University of Houston – Clear Lake
Physics and Space Science Seminar

mK to km: How Millikelvin Physics is Reused to Explore the Earth Kilometers Below the Surface

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American Physical Society Distinguished Lecturer
on the Applications of Physics

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Transitioning from Academic Physics to the "Real World"

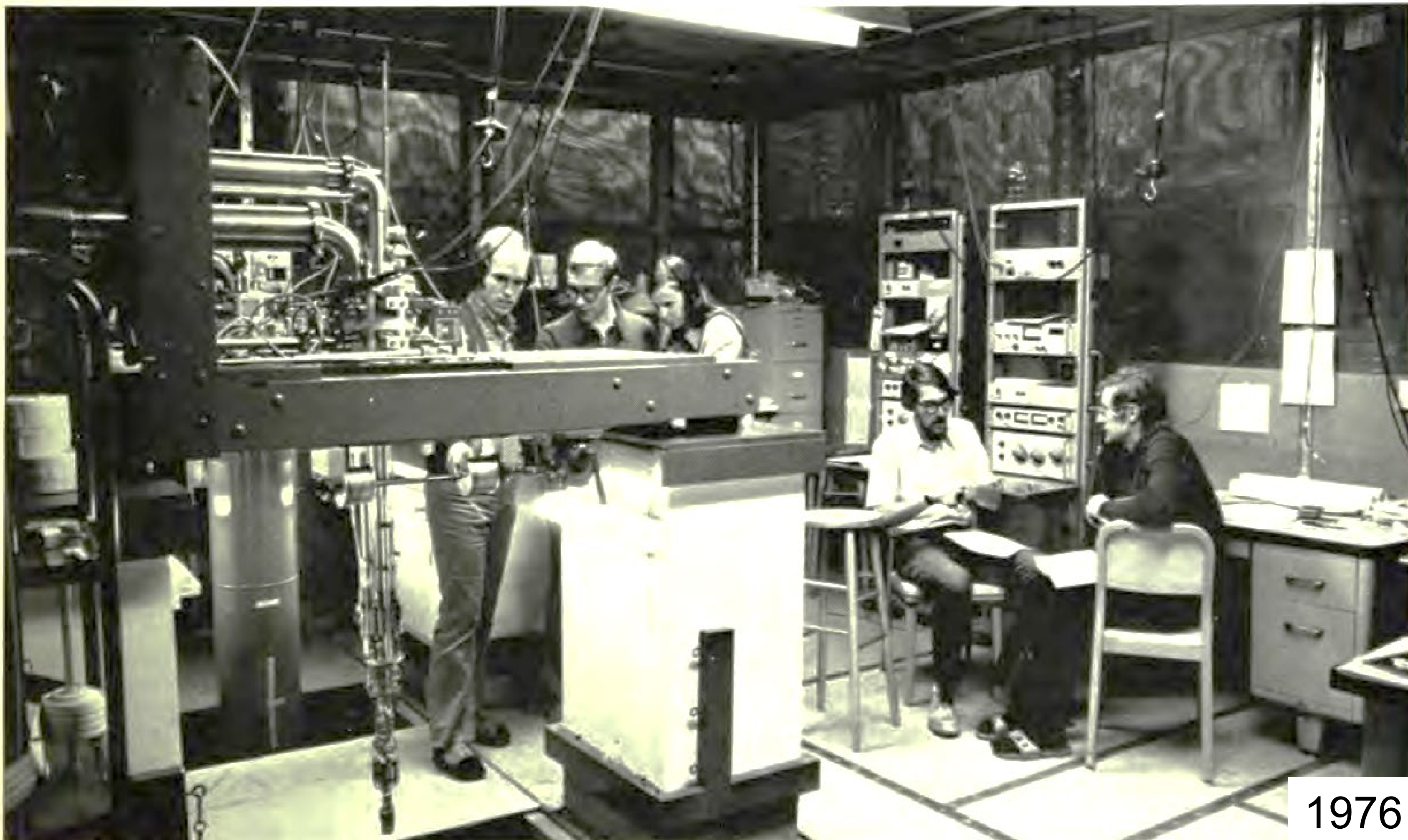
This is a fully worked out example of how one physicist made the transition from esoteric laboratory science to very practical real-world inventions.

By the end of this talk, you will have learned how to measure which way the wind was blowing 10 million years ago, and how to measure the sizes of pores in sedimentary rock – and why those are important.

You will also get a lesson in corporate jujitsu.

Your experiences will be different. I adapted to my time and place. You will adapt to yours.

Graduate School: University of California, San Diego
Superfluid ^3He T < 0.003 K



1976

A dilution refrigerator with its pumping lines emerging above (left foreground) hangs over an open pit in Wheatley's copper-screened lab. Another one (behind it and to the left) is enclosed in its Dewar. Wheatley's assistants shown in this photo are (left to right) Douglas Paulson, Ronald Sager, Evelin Pichelman, Robert Kleinberg and Matti Krusius. Photograph by Douglas Paulson. Figure 1

Why the Oil Industry?

1970s Gas Lines

Grad School Housemates

RV Knorr

Grad School Experience

Tek 5103

Pressing National Need

Geoscience

Measurements

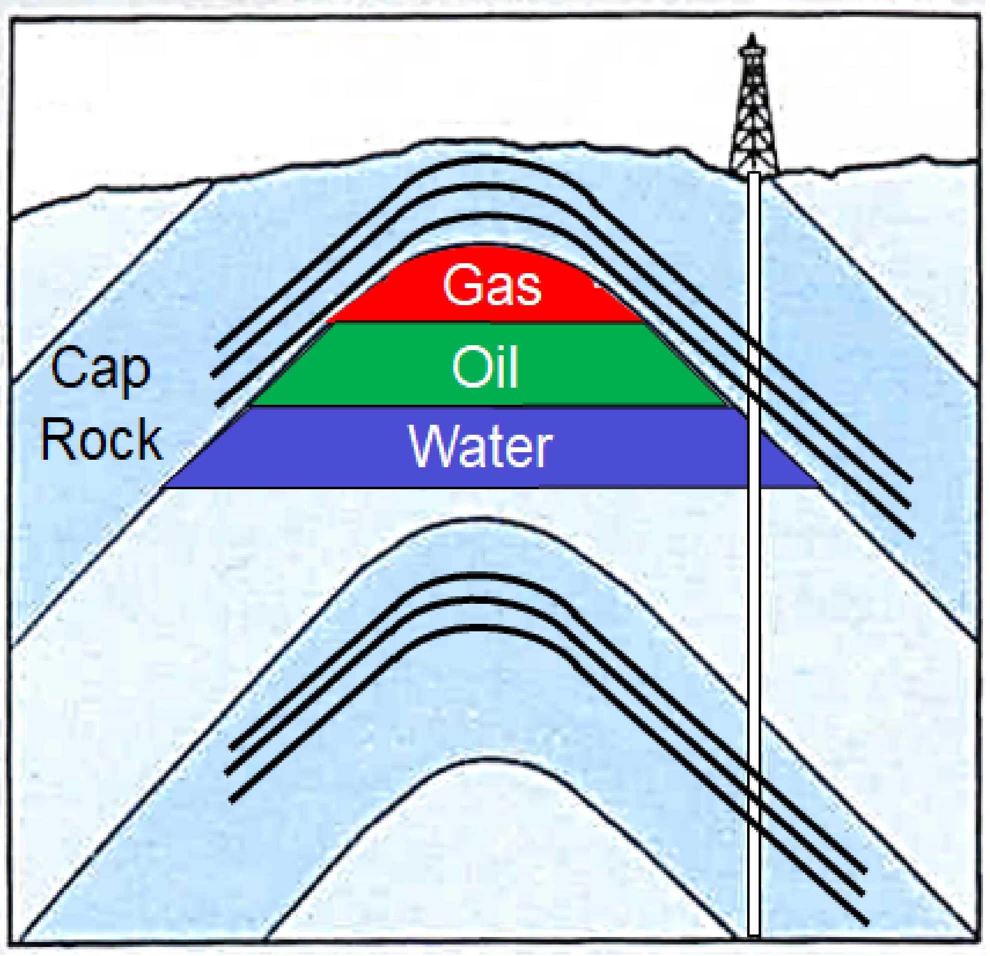
EXXON

Schlumberger

Part I

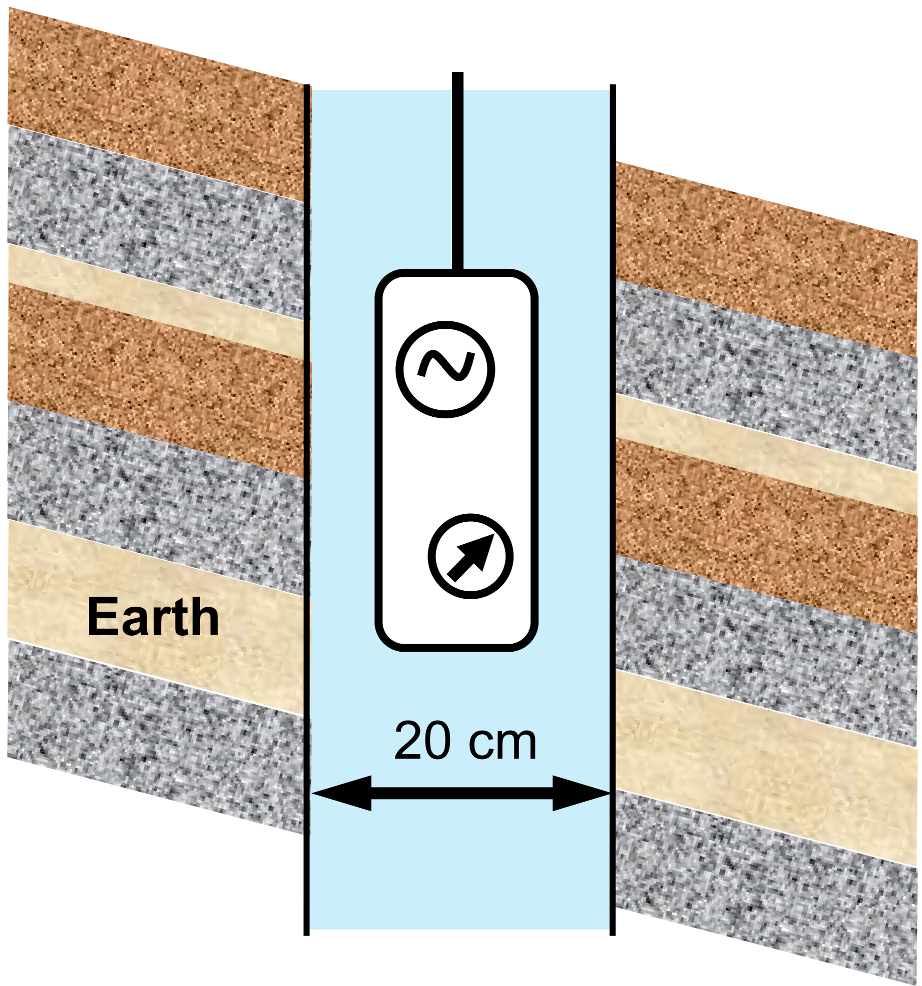
Which Way Was the Wind Blowing Ten Million Years Ago?

