GEOLOGIC NOTE

Pore-throat sizes in sandstones, tight sandstones, and shales

Philip H. Nelson

ABSTRACT

Pore-throat sizes in siliciclastic rocks form a continuum from the submillimeter to the nanometer scale. That continuum is documented in this article using previously published data on the pore and pore-throat sizes of conventional reservoir rocks, tight-gas sandstones, and shales. For measures of central tendency (mean, mode, median), pore-throat sizes (diameters) are generally greater than 2 μm in conventional reservoir rocks, range from about 2 to 0.03 μm in tight-gas sandstones, and range from 0.1 to 0.005 μm in shales. Hydrocarbon molecules, asphaltenes, ring structures, paraffins, and methane, form another continuum, ranging from 100 Å (0.01 μm) for asphaltenes to 3.8 Å (0.00038 μm) for methane. The pore-throat size continuum provides a useful perspective for considering (1) the emplacement of petroleum in consolidated siliciclastics and (2) fluid flow through fine-grained source rocks now being exploited as reservoirs.

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Phil Nelson is a member of the Central Energy Resources Team of the U.S. Geological Survey, which provides assessments of undiscovered oil and gas. He held research positions in mineral exploration with Kennecott Exploration Services, radioactive waste storage with Lawrence Berkeley Laboratory, and petroleum production with Sohio Petroleum Company. His current interests are in the characteristics of tight-gas resources and the pressure and temperature regimes of sedimentary basins.

ACKNOWLEDGEMENTS

Encouragement and comments for expansion and elaboration of the pore-throat spectrum came from several people, including G. Beck of EOG Resources; R. Merkel of Newfield Exploration Company; D. Houseknecht, M. Lewan, N. Fishman, and P. Hackley of the U.S. Geological Survey; and AAPG reviewers T. Olson, V. Hitchings, and R. Worden.

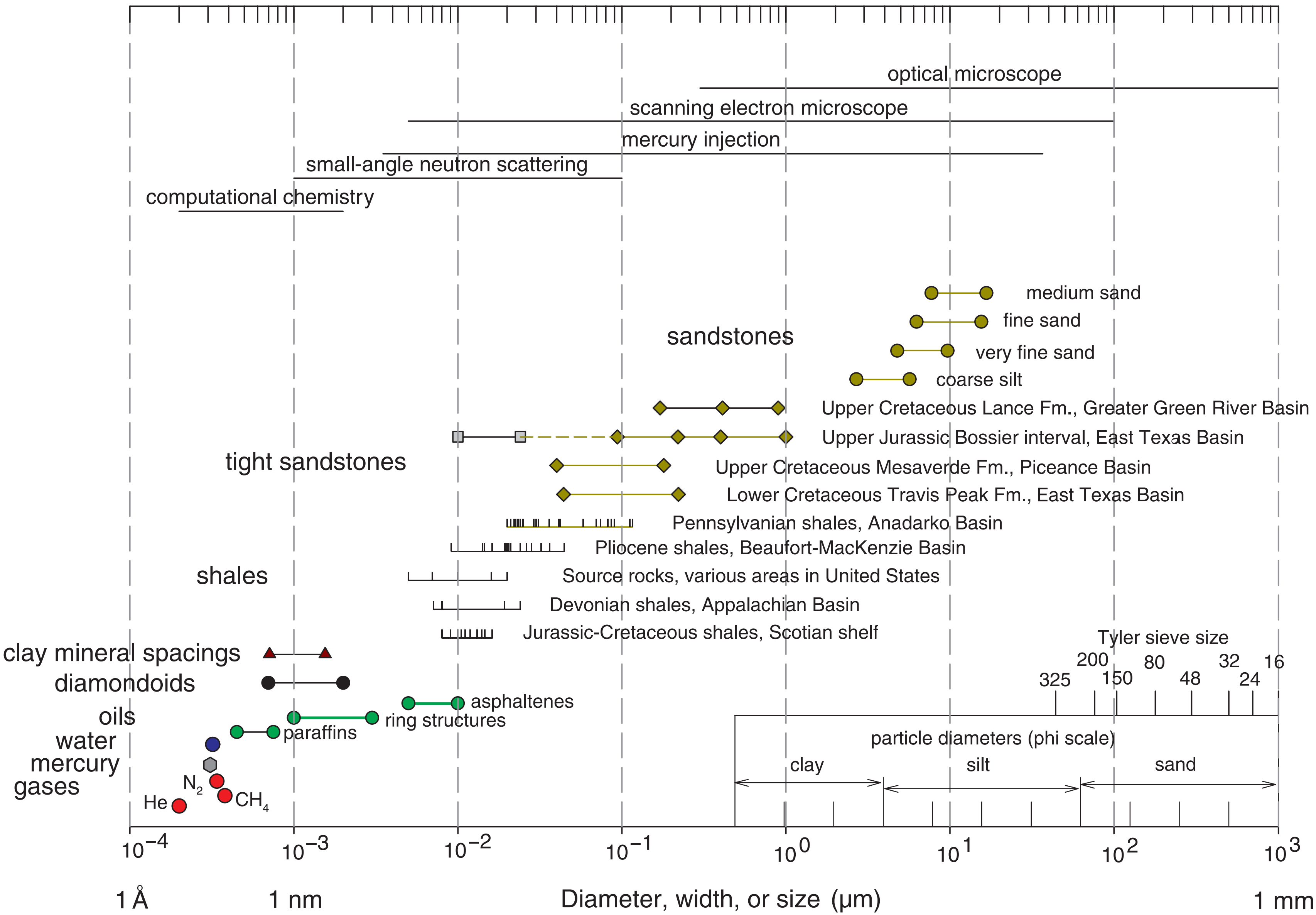

Figure 2. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.

Table 1. Summary of Measurements of Pore-Throat Size and Other Parameters for Siliciclastic Rocks, Selected from Published Sources*

Source of Samples	No.**	Pore-Throat Diameter (μm)			Method**	Model**	Statistic**	Porosity (%)	Permeability	Depth (ft)
		Min.	Max.	Avg.						
Medium-grained sandstones, various, worldwide	3	9.000	23.000	16.667	Hg	C	ET	14	25.5 md	6560
Fine-grained sandstones, various, worldwide	12	4.000	30.000	15.500	Hg	C	ET	18.1	19.6 md	6560
Very fine-grained sandstones, various worldwide	6	8.000	13.000	9.667	Hg	C	ET	24.2	109.7 md	6560
Coarse siltstones, various, worldwide	6	4.000	7.000	5.667	Hg	C	ET	26.3	22.3 md	6560
Upper Cretaceous Lance Formation, Greater Green River Basin	7	0.362	2.520	0.895	Hg	C	ET	7.5	17.7 μd	8713
Upper Jurassic Bossier interval, East Texas Basin, reservoir rock	9	0.094	1.000	–	Hg	C	MO	7.5	12.2 μd	12,000
Upper Jurassic Bossier interval, East Texas Basin, nonreservoir rock	4	0.010	0.024	–	Hg	C	MO	4.5	0.25 μd	12,000
Upper Cretaceous Mesaverde Formation, Piceance Basin	44	0.040	0.180	–	gas	T	CO	7	2.1 μd	6513
Lower Cretaceous Travis Peak Formation, East Texas Basin	13	0.044	0.220	0.118	gas	T	CO	4.9	1.5 μd	9347
Pennsylvanian shales, Anadarko Basin	21	0.020	0.116	0.050	Hg	C	ET	–	–	12,354
Pliocene shales, Beaufort-Mackenzie Basin	20	0.009	0.044	0.023	Hg	C	GM	7.5	–	8885
Source rocks, various, United States	5	0.005	0.020	0.012	V	S	ME	–	–	–
Devonian shales, Appalachian Basin, organic poor	6	0.007	0.008	0.008	Hg	C	ME	7.2	1.4 μd	Outcrop
Devonian shales, Appalachian Basin, organic rich	6	0.019	0.024	0.022	Hg	C	ME	3.6	5.1 nd	Outcrop
Jurassic and Cretaceous shales, Scotian shelf	10	0.009	0.016	0.012	Hg	C	GM	4.9	1.9 nd	16,800

*The pore-throat-size ranges and averages given here do not match values shown in Figure 2 in all cases. Porosity value is the arithmetic average; permeability value is the geometric mean; depth value is the average depth. Further details and references are given in the text.

**No. = number of samples. Method: Hg = mercury injection; gas = gas flow; V = both mercury injection and small angle neutron scattering. Model: C = cylindrical capillary; T = tabular; S = spherical in the case of small angle neutron scattering. Statistic: ET = entry threshold; MO = mode; CO = computational; GM = geometric mean; ME = median.

It's A Small World After All - The Pore Throat Size Spectrum*

Philip H. Nelson[1]

Search and Discovery Article #50218 (2009)
Posted January 19, 2010

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Denver, Colorado, June 7-10, 2009

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Abstract

As extraction of oil and gas from poor-quality reservoir rocks becomes more prevalent in the United States, knowledge of the size and character of pore throats and pore space in these reservoirs with respect to their potential for producing hydrocarbons becomes even more important than in the past. This small "world", which ranges from angstroms to nearly a millimeter, is viewed through such tools as the optical microscope, scanning electron microscope, mercury injection and computational chemistry. Permeability provides a length scale that is strongly, but not uniquely, related to pore-throat size. Nor can pore-throat size be determined unambiguously with other techniques. Each method of investigation, whether microimaging, mercury injection or gas-flow experiments, requires a physical model of pore-throat geometry in order to convert the measurements to a microscopic size. The choice of a flow model influences the choice of a statistic (mean, median or single value) to represent pore-throat size in a given sample. Experimental results drawn from past studies are combined into a spatial spectrum to help envision the relations among pore-throat sizes in sandstones, tight sandstones and shales.

Selected References

Katz, A.J. and A.H. Thompson, 1986, Quantitative prediction of permeability and electrical conductivity in porous rock, *in* Society of Exploration Geophysicists, 56th annual meeting: SEG Abstracts, v. 1, p. 6-7.

Luffel, D.L., W.E. Howard, and E.R. Hunt, 1991, Travis Peak core permeability and porosity relationships at reservoir stress: SPE Formation Evaluation, v. 6/3, p. 310-318.

