EGEE 497/EME 597

GEOTHERMAL ENERGY ENGINEERING

1. INTRODUCTION

EGEE 497 & EME 597 – GEOTHERMAL ENERGY ENGINEERING SYLLABUS

Lecture: TuTh 12:05-01:20 (Blended course: both in-class and online)
Location: 306 Hammond Building
Resource Page: https://personal.ems.psu.edu/~fkd/courses/eme_497/index.html
Texts: Selected texts on reserve in EMS Library and on `canvas.psu.edu`.[1]
Instructor: *Derek Elsworth* 231 Hosler elsworth@psu.edu
Prerequisites: None, but understanding of EME 301 & 303, recommended.
Grading:

Review pre-existing student-created videos & quizzes	30%
Participation or pre-recorded lectures & quizzes	30%
Individual 20 min presentations on topical area(s)	30%
Comprehension of student videos – online quizzes	10%
Total	100%

Topic		**Sub-Topic**	**Reading**[1]	**Week**
1. Introduction		Overview; scientific challenges; economic perspective, development of geothermal reservoir engineering.	WG1 + AG1	#1
2. Thermal Characteristics				
2:1	Sources of Geothermal Heat	Origins of heat, heat transfer, geological environments, reservoir systems – conductive, convective-liquid-dominated and convective-vapor-dominated, reservoir evolution.	WG2 + AG2	#2
2:2	Thermodynamics	First law, second law, Gibbs function and Energy, Efficiency.	WG3	#3
3. Fluid Flow and Geochemistry				
3:1	Subsurface Fluid Flow	Porosity and permeability, porous and fractured reservoirs, head and pressure, storage, properties of real geothermal reservoirs.	WG4	#4
3:2	Simple Quantitative Models	Concepts of storage, pressure transient models, lumped parameter models, steam reservoir with immobile water, reserves, fractured media.	AG2-3	#5
3:3	Chemistry of Geothermal Fluids	Geochemistry of geothermal fluids, chemical systems, saturation and law of mass action, kinetics, gases in geothermal fluids, fluid flow and mixing, modeling.	WG5	#6
4. Resource Exploration and Characterization		Geology (WG6), geophysics (WG7), resource assessment (WG8), drilling (WG9), interpretation of downhole measurements (AG4), downhole measurements (AG5), measurements during drilling (AG6), well completion (AG7), production testing (AG8).	WG6-9 + AG4-8	#7+#8
5. Geothermal Energy Recovery and Conversion				
5:1	Geothermal Power – Hydrothermal	History of production, dry steam resources, hydrothermal systems, binary generation facilities.	WG10	#9
5:2	Geothermal Power – SedHeat	Key issues in SedHeat and EGS, behaviors, fluid flow and heat transport modes, utilization of O&G technologies. https://youtu.be/8wOTesyA66c		#10
5:3	Geothermal Power – EGS	Concept, resource size, characteristics, methods of stimulation and permeability evolution, history. Reservoir management and sustainability. https://youtu.be/EzeE0DlarUg	WG13	#11
5:4	Direct Use	Reservoir assessment, modes of heat transfer, establishing feasibility, district heating, aquaculture, drying.	WG12	#12
5:5	Low Temperature Geothermal – GSHP	Basic principles, thermodynamics, shallow subsurface thermal reservoirs, thermal storage and thermal transport in soils, design.	WG11 + MR5+6	#13
5:6	Underground Thermal Storage	Principles, conductive and convective transport, chromatographic effect, multi-well and huff-n-puff systems.	MR4	#14

References[1]/Resources:

1. Grant, M.A. and Bixley, P.F. Geothermal Reservoir Engineering. Second Edition. Elsevier. 2011. [AG]
2. Glassley, W.E. Geothermal Energy. Second Edition. CRC Press. 2015. [WG]
3. Rosen, M.A. and Koohi-Fayegh, S. Geothermal Energy. Sustainable Heating and Cooling Using the Ground. 2017. [MR]
4. Penrose SedHEAT: https://www.youtube.com/channel/UCBHQHy4hVyBJQFogrKvKUAg
5. Great Lakes SedHEAT: https://igws.indiana.edu/glsn/speakers

Course Conduct:
Penn State's policy on academic integrity applies to all aspects of course deliverables. Students are encouraged to work together on all assignments but must submit independent work for all graded deliverables and exams. Further details are available for academic integrity and code of conduct at:
https://www.ems.psu.edu/undergraduate/academic-advising/policies-procedures-and-forms/academic-integrity-undergraduates

~~Per *AD 42-27* class attendance for this course is encouraged. "A student should attend every class for which the student is scheduled and should be held responsible for all work covered in the courses taken."~~ Reasons for late deliverables should be appropriately corroborated (e.g. doctor's note, etc.).

This syllabus may be updated during the semester and you will be responsible for abiding with any such changes.

Additional generic Penn State policies that apply to this course are at:
https://www.ems.psu.edu/~elsworth/courses/eme_303/outline_add.docx

Grade Divisions: A (>93.3%); A- (>90.0%), B+ (>86.6%); B (>83.3%); B- (>80.0%), C+ (>75.0%);
C (>70.0%), D (>60.0%); F (<60.0%)

Spring 2026 Calendar – At-a-Glance [In-class and Online]

January 2026

Su	Mo	Tu	We	Th	Fr	Sa	Wk	Deliv	Tuesday	Thursday	
11	12	13	14	15	16	17	1	I-c	0. Organizational Meeting	1. Introduction	
18	19	20	21	22	23	24	2	I-c	2.1 Sources of Geothermal Heat		
25	26	27	28	29	30	31	3	I-c	2.2 Thermodynamics of Geothermal Reservoirs		

February 2026

Su	Mo	Tu	We	Th	Fr	Sa	Wk	Deliv		
○	2	3	4	5	6	7	4	I-c	3.1 Subsurface Fluid Flow	
8	9	10	11	12	13	14	5	I-c	3.2 Simple Quantitative Models	[JP]
○	16	17	18	19	20	21	6	I-c	3.3 Chemistry of Geothermal Fluids	
22	23	24	25	26	27	28	7	I-c	4.1 Resour. Exp. & Charac. – Geology/Geophysics	

March 2026

Su	Mo	Tu	We	Th	Fr	Sa	Wk	Deliv		
○	2	3	4	5	6	7	8	I-c	4.2 Resour. Exp. & Charac. – Drilling/completion	[WP]
8	~~9~~	~~10~~	~~11~~	~~12~~	~~13~~	14				
15	16	17	18	19	20	21	9	I-c	5.1 Hydrothermal Systems	[JF]/[GB]
○	23	24	25	26	27	28	10	I-c	5.2 Sedimentary Geothermal Reservoirs	
29	30	31	1	2	3	4	11	I-c	5.3 EGS	[JM]

April 2026

Su	Mo	Tu	We	Th	Fr	Sa	Wk	Deliv		
○	6	7	8	9	10	11	12	I-c	5.4 Direct Use	[PF]
12	13	14	15	16	17	18	13	I-c	5.5 Low Temp. – Heat Pumps	
19	20	21	22	23	24	25	14	I-c	5.6 Underground Thermal Storage	[SG]
26	27	28	29	30	1	2	15	I-c	6. New Video Viewing and Quizzes	

May 2026

Su	Mo	Tu	We	Th	Fr	Sa
3	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	9

○ Assignment submissions

***Class modalities**

I-c	In-class or alternatively completed asynchronously online and verified by quiz
O-S	Online-Synchronous – no In-class meeting but simultaneous zoom broadcast
O-A	Online-Asynchronous – no In-class meeting/no zoom broadcast but recorded lecture verified by quiz

INDIVIDUAL PRESENTATION RUBRIC

In this class, you will develop instructional materials to cover topical areas selected from the syllabus. Each student will be responsible for a single individual presentation on a topical area of their choice. These will be prepared as powerpoint or pdf presentations that follow a loosely-prescribed outline which are then recorded by the students and uploaded online as a tutorial. The narrated recording must be >20 minutes long.

The objectives of this are to: (i) encourage students to explore and to think critically and creatively about a particular topical area, (ii) to understand this area in sufficient depth to communicate and share this understanding with a student audience as a tutorial, and (iii) to learn from the other student tutorials that cover a broad range of topics in the course outline.

Schedule:	**Deliverables**
Week 0 – Organization	
Week 3 – Select a topical area and assemble review materials	[Submit title Su after wk# 3]
Week 5 – Prepare presentation plan/outline	[Submit outline Su after wk#5]
Week 7 – Prepare presentation	[Submit ppt/pdf Su after wk#7]
Week 9 – Narrate ppt/pdf and upload	[Upload video Su after wk#9]
Week 11 – Prepare quiz questions to narration on `canvas.psu.edu`	[Submit questions Su after wk#11]
Weeks 13-15 – Students complete online class material from all other students	[Take other quizzes]

Students will work individually to develop powerpoint or pdf (projected) presentations to communicate the principles of the prescribed topics(s) to this class. The presentations may be ppt presentations (slide show mode) or use screen capture to record the material and will be posted and available to the other students.

The full suite of topical areas are as prescribed in the syllabus with baseline initial and structured resource materials also given in the form of three principal resource texts. These resources will be supplemented by the participants from any available auxiliary resources.

Presentations should include some description of:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?
2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.
3. **For Each Sub-Topic:**
    a. **Detailed Explanation of the Topic [40%]** Describe the physical principles in detail and at a pace that is tutorial for an audience.
    b. **Example Hand-Calculation [10%]** Simple calculation to demonstrate the technique.
    c. **Case Study [10%]** If appropriate.
4. **Conclusion [20%]** Summarize important/key points from the presentation.

OBS Studio may be of interest to you in recording your materials to .m4v format: `https://obsproject.com`

But the easiest way is to follow the **"PPT-to-Movie"** demonstration on the course homepage.

Grading:

To be based on the quality and content of the topical self-presentations and on comprehension of the complementary presentations. Grades to be based broadly on the scoring rubric above.

Sample Quiz Question:

1. Power recovered from sensible heat from a geothermal reservoir/well may be define as
    a. Power = Mass rate of flow * specific heat capacity * temperature change
    b. Power = Mass rate of flow * elevation change
    c. Power = Enthalpy
    d. Power = Entropy * temperature change
2. Question 2……etc.
    a. Answers to Q2

AN OVERVIEW OF CONCEPTS AND UNITS

A deep understanding of the peculiarities and complexities of different forms of energy and their stores and conversions requires quantification of these qualities and processes. For this, we must introduce a certain number of scientific concepts and measures and their associated units.

The first problem we encounter in formulating a way to talk about energies is that the common usages of many of the key terms are misleading. As Henk Tennekes has noted, "We have made a terrible mess of simple physical concepts in ordinary life." Few of these muddles are as ubiquitous and annoying as those involving terms such as "energy," "power," and "force."

A knowledge of basic mechanics helps get us started in sorting these terms out. *Force* is defined as the intensity with which we try to displace—push, pull, lift, kick, throw—an object. We can exert a large force even if the huge boulder we are trying to push remains immobile. We accomplish *work*, however, only when the object of our attention moves in the direction of the applied force. In fact, we define the amount of work performed as the product of the force applied and the distance covered. *Energy*, as the common textbook definition puts it, is "the capacity for doing work" and thus will be measured in the same units as work. If we measure force in units of newtons (N, named for Sir Isaac Newton) and distance in meters (m), our measure of work will be the awkward-sounding Newton-meter. To simplify, scientists call one Newton-meter a joule (J), named for James Prescott Joule (1818–1889), who published the first accurate calculation of the equivalence of work and heat. The joule is the standard scientific unit for energy and work. *Power* is simply a rate of doing work, that is, an energy flow per unit of time; its measure is thus joules per second. We call one joule per second a watt (W) after James Watt (1736–1819), the inventor of the improved steam engine and the man who set the first standard unit of power, which as it happens was not the watt but the horsepower (hp), a unit equal to roughly 750 W.

To go further we need to move from pushing and shoving (which we call mechanical or kinetic energy) to heating (thermal energy). We define a unit called the calorie as the amount of heat needed to raise the temperature of one gram of water from 14.5 to 15.5°C. (You needn't worry about why we define it this way.) Using this unit will help us compare thermal energies, but again it does not offer an all-encompassing measure that will allow us to compare different forms of energy.

At this point you might be asking, What is energy? This turns out to be a hard question to answer. Even one of the grand summations of modern physics is of little help: "It is important to realize that in physics today, we have no knowledge of what energy *is*. We do not have a picture that energy comes in little blobs of a definite amount," wrote Richard Feynman in his famous *Lectures on Physics*. If forced to choose, I would opt for David Rose's evasive answer: Energy "is an abstract concept invented by physical scientists in the nineteenth century to describe quantitatively a wide variety of natural phenomena."

Our modern understanding of energy includes a number of profound realizations: that mass and energy are equivalent; that many conversions link various kinds of energies; that no energy is lost during these conversions (this is the first law of thermodynamics); and that this conservation of energy is inexorably accompanied by a loss of utility (the second law of thermodynamics). The first realization—initially called an "amusing and attractive thought" in a letter Einstein wrote to a friend—is summed up in perhaps the best known of all physical equations: $E = mc^2$.

The second realization is demonstrated constantly by myriads of energy conversions throughout the universe. Gravitational energy sets galaxies in motion, keeps the Earth orbiting around the Sun, and holds down the atmosphere that makes our planet habitable. Conversion of nuclear energy within the Sun releases an incessant stream of electromagnetic (solar, radiant) energy. A small share of that energy reaches the Earth, which itself also releases geothermal energy. Heat from both these processes sets in motion the atmosphere, the oceans, and the Earth's huge tectonic plates.

A tiny share of the Sun's radiant energy is transformed through photosynthesis into stores of chemical energy that are used by many kinds of bacteria and by plants. Heterotrophs—organisms ranging from bacteria, protists, and fungi to mammals—ingest and reorganize plant tissues into new chemical bonds and use them also to generate mechanical (kinetic) energy. Chemical energy stored over many millions of years in fossil fuels is released through combustion in boilers and engines as thermal energy, which many processes then convert into mechanical, chemical, or electromagnetic energy.

The second law of thermodynamics addresses the inescapable reality that the potential for useful work steadily diminishes as we move along energy conversion chains. There is a measure associated with this loss of useful energy, and it is called ***entropy***: while energy is conserved in any conversion, the conversion can only increase the entropy of the system as a whole. There is nothing we can do about this decrease of utility. A barrel of crude oil is a low-entropy store of very useful energy that can be converted to heat, electricity, motion, and light. Hot air molecules leaving an engine exhaust or surrounding a light bulb represent a high-entropy state in which there is an irretrievable loss of utility.

Loss of complexity and the rise of homogeneity are the unavoidable consequences of this unidirectional entropic dissipation in any closed system. (You can see this if you compare the multitude of complex organic molecules making up crude oil with the sameness of the few kinds of simple molecules making up hot exhaust gas.) In contrast, all living organisms—from bacteria to civilizations—are open systems, constantly importing and exporting energy, and hence are able to maintain themselves in a state of chemical and thermodynamic disequilibrium. They are temporarily defying the entropic trend as their growth and evolution bring greater heterogeneity and higher complexity.

Using unadjusted units to quantify this multitude of processes would be inconvenient: actual figures would nearly always be either trailed or preceded by many zeros. Both joules and watts represent very tiny amounts of measured energy and power: about thirty micrograms of coal—or two seconds' worth of a vole's metabolism account for one joule. One watt is the power of a very small burning candle or a hummingbird's rapid flight.

Multiples are inevitable, and we therefore introduce a series of prefixes to abbreviate the most useful multiples: a kilogram of good coal contains nearly thirty million joules, or thirty megajoules (MJ), of energy, and the world now consumes fossil fuels at the rate of roughly ten trillion watts (TW). We attach the same prefixes to the units that we use to measure electrical energy: Volts (V), which are a measure of the difference in electric potential between two points of a conductor, and amperes (A), which measure the intensity of an electric current. The power of an electrical system is the product of voltage and current, which means that one volt-ampere is also one watt.

Table 1 lists the complete set of multiples as well as the submultiples, which are needed much less frequently when we are dealing with everyday energy flows. Magnitudes of some energy stores and flows are listed in tables 2 and 3. Examples of power ratings of continuous energy conversions are given in table 4, and those of ephemeral phenomena are shown in table 5.

Rates and ratios are important for understanding energy stores, flows, and effects. *Energy density*—the amount of energy stored in a unit mass of a resource (joules per kilogram, J/kg)—is a useful comparative measure for foodstuffs and fuels. Humans would need a daily intake of many kilograms of low-energy-density foods

Table 1 Prefixes of Scientific Units

Prefix	Abbreviation	Scientific notation
deka	da	10^{1}
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}
exa	E	10^{18}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Table 2 Energy Stores

Energy of	Magnitude
Global coal resources	200,000 EJ
Global plant mass	10,000 EJ
Latent heat of a thunderstorm	5 PJ
Coal load in a 100-t hopper car	2 TJ
Barrel of crude oil	6 GJ
Bottle of white table wine	3 MJ
A small chickpea	5 kJ
Fly on a kitchen table	9 mJ
A 2-mm raindrop on a blade of grass	4 μJ

Table 3 Energy Flows

Energy of	Magnitude
Solar radiation reaching the Earth	5500000 EJ
Global net photosynthesis	2000 EJ
Global fossil fuel production	300 EJ
Typical Caribbean hurricane	38 EJ
Largest H-bomb tested in 1961	240 PJ
Latent heat of a thunderstorm	5 PJ
Hiroshima bomb of 1945	84 TJ
Basal metabolism of a large horse	100 MJ
Daily adult food intake	10 MJ
Striking a typewriter key	20 mJ
Flea hop	100 nJ

Table 4 Powers of Continuous Phenomena

Energy flows	Power
Global intercept of solar radiation	170 PW
Wind-generated waves on the ocean	90 PW
Global gross primary productivity	100 TW
Global Earth heat flow	42 TW
Worldwide fossil fuel combustion	10 TW
Florida Current between Miami and Bimini	20 GW
Large thermal power plant	5GW
Basal metabolism of a 70-kg man	80 W

Table 5 Powers of Short-Lived Phenomena

Energy flows	Duration	Power
Richter magnitude 8 earthquake	30 s	1.6 PW
Large volcanic eruption	10 h	100 TW
Thunderstorm's kinetic energy	20 min	100 GW
Large WWII bombing raid	1 h	20 GW
Average U.S. tornado	3 min	1.7 GW
Four engines of Boeing 747	10 h	60 MW
Watt's largest steam engine	10 h	100 kW
Running 100-m dash	10 s	1.3 kW
Machine-washing laundry	20 min	500 W
Playing a CD	60 min	25 W
Candle burning to the end	2 h	5 W
Hummingbird flight	3 min	0.7 W

such as fruits and vegetables to maintain themselves, whereas less than half a kilogram of rice, which has a high energy density, will do. Conversely, gasoline makes a great portable fuel because its energy density is nearly three times that of air-dried wood. Table 6 shows the energy densities of some common fuels, foods, and their metabolic products.

Power density—the rate at which energies are produced or consumed per unit of area (watts per square meter, W/m^2)—is a critical structural determinant of energy production systems. The power density of fuel production from a large open-cast mine extracting excellent bituminous coal from a thick seam is easily more than 1000 W/m^2; the power density of electricity generation in a large hydrostation whose dam creates the huge reservoir needed to store a sufficient volume of water may be as low as a few W/m^2. In order to illustrate the spatial aspect of various energy conversions, values of power densities are

Table 6 Ranges of Energy Densities of Common Fuels and Foodstuffs

Energy density	(MJ/kg)
Hydrogen	114.0
Gasolines	46.0–47.0
Crude oils	42.0–44.0
Pure plant oils	38.0–37.0
Natural gases	33.0–37.0
Butter	29.0–30.0
Ethanol	29.6
Best bituminous coals	27.0–29.0
Pure protein	23.0
Common steam coals	22.0–24.0
Good lignites	18.0–20.0
Pure carbohydrates	17.0
Cereal grains	15.2–15.4
Air-dried wood	14.0–15.0
Cereal straws	12.0–15.0
Lean meats	5.0–10.0
Fish	2.9–9.3
Potatoes	3.2–4.8
Fruits	1.5–4.0
Human feces	1.8–3.0
Vegetables	0.6–1.8
Urine	0.1–0.2

Table 7 Efficiencies of Common Energy Conversions (percent)

Conversions	Energies	Efficiencies
Large electricity generators	M → e	98–99
Large power-plant boilers	c → t	90–98
Large electric motors	e → m	90–97
Best home natural-gas furnaces	c → t	90–96
Dry-cell batteries	c → e	85–95
Human lactation	c → c	85–95
Overshot waterwheels	m → m	60–85
Small electric motors	e → m	60–75
Large steam turbines	t → m	40–45
Improved wood stoves	c → t	25–45
Large gas turbines	c → m	35–40
Diesel engines	c → m	30–35
Mammalian postnatal growth	c → c	30–35
Best photovoltaic cells	r → e	20–30
Best large steam engines	c → m	20–25
Internal combustion engines	c → m	15–25
High-pressure sodium lamps	e → r	15–20
Mammalian muscles	c → m	15–20
Traditional stoves	c → t	10–15
Fluorescent lights	e → r	10–12
Steam locomotives	c → m	3–6
Peak crop photosynthesis	r → c	4–5
Incandescent light bulbs	e → r	2–5
Paraffin candles	c → r	1–2
Most productive ecosystems	r → c	1–2
Global photosynthetic mean	r → c	0.3

Energy labels: c—chemical, e—electrical, m—mechanical (kinetic), r—radiant (electromagnetic, solar), t—thermal shown in figures 1 and 2, graphs plotting areas against power.

The *efficiency* of an energy conversion is the ratio of the amount of energy output to the amount input. This measure is used to describe the performance of energy converters such as boilers, engines, photovoltaic cells, or lights. Efficiencies of common converters are listed in table 7. *Energy intensity* is the cost of a product or service in energy terms. Titanium and aluminum are highly energy-intensive, for example, whereas iron and glass are fairly cheap. Typical ranges of the energy costs of common materials are given in table 8.

Technical advances keep pushing efficiencies up and energy intensities down: today's best lights are about twenty times as efficient as the first light bulbs of more than a hundred years ago, and production of a kilogram of steel now requires less than one-tenth the energy it did two centuries ago.

The best way to understand the world of energy and power units is to get a small calculator and do exercises rooted in the realities all around us. How much energy does it take to play Mozart's last piano concerto? What volume of gasoline contains energy equivalent to a cord of stacked, air-dry wood? What is the kinetic power of an arrow shot from a modern compound bow? How much more powerful are the four engines of a Boeing 747 than the eight engines on B-52 bomber? What share of daily metabolism can be supplied by a slice of whole-wheat bread?

If you are so inclined, the figures listed in the tables given here, the ranges shown in the power density figure, and the hundreds of numbers scattered through the book will lead you to a virtually unlimited supply of such challenges—and hence to an insider's understanding of energies.

Table 8 Typical Energy Costs of Common Materials (MJ/kg)

Material	Energy cost	Made or extracted from
Aluminum	227–342	Bauxite
Bricks	2–5	Clay
Cement	5–9	Clay and limestone
Copper	60–125	Sulfide ore
Glass	18–35	Sand, etc.
Iron	20–25	Iron ore
Limestone	0.07–0.1	Sedimentary rock
Nickel	230–70	Ore concentrate
Paper	25–50	Standing timber
Polyethylene	87–115	Crude oil
Polystyrene	62–108	Crude oil
Polyvinylchloride	85–107	Crude oil
Sand	0.08–0.1	Riverbed
Silicon	230–235	Silica
Steel	20–50	Iron
Sulfuric acid	2–3	Sulfur
Titanium	900–940	Ore concentrate
Water	0.001–0.01	Streams, reservoirs
Wood	3–7	Standing timber

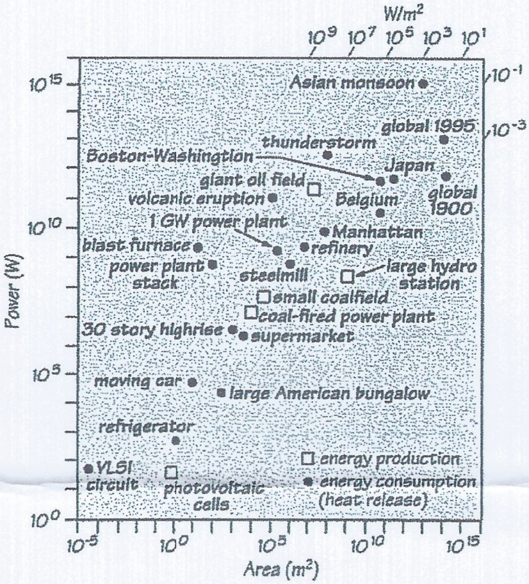


Figure 1
Power densities of various energy production and consumption phenomena.

