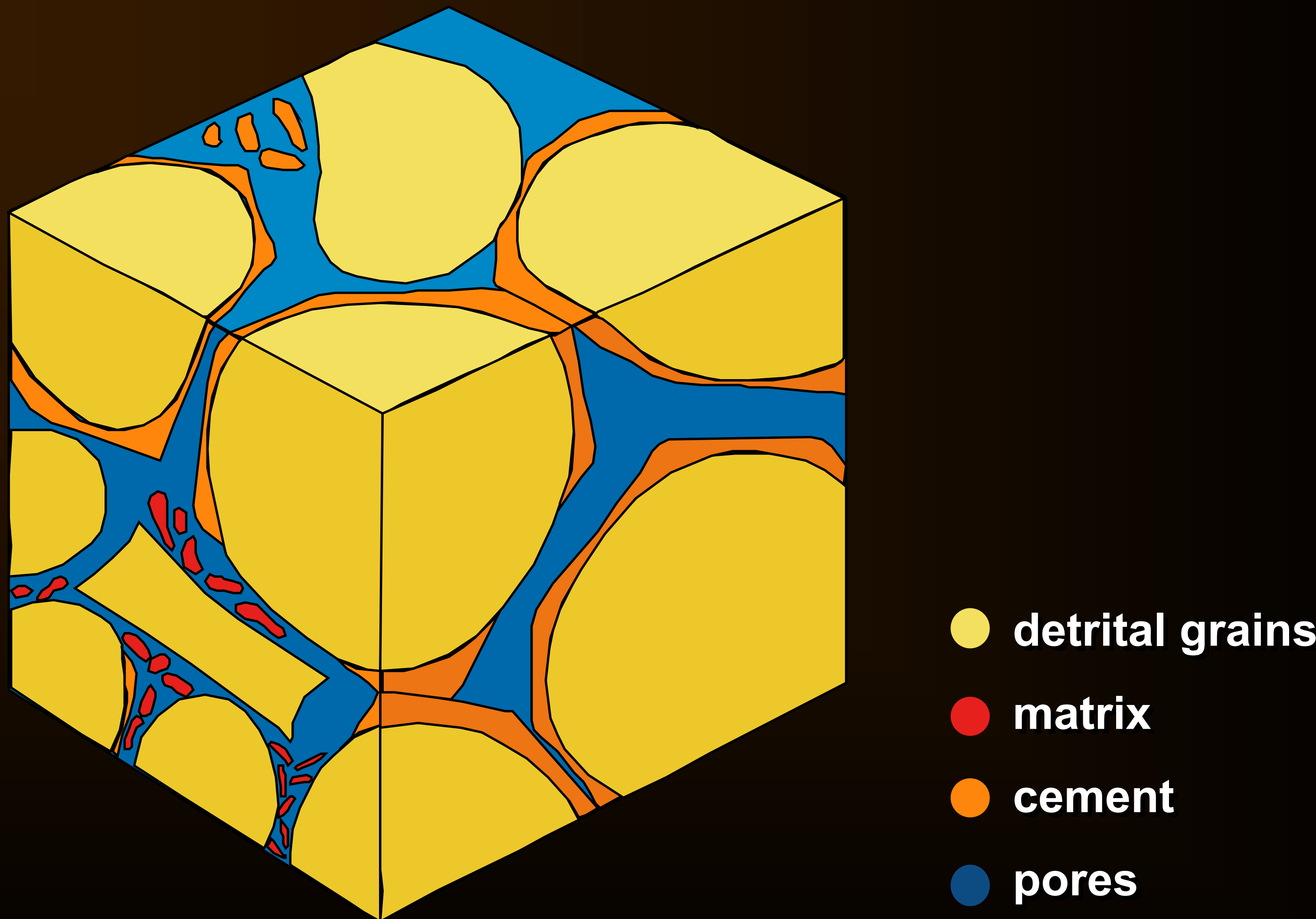
by

S. Bloch

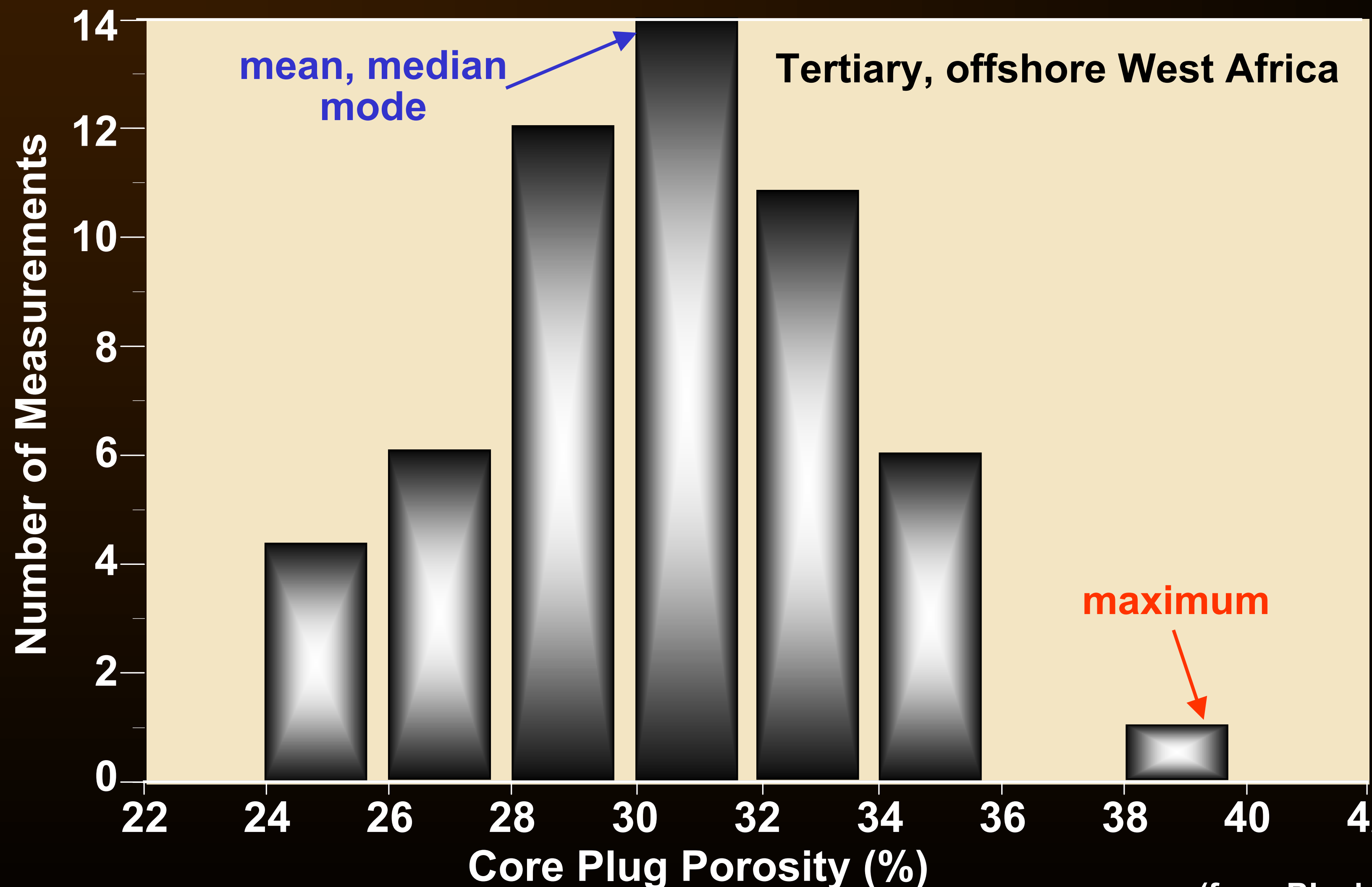


Graphics: P. M. Kay

Volumetric Components of Sandstones

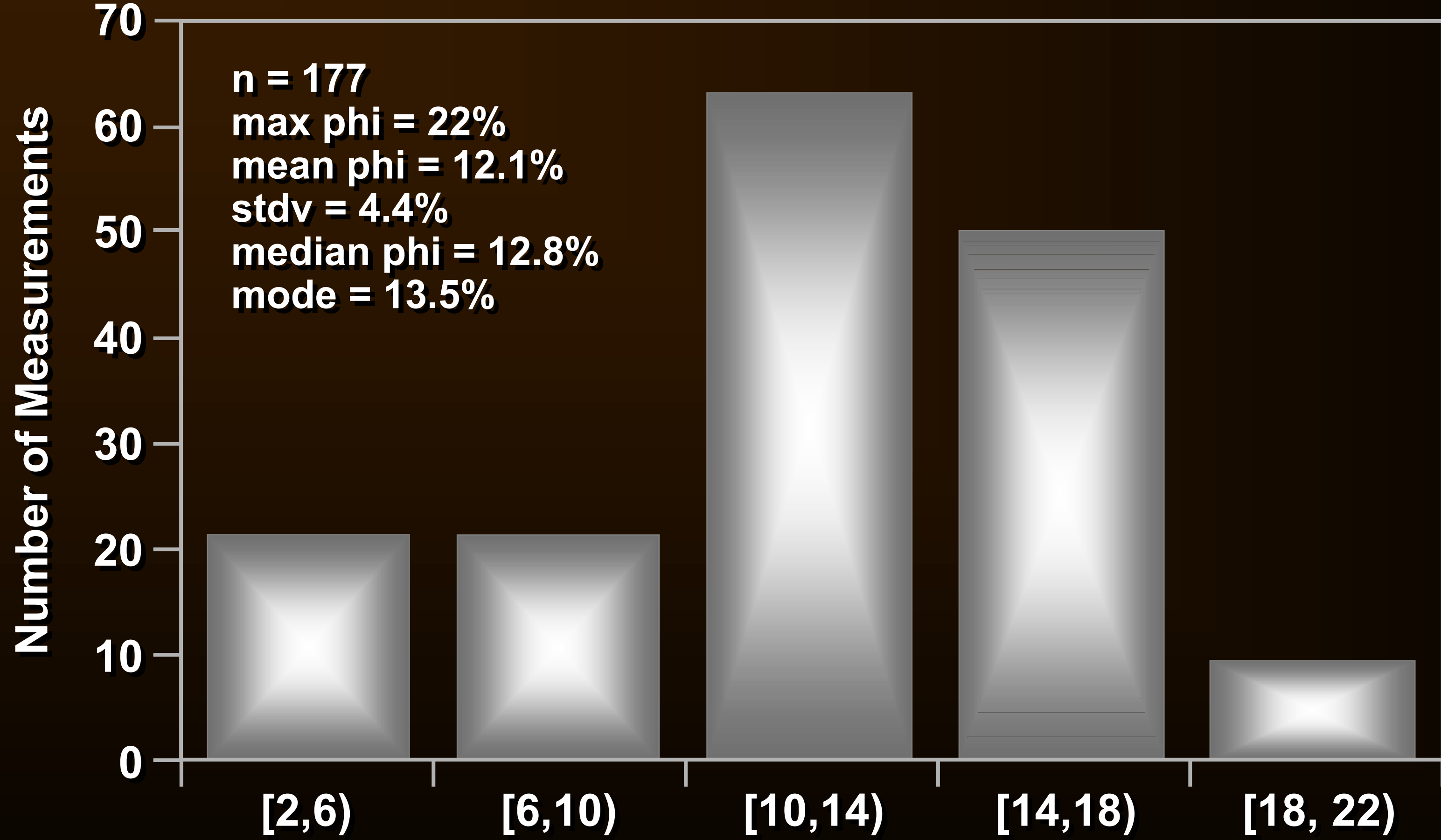


Normal Distribution of Porosity in a Sandstone with a Moderate Diagenetic Imprint

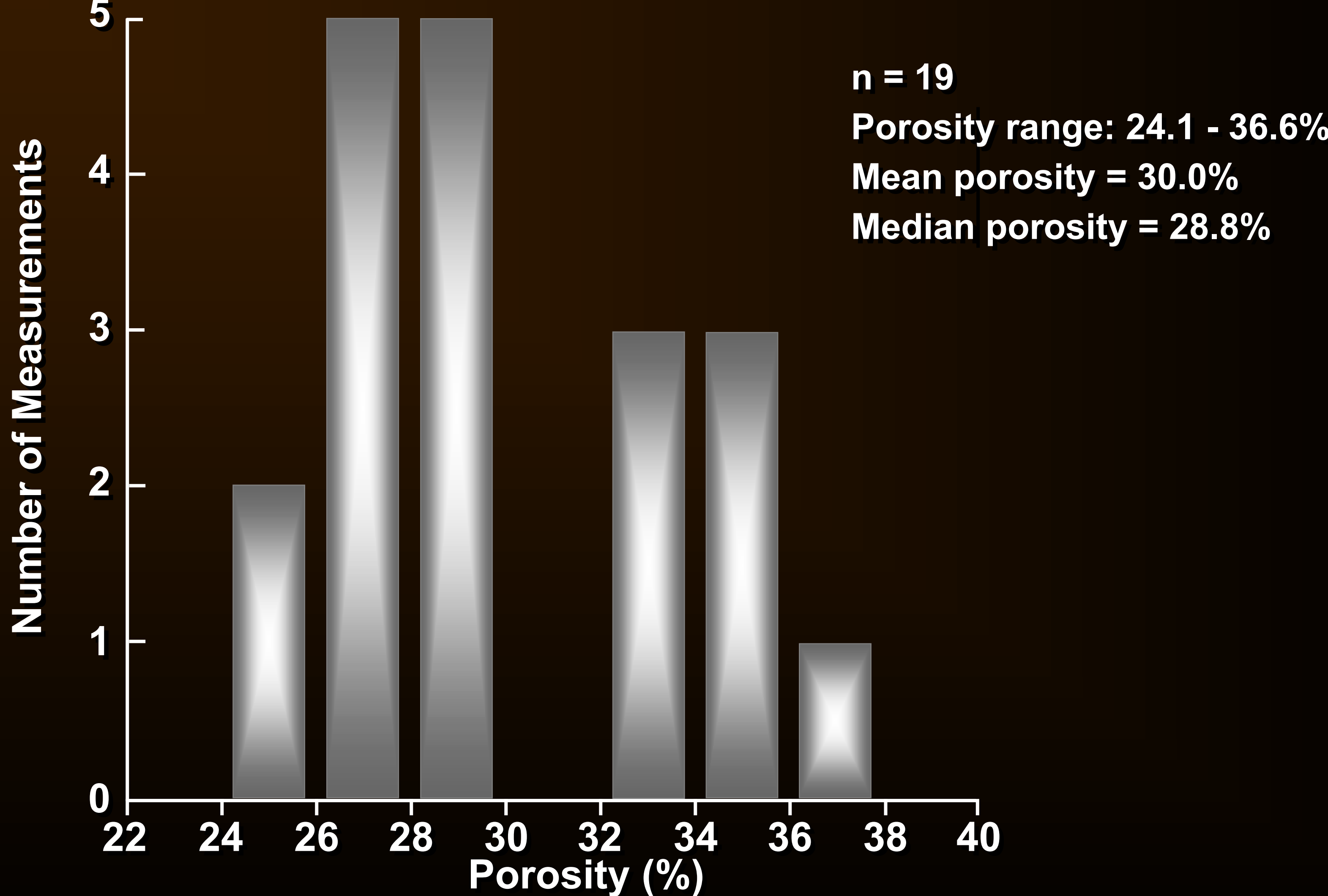


(from Bloch et al., 2002)

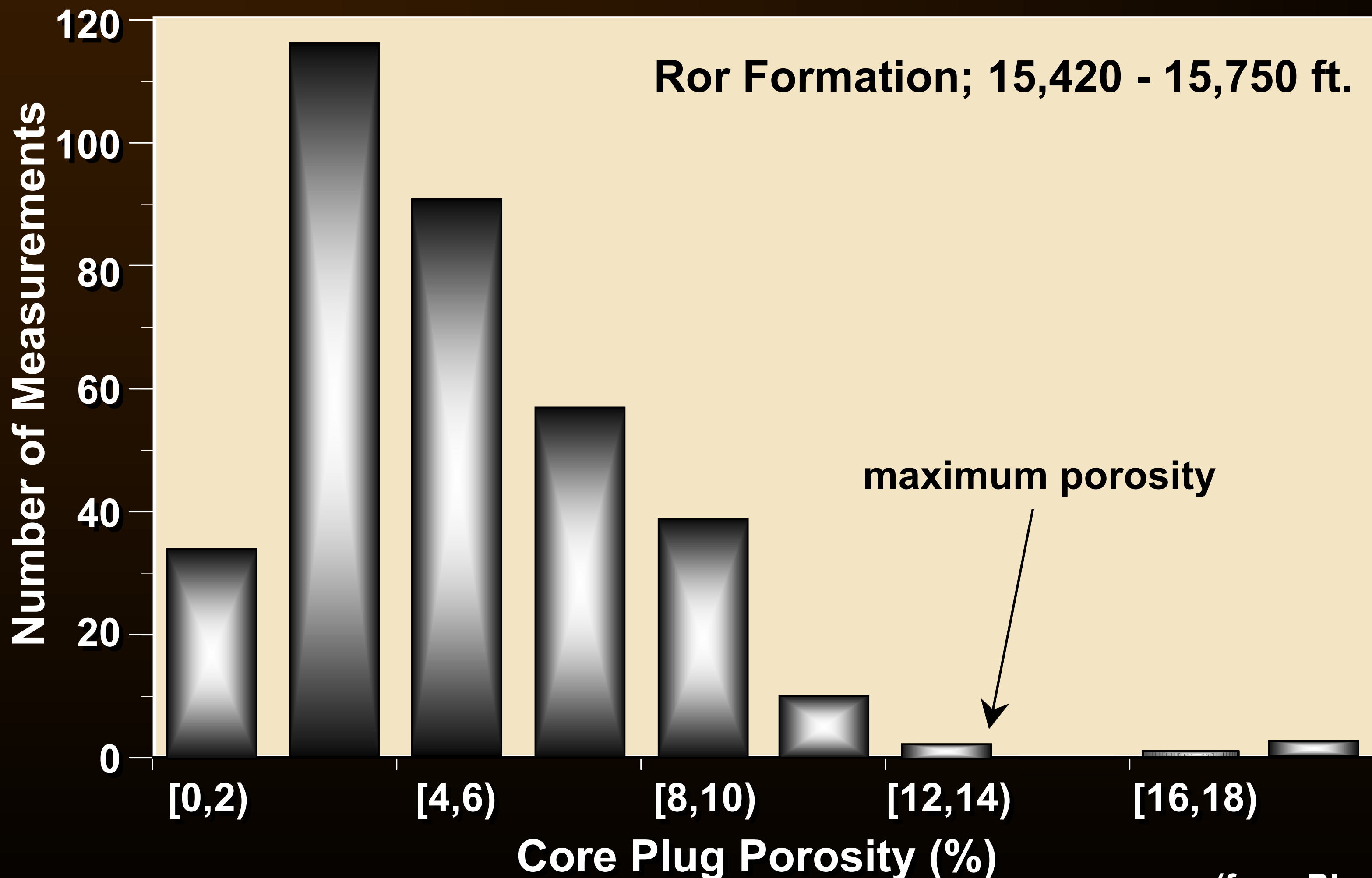
Porosity Distribution in Sampled Intervals of an Oligocene Sandstone, East Asia



Porosity Distribution in an Inadequately Sampled Sand Population

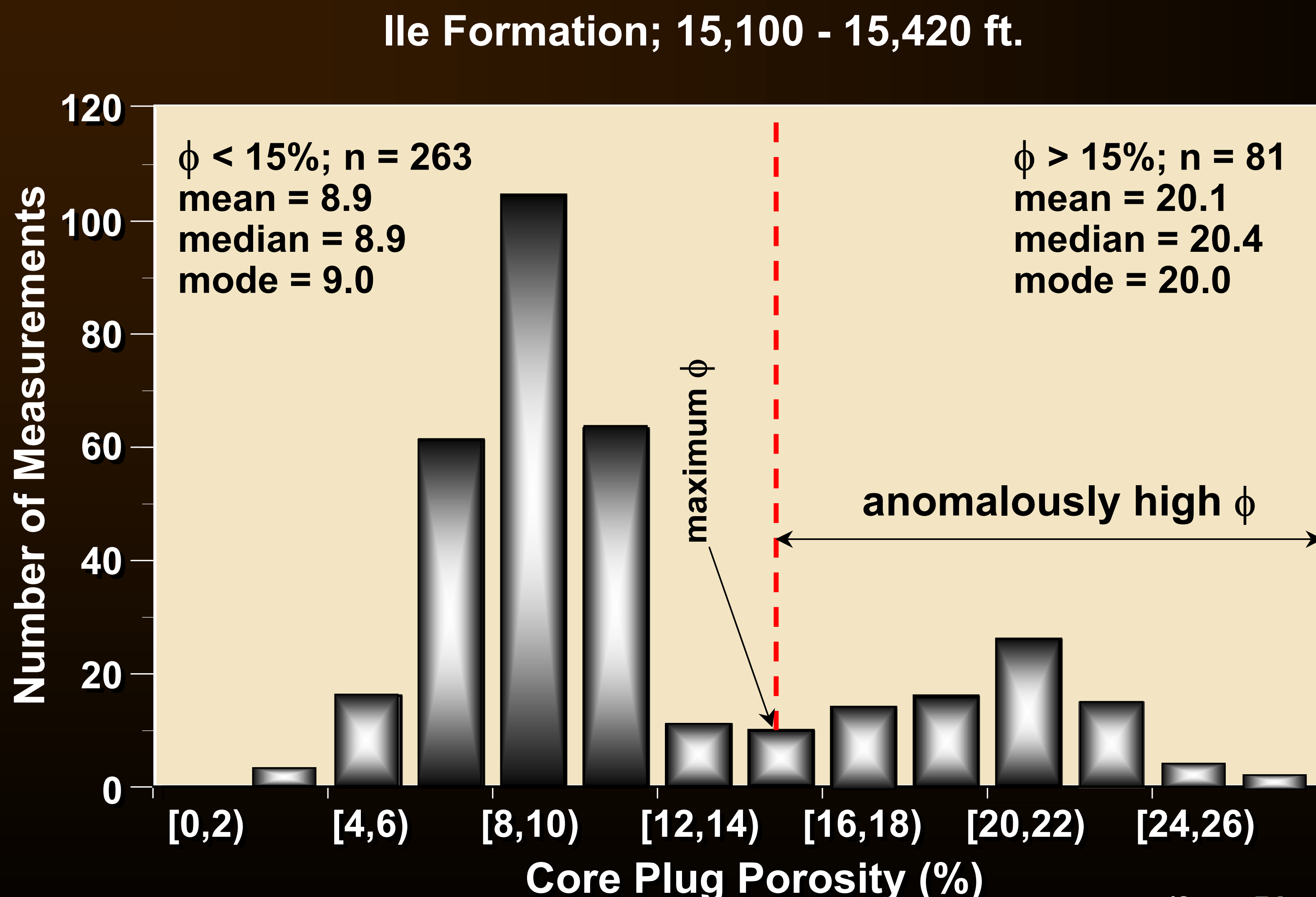


Lognormal Distribution of Porosity in Heavily Cemented Sandstones



(from Bloch et al., 2002)

Bimodal Distribution of Porosity in Chlorite-Coated Sandstones



(from Bloch et al., 2002)

Applications of Porosity & Permeability Prediction

- **Exploration**
  - pre-drill evaluation of resources in potential reservoirs
- **Production**
  - pore volume, hydrocarbon pore volume, recoverable reserves, production rates, well spacing, fluid injection, etc.
- **Reservoir Simulation**
  - "soft" input data
- **Basin Modeling**
  - hydrocarbon migration
  - distribution of hydrocarbon saturation
  - thermal conductivity
- **Interpretation of Seismically Derived Attributes**
  - porosity, lithology, fluid saturation → acoustic impedance