You have drilled a water well.
Where is the oil and natural gas?



Rules of the Game

You don't put the sample into the machine, you put the machine into the sample.



More Rules of the Game

Apparatus must operate after being:

> transported in arctic, tropical, desert, or marine environments
> subjected to 100 g shock
> dragged through kilometers of rough rock borehole

Apparatus must operate while:

> exposed to –25°C to +175°C in salt-saturated water at 140 MPa
> temperature conditions are changing
> moving at 15 cm/s

Apparatus must operate:

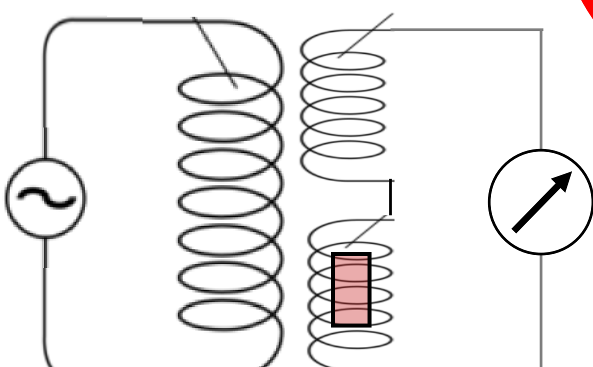
> at the end of 10 kilometers of multiconductor cable
> autonomously, and simultaneously with other nuclear, electromagnetic, and acoustic instruments

I'm a *low temperature* physicist.
What the heck am I doing here?

Once the initial panic subsided . . .

Exciting Millikelvin Physics . . . With No Practical Application

Magnetic Susceptibility Thermometry



Curie-Weiss

$$\chi = \frac{C}{T - T_c}$$

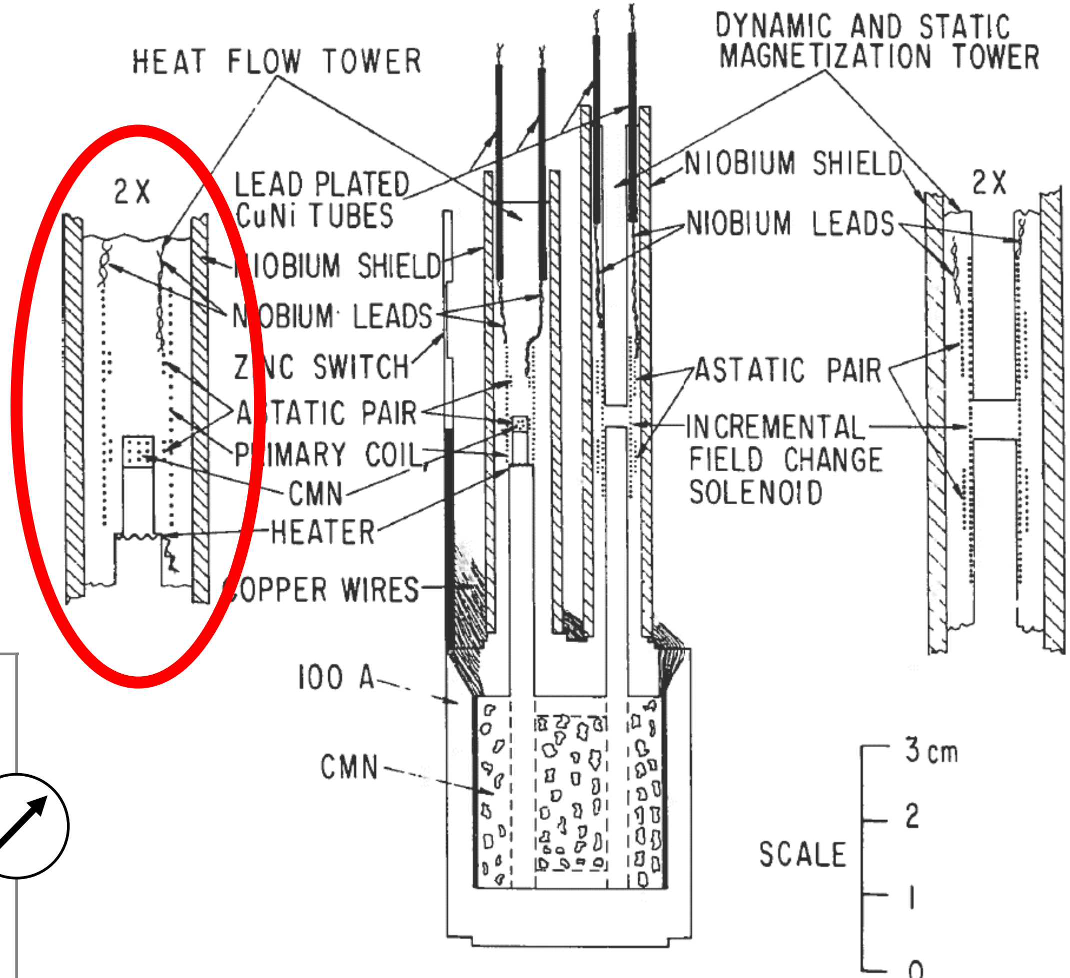


Fig. 1. Scale drawing of the adiabatic demagnetization cell.

Heat Flow in Superfluid ^{3}He*

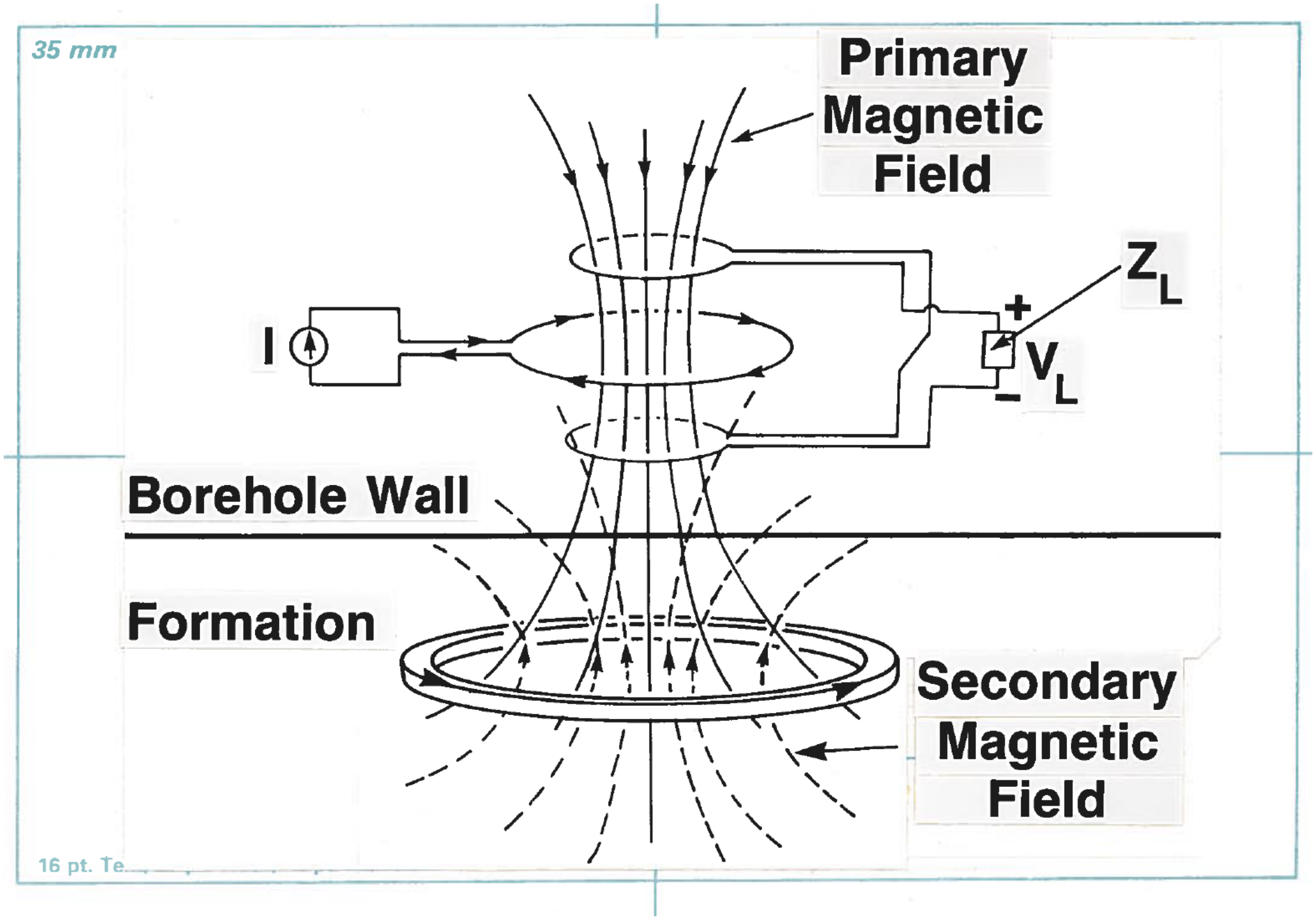
R. T. Johnson, R. L. Kleinberg, R. A. Webb, and J. C. Wheatley

Department of Physics, University of California at San Diego, La Jolla, California

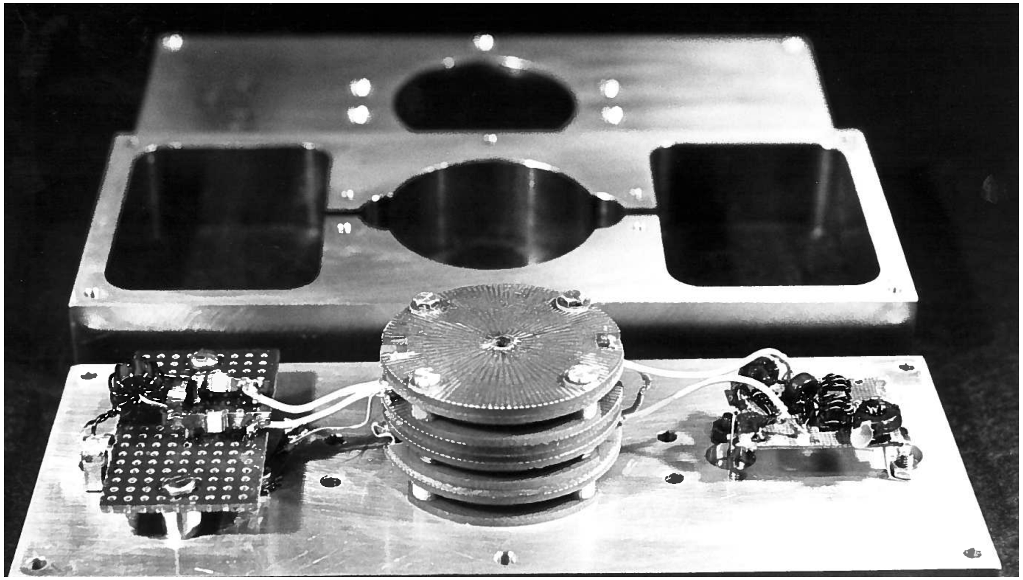
(Received September 3, 1974)