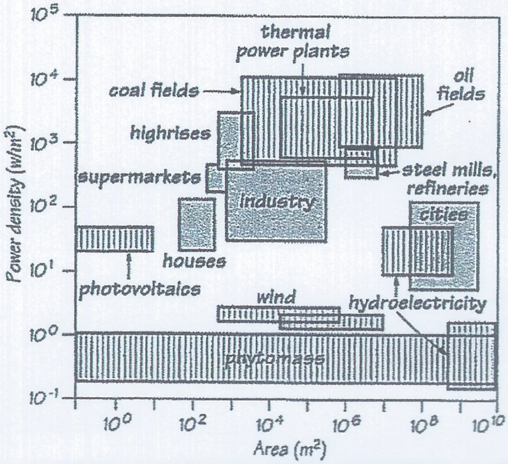


Figure 2
Typical ranges of areas and power densities in large-scale modern energy production (lines) and in household and industrial consumption (dots).

THE ENERGY NEW DEAL
RELATED TO SUBSURFACE ENERGY OPTIONS

Derek Elsworth (Pennsylvania State University)

Some Key Issues in Energy Supply

- Needs
- Constraints
- Solutions

Low Carbon Fuel Solutions

- Gas Shales
- Coalbed Methane (CBM/Coalseam gas)
- Methane Hydrates

Carbon Management Solutions

- CO_2 sequestration

Zero Carbon Solutions

- EGS Geothermal
- Nuclear power
- Hydropower/Pumped Storage/CAES
- Wind
- Solar PV and Thermal

New Zealand Energy Picture

Sustainable Energy in New Zealand

Sustainable Energy in New Zealand
EGEE 497 – Sp 2019

What: This course will examine methods of energy recovery and conversion from conventional fossil fuels through renewables. Students will investigate the political, economic, scientific and technological factors driving the recovery and utilization of energy using New Zealand as an archetypical example – one where unusually 40% of primary energy is supplied by renewables. This compares with approximately 6% in the United States and an average of 8% in OECD countries.

When: Spring semester with a field trip to New Zealand during spring break.

How: This course will use occasional guest lectures, instructor-guided discussions, student presentations, and research to address the important contemporary issues of energy supply and use, and the environmental consequences of energy choices.

Where: Principally at University Park, but including … of New Zealand during th…

EGEE 497 - Sustainable Energy in New Zealand

Flyer   Syllabus

Derek Elsworth, Energy and Mineral Engineering and Geoscienc…

This course examines methods of energy re… renewables. Students investigate the … and utilization of energy using …

Resources o…

…ugh
…e recovery

…n Petroleum & Natural Gas
…ective on Nuclear Energy
…l Perspective on Non-Depletable Energy Resources

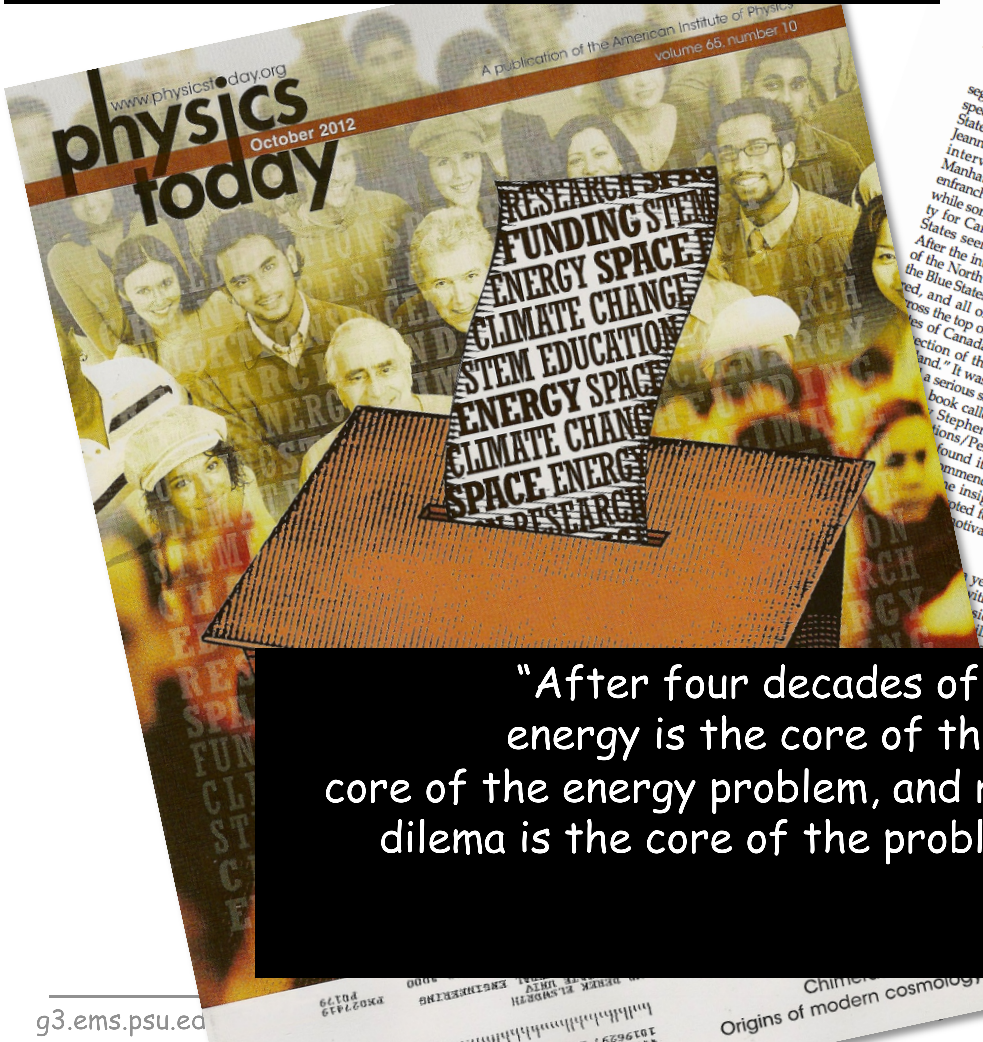
CAUSE 2013 — Energy, Environment and Society

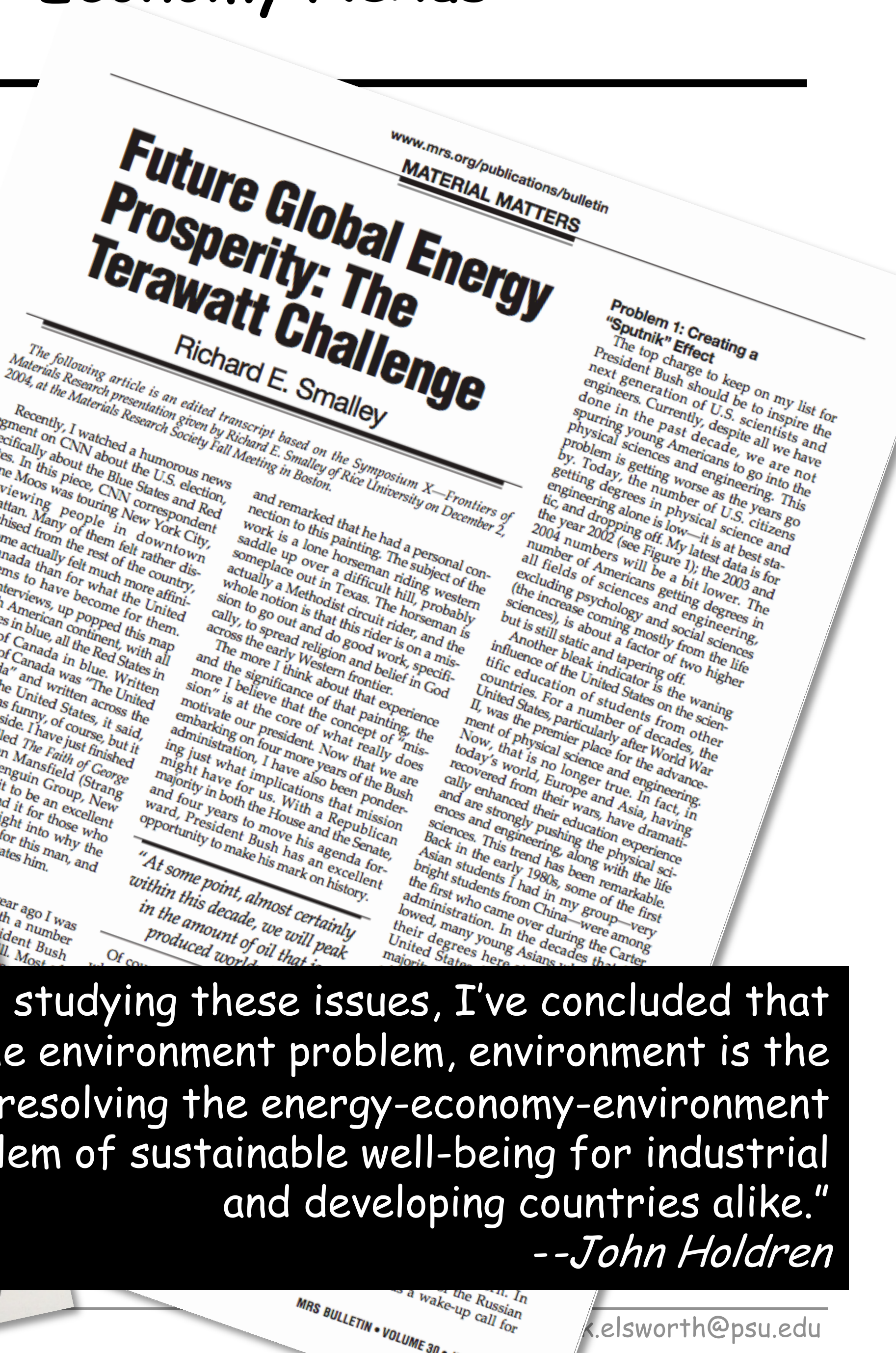
The "Energy" New Deal — Down Under

CAUSE Home   CAUSE 2013 Home   Overview   Syllabus

Energy-Environment-Economy Nexus

"…. we can see how energy is the key to solving all of the rest of the problems – from water to population"
--Richard E. Smalley




www.mrs.org/publications/bulletin
MATERIAL MATTERS

Future Global Energy Prosperity: The Terawatt Challenge

Richard E. Smalley

The following article is an edited transcript based on the Symposium X—Frontiers of Materials Research presentation given by Richard E. Smalley of Rice University on December 2, 2004, at the Materials Research Society Fall Meeting in Boston.

Recently, I watched a humorous news segment on CNN about the U.S. election, specifically about the Blue States and Red States. In this piece, CNN correspondent Jeanne Moos was touring New York City, interviewing people in downtown Manhattan. Many of them felt rather disenfranchised from the rest of the country, while some actually felt much more affini-
y for Canada than for what the United
States seems to have become for them.
ter the interviews, up popped this map
he North American continent, with all
Blue States in blue, all the Red States in
nd all of Canada in blue. Written
the top of Canada was "The United
of Canada" and written across the
on of the United States, it said,
d." It was funny, of course, but it
serious side. I have just finished
book called *The Faith of George*
Stephen Mansfield (Strang
ions/Penguin Group, New
found it to be an excellent
mmend it for those who
e insight into why the
oted for this man, and
otivates him.

year ago I was
vith a number
sident Bush
ll. Most

and remarked that he had a personal connection to this painting. The subject of the work is a lone horseman riding western saddle up over a difficult hill, probably someplace out in Texas. The horseman is actually a Methodist circuit rider, and the whole notion is that this rider is on a mission to go out and do good work, specifically, to spread religion and belief in God across the early Western frontier.

The more I think about that experience and the significance of that painting, the more I believe that the concept of "mission" is at the core of what really does motivate our president. Now that we are embarking on four more years of the Bush administration, I have also been pondering just what implications that mission might have for us. With a Republican majority in both the House and the Senate, and four years to move his agenda forward, President Bush has an excellent opportunity to make his mark on history.

> *"At some point, almost certainly within this decade, we will peak in the amount of oil that is produced world*

Of co

Problem 1: Creating a "Sputnik" Effect

The top charge to keep on my list for President Bush should be to inspire the next generation of U.S. scientists and engineers. Currently, despite all we have done in the past decade, we are not spurring young Americans to go into the physical sciences and engineering. This problem is getting worse as the years go by. Today, the number of U.S. citizens getting degrees in physical science and engineering alone is low—it is at best static, and dropping off. My latest data is for the year 2002 (see Figure 1); the 2003 and 2004 numbers will be a bit lower. The number of Americans getting degrees in all fields of sciences and engineering, excluding psychology and social sciences (the increase coming mostly from the life sciences), is about a factor of two higher but is still static and tapering off.

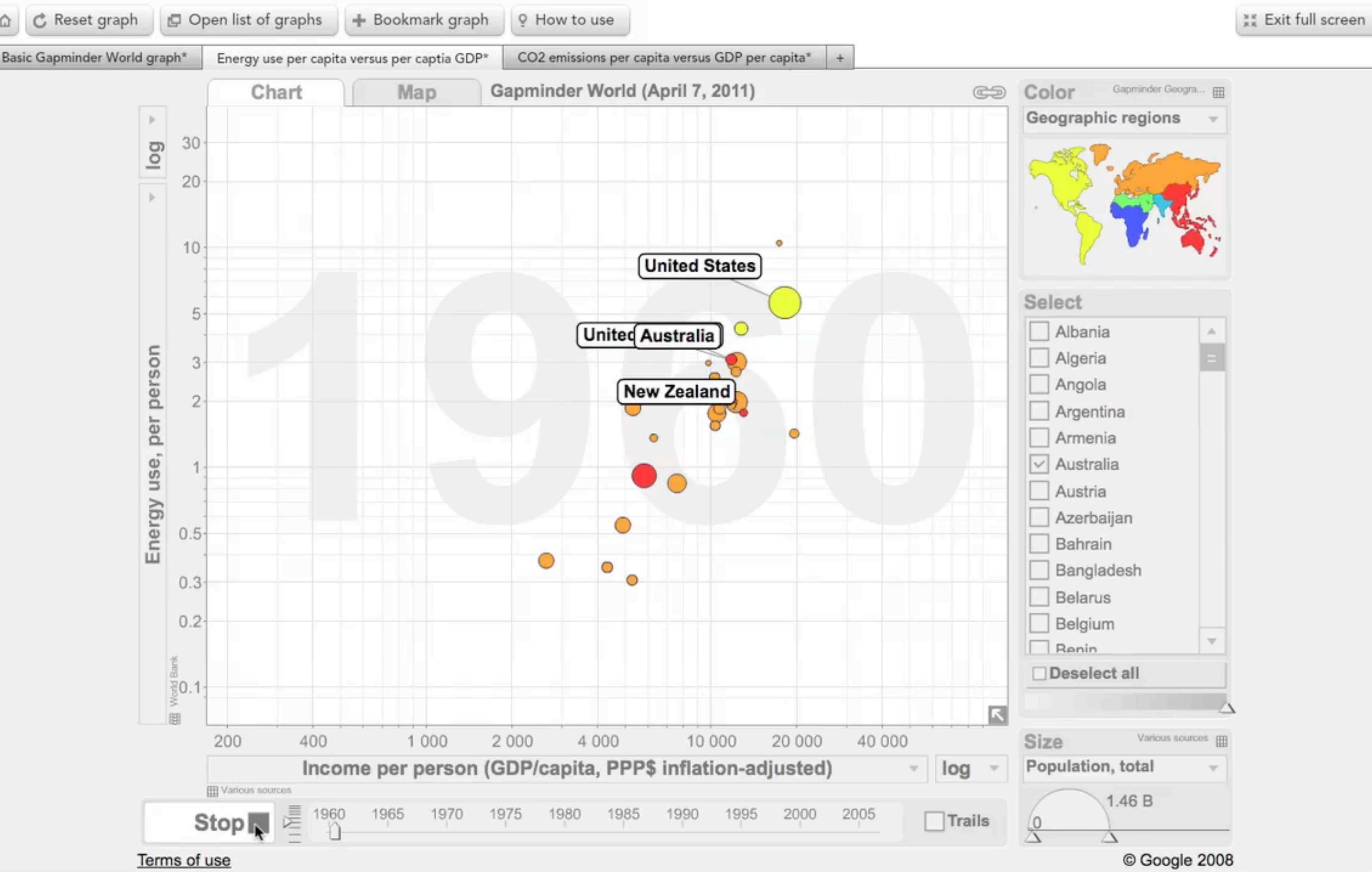
Another bleak indicator is the waning influence of the United States on the scientific education of students from other countries. For a number of decades, the United States, particularly after World War II, was the premier place for the advancement of physical science and engineering. Now, that is no longer true. In fact, in today's world, Europe and Asia, having recovered from their wars, have dramatically enhanced their education experience and are strongly pushing the physical sciences and engineering, along with the life sciences. This trend has been remarkable. Back in the early 1980s, some of the first Asian students I had in my group—very bright students from China—were among the first who came over during the Carter administration. In the decades that followed, many young Asians

n. In
the Russian
a wake-up call for

MRS BULLETIN • VOLUME 30

"After four decades of studying these issues, I've concluded that energy is the core of the environment problem, environment is the core of the energy problem, and resolving the energy-economy-environment dilema is the core of the problem of sustainable well-being for industrial and developing countries alike."
--John Holdren

Energy & Environment: Complementary Drivers?



[Hans Rosling http://www.gapminder.org/]

Close-Out Editorial on 2008-2016 US Administration

Observations:

GHG dropped/flat on 4 occasions:

1980s, 1992, 2009 (recessions)

2014 (growth)

Electricity from Gas:

21% 2008

33% 2015

Employment:

~2.2M Energy efficiency jobs

~1.1M Fossil fuel for electricity

GapMinder Linkage:

US Energy use 2.5% less in 2015 vs 2008 but economy 10% larger

[Obama, Science, 2017]

CLIMATE AND ENERGY

The irreversible momentum of clean energy

Private-sector efforts help drive decoupling of emissions and economic growth

By **Barack Obama**

The release of carbon dioxide (CO_2) and other greenhouse gases (GHGs) due to human activity is increasing global average surface air temperatures, disrupting weather patterns, and acidifying the ocean (*1*). Left unchecked, the continued growth of GHG emissions could cause global average temperatures to increase by another 4°C or more by 2100 and by 1.5 to 2 times as much in many midcontinent and far northern locations (*1*). Although our understanding of the impacts of climate change is increasingly and disturbingly clear, there is still debate about the proper course for U.S. policy—a debate that is very much on display during the current presidential transition. But putting near-term politics aside, the mounting economic

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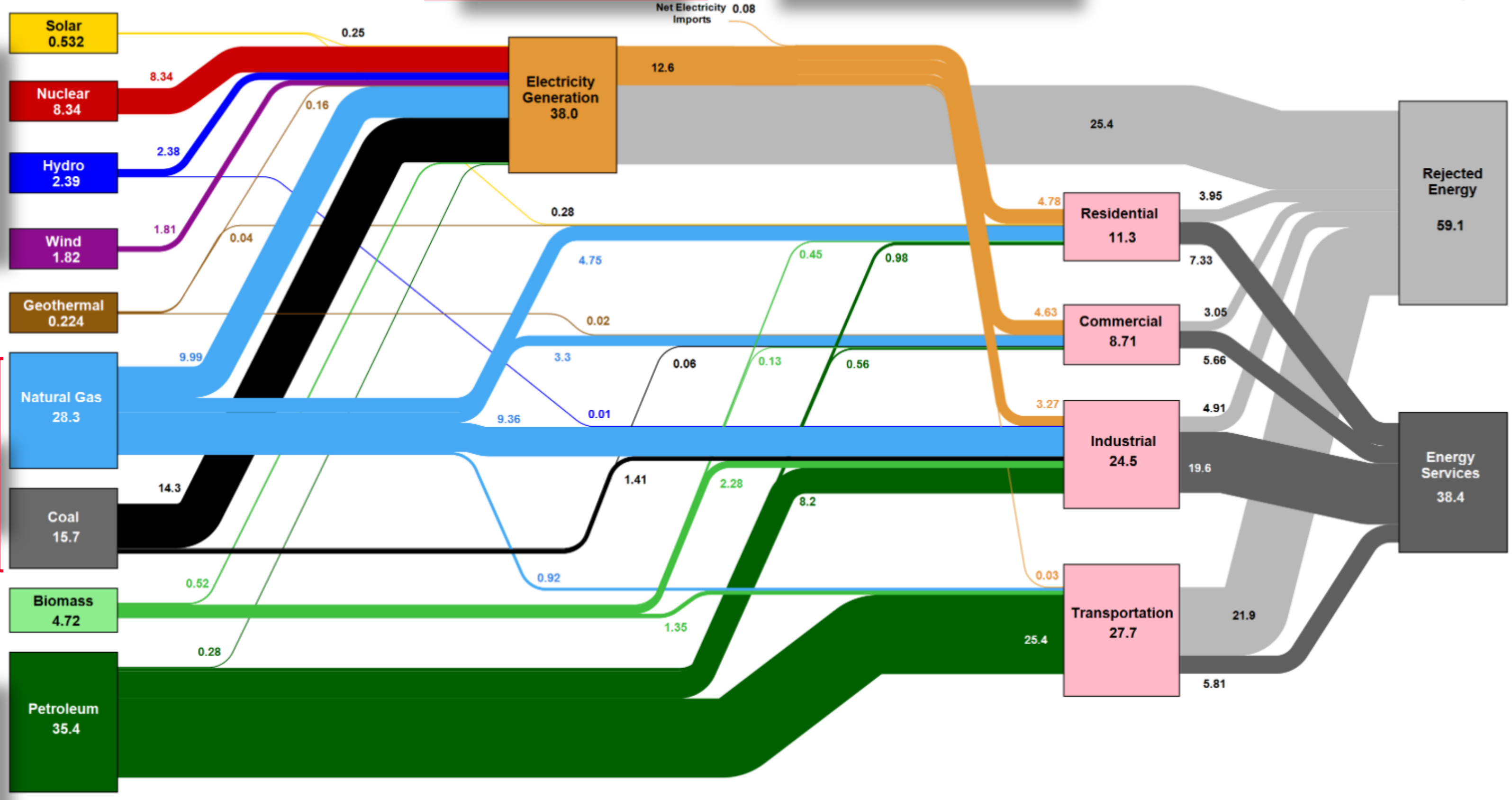
President of the United States, Washington, DC 20500, USA. Email: press@who.eop.gov. After 20 January 2017: contact@obamaoffice44.org

US Energy Consumption 2015 – Key R&D Strategies
~100 Quads = 100 EJ = 100 tcf CH_4 (~20% of World)



Electric Energy Storage

Electricity Distribution

Zero-Emissions Net Energy Production

Fuel Switching

CCS

Fuel Switching

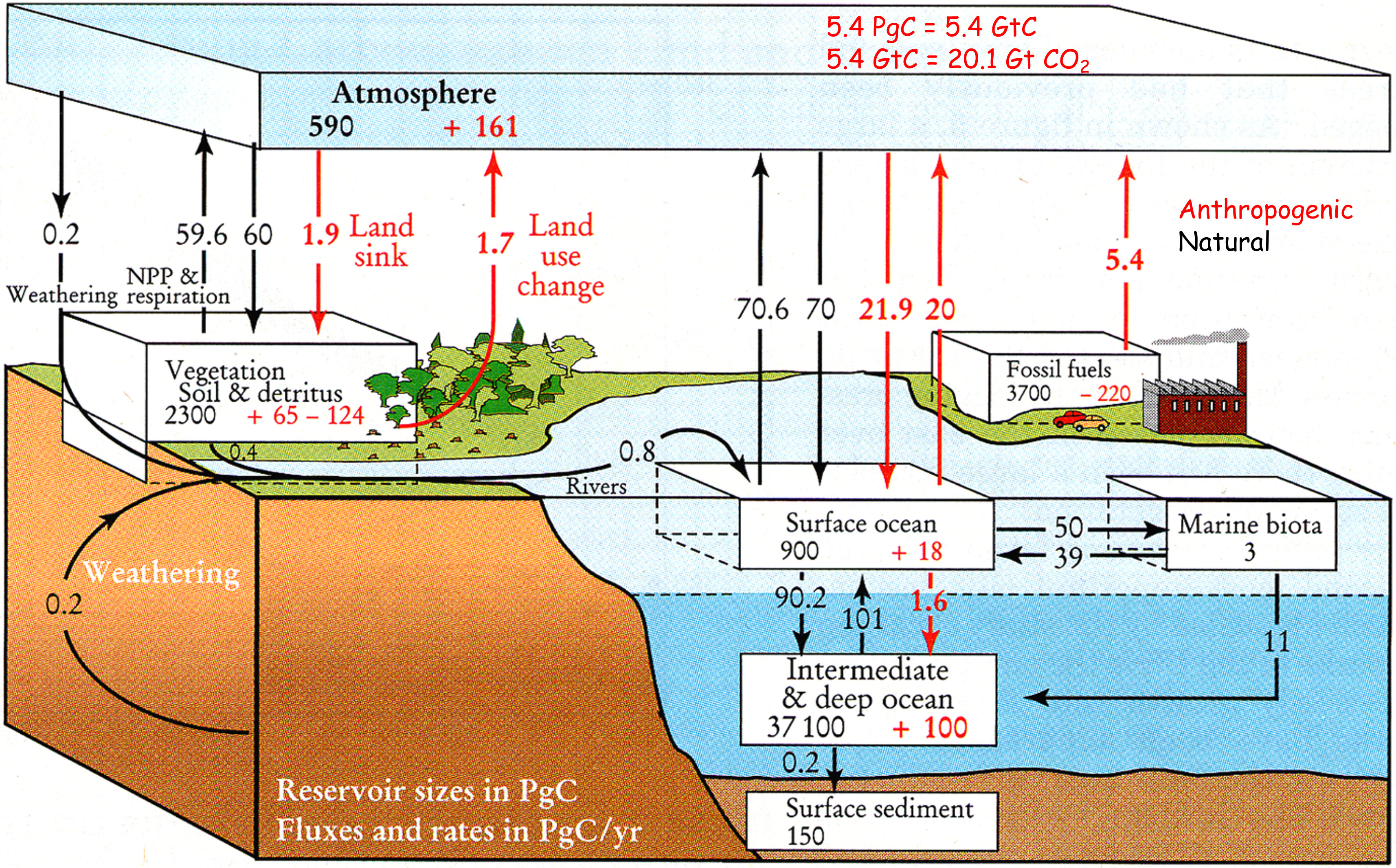
End-Use Efficiency

Conservation

Climate/Environmental Impacts

[After Pat Dehmer, US DOE, Office of Science, 2009; Sankey Diagram from LLNL]

Global Carbon Cycle



5.4 PgC = 5.4 GtC
5.4 GtC = 20.1 Gt CO_2

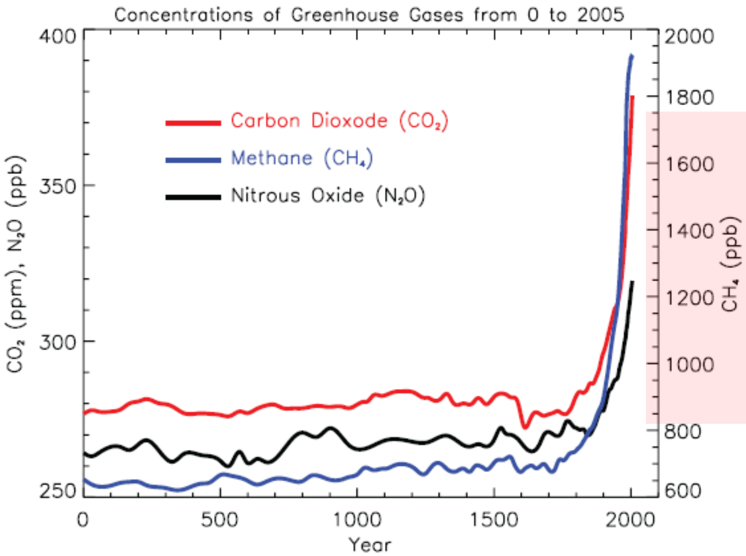
[Sarmiento and Gruber, *Physics Today*, 2002.]