Luffel, D.L., K.L. Herrington, and C.W. Harrison, III., 1991, Fibrous illite controls productivity in Frontier gas sands, Moxa Arch, Wyoming, *in* J.W. Crafton, chairperson, Proceedings; SPE Rocky Mountain regional; Low permeability reservoirs symposium and exhibition, p. 695-704.

Nelson, P.H., 2009, Pore throat sizes in sandstone, tight gas sandstones and shales: AAPG Bulletin, v. 93/3, p. 329-340.

Wardlaw, N.C. and J.P. Cassan, 1979, Oil recovery efficiency and the rock-pore properties of some sandstone reservoirs: Canadian Petroleum Geology, Bulletin v. 27/2, p. 117-138.

It's a small world after all-- The pore throat size spectrum

Phil Nelson

June, 2009

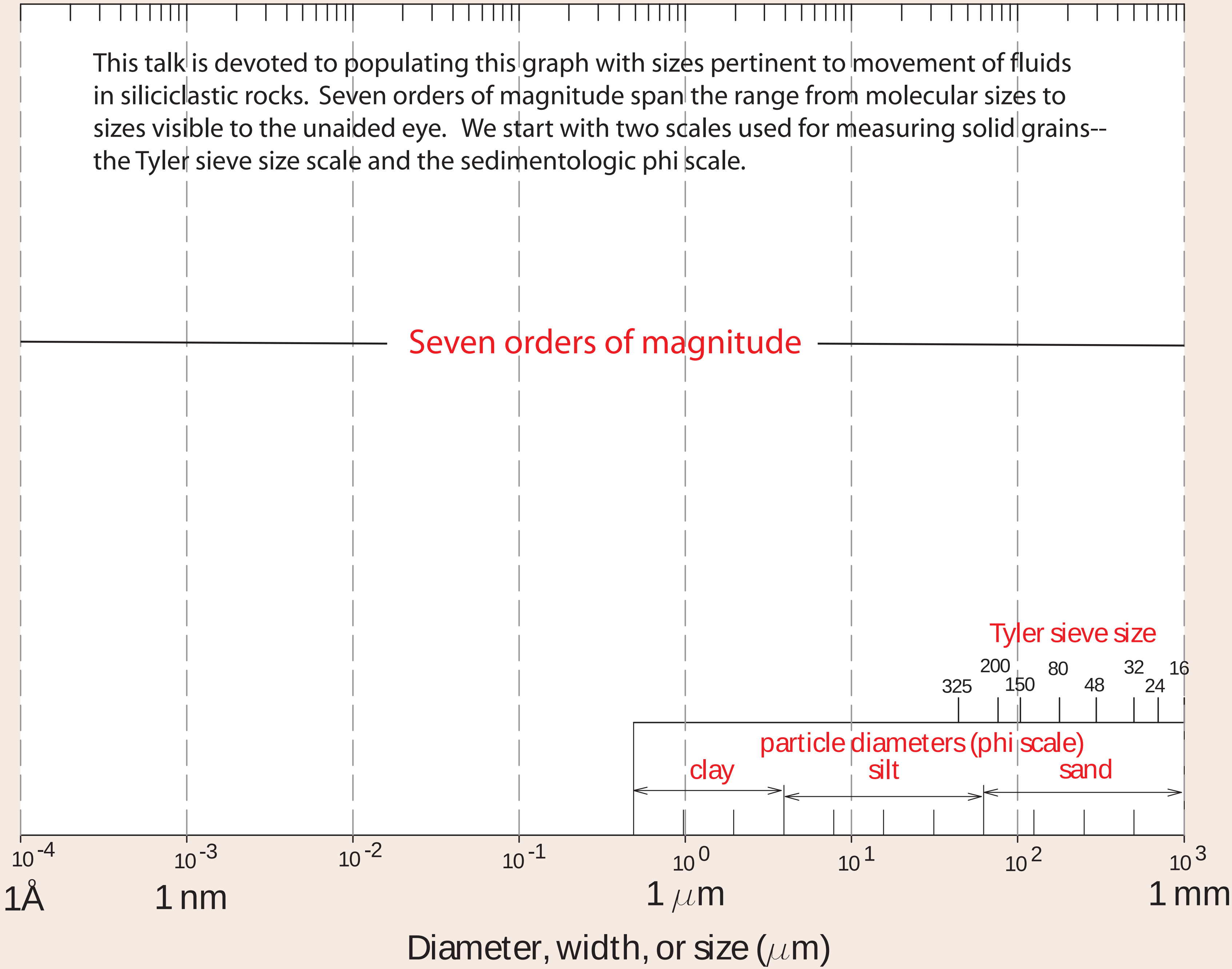
USGS
science for a changing world

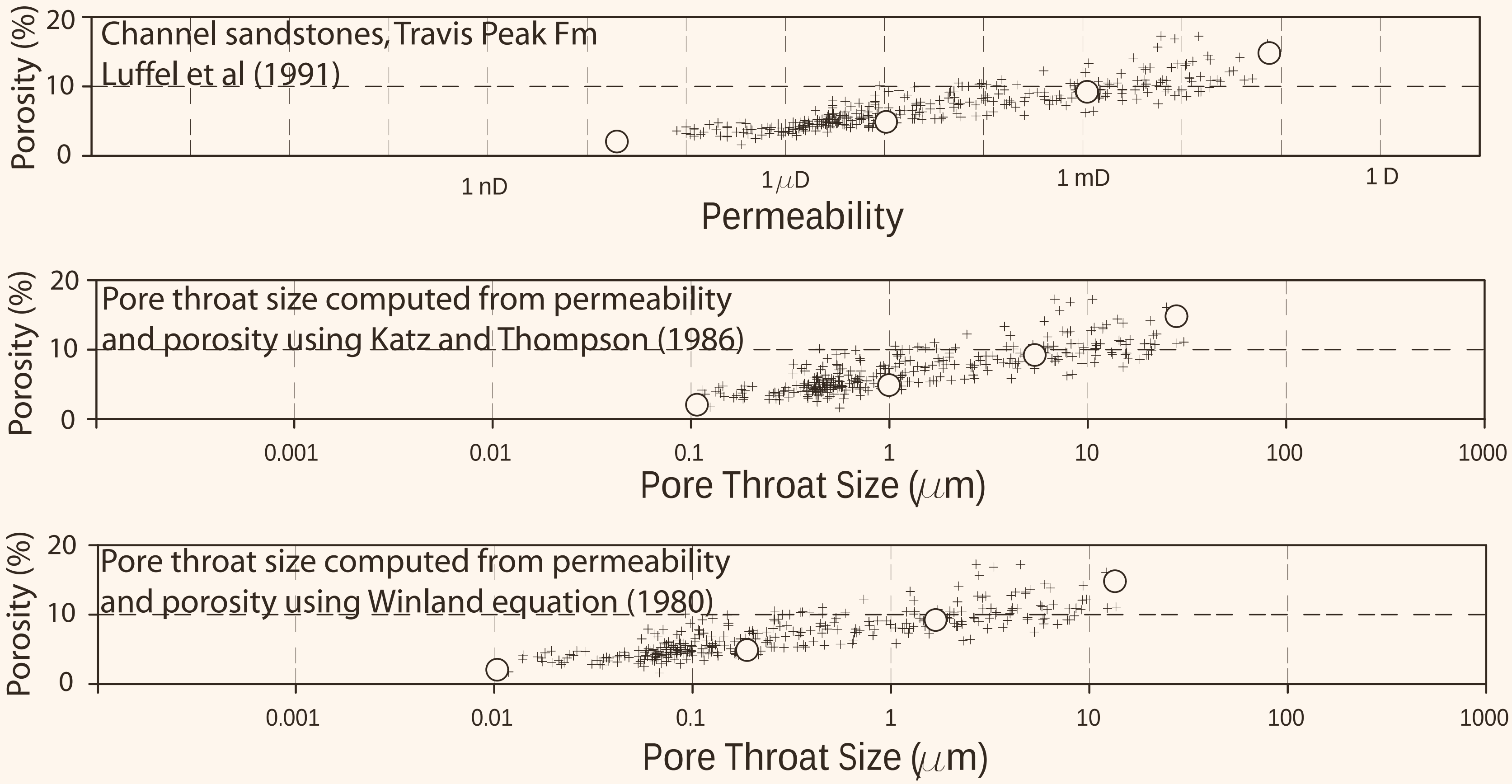
This talk is an elaboration of a short paper:

Nelson, P.H., 2009, Pore throat sizes in sandstones, tight gas sandstones, and shales, American Association of Petroleum Geologists Bulletin, v. 93, n. 3, p. 329-340.

References for information given on the following slides are cited in the paper.