JLTP 18,5/6,501-517 (1975)

Balanced-Secondary Mutual Inductance Coil Set Turned Inside Out & Applied to the Borehole Wall



R.L. Kleinberg, W.C. Chew, D.D. Griffin, "Noncontacting Electrical Conductivity Sensor for Remote, Hostile Environments", IEEE Transactions on Instrumentation and Measurement, 38, 22 (1989)



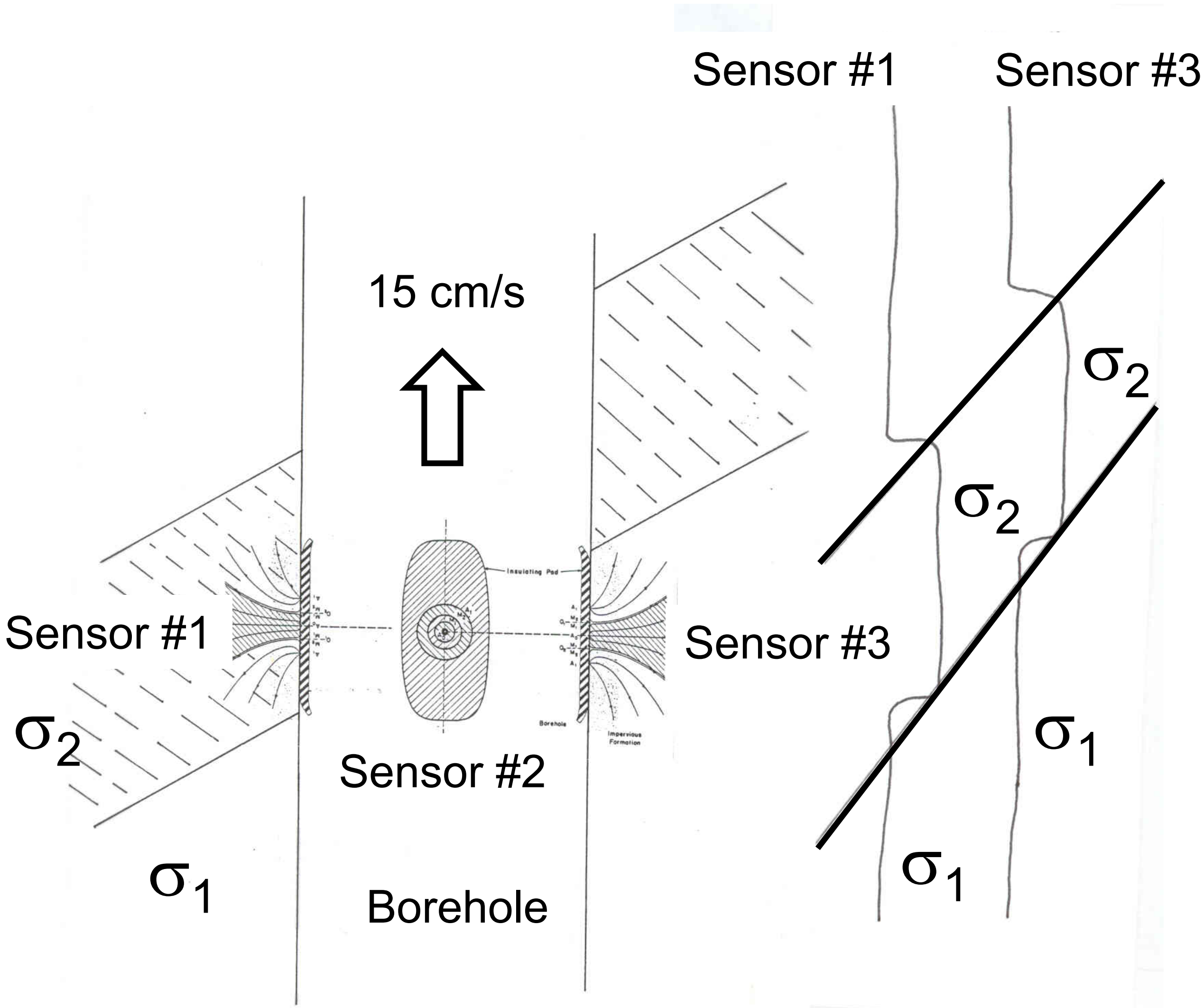
CMRR = -70dB @ 2 μm tolerance

Laboratory Prototype

Would not survive dunking in a bathtub, but proved the principle

Put sensors on the four arms of a borehole-robust apparatus

Measure the Slope of the Subsurface



Which way was the wind blowing?
We know in today's deserts by looking at sand dunes.

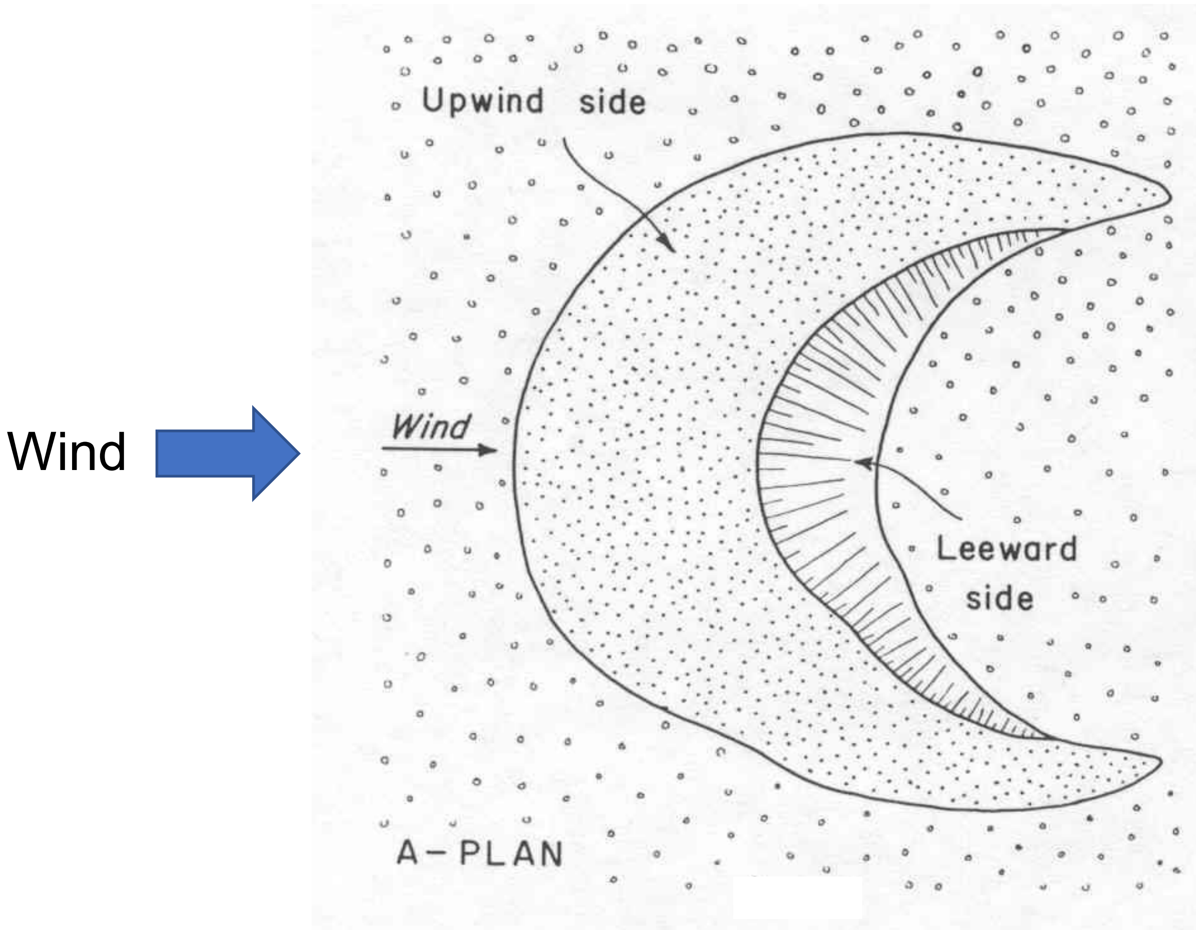


Figure 5.9 Desert barkhan dune and its

Which way was the wind blowing?
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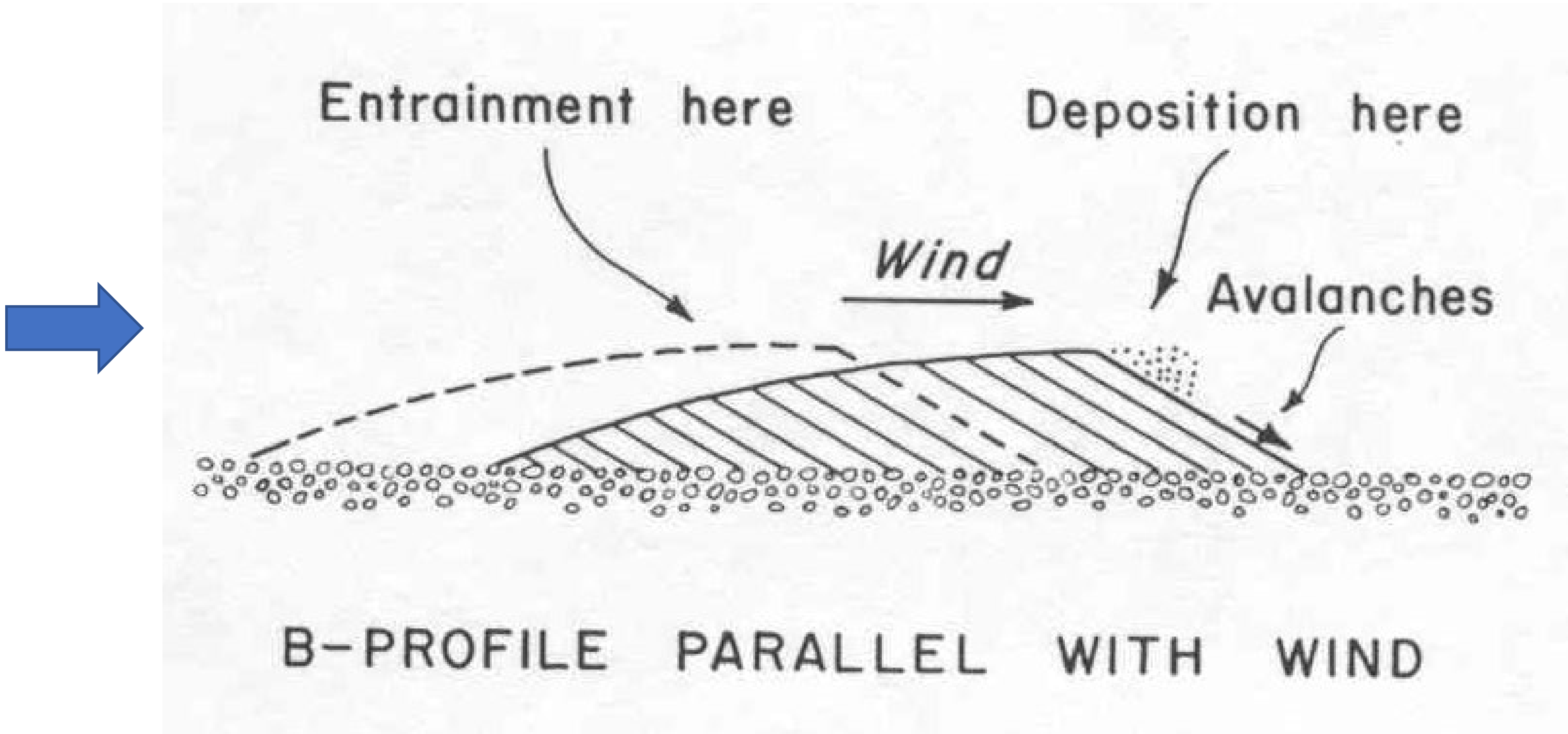
Wind