Climate Change – Equivocal –versus- Unequivocal

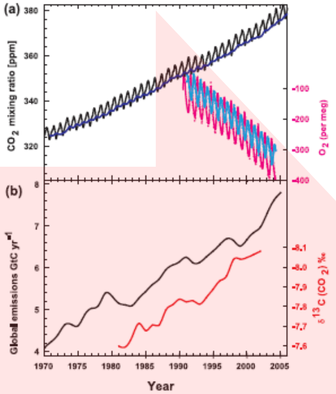
CO2 versus historic time – IPCC

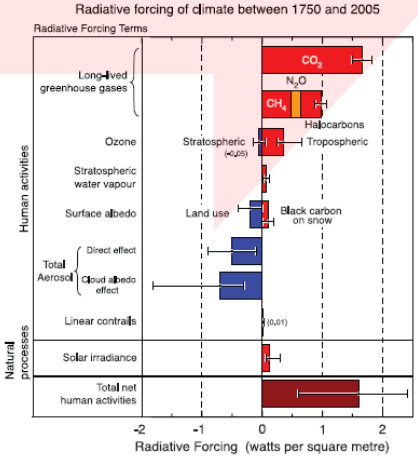
Parsing Filter

Global Mean Temperatures

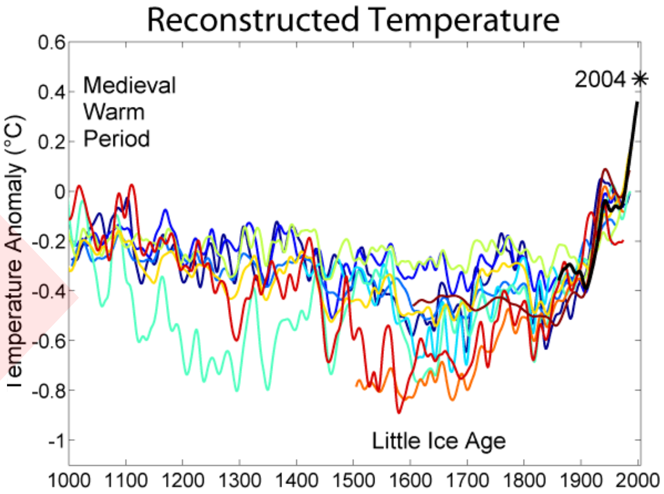


FAQ 2.1, Figure 1. *Atmospheric concentrations of important long-lived green-house gases over the last 2,000 years. Increases since about 1750 are attributed t human activities in the industrial era. Concentration units are parts per million (ppi or parts per billion (ppb), indicating the number of molecules of the greenhouse ga per million or billion air molecules, respectively, in an atmospheric sample. (Data combined and simplified from Chapters 6 and 2 of this report.)*



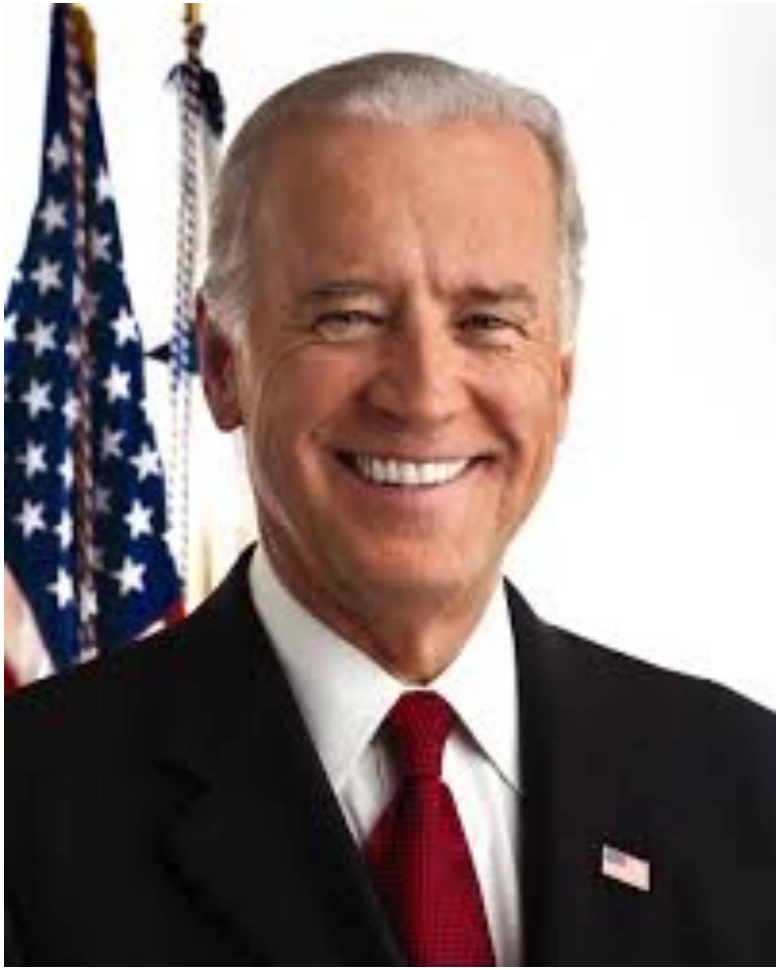


FAQ 2.1, Figure 2. *Summary of the principal components of the radiative forcing of climate change. All these radiative forcings result from one or more factors that affect climate and are associated with human activities or natural processes as discussed in the text. The values represent the forcings in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapour, surface albedo, aerosols and contrails. The only increase in natural forcing of any significance between 1750 and 2005 occurred in solar irradiance. Positive forcings lead to warming of climate and negative forcings lead to a cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value. (Figure adapted from Figure 2.20 of this report.)*



Science is Parsed through a Legislative Filter

Science is Parsed through a Legislative Filter



Administration's Energy Plan

- Within 10 years save more oil than we currently import from the Middle East and Venezuela combined.
- Put 1 million plug-in hybrid cars – cars that can get up to 150 miles per gallon – on the road by 2015.
- Generate 10 percent of our electricity from renewable sources by 2012, and 25 percent by 2025.
- Implement an economy-wide, cap-and-trade program to reduce greenhouse gas emissions 80% by 2050.

Pat Dehmer, DOE Office of Science, March 2009

Administration's Energy Plan

Sub-Surface Baseload Energy

- Within 10 years save more oil than we currently import from the Middle East and Venezuela combined.

Demand-Side Reduction

- Put 1 million plug-in hybrid cars – cars that can get up to 150 miles per gallon – on the road by 2015.

Stationary Sources and CCS

- Generate 10 percent of our electricity from renewable sources by 2012, and 25 percent by 2025.

Geothermal and Other Sources

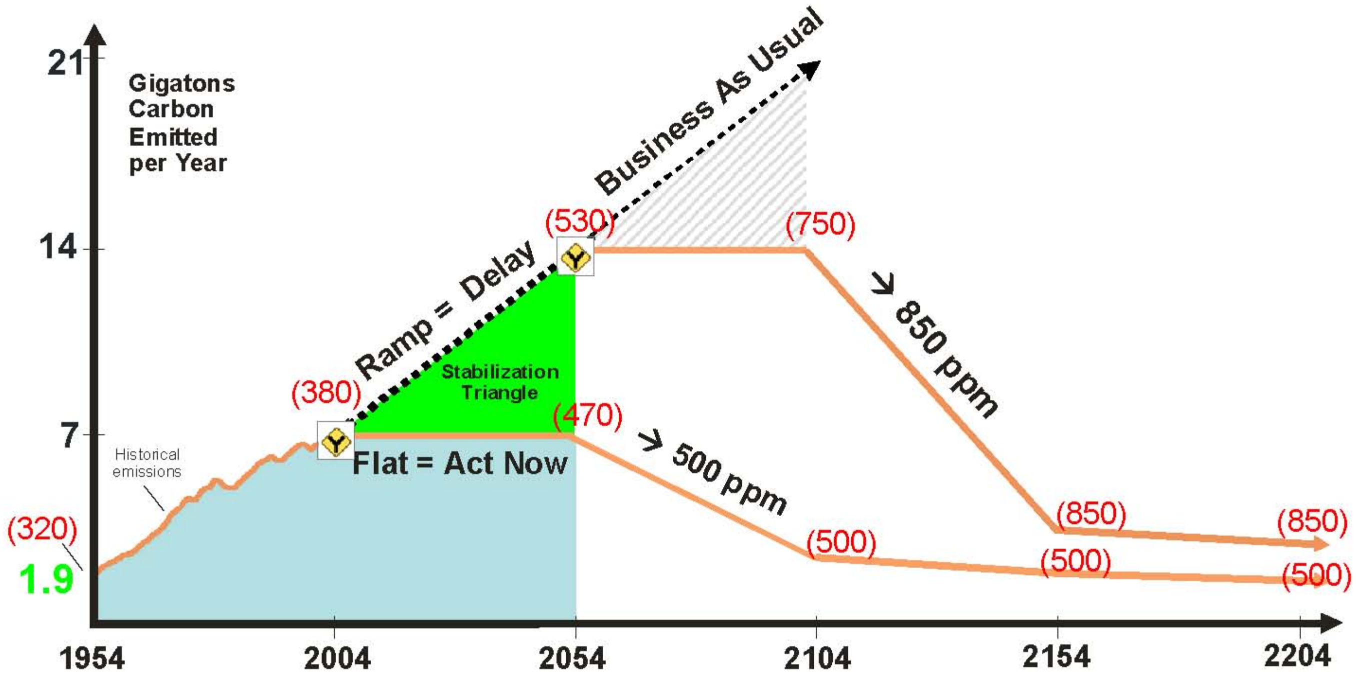
- Implement an economy-wide, cap-and-trade program to reduce greenhouse gas emissions 80% by 2050.

Fuel Switching to low(er) Carbon fuels and Carbon Capture & Storage

Pat Dehmer, DOE Office of Science, March 2009

Capacity Needs – Socolow Wedges

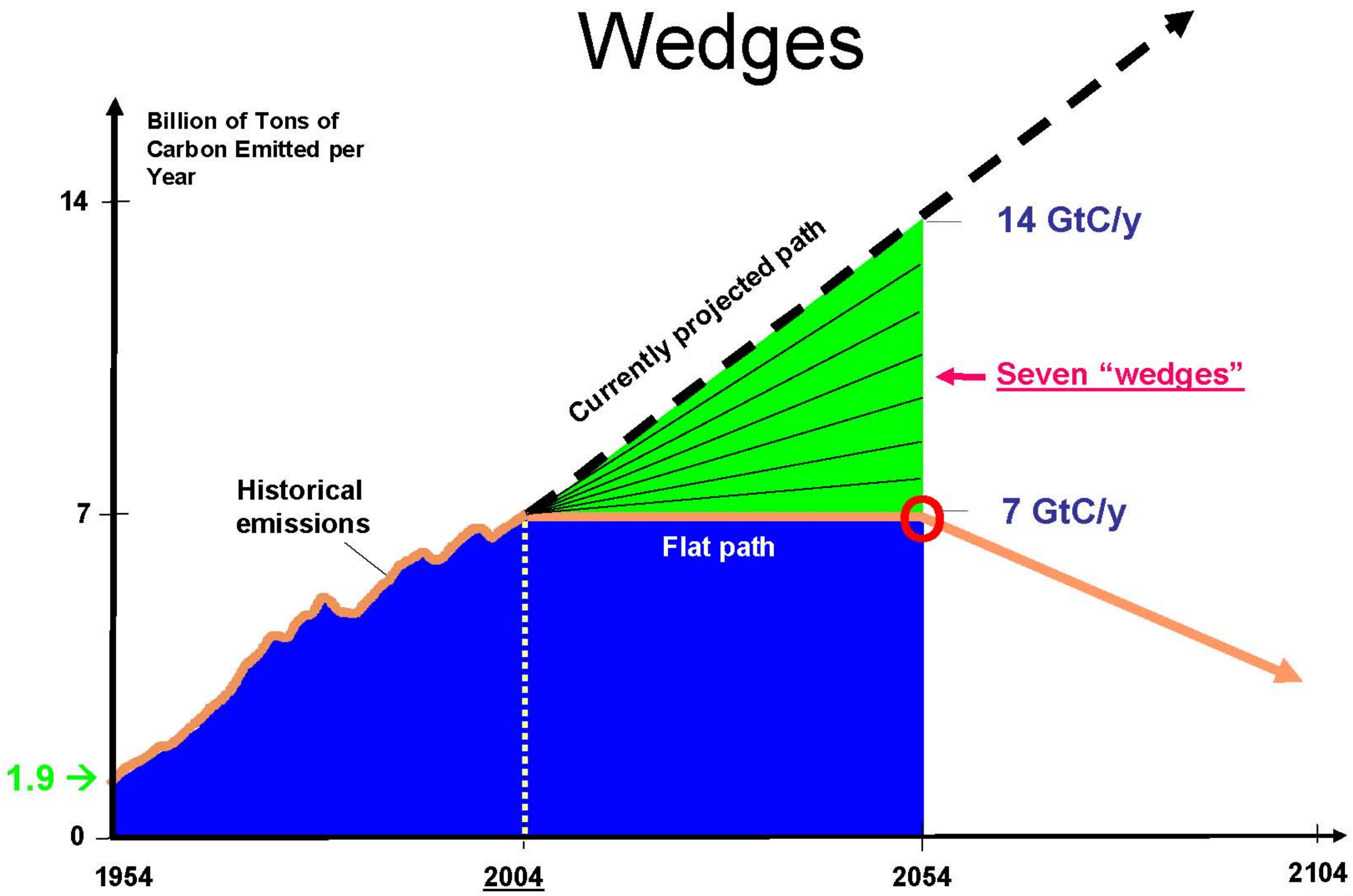
The Stabilization Triangle:
Beat doubling or accept tripling



Values in parentheses are ppm. Note the identity (a fact about the size of the Earth's atmosphere): 1 ppm = 2.1 GtC.

[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

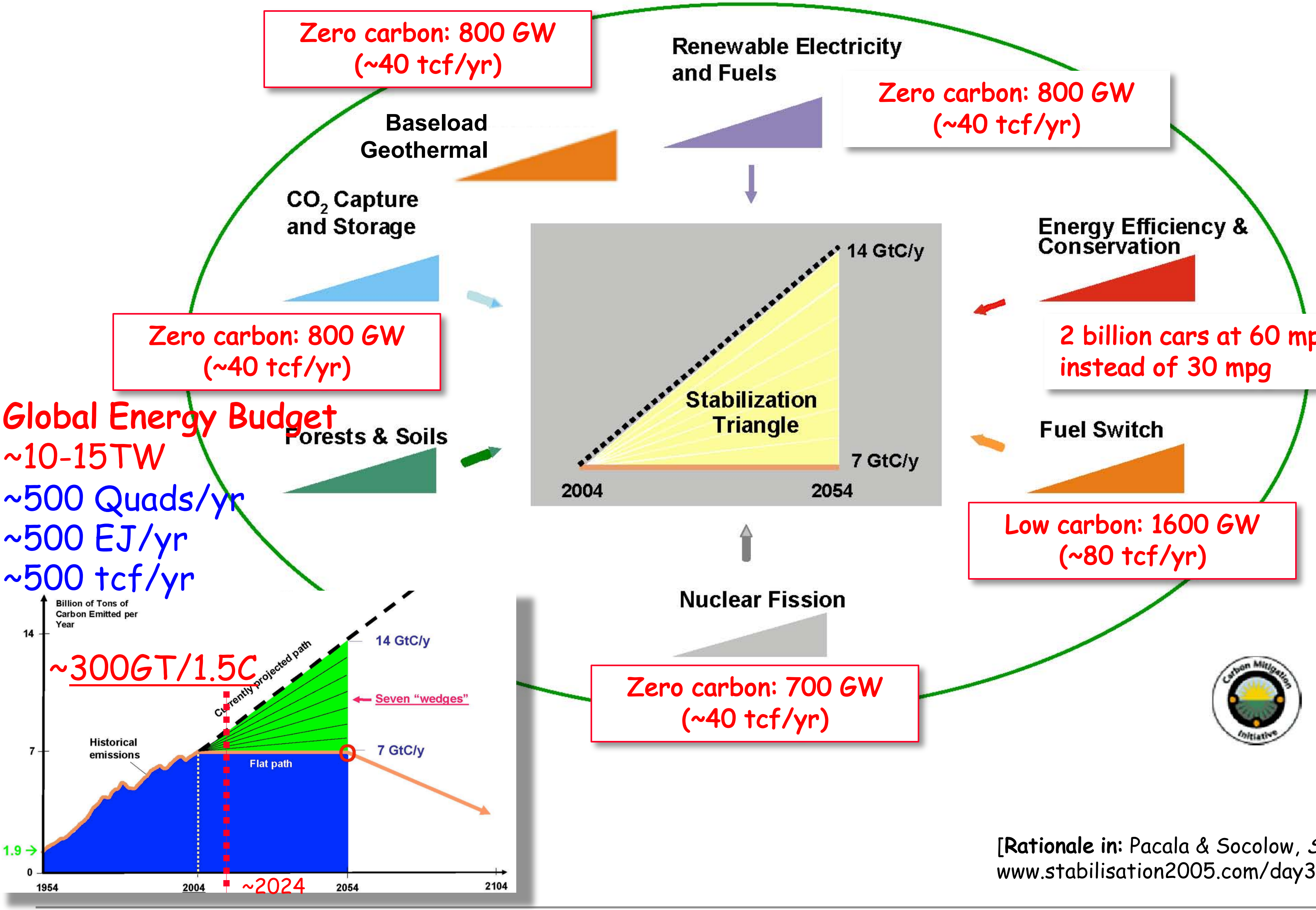
Capacity Needs – Socolow Wedges



[**Rationale in:** Pacala & Socolow, *Science*, 2004,
www.stabilisation2005.com/day3/**Socolow**.pdf]

Capacity Needs – Stabilization Wedges

Fill the Stabilization Triangle with Seven Wedges



Zero carbon: 800 GW
(~40 tcf/yr)

Zero carbon: 800 GW
(~40 tcf/yr)

Zero carbon: 800 GW
(~40 tcf/yr)

2 billion cars at 60 mpg
instead of 30 mpg

Low carbon: 1600 GW
(~80 tcf/yr)

Zero carbon: 700 GW
(~40 tcf/yr)

Global Energy Budget
~10-15TW
~500 Quads/yr
~500 EJ/yr
~500 tcf/yr

[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

Sub-Surface Energy/Engineering Solutions

Low-Carbon Fuel Solutions?

Unconventional Hydrocarbons

- Gas shales
- Coalbed methane
- Methane hydrates

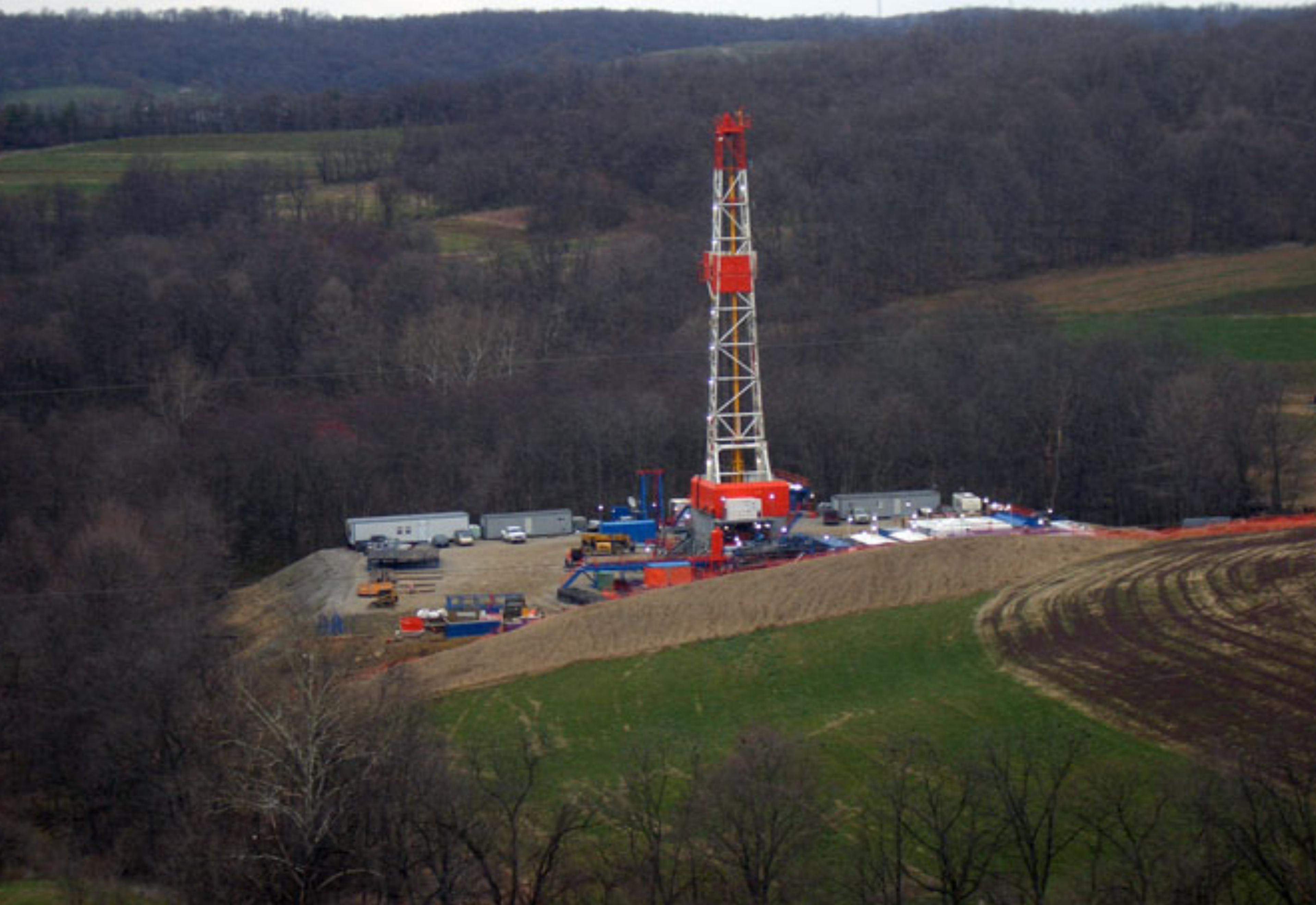
Carbon Management Solutions?