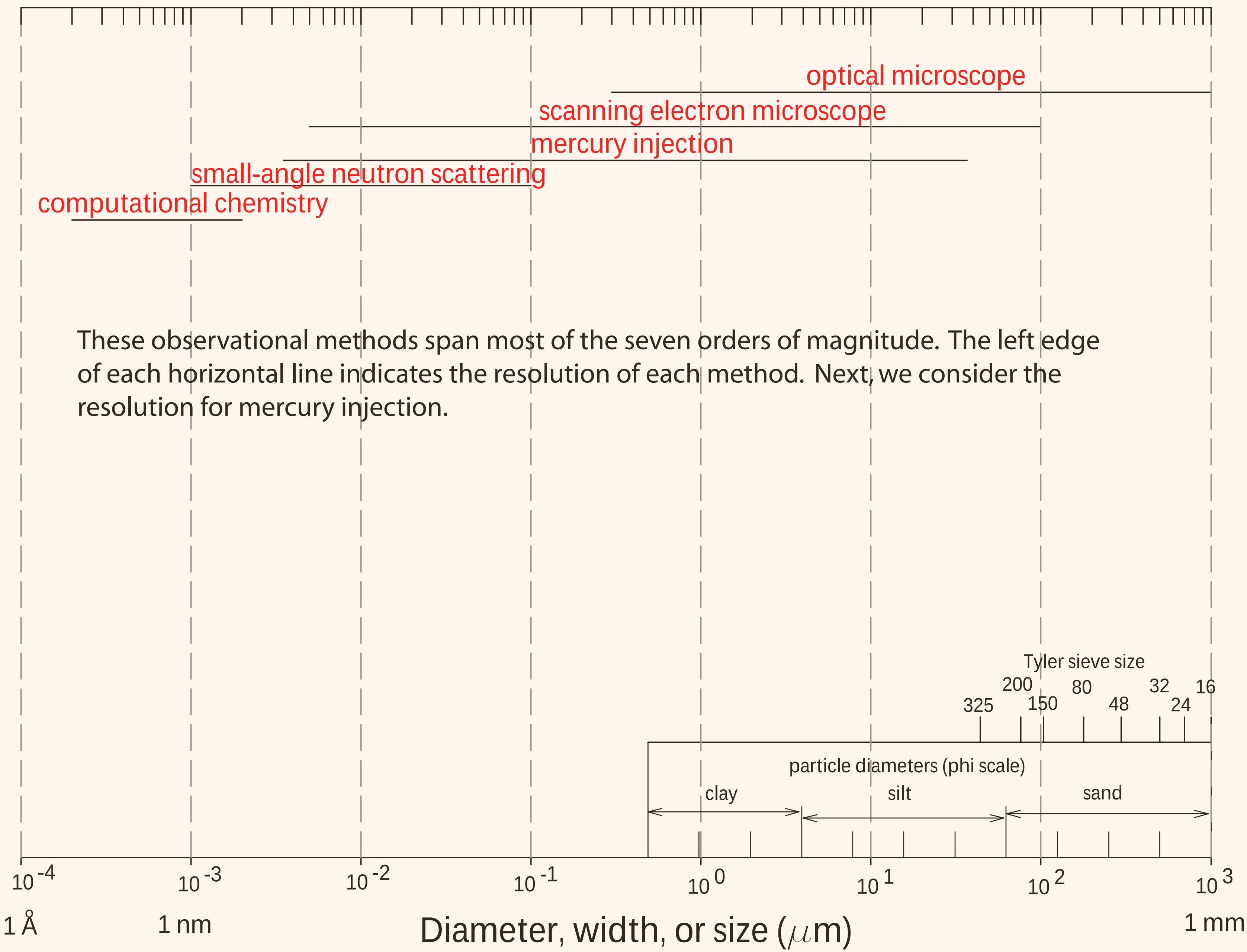
This talk is devoted to populating this graph with sizes pertinent to movement of fluids in siliciclastic rocks. Seven orders of magnitude span the range from molecular sizes to sizes visible to the unaided eye. We start with two scales used for measuring solid grains--the Tyler sieve size scale and the sedimentologic phi scale.





Although we specify permeability in units of darcies (D), millidarcies (mD), microdarcies (μD), or nanodarcies (nD), the physical dimension of permeability is the square of length. The permeability scale at the top is compressed so that two decades of permeability correspond to one decade of pore throat size. The two transforms used to compute a pore throat size give different results because the porosity factor differs between the two transforms. The four open circles show the migration of the two extremes and two intermediate permeability values.

Because using permeability data to derive a size presents some problems, other measurement methods will be used in the remainder of this discussion rather than permeability data.



These observational methods span most of the seven orders of magnitude. The left edge of each horizontal line indicates the resolution of each method. Next, we consider the resolution for mercury injection.

Capillary pressure in cylindrical capillary at static equilibrium:

$$P(\text{dynes}) = 2\,\sigma\,(\text{dyne/cm})\,\cos\theta \,/\, R(\text{cm})$$

For a mercury-air system and converting to units of psi, um:

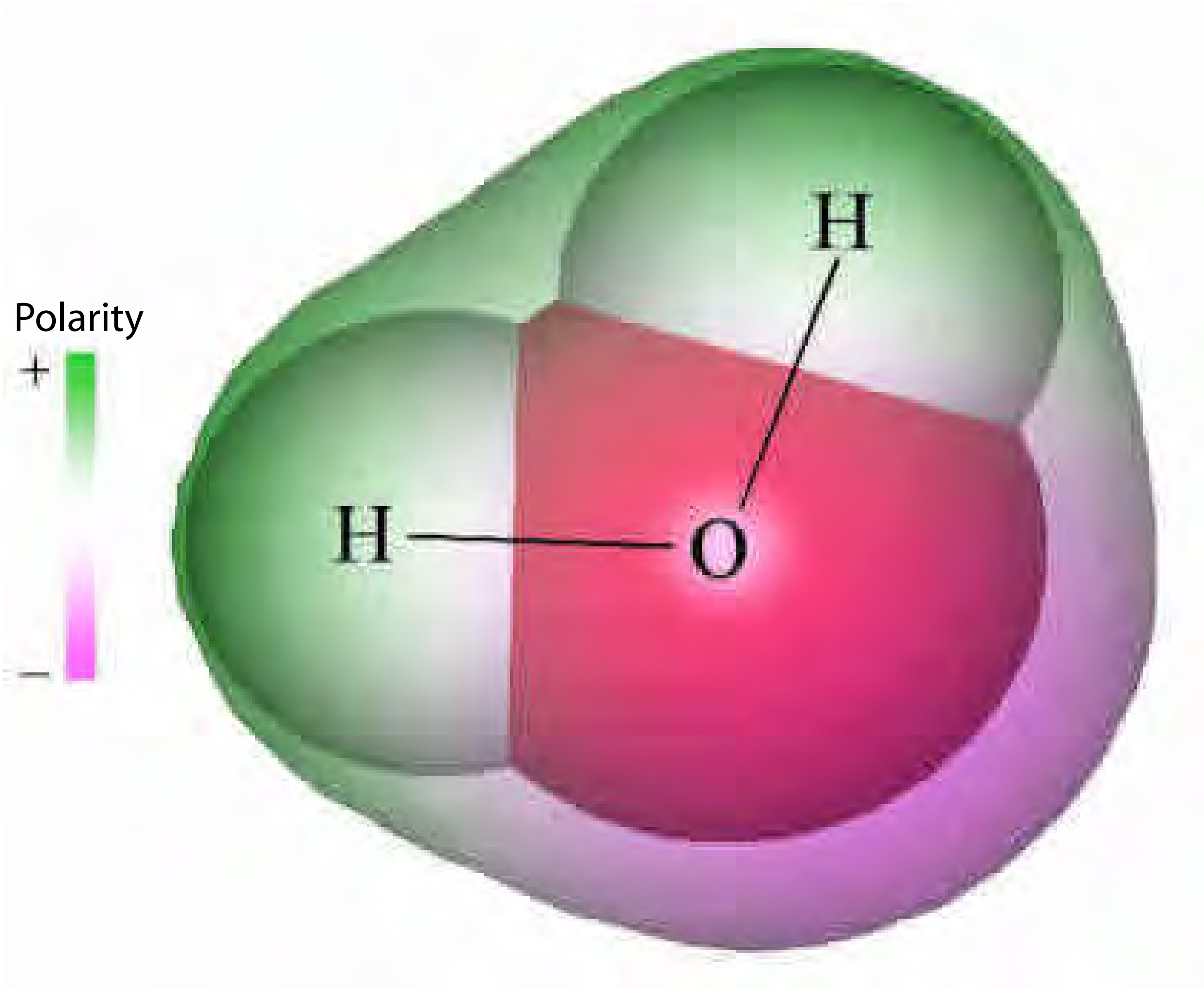
$$P\ (\text{psi}) = 213 \,/\, D(\mu\text{m})$$