Adequacies of Essential Geologic Controls of Oil & Gas for Plays/Prospects

PLAY_____________________________ _____________________________ PROSPECT

a. ____ TRAP - SEAL - TIMING

Closure Volume
Seal
Timing

b. ____ RESERVOIR - POROSITY - PERMEABILITY

- RESERVOIR FACIES THICKNESS (no nondeposition, facies change, truncation, or faulting; adequate net/gross
- POROSITY (primary or secondary, not plugged or cemented)
- PERMEABILITY & CONTINUITY

c. ____ SOURCE - MATURATION - MIGRATION

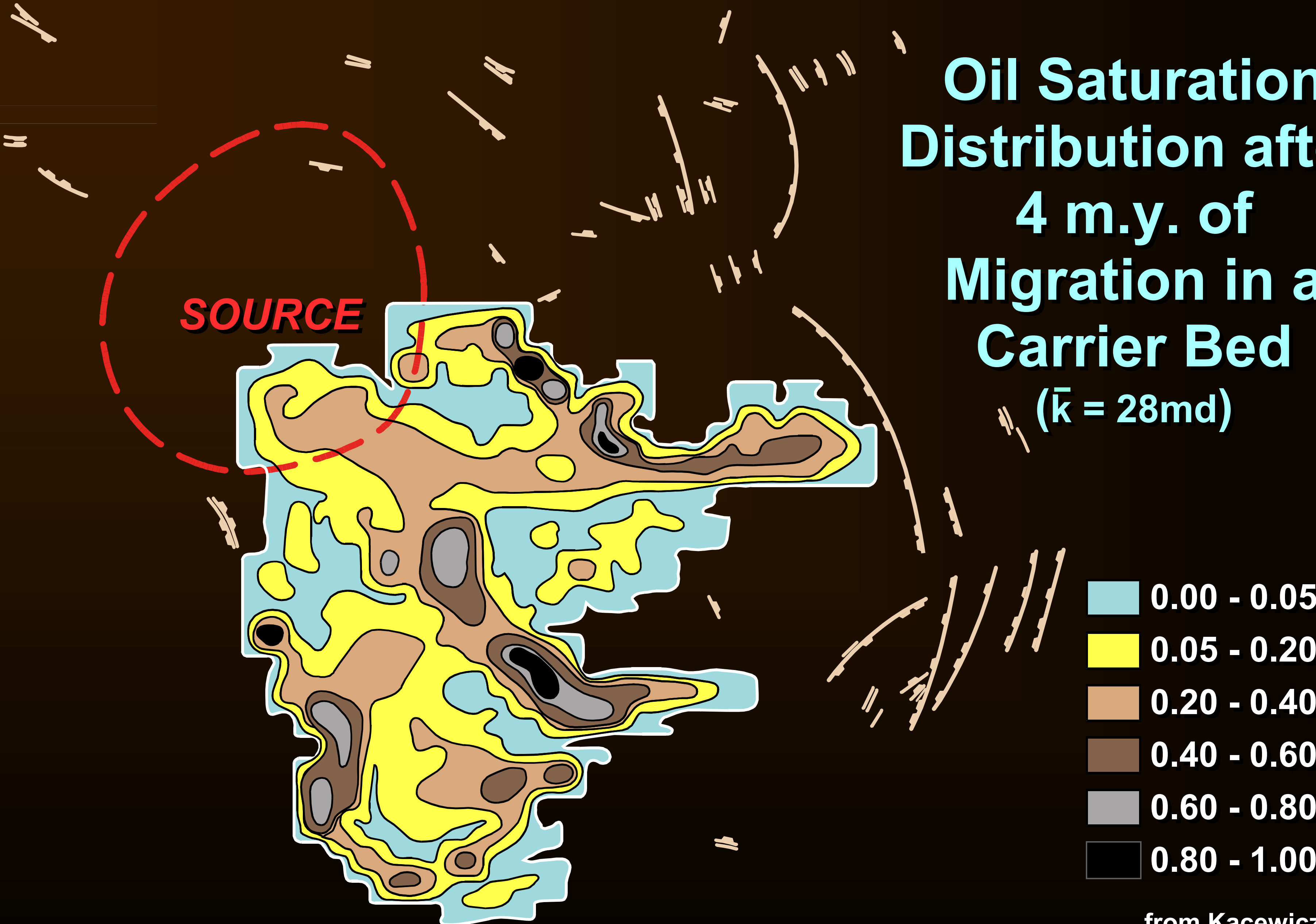
Organic Quantity & Quality
Maturation
Migration

d. ____ PRESERVATION - HC QUALITY - RECOVERY

Preservation
Hydrocarbon Quality & Concentration
Recovery

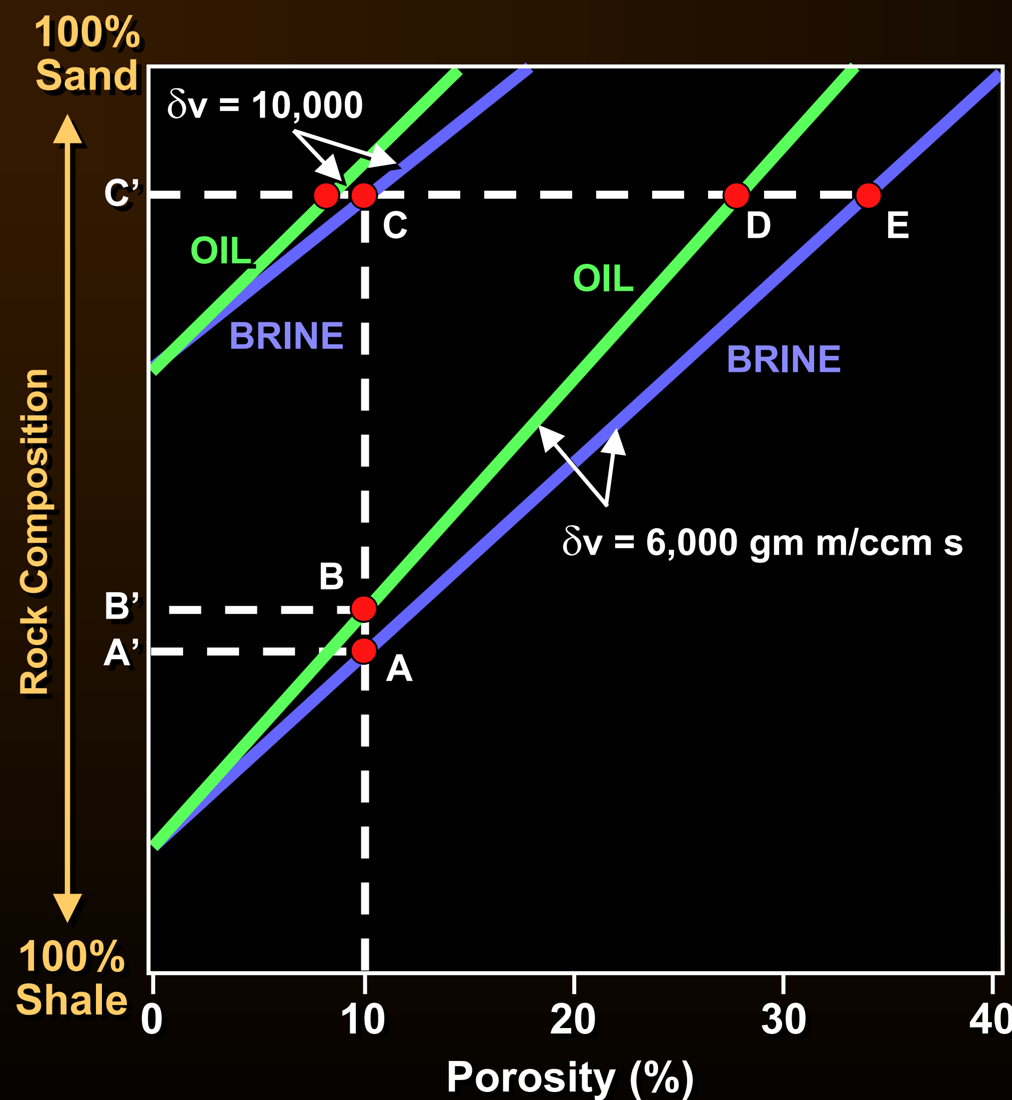
(from White, 1993)

Oil Saturation Distribution after 4 m.y. of Migration in a Carrier Bed
($\bar{k}$ = 28md)



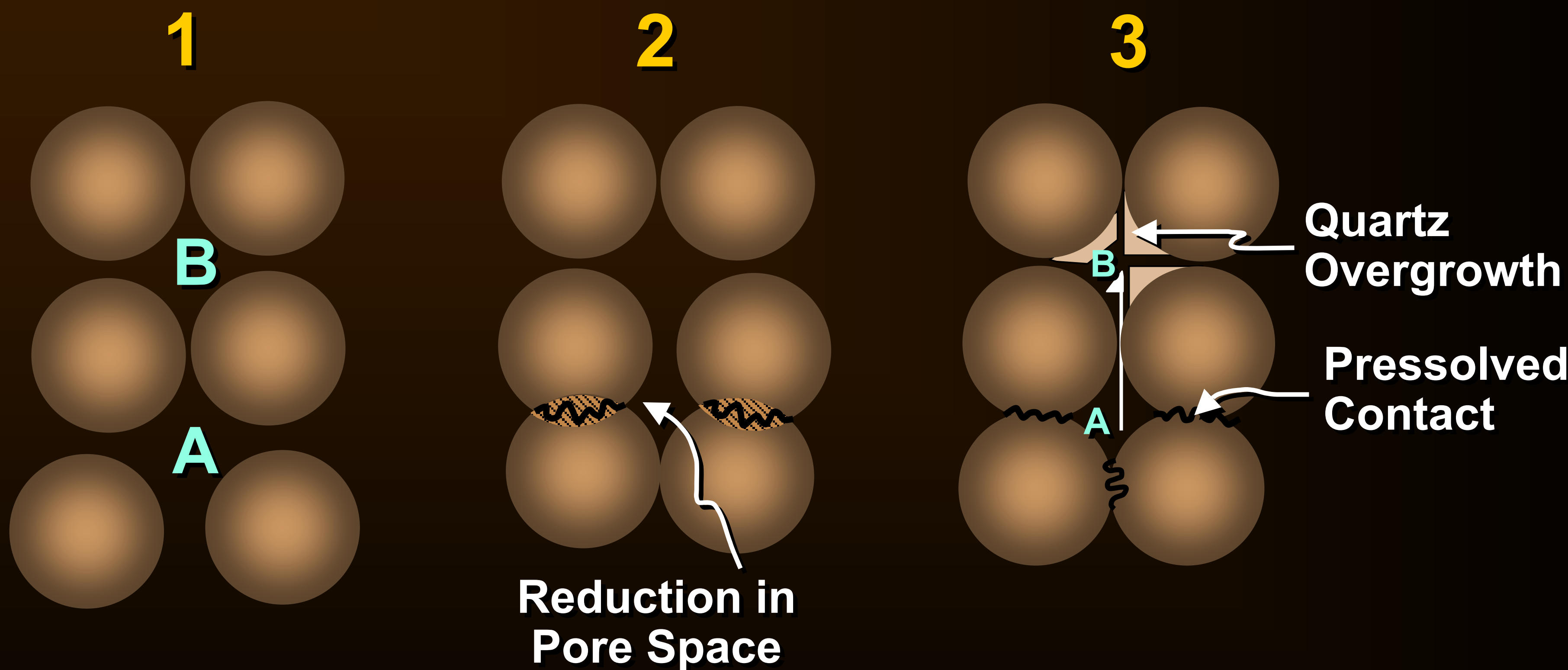
from Kacewicz, 1993

Reservoir Properties (lithology, porosity, pore fluid) vs Acoustic Impedance



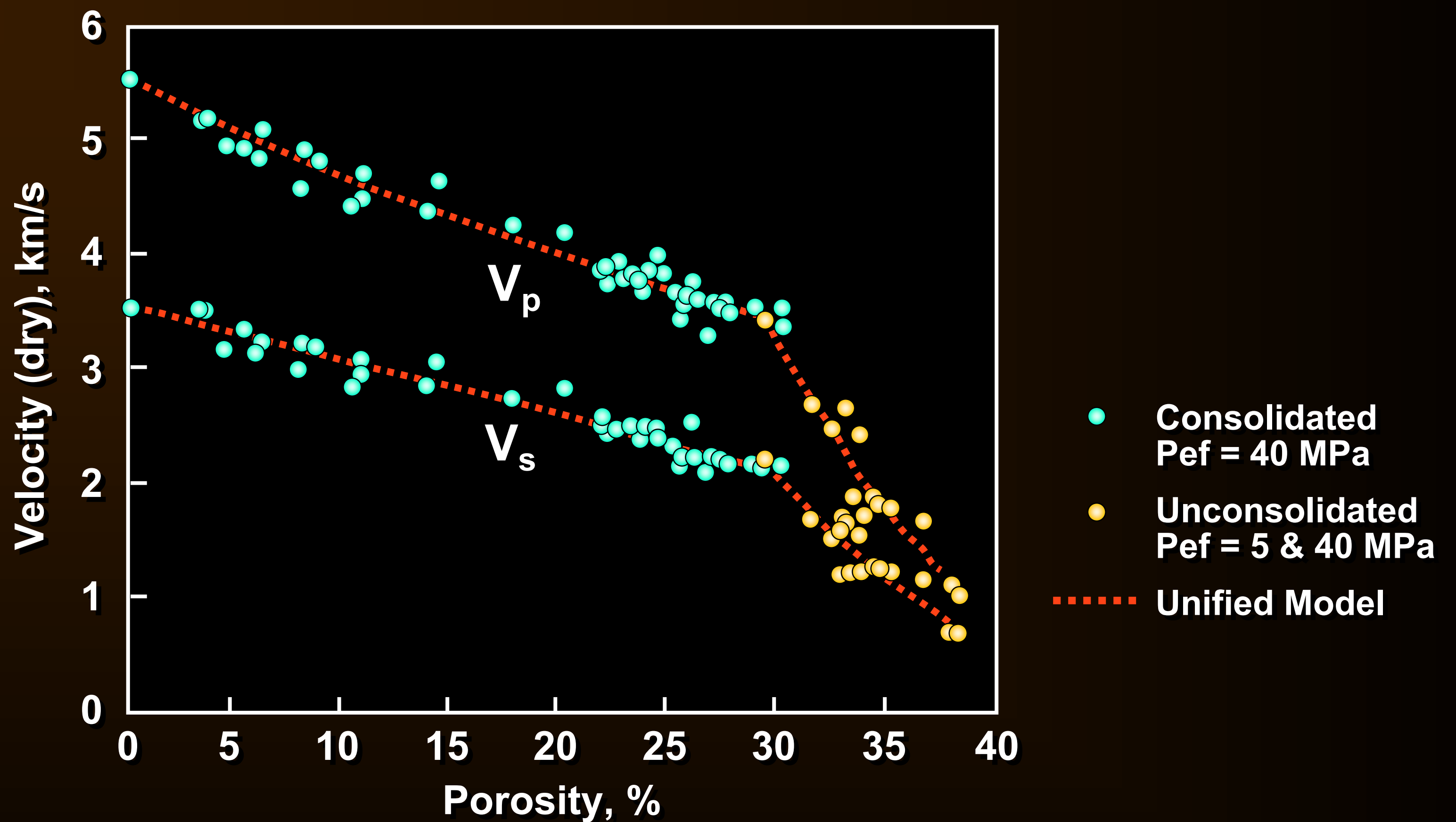
(from Hardage, 1992)

Silica Cementation by Pressure Solution



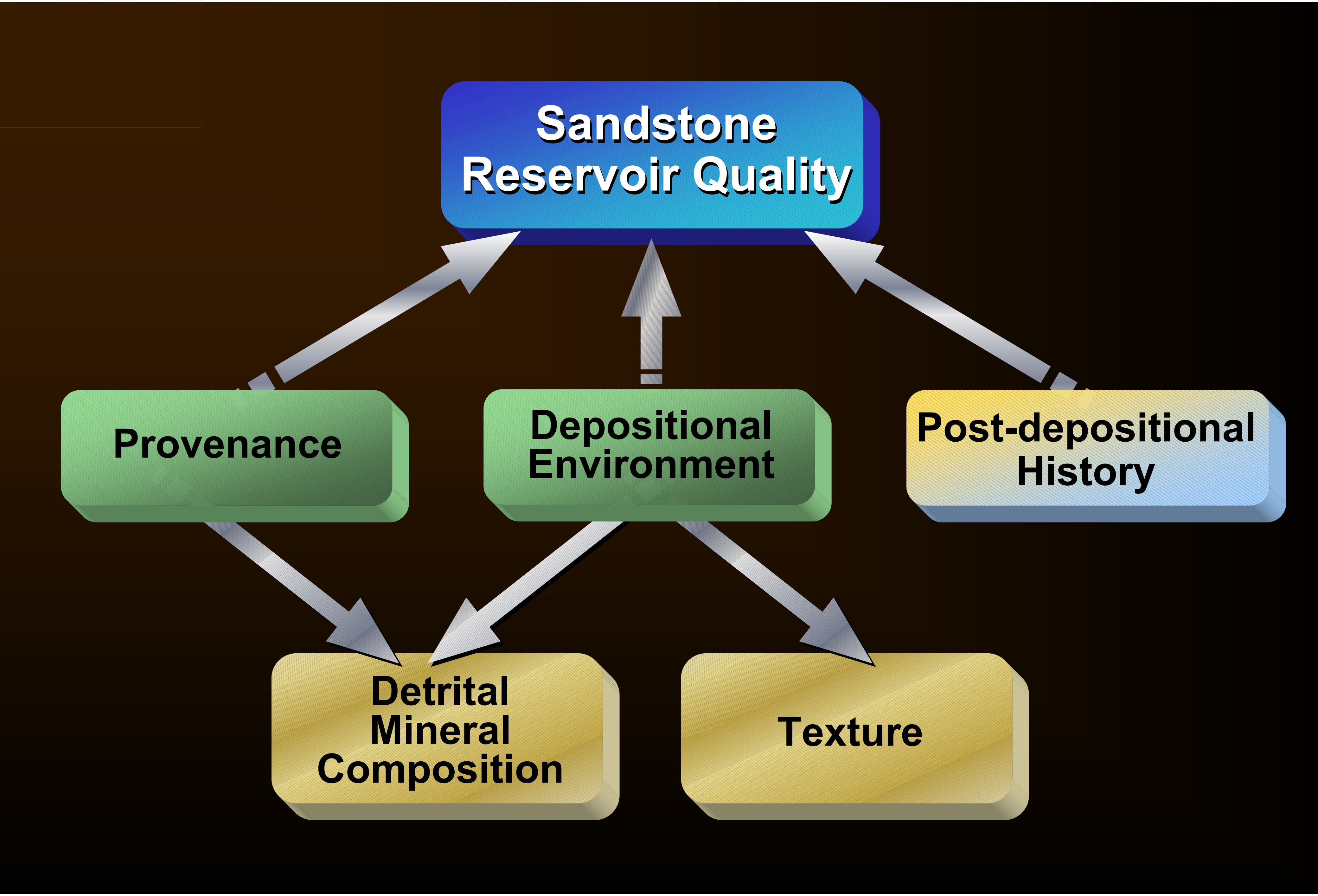
(from Sibley and Blatt, 1976)

Consolidation Porosity vs. V_p and V_s



For moderately well-sorted sands "consolidation porosity" for clean arenites is 30%, and for arenites 29%. Clean arenites have < 2% V_{clay}, arenites have 2% - 12% V_{clay}. The transition from "unconsolidated" to "consolidated" sands (at 30% to 29% porosity) is expressed by pronounced deflections in dry frame P- and S-wave velocities. Fluid substitution modeling indicates a negligible fluid effect on velocity below the consolidation porosity of 29% to 30%.

(Vernik, 1998)


Sandstone
Reservoir Quality
Provenance
Depositional
Environment
Post-depositional
History
Detrital
Mineral
Composition
Texture

Requirements for Adequate Predictions

1. High predictive accuracy should be achieved from a limited number of geological input parameters

2. Input parameters should be simple enough to be estimated from available geological information with reasonable confidence

3. Prediction should be based on multiple techniques

Porosity of Artificially Mixed Sand

SIZE → / ↓ SORTING	COARSE		MEDIUM		FINE		VERY FINE	
	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
EXTREMELY WELL SORTED	43.1	42.8	41.7	41.3	41.3	43.5	42.3	43.0
VERY WELL SORTED	40.8	41.5	40.2	40.2	39.8	40.8	41.2	41.8
WELL SORTED	38.0	38.4	38.1	38.8	39.1	39.7	40.2	39.8
MODERATELY SORTED	32.4	33.3	34.2	34.9	33.9	34.3	35.6	33.1
POORLY SORTED	27.1	29.8	31.5	31.3	30.4	31.0	30.5	34.2
VERY POORLY SORTED	28.6	25.2	25.8	23.4	28.5	29.0	30.1	32.6

(from Beard and Weyl, 1973)

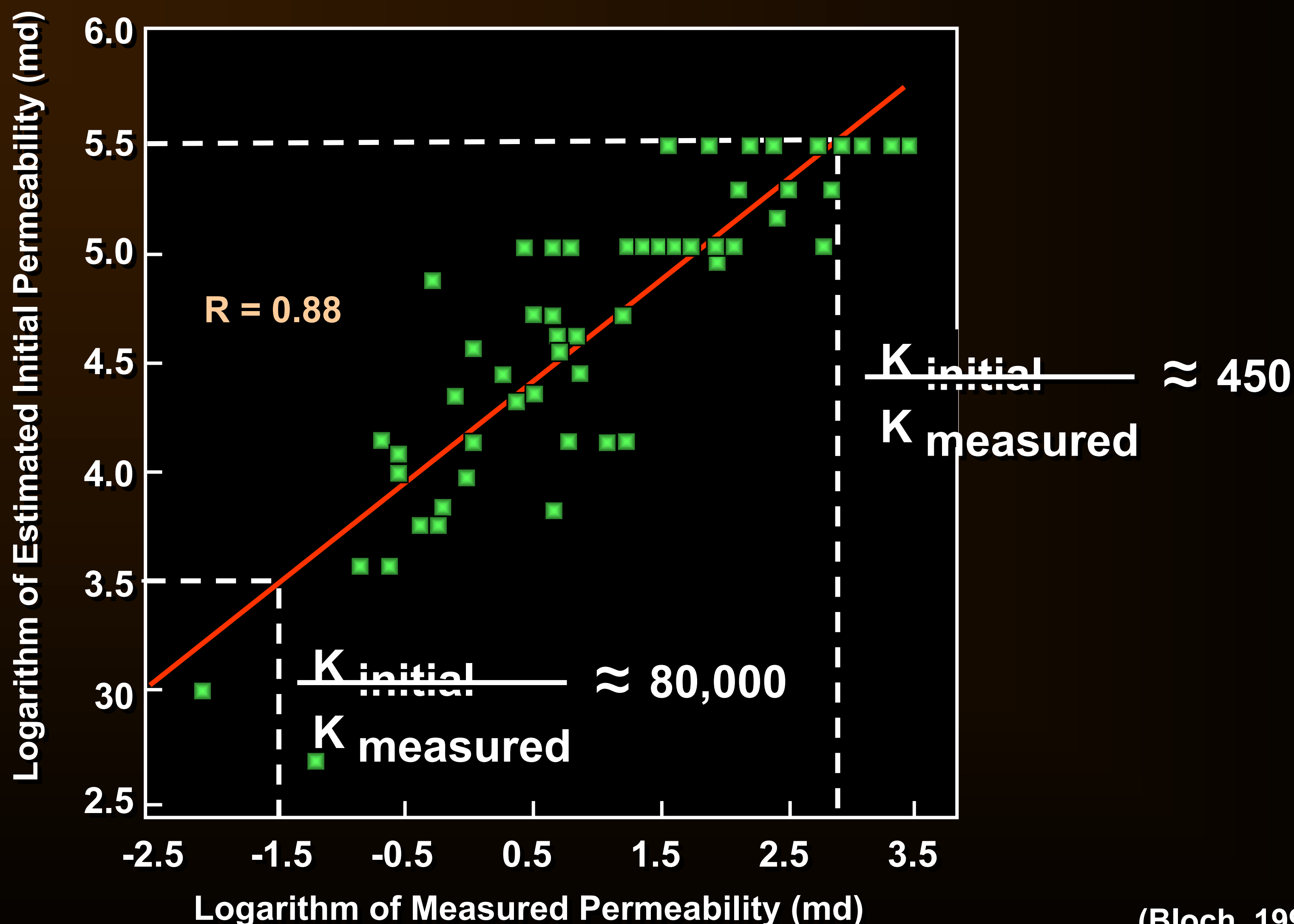
Average Permeability (Darcys) of Artificially Mixed, Wet-Packed Sand