- Carbon Capture and Sequestration

Zero-Carbon Solutions?

- EGS Geothermal – The new landscape
- Nuclear power
- Hydropower/Pumped storage/CAES
- Wind
- Solar PV and thermal

Low-Carbon Fuel Solution? – Gas Shales



Implications for Energy Independence, Energy Security and for Climate Change?

APRIL 11, 2011

Libya's Civil War
A GRAVE SCANDAL AT ARLINGTON

People Power for Palestine
BY JOE KLEIN

BATTER UP! YOUR GUIDE TO THE 2011 BASEBALL SEASON

The last great work of David Foster Wallace
BY LEV GROSSMAN

TIME

ENVIRONMENT SPECIAL

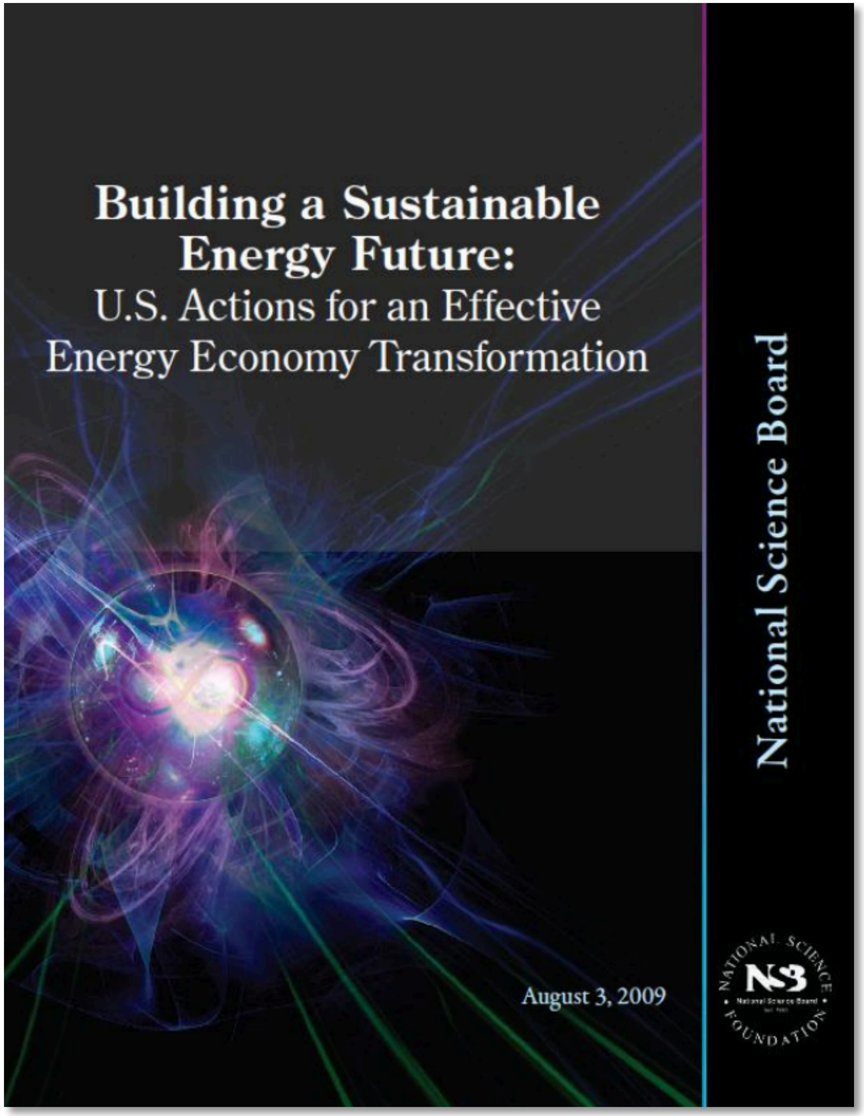
THIS ROCK COULD POWER THE WORLD

WHY SHALE CAN SOLVE THE ENERGY CRISIS
BY BRYAN WALSH

A century's worth is buried in our backyards ...

... but drilling for it threatens our land

www.time.com



Building a Sustainable Energy Future:
U.S. Actions for an Effective Energy Economy Transformation

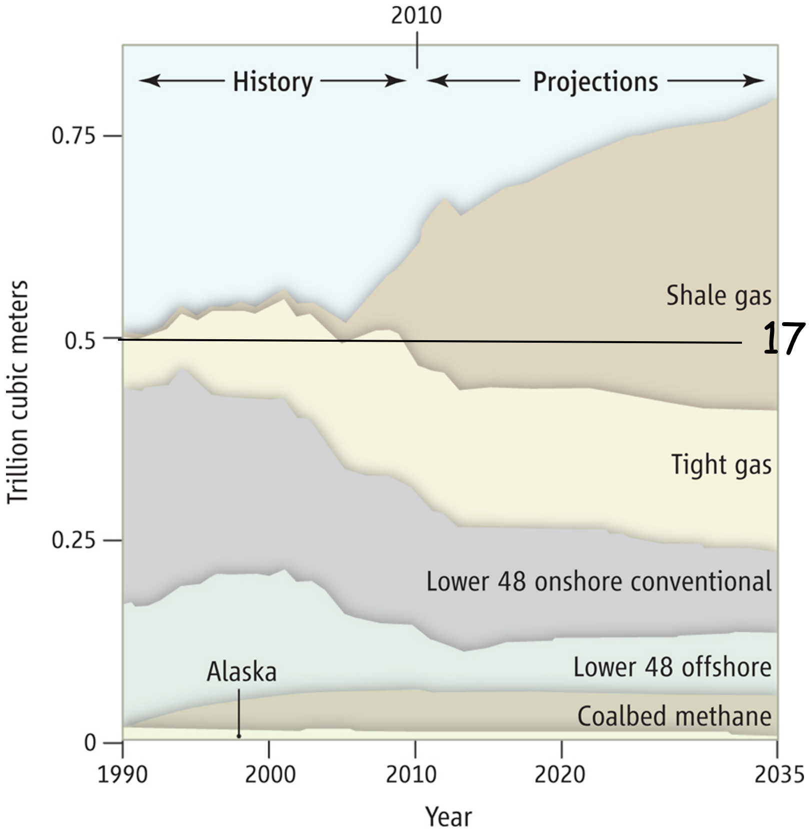
August 3, 2009

National Science Board

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

Projected Growth and Opportunities

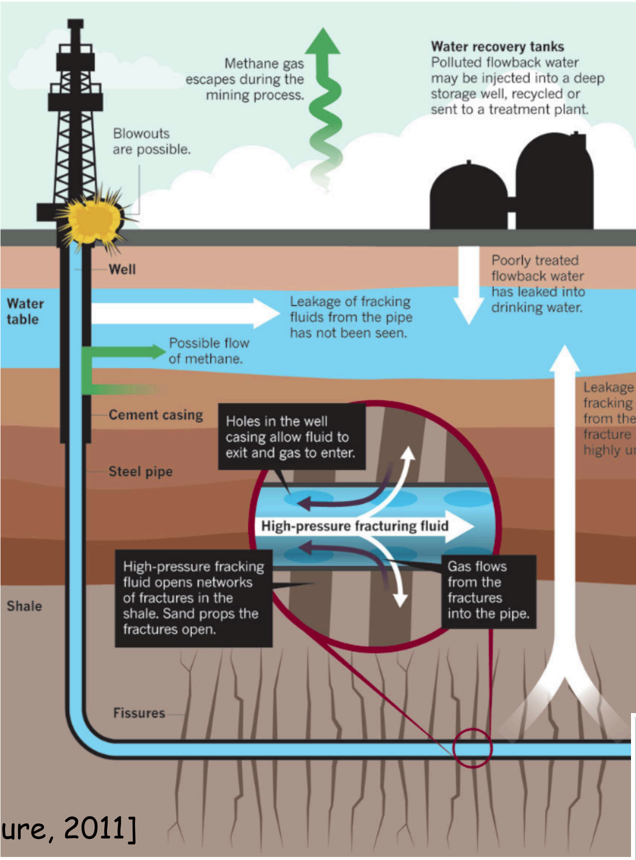
Natural Gas Utilization



17Tcf

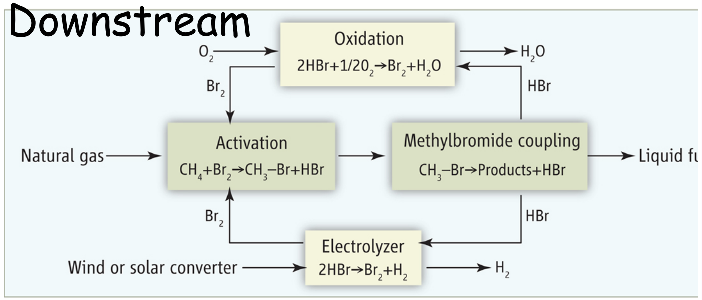
[Science, Oct 18, 2012]

Upstream



[Nature, 2011]

Downstream



O_2 → Oxidation $2HBr+1/2O_2 \rightarrow Br_2+H_2O$ → H_2O

Natural gas → Activation $CH_4+Br_2 \rightarrow CH_3{-}Br+HBr$ → Methylbromide coupling $CH_3{-}Br \rightarrow$ Products+HBr → Liquid fu

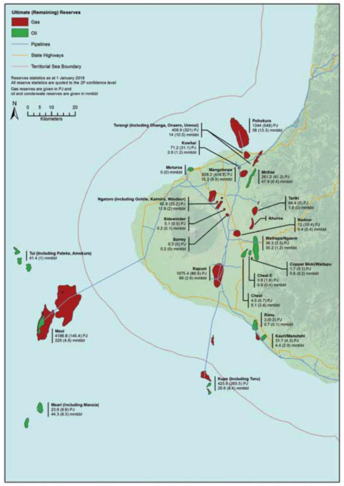
Wind or solar converter → Electrolyzer $2HBr \rightarrow Br_2+H_2$ → H_2

Br_2

HBr

Br_2

HBr



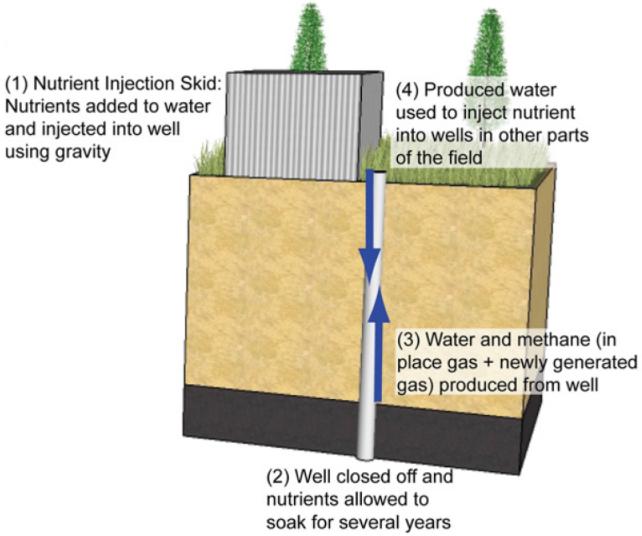
Microbially-Enhanced CBM (MECBM)

Geographic Distribution

Coalbed methane fields, lower 48 states

[~100 Tcf recoverable]

Methods of production



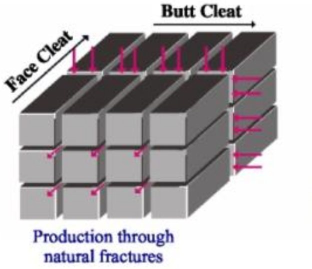
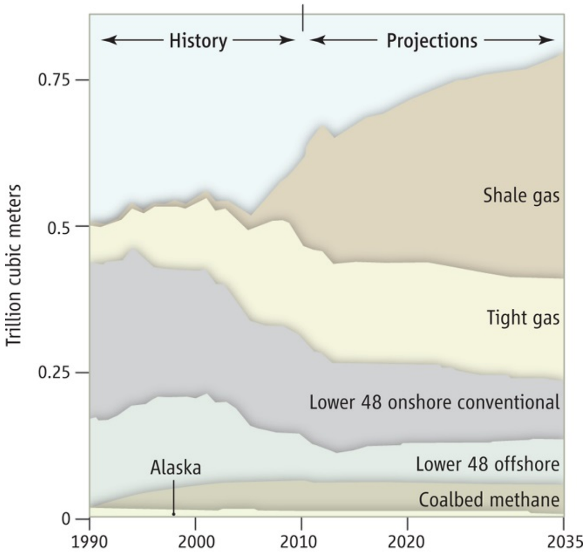


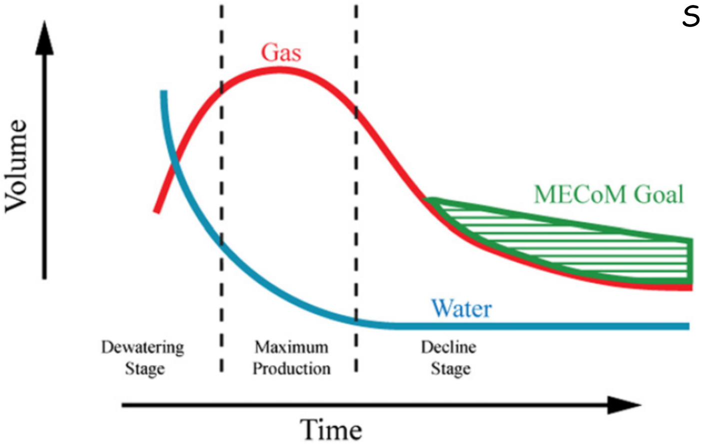
Figure 1. Coalbed Methane Develop

Projected US Gas Production



[Science, Oct 18, 2012]

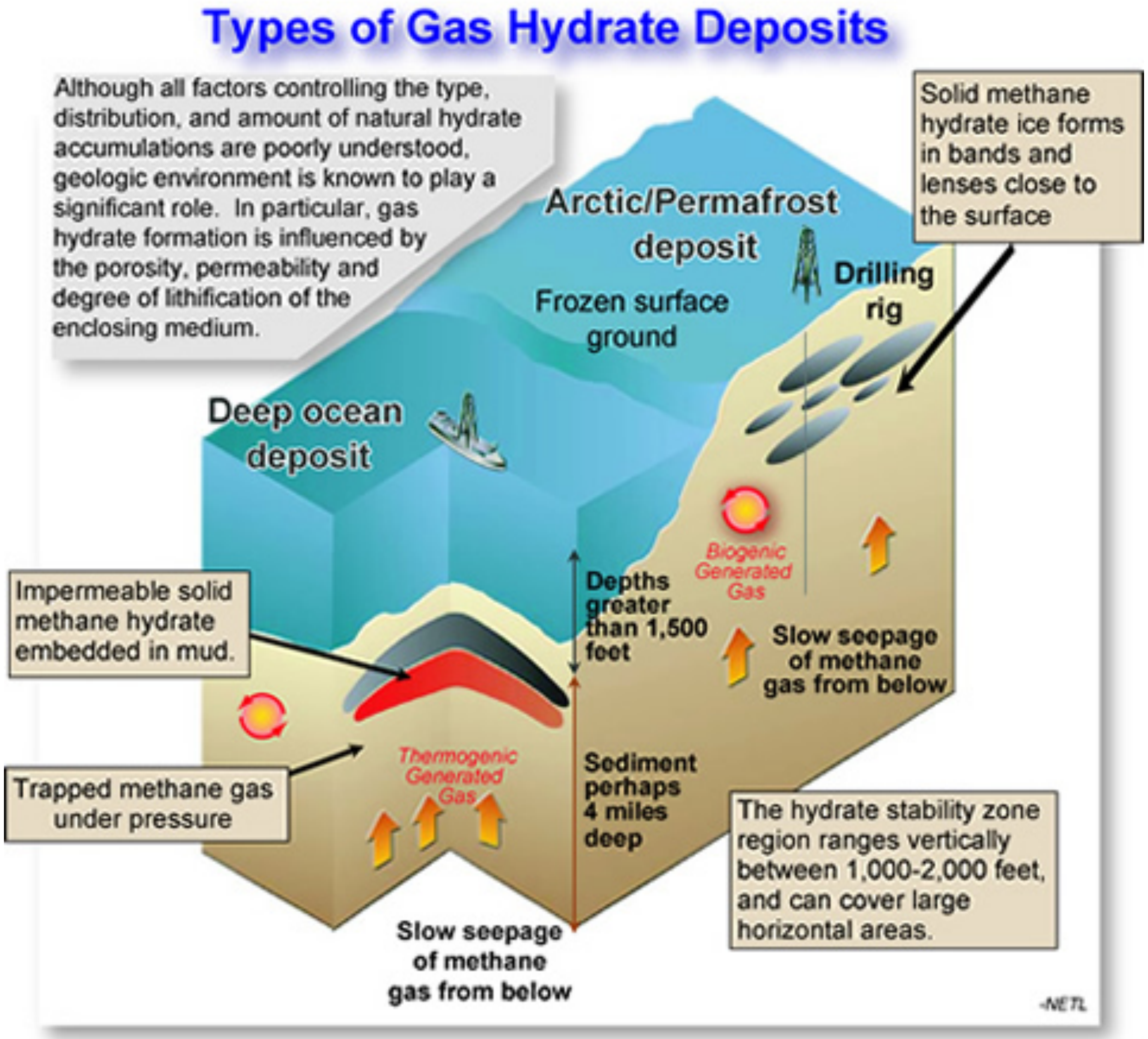
MECBM Scheduling



Principal Issues
Environmental Effects
Rate Limits on Production
Dewatering
Desorption - Capacity
Advection – Perm Evolution
Sequestration

[Nuccio, 2000]

Low-Carbon Fuel Solution? – Methane Hydrates



Types of Gas Hydrate Deposits

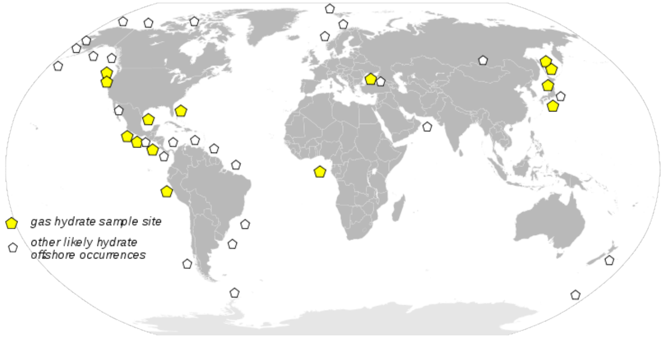
Although all factors controlling the type, distribution, and amount of natural hydrate accumulations are poorly understood, geologic environment is known to play a significant role. In particular, gas hydrate formation is influenced by the porosity, permeability and degree of lithification of the enclosing medium.

Solid methane hydrate ice forms in bands and lenses close to the surface

Impermeable solid methane hydrate embedded in mud.

Trapped methane gas under pressure

The hydrate stability zone region ranges vertically between 1,000-2,000 feet, and can cover large horizontal areas.



Projected Clathrate Reserve/Resource: - / 10^5-10^6 Tscf

Capacity Needs – Socolow Wedges

Replace Coal Fired Plants with Gas-Fired Generation

Pulrose Gas Power Station, Isle of Man, UK

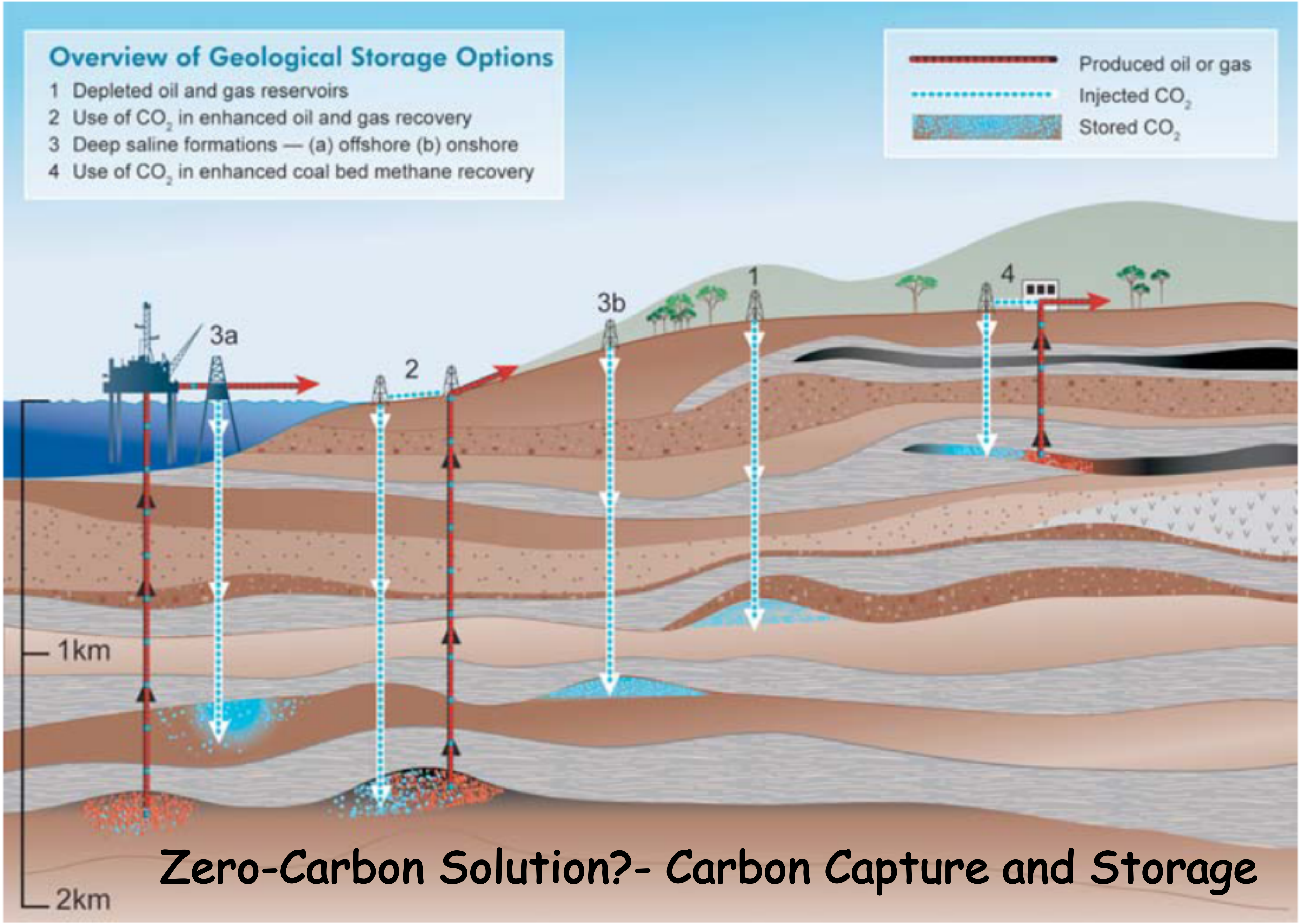
Effort needed by 2054 for 1 wedge:

1600 GW of coal-fired generating capacity

~80 Tcf/yr Natural gas

CO_{2coal}/CO_{2gas} ratio is ~1.78 for equivalent thermal energy

Zero-Carbon Solution?- Carbon Capture and Storage

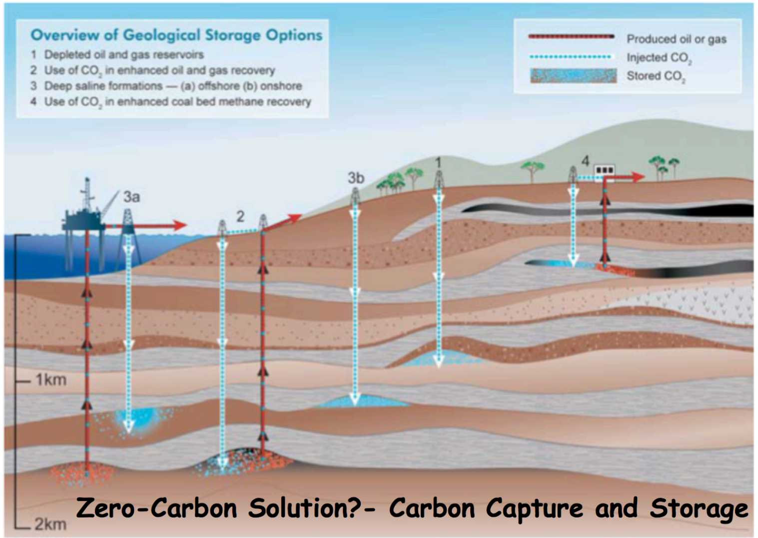


Courtesy of CO2CRC, http://www.co2crc.com.au/

Capacity Needs – Socolow Wedges

Power with Carbon Capture and Storage

Project



Zero-Carbon Solution?- Carbon Capture and Storage

Courtesy of CO2CRC, http://www.co2crc.com.au/

Effort needed by 2054 for 1 wedge:

Carbon capture and storage at 800 GW coal power plants.