At maximum pressure of 60,000 psi

$D(\mu m) = 213 / 60{,}000\ \text{psi} = 0.00355$

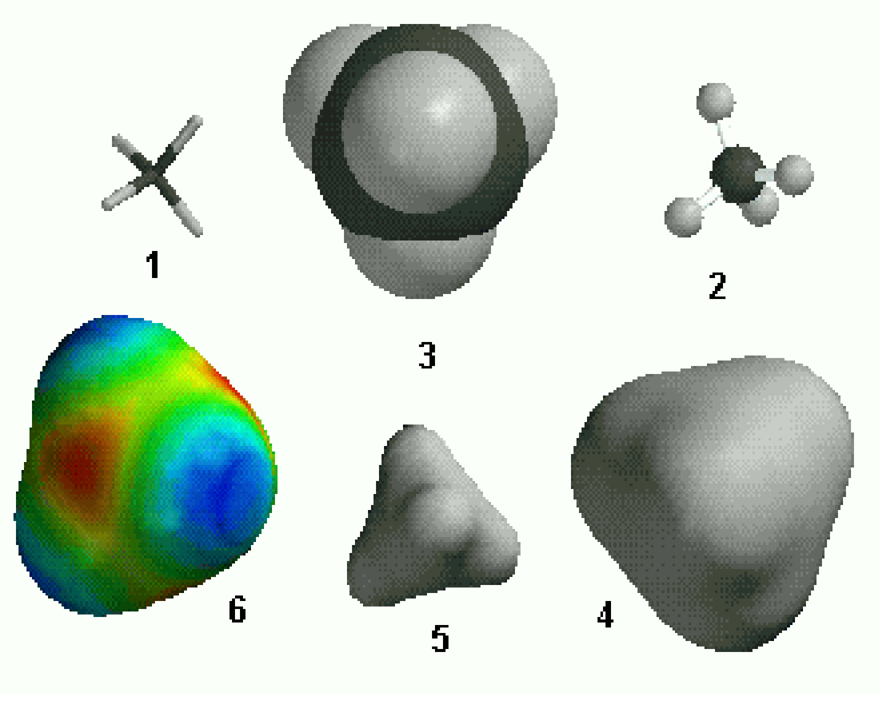
or $D = 3.55$ nm

Water Molecule

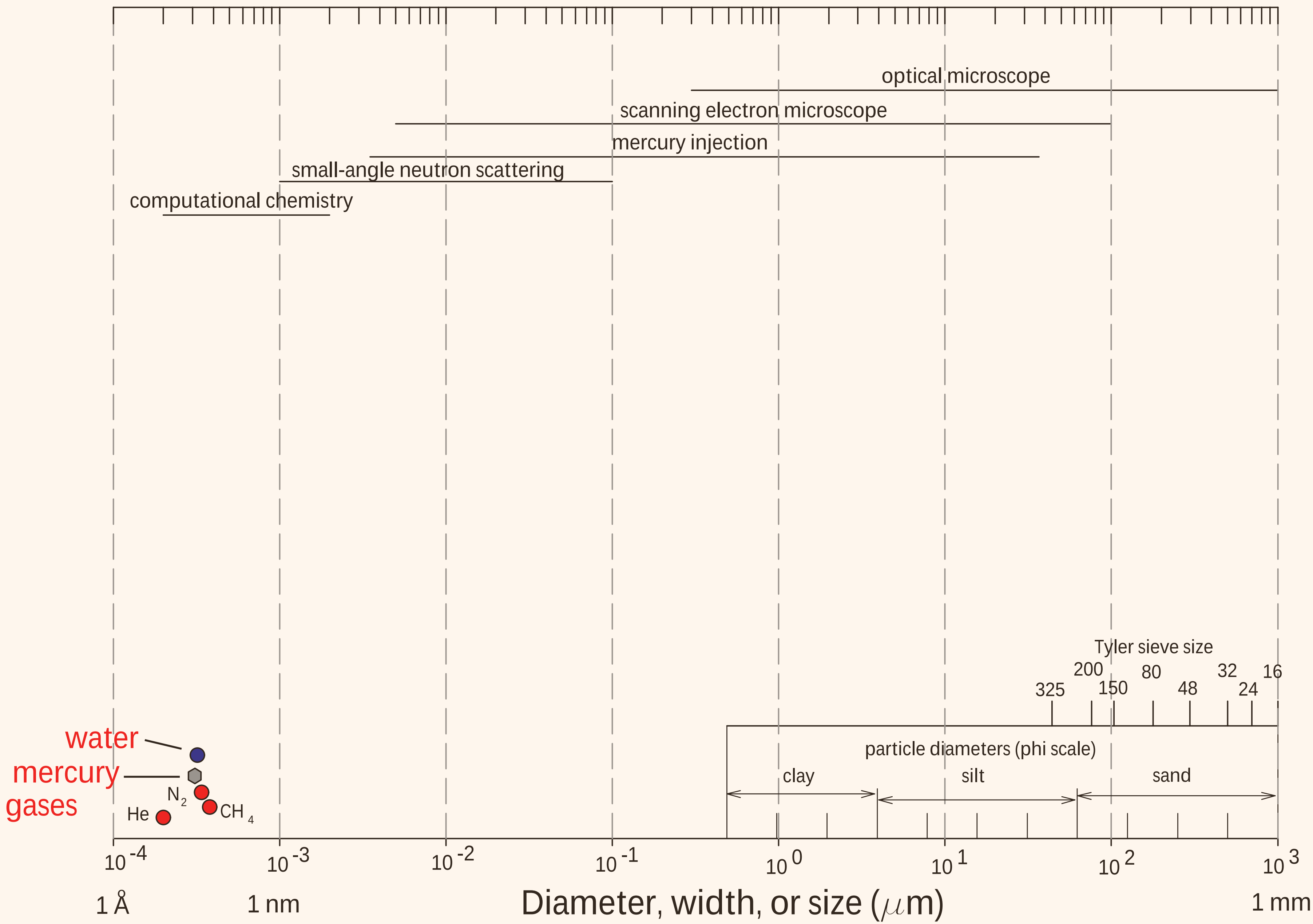


From:
http://www.lsbu.ac.uk/water/molecule.html

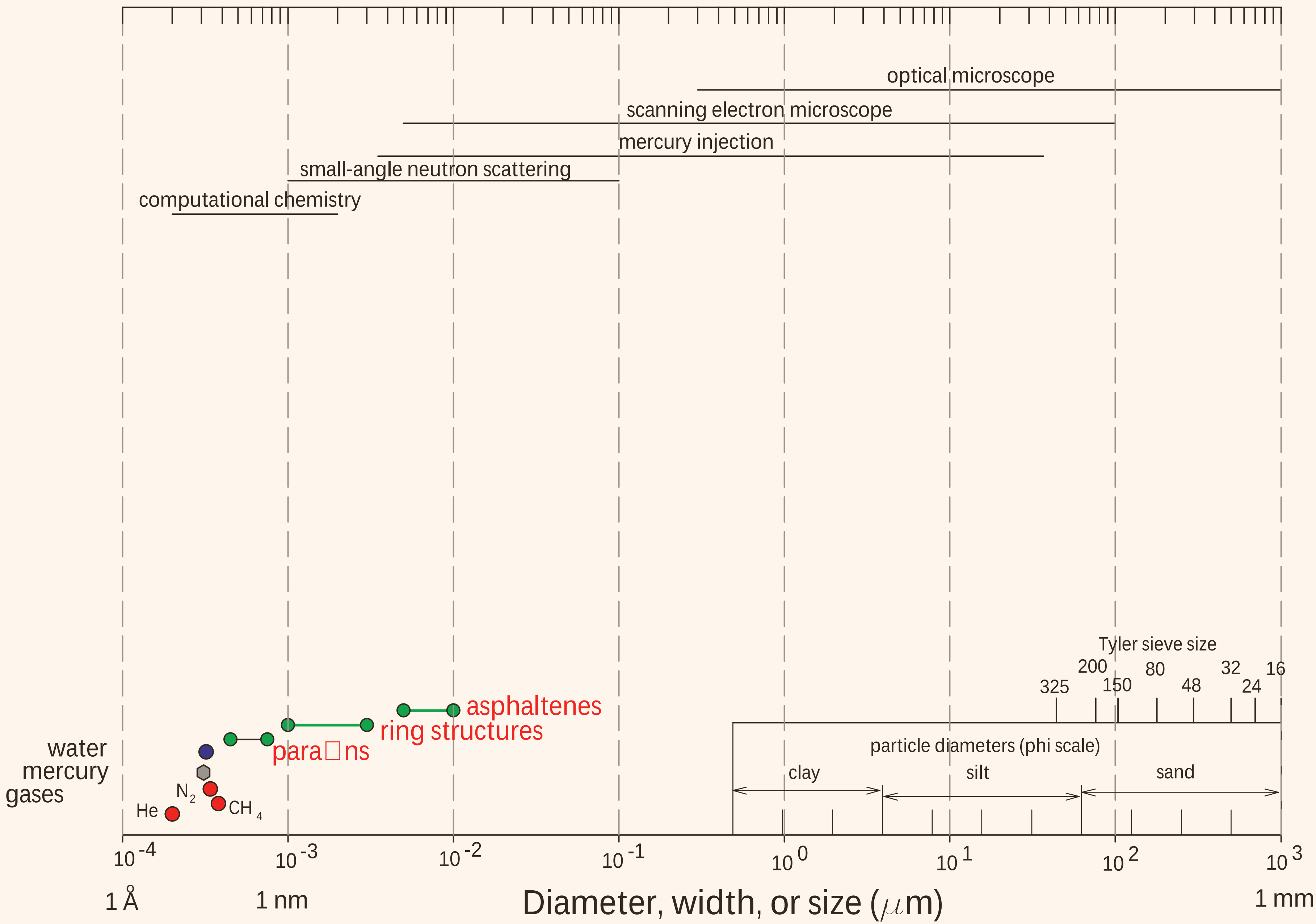
Methane



From:
http://courses.chem.psu.edu/chem38/mol-gallery/methane/methane.html

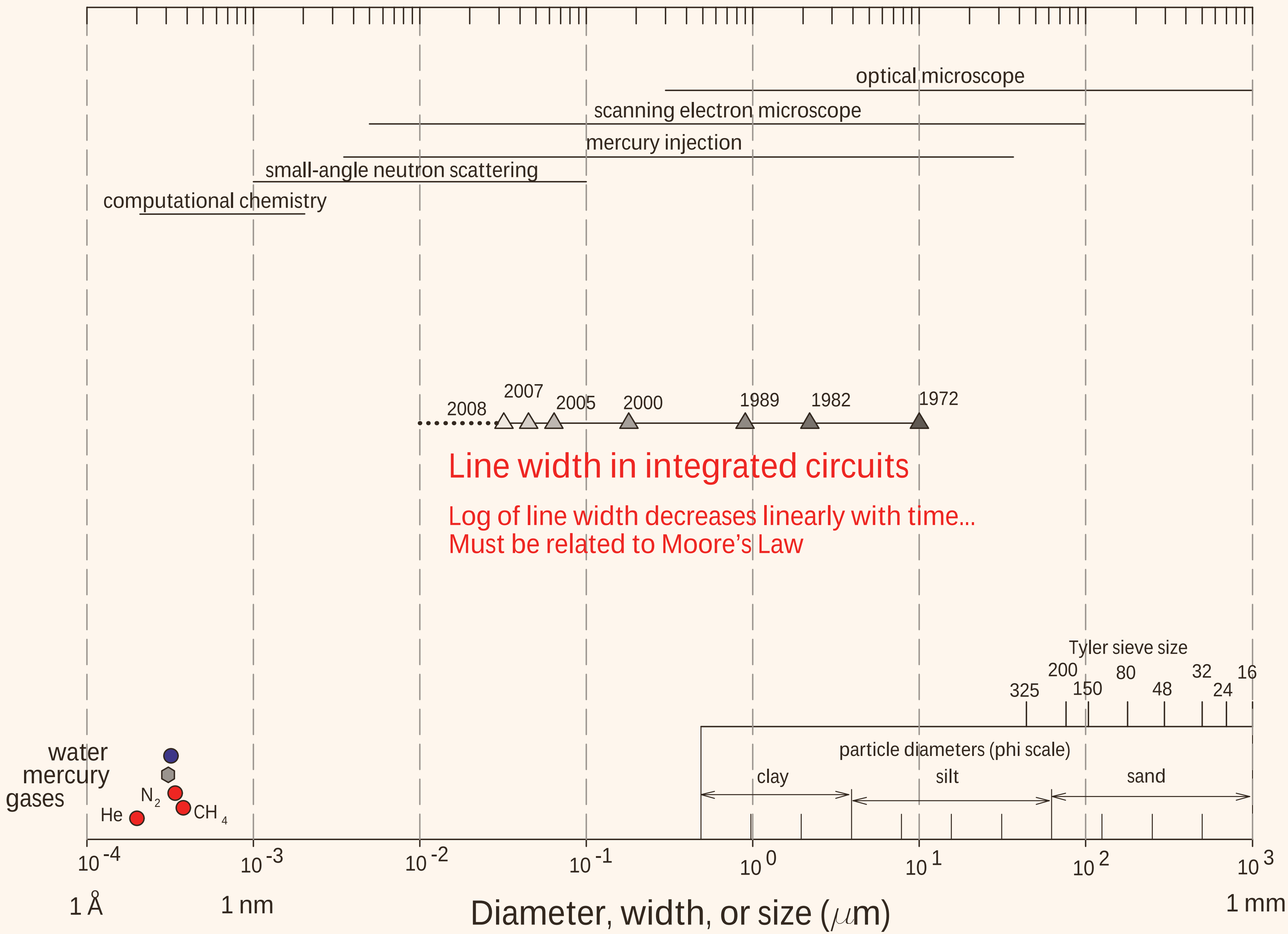


optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
N2
CH4
He
10 -4
10 -3
10 -2
10 -1
10 0
10 1
10 2
10 3
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