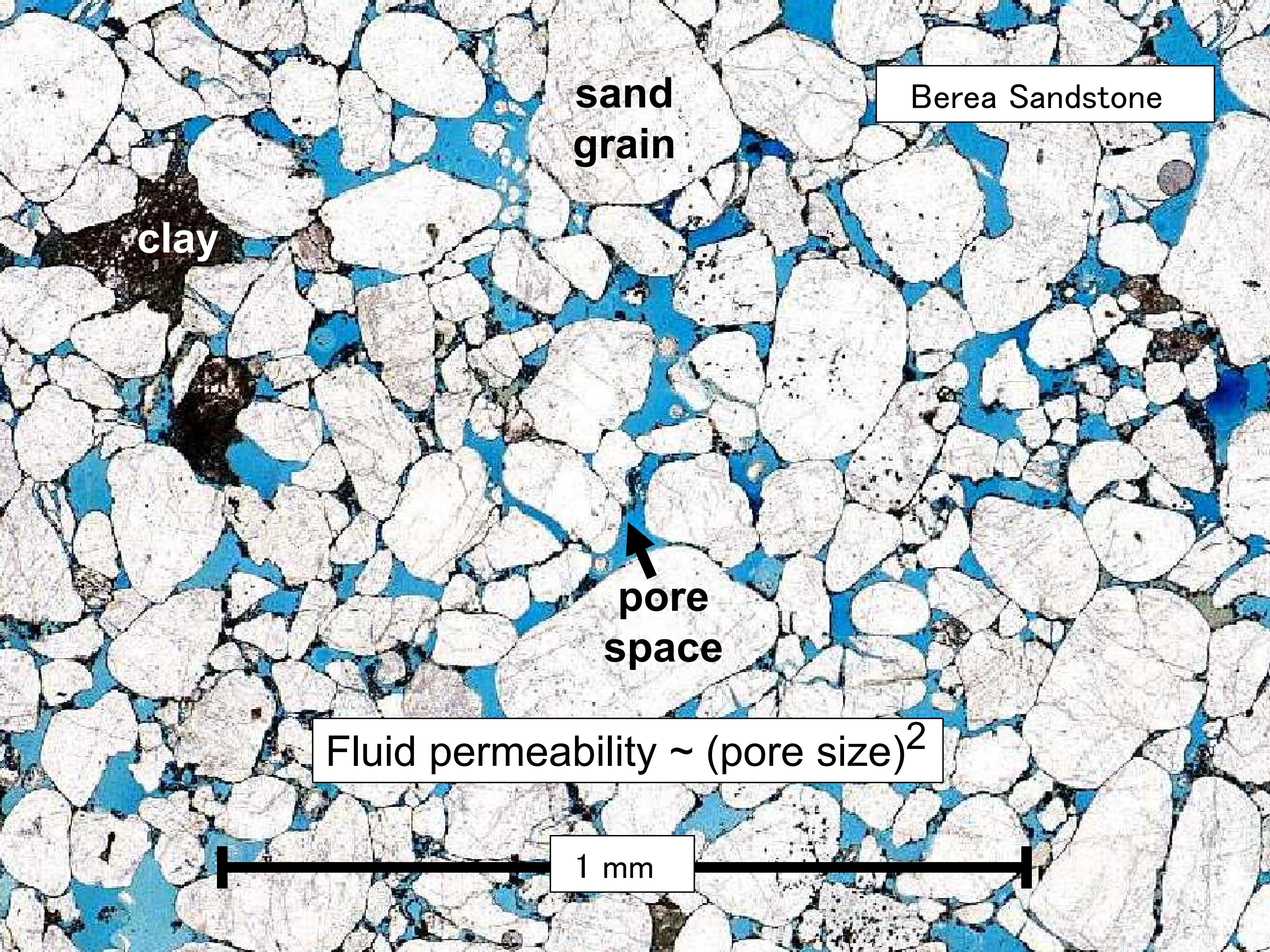


Corporate Jujitsu

- This was not the approach initially endorsed by management
- It started as a "skunk works" project, after hours and on weekends
- After some initial favorable results, I got a technician
- After more favorable results, a theorist asked to join the team
- Our development group in Paris had their own ideas how to do it
    - I built a copy of their device, optimized it, and showed that my approach was superior
- The instrument was successful, and saved our business in the most important oil field of the day
- When we were done, the technician, the theorist, and I "had time on our hands" . . . during which we invented something even more important . . .

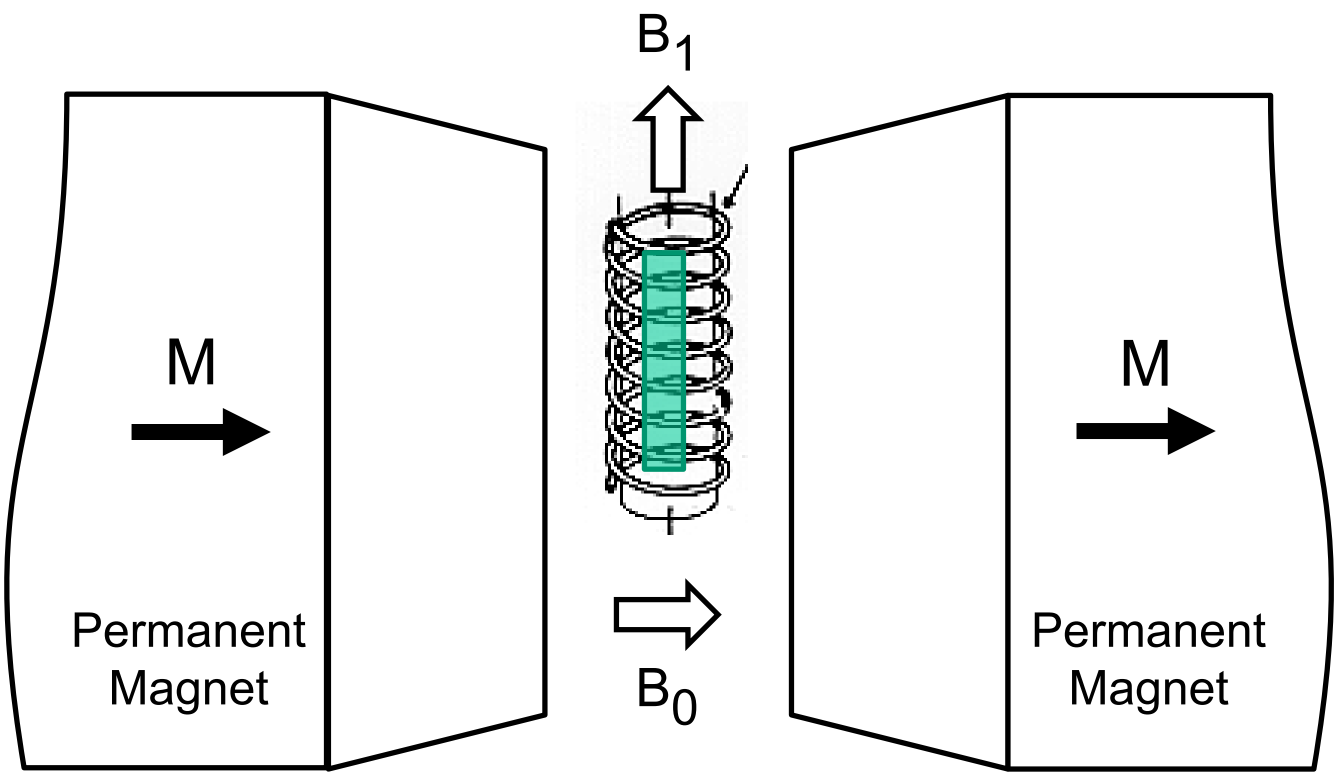
Part II

How Large Are Pores in Rock Two Miles Below the Earth's Surface?

