Challenges in resource exploration for the applied earth sciences

Titusville, Pennsylvania
August 27, 1859

Courtesy of the Pennsylvania Historical & Museum Commission, Drake Well Museum, Titusville, PA., United States: www.drakewell.org.

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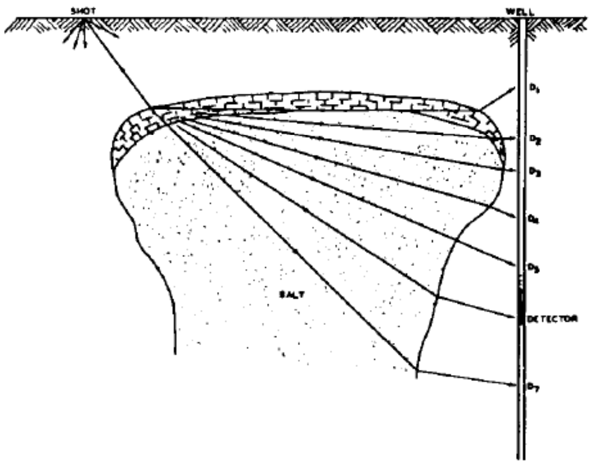
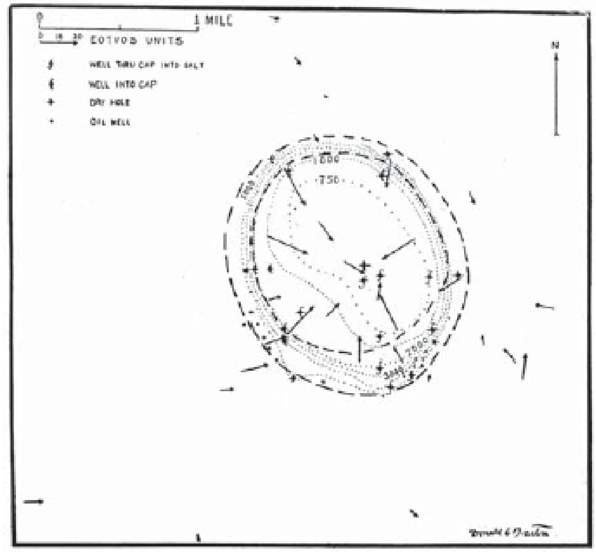
Schlumberger, 1982—2009
Senior Research Scientist, Yale

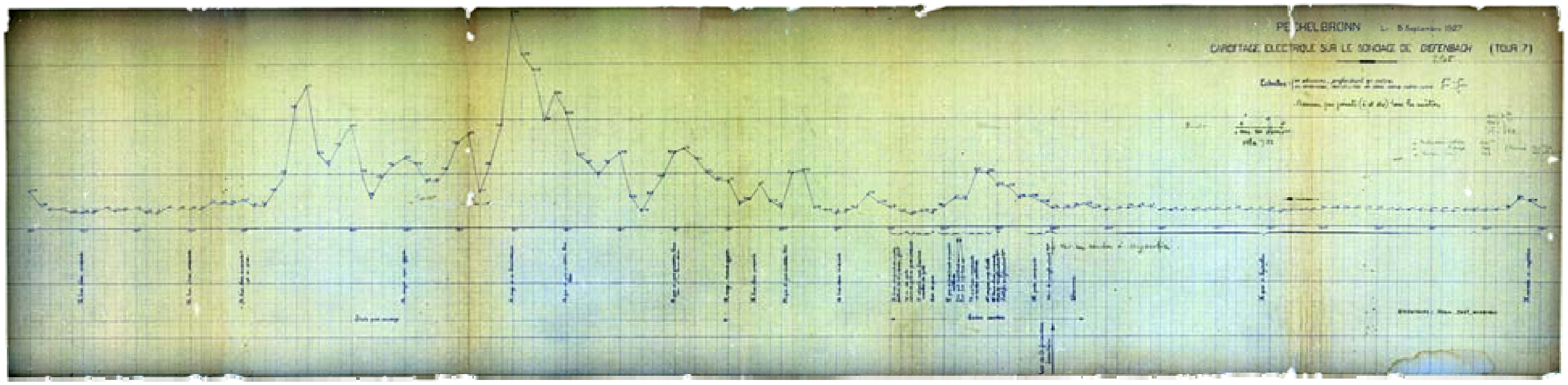


First exploration seismic surveys along Gulf Coast, 1920-1924



Discovery of Nash Dome by gravity, 1924

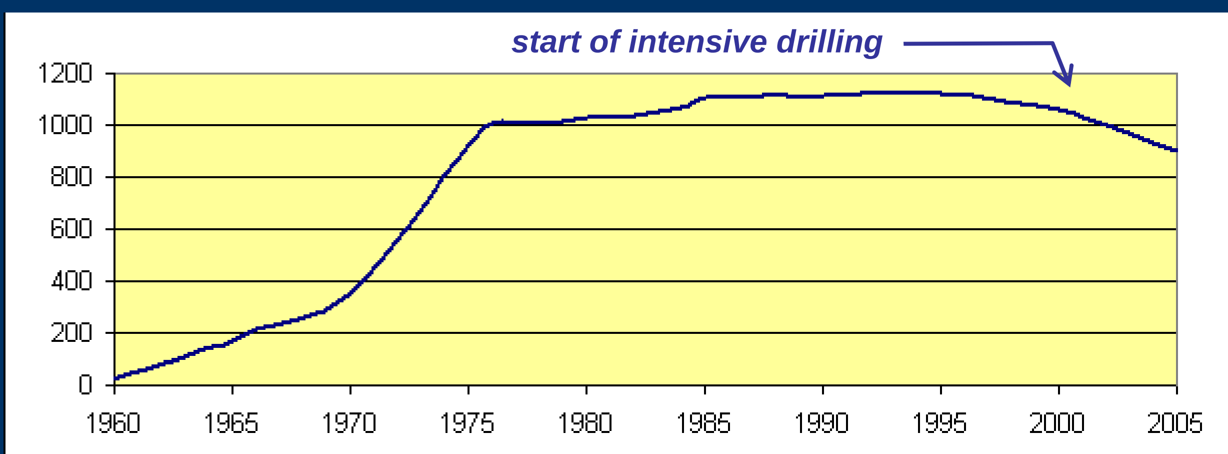
First electrical well log, Pechelbronn, France, September 5, 1927



Declining production rates

Daqing oil field in China is one of the world's largest land oil fields, producing about 1 million barrels per day.

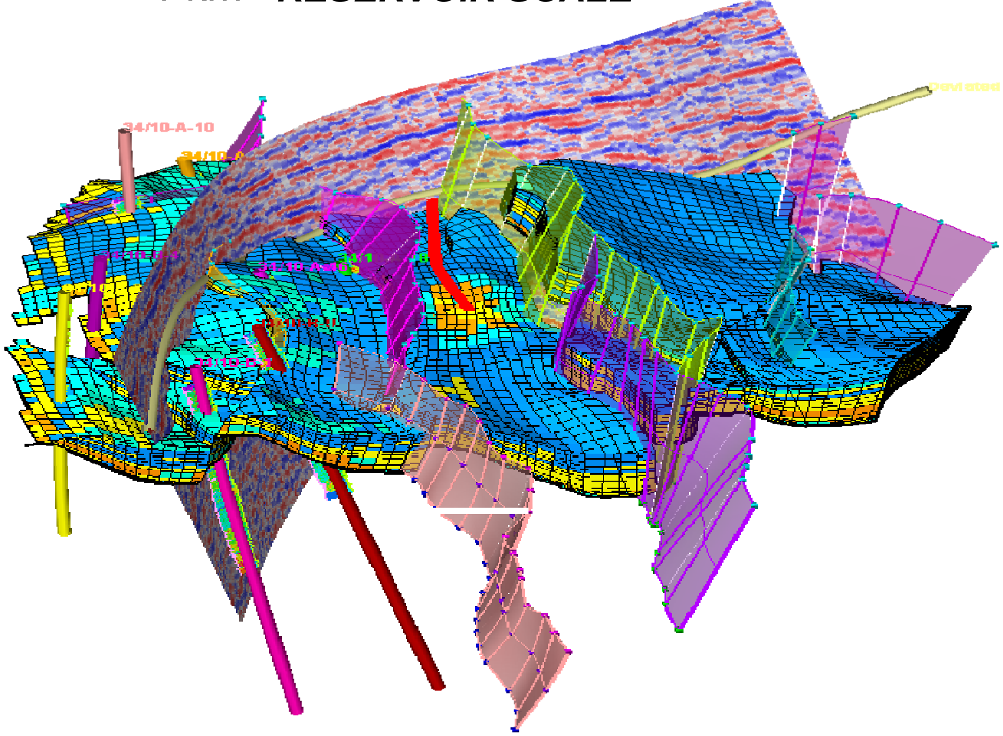
Despite drilling 10,000 wells during the past ten years, oil production has declined by 20%.



Challenge #1: *We are just beginning to come to grips with the importance of heterogeneity in the earth and how it limits our ability to explore for and exploit underground resources in a sustainable way.*

The earth is heterogeneous on all scales.