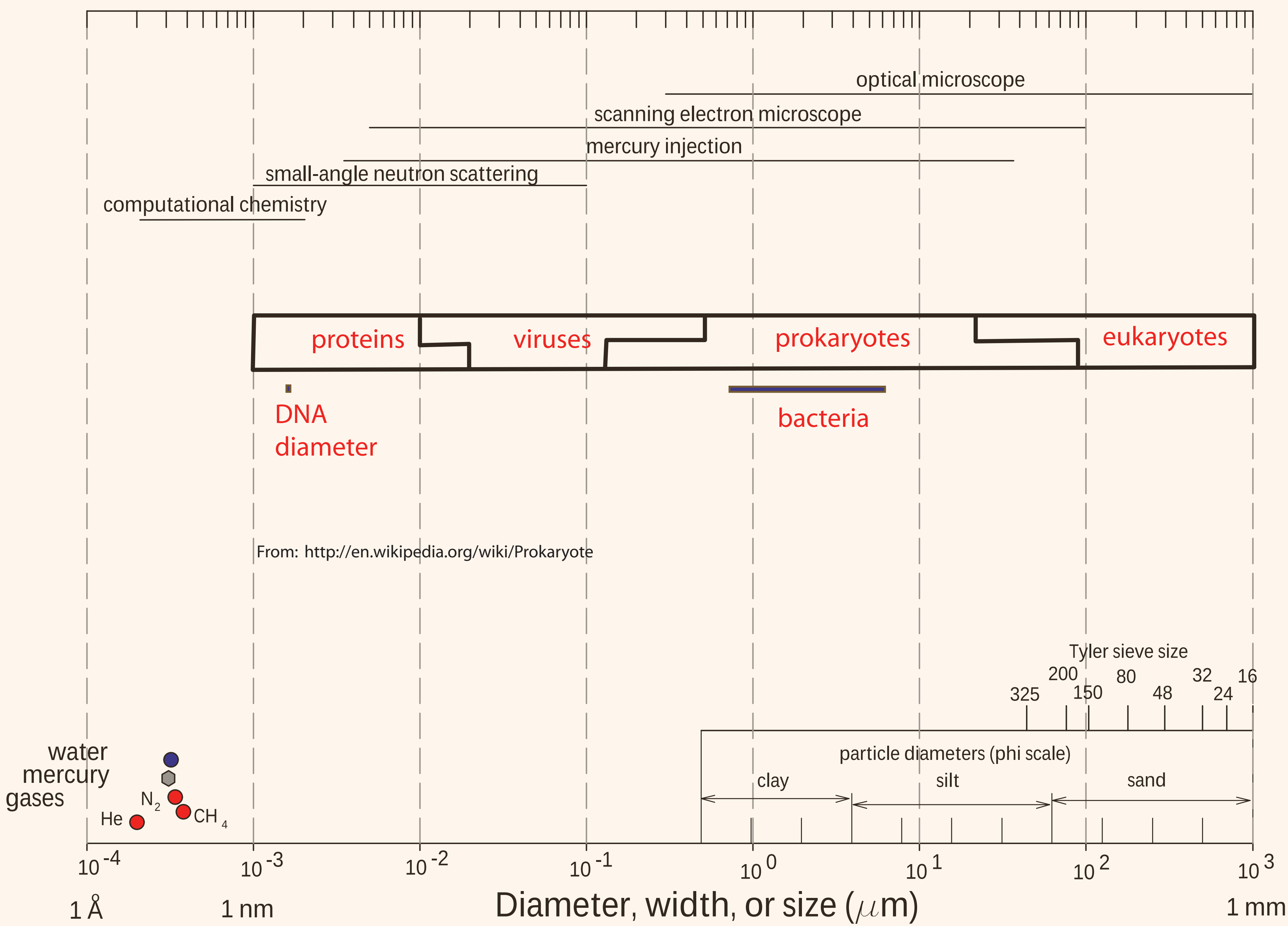

optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
Tyler sieve size
325
200
150
80
48
32
24
16
asphaltenes
ring structures
para□ns
water
mercury
gases
N_2
He
CH_4
particle diameters (phi scale)
clay
silt
sand
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

That's it for molecules. Before going on to rocks, in the next two slides consider two other areas of inquiry where the small world is of paramount interest:

(1) fabrication of integrated circuits and (2) biology.



optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
2008
2007
2005
2000
1989
1982
1972
Line width in integrated circuits
Log of line width decreases linearly with time...
Must be related to Moore's Law
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
N_2
He
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm



optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
proteins
viruses
prokaryotes
eukaryotes
DNA diameter
bacteria
From: http://en.wikipedia.org/wiki/Prokaryote
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
N_2
He
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

Wardlaw and Cassan (1979) measured 27 sandstone samples:

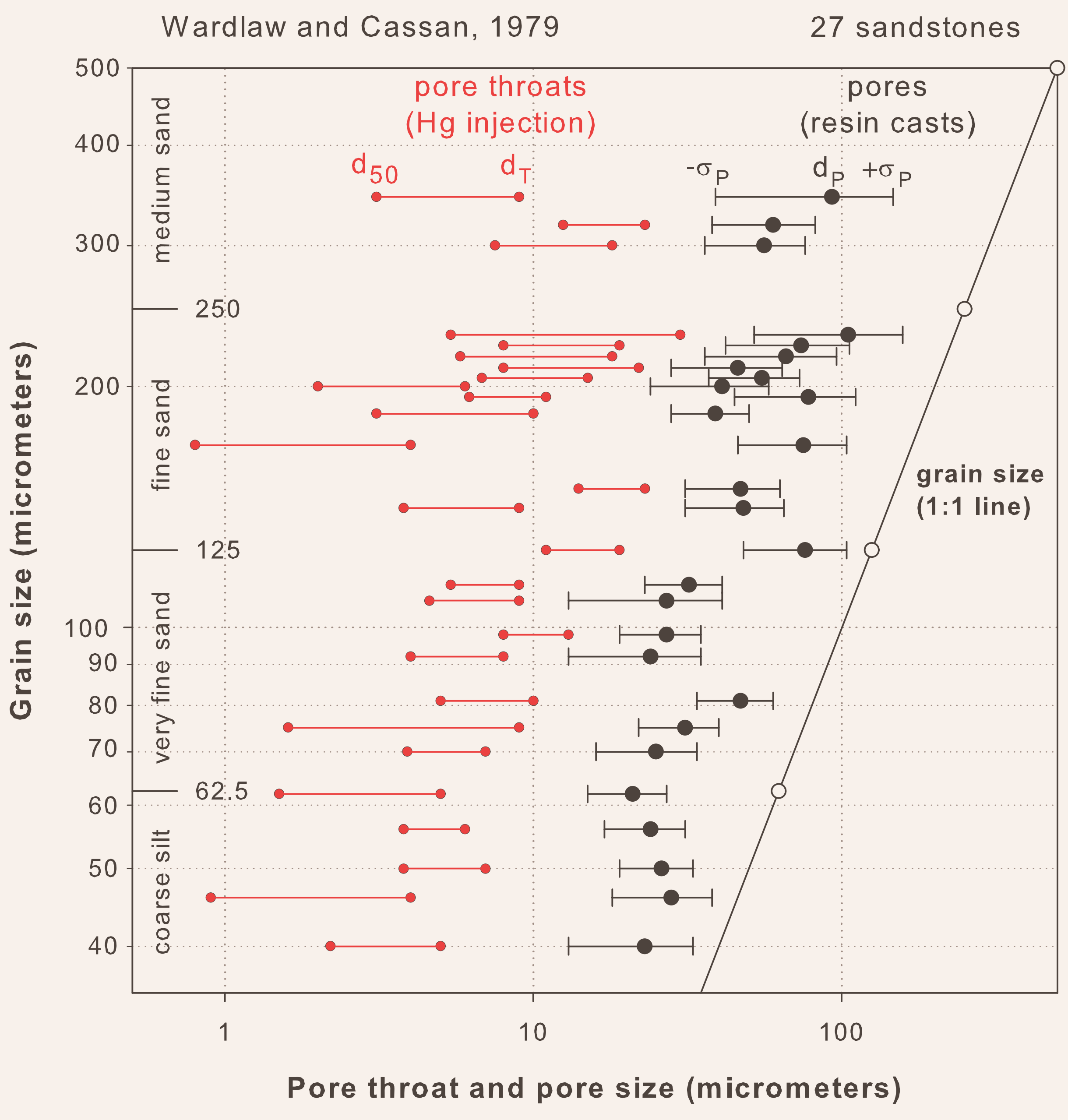
Mean particle size from thin section.

Mean pore size and standard deviation
from resin casts of pore space.