~40 Tcf/yr Natural gas

[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

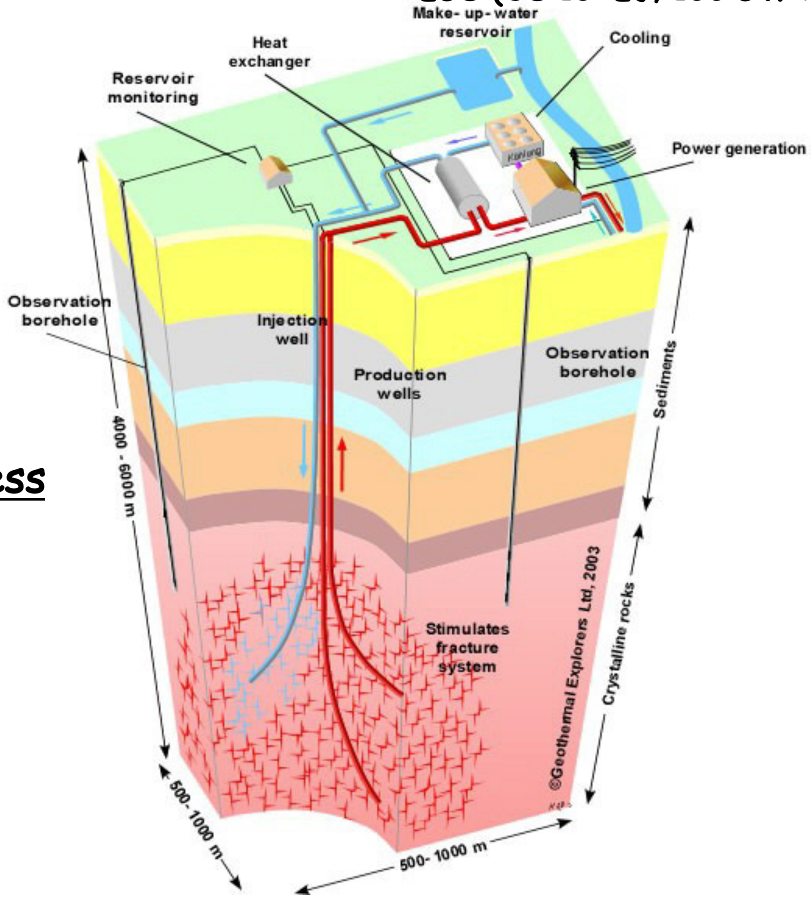
Zero-Carbon Solution? - Enhanced Geothermal Systems

Challenges

- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues

Resource

- Hydrothermal (US:10^4 EJ)
- EGS (US:10^7 EJ; 100 GW in 50y)



Observation

- Stress-sensitive reservoirs
- T H M C all influence via effective stress
- Effective stresses influence
  - Permeability
  - Reactive surface area
  - Induced seismicity

Understanding T H M C is key:

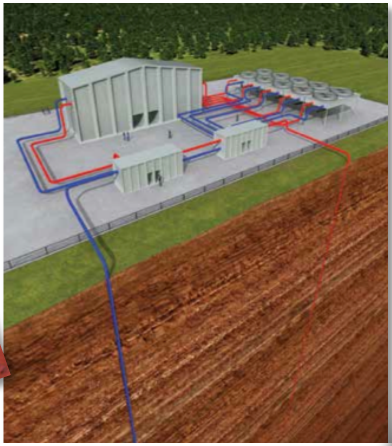
- Size of relative effects of THMC(B)
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

Permeability
Reactive surface area
Induced seismicity

Hydrothermal v Engineered Geothermal Reservoirs

SedHeat Initiative

http://geothermal.tcu.edu



PENROSE CONFERENCE

Predicting and Detecting Natural and Induced Flow Paths for Geothermal Fluids in Deep Sedimentary Basins

October 19 – 23, 2013, Newpark Hotel, Park City Utah

SedHeat was created to provide a central exchange of information and an opportunity to link researchers with common goals for a common purpose. It provides a place to foster training, mentor emerging scholars and a venue to present and exchange ideas. Our purpose is to build and sustain a diverse and interdisciplinary network of researchers who are focused on addressing the basic science, engineering and educational challenges for sustainable geothermal energy development from sedimentary basins.

WHAT WE DO

Our intention is to continually grow as a network, as well as attract new parties interested in the topic of sedimentary-basin geothermal energy.

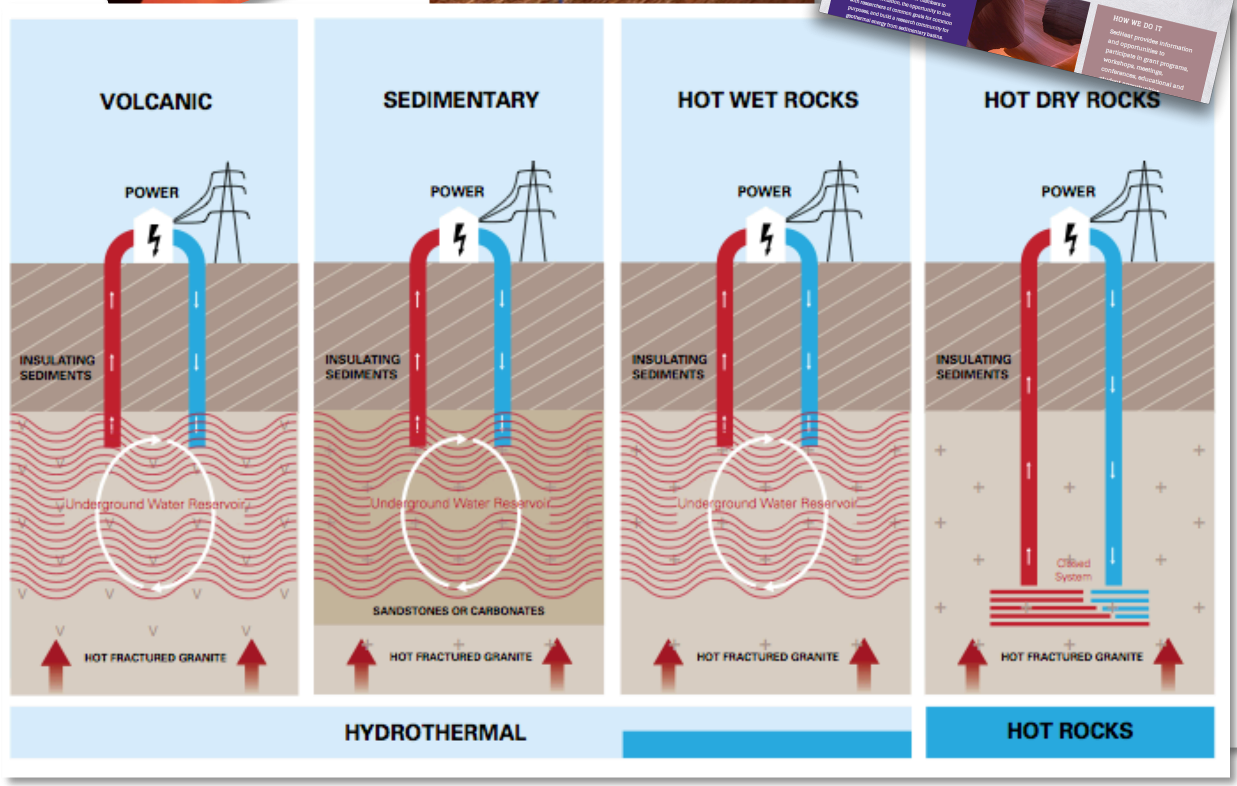
- > Steering Committee
- > RCN Members
- > Grant Programs
- > Join RCN
- > Workshops & Meetings
- > Travel Grants

RESEARCH COORDINATION NETWORK

The Research Coordination Network (RCN) provides a central location for members to exchange information, the opportunity to link with researchers of common goals for common purposes, and build a research community for geothermal energy from sedimentary basins.

HOW WE DO IT

SedHeat provides information and opportunities to participate in grant programs, workshops, meetings, conferences, educational and



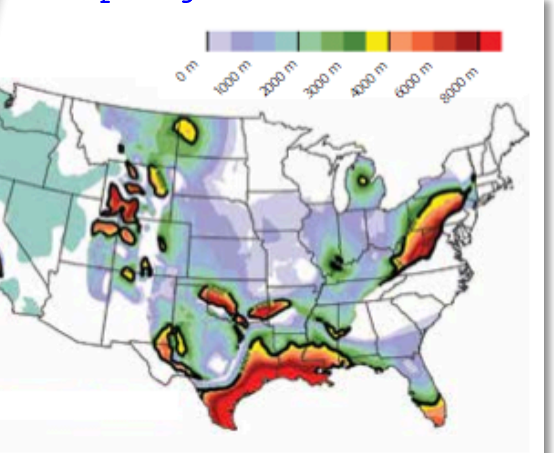


Figure 1: Distribution of sediment thickness in the conterminous U.S. 4 km isopach in black. Numerous Basin and Range basins over 4 km excluded for small resolution (Tester, et al., 2006)

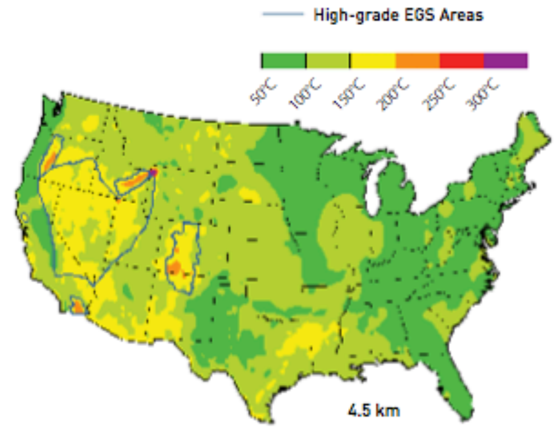
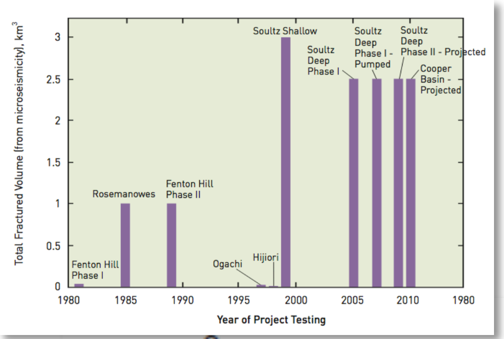
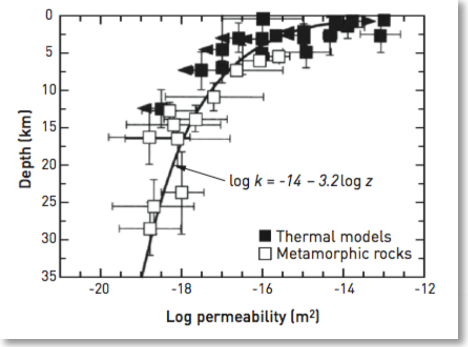
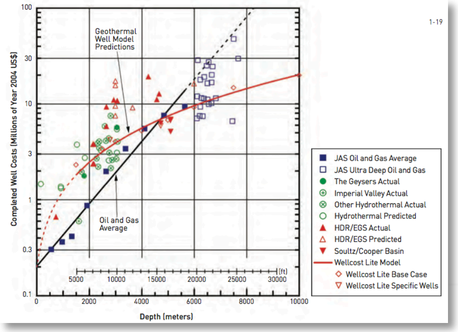


Figure 2: Average temperature at 4.5 km, conterminous United States. (Tester, et al., 2006, after Blackwell and Richards, 2004)

Can EGS ever be Viable?

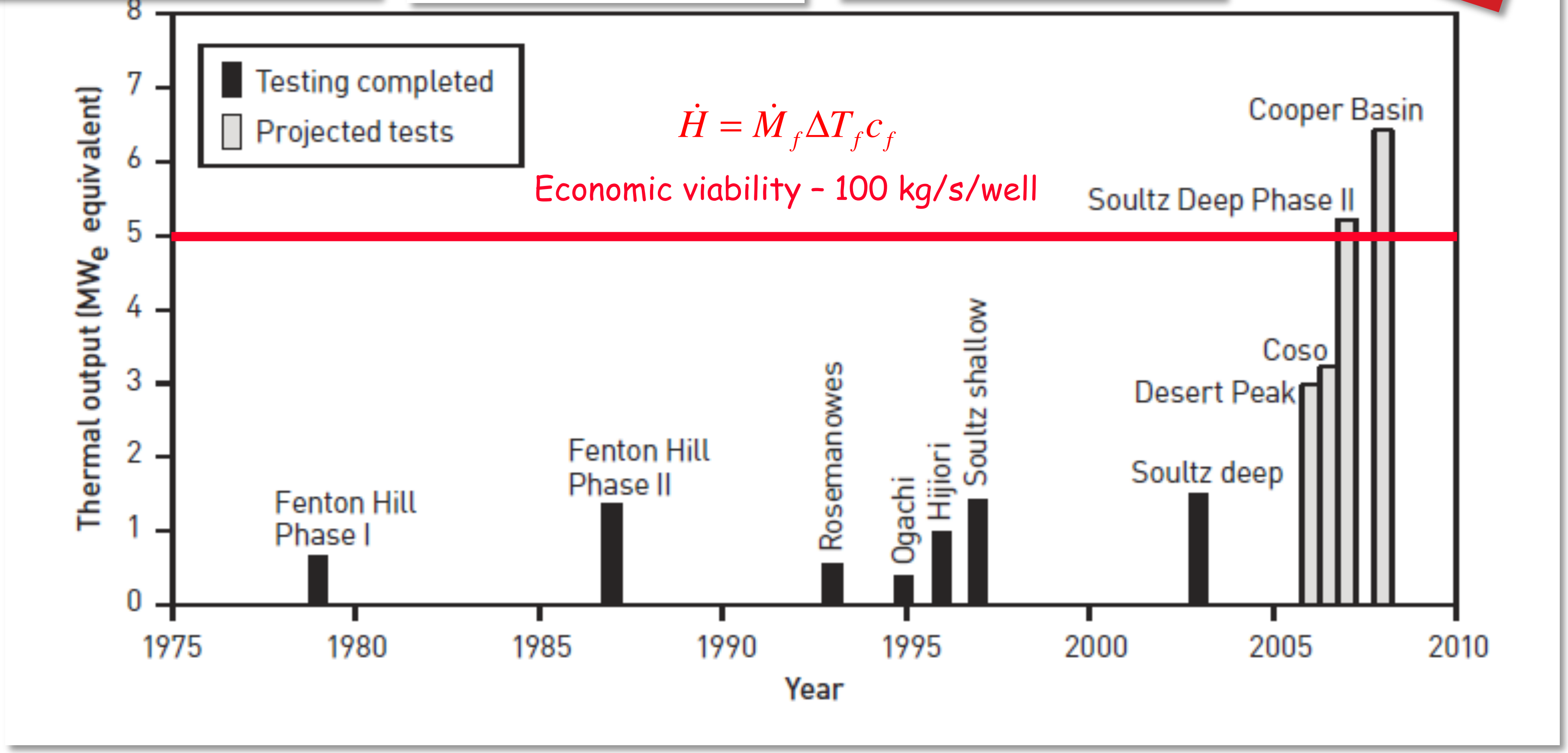







The Future of Geothermal Energy

Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century

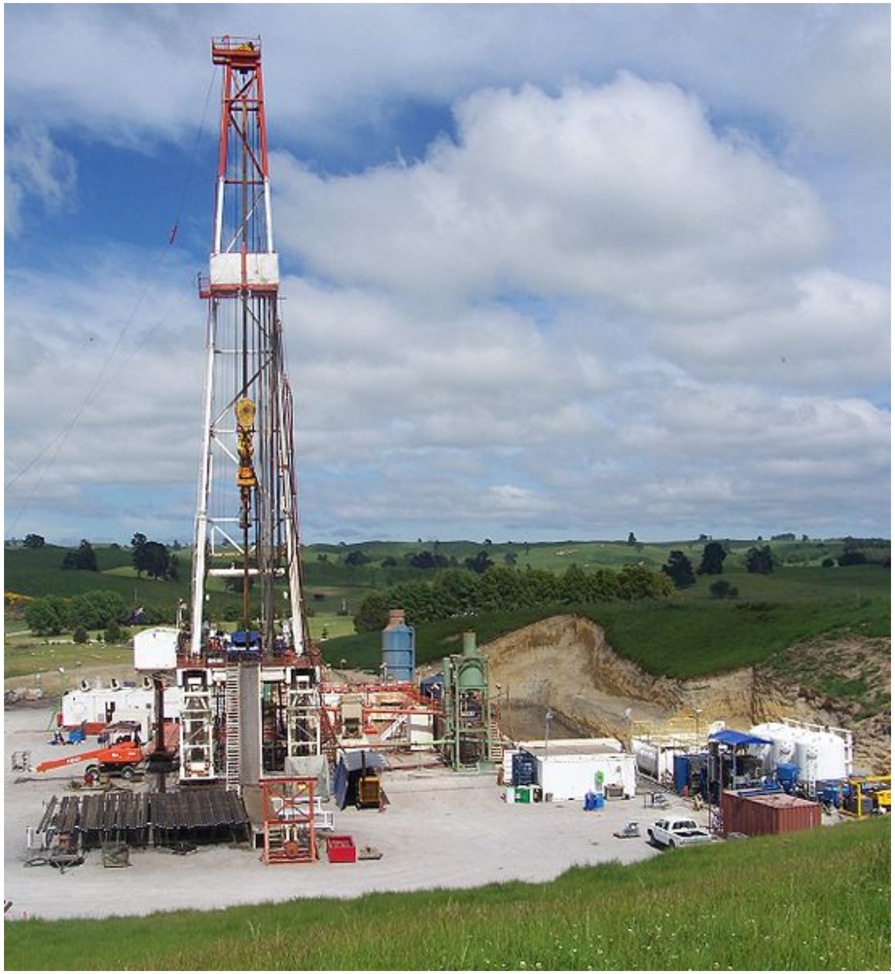


$$\dot{H} = \dot{M}_f \Delta T_f c_f$$

Economic viability – 100 kg/s/well

Capacity Needs - Socolow Wedges

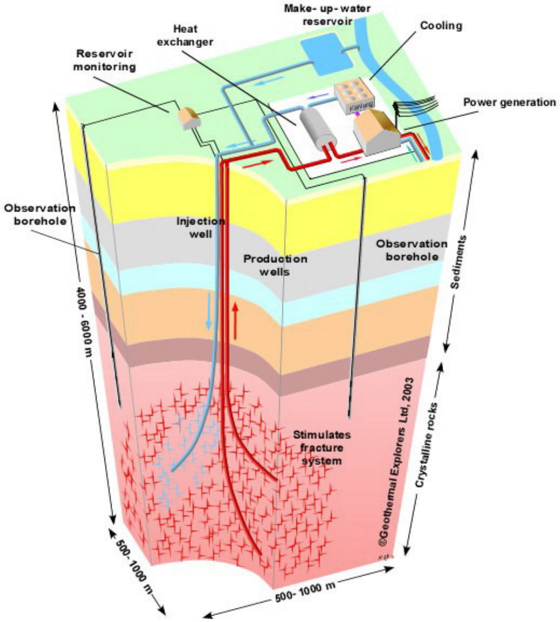
Retire Coal Fired Plants and Replace with EGS



Effort needed by 2054 for 1 wedge:

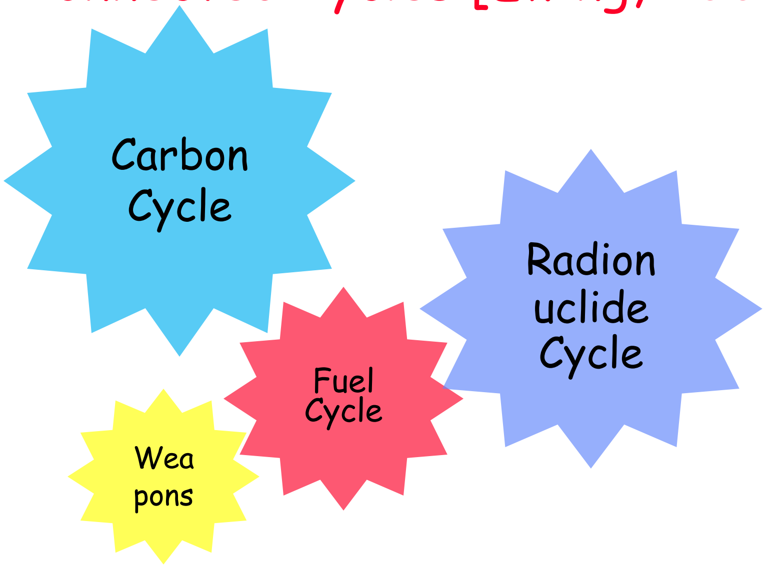
800 GW of EGS capacity

~40 Tcf/yr Natural gas



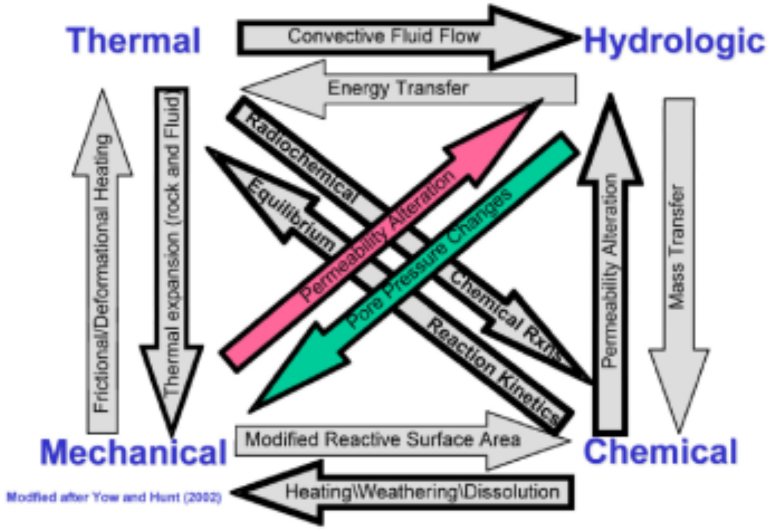
Zero Carbon Solution? – Nuclear Power

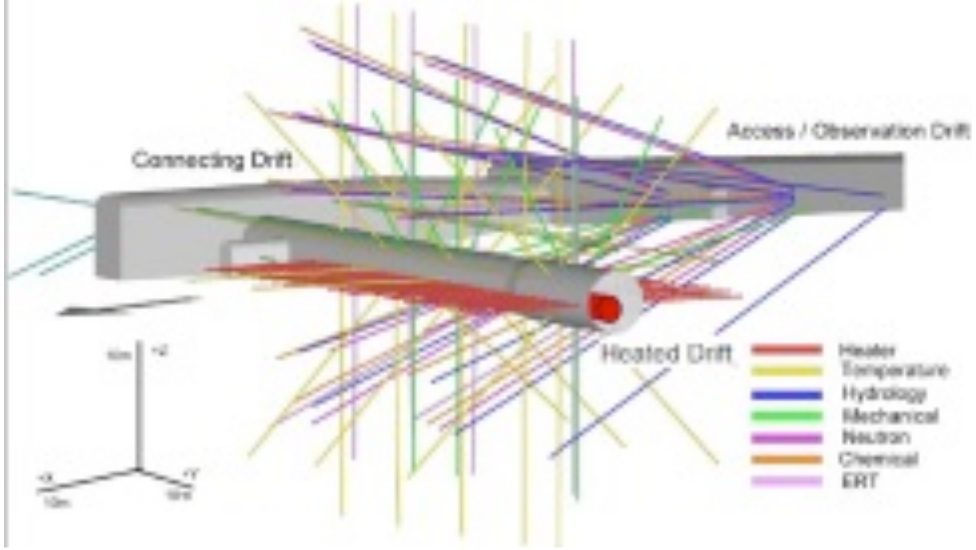
Connected Cycles [Ewing, 2007]