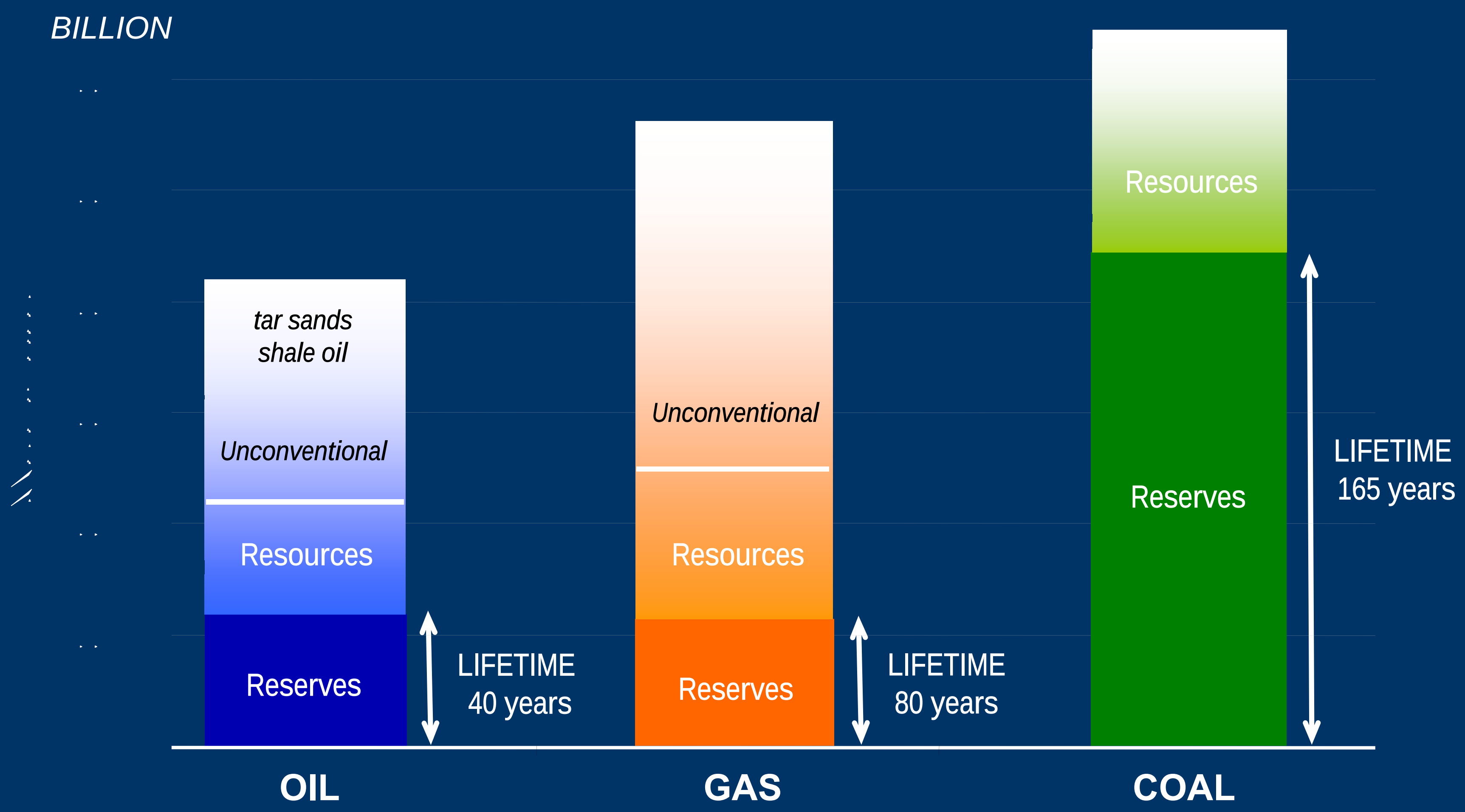
1 km ***RESERVOIR SCALE***



100 μm ***PORE SCALE***

The problem is not reserves…

IEA, Resources to Reserves, 2005
BP Statistical Review, 2008

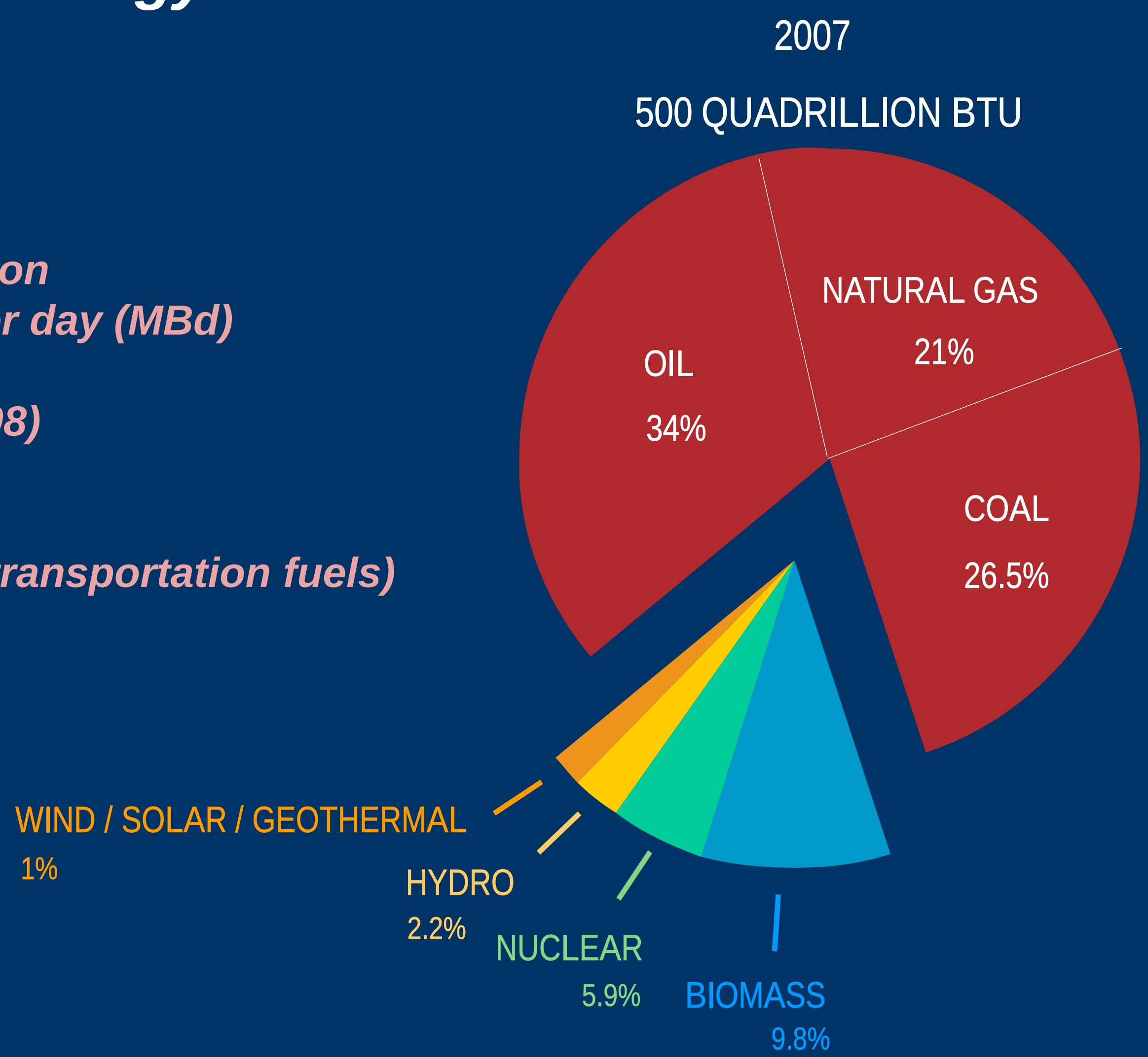


LIFETIME = Reserves/Production-rate (2005)

Fossil Fuels supply over 80% of today's energy mix

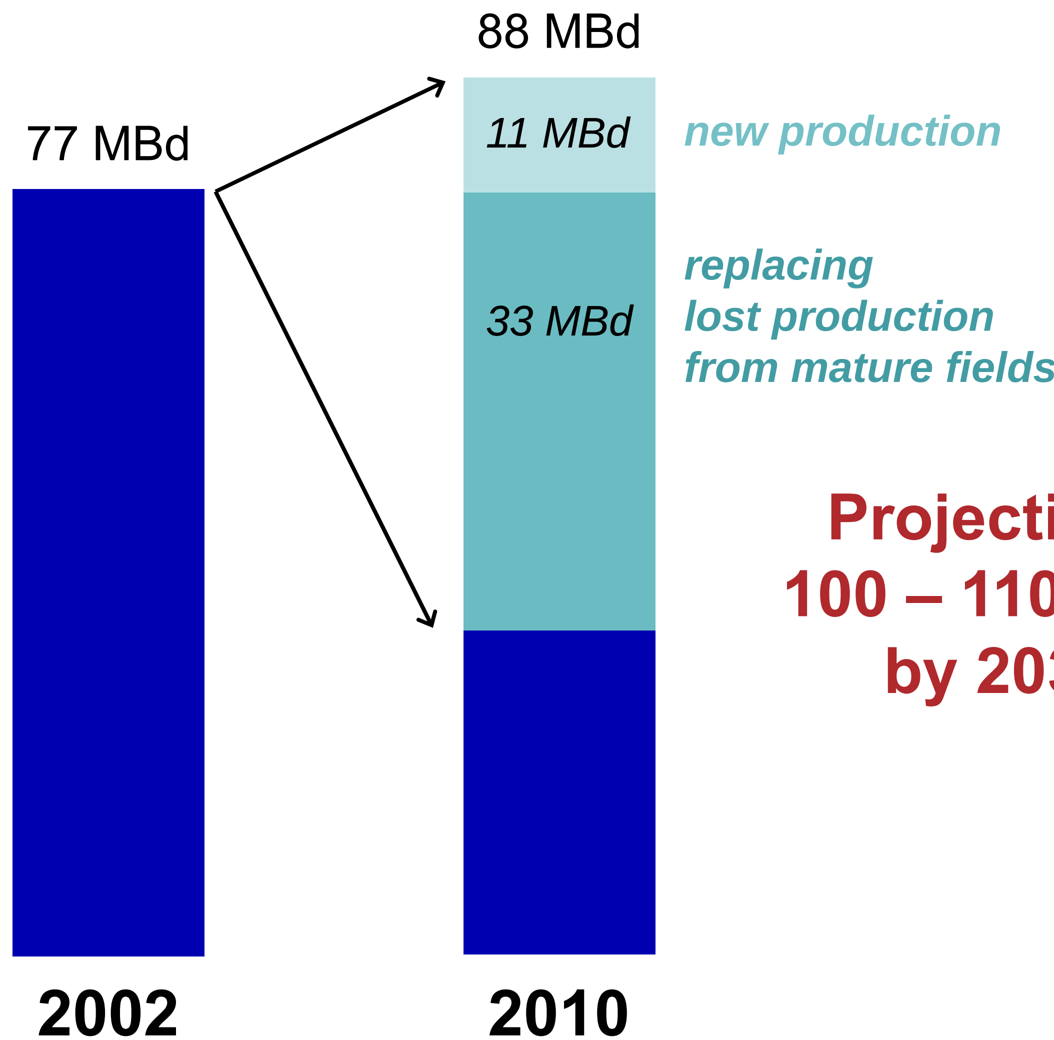
World oil consumption
85 million barrels per day (MBd)

US oil statistics (2008)
20 MBd consumed
7 MBd produced
13 MBd imported (~transportation fuels)



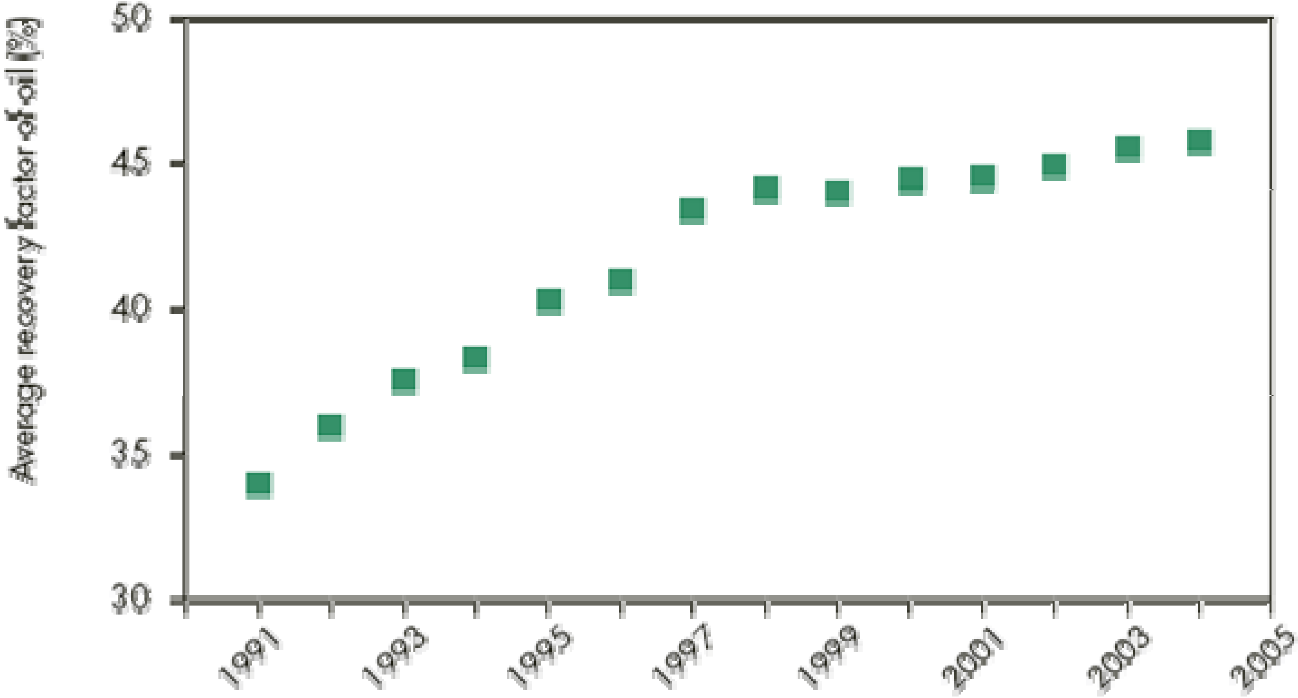
Source: BP Statistical Review, 2009, IEA Key Energy Statistics, 2009

The problem with production rates



Projections
100 – 110 MBd
by 2030

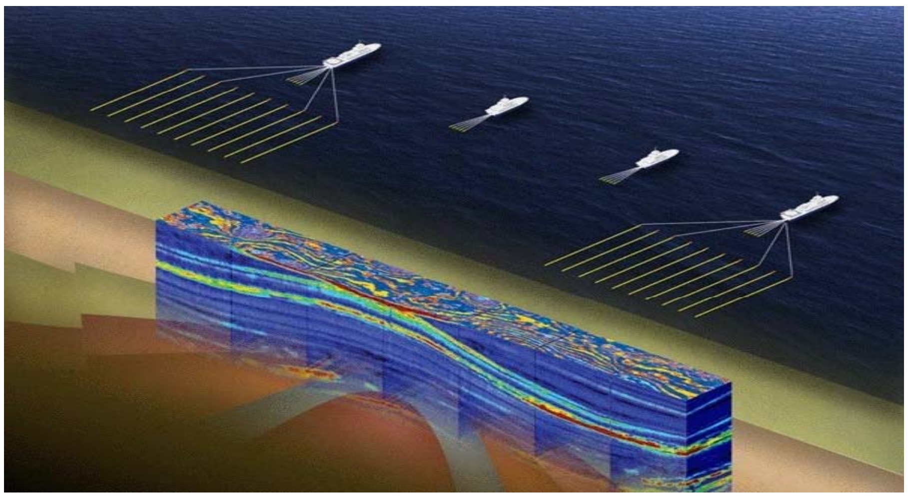
Figure 2.10 • Evolution of expected recovery factor in Norway

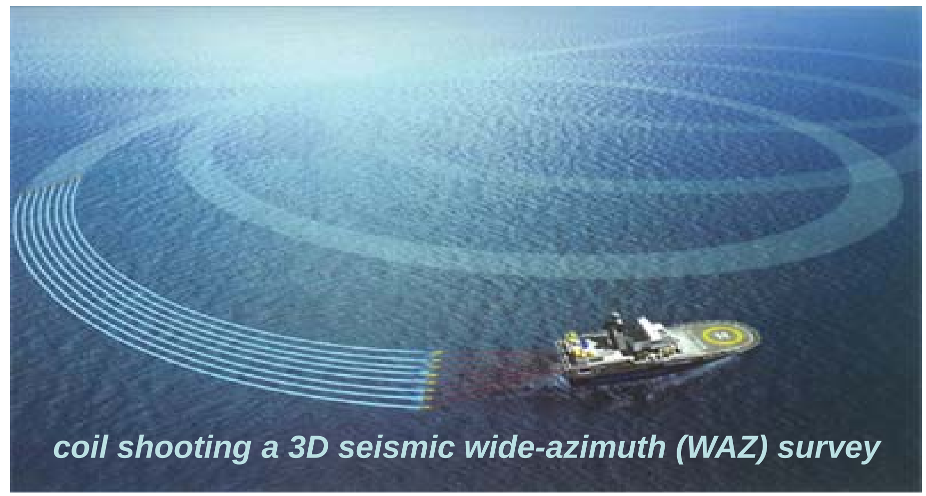


The 50% line is the future goal of the Norwegian government.

Courtesy of Norwegian Petroleum Directorate.