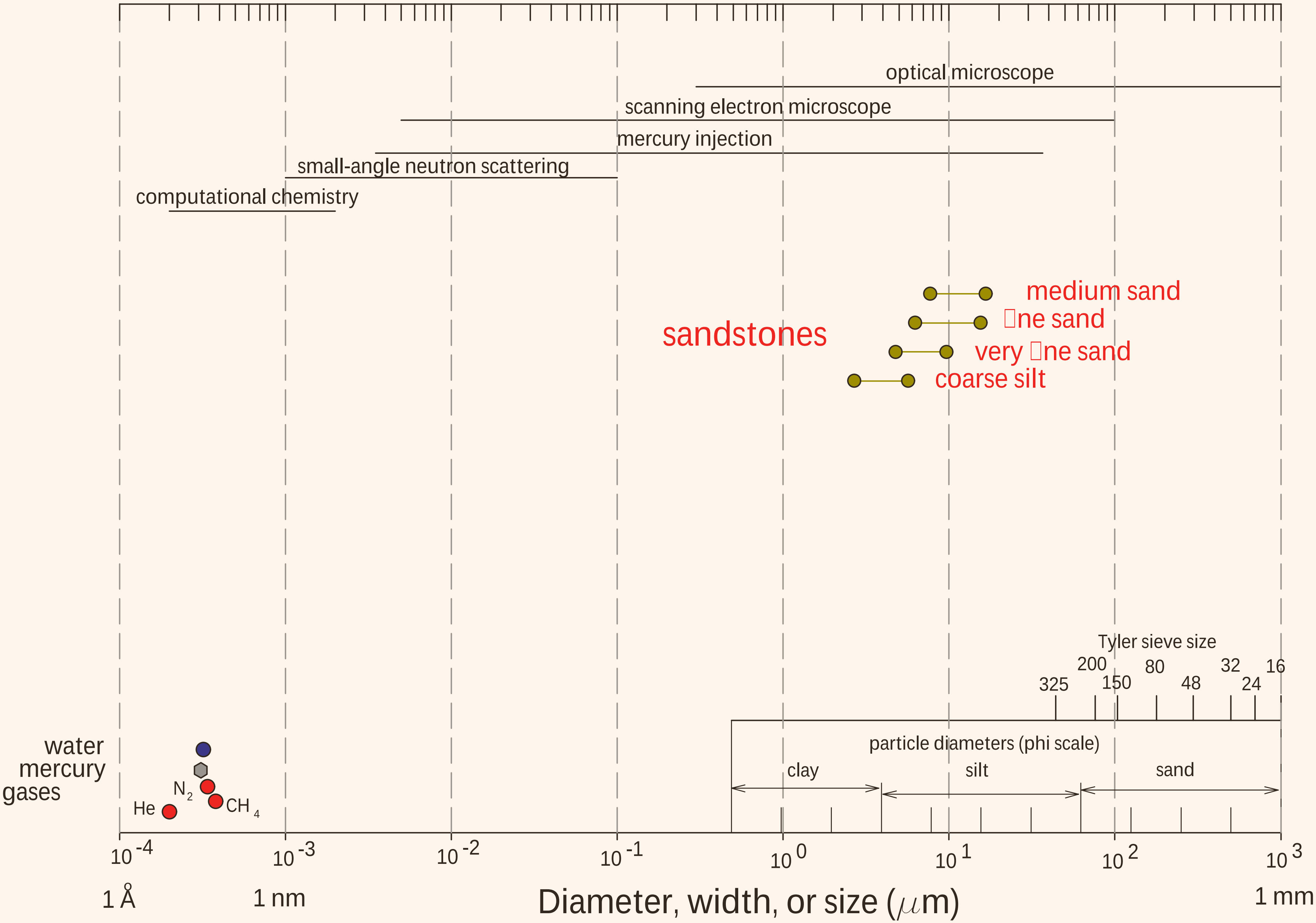
Pore throat diameter by mercury injection at threshold pressure
and at 50% mercury saturation.

The next slide shows their data on a plot similar to their original publication, where d_{50} represents the pore throat size at 50% mercury saturation and d_T represents the size at entry pressure.

The following slide shows their data plotted on the pore throat size spectrum. These data represent good quality reservoir sandstones.



Wardlaw and Cassan, 1979
27 sandstones
pore throats
(Hg injection)
pores
(resin casts)
d_{50}
d_T
$-\sigma_P$
d_P
$+\sigma_P$
medium sand
fine sand
very fine sand
coarse silt
250
125
62.5
grain size
(1:1 line)
500
400
300
200
100
90
80
70
60
50
40
1
10
100
Grain size (micrometers)
Pore throat and pore size (micrometers)

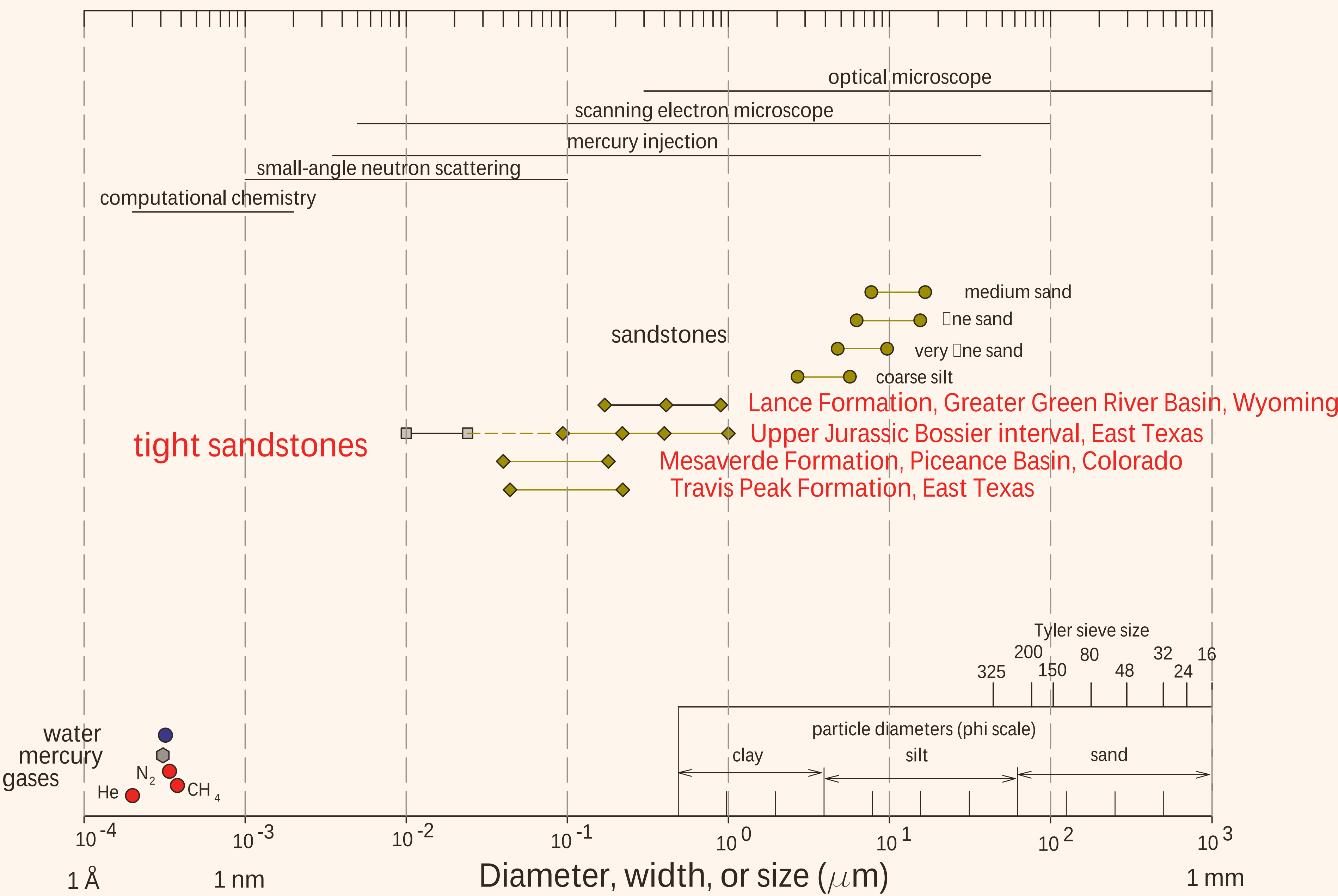


optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
sandstones
medium sand
ﬁne sand
very ﬁne sand
coarse silt
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
He
N_2
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

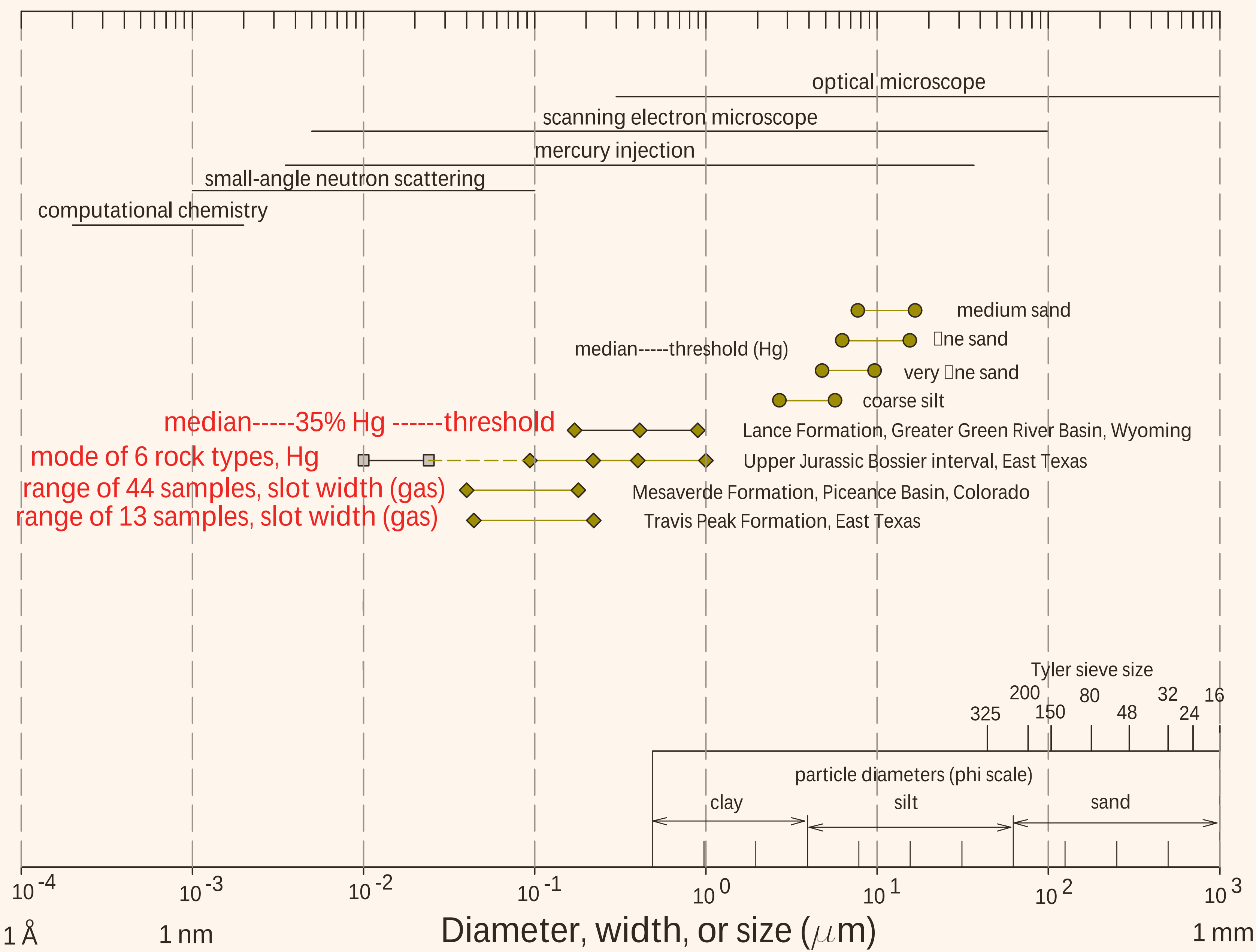
Slot-like pores have been observed in tight gas sandstones, as shown in the next slide. Some investigators use a slot pore model to compute pore throat size, instead of the cylindrical model used for mercury injection measurements.