SIZE →	COARSE		MEDIUM		FINE		VERY FINE	
↓ SORTING	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
EXTREMELY WELL SORTED	475	238	119	59	30	15	7.4	3.7
VERY WELL SORTED	458	239	115	57	29	14	7.2	3.6
WELL SORTED	302	151	76	38	19	9.4	4.7	2.4
MODERATELY SORTED	110	55	28	14	7.0	3.5	2.1*	1.1*
POORLY SORTED	45	23	12	6.0	3.7*	1.9*	0.93*	0.46*
VERY POORLY SORTED	14	7.0	3.5	1.7*	0.83*	0.42*	0.21*	0.10*

* from formula of Krumbein & Monk (1942)

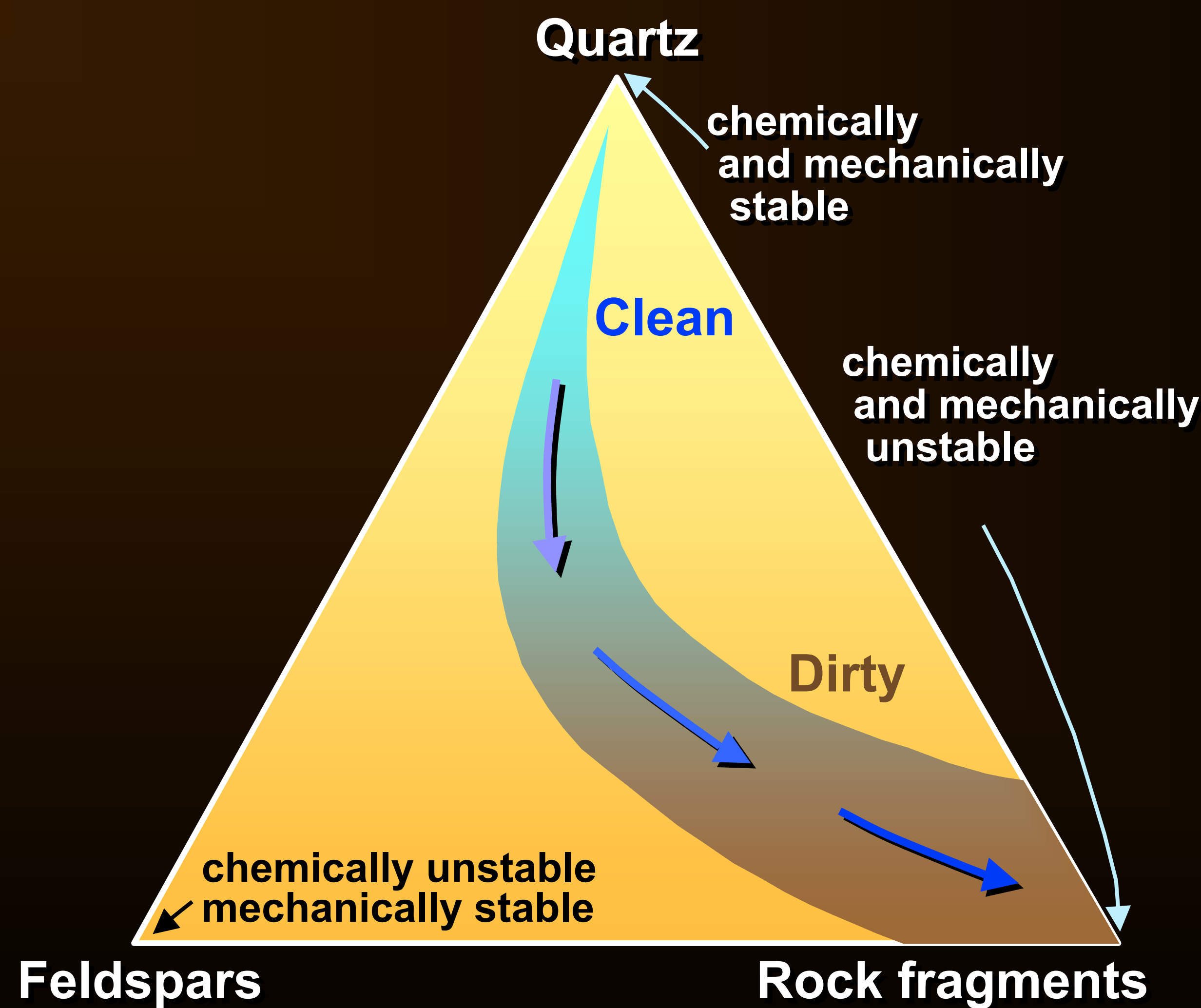
(from Beard and Weyl, 1973)

Measured Permeability Correlates Well with Estimated Initial Permeability, Yacheng Field



(Bloch, 1991)

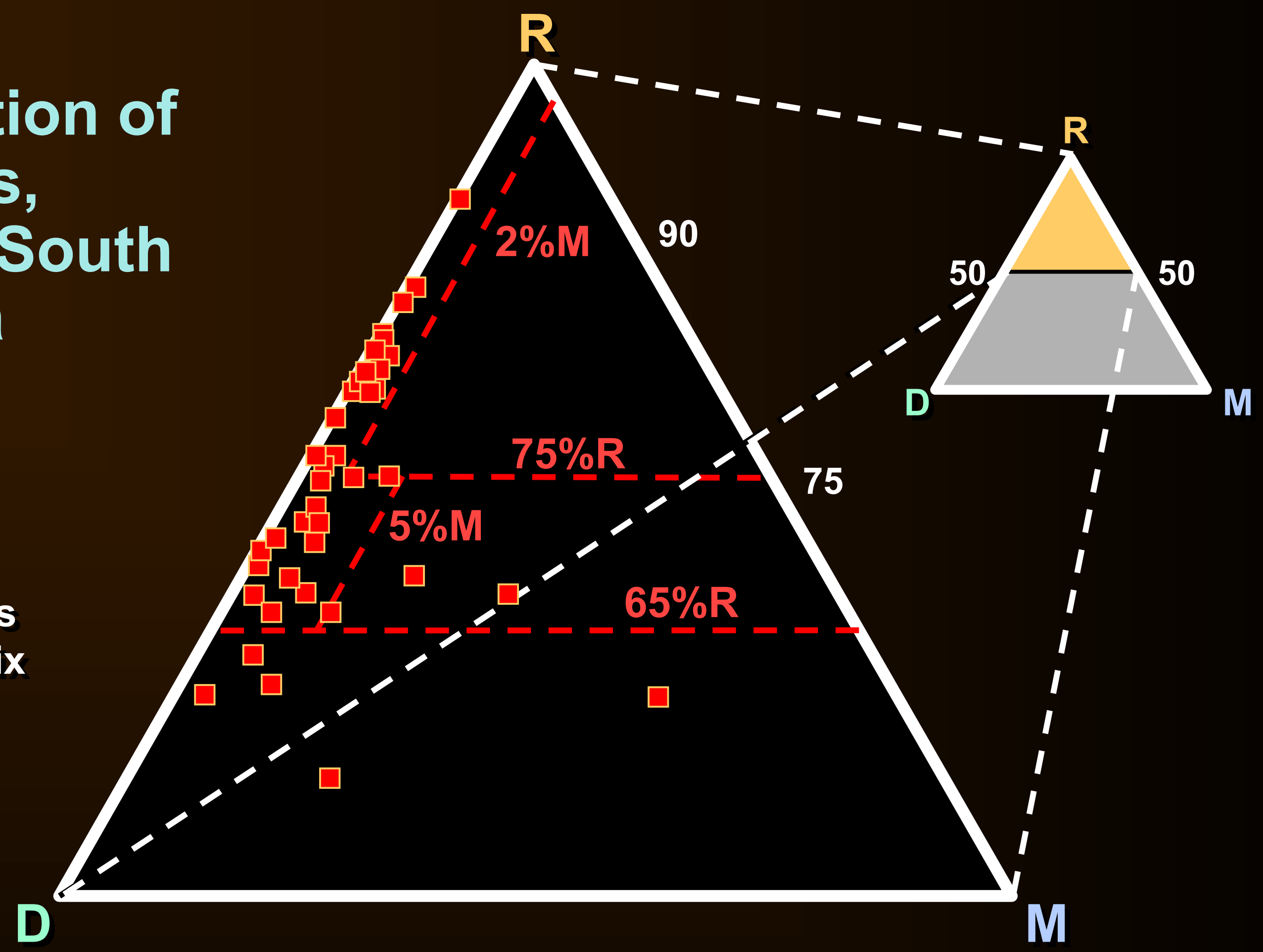
Compositional Controls on Diagenesis



(from Hayes, 1979)

RDM Classification of Sandstones, Yacheng Field, South China Sea

R = rigid grains
D = ductile grains
M = detrital matrix

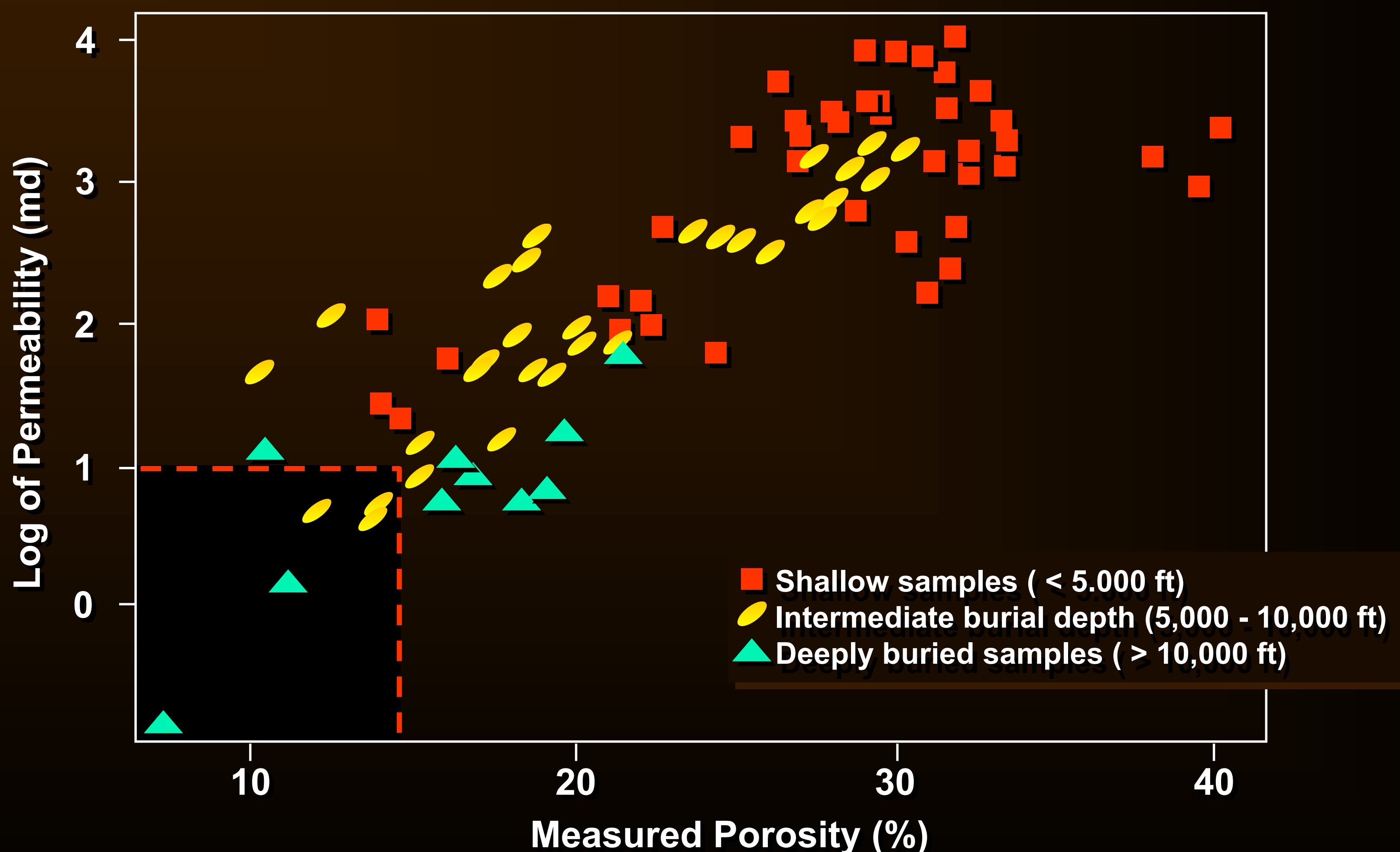


upper medium and coarser grained ss (median diameter > 0.36 mm)

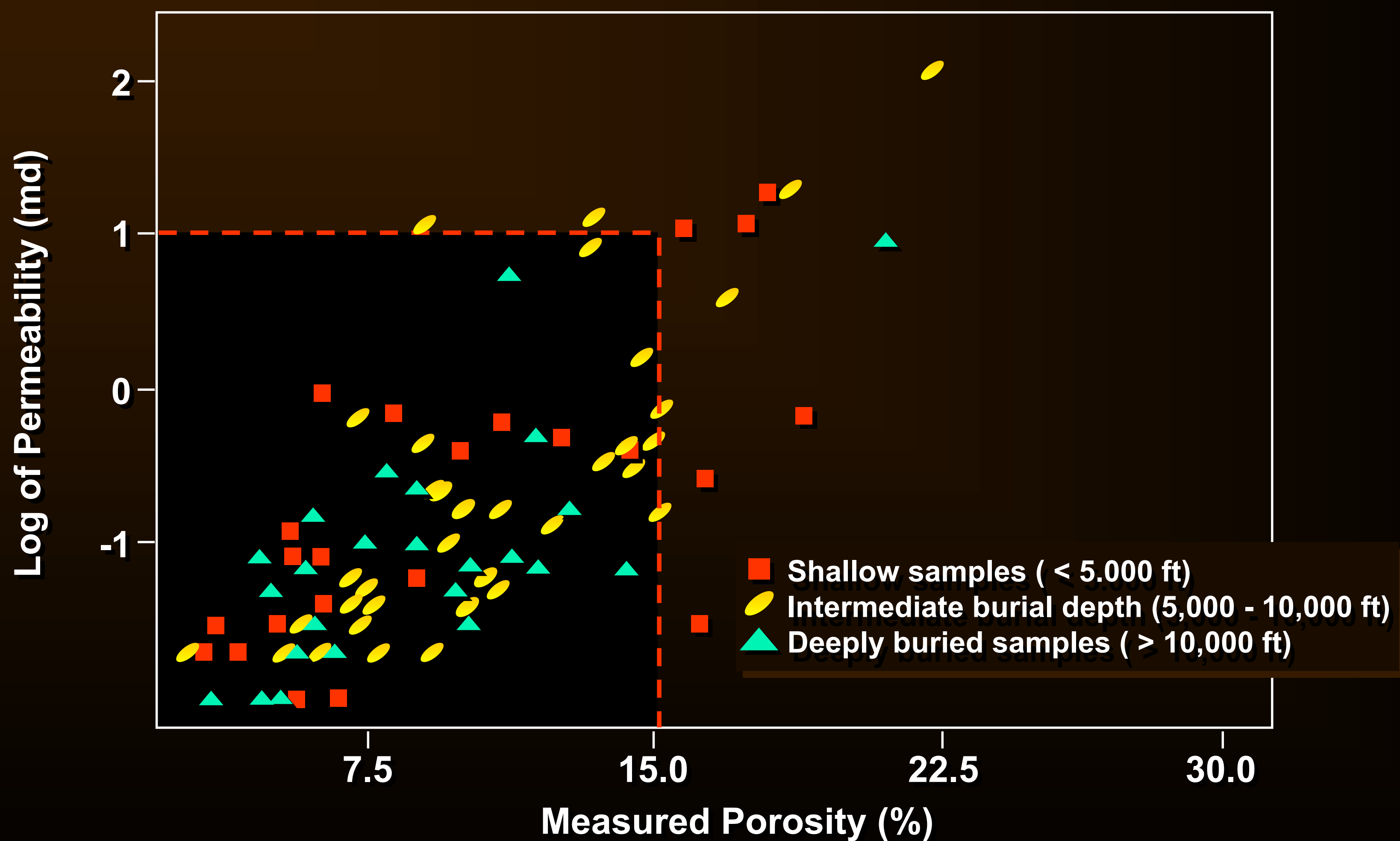
R > 75% and M < 2% ⟶ k > 100 md (a few exceptions)
75% > R > 65% and M < 5% ⟶ k < 100 md (a few exceptions)
R < 65% ⟶ k < 1 md (a few exceptions)

(Bloch, 1991)

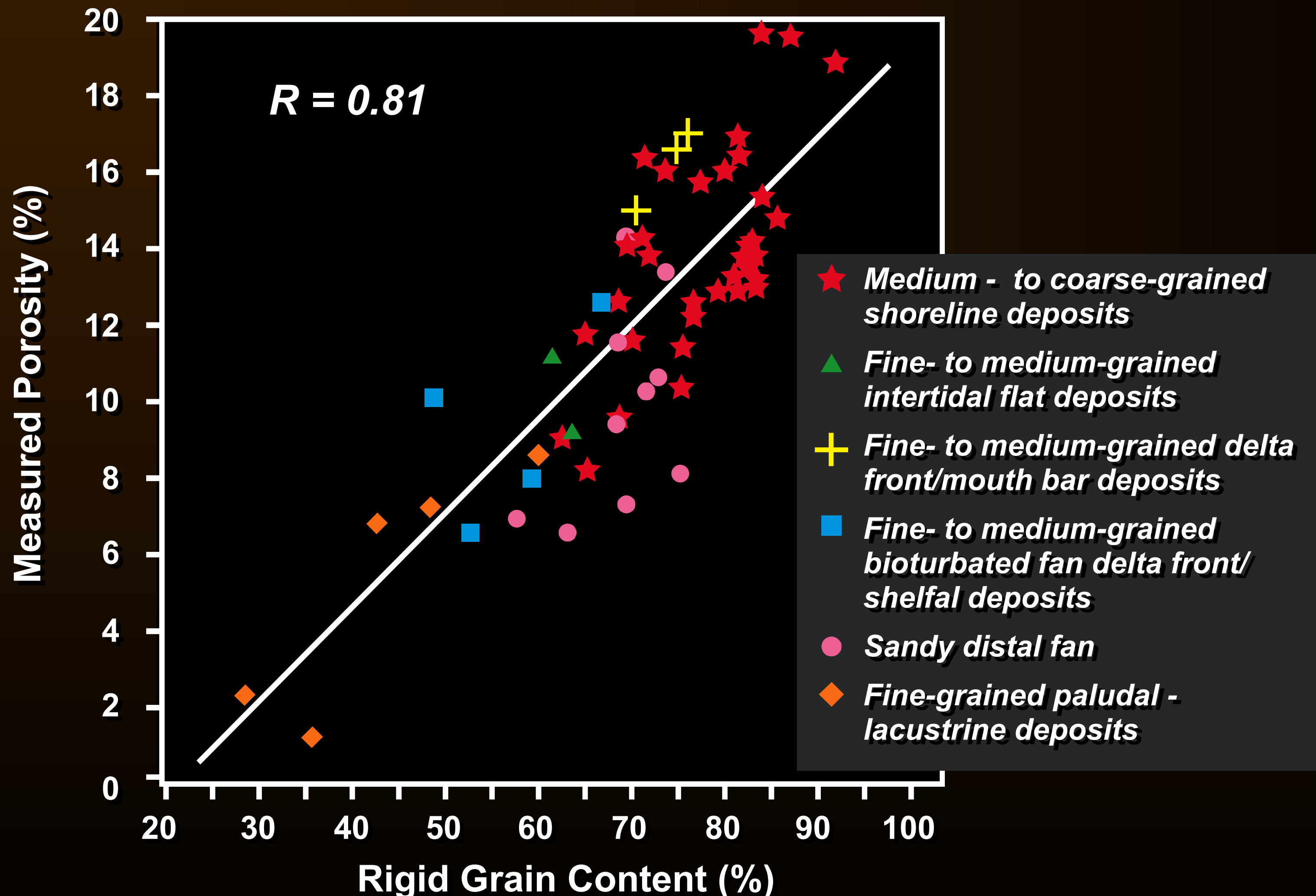
Weakly-cemented (<10% cement) sandstones with a rigid grain content >85% generally have high porosity and permeability



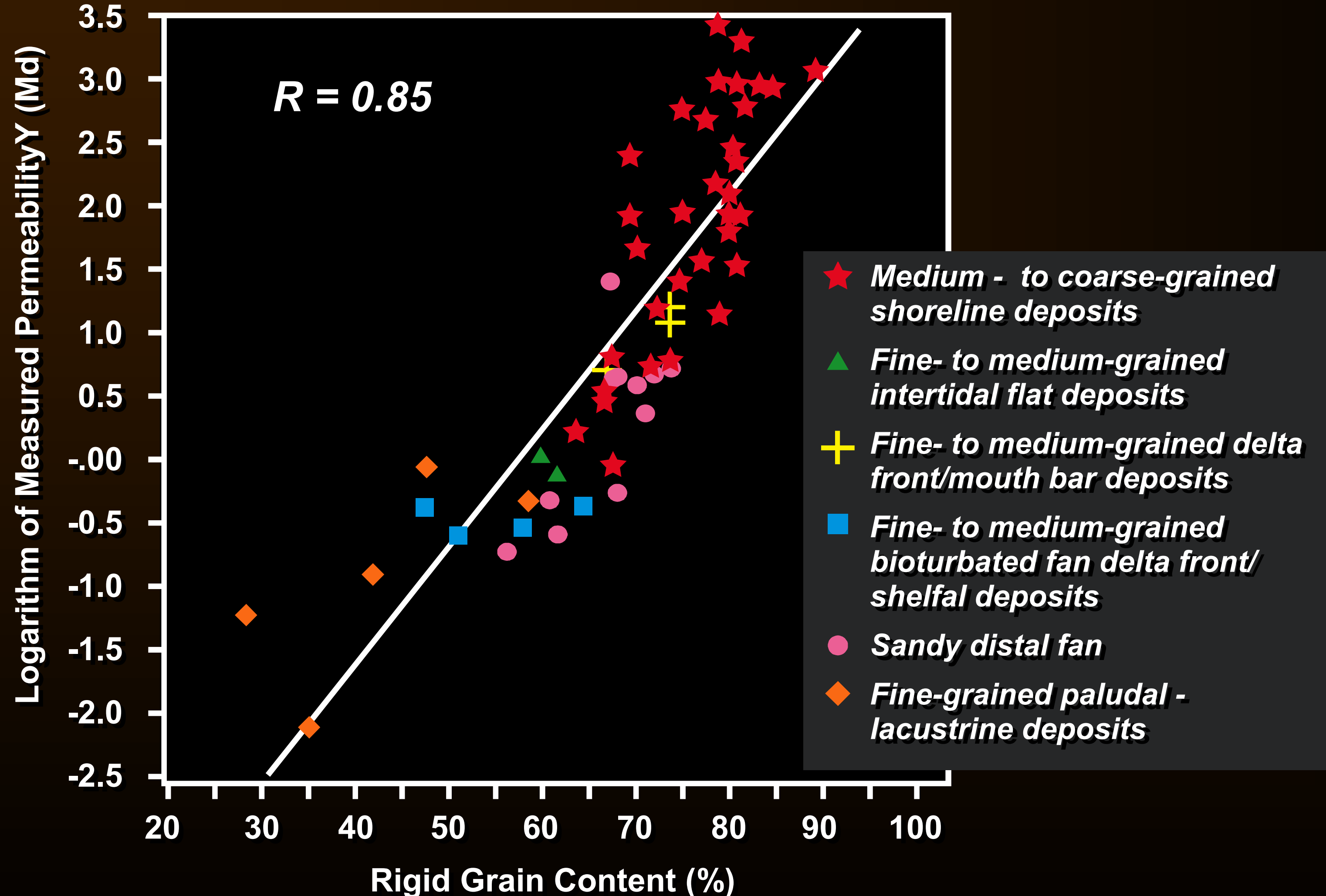
Weakly-cemented (<10% cement) sandstones with a rigid grain content <70% have low porosity and permeability