***SEAM** is the first attempt to fully simulate a modern 3D seismic survey over a realistic geological model.*



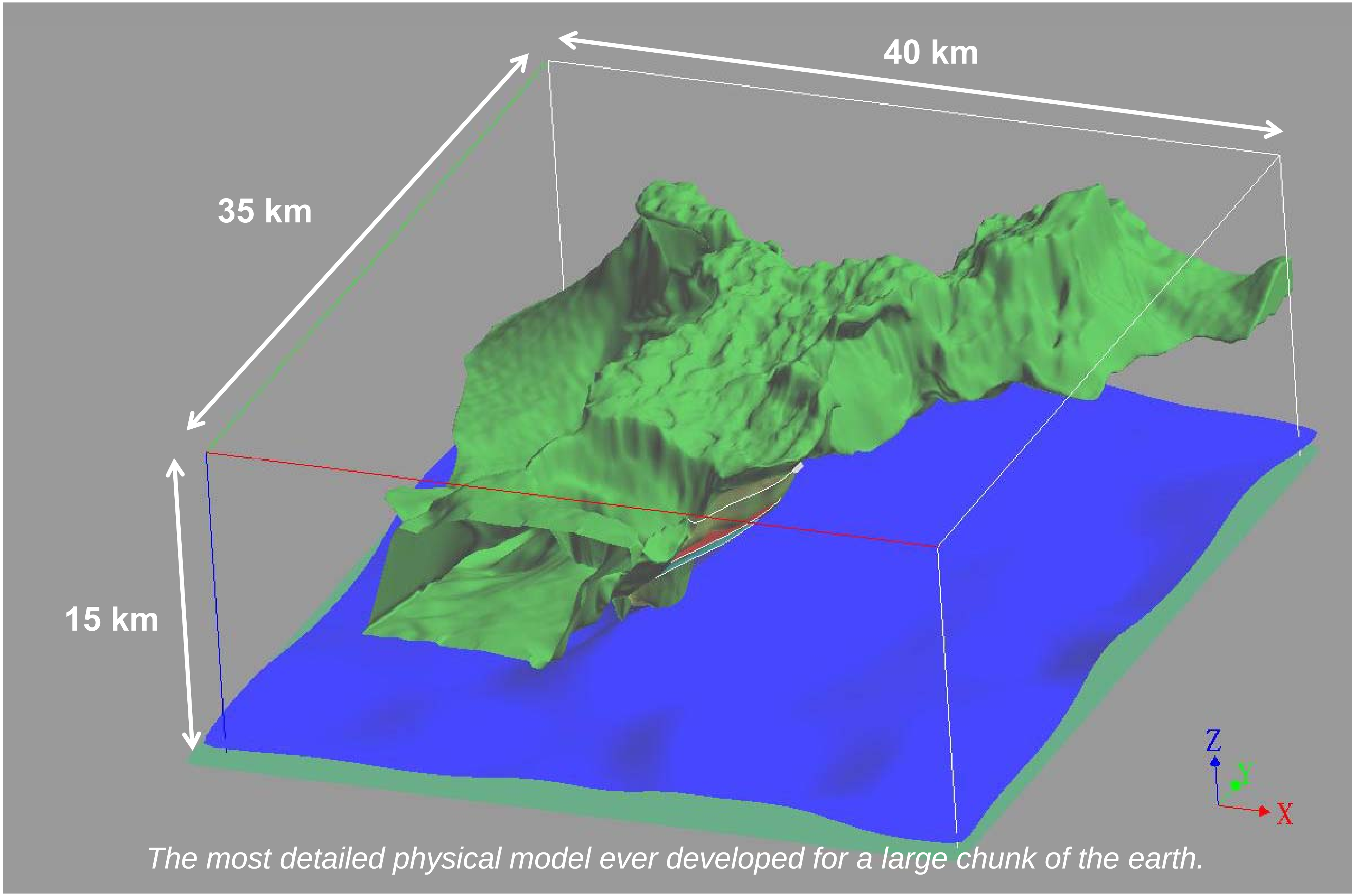


coil shooting a 3D seismic wide-azimuth (WAZ) survey

SEAM

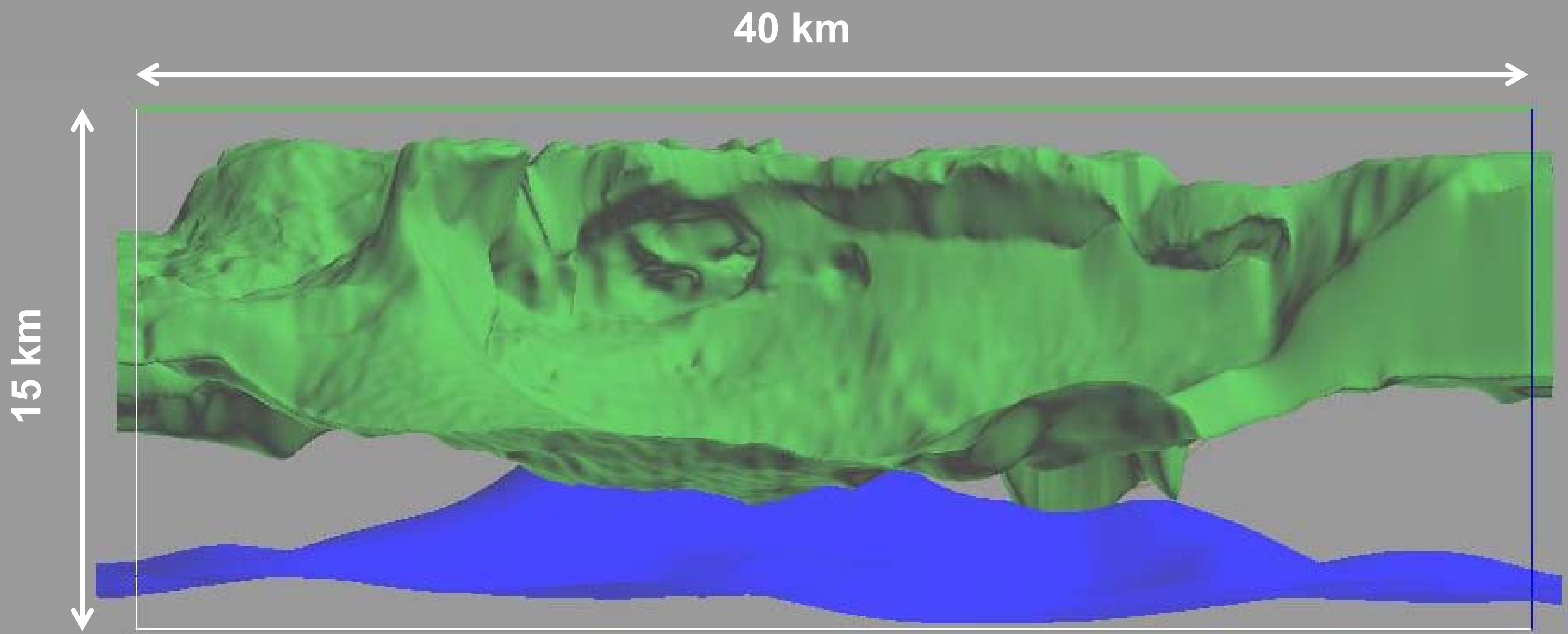
SEG Advanced Modeling

The model is a deep Gulf Coast salt complex

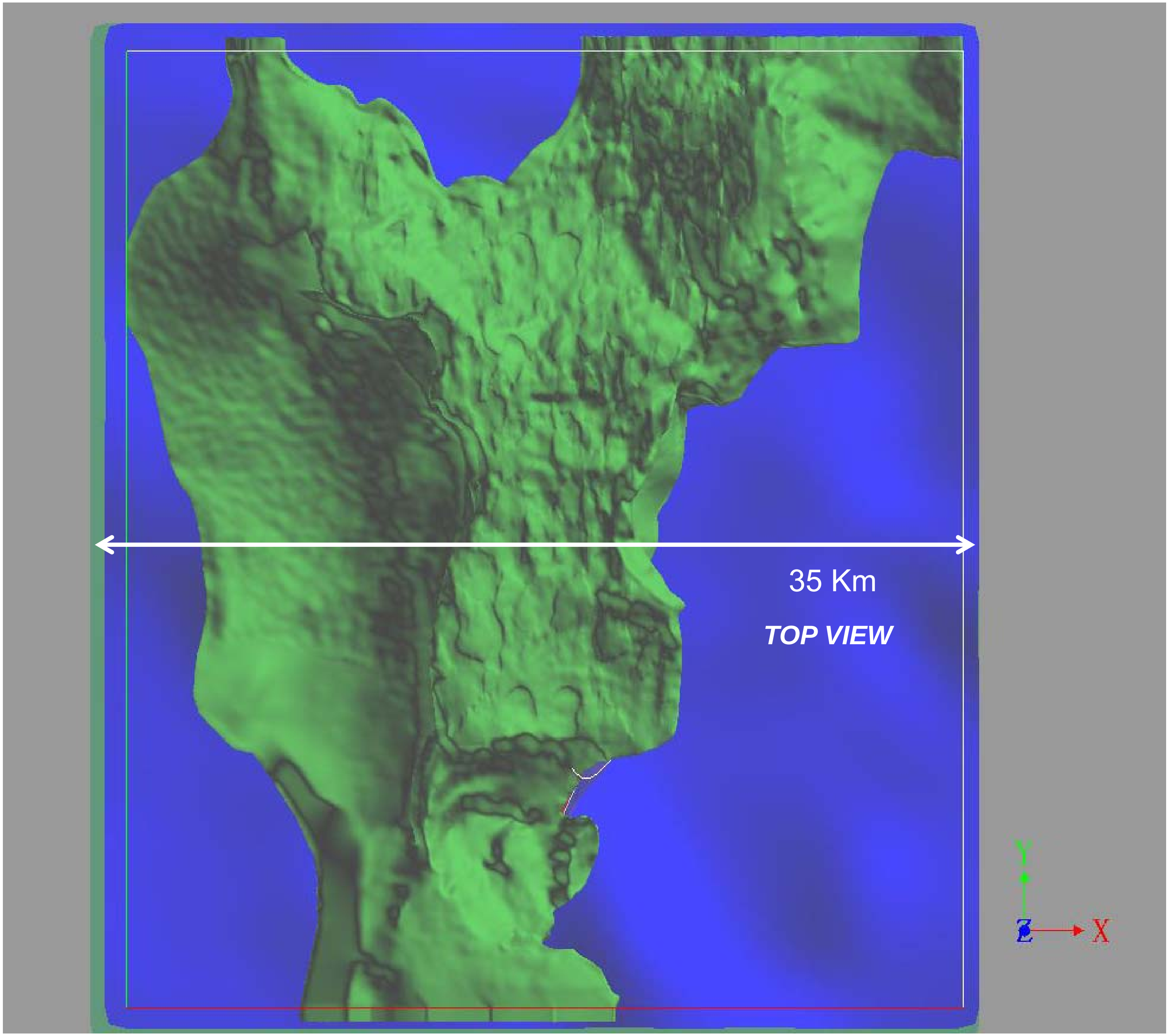


Gulf Coast salt complex

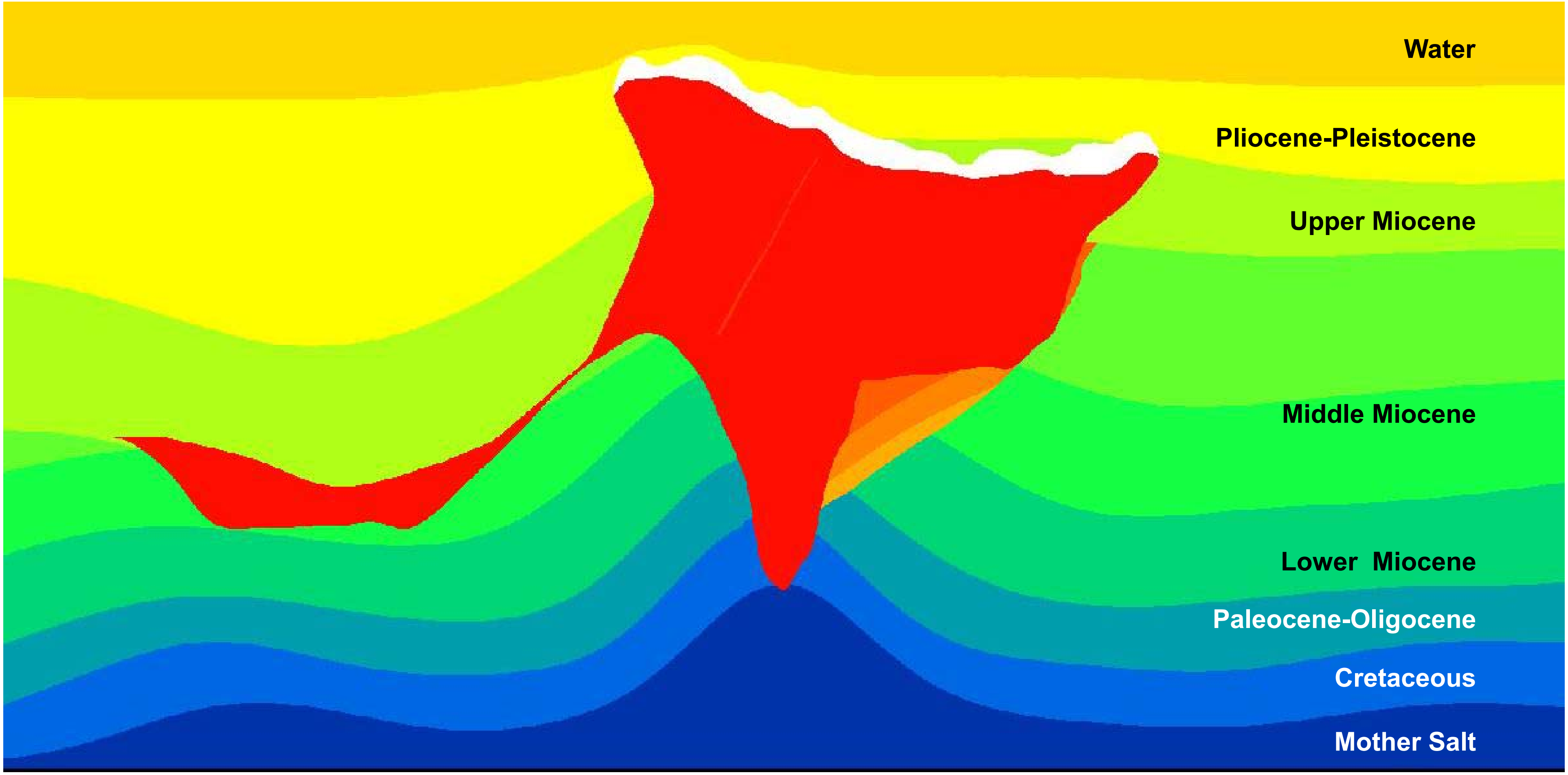
VIEW FROM THE WEST