Pore throat sizes for tight gas sandstones are plotted on the pore throat size spectrum -- values are generally less than one micrometer.

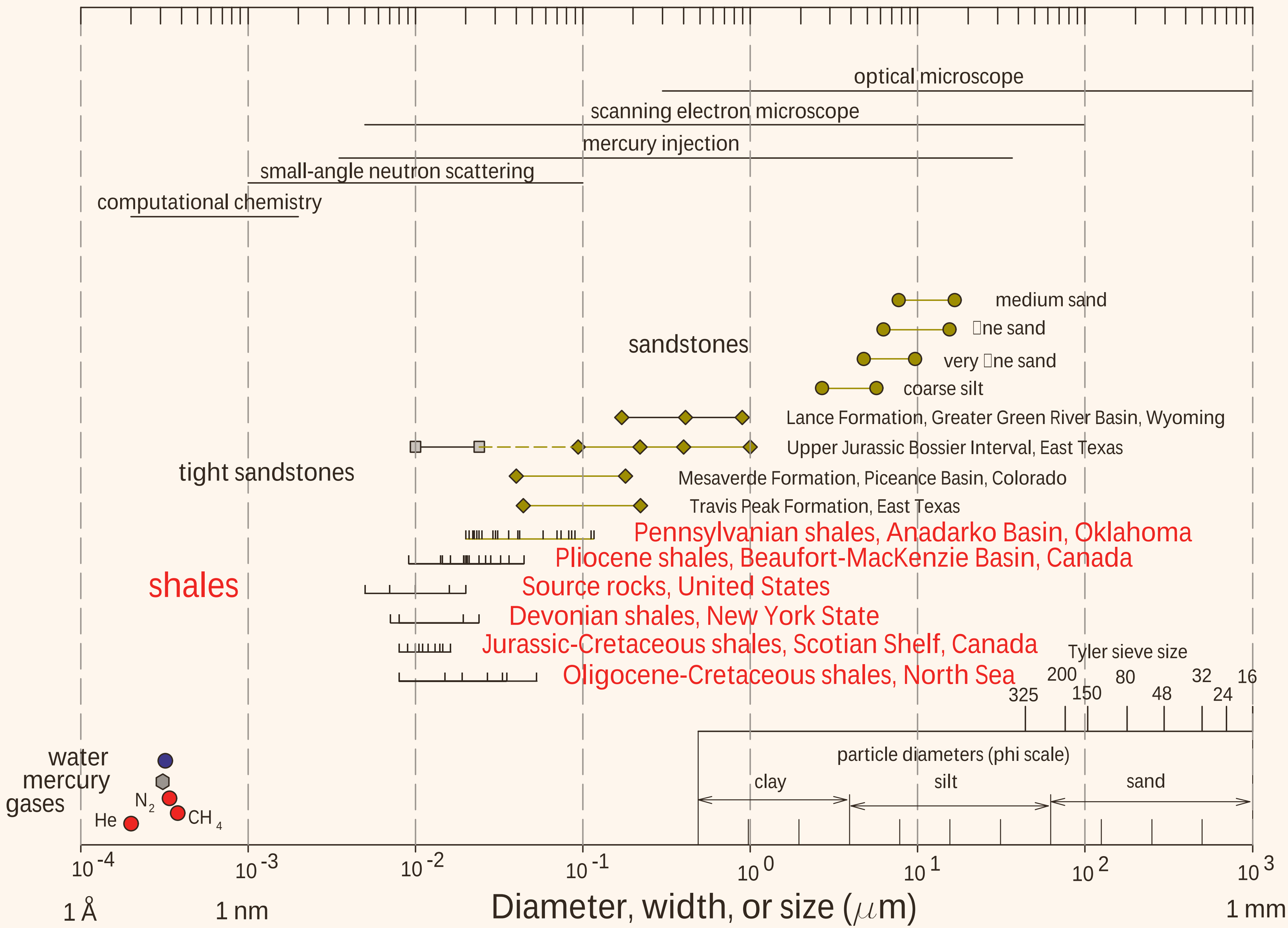
-5
10 m
MWX-3 5830 SLOT PORE 1400X
Provided by
Dan Soeder

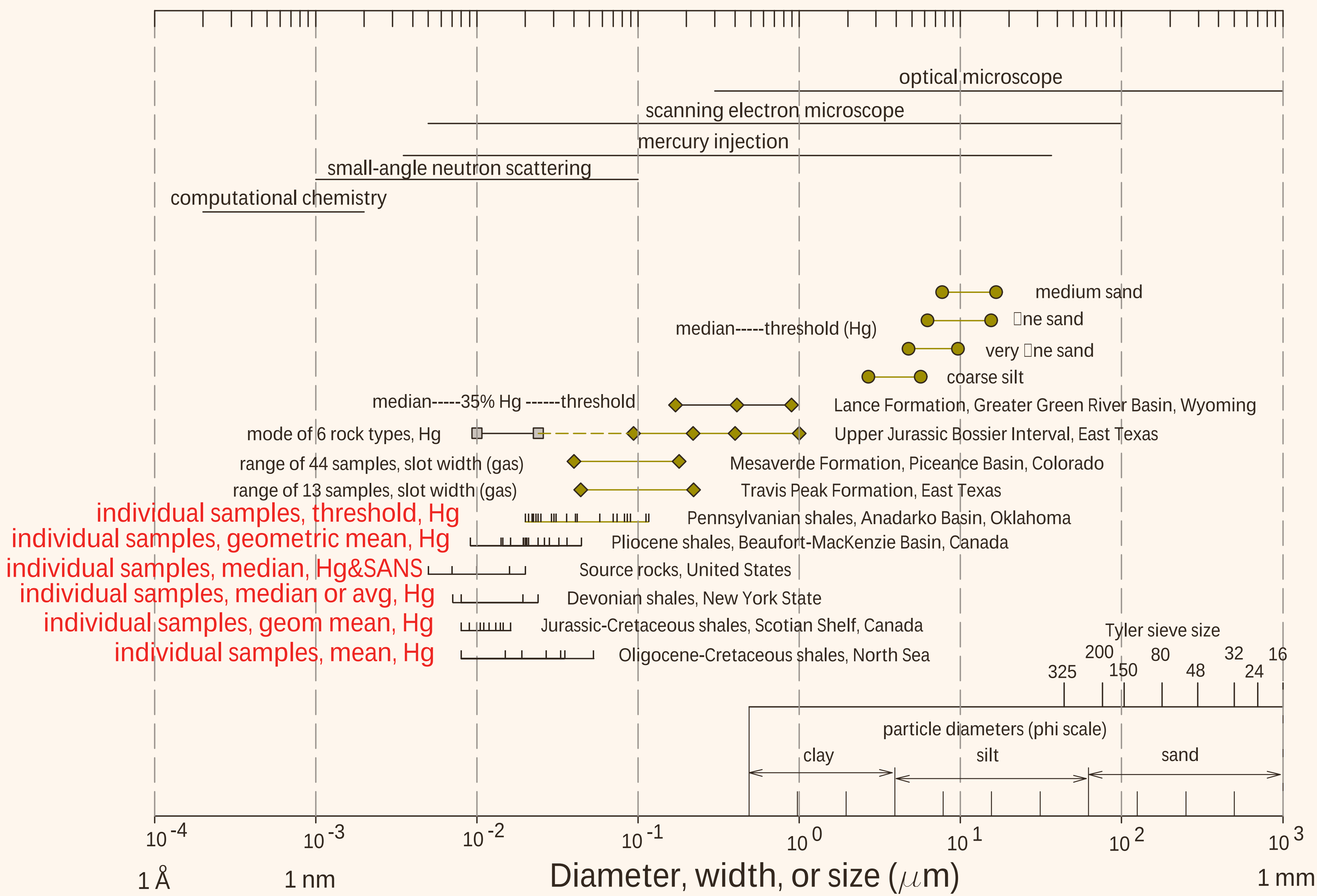


optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
medium sand
ﬁne sand
sandstones
very ﬁne sand
coarse silt
Lance Formation, Greater Green River Basin, Wyoming
tight sandstones
Upper Jurassic Bossier interval, East Texas
Mesaverde Formation, Piceance Basin, Colorado
Travis Peak Formation, East Texas
Tyler sieve size
200
80
32
16
325
150
48
24
water
mercury
gases
particle diameters (phi scale)
clay
silt
sand
N2
He
CH 4
10 -4
10 -3
10 -2
10 -1
10 0
10 1
10 2
10 3
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