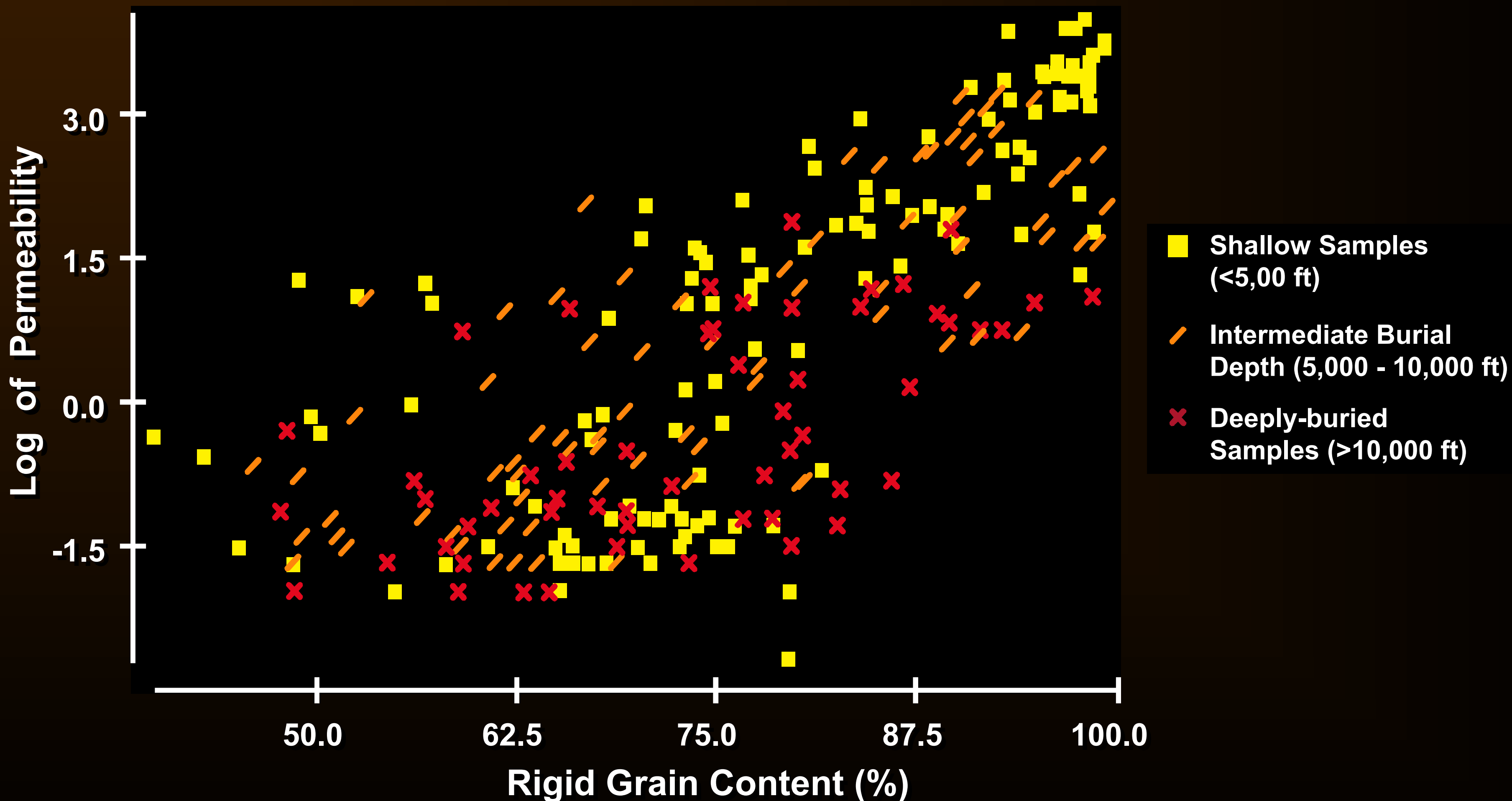
Measured Porosity Correlates Well with Rigid Grain Content



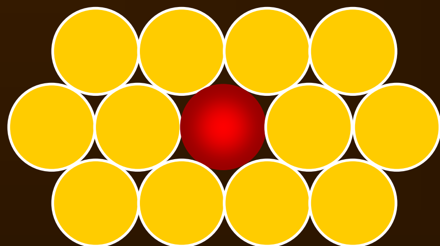
Measured Permeability Correlates Well with Rigid Grain Content



Permeability in weakly-cemented samples (<10% cement) correlates well with detrital composition (rigid grain content)

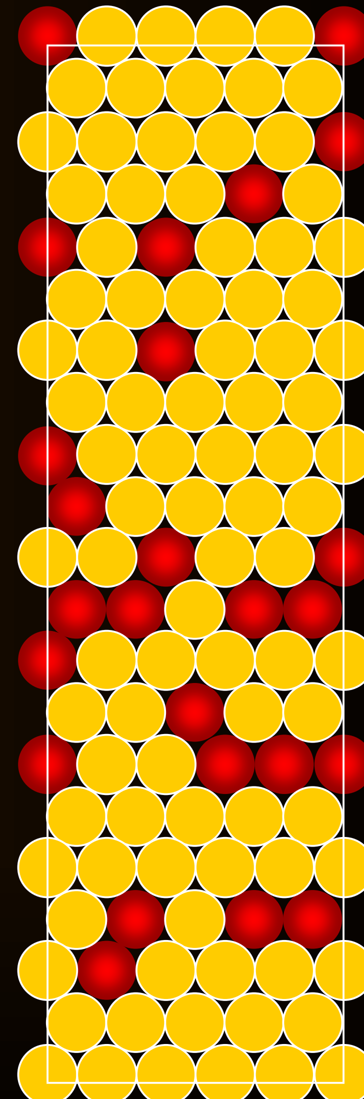


Compaction of Ductile Grains is a Function of Sorting



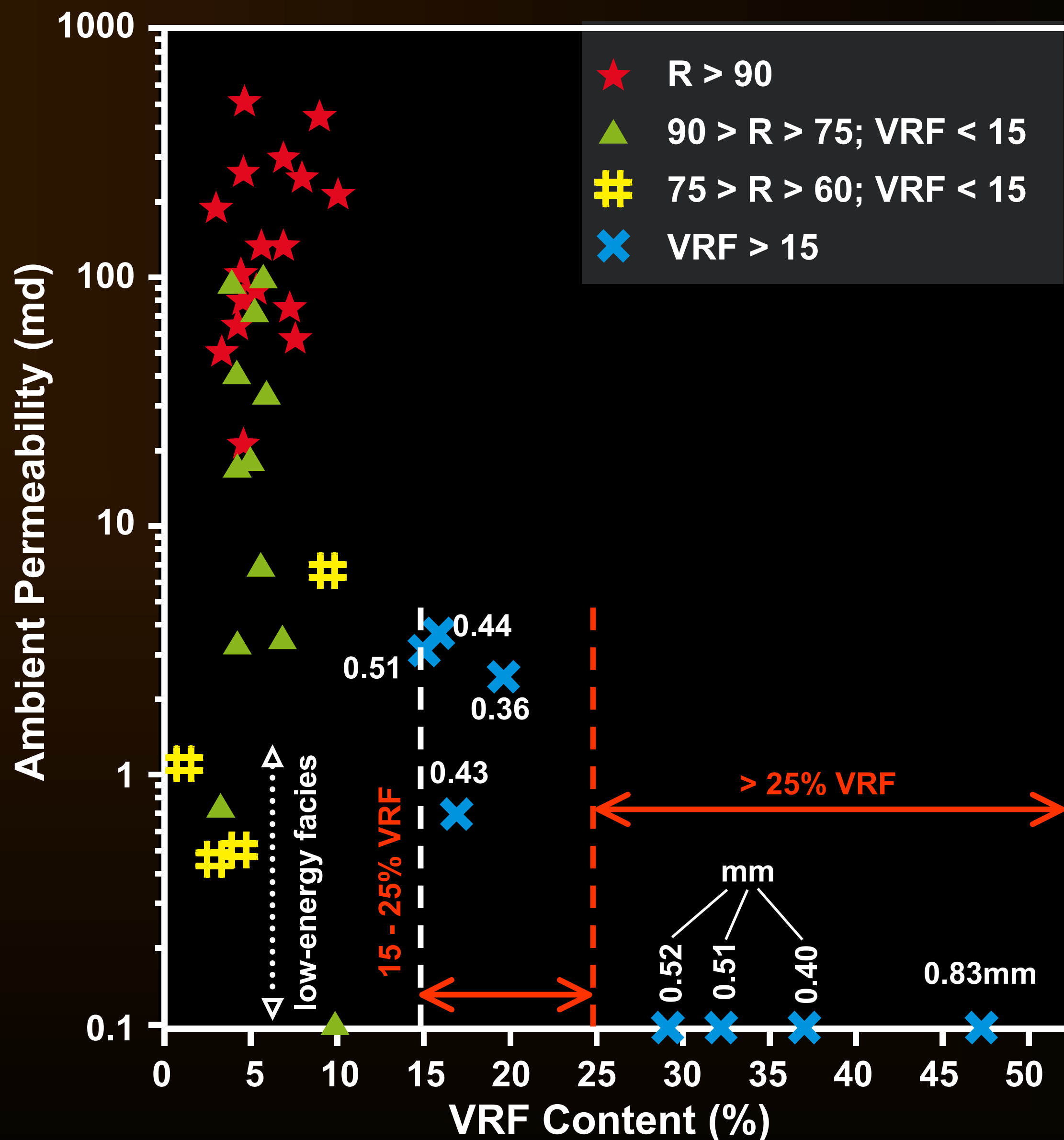
- A ductile grain (brown) can be protected from compaction by bridging of rigid grains

- Example of random distribution of ductile grains in a sandstone
- Although the abundance of ductile grains is 20%, only 15% are in deformable positions

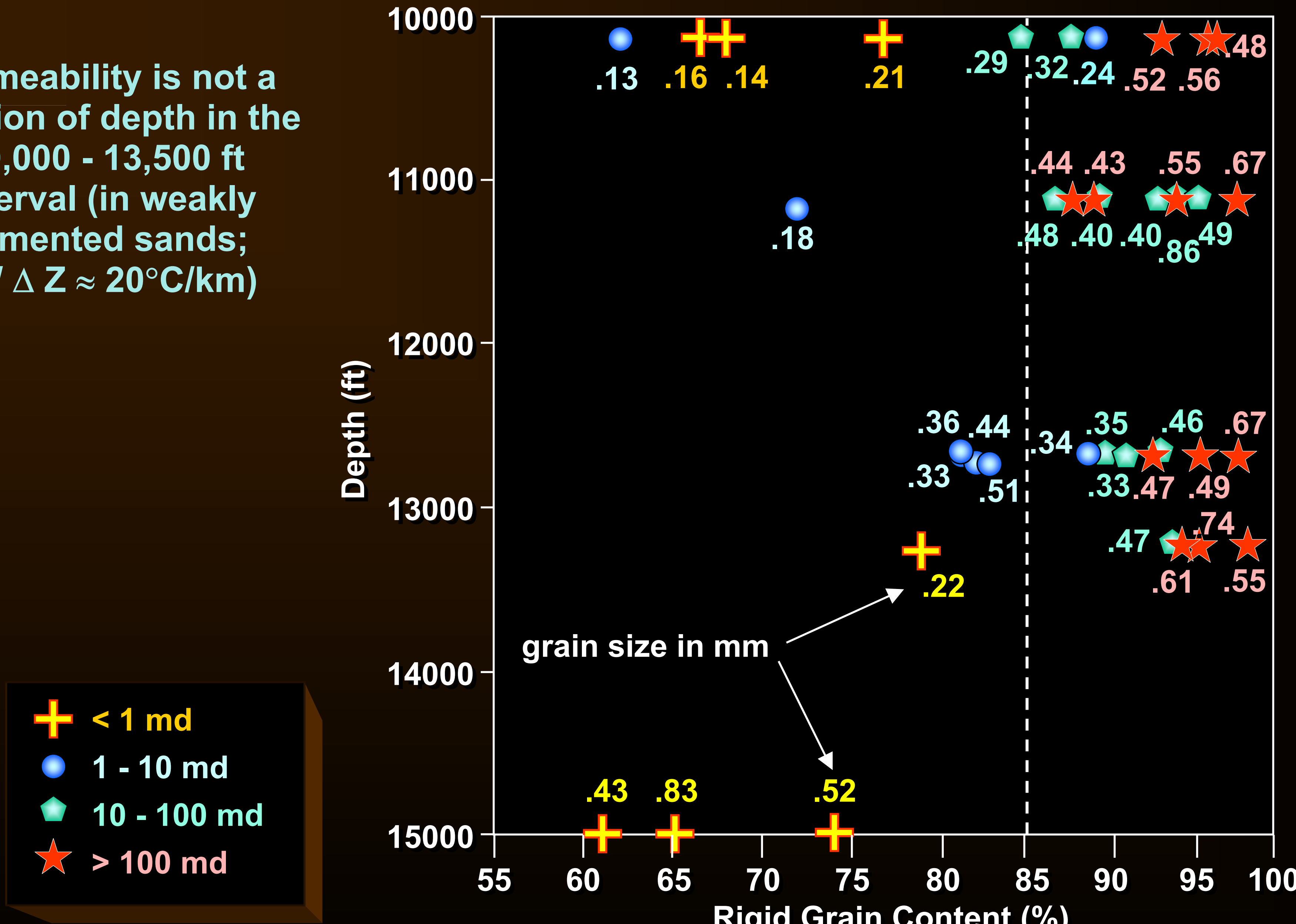


(from Franks, 1981; unpub.)

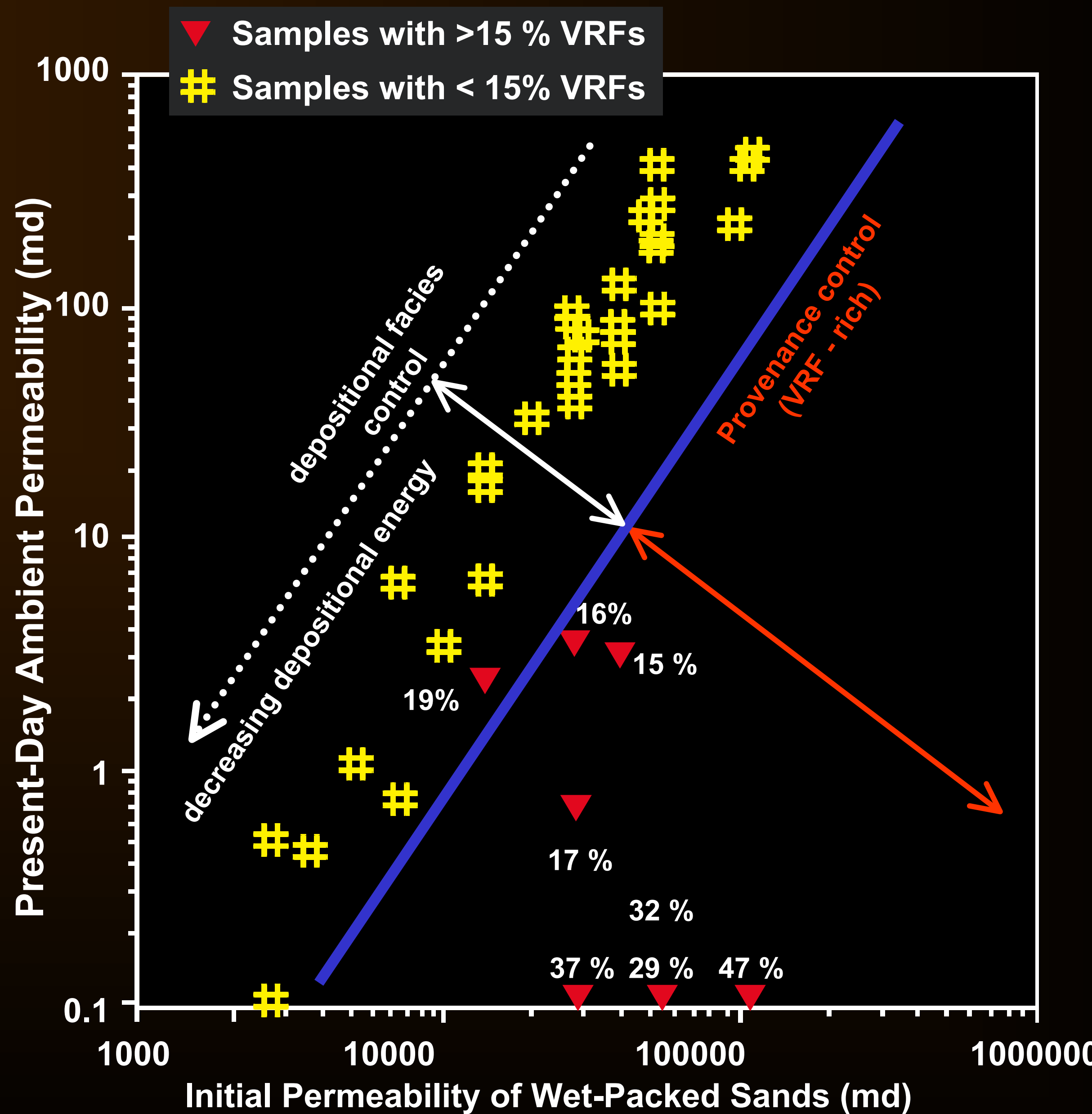
In sandstones with VRFs > 25%, permeability is very low regardless of grain size, at depths > 10,000 ft



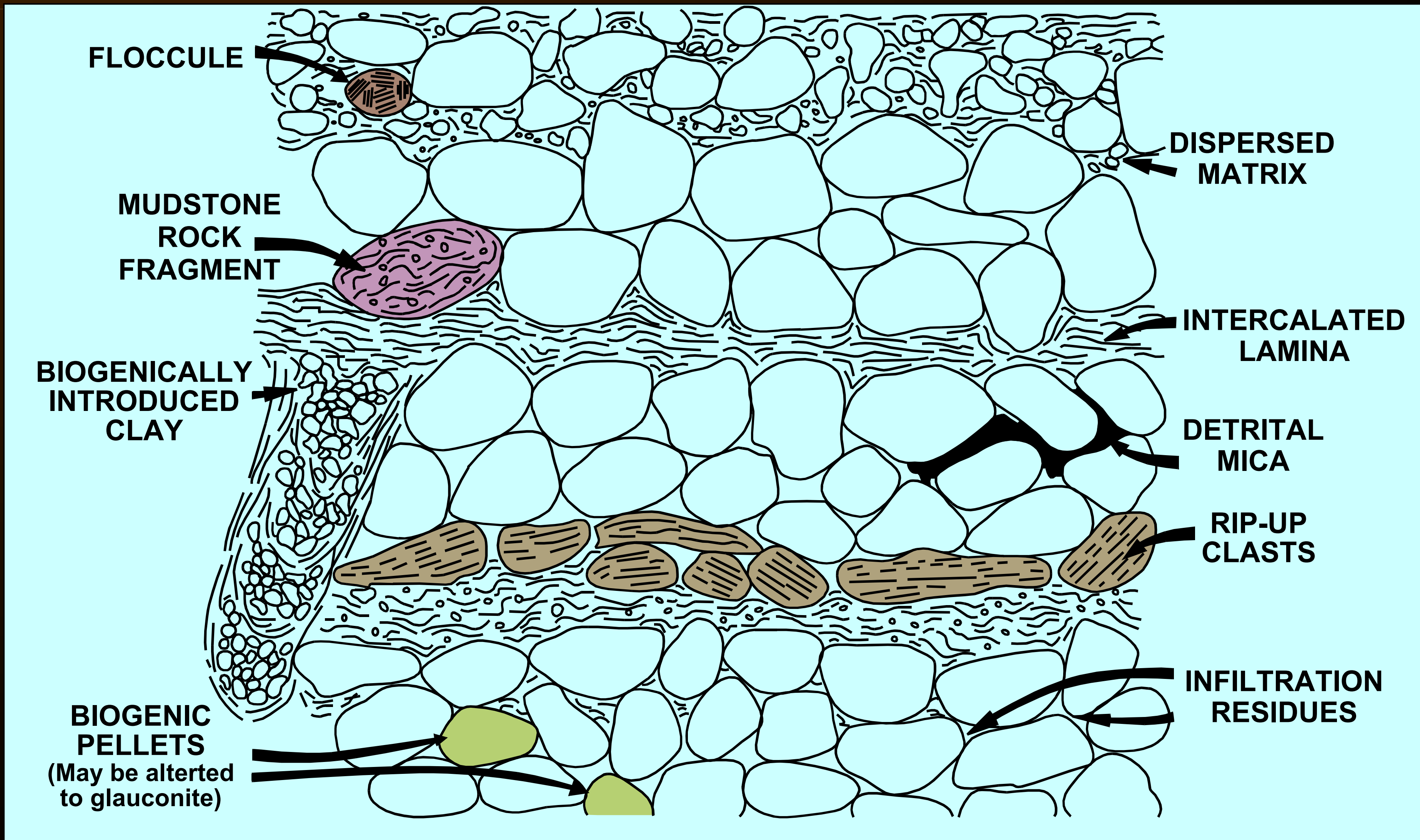
Permeability is not a function of depth in the 10,000 - 13,500 ft interval (in weakly cemented sands; $\Delta T / \Delta Z \approx 20°C/km$)



There is an excellent correlation between initial and present-day permeability in weakly cemented sandstones (<10% cement), except for VRF-rich samples