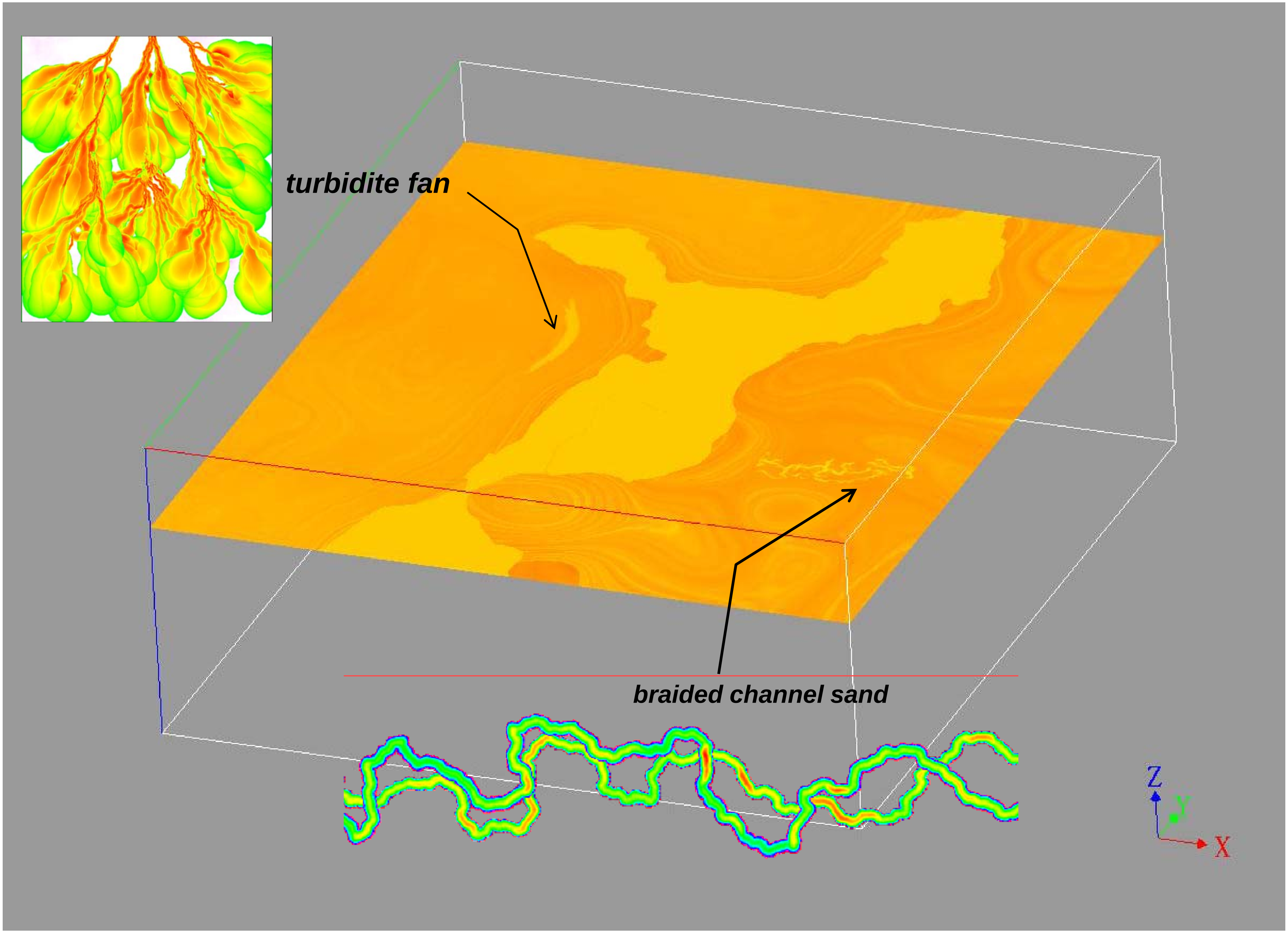
The most detailed physical model ever developed for a large chunk of the earth.

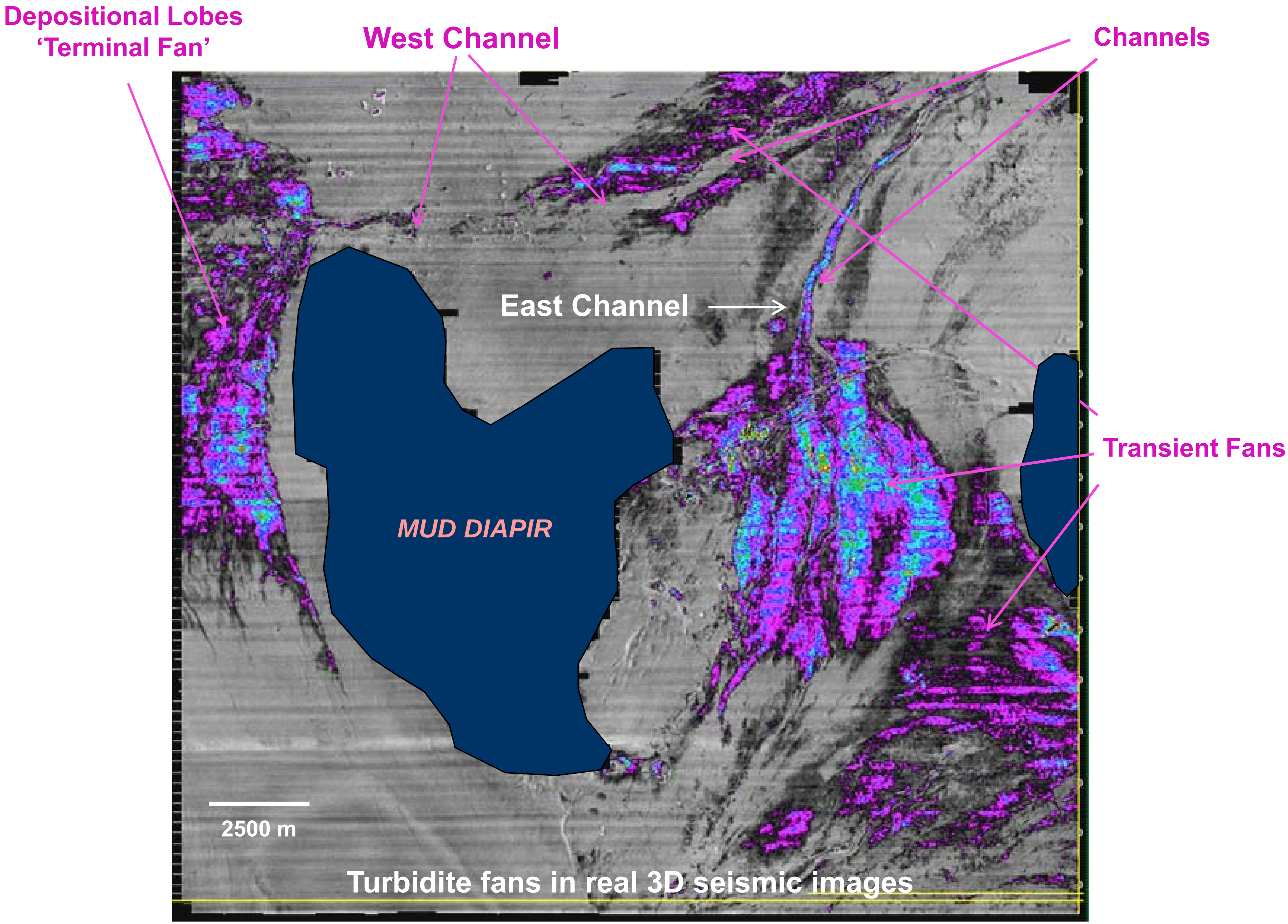

35 Km
TOP VIEW
Y
Z
X

All major structural and stratigraphic horizons in the Gulf Coast are represented.

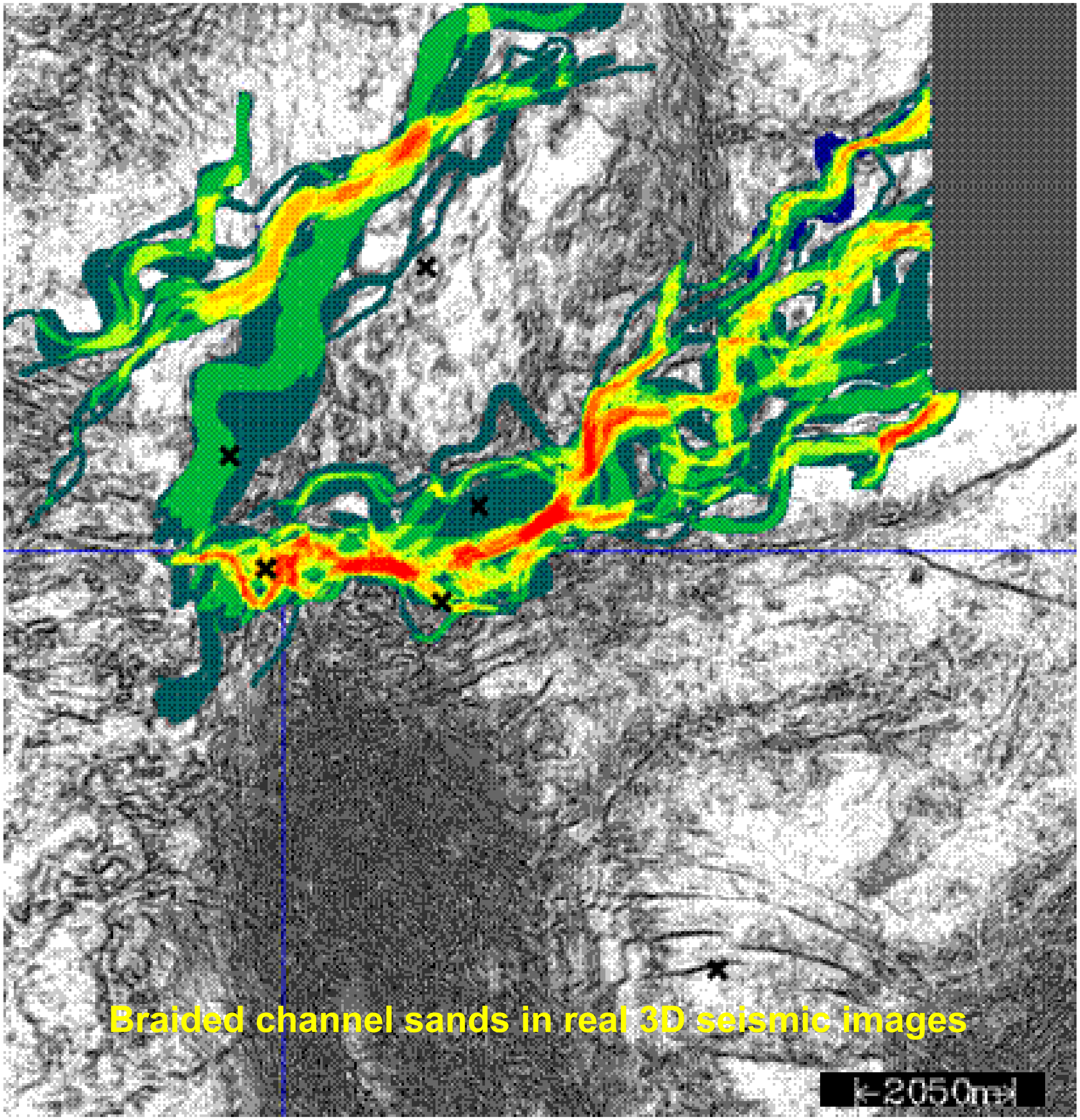


Layer properties represented at the cm scale from well logs and averaged up.


turbidite fan
braided channel sand
Z
Y
X



Dayo Adeogbas (2003)