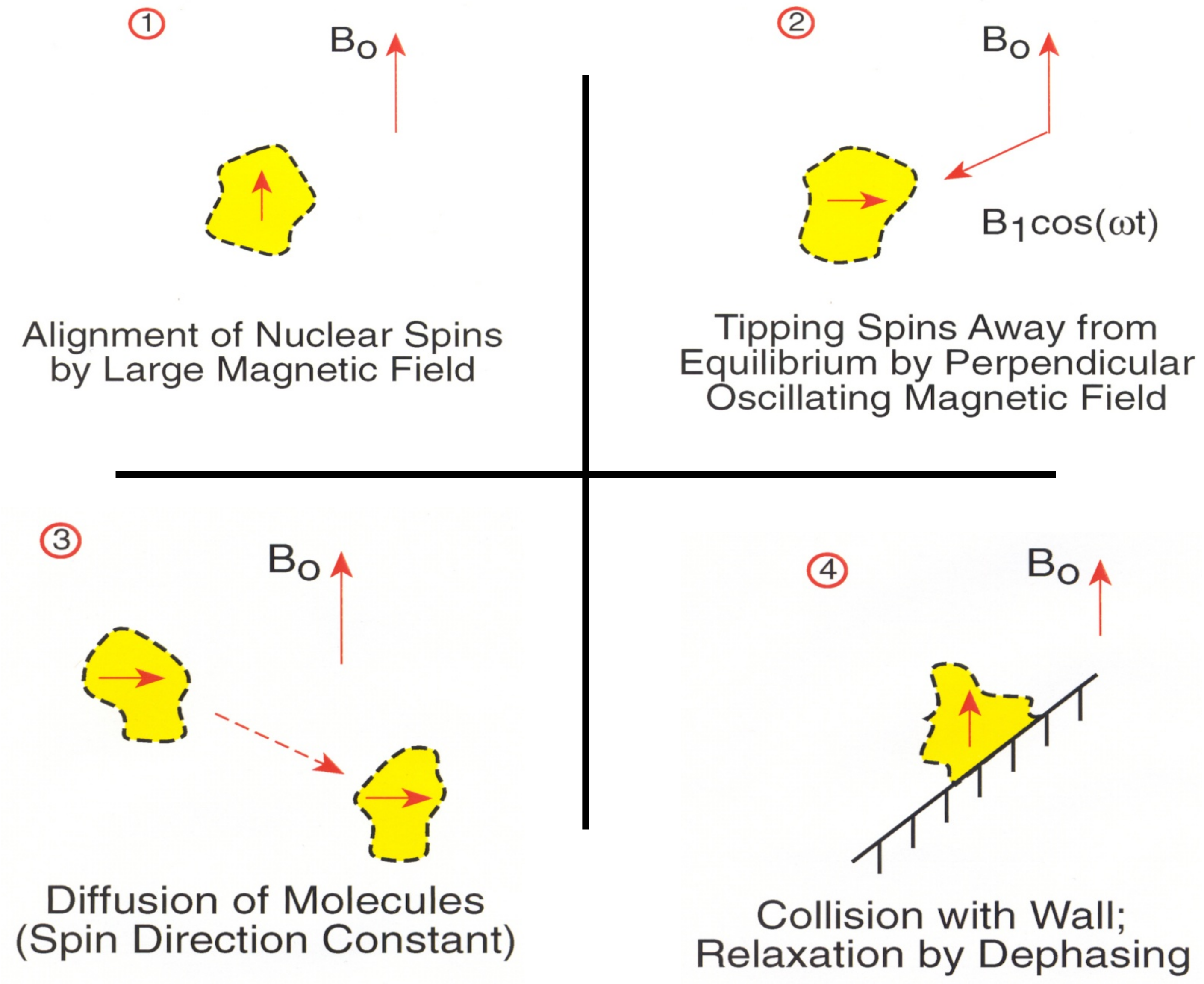

Berea Sandstone
sand grain
clay
pore space
Fluid permeability ~ (pore size)^2
1 mm

Nuclear Magnetic Resonance

- Strong constant magnetic field B_0
- Oscillating magnetic field B_1 perpendicular to B_0
- Oscillating field frequency $\omega = \gamma B_0$ (For protons: 42.58 MHz/T)

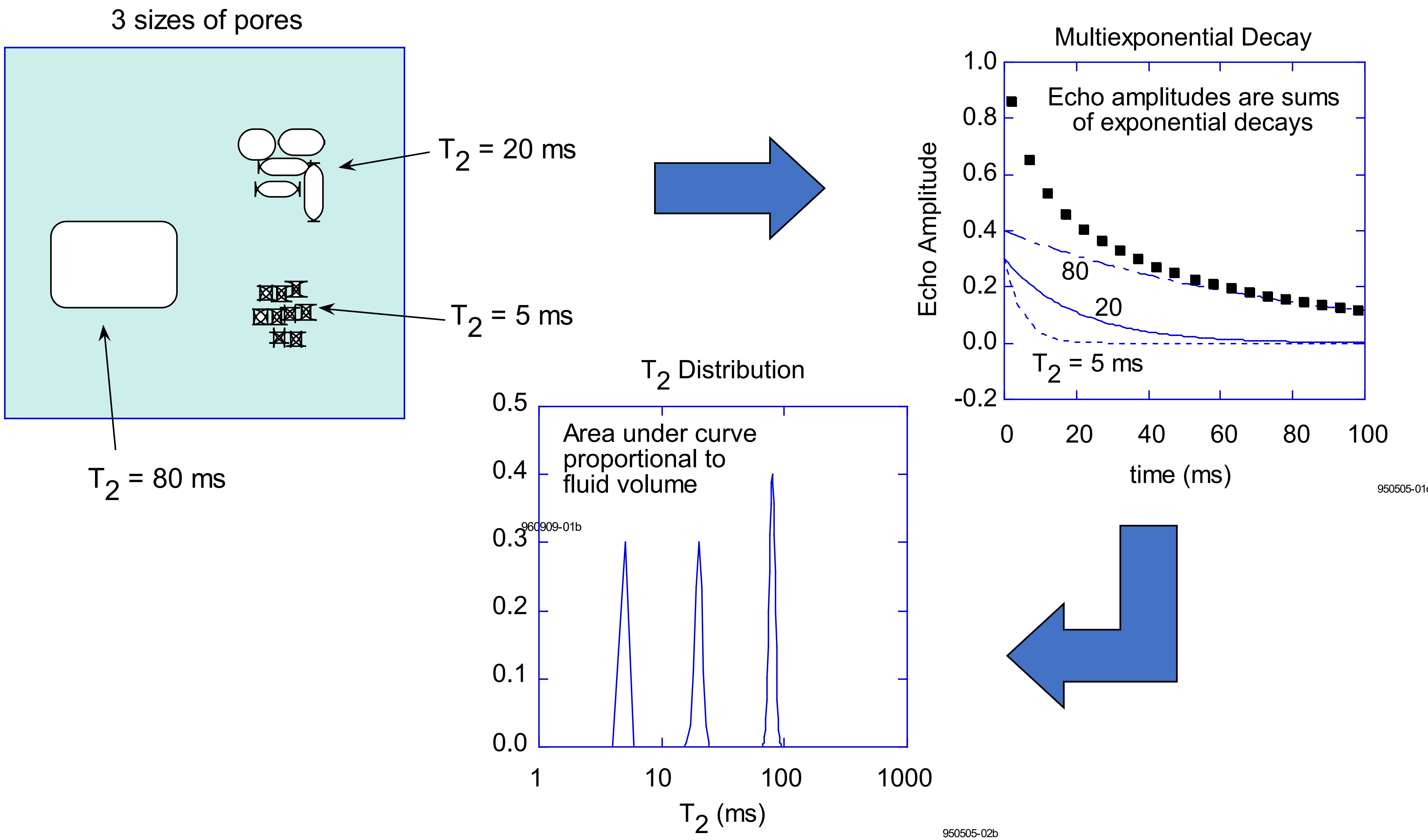


NMR of Fluids in Porous Media

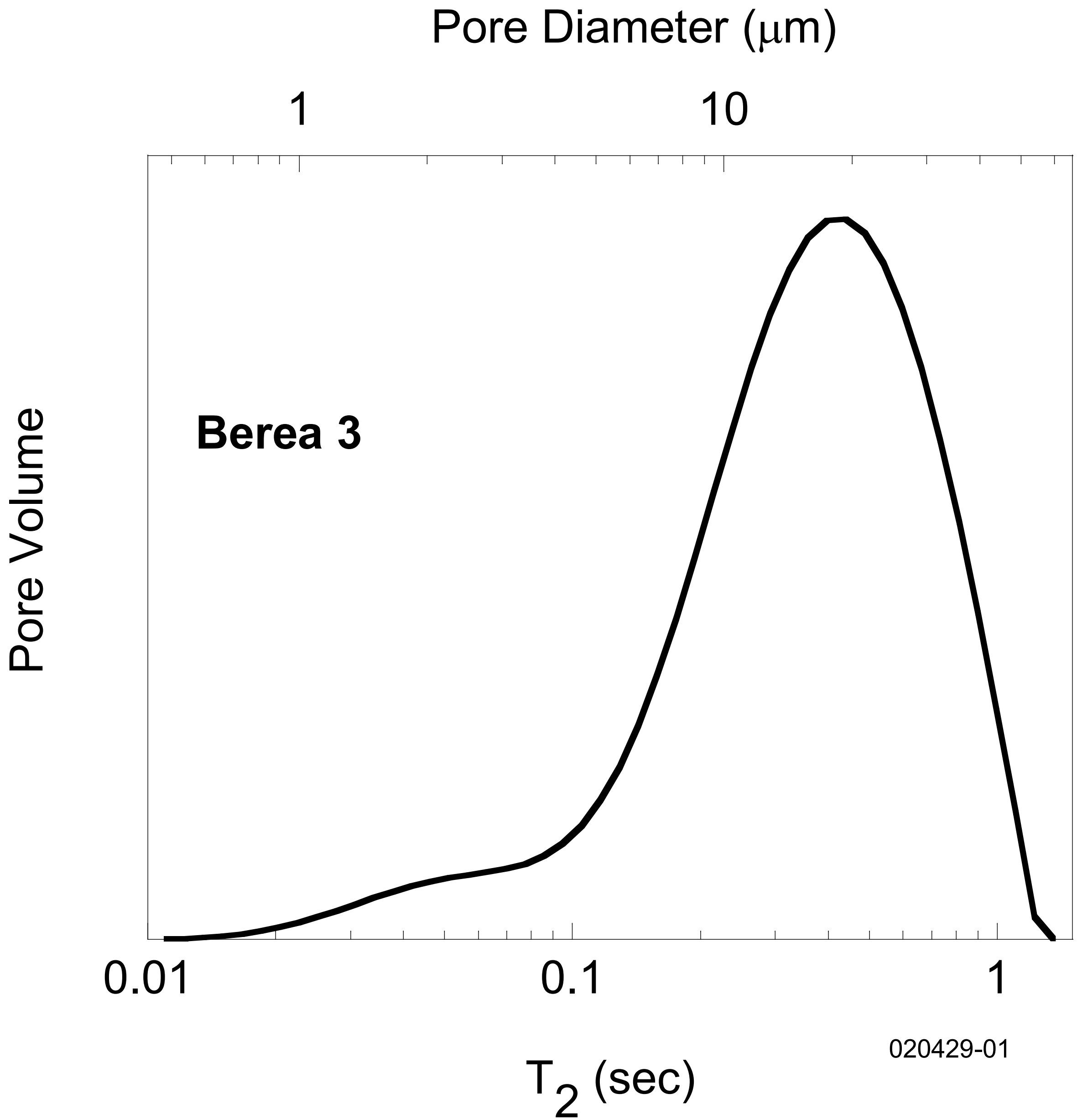


Mechanism of NMR Relaxation of Fluids in Rocks
Kleinberg, Kenyon, Mitra, Journal of Magnetic Resonance, A108, 206 (1994)