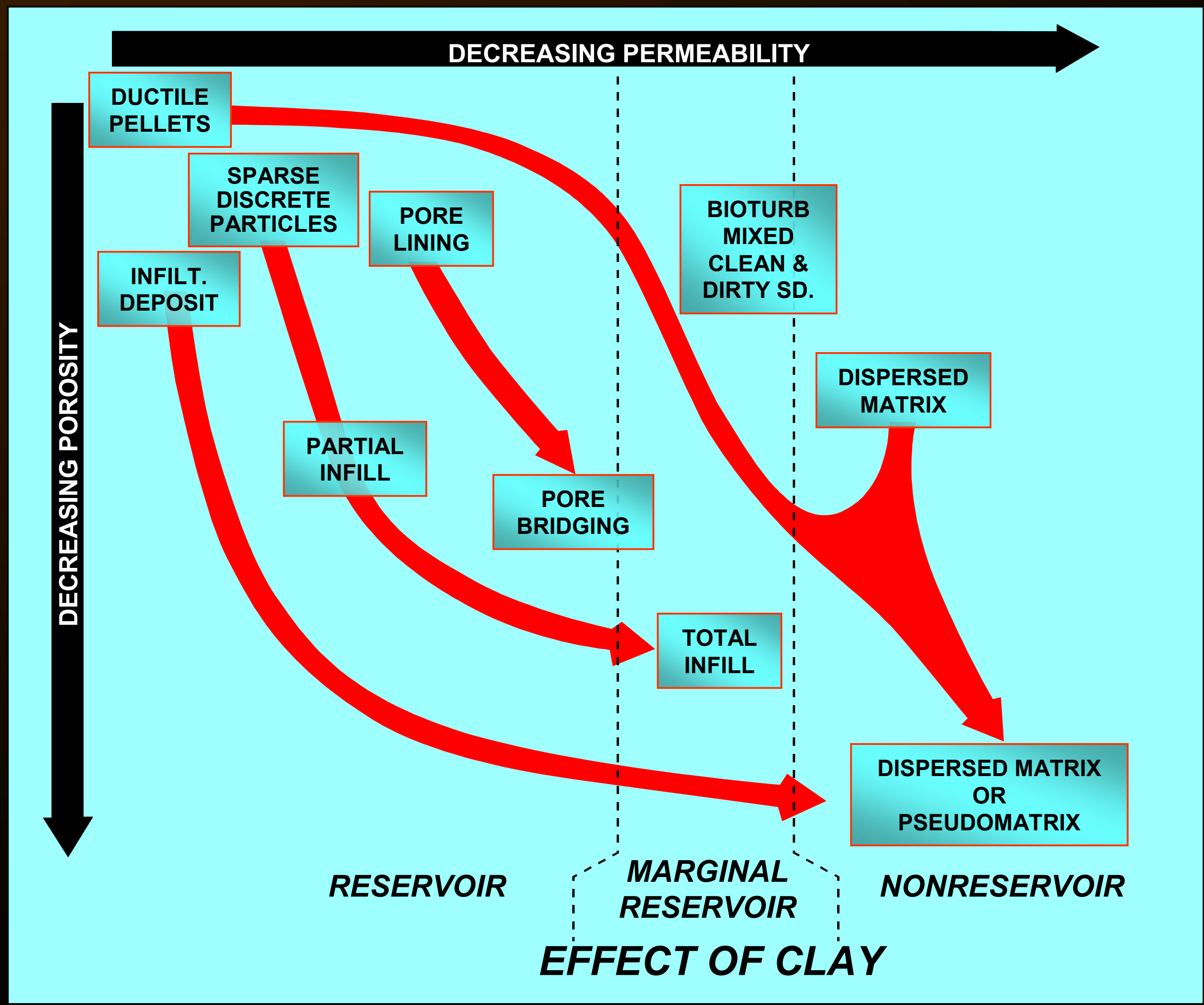


Modes of Occurrence of Allogenic Clay in Sandstones



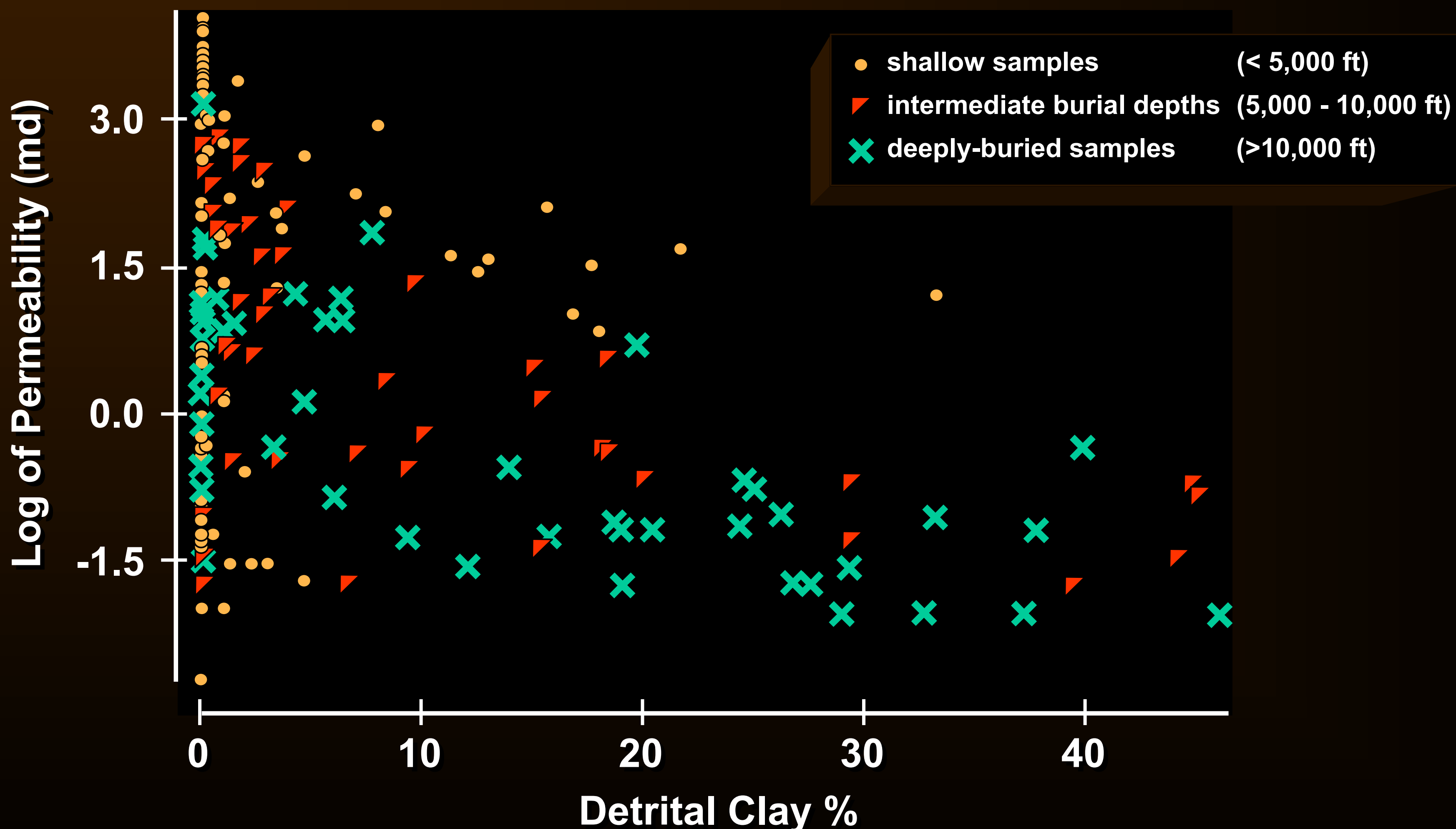
(from Wilson and Pittman, 1977)

Porosity and Permeability in Sandstone are Affected by the Amount and Mode of Occurrence of Clay Minerals, and by the Amount of Compaction



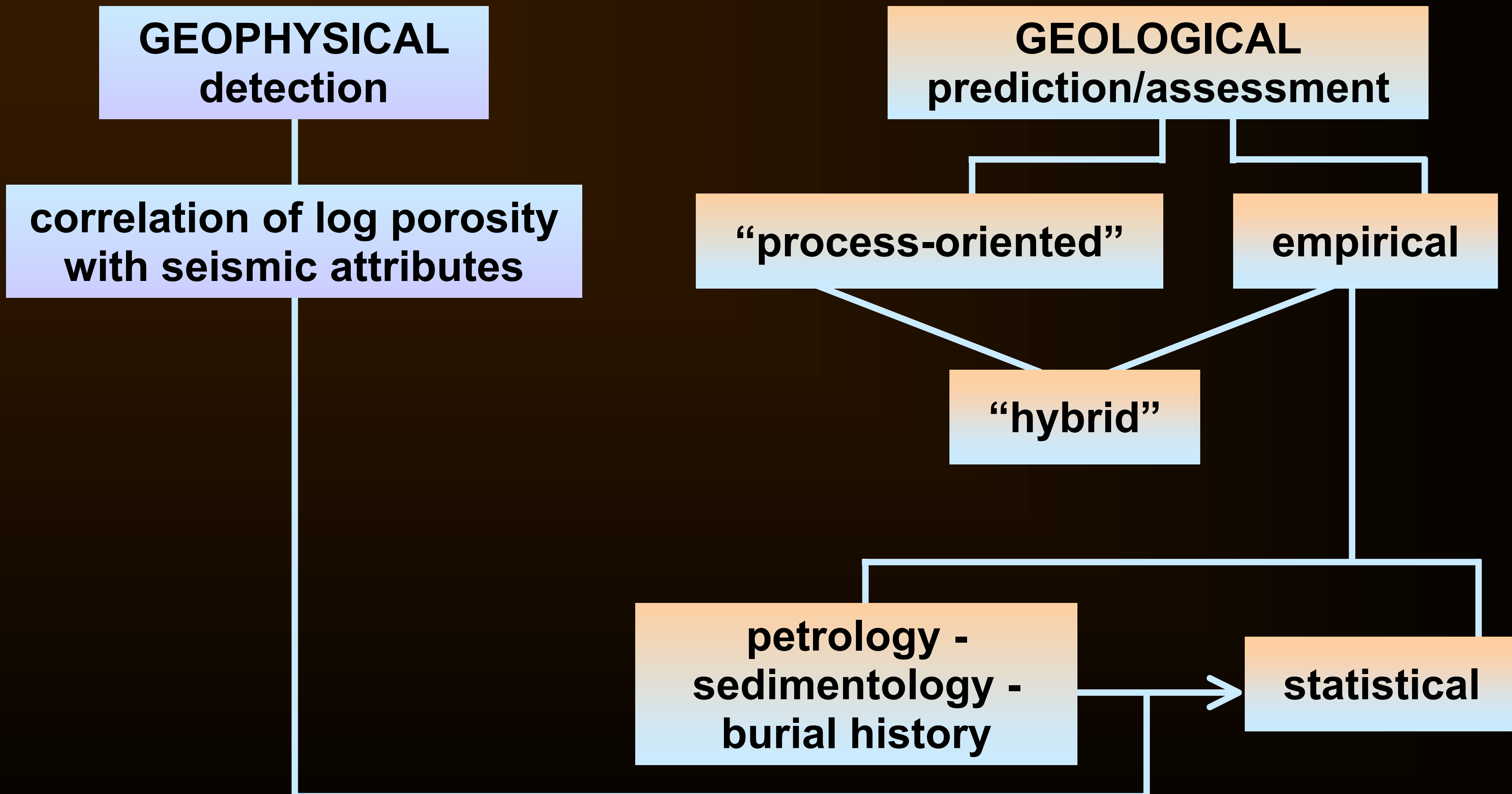
(from Pittman, 1989)

There is no discernible correlation between k and detrital clay abundance but sandstones with >20% of detrital clay generally have low k



(Bloch, 1994)

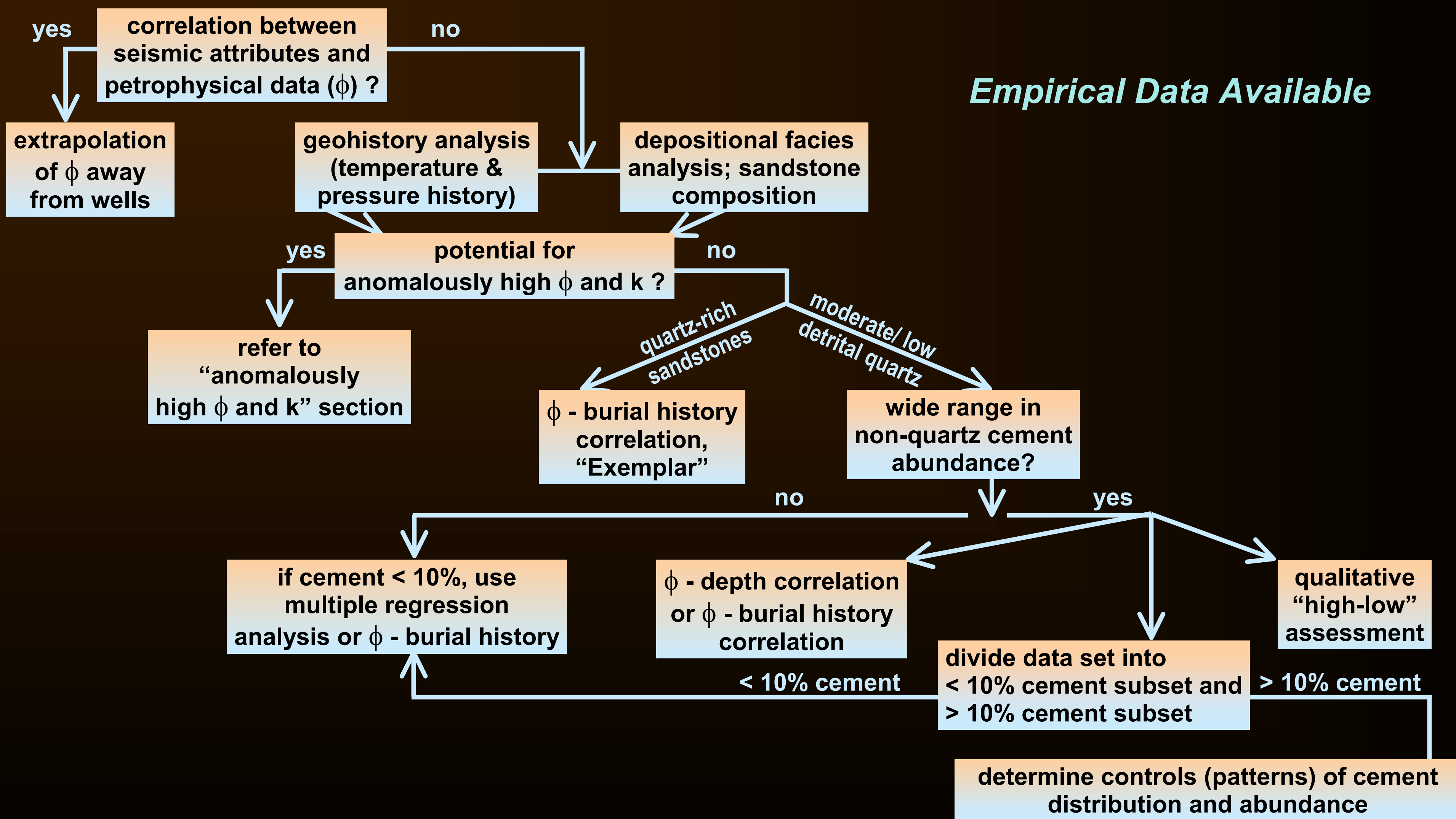
Approaches to Reservoir Quality "Prediction"



Requirements for Adequate Predictions

- High predictive accuracy should be achieved from a limited number of geological input parameters
- Input parameters should be simple enough to be estimated from available geological information with reasonable confidence
- Prediction should be based on multiple techniques

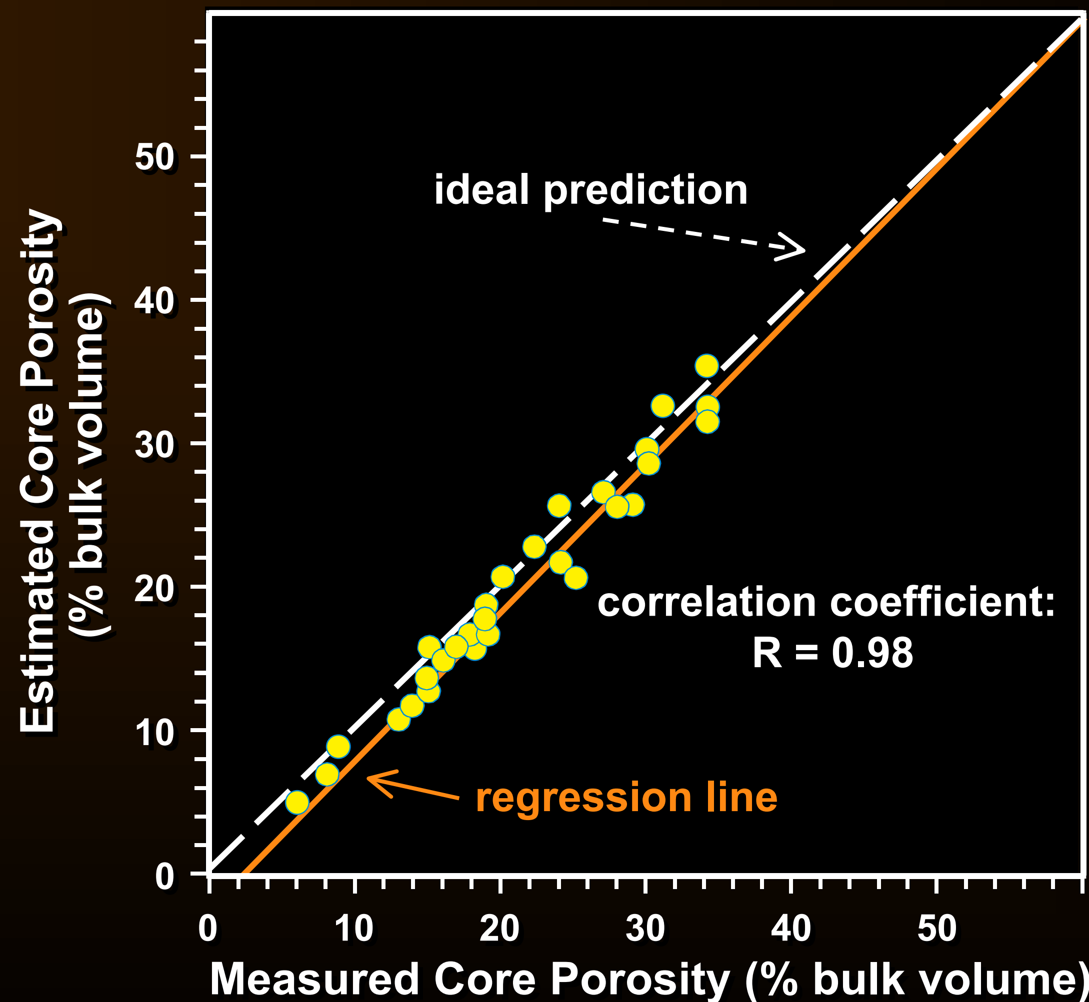
Pre-Drill Prediction/Assessment of Porosity and Permeability in Mature Basins



(modified from Bloch and Helmold, 1995)

"Global" Porosity Prediction Equation for sandstones with < 5% cement

ϕ = 18.60 + (4.73 x ln quartz) + (17.37/sorting) - (3.8 x depth x 10^{-3}) - (4.65 x ln age)



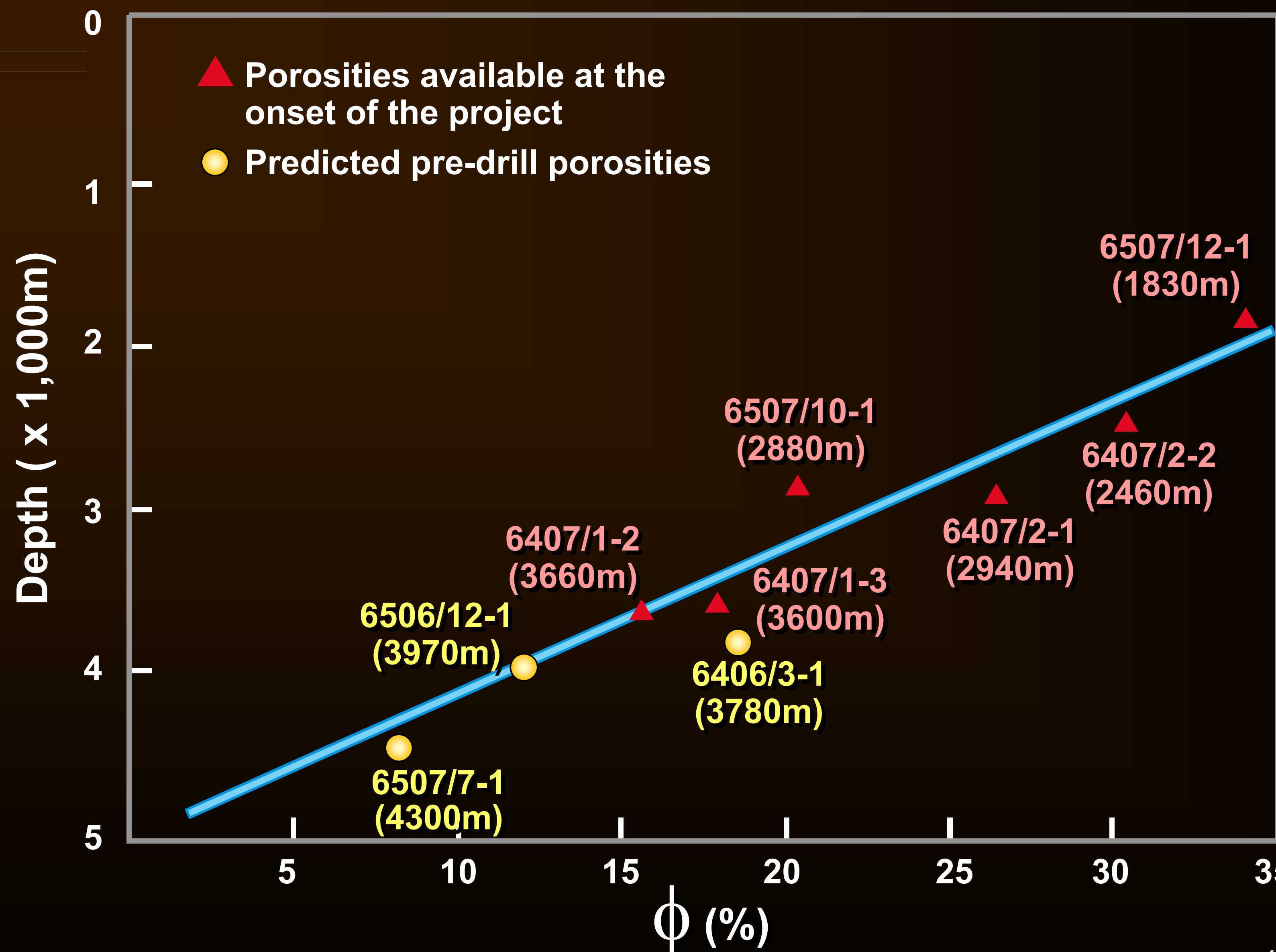
(Scherer, 1987)

Approximate Ranges in Cement Volumes for Different Styles of Diagenesis

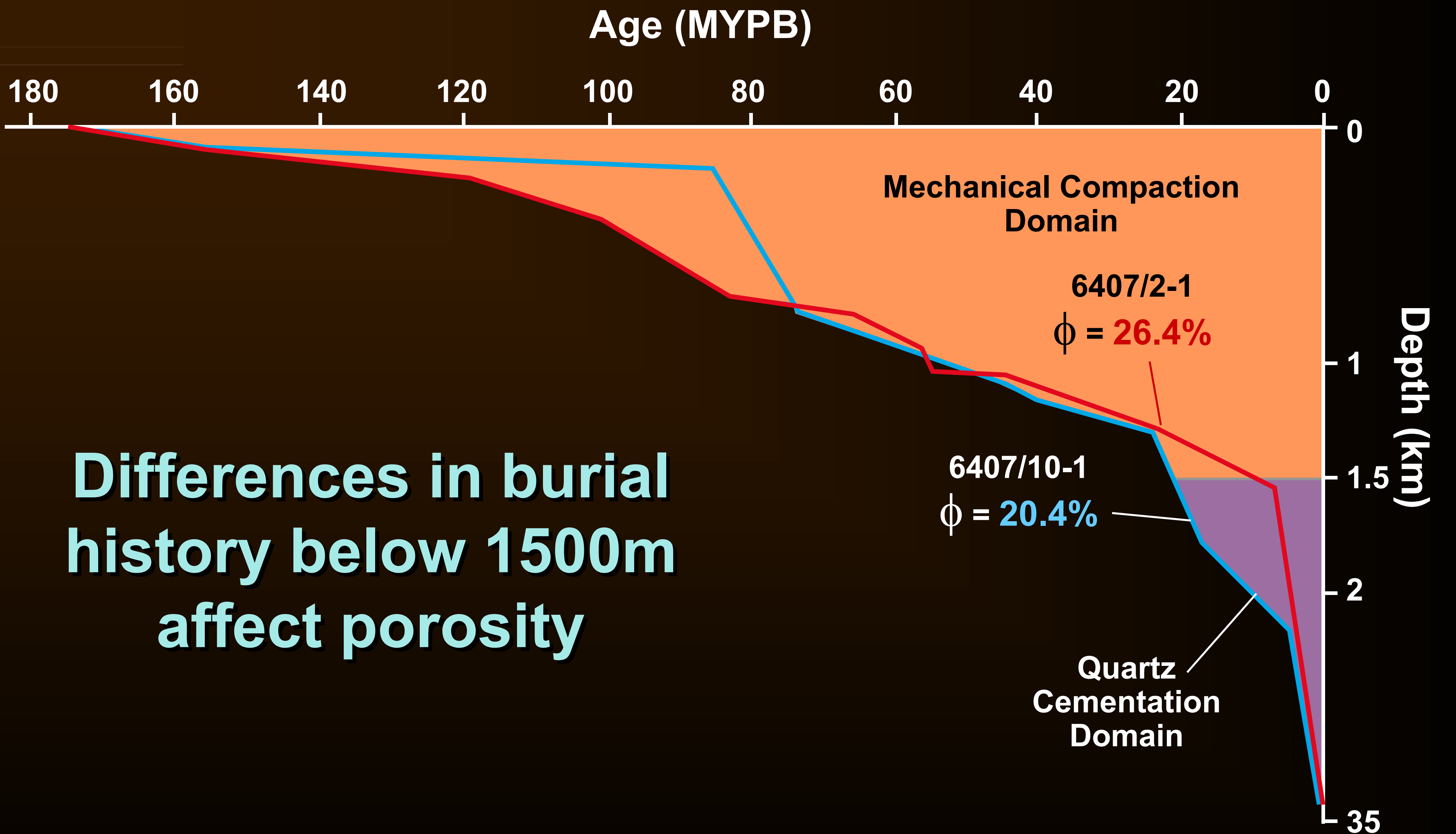
Style of Diagenesis	Range in Volume of Principal Cement	Range in Volume of Ancillary Cements
Quartz dominated	5 -15% (increases with temperature of burial)	3 - 5%, <5% late carbonate*
Clay dominated	10 - 20% (only illite dominated increases with temperature of burial)	< 5% quartz, <5% late carbonate*
Early clay/late quartz	5 - 10% clay, < 5% quartz	< 5% late carbonate*
Early carbonate/ evaporite dominated	≤ 20 - 30% (increases in proximity to evaporites/saline lake deposits)	
Zeolite	5 - 20% (increases with increasing lithic content)	≤ 10% clay, ≤ 10% late carbonate*