Braided channel sands in real 3D seismic images
t=2050ms

SEAM Model

Gulf Coast salt dome complex

40km x 35km x 15km

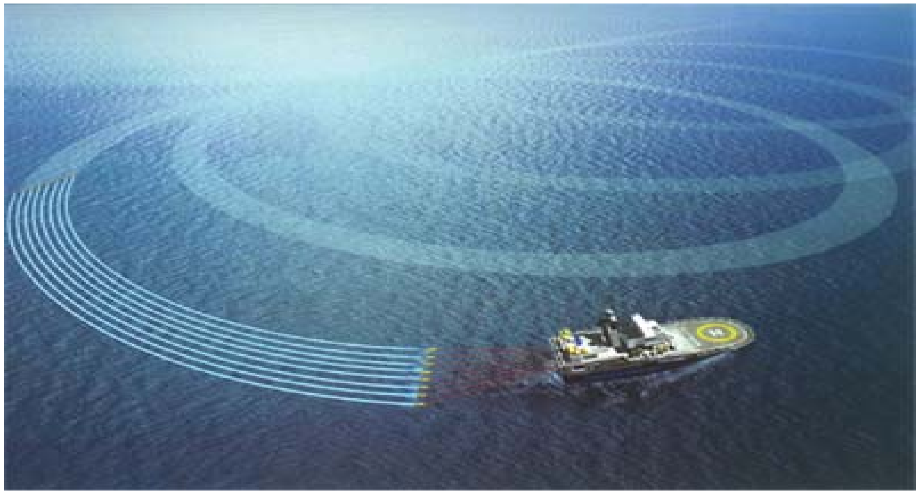
Stratigraphy at cm scale from logs

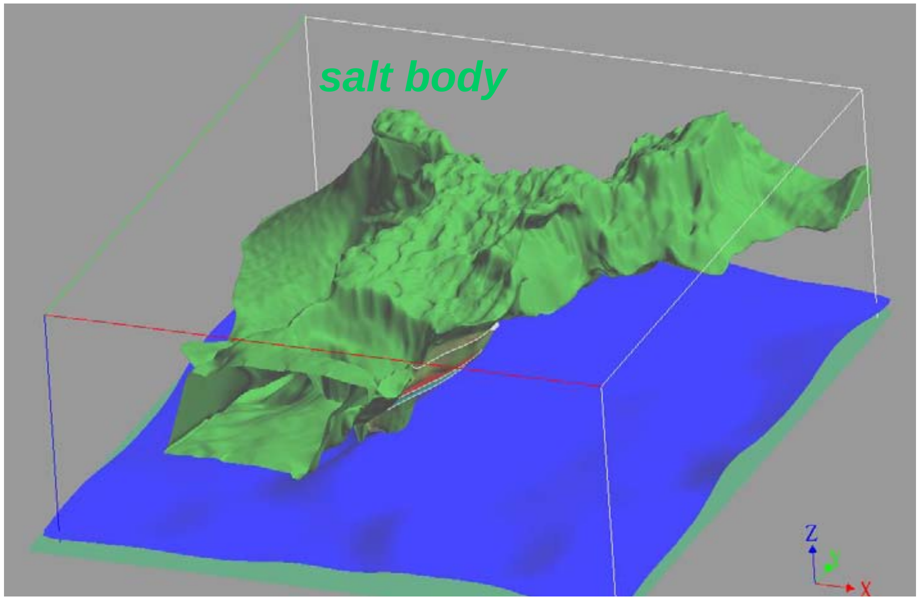
100 GB to represent at 10m resolution

>>100 000 hrs of CPU time

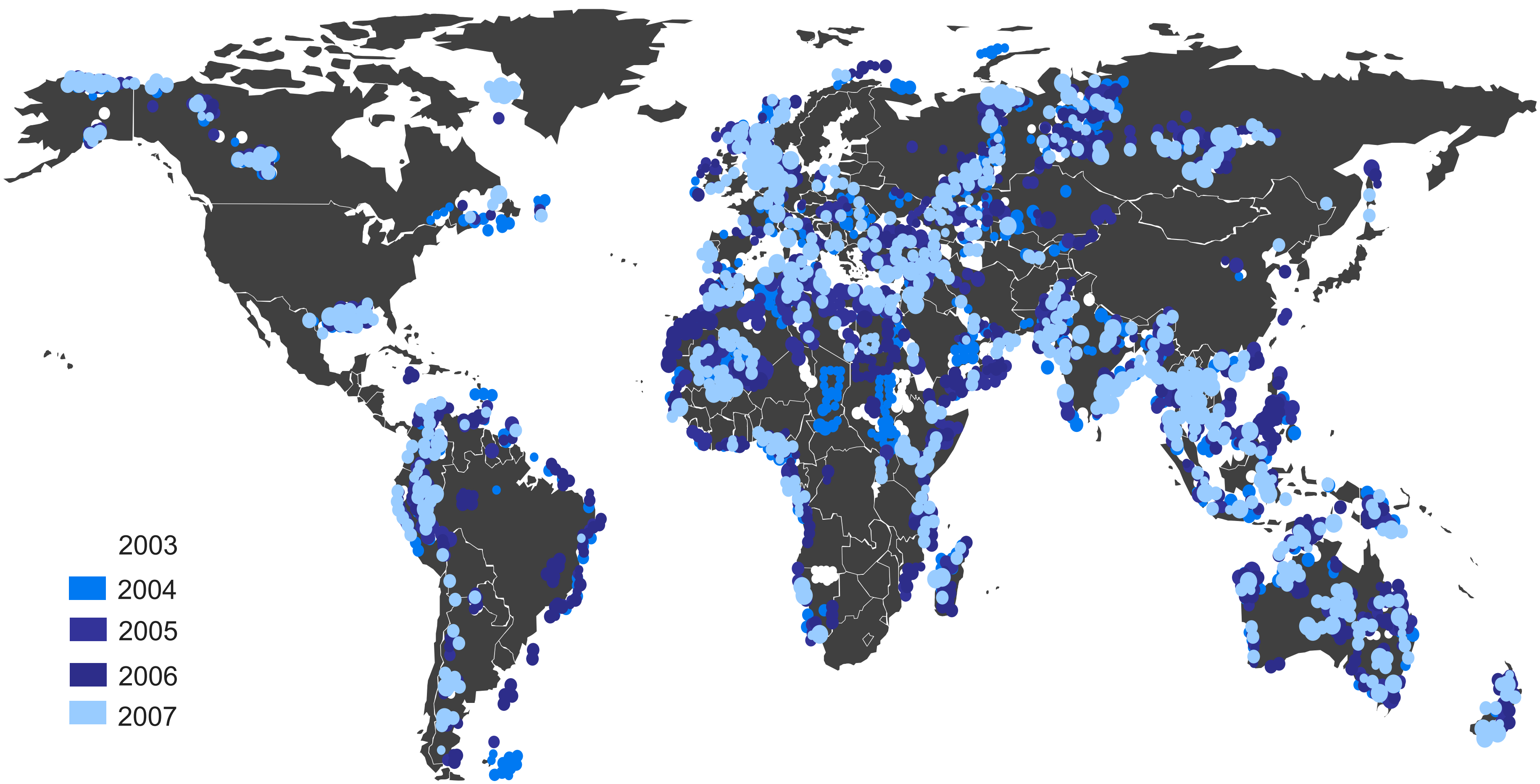
Staggered-grid acoustic and elastic FD codes

120 TB of seismic data

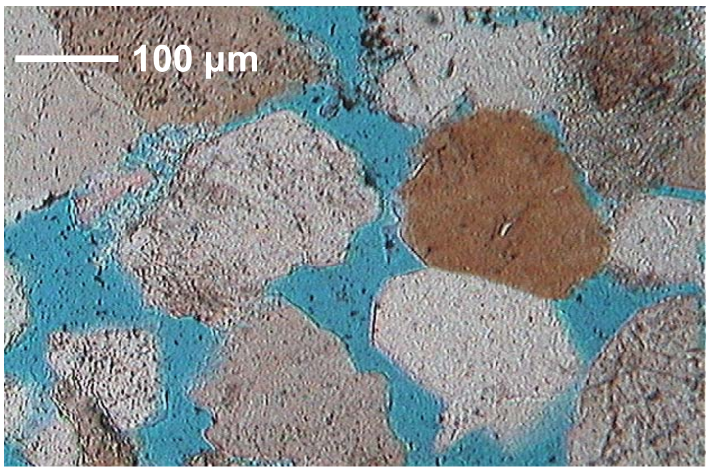




3D Seismic Exploration Leases



Advanced Energy Consortium *aims to manipulate fluid-solid interactions in reservoir rocks in-situ at the pore scale.*

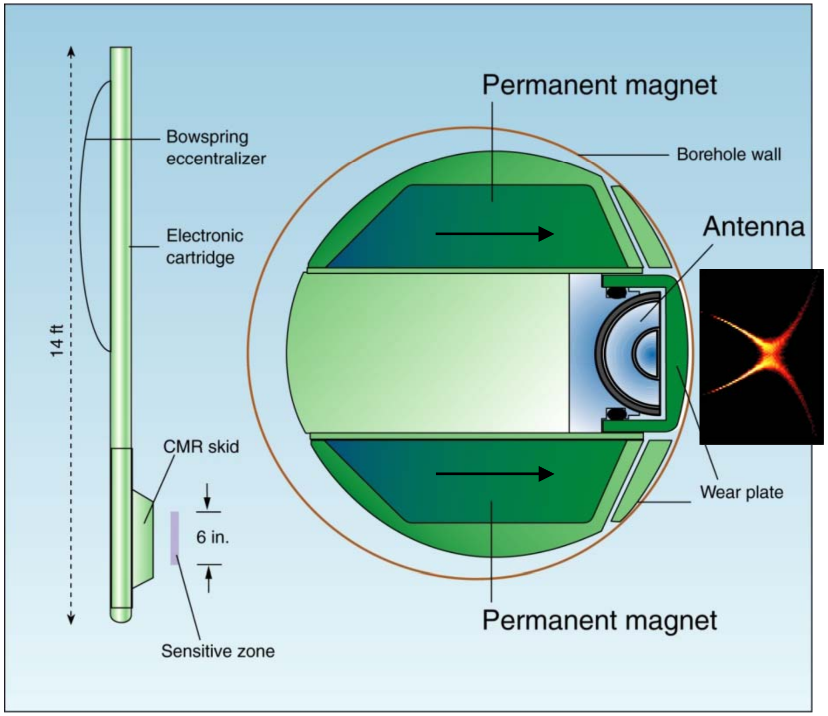


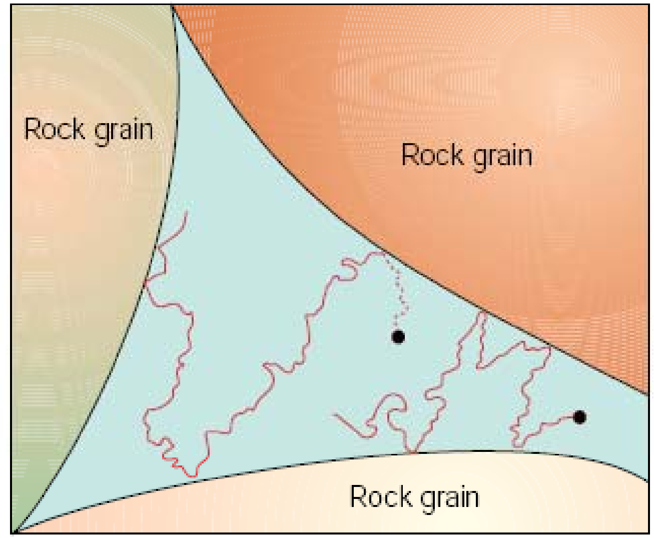
AEC MEMBERS

The Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin
Managing Organization
Technical Lead

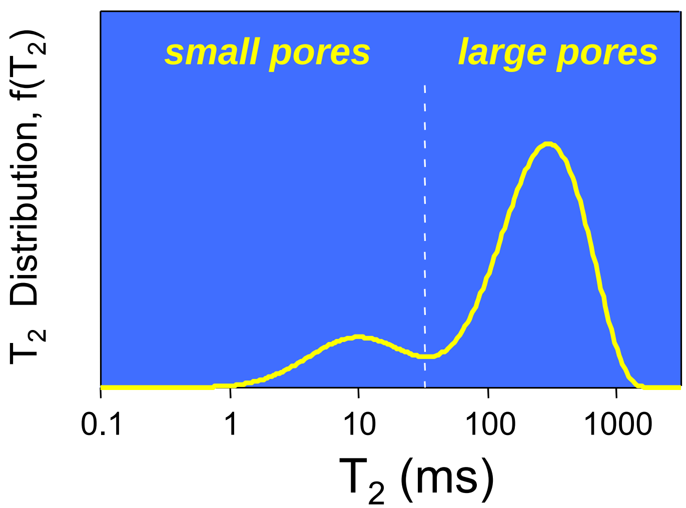
Richard E. Smalley Institute for Nanoscale Science and Technology
Rice University
Technical Partner