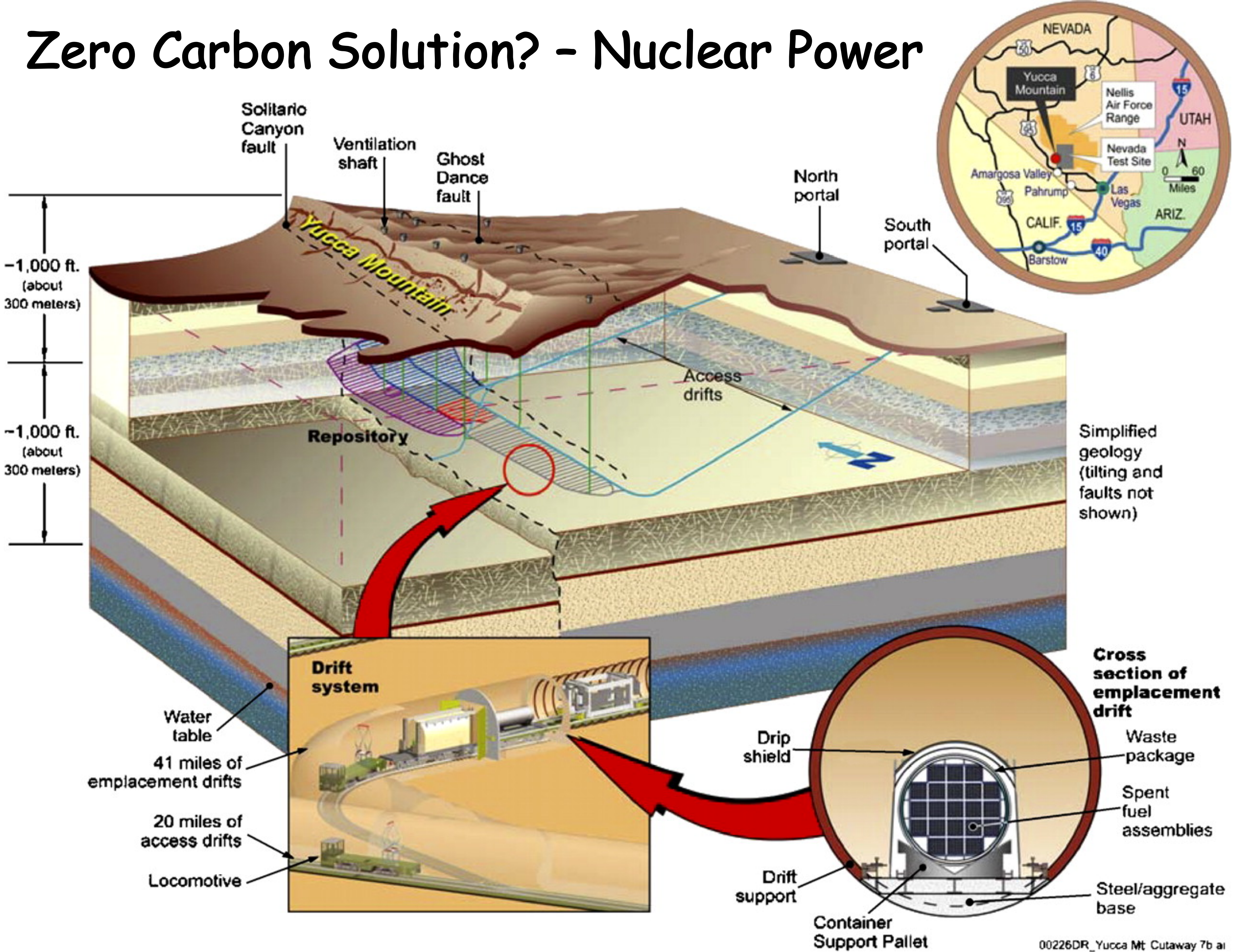
Waste Disposal and Politics

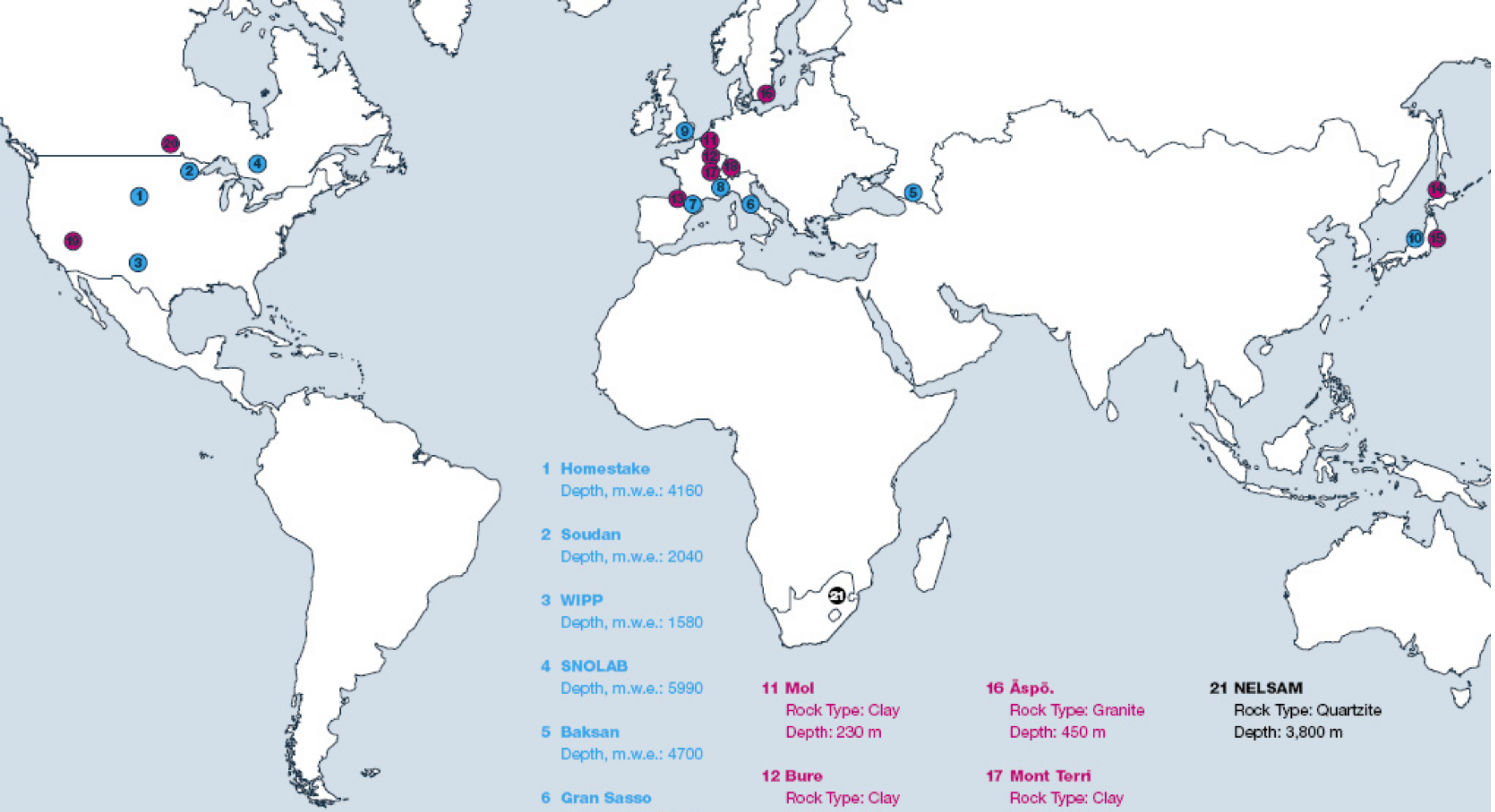
Intense Process Feedbacks





Zero Carbon Solution? – Nuclear Power





1 Homestake
Depth, m.w.e.: 4160

2 Soudan
Depth, m.w.e.: 2040

3 WIPP
Depth, m.w.e.: 1580

4 SNOLAB
Depth, m.w.e.: 5990

5 Baksan
Depth, m.w.e.: 4700

6 Gran Sasso
Depth, m.w.e.: 3030

7 Canfranc
Depth, m.w.e.: 2450

8 Fréjus/Modane
Depth, m.w.e.: 4150

9 Boulby
Depth, m.w.e.: 2805

10 Kamioka
Depth, m.w.e.: 2050

11 Mol
Rock Type: Clay
Depth: 230 m

12 Bure
Rock Type: Clay
Depth: 450 m

13 Tournemire
Rock Type: Clay
Depth: 300 m

14 Horonobe
Rock Type: Sedimentary
Depth: 1,000 m

15 Tono (Mizunami)
Rock Type: Granite
Depth: 1,000 m

16 Äspö.
Rock Type: Granite
Depth: 450 m

17 Mont Terri
Rock Type: Clay
Depth: 300 m

18 Grimsel
Rock Type: Granite
Depth: 450 m

19 Yucca Mountian
Rock Type: Volcanic tuff
Depth: 300 m

20 Pinawa
Rock Type: Granite
Depth: 450 m

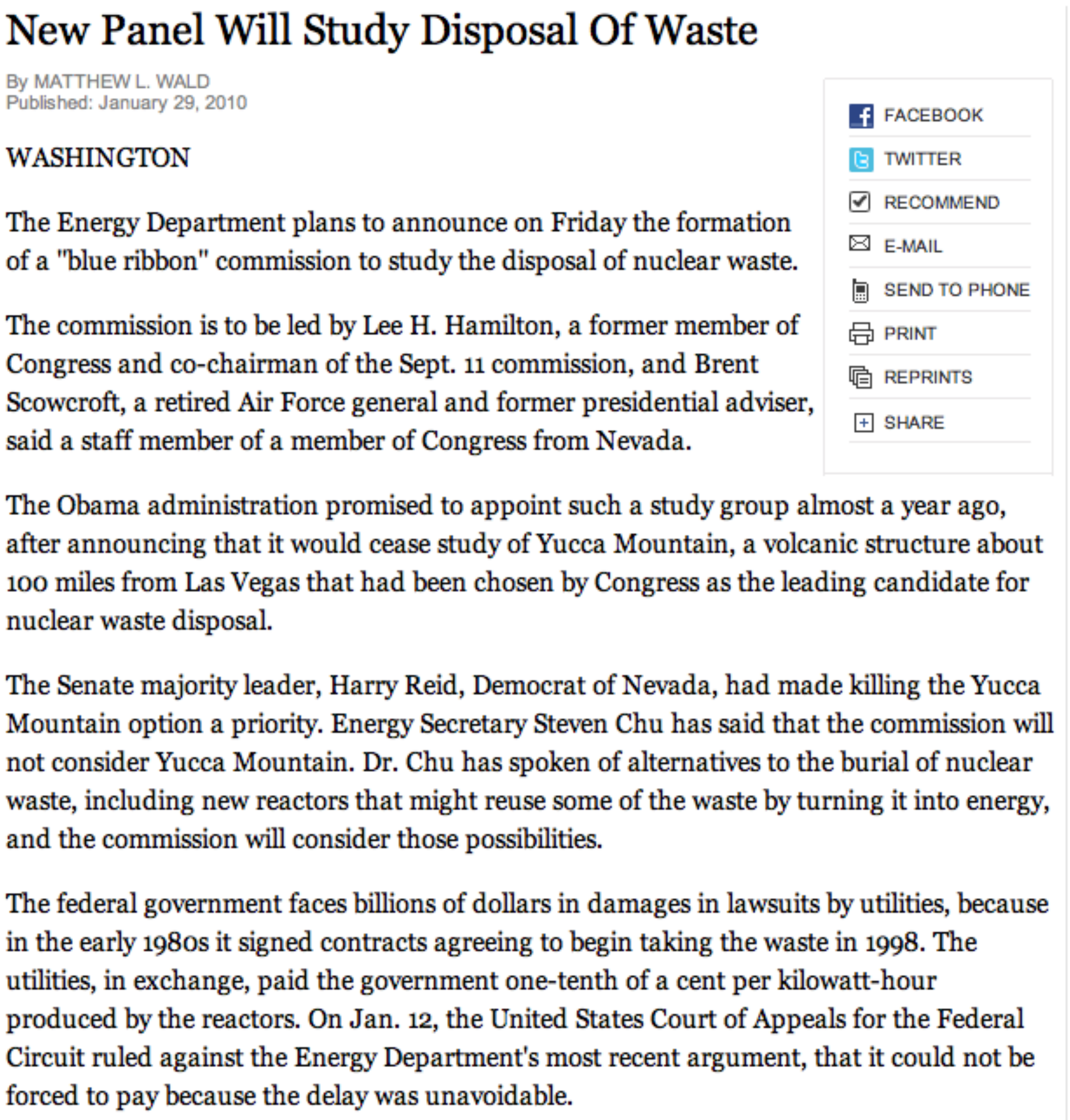
21 NELSAM
Rock Type: Quartzite
Depth: 3,800 m

Figure 1: Underground laboratories worldwide. Physics laboratories (blue) are listed with their depths in meters water equivalent. Laboratories for research into the long-term (~million-year) isolation of high-level nuclear waste, shown in red, are listed with actual depth. The NELSAM laboratory (black) is for earthquake research.

Yucca Mountain in the News

Off-Again?

[NYT, January 29, 2009]



New Panel Will Study Disposal Of Waste

By MATTHEW L. WALD
Published: January 29, 2010

WASHINGTON

The Energy Department plans to announce on Friday the formation of a "blue ribbon" commission to study the disposal of nuclear waste.

The commission is to be led by Lee H. Hamilton, a former member of Congress and co-chairman of the Sept. 11 commission, and Brent Scowcroft, a retired Air Force general and former presidential adviser, said a staff member of a member of Congress from Nevada.

The Obama administration promised to appoint such a study group almost a year ago, after announcing that it would cease study of Yucca Mountain, a volcanic structure about 100 miles from Las Vegas that had been chosen by Congress as the leading candidate for nuclear waste disposal.

The Senate majority leader, Harry Reid, Democrat of Nevada, had made killing the Yucca Mountain option a priority. Energy Secretary Steven Chu has said that the commission will not consider Yucca Mountain. Dr. Chu has spoken of alternatives to the burial of nuclear waste, including new reactors that might reuse some of the waste by turning it into energy, and the commission will consider those possibilities.

The federal government faces billions of dollars in damages in lawsuits by utilities, because in the early 1980s it signed contracts agreeing to begin taking the waste in 1998. The utilities, in exchange, paid the government one-tenth of a cent per kilowatt-hour produced by the reactors. On Jan. 12, the United States Court of Appeals for the Federal Circuit ruled against the Energy Department's most recent argument, that it could not be forced to pay because the delay was unavoidable.

Yucca Mountain in the News

Or On-Again?

[NYT, June 29, 2010]

Administration Cannot Drop Bid for Nuclear Waste Dump in Nevada, Panel Finds

By MATTHEW L. WALD

Published: June 29, 2010

WASHINGTON — In a setback for the Obama administration, a panel of judges at the Nuclear Regulatory Commission ruled on Tuesday that the Energy Department could not withdraw its application to open a nuclear waste dump at Yucca Mountain in Nevada.

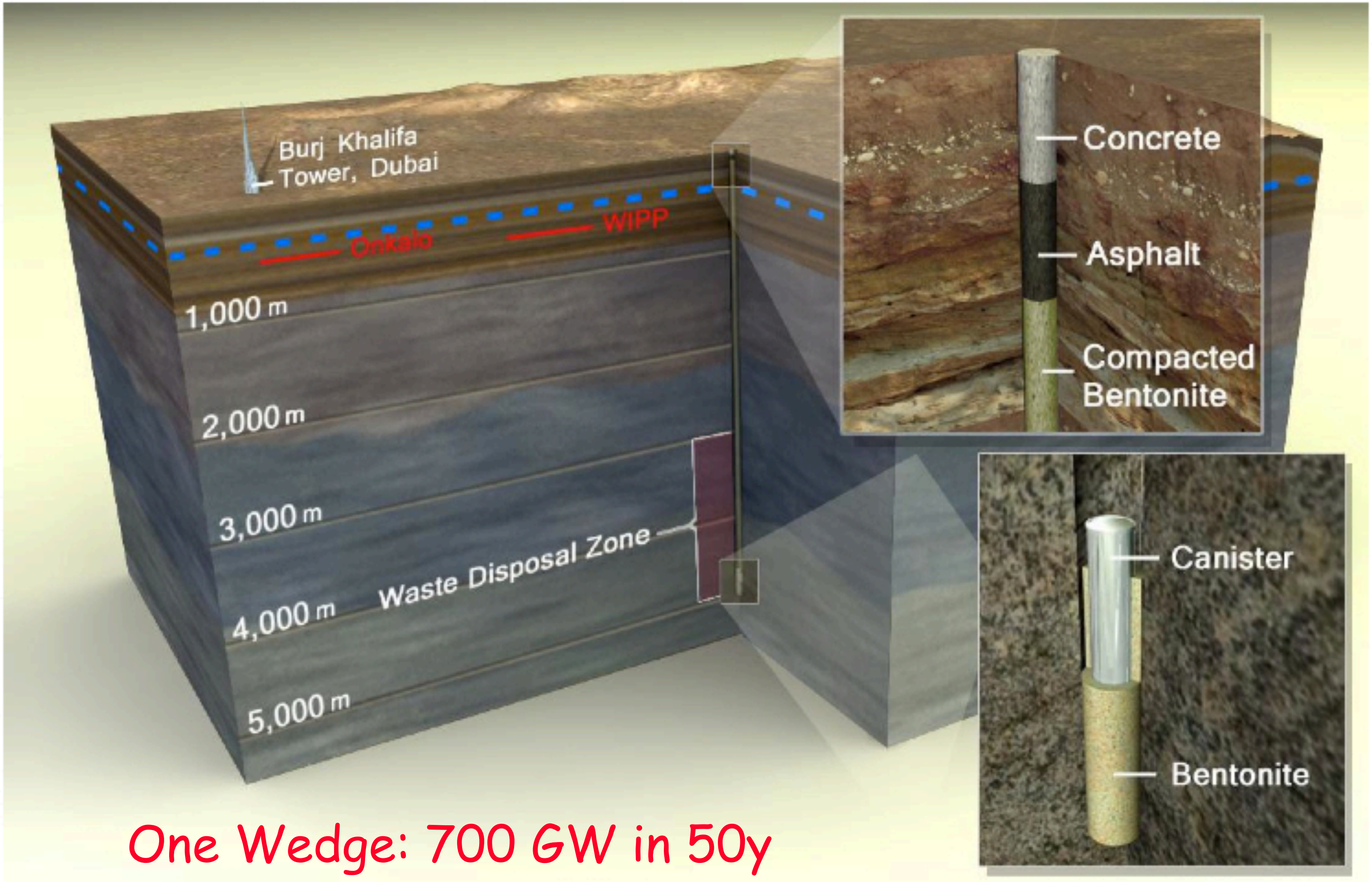
The New York Times

Congress selected the Yucca Mountain location in 1987.

Making good on a campaign pledge by President Obama, the Energy Department had formally sought to drop its plan for Yucca Mountain, a volcanic structure about 100 miles from Las Vegas. But states with major accumulations of waste from nuclear weapons production had petitioned to prevent the department from doing so.

In a 47-page decision, the three-member panel of administrative judges said the Energy Department lacked the authority to drop the petition because it would flout a law passed by Congress.

The New US Plan



One Wedge: 700 GW in 50y
40 Tcf/y

[http://www.forbes.com/]

Sub-Surface Energy/Engineering Solutions

Low-Carbon Fuel Solutions?

Unconventional Hydrocarbons

- Gas shales
- Coalbed methane
- Methane hydrates

Carbon Management Solutions?

- Carbon Capture and Sequestration

Zero-Carbon Solutions?

- EGS Geothermal – The new landscape
- Nuclear power
- Hydropower/Pumped storage/CAES
- Wind
- Solar PV and thermal

The Green New Deal

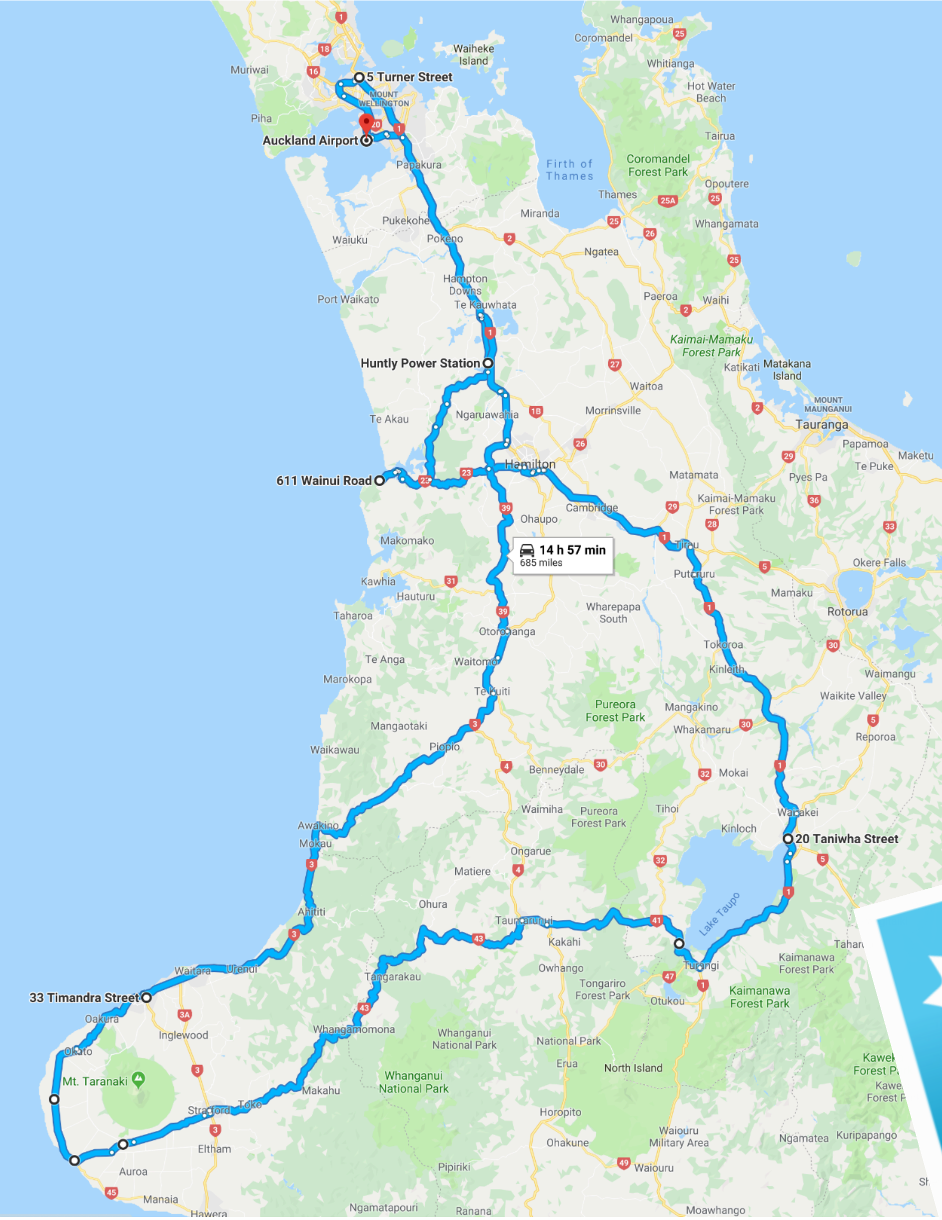

A GREEN NEW DEAL

A PROGRESSIVE VISION for ENVIRONMENTAL SUSTAINABILITY and ECONOMIC STABILITY


A Green New Deal, It's high time that we grow America's manufacturing sector and fix our crumbling infrastructure in an evironmentally sustainable way.

www.facebook.com/DemocraticSocialist

Sustainable Energy in New Zealand

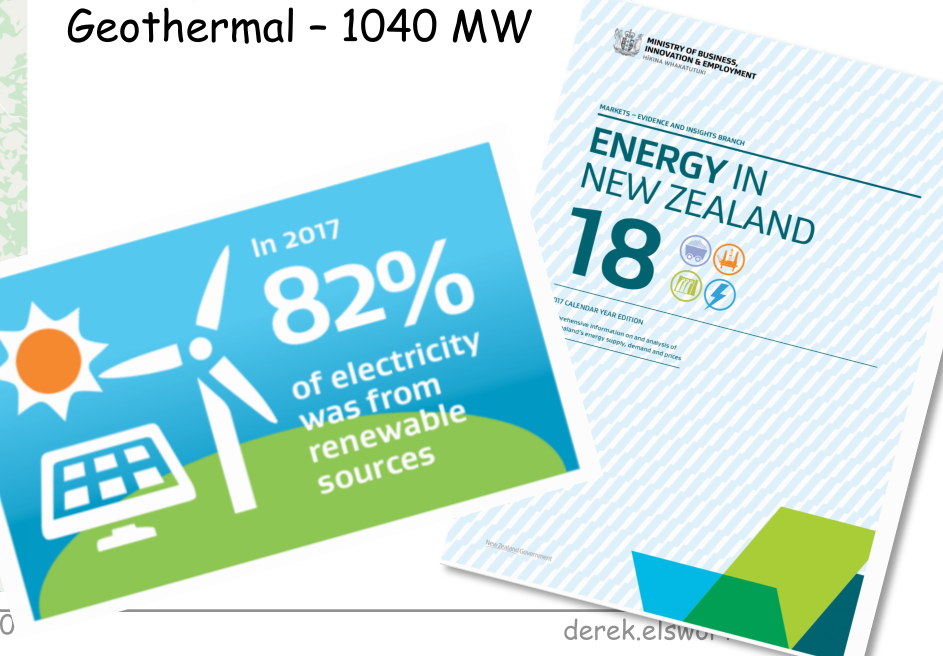


Annual Consumption – 1 EJ (NZ)
100 EJ (USA)