*Can be locally < 20 - 30%

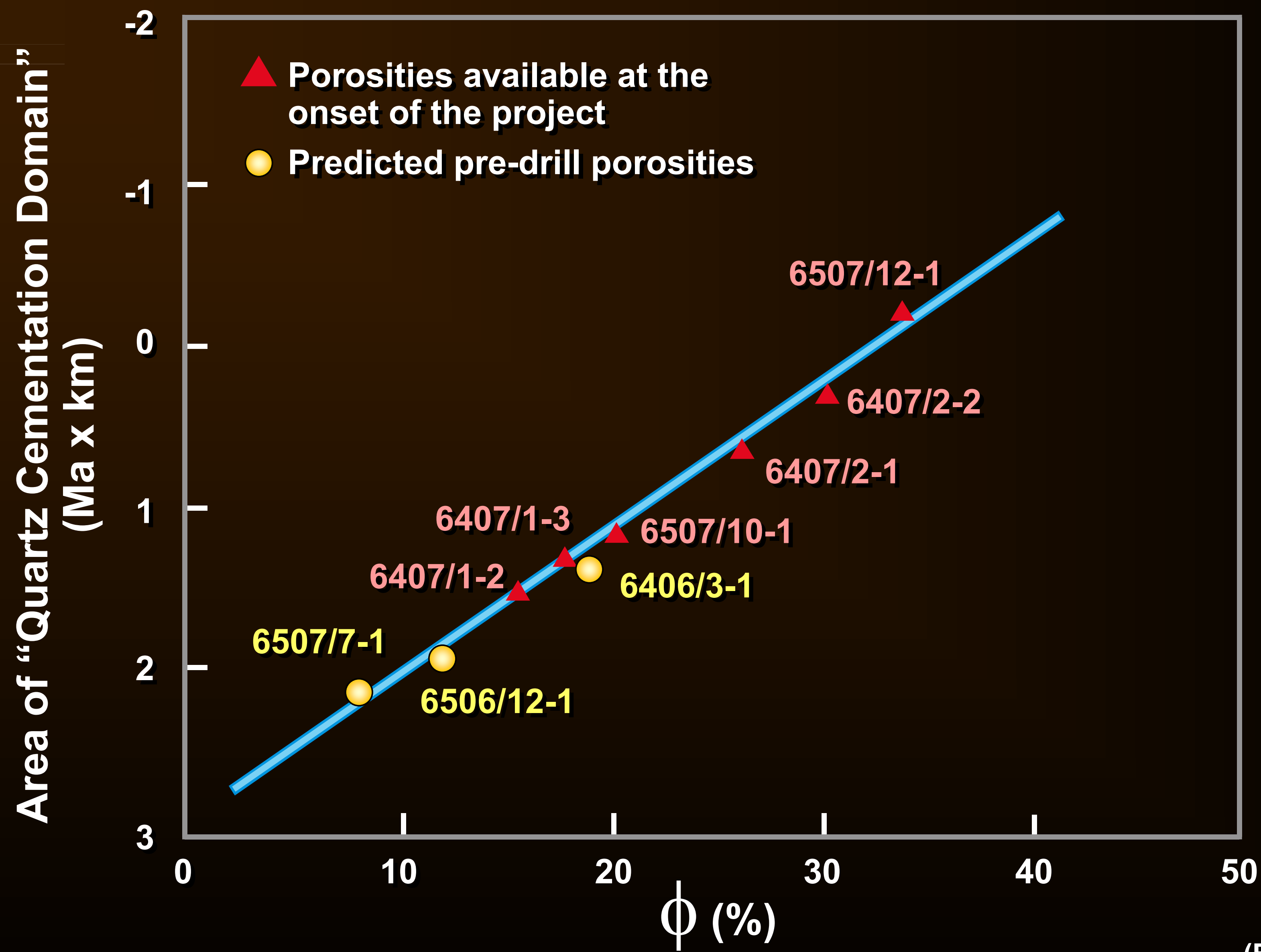
From Primmer et al., 1997


Porosities available at the onset of the project
Predicted pre-drill porosities
Depth (x 1,000m)
0
1
2
3
4
5
5
10
15
20
25
30
35
ϕ (%)
6507/12-1 (1830m)
6507/10-1 (2880m)
6407/2-2 (2460m)
6407/2-1 (2940m)
6407/1-2 (3660m)
6407/1-3 (3600m)
6506/12-1 (3970m)
6406/3-1 (3780m)
6507/7-1 (4300m)
(Bloch, 1994)

Differences in burial history below 1500m affect porosity



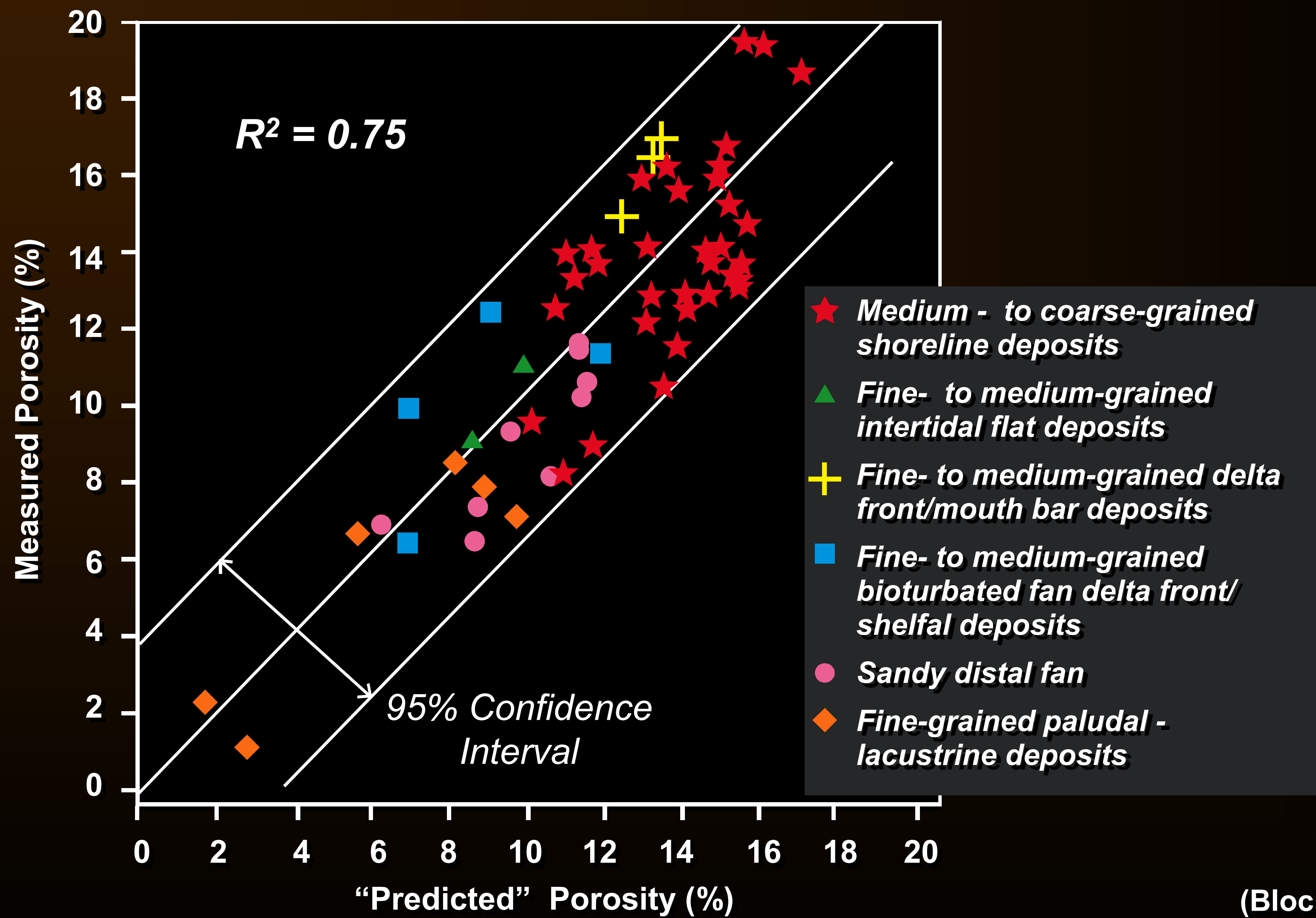
(Bloch, 1994)



Porosities available at the onset of the project
Predicted pre-drill porosities
Area of "Quartz Cementation Domain" (Ma x km)
-2
-1
0
1
2
3
0
10
20
30
40
50
ϕ (%)
6507/12-1
6407/2-2
6407/2-1
6507/10-1
6407/1-3
6406/3-1
6407/1-2
6507/7-1
6506/12-1

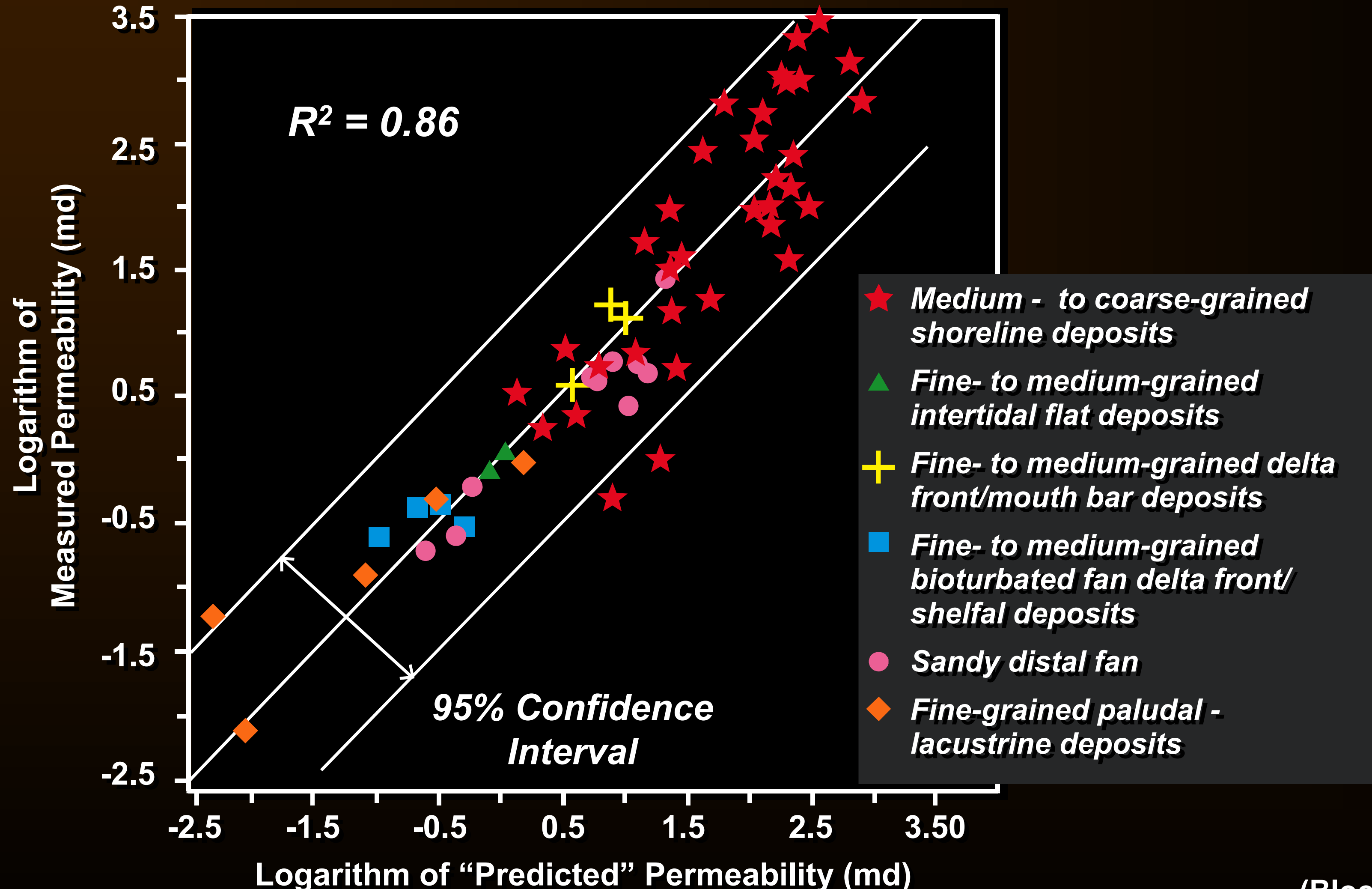
(Bloch, 1994)

Porosity (%) = - 6.1 + 9.8 (1/sort) + 0.17 (Rigid Grain Content)



(Bloch, 1994)

$$\text{Log}_{10}\ (\text{PERM}) = -4.67 + 1.34\ (\text{grsz}) + 4.08\ (1/\text{sort}) + 3.42\ (R/100)$$



(Bloch, 1994)

Example of a Porosity & Permeability Prediction in Sandstones: Summary

Input Data

A. Outcrop samples and samples from closest wells

B. "Best estimate" burial/thermal history data

Porosity Prediction Approaches

Approach 1

1. Use "best estimate" thermal history data to calculate present-day vitrinite reflectance values in target (based on Burnham & Sweeney kinetic model)
2. Use Schmoker & Hester regression equations of R_O vs. porosity

Approach 2

1. Use "Exemplar" to simulate mean porosity and cement abundance evolution
2. Calculate permeability
3. Use Monte Carlo analysis to obtain probabilistic porosity predictions

Predicted Total Mean Porosity

		R_O - Porosity regression	"Exemplar"
Po. ss	10th percentile	7%	9%
Po. ss	50th percentile	11%	14%
Po. ss	90th percentile	15%	19%
Mu. ss	10th percentile	13%	13%
Mu.ss	50th percentile	18%	19%
Mu.ss	90th percentile	23%	24%

Example of a Porosity & Permeability Prediction in Sandstones: Input

A. Expected Lithology in the Proposed Well

(Based on upthrusted outcrop samples and samples from closest wells)

1. Detrital composition: quartz-rich (> 85% quartz)
2. Texture: medium to coarse grain size (~0.50mm), moderate sorting

B. Diagenesis

Diagenetic History:

Siderite very early (<40^{O} C) I

Kaolinite Compaction

Quartz >75^{o} I

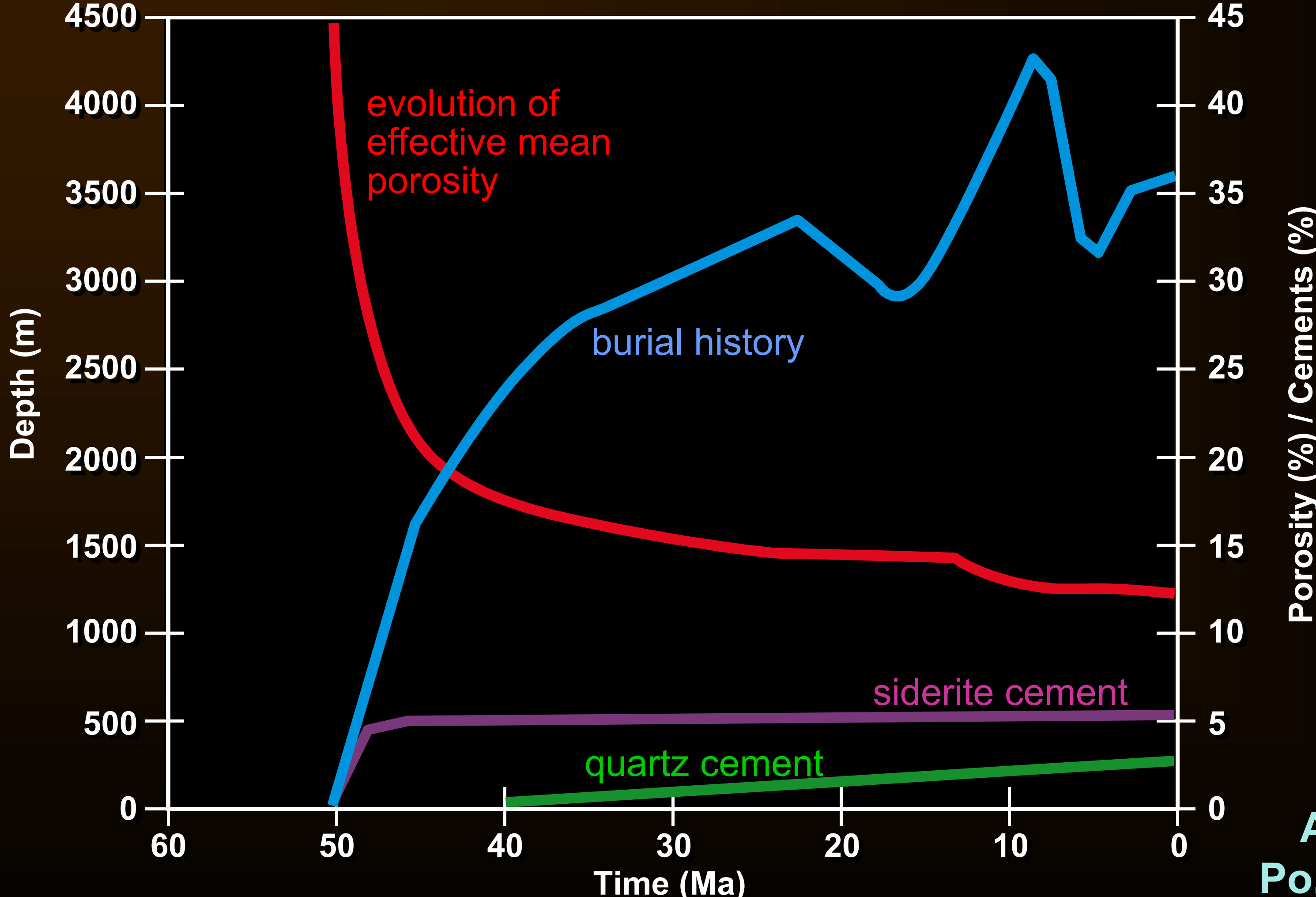
Fracturing (fractured quartz) I

Ankerite (minor ankerite in fractures)

Oil Emplacement (oil in fractures)

Uplift oxidation of siderite and precipitation of hematite

Predicted Evolution of Effective Porosity and Cement Abundances

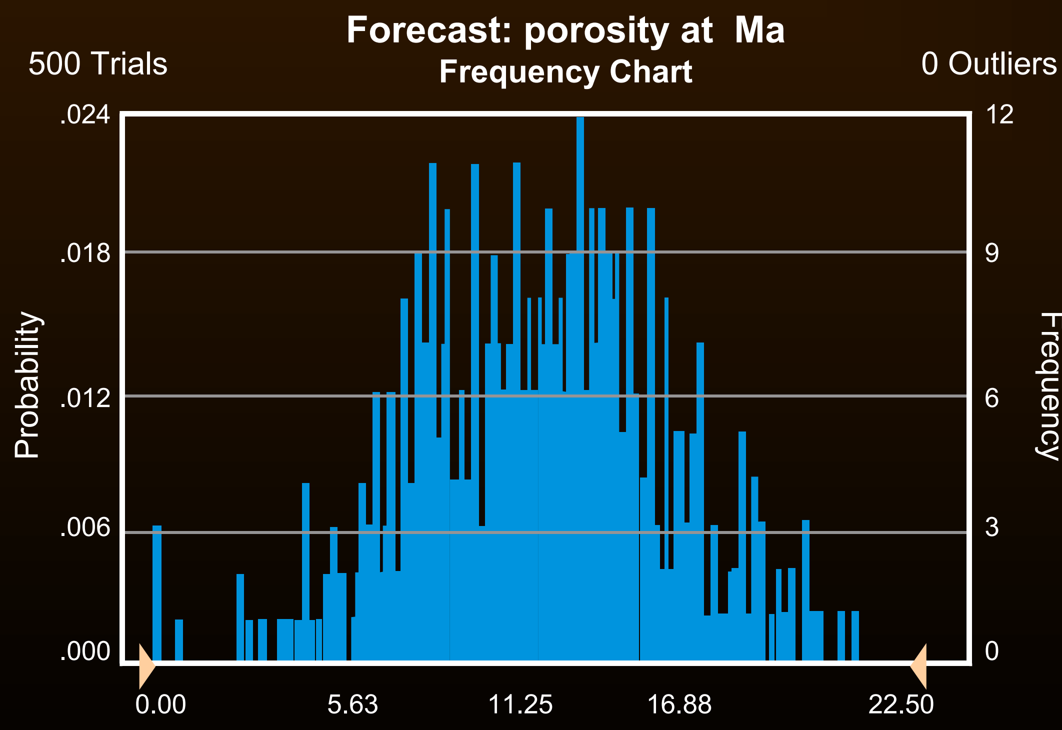


AG-1 Well,
Po. Sandstone

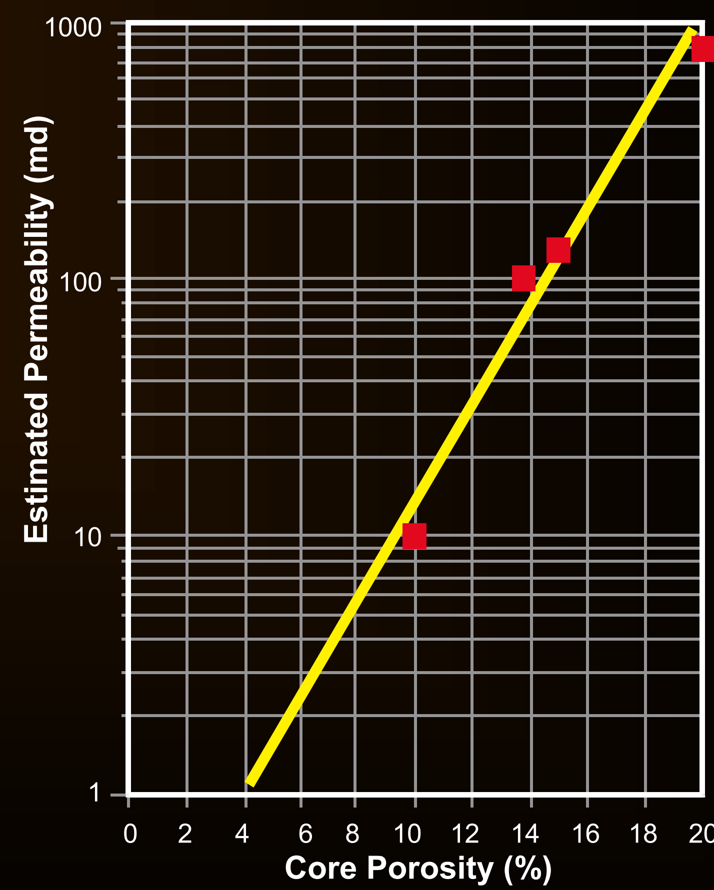
Example of a Porosity & Permeability Prediction in Sandstones: Output