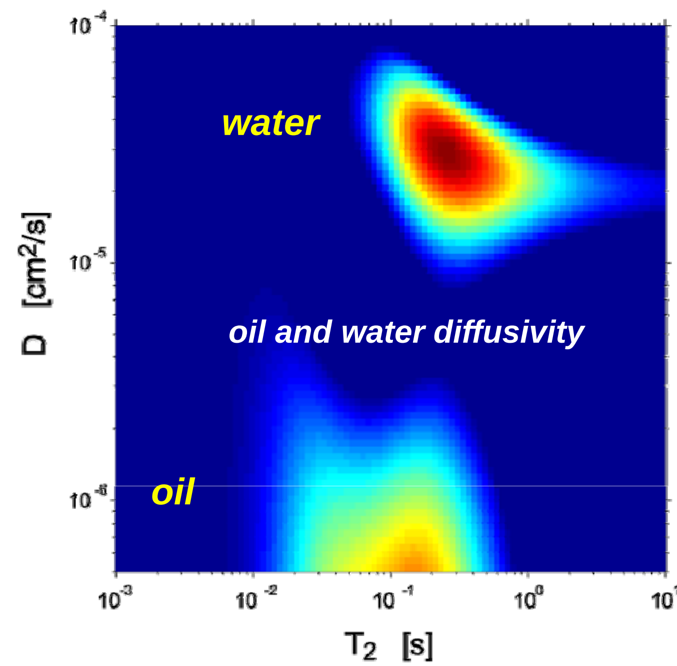
Magnetic resonance in porous media





$$M(t) = \int dT_2 \; f(T_2)\exp\{-t/T_2\}$$





Continuous MRI in an oil reservoir

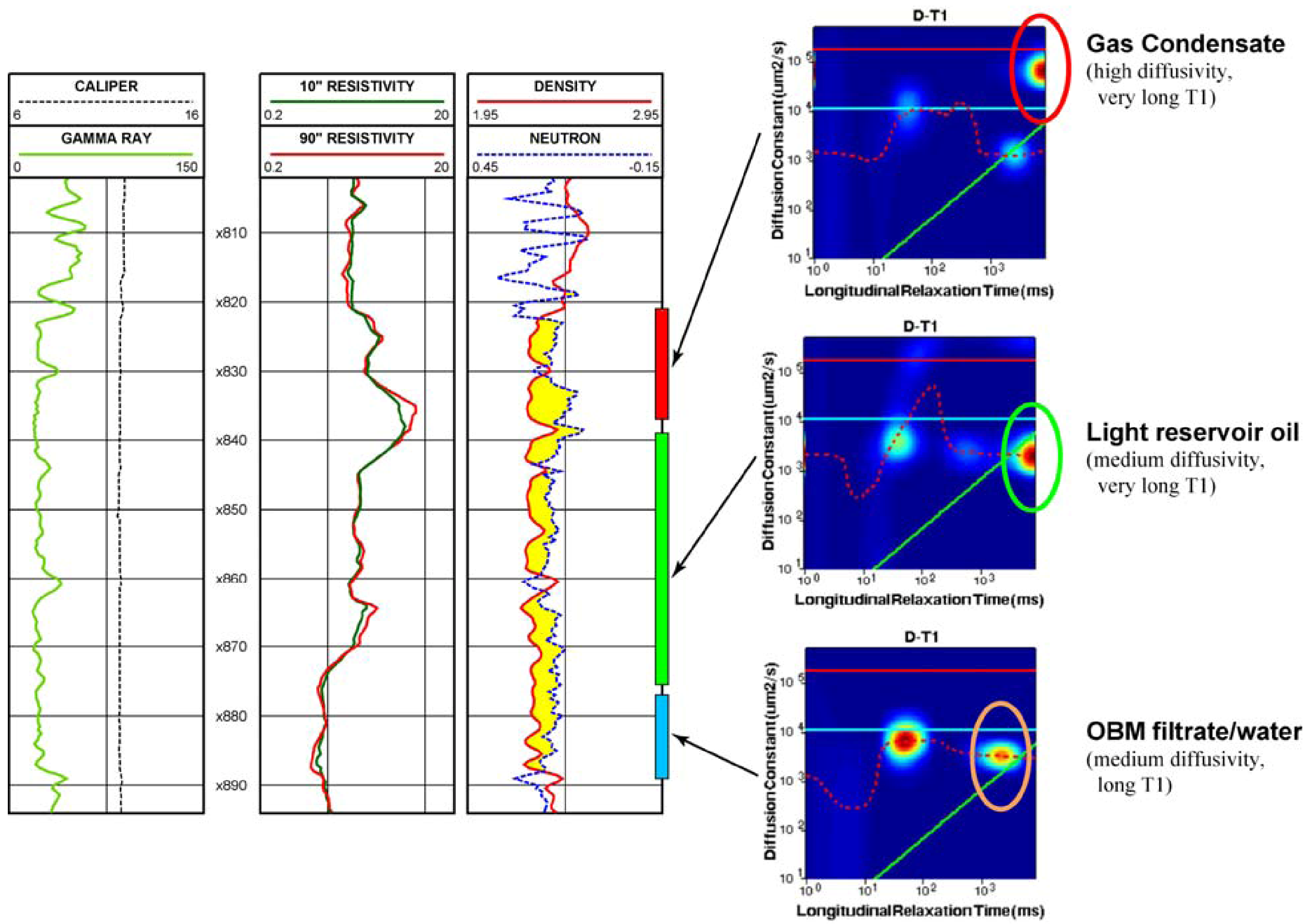


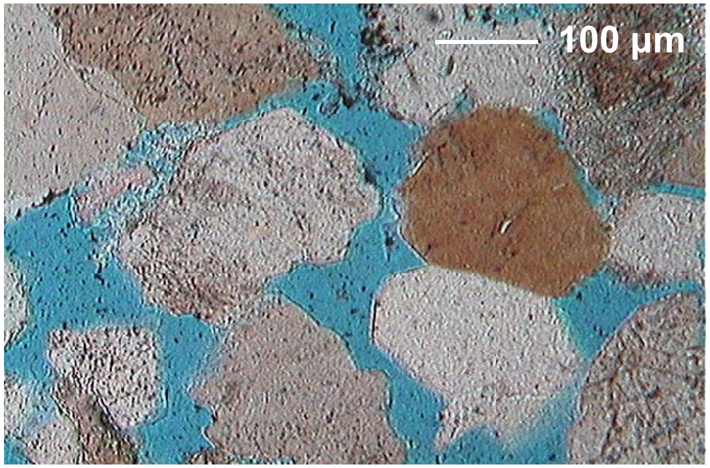
Figure 11. Triple combo logs show a hydrocarbon zone, but do not discriminate the change in fluid type. However the NMR 4 inch DOI data clearly show the change in response from light oil to gas condensate. Shallower shells do not show a clear boundary between fluids because oil filtrate dominates the response.

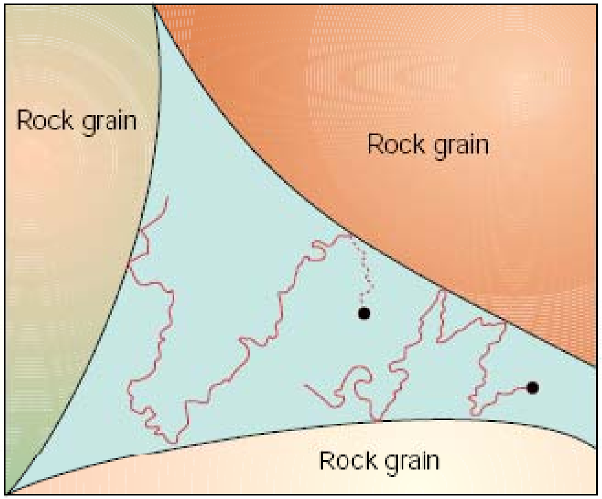
N. Heaton et al., SPWLA 48th Annual Logging Symposium, 2007, Paper P.

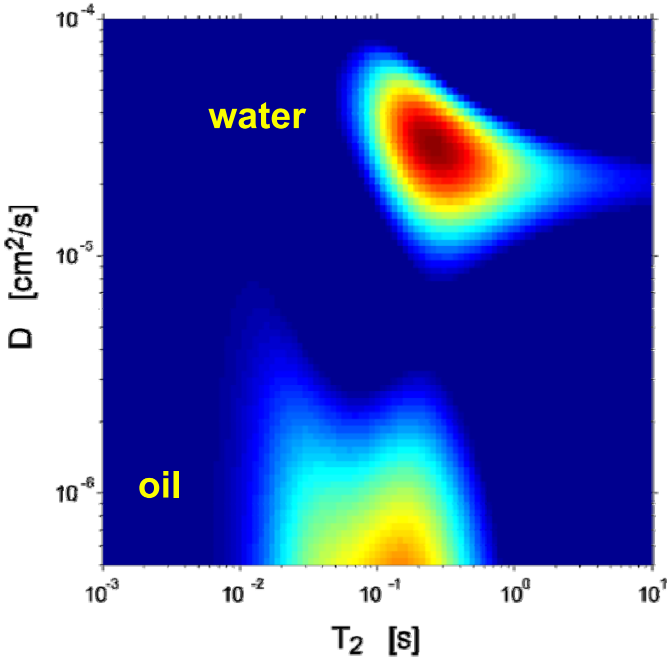
Advanced Energy Consortium goals

(1) Create novel surfactants to release bound oil using surface-functionalization methods of nanotechnology.

(2) Create "nanosensors" (tracers) that will move with the reservoir flow and keep a record (P,T) of their trip.







nature
Vol 460 | Issue no. 7255 | 30 July 2009

The shale revolution

The vast reserves of US natural gas must be used judiciously to ease the transition to clean energy.

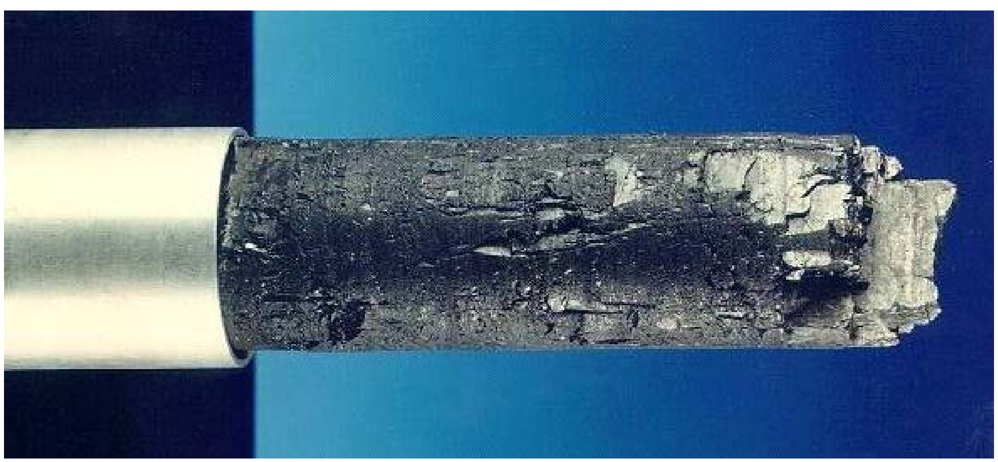
Several years ago, it looked as though the United States was running short of natural gas. Prices spiked as declining production in old fields collided with increasing industrial demand. Electric utilities shifted from 'clean' gas back to cheap coal, and suppliers began building terminals to import liquefied natural gas from abroad. Yet today, coal-fired power is again on the wane, ports for liquefied natural gas are idling below capacity, and the nation is awash with gas.

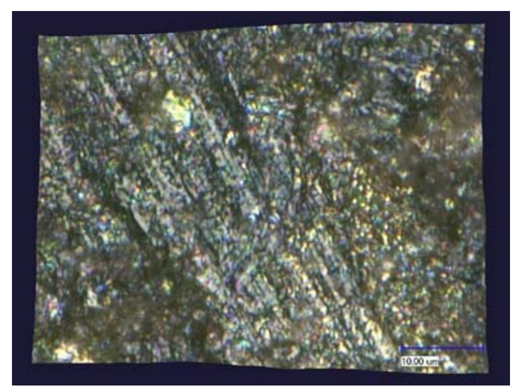
So what happened? Clearly, the threat of carbon regulation has curbed industry's appetite for coal, and the sagging economy has depressed energy demand across the board. But just as importantly, natural-gas production is again on the rise. Thanks to advances in drilling technology, including horizontal drilling and more effective rock fracturing, producers have at last unlocked the vast quantities of gas trapped underground in impermeable strata of shale.