Analyze NMR Multiexponential Decay to Find Pore Size Distribution



Pore Size Distribution from NMR



Nuclear Magnetic Resonance Experience

SQUID-Detected NMR of Liquid ^{3}He

Conventional NMR of Layered Intercalation Materials

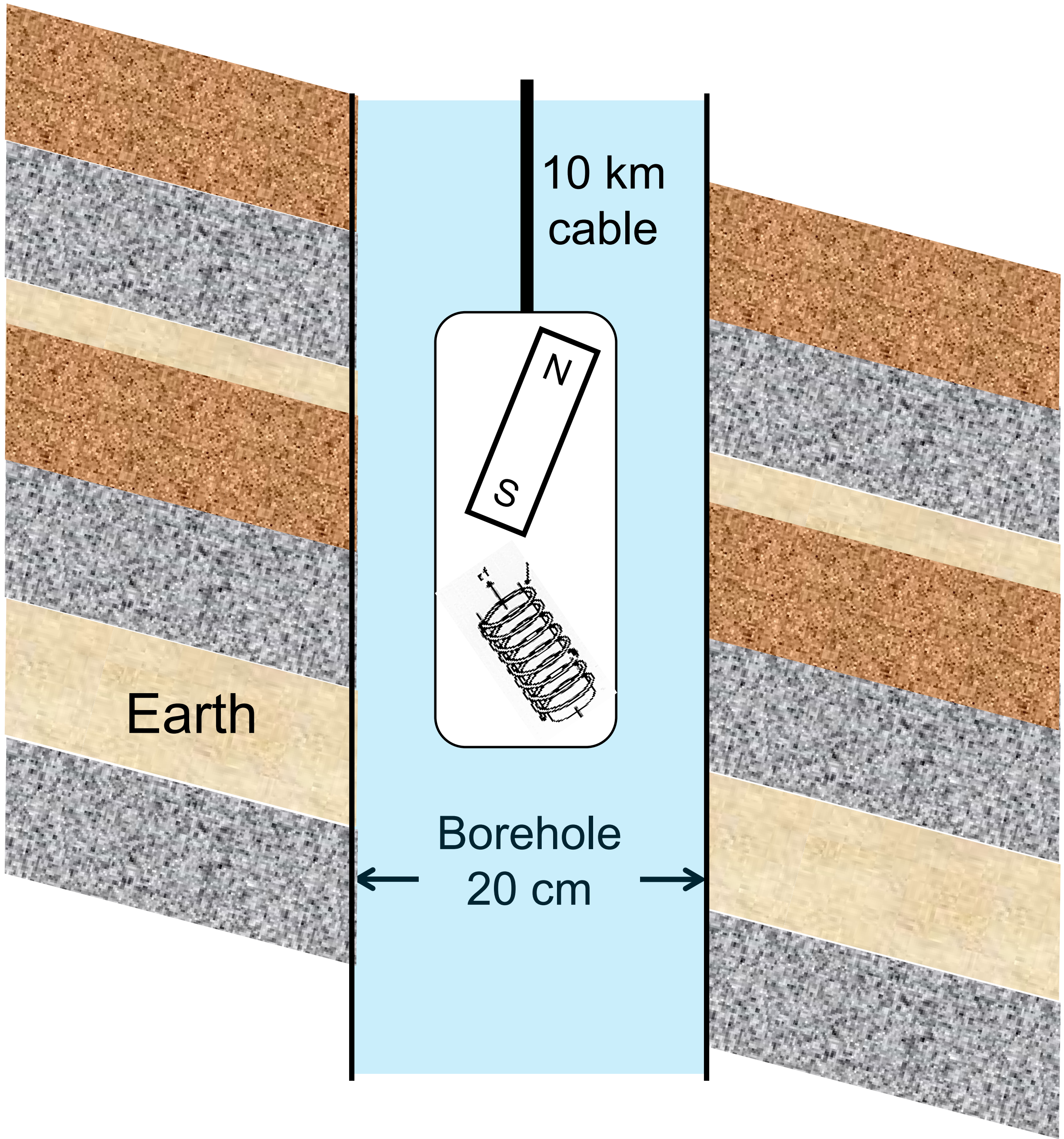
???

Borehole NMR

???

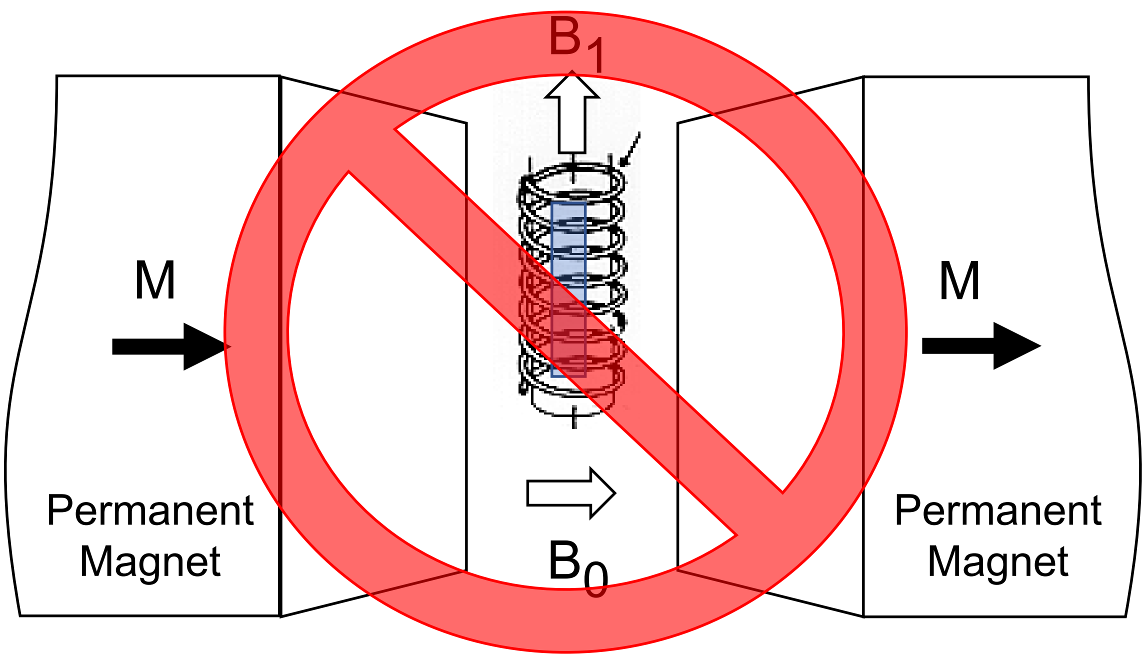
How hard can this be? . . .

Rules of the Game

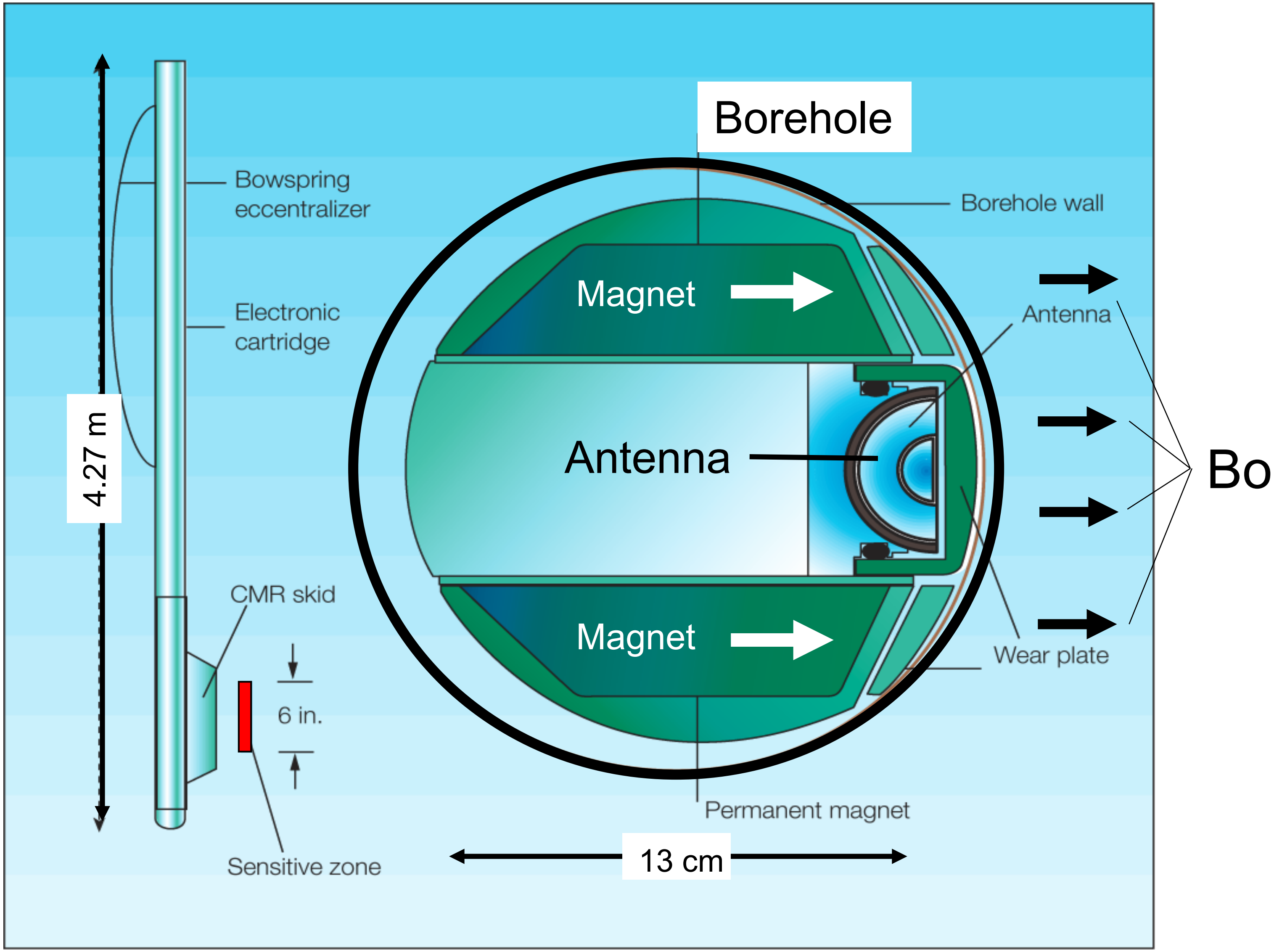


Borehole Nuclear Magnetic Resonance
Focus on Physics Principles

- Strong constant magnetic field B_0
- Oscillating magnetic field B_1 perpendicular to B_0
- Oscillating field frequency $\omega = \gamma B_0$ (For protons: 42.58 MHz/T)