Forecast: porosity of Po. Fm. At 0 Ma

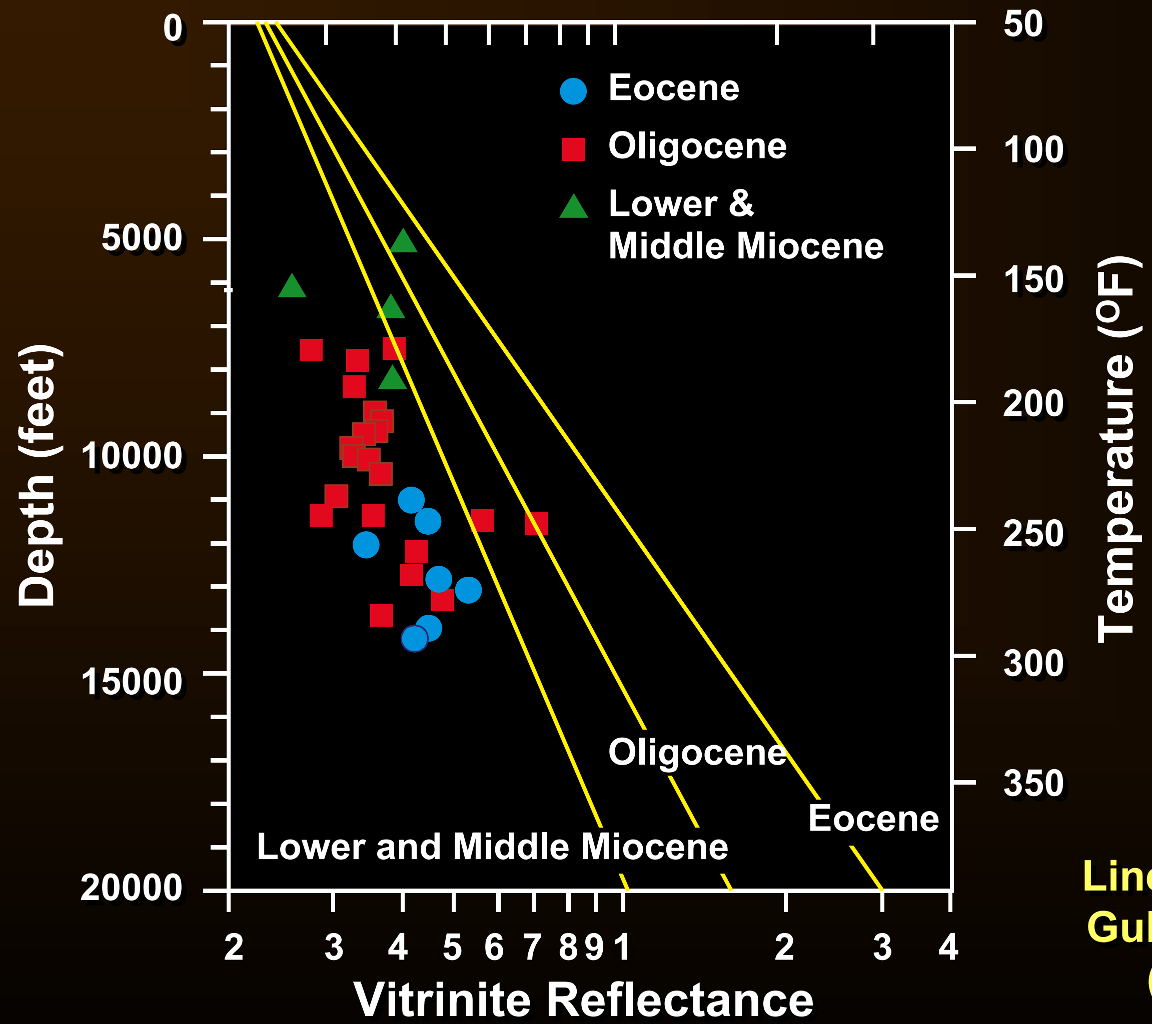
		% Effective Porosity
P10	10%	6.75
	20%	8.14
	30%	9.25
	40%	10.31
P50	50%	11.35
	60%	12.24
	70%	13.06
	80%	14.06
P90	90%	15.65



Permeability = f (effective porosity, average grain size of 0.50mm, <10% clay)

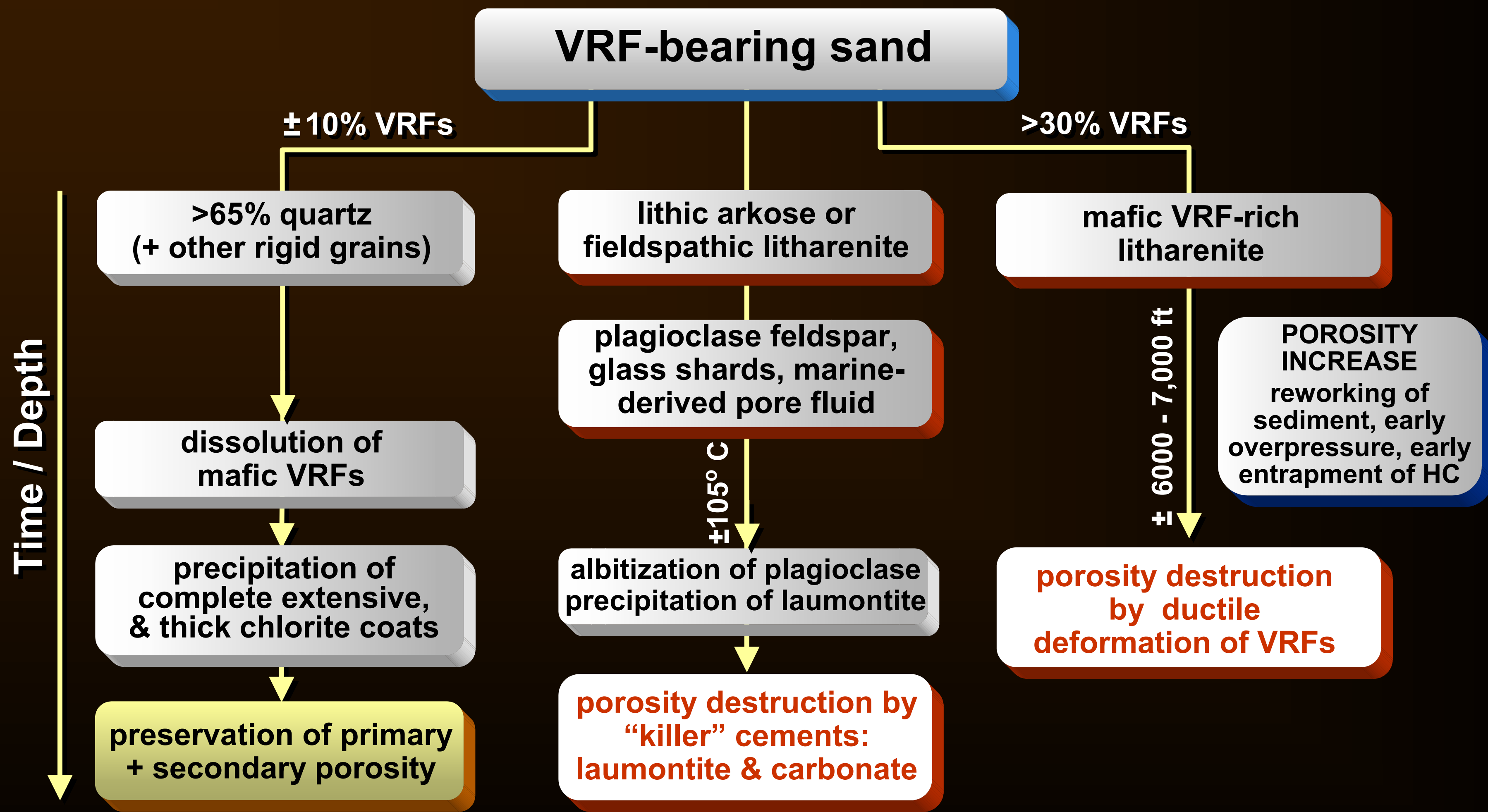


VR values in the southern San Joaquin basin do not correlate with depth of burial

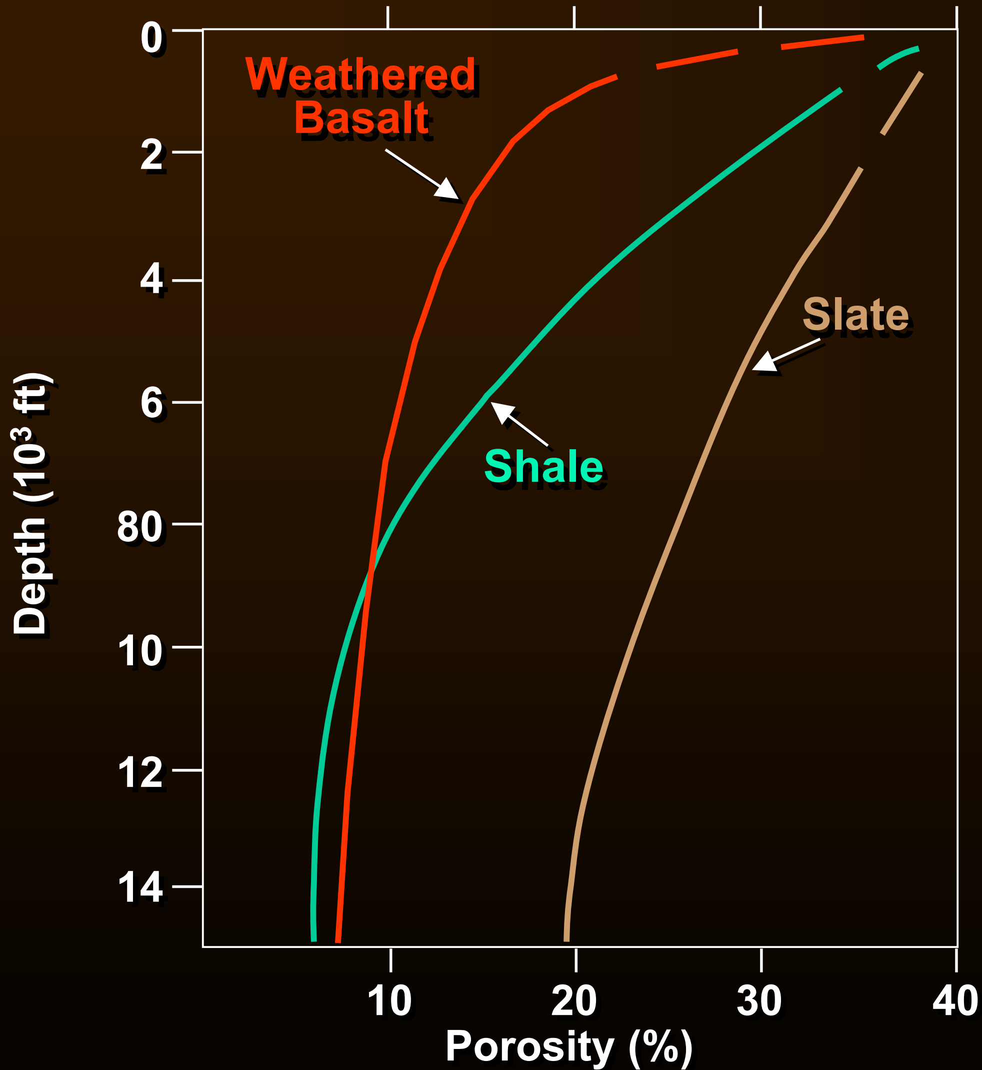


Lines denote trends for Gulf Coast sandstones (*from Dow, 1978*)

Reservoir Quality in Volcaniclastic Sandstones



Compaction Model with 50% Quartz: 50% Lithic Sands for Slate, Shale and Weathered Basalt



Effect on Curve

Decreases Porosity

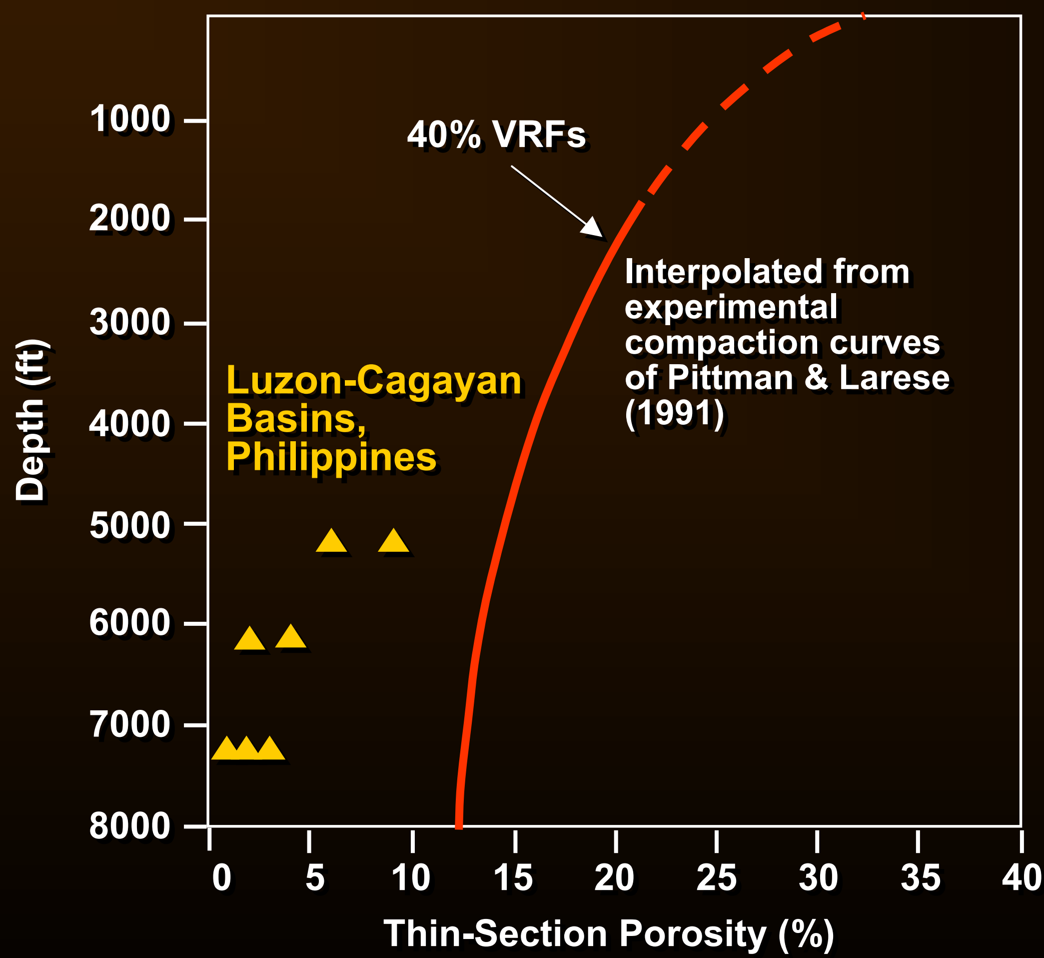
- High geothermal gradient
- Decrease in sorting
- Cement (Depends on Timing)

Increases Porosity

- Relatively early overpressure
- Creation of secondary porosity
- Entrapment of hydrocarbons

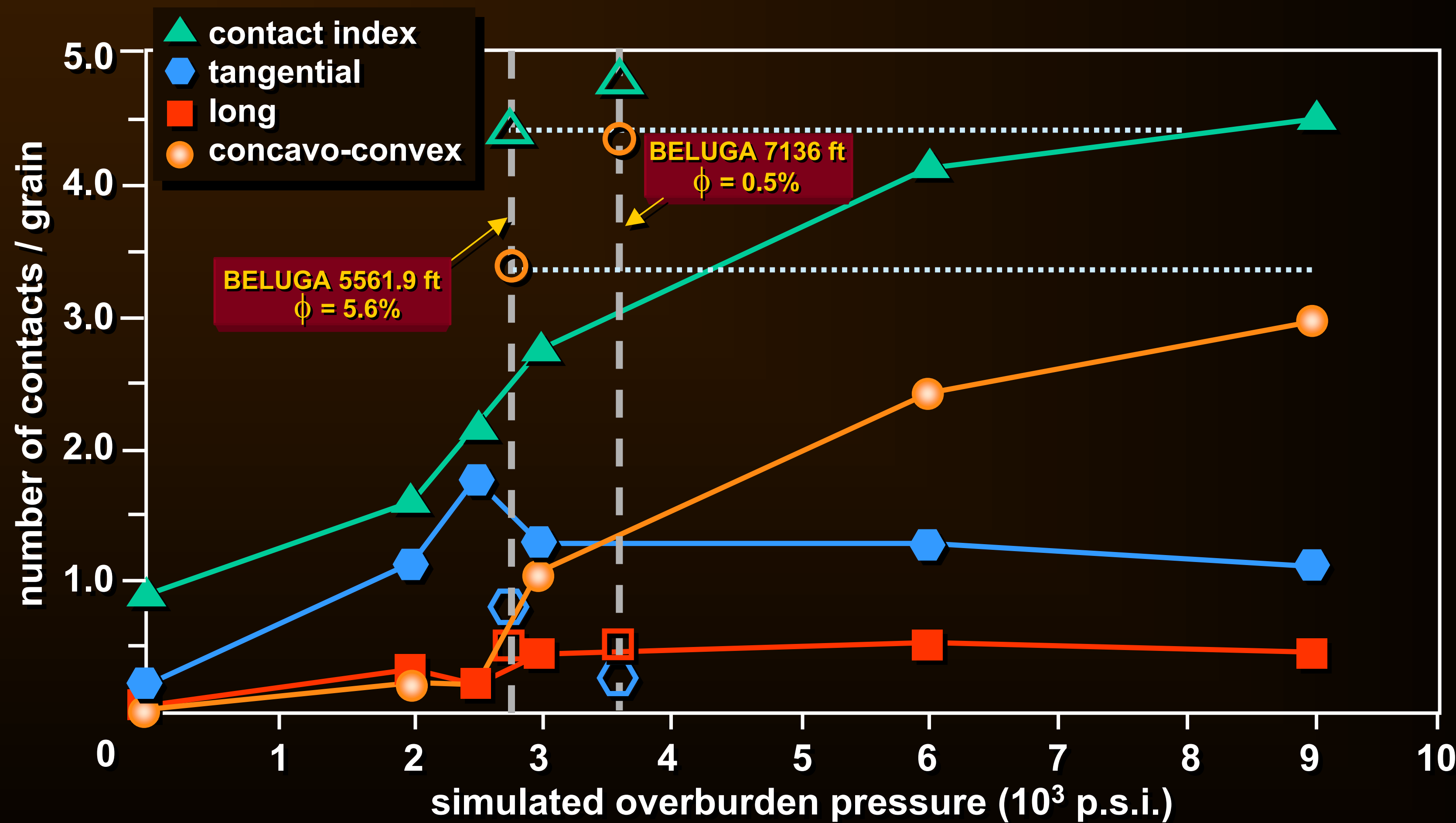
(from Pittman & Larese, 1991)

In moderately-sorted, VRF-rich (>35% VRFs) sandstones, reservoir quality is drastically reduced below approximately 6,000 ft



Comparison of Geologic & Experimental Compaction

Contact index and contact types as a function of simulated overburden pressure, for compaction tests conducted with Eagle River sand and triaxial overburden apparatus



(from Kurkjy, 1988)

Approach to Reservoir Quality Prediction in Sandstones with a Wide Range of Pore-Filling Cements

Calibration Data Set

< 10% Cement
Predictive Model Based on Multiple Regression Analysis

> 10% Cement
Predictive Model Based on Understanding the Origin and 3D Distribution Pattern of Cement(s)

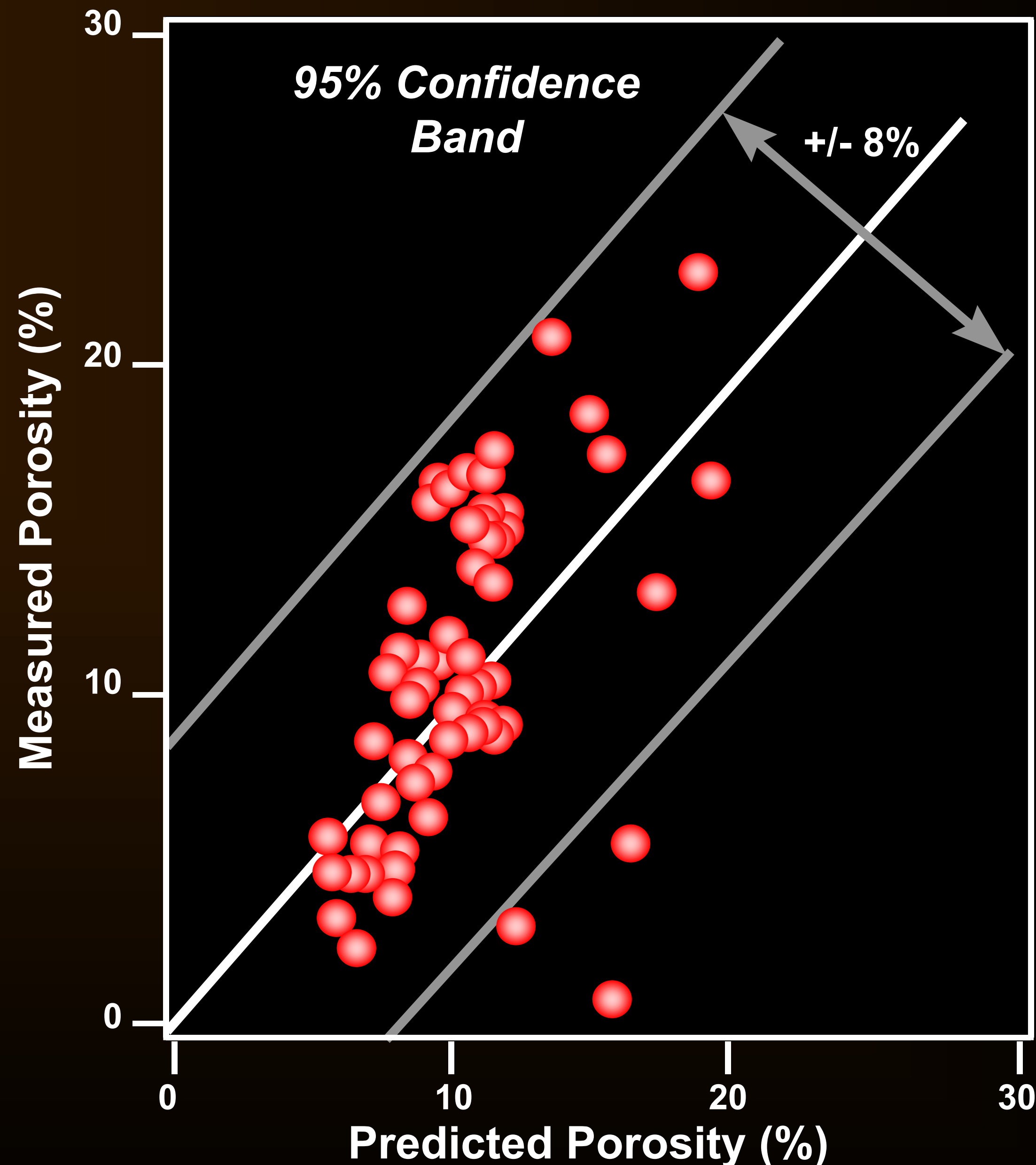
Conclusions

Occurrence and Abundance of Laumontite in Middle Eocene-Late Oligocene Arkosic Sandstones of the San Emigdio Area Exhibit Distinct Patters:

Temperature	**>215^{O} F (~100^{O} C)**
Geologic Time	**Most Abundant in Upper Oligocene**
Areal Distribution	**South of the White Wolf Fault; Abundance Decreases Systematically from N to S** (Increasing Distance from Volcanic Center ?)