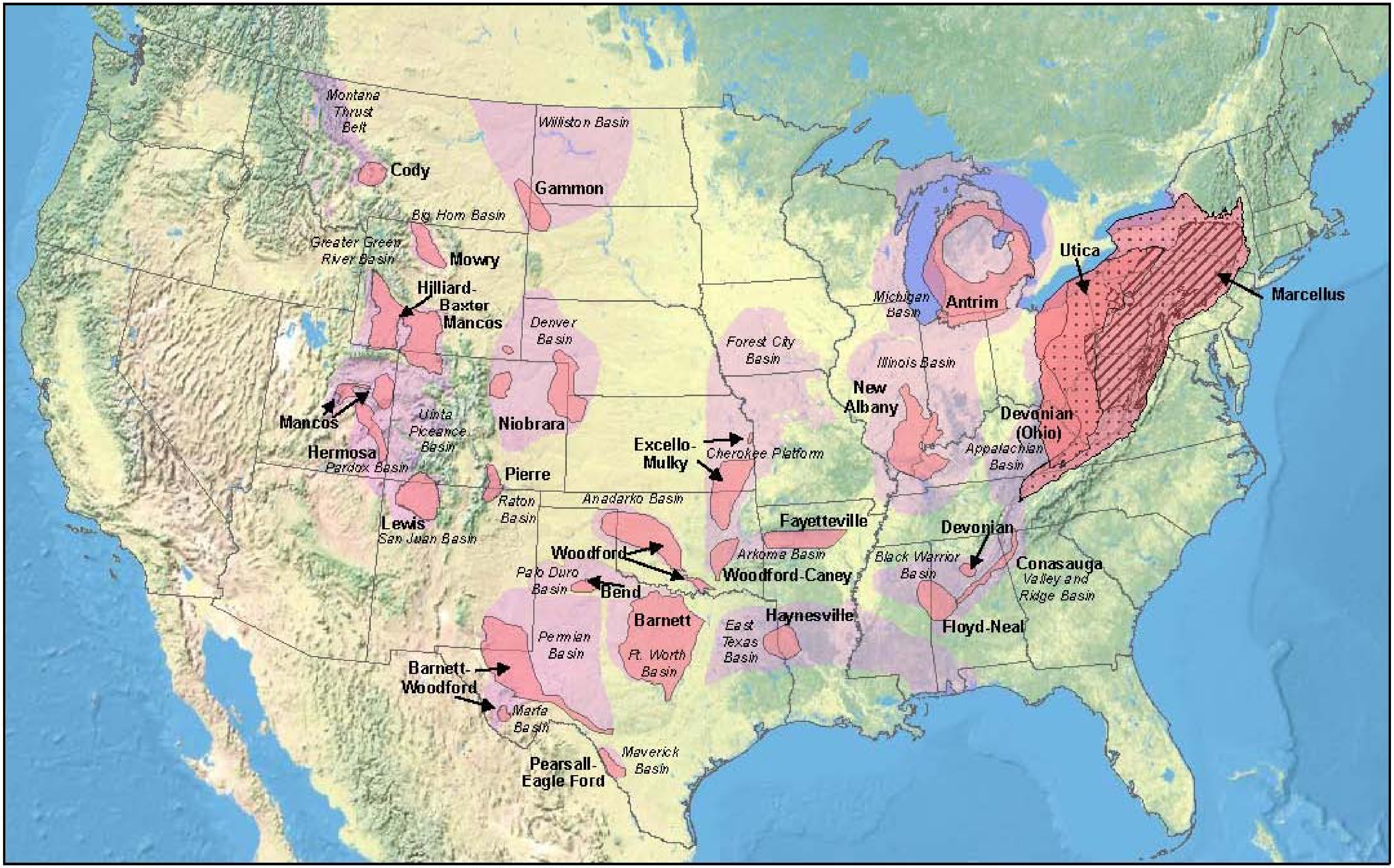
The Potential Gas Committee, a volunteer group of industry, government and academic experts headquartered in Golden, Colorado, increased its estimate of recoverable gas reserves by 39% in its biennial report released last month, mostly because of shale gas. The new total, almost 60 trillion cubic metres, is equivalent to about a century's worth of gas at current usage rates.

Policy-makers everywhere should take note. Shale formations similar to those that have upended the US natural-gas market exist all over the world. Early explorations are already under way in Canada and several European countries, many of which are overly reliant on

geology → horizontal drilling → geomechanics (rock texture) → reservoir engineering (hydro-fracturing) → geophysical monitoring







United States Shale Gas Plays

www.eia.doe.gov
Energy Information Administration
Office of Oil and Gas

Shale Gas Plays
Basins

Stacked Appalachian Plays

Marcellus
Utica
Devonian (OH shale)

November 2008

Miles
0 150 300 600

N

SEAM is sponsored by the Society of Exploration Geophysicists and funded by a consortium of oilfield service and oil companies, with support from the US Government through an initiative called RPSEA. Project leader is Michael Fehler, formerly of Los Alamos National Lab, currently at **MIT**.

Thanks to Richard Day of Conoco Phillips & Joe Stefani of Chevron for the screen shots of the model.

AEM (Advanced Energy Consortium) is an industry consortium managed by the Bureau of Economic Geology and the Jackson School of Geosciences at the **University of Texas at Austin**.

Resource issues will more and more require the solution of interlinked, interdisciplinary problems involving heterogeneity:

- oil & gas exploration

- carbon storage

- water management

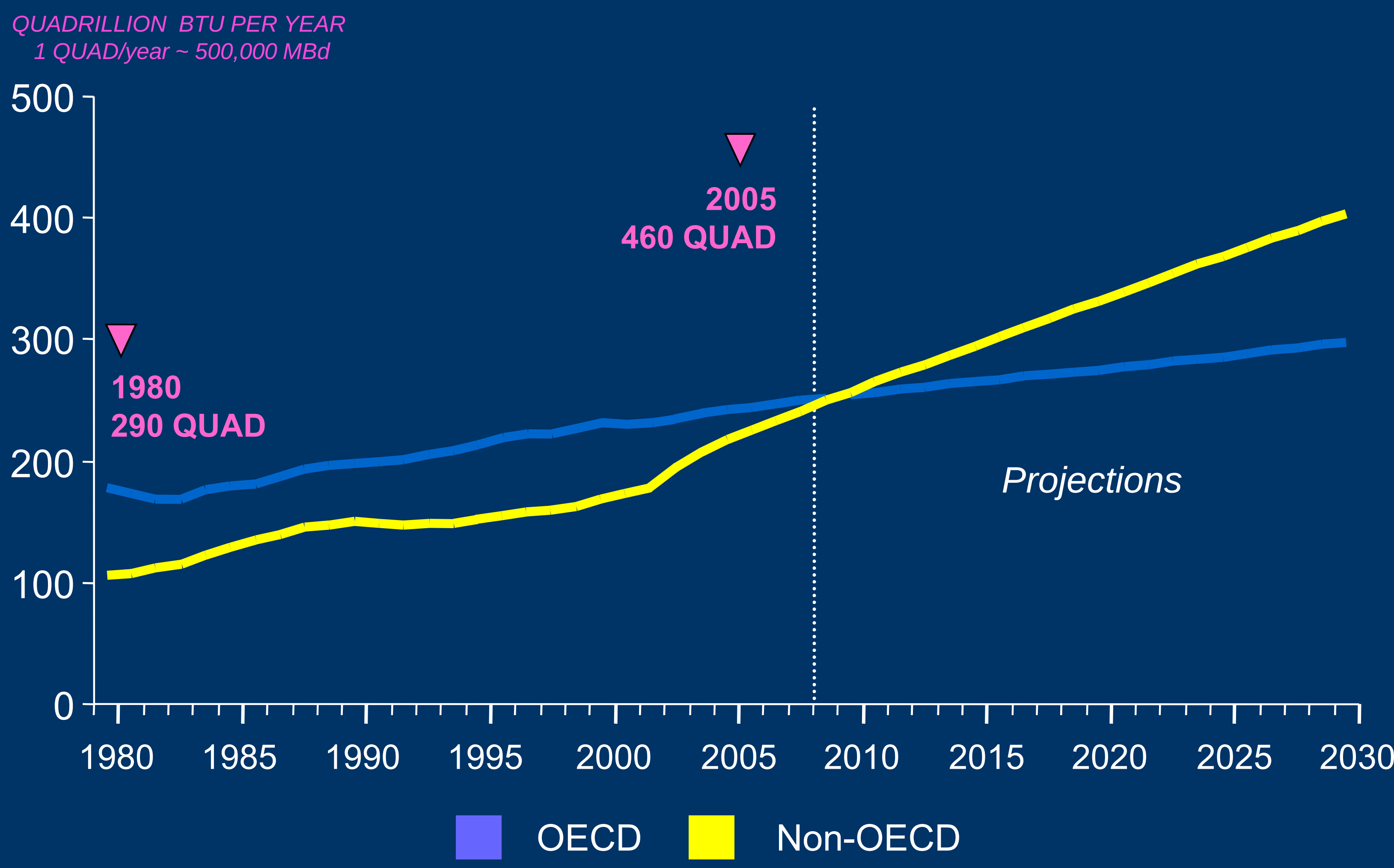
- infrastructure management

Abundance of data (and much much more coming).

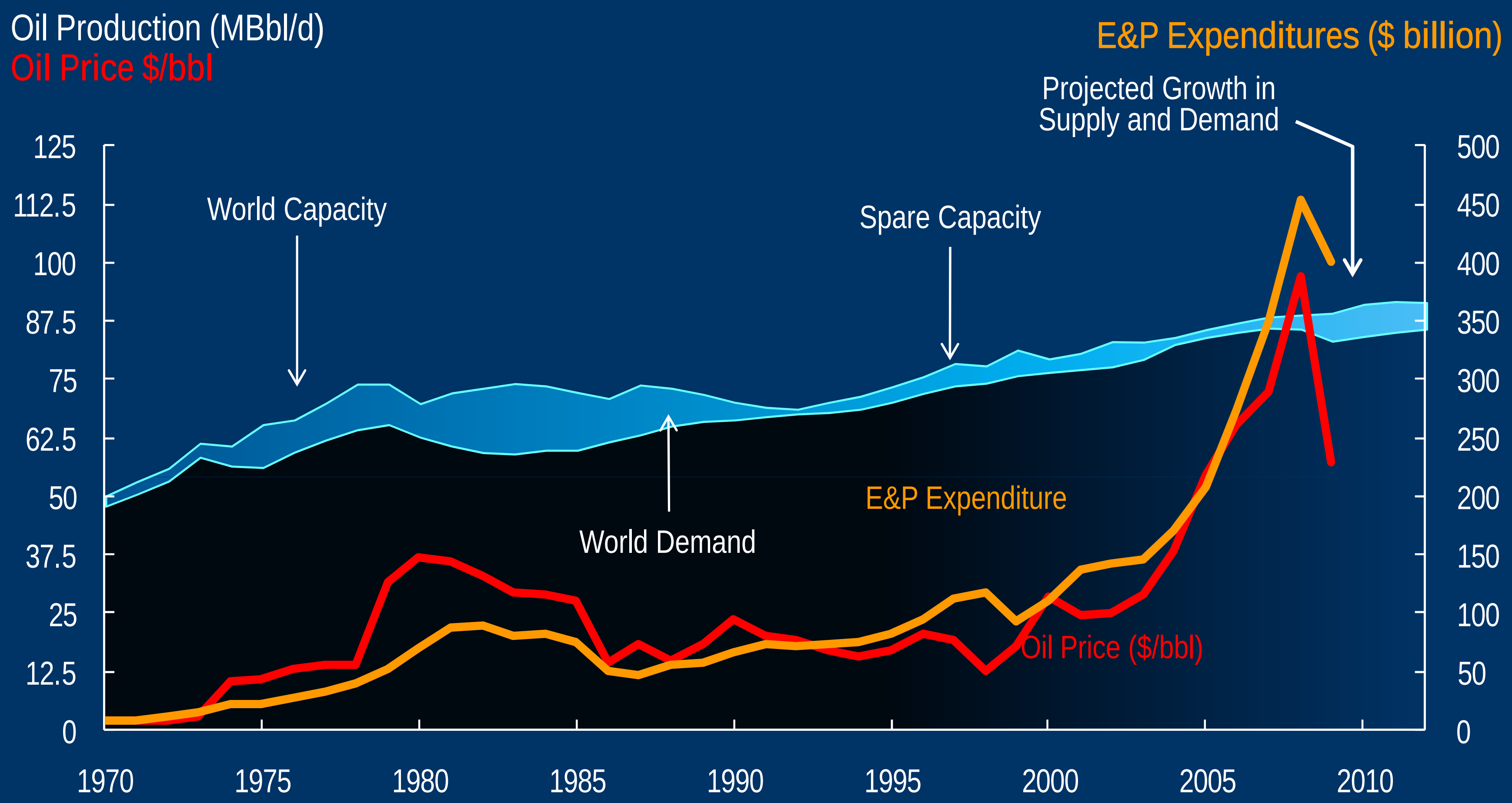
Need much better interpretative physical and geological models, built around better understanding of fluid-solid interactions in the crust over a wide range of scales.