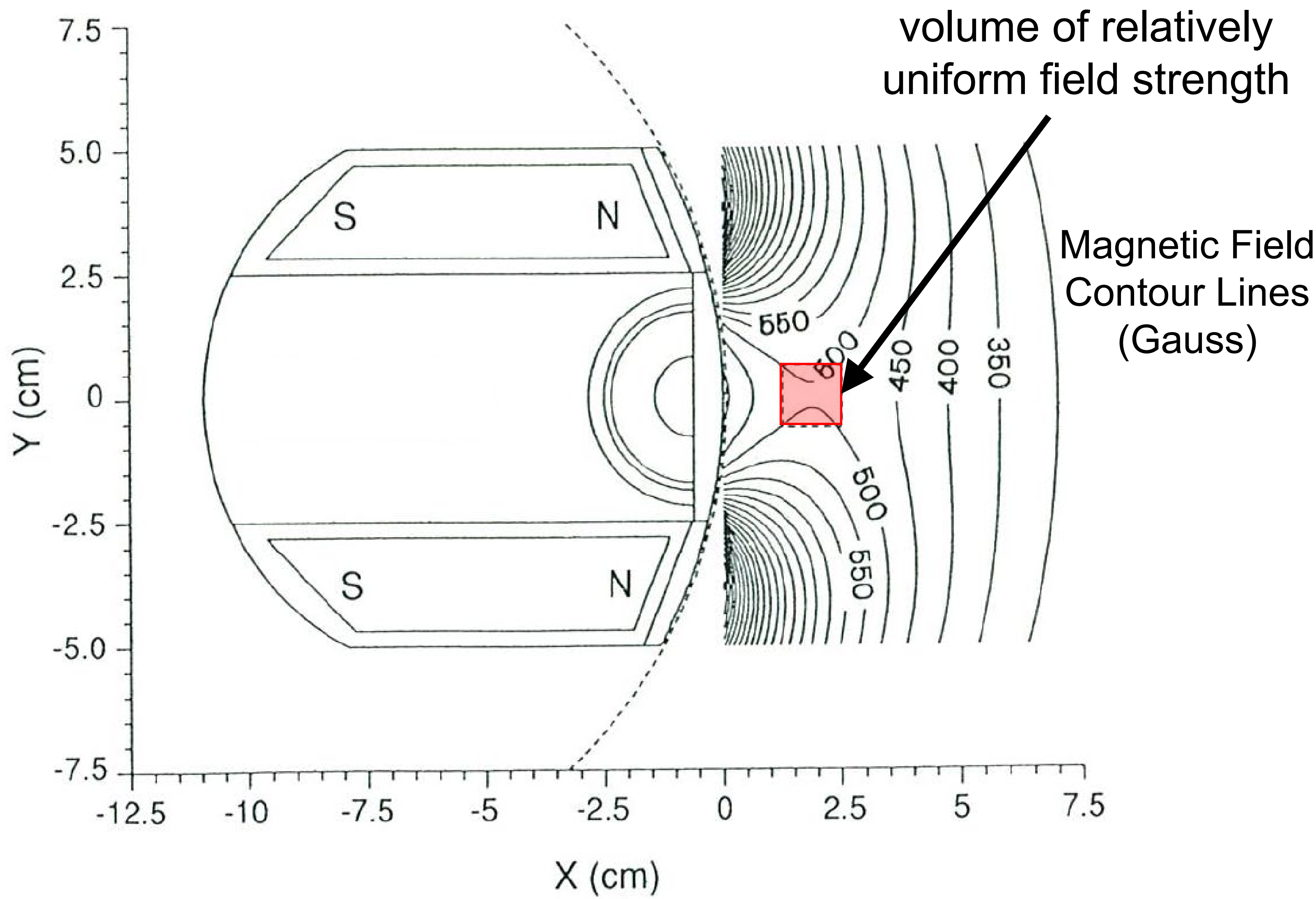


With time on our hands, we came up with this



Novel NMR Apparatus for Investigating an External Sample
Kleinberg, Sezginer, Griffin, Fukuhara, Journal of Magnetic Resonance 97, 466 (1992)

Field Strength Saddle Point Inside Earth



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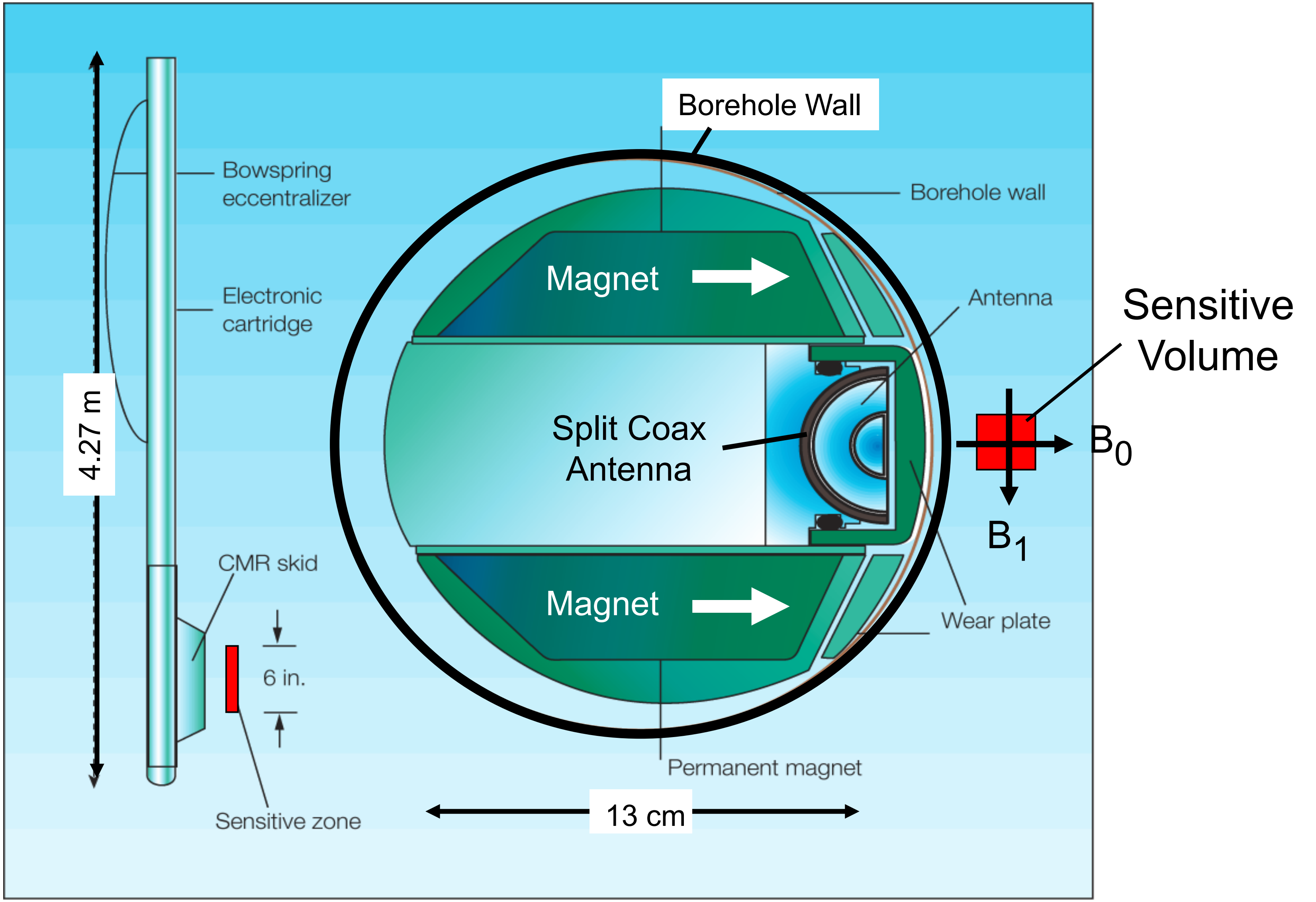
Kleinberg, Sezginer, Griffin, Fukuhara, Journal of Magnetic Resonance 97, 466 (1992)

Underground Nuclear Magnetic Resonance



Novel NMR Apparatus for Investigating an External Sample
Kleinberg, Sezginer, Griffin, Fukuhara, Journal of Magnetic Resonance 97, 466 (1992)

Mating Borehole NMR with Unmanned Submarine

4000 m water depth: ~0°C, ~6000 psi
I might even have said it was “too easy”.

NMR Laboratory

Kleinberg, Flaum, Griffin, Brewer, Malby, Peltzer, Yesinowski, "Deep Sea NMR: Methane Hydrate Growth Habit in Porous Media and its Relationship to Hydraulic Permeability, Deposit Accumulation, and Submarine Slope Stability", Journal of Geophysical Research 108(B10): 2508. (2003)