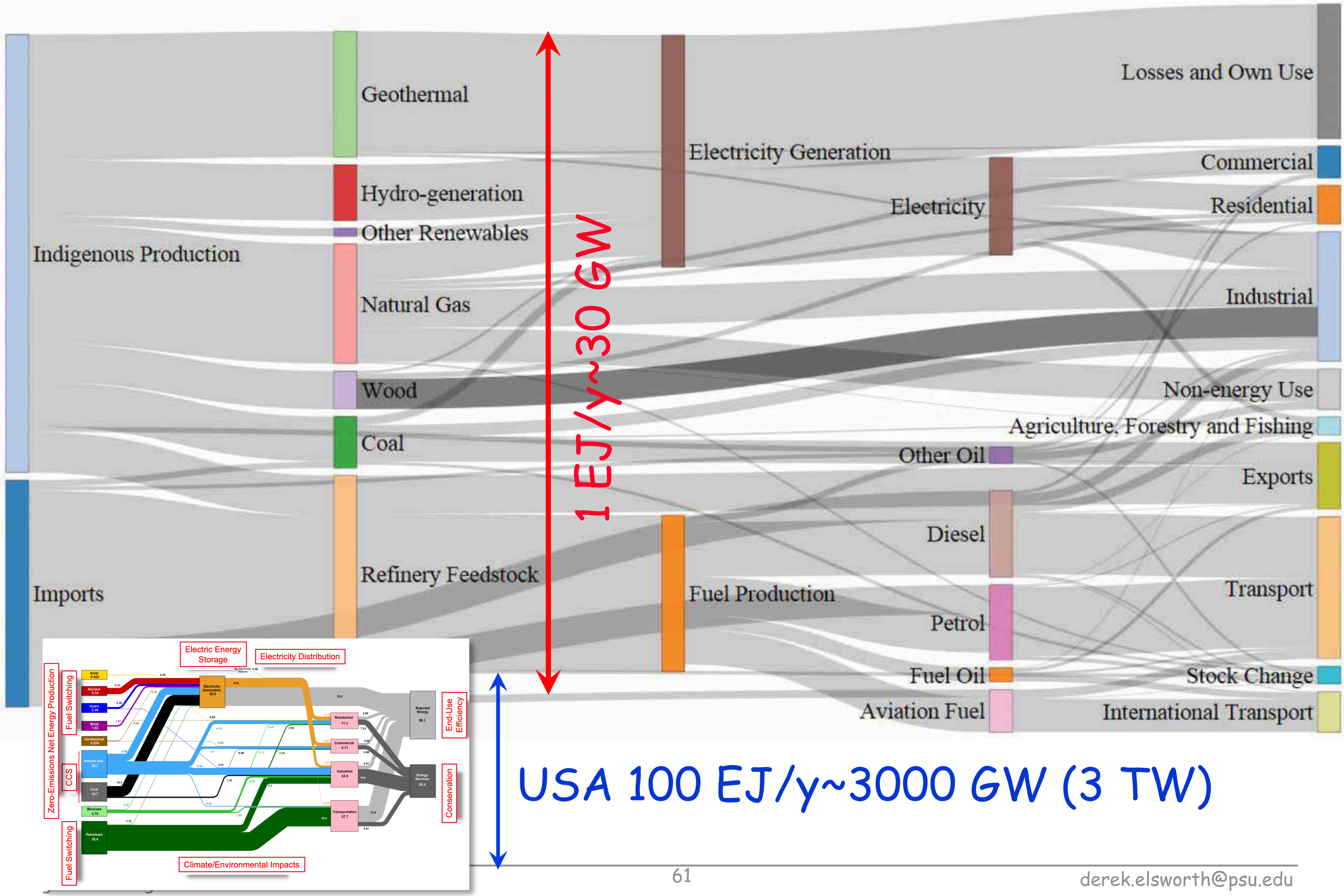
NZ Energy consumption 1 EJ/yr ~ 30 GW

Typically 50/50 Electricity/Transportation

Thermal – 1400 MW (Huntly)
Gas (360 MW)
Coal (4 x 250 MW)
Wind – 2000 MW (Capacity??)
Hydropower – 2000 MW (Capacity??)
Geothermal – 1040 MW



Sankey Chart for NZ Energy Consumption



1 EJ/y~30 GW

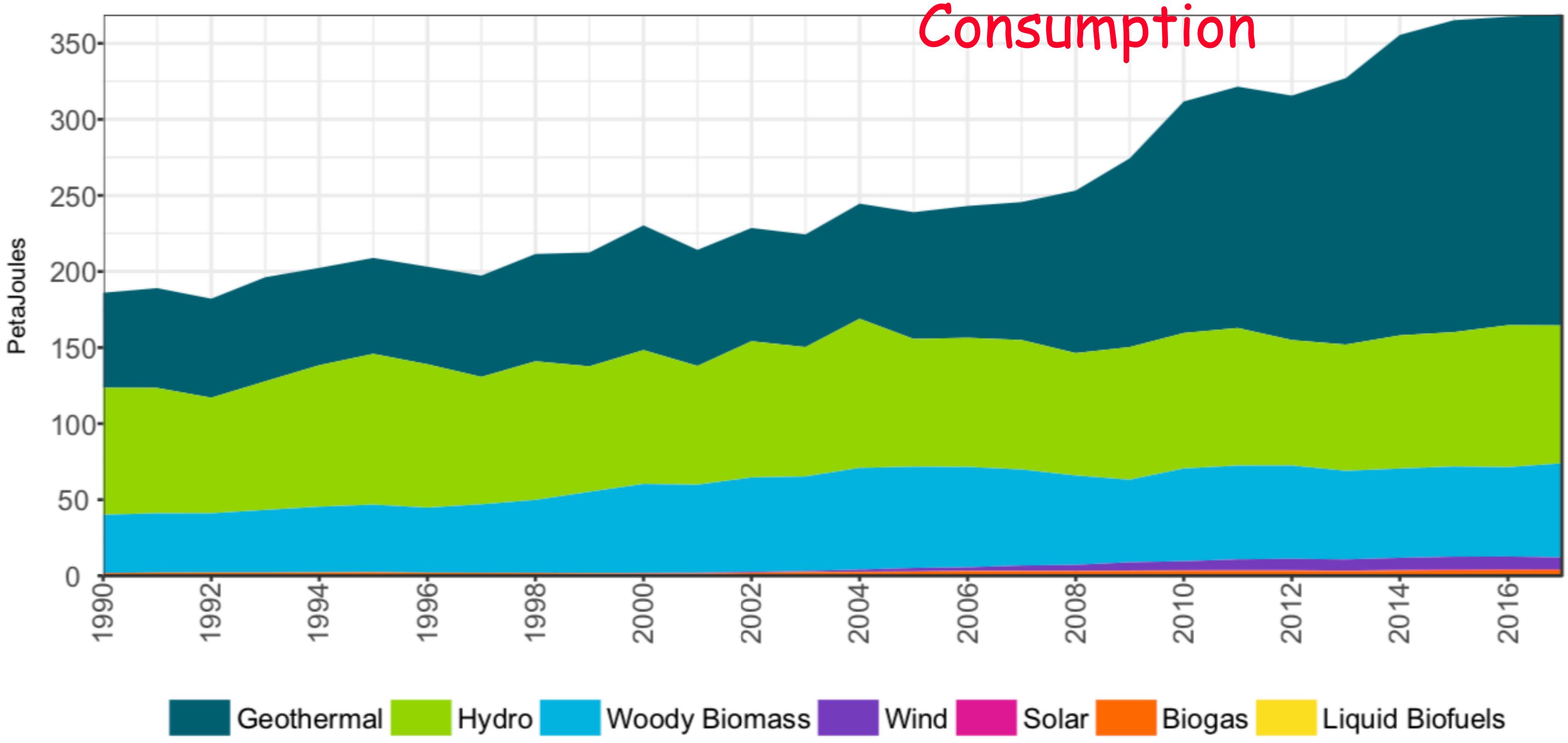
USA 100 EJ/y~3000 GW (3 TW)

derek.elsworth@psu.edu

Renewable Energy in NZ
(1000 PJ total)

Figure 23: Total Renewable Primary Energy Supply

0.35 EJ of 1 EJ total NZ Consumption



Concluding Remarks

Our current predicament is carbon-energy constrained…..

Low-carbon, carbon-neutral and carbon-negative solutions offer a potential path forward that:

- May mitigate climate change issues
- Are an orderly – non-Malthusian solution

For low(er)-carbon fuels (Natural gas)

- Avoids the policy-based "tragedy of the commons"
- Industry driven with an appropriate profit motive

For others (CCS/EGS/Nuclear/Intermittency Solving)

- Significant investment needed (sub-economic)
- Government-sponsored R&D/legislated/subisdy-abating
- Fascinating science-based problems to solve (IS..)

Your choice for which are Good, Bad or Ugly…. but

……….. any selection is ultimately subject to policy choices

…..(hopefully) based on sound scientific input…..

2. THERMAL CHARACTERISTICS

2. THERMAL CHARACTERISTICS

2.1 Sources of Geothermal Heat
2.2 Thermodynamics

2_1 Heat Flow in the Earth

Recap:

Budgets - US 20% of world energy use/capacity - 100 Quads = 100 EJ = 100 TCF CH4
Hydrates: 10^6 EJ
Geothermal - US-Hydrothermal 10^4 EJ; US-EGS 10^7 EJ

Movies:

Plate Tectonics: https://www.nationalgeographic.org/media/plate-tectonics/

Resources: WG2 + AG2

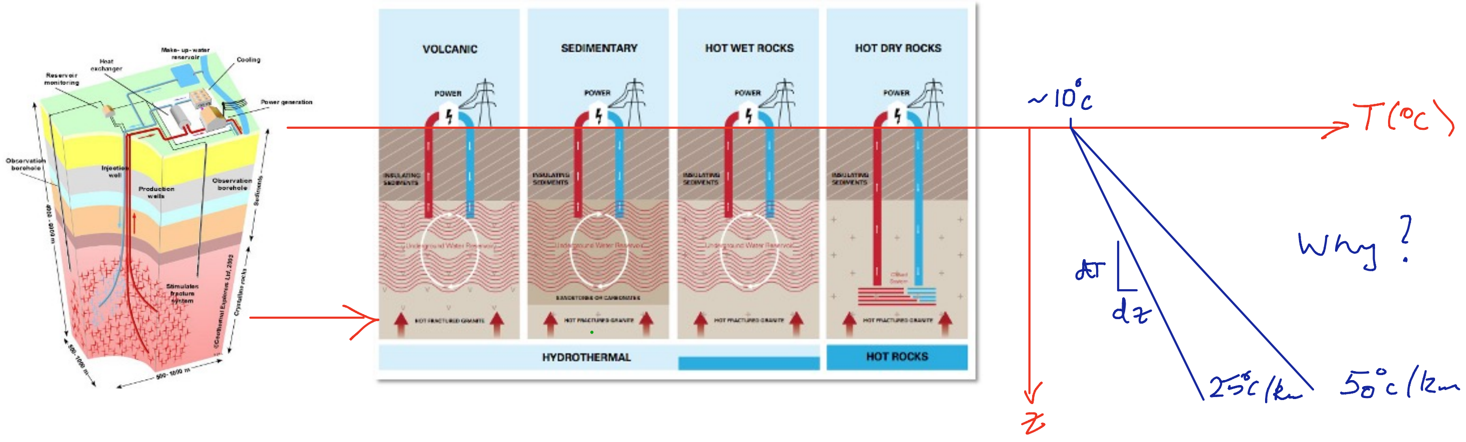
Plate Tectonics: http://www.columbia.edu/itc/ldeo/v1011x-1/jcm/Topic3/Topic3.html

Earth's Internal Heat Budget: https://en.wikipedia.org/wiki/Earth%27s_internal_heat_budget

Geothermal Gradient: https://en.wikipedia.org/wiki/Geothermal_gradient

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Origin of Earth's Geothermal gradient?

Why high and low in different locations?

Is heat flux sufficient to resupply or is heat reserve sufficiently large?

Origin of the Earth's Heat/Geothermal Gradient:

3. For Each Sub-Topic:

a. Detailed Explanation of the Topic [40%] Describe the physical principles in detail and at a pace that is tutorial for an audience.

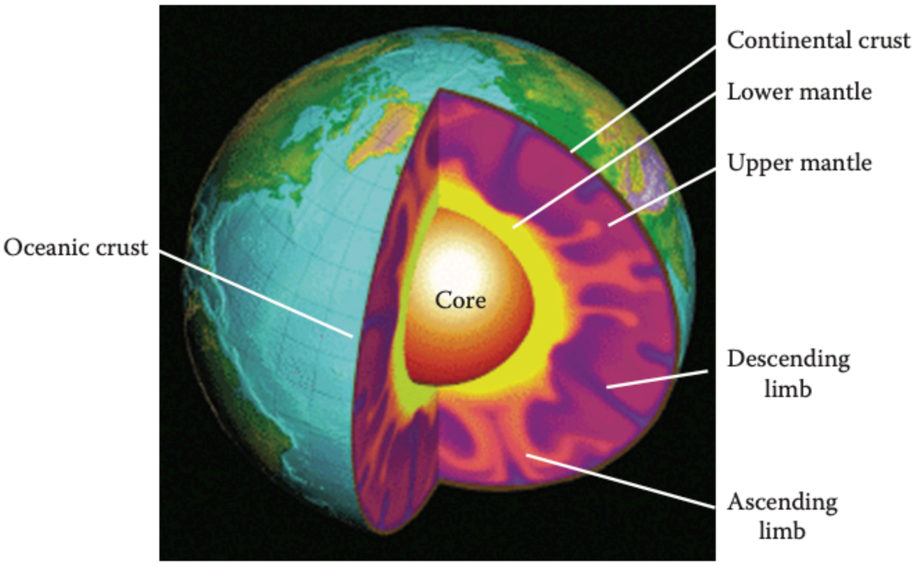
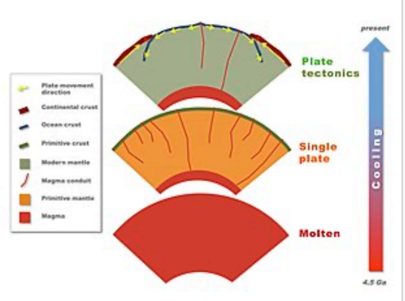


FIGURE 2.1 Interior of the earth, shown in a cutaway that depicts the outer edge of the liquid core (reflecting orange sphere), the lower mantle (yellow), the upper mantle (pink and purple), and the crust. Ascending limbs of convection cells are shown as the orange-tinted plumes extending from the lower mantle through the upper mantle to the base of the crust. Descending limbs of convection cells are shown as the darker purple features extending into the mantle from the base of the crust. (From United States Geological Survey, http://geomag.usgs.gov/about.php.)

Formation of the Earth - ~4,560 Ma - accretion from solar nebula - spherically differentiated

Moon - likely a product of meteoritic impact - tectonically dead.



Earth's tectonic evolution over time from a molten state at 4.5 Ga,[8] to a single-plate lithosphere,[20] to modern plate tectonics sometime between 3.2 Ga[21] and 1.0 Ga[22]

Radius of Earth - ~4,000 miles / ~6,400 km

Core is solid iron (r=1,200km) and molten to (r=3,480 km)
Differentiated by density
T ~5,700K to 4,000K

Lower then upper mantle - liquid but highly viscous

Rigid/solid plates ~70km

Heat supply: 40% from core / 60% from long-lived radioactive isotopes

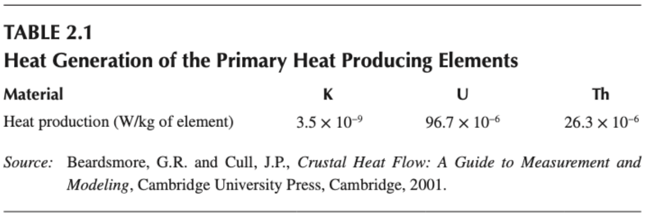


TABLE 2.1
Heat Generation of the Primary Heat Producing Elements

Material	K	U	Th
Heat production (W/kg of element)	3.5×10^{-9}	96.7×10^{-6}	26.3×10^{-6}

Source: Beardsmore, G.R. and Cull, J.P., *Crustal Heat Flow: A Guide to Measurement and Modeling*, Cambridge University Press, Cambridge, 2001.

Plate Tectonics

Plate Tectonics: http://www.columbia.edu/itc/ldeo/v1011x-1/jcm/Topic3/Topic3.html

Continental and Oceanic crust - only interested in continental?
Evolution over time - continental drift
Current plates and their boundaries - constructive and destructive.

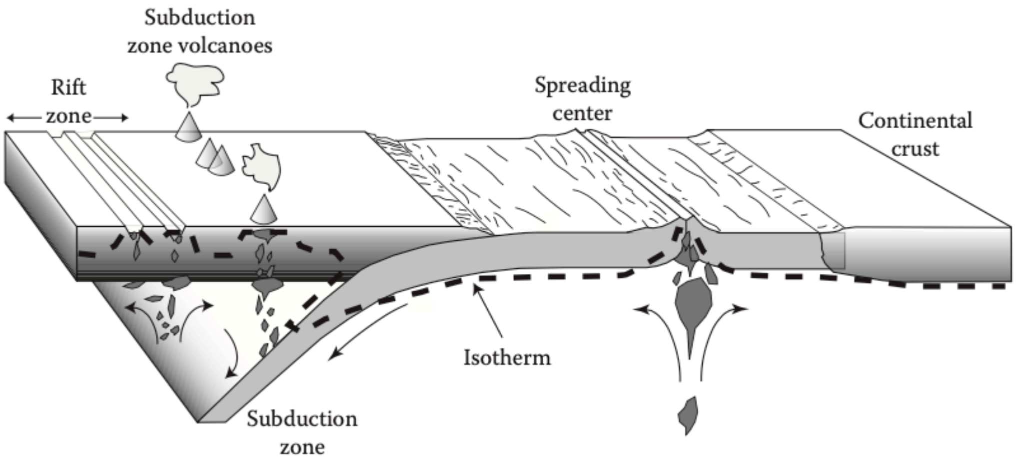


FIGURE 2.5 Schematic diagram showing the configuration of the main elements that compose plate tectonic structures. The arrows indicate local motion of convecting mantle material. The gray, irregular masses represent magma bodies as they ascend from the mantle into the crust. Note that the bulk of magma that occurs in the earth is found at spreading centers, subduction zone volcanoes, or rift zones.

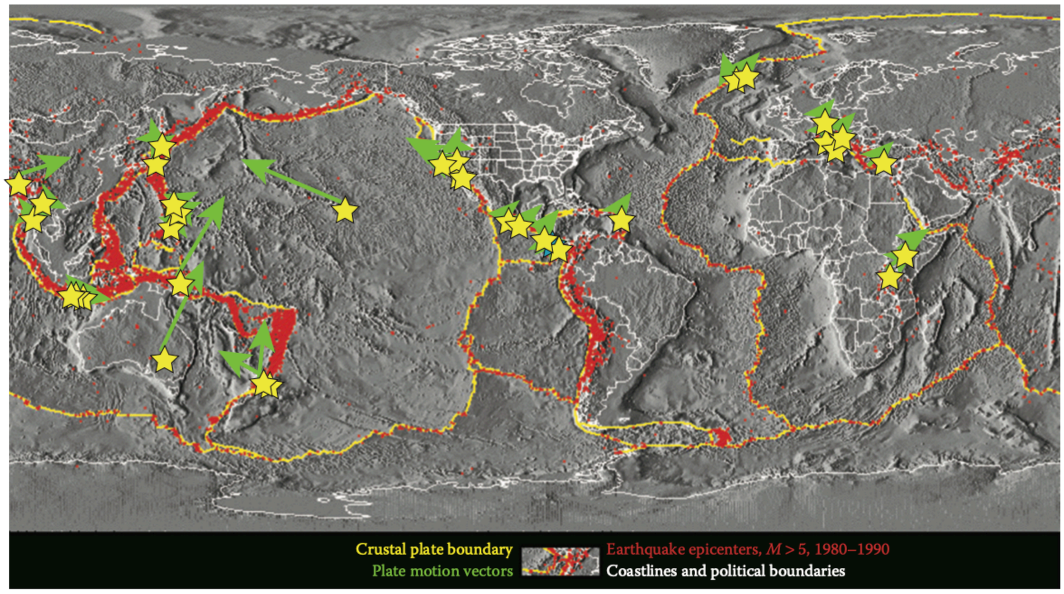


FIGURE 2.6 Global map showing the locations of earthquakes (red dots) that indicate plate boundaries (yellow lines), political boundaries (in white), and the locations of the world's geothermal power plants (stars). The directions of some plate motions are shown by the green arrows, with the length of the arrow corresponding to relative velocity of plate motion. Note the strong correlation between power plant sites and plate boundaries. There are many more power plants than stars because many sites have several power plants. The global map, earthquake data, and boundaries are from the National Oceanic and Atmospheric Administration Plates and Topography Disc and the power plant sites from the International Geothermal Association website (http://iga.igg.cnr.it/geo/geoenergy.php).

Internal Heat Budget

Earth's Internal Heat Budget: https://en.wikipedia.org/wiki/Earth%27s_internal_heat_budget

Contributions from:

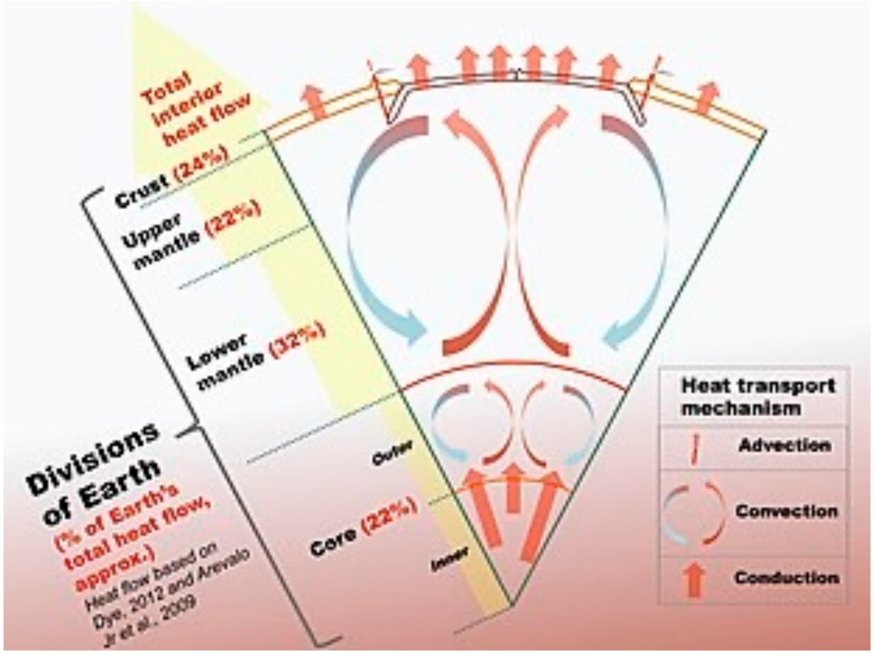
Radioactive decay ~60%	~15-14 TW
Proimordial heat (core) ~40%	~12-30 TW

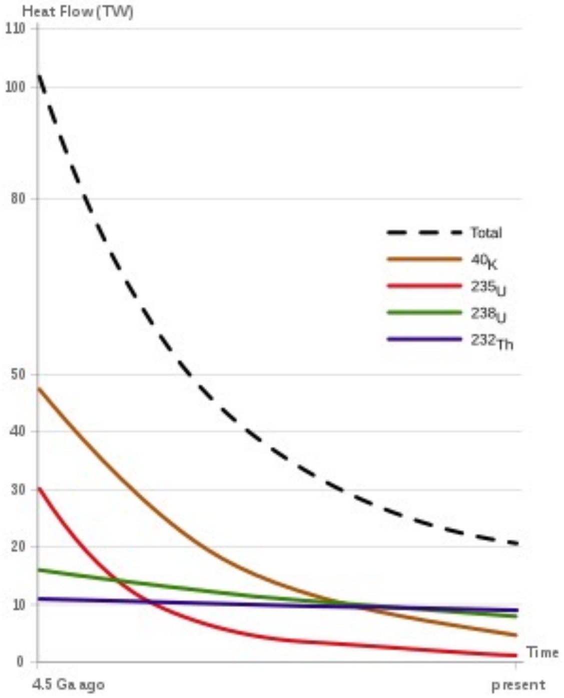
Total flow: ~47 TW (note fossil budget ~10-15 TW) 47 TW ~ 92 mW/m^2

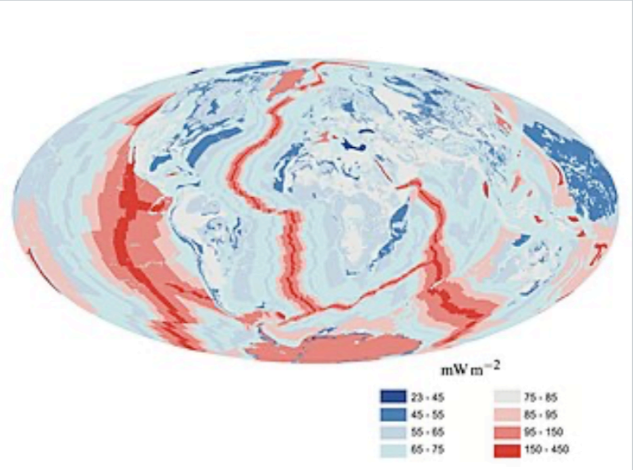
Overall heat flow:

Contribution from radioactive decay

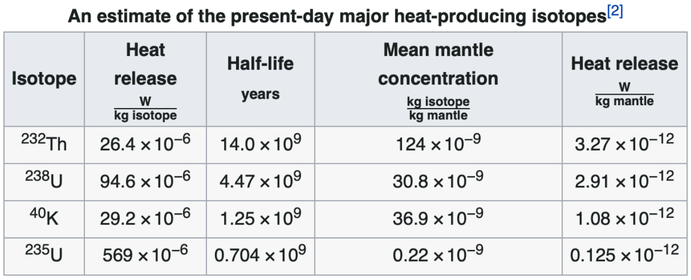
Result of heat flow - on surface







Global map of the flux of heat, in mW/m^2, from Earth's interior to the surface.[1] The largest values of heat flux coincide with mid ocean ridges, and the smallest values of heat flux occur in stable continental interiors.