Extra Slides

Demand for energy will grow 40+% by 2030 with a shift to developing economies

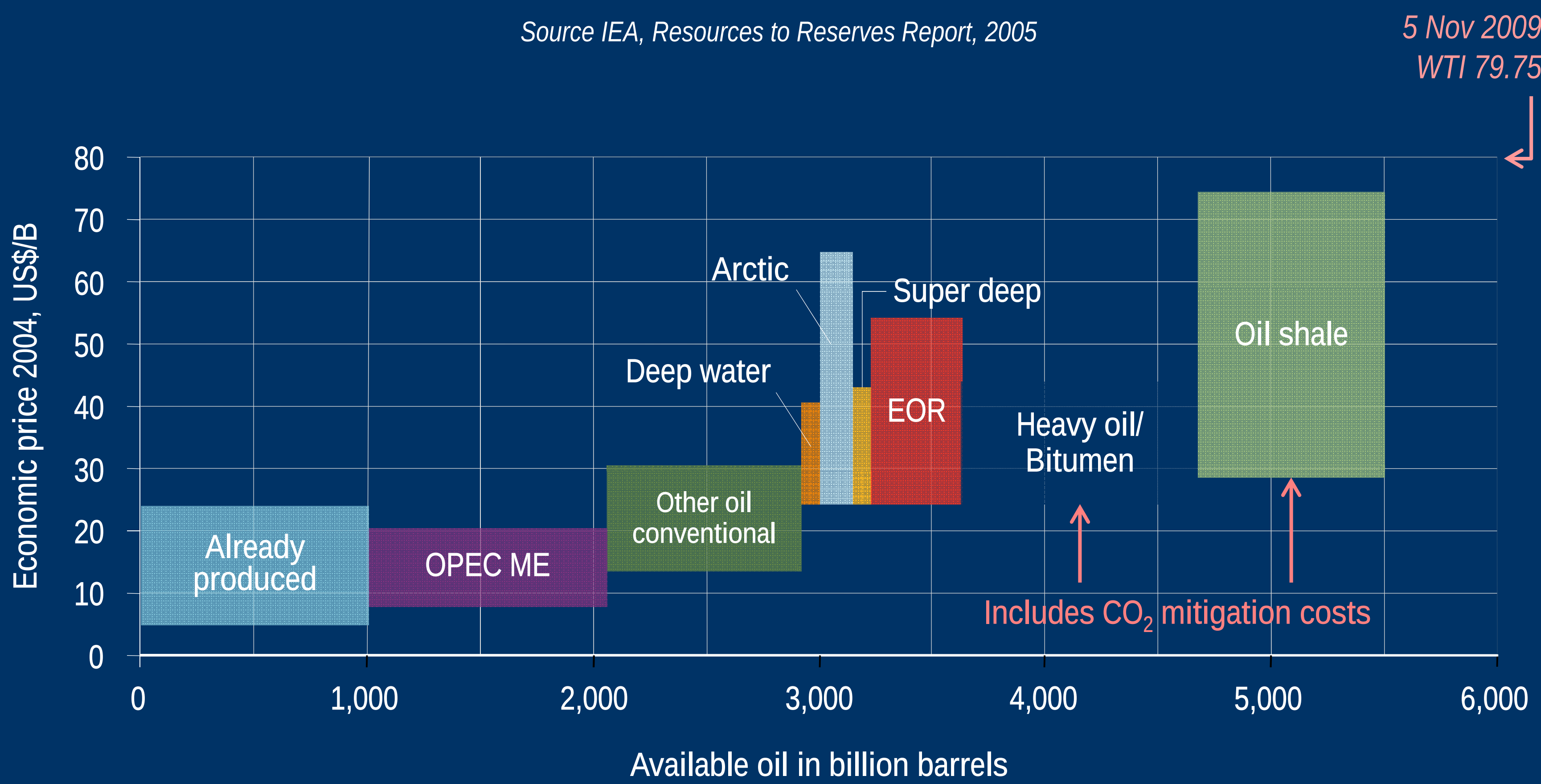


Source: Energy Information Agency, 2007



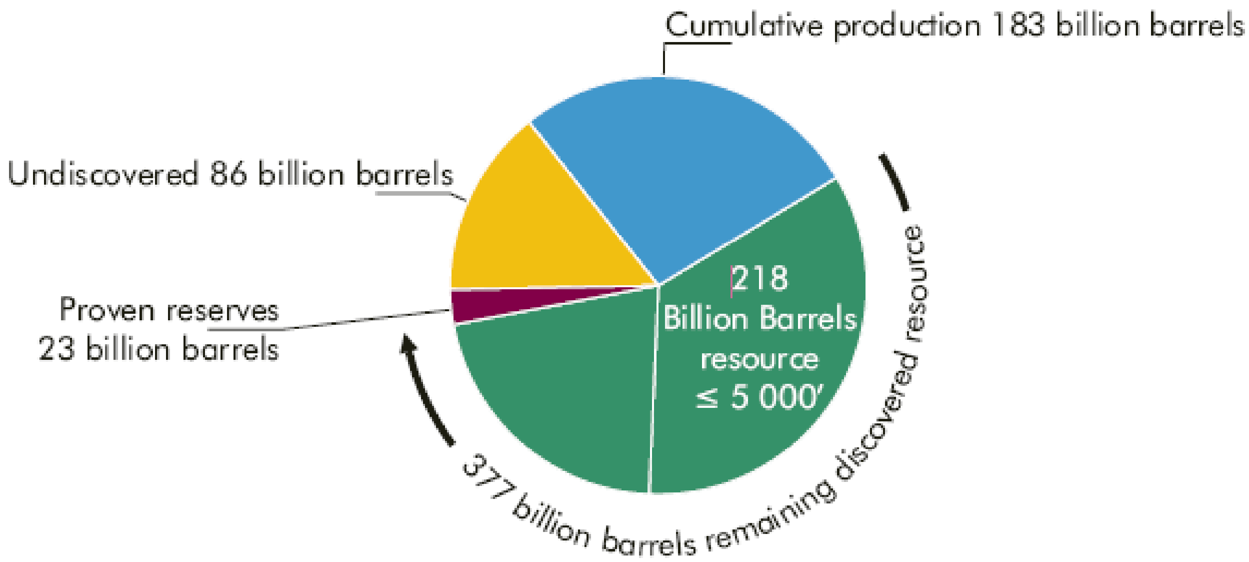
Source: BP Statistical Review, IEA World Energy Outlook, Monthly Oil Market Report, Medium-Term Oil Market Report, Lehman/Barclays. Revised 07/09

Challenges Supply & Cost



Recovery, recovery, recovery

Figure 2.9 • Un-recovered oil left over in United States fields



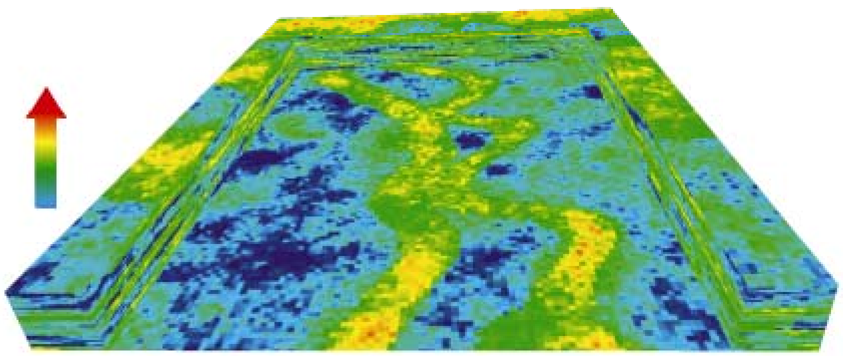
After United States Department of Energy; DoE 2004.

In the United States, there is a lot of oil left underground (more than 2x cumulative production)

Two types of oil left behind

Bypassed oil and Bound (residual) oil

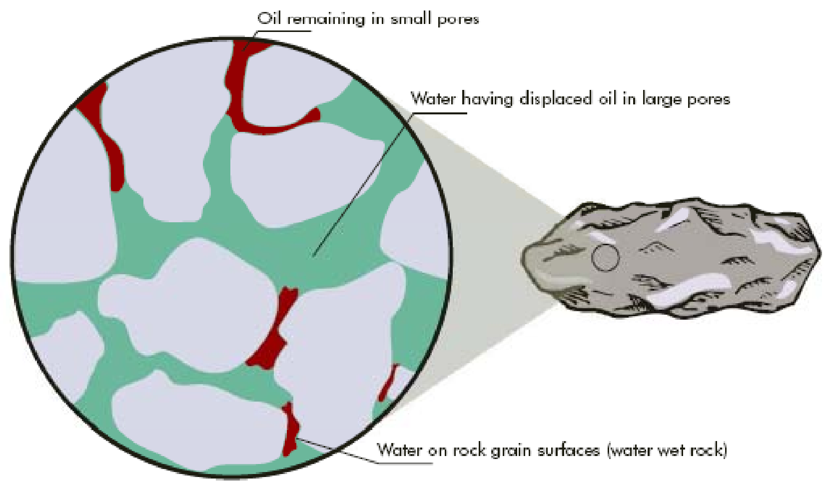
Figure 2.11 • *By-passed oil*



Water, in blue, has swept out the oil but left some channels still containing oil (high concentration in yellow and red, lower concentration in green). The oil may have been left behind because, for example, the channels have lower permeability.

This illustration, not based on factual data, is reproduced from Yeten 2002, courtesy of Fikri Kuchuk, Schlumberger.

Figure 2.15 • *Residual oil left in small pores after water has displaced the oil from large pores (cartoon definition)*



mapping or remote sensing problem (macro physics)

flow in porous media problem (macro and nanophysics)

There seems little doubt that the present period of unusual warmth will eventually give way to a time of colder climate, but there is no consensus as to the magnitude or rapidity of the transition. The onset of this climatic decline could be several thousand years in the future, although there is a finite probability that a serious worldwide cooling could befall the earth within the next 100 years

—UNDERSTANDING CLIMATE CHANGE: A program for action, National Academy of Sciences, 1975

Oil and Gas Resources: Academy Calls USGS Math "Misleading"

In 1922, before the discovery of a vast pool of oil under eastern Texas, the U.S. Geological Survey solemnly predicted that the nation's cumulative oil production would not exceed 15 billion barrels, a figure that suggested the United States might soon run out of oil. Happily, the Geological Survey was wrong, although its estimate was not unreasonable considering the infant state of petroleum geology.

Now, with the passage of more than half a century, it looks as if the Geological Survey may have erred again, this time on the high side. According to a new survey* put out by the National Academy of Sciences concerning fuels and basic material resources, the amount of oil and gas left to be discovered and produced with current technology in the United States is "considerably smaller" than the 200 to 400 billion barrels of oil and the 1000 to 2000 trillion cubic feet of natural gas estimated as of last March by the Geological Survey.

A more realistic estimate, in the opinion of the Academy's Committee on Mineral Resources and the Environment, is that 113 billion barrels of oil and 530 trillion cubic feet of gas remain to be found and produced onshore and offshore, mostly in Alaska. The

* *Mineral Resources and the Environment* (National Academy of Sciences, Washington, D.C., February 1975), 348 pp.

main implication of the Academy committee's lower estimates (which are in addition to proved reserves) is that a large increase in annual production of oil and gas in the United States is "very unlikely."

Two years in the making, the Academy report broadly reviews national supply-and-demand prospects for fossil fuels and essential metals. Among the report's main conclusions is the thought that industrialized nations face the possibility of a "series of shocks of varying severity" in the not-so-distant future as shortages occur in one critical material after another—not as a consequence of international cartels, but of the physical limits of the earth's resources. The committee foresees declining national self-sufficiency in copper, and it recommends nonmilitary stockpiling for some "threatened materials" such as tin, helium, mercury, and the platinum metals, supplies of which may be limited by political action or waning resources, and for which there are no ready substitutes.

Beyond stockpiling, emphasized Brian Skinner, a Yale geologist and chairman of the committee, in a news conference on 11 February, the report urges the adoption of a conservation ethic "as a kind of national religion," both for fuels and scarce industrial materials.

Skinner and the resource committee also make a point of trying to disabuse policymakers of the notion that technology will come quickly to the rescue

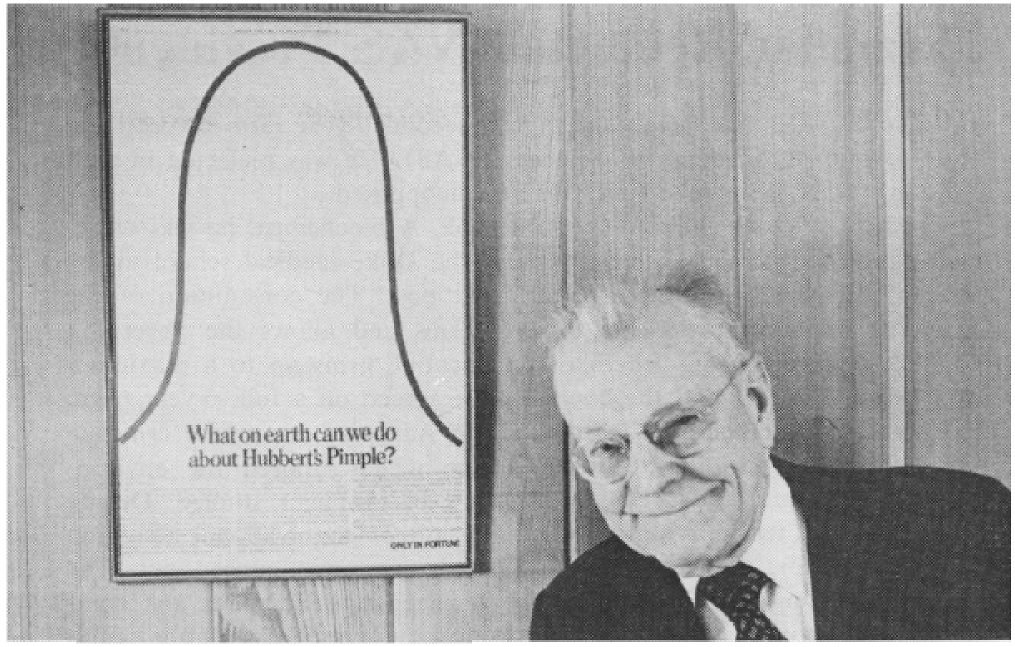


Photo by Eric Poggenpohl

M. King Hubbert believes the petroleum era will be a brief blip in human history.

cussed prediction that U.S. oil and gas resources would turn out to be smaller than generally presumed, and that oil production would reach a peak and begin to decline in 10 to 15 years. (Oil production in the United States has been declining since late 1970 and gas production appears to have reached a peak in 1974.)

Hubbert was then one of the Shell Oil Company's leading exploration geophysicists, but his gloomy predictions branded him as a maverick out of step with the cornucopian philosophy of the oil industry. "My grandchildren may have to worry about oil shortages, but in a recent discussion of resource estimates.† The industry's second reaction was to try to prove Hubbert wrong. Within a year, other industry estimators were leapfrogging each other with higher and higher estimates. The Geological Survey trumped them all in 1961 with an estimate that U.S. oil production would eventually exceed 500 billion barrels, or more than five times the amount produced in the industry's first century.

Most of the industry's estimators kept their methods to themselves, and thus beyond scrutiny. Hubbert derived his from a straightforward statistical