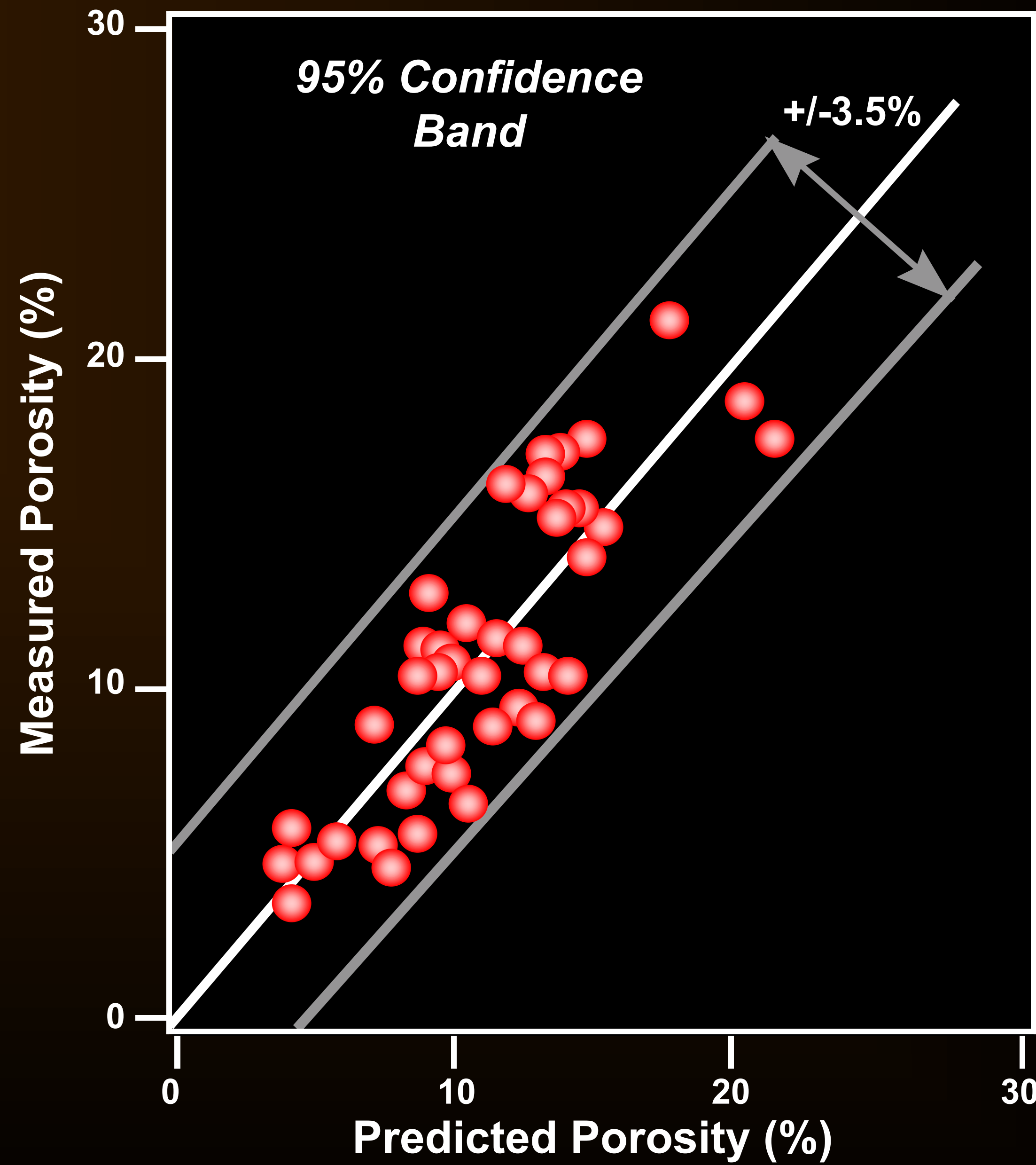
Measured vs Predicted Porosity

Regression on Detrital Matrix and Depth for All Samples

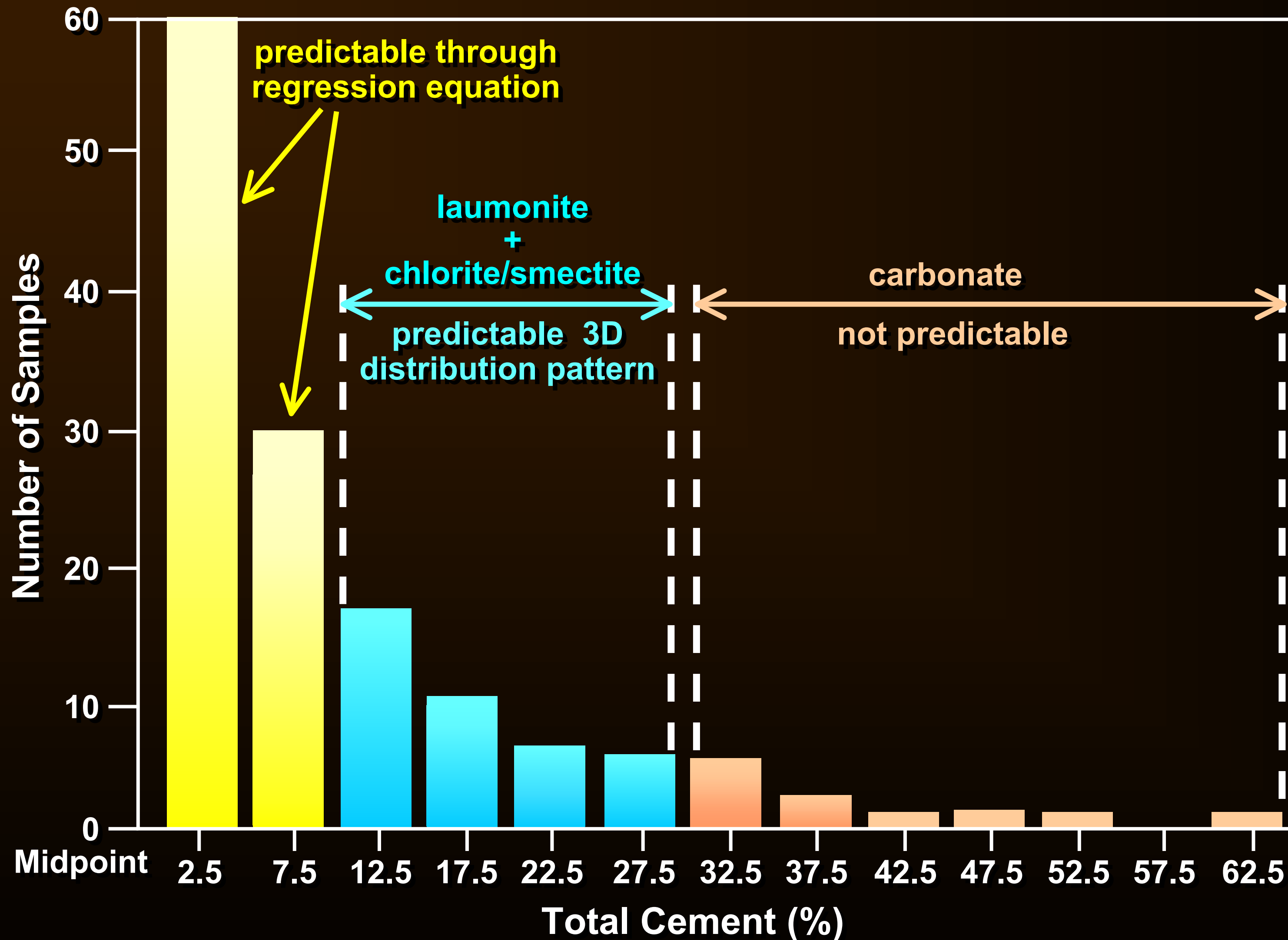


Measured vs Predicted Porosity

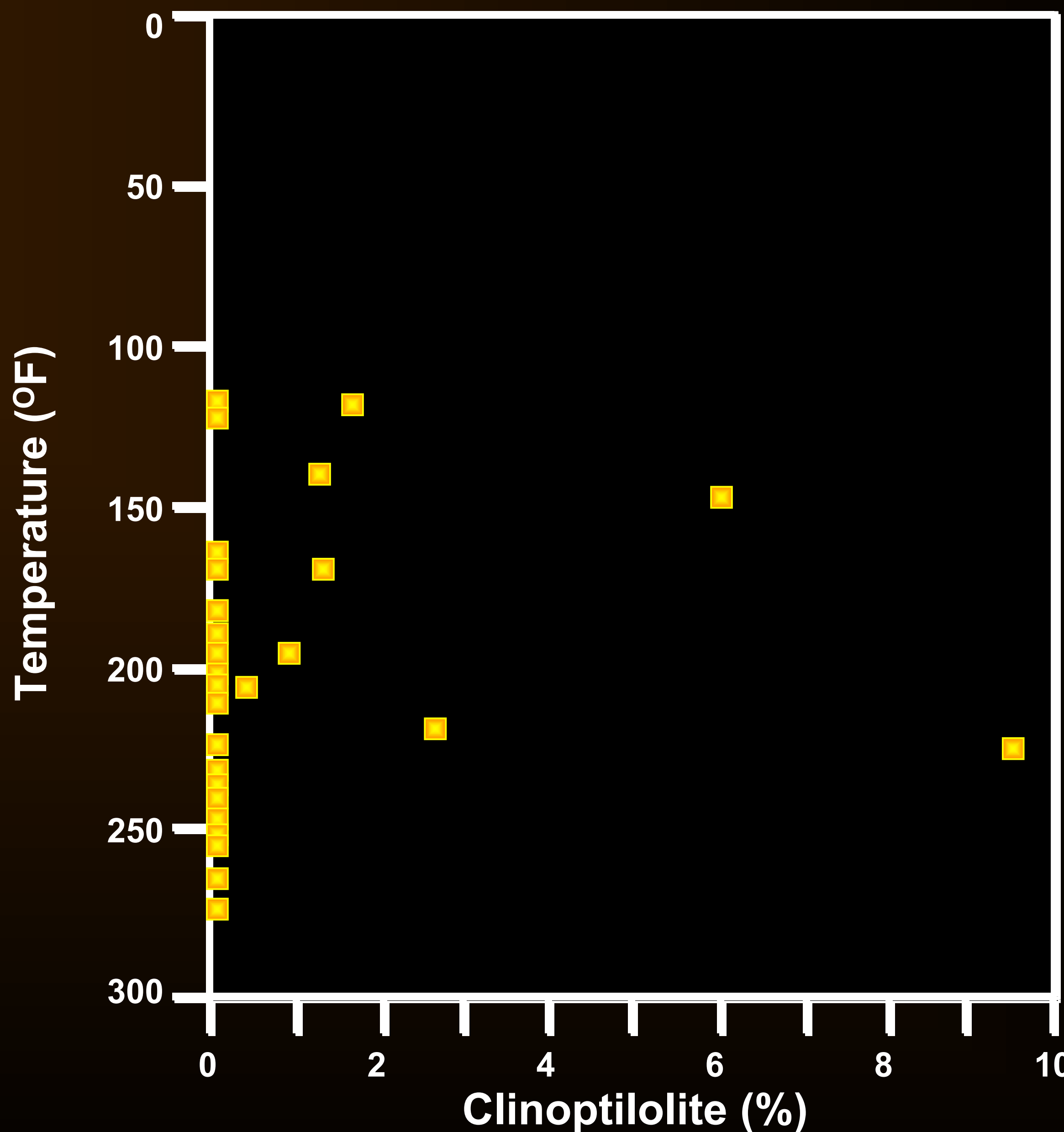
Regression on Detrital Matrix and Depth for Samples with <u>≤10% Cement</u>



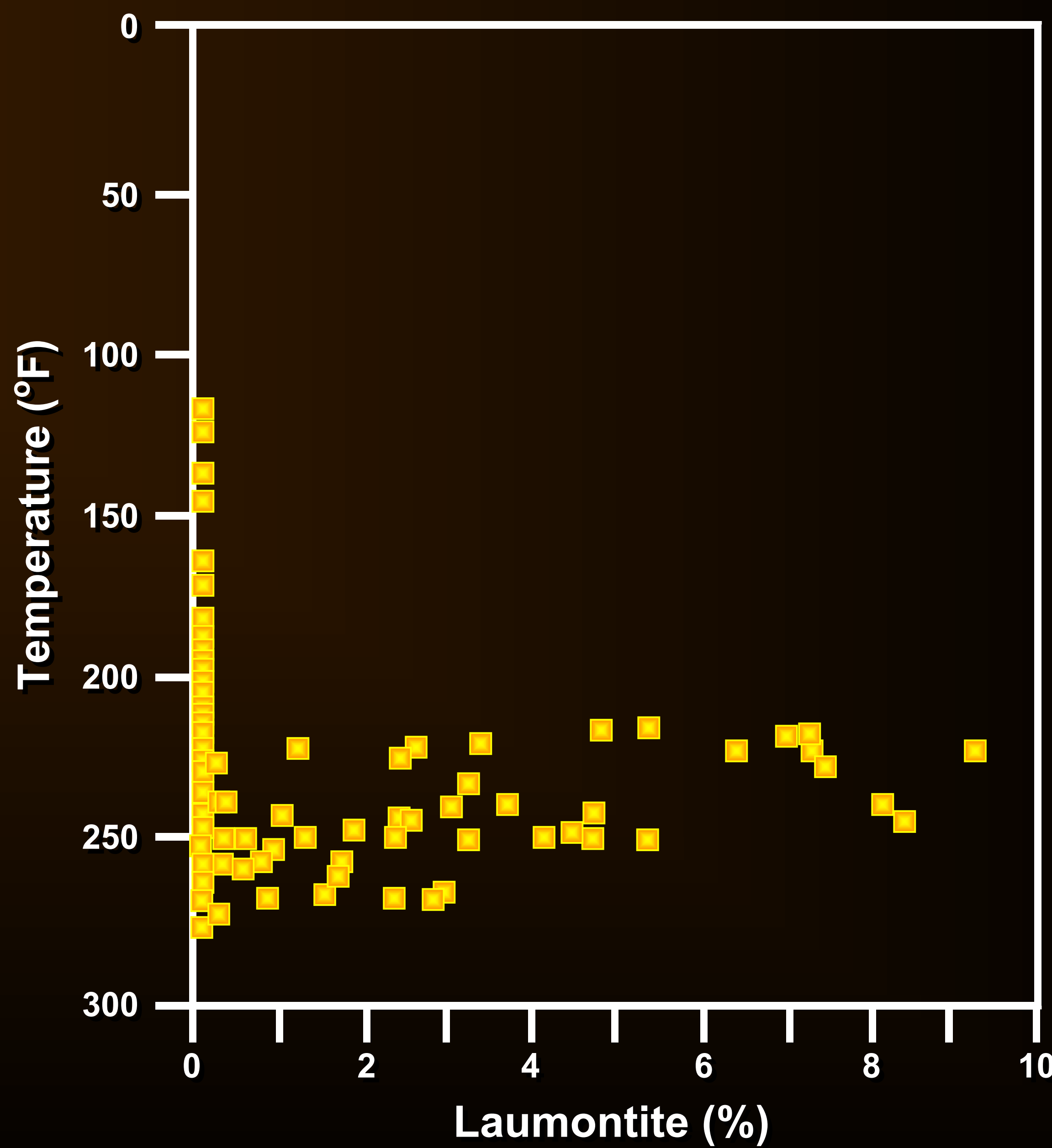
Three Prediction Subsets



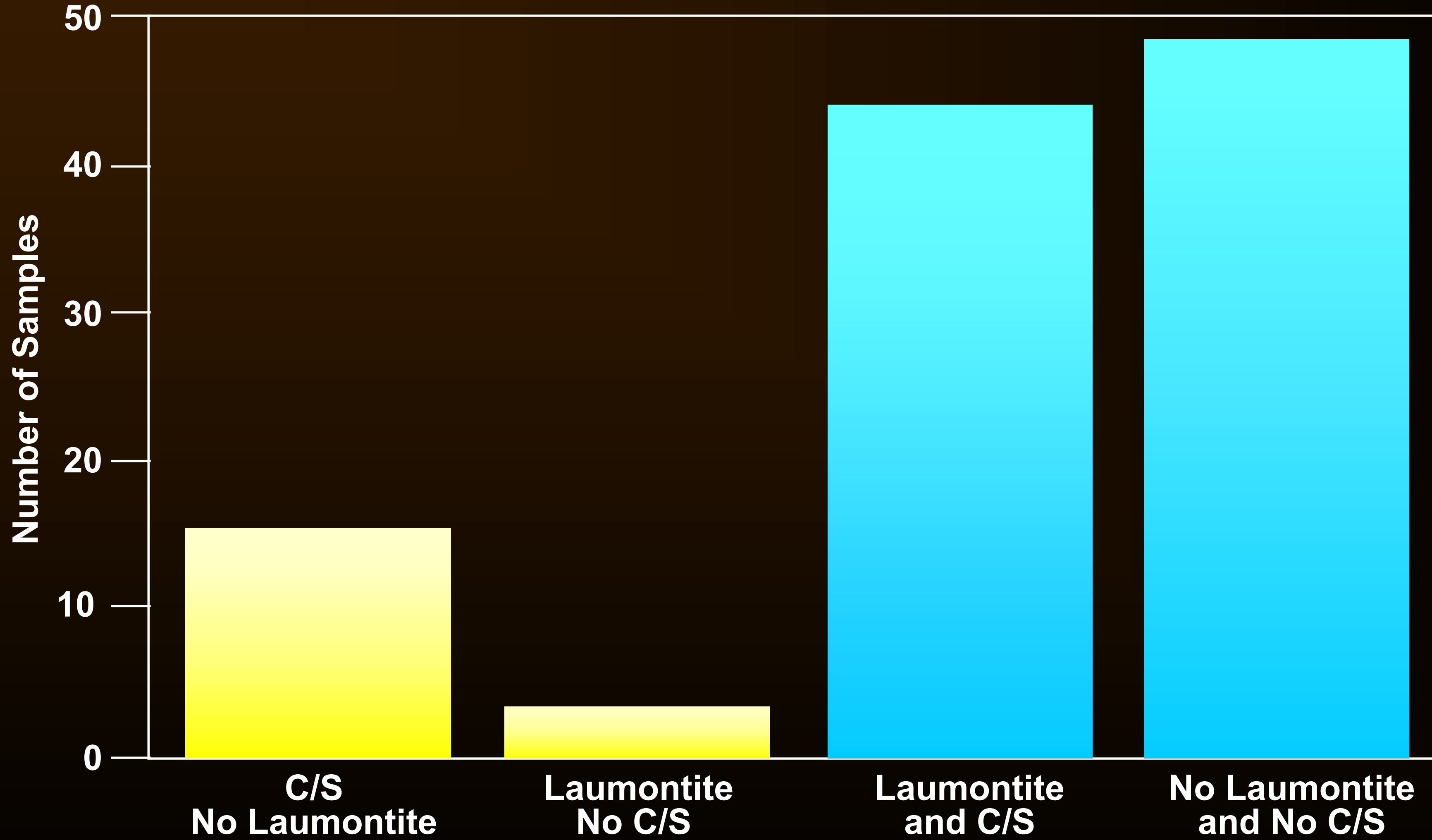
Clinoptilolite Occurs Only Below 215° F



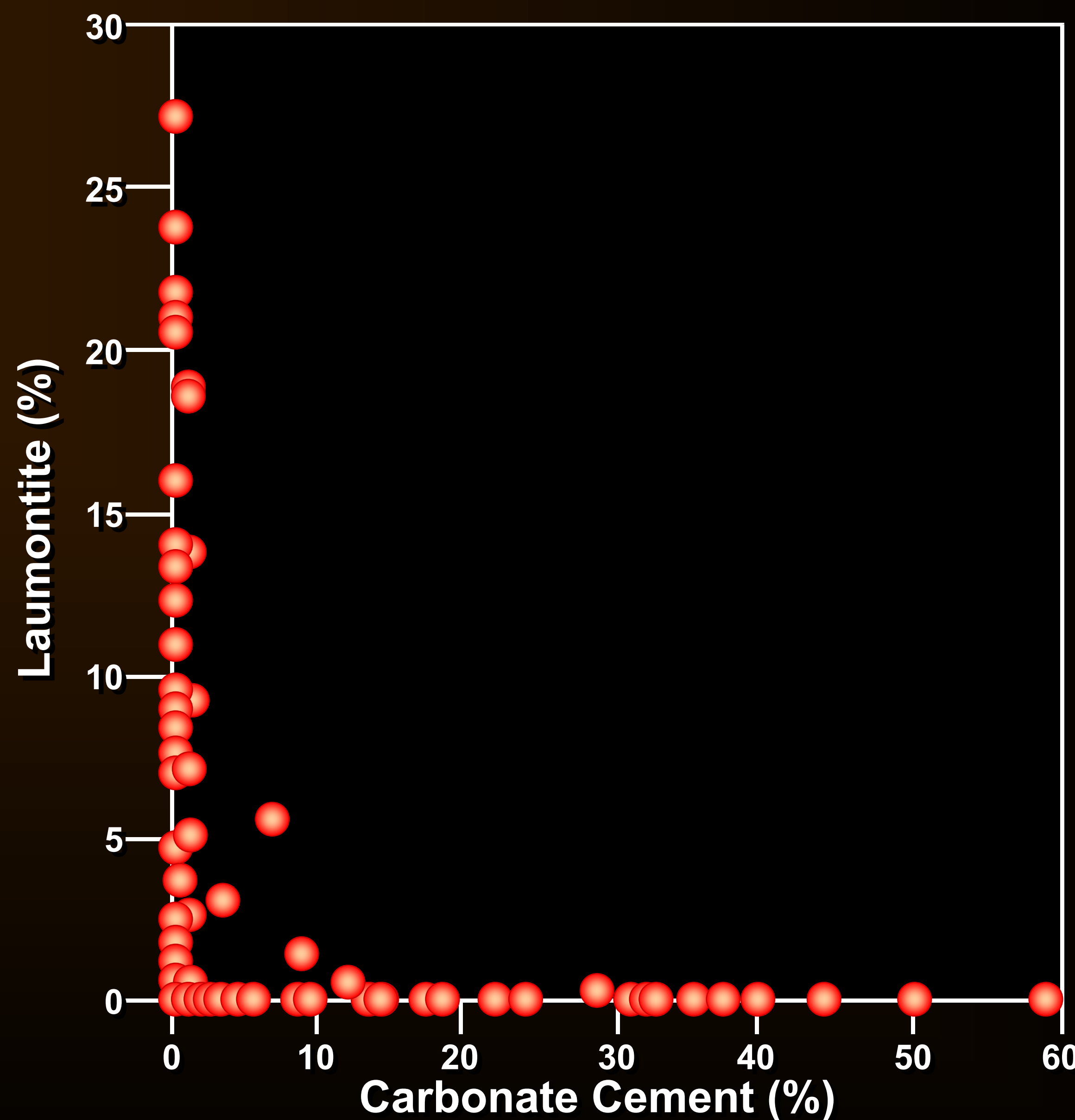
Laumontite Occurs Only Above 215° F



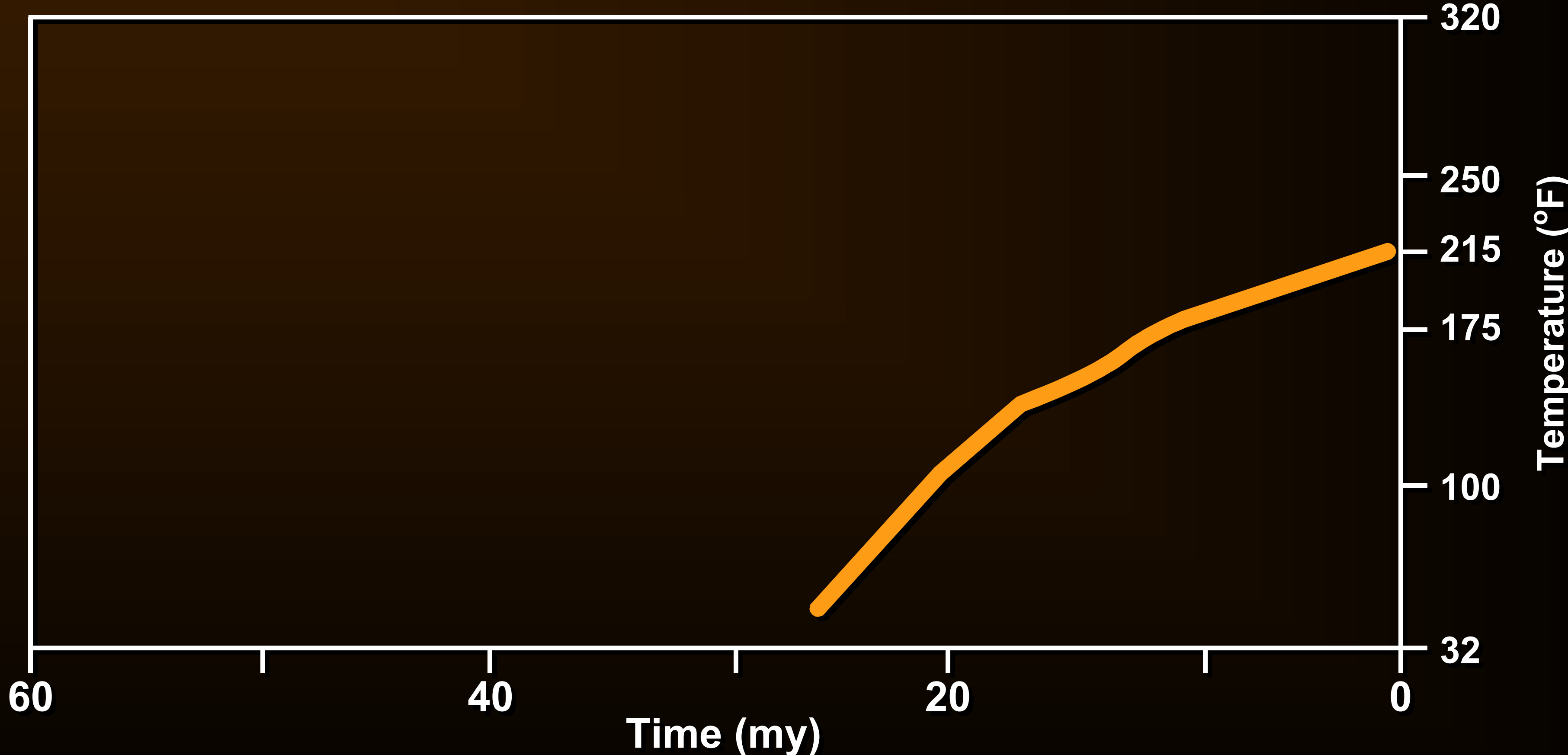
Chlorite/Smectite and Laumontite Display a Sympathetic Relationship on a Thin-Section Scale



Laumontite and Carbonate Cements Are Mutually Exclusive



Some of the Laumontite is Geologically Very Young



At Temperatures > 225° F, Zeolite Abundance in Zemorrian ss (late early & late Oligocene) Decreases from North to South (?)