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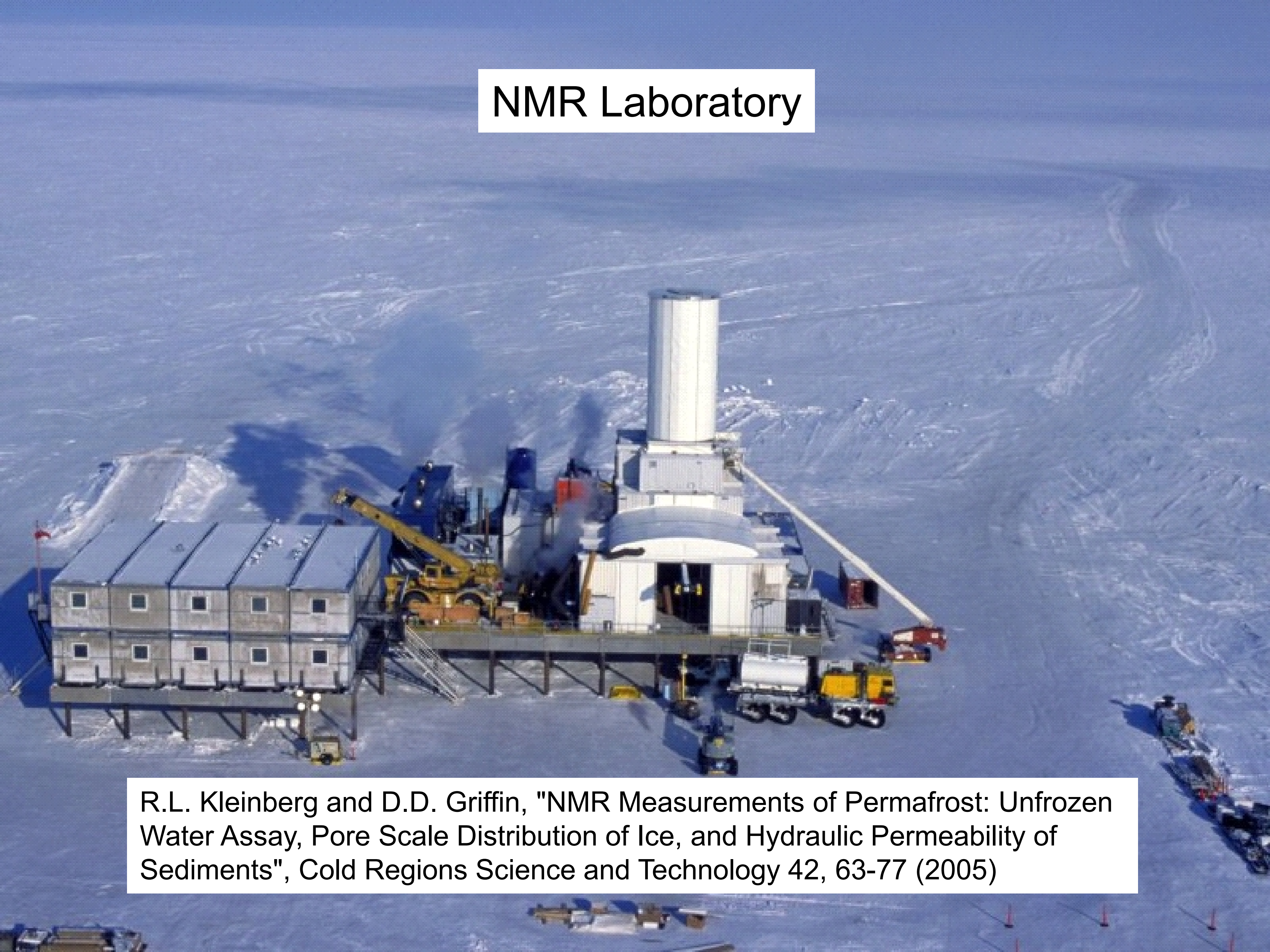
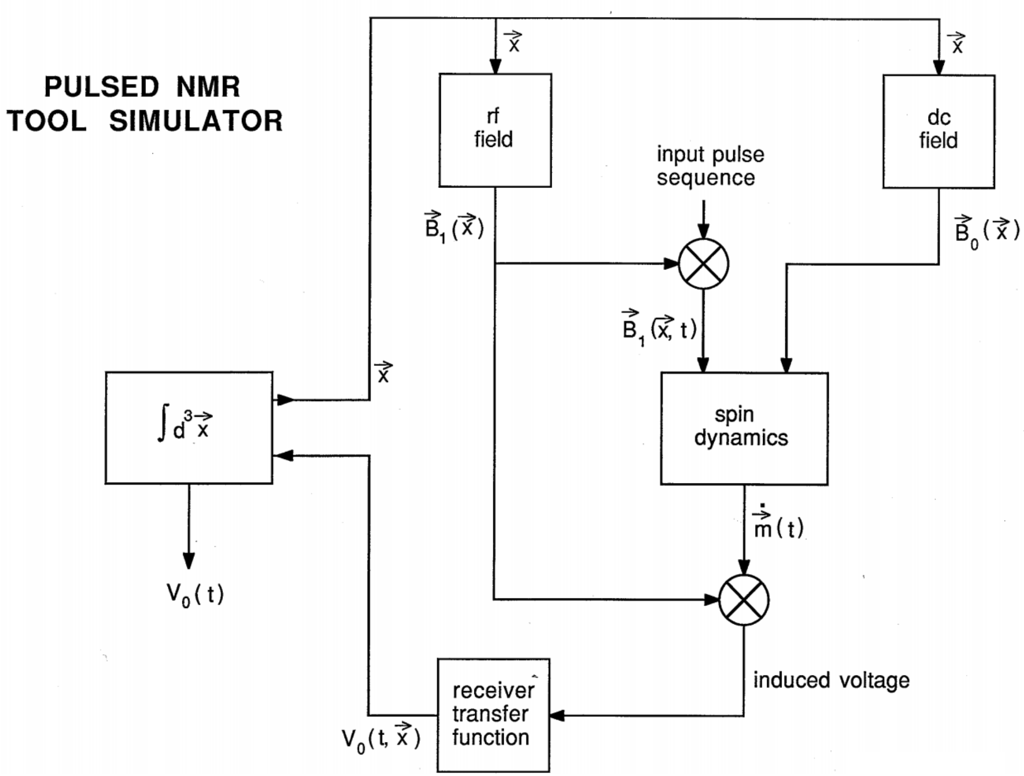
NMR Laboratory

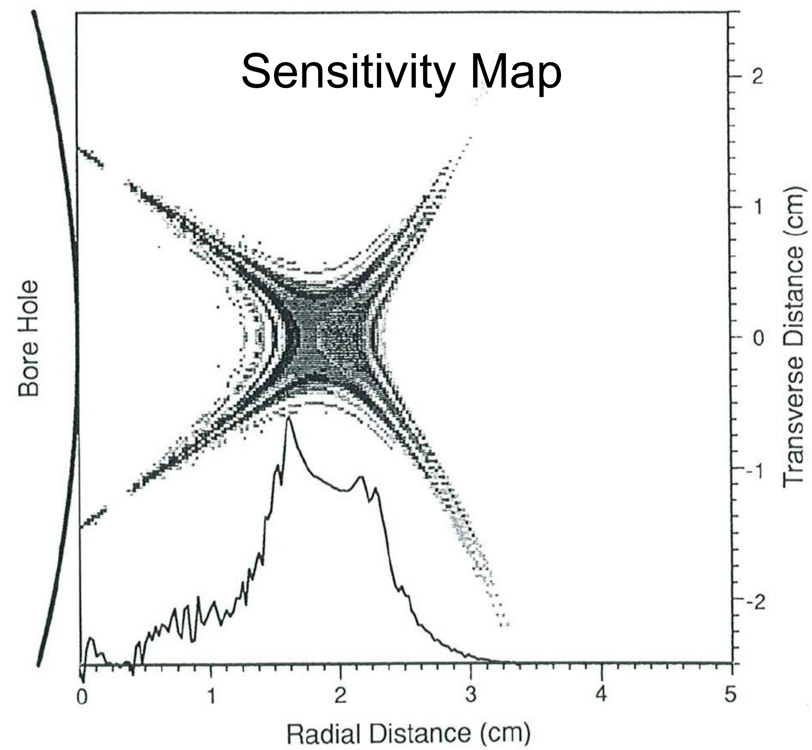


R.L. Kleinberg and D.D. Griffin, "NMR Measurements of Permafrost: Unfrozen Water Assay, Pore Scale Distribution of Ice, and Hydraulic Permeability of Sediments", Cold Regions Science and Technology 42, 63-77 (2005)

The Role of the Theorist / Modeler

- Design based on physics principles
- Theory of the measurement
- Optimization of design
- Performance prediction





To Sum Up

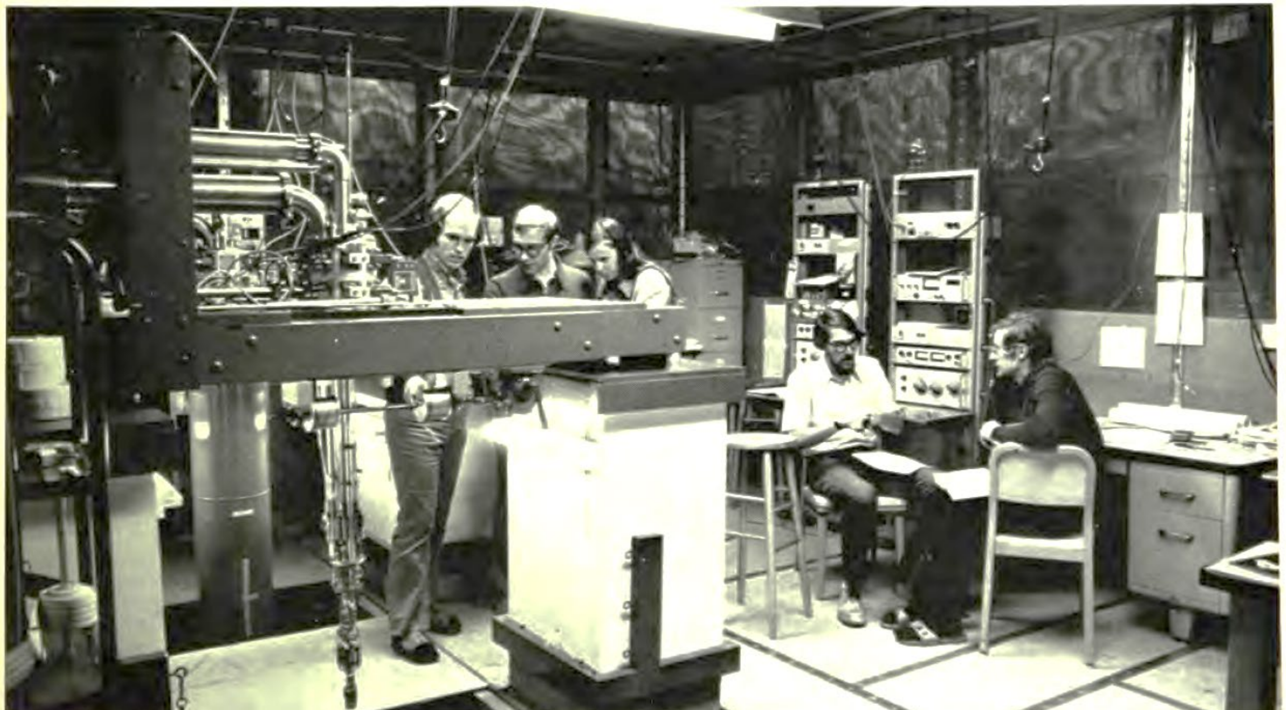
There are challenging and interesting problems to be solved in unexpected places.

Your physics education has provided you with a tool box of techniques and skills that may prove to be useful in unexpected ways in the future.

Your experiences will be different. I adapted to my time and place. You will adapt to yours.

Acknowledgements (UCSD):

Richard Johnson, Richard Webb[†], Richard Harms, Doug Paulson, Ron Sager, Evelin Sullivan, Matti Krusius, Paul Warkentin, James Day, **John C. Wheatley**[†]



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John C. Wheatley, Helium Three
Physics Today 29, 2, 32 (1976); doi: 10.1063/1.3023313

Acknowledgements (Schlumberger):

Doug Griffin
Weng Chew
Apo Sezginer
Masafumi Fukuhara
Brian Clark
and many more over the years

Schlumberger

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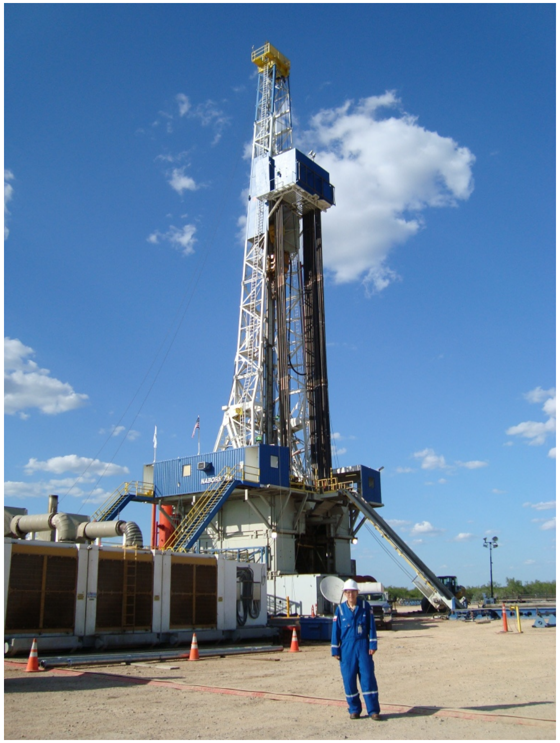
Member of the National Academy of Engineering



Dimmit County, Texas