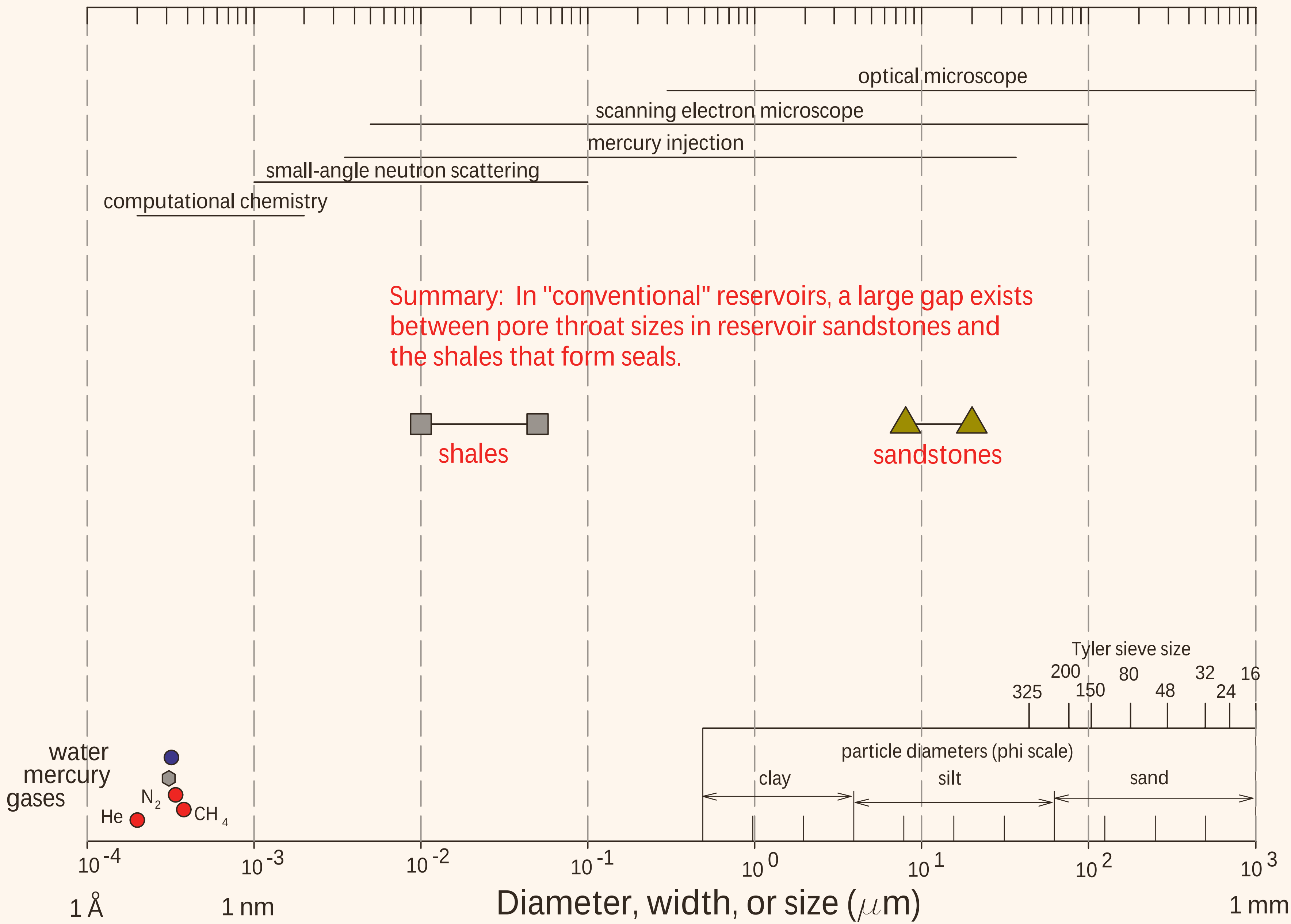

optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
medium sand
ﬁne sand
median-----threshold (Hg)
very ﬁne sand
coarse silt
median-----35% Hg ------threshold
Lance Formation, Greater Green River Basin, Wyoming
mode of 6 rock types, Hg
Upper Jurassic Bossier interval, East Texas
range of 44 samples, slot width (gas)
Mesaverde Formation, Piceance Basin, Colorado
range of 13 samples, slot width (gas)
Travis Peak Formation, East Texas
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

Values for shales are shown next. As was the case with tight gas sandstones, different investigators give different measures of the pore throat spectrum. However, such differences are relatively unimportant on the logarithmic scale used for the plot.

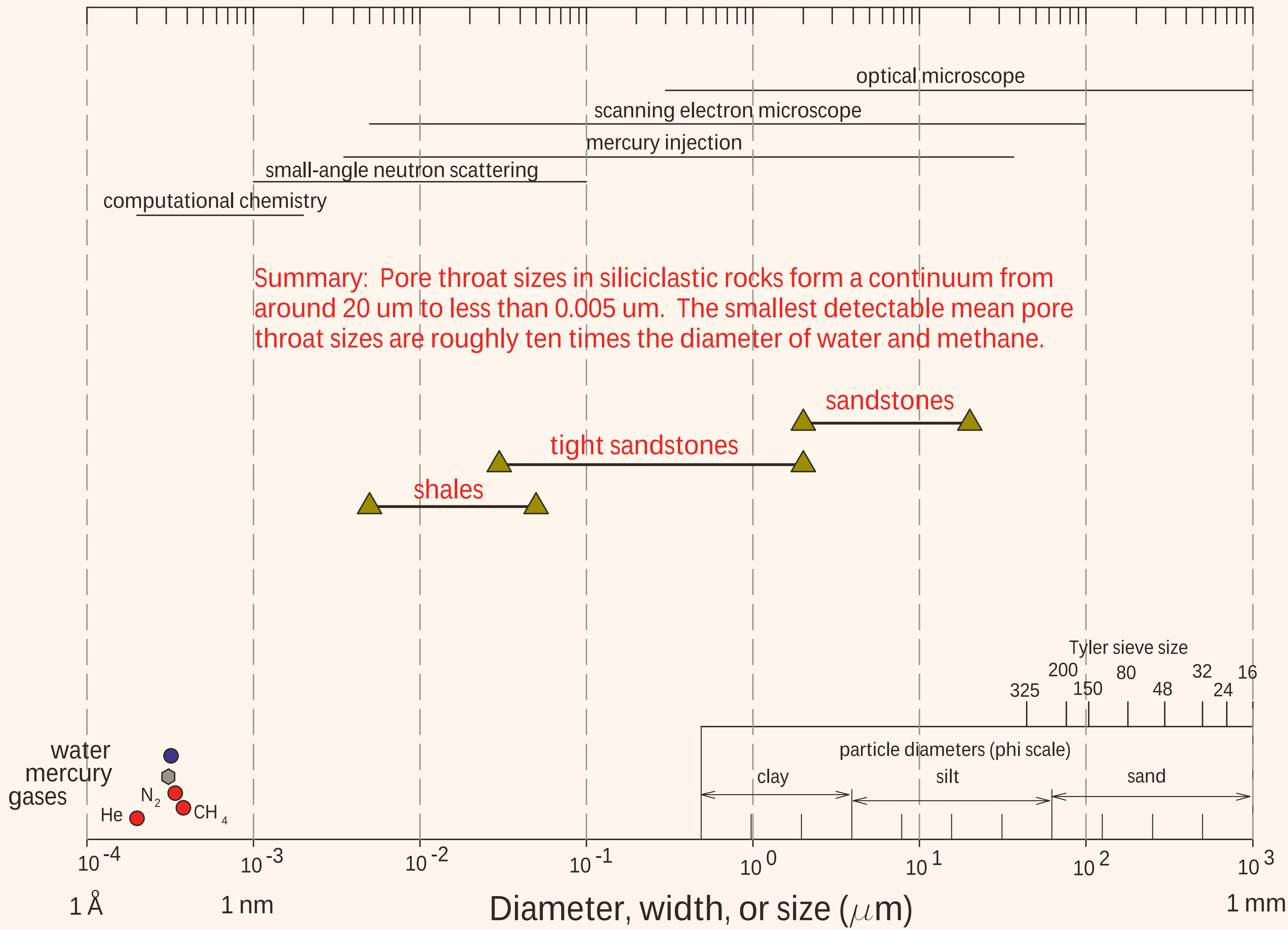

optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
medium sand
fine sand
sandstones
very fine sand
coarse silt
Lance Formation, Greater Green River Basin, Wyoming
Upper Jurassic Bossier Interval, East Texas
tight sandstones
Mesaverde Formation, Piceance Basin, Colorado
Travis Peak Formation, East Texas
Pennsylvanian shales, Anadarko Basin, Oklahoma
Pliocene shales, Beaufort-MacKenzie Basin, Canada
shales
Source rocks, United States
Devonian shales, New York State
Jurassic-Cretaceous shales, Scotian Shelf, Canada
Tyler sieve size
Oligocene-Cretaceous shales, North Sea
200 80 32 16
325 150 48 24
water
mercury
gases
particle diameters (phi scale)
clay
silt
sand
N_2
He
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm



optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
medium sand
ﬁne sand
median-----threshold (Hg)
very ﬁne sand
coarse silt
median-----35% Hg ------threshold
Lance Formation, Greater Green River Basin, Wyoming
mode of 6 rock types, Hg
Upper Jurassic Bossier Interval, East Texas
range of 44 samples, slot width (gas)
Mesaverde Formation, Piceance Basin, Colorado
range of 13 samples, slot width (gas)
Travis Peak Formation, East Texas
individual samples, threshold, Hg
Pennsylvanian shales, Anadarko Basin, Oklahoma
individual samples, geometric mean, Hg
Pliocene shales, Beaufort-MacKenzie Basin, Canada
individual samples, median, Hg&SANS
Source rocks, United States
individual samples, median or avg, Hg
Devonian shales, New York State
individual samples, geom mean, Hg
Jurassic-Cretaceous shales, Scotian Shelf, Canada
individual samples, mean, Hg
Oligocene-Cretaceous shales, North Sea
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
10 -4
10 -3
10 -2
10 -1
10 0
10 1
10 2
10 3
1 Å
1 nm
Diameter, width, or size (μm)
1 mm



optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
Summary: In "conventional" reservoirs, a large gap exists between pore throat sizes in reservoir sandstones and the shales that form seals.
shales
sandstones
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
He
N_2
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm



optical microscope
scanning electron microscope
mercury injection
small-angle neutron scattering
computational chemistry
Summary: Pore throat sizes in siliciclastic rocks form a continuum from around 20 um to less than 0.005 um. The smallest detectable mean pore throat sizes are roughly ten times the diameter of water and methane.
sandstones
tight sandstones
shales
Tyler sieve size
325
200
150
80
48
32
24
16
particle diameters (phi scale)
clay
silt
sand
water
mercury
gases
N_2
He
CH_4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1 Å
1 nm
Diameter, width, or size (μm)
1 mm

Exploitation of tight gas sandstones and shales requires access to smaller and smaller pore spaces within the pore-size spectrum.

It is hoped that this overview provides a useful perspective on these new developments.