An estimate of the present-day major heat-producing isotopes[2]

Isotope	Heat release $\frac{W}{\text{kg isotope}}$	Half-life years	Mean mantle concentration $\frac{\text{kg isotope}}{\text{kg mantle}}$	Heat release $\frac{W}{\text{kg mantle}}$
^{232}Th	26.4×10^{-6}	14.0×10^{9}	124×10^{-9}	3.27×10^{-12}
^{238}U	94.6×10^{-6}	4.47×10^{9}	30.8×10^{-9}	2.91×10^{-12}
^{40}K	29.2×10^{-6}	1.25×10^{9}	36.9×10^{-9}	1.08×10^{-12}
^{235}U	569×10^{-6}	0.704×10^{9}	0.22×10^{-9}	0.125×10^{-12}

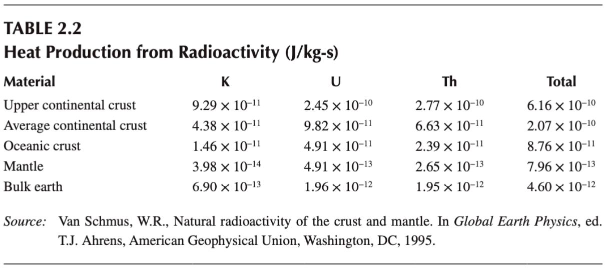


TABLE 2.2

Heat Production from Radioactivity (J/kg-s)

Material	K	U	Th	Total
Upper continental crust	9.29×10^{-11}	2.45×10^{-10}	2.77×10^{-10}	6.16×10^{-10}
Average continental crust	4.38×10^{-11}	9.82×10^{-11}	6.63×10^{-11}	2.07×10^{-10}
Oceanic crust	1.46×10^{-11}	4.91×10^{-11}	2.39×10^{-11}	8.76×10^{-11}
Mantle	3.98×10^{-14}	4.91×10^{-13}	2.65×10^{-13}	7.96×10^{-13}
Bulk earth	6.90×10^{-13}	1.96×10^{-12}	1.95×10^{-12}	4.60×10^{-12}

Source: Van Schmus, W.R., Natural radioactivity of the crust and mantle. In *Global Earth Physics*, ed. T.J. Ahrens, American Geophysical Union, Washington, DC, 1995.

Glassley – Heat flow map

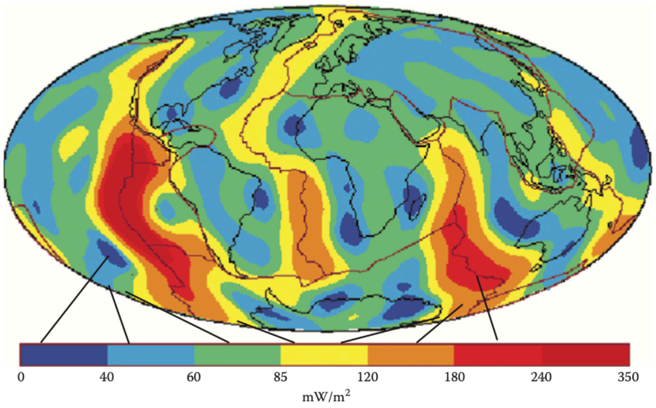
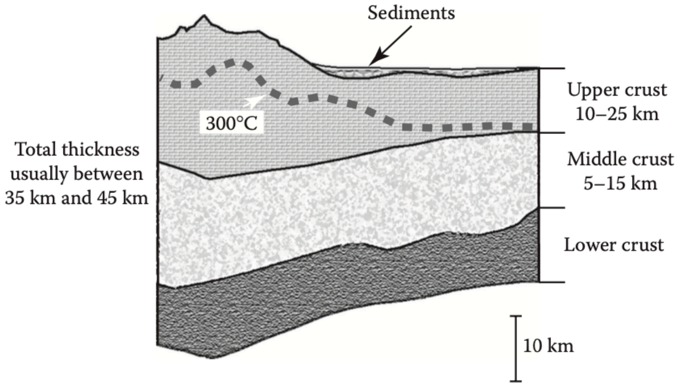


FIGURE 2.7 Low resolution global map showing the distribution of heat flow at the surface. Compare this figure with that in Figure 2.6 to see the relationship between plate boundaries, geothermal power plants, and heat flow. (From International Heat Flow Commission, http://www.geophysik.rwth-aachen.de/IHFC/heatflow.html.)

Glassley – Crustal heat flow



Blackwell – SMU – heat flow map

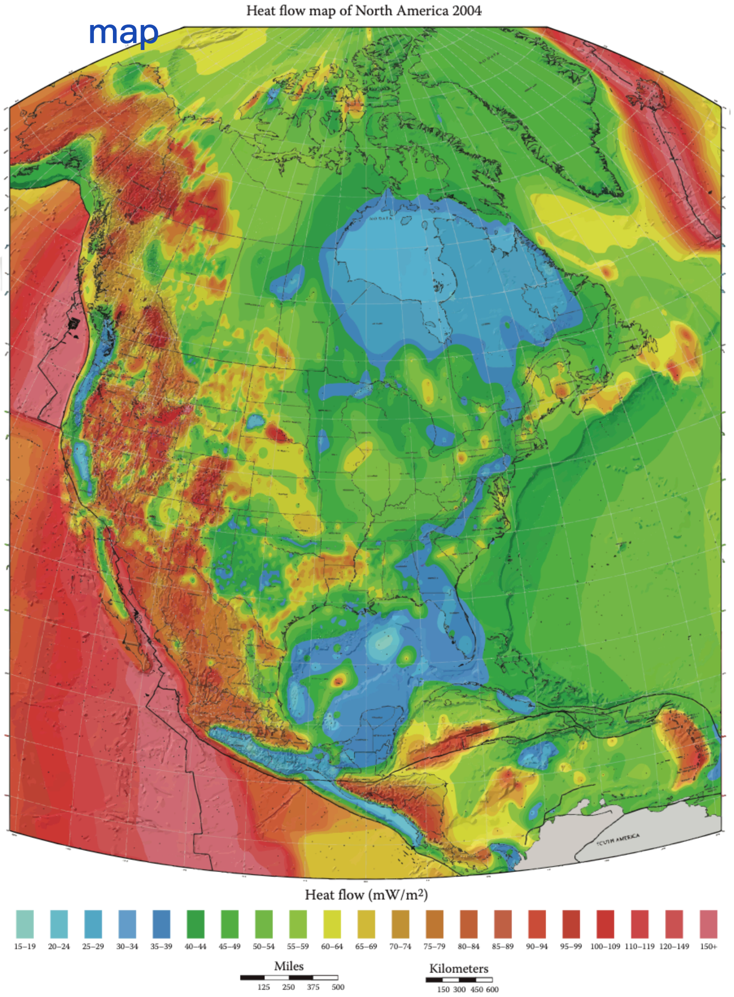
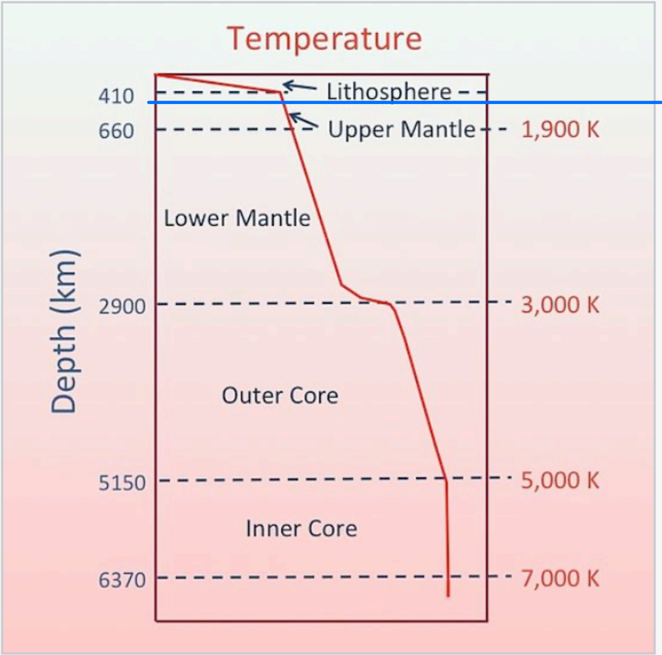


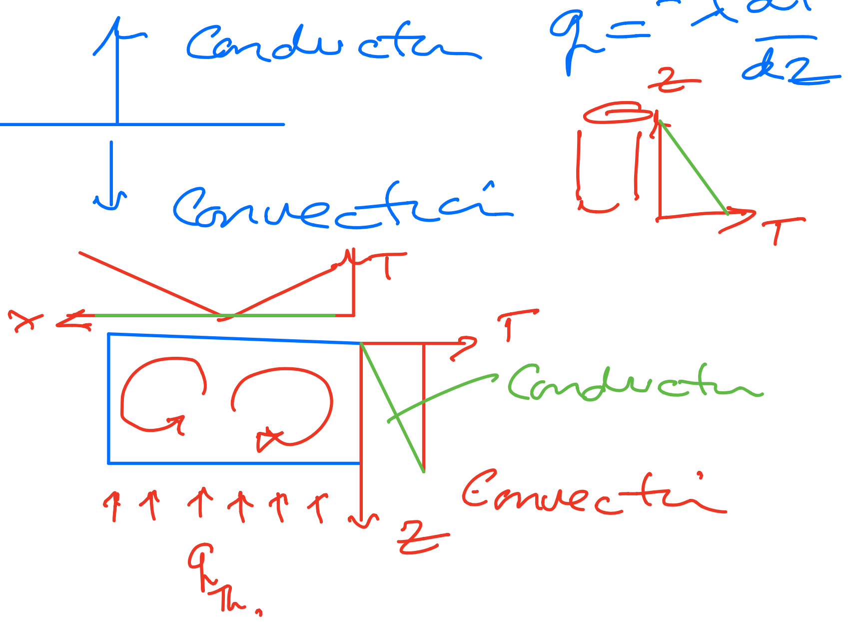
FIGURE 2.9 Heat flow map of North America 2004. (From Geothermal Laboratory, Southern Methodist University. http://smu.edu/geothermal/2004NAMap/Geothermal_MapNA_7x10in.gif.)

Heat Flow - Influence on Geothermal Gradient

Geothermal Gradient: https://en.wikipedia.org/wiki/Geothermal_gradient



Temperature profile of inner Earth, schematic view (estimated).



$$q = -\lambda \frac{dT}{dz}$$

Conduction

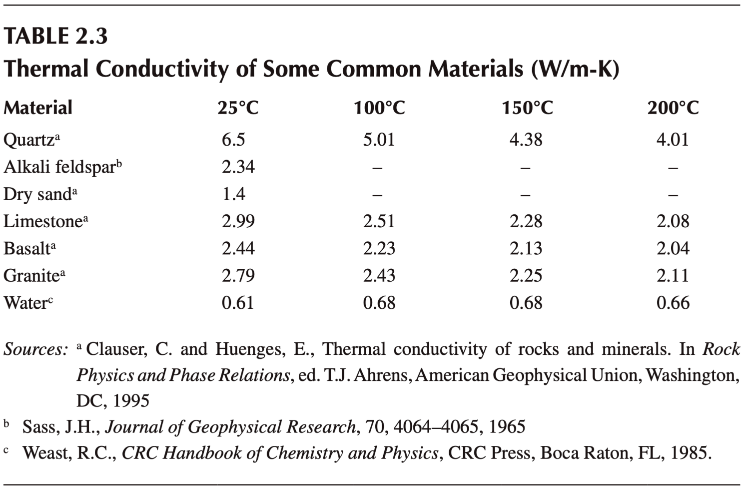


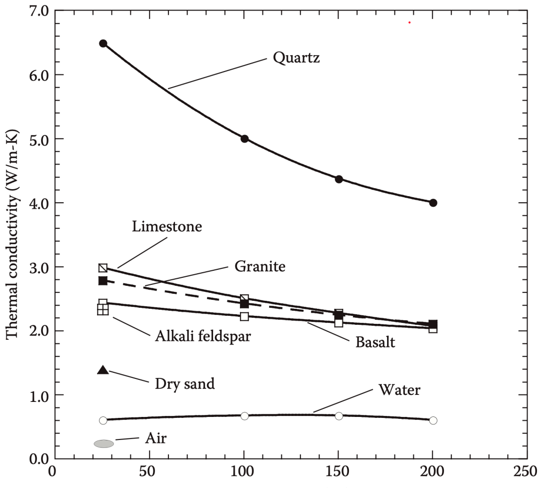
TABLE 2.3
Thermal Conductivity of Some Common Materials (W/m-K)

Material	25°C	100°C	150°C	200°C
Quartz[a]	6.5	5.01	4.38	4.01
Alkali feldspar[b]	2.34	–	–	–
Dry sand[a]	1.4	–	–	–
Limestone[a]	2.99	2.51	2.28	2.08
Basalt[a]	2.44	2.23	2.13	2.04
Granite[a]	2.79	2.43	2.25	2.11
Water[c]	0.61	0.68	0.68	0.66

Sources: [a] Clauser, C. and Huenges, E., Thermal conductivity of rocks and minerals. In *Rock Physics and Phase Relations*, ed. T.J. Ahrens, American Geophysical Union, Washington, DC, 1995

[b] Sass, J.H., *Journal of Geophysical Research*, 70, 4064–4065, 1965

[c] Weast, R.C., *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, FL, 1985.

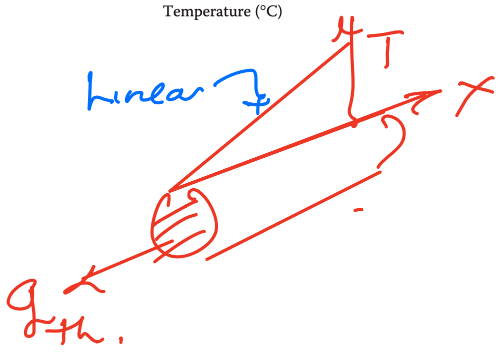


Fourier's Law

$$q = -\lambda \frac{dT}{dx}$$

$\lambda \doteq W/(m.K)$

$\therefore q \doteq \frac{W}{m.\cancel{K}} \frac{\cancel{K}}{m} \doteq \frac{W}{m^2}$



Transient Conduction

Conservation of Energy: $\frac{d}{dx} q_x + \rho c \frac{dT}{dt} = 0$

$$\boxed{\lambda \frac{d^2 T}{dx^2} = \rho c \frac{dT}{dt}}$$

Diffusion Equation.

Coefficients

Thermal conductivity (λ) Water ~ 0.5 W/m.K

Rock ~ 1-5 W/m.K

Density (ρ) Water ~ 1000 kg/m³

Rock/Magma – 2700 kg/m³

Specific Heat Capacity (C)

C_p ≐ @ constant pressure

C_v ≐ @ constant volume

$$\rho C_p = \rho C_v + \alpha^2 \left(\frac{VT}{\beta} \right)$$

where:

α is the coefficient of thermal expansion
β is the coefficient of compressibility
V is the molar volume
T is the absolute temperature (K)

To first order for rock: $K = \frac{k}{c\rho} \sim 30\ m^2/yr.$

(Thermal diffusivity).

Rock (granite) $C_p = C_v \sim$ 918 J/kg.K

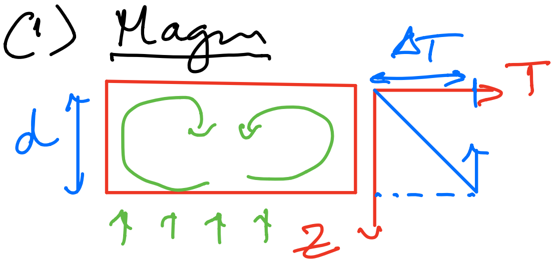
Water 4187 J/kg.K.

Convection

Free-Convection: http://www.columbia.edu/itc/ldeo/v1011x-1/jcm/Topic3/Topic3.html

Note: Two types - (i) Free-convection in the mantle
(ii) Free-convection of water in a porous medium

(i) Magma



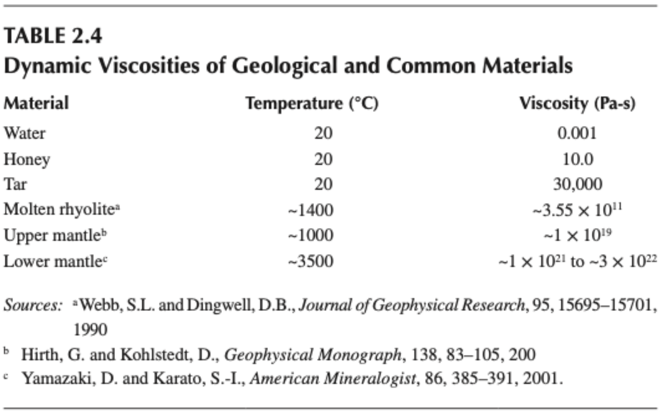


TABLE 2.4
Dynamic Viscosities of Geological and Common Materials

Material	Temperature (°C)	Viscosity (Pa-s)
Water	20	0.001
Honey	20	10.0
Tar	20	30,000
Molten rhyolite[a]	~1400	~3.55×10^{11}
Upper mantle[b]	~1000	~1×10^{19}
Lower mantle[c]	~3500	~1×10^{21} to ~3×10^{22}

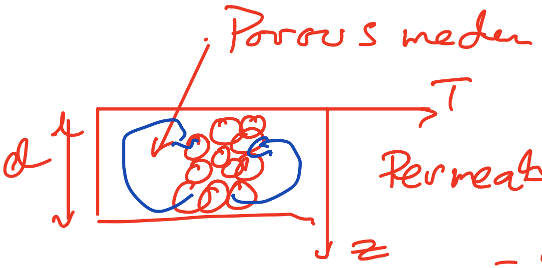
Sources: [a] Webb, S.L. and Dingwell, D.B., *Journal of Geophysical Research*, 95, 15695–15701, 1990
[b] Hirth, G. and Kohlstedt, D., *Geophysical Monograph*, 138, 83–105, 200
[c] Yamazaki, D. and Karato, S.-I., *American Mineralogist*, 86, 385–391, 2001.

$$Ra = \frac{\text{Buoyant F}}{\text{Viscous F}} = \frac{\alpha \Delta T g \rho d^3}{\mu K}$$

$Ra > 1000 \longrightarrow$ Free convection

α = Thermal expansion coeff

(ii) Porous medium



Permeability, k

$$v = \frac{k}{\mu}\frac{dp}{dx}$$

Rayleigh-Darcy No, Ra

Replace: $\frac{g\rho \boxed{d^2}}{\mu} \longrightarrow \frac{g\rho \boxed{k}}{\mu}$

$$Ra = \frac{\alpha \Delta T g \rho \boxed{d\,k}}{\mu K} \doteq \frac{\left(1/\cancel{K}\right)\cancel{K}\cdot \cancel{m}/s^2\; kg/\cancel{m^3}\; \cancel{m^3}}{Pa\cdot s\cdot m^2/\cancel{s}}$$

Plate Tectonics - Distribution of Geothermal Resources

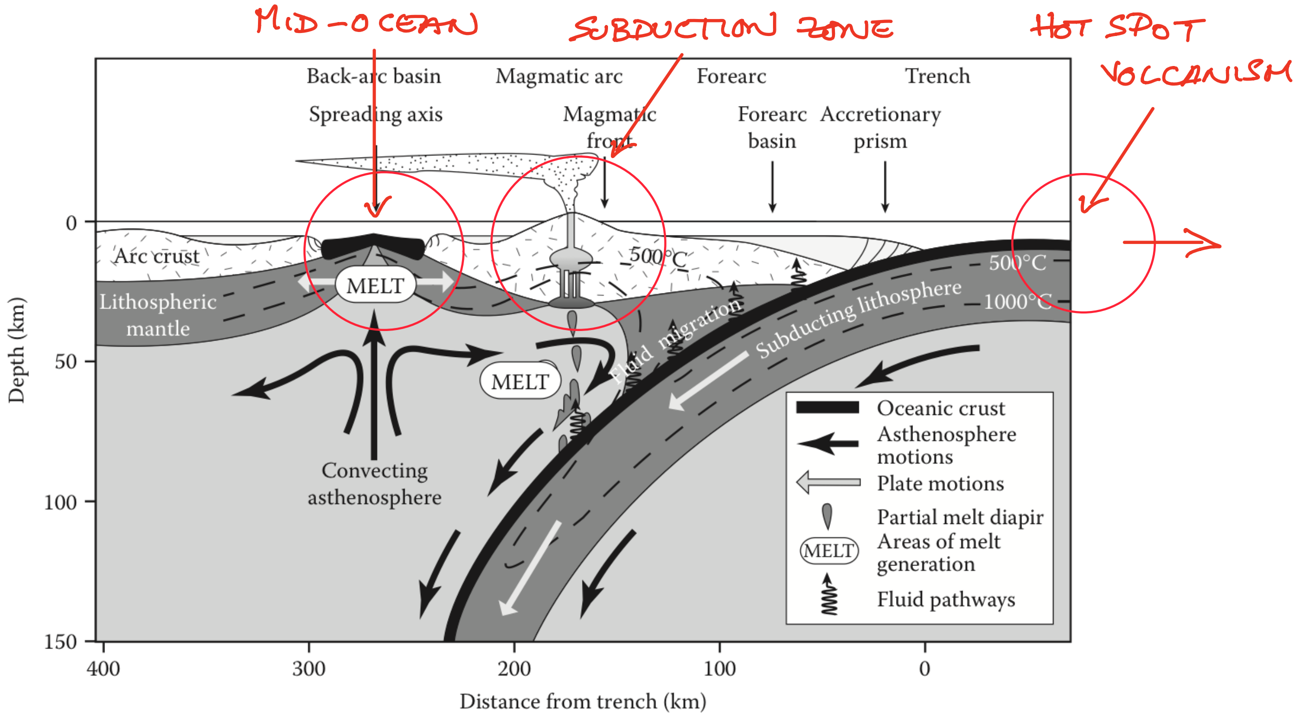


FIGURE 2.8 Schematic cross section through a subduction zone similar to that in Japan. (Modified from DuHamel, J., 2009. Wry heat—Arizona history Chapter 5: Jurassic time. http://tucsoncitizen.com/wryheat/tag/subduction/.)

Three Principal Environments

Destructive boundaries - subduction zones - e.g. The Geysers, CA
Constructive boundaries - mid-ocean ridges - e.g. Iceland
Hot spots - volcanoes - e.g. Hawaii

See prior photos by location

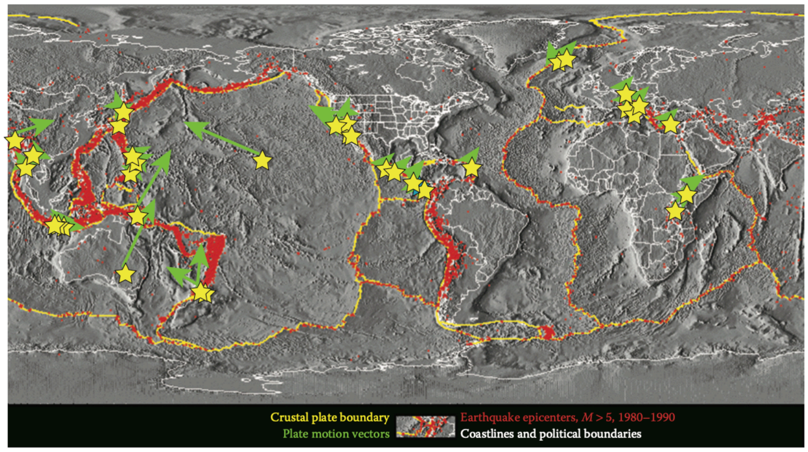


FIGURE 2.6 Global map showing the locations of earthquakes (red dots) that indicate plate boundaries (yellow lines), political boundaries (in white), and the locations of the world's geothermal power plants (stars). The directions of some plate motions are shown by the green arrows, with the length of the arrow corresponding to relative velocity of plate motion. Note the strong correlation between power plant sites and plate boundaries. There are many more power plants than stars because many sites have several power plants. The global map, earthquake data, and boundaries are from the National Oceanic and Atmospheric Administration Plates and Topography Disc and the power plant sites from the International Geothermal Association website (http://iga.igg.cnr.it/geo/geoenergy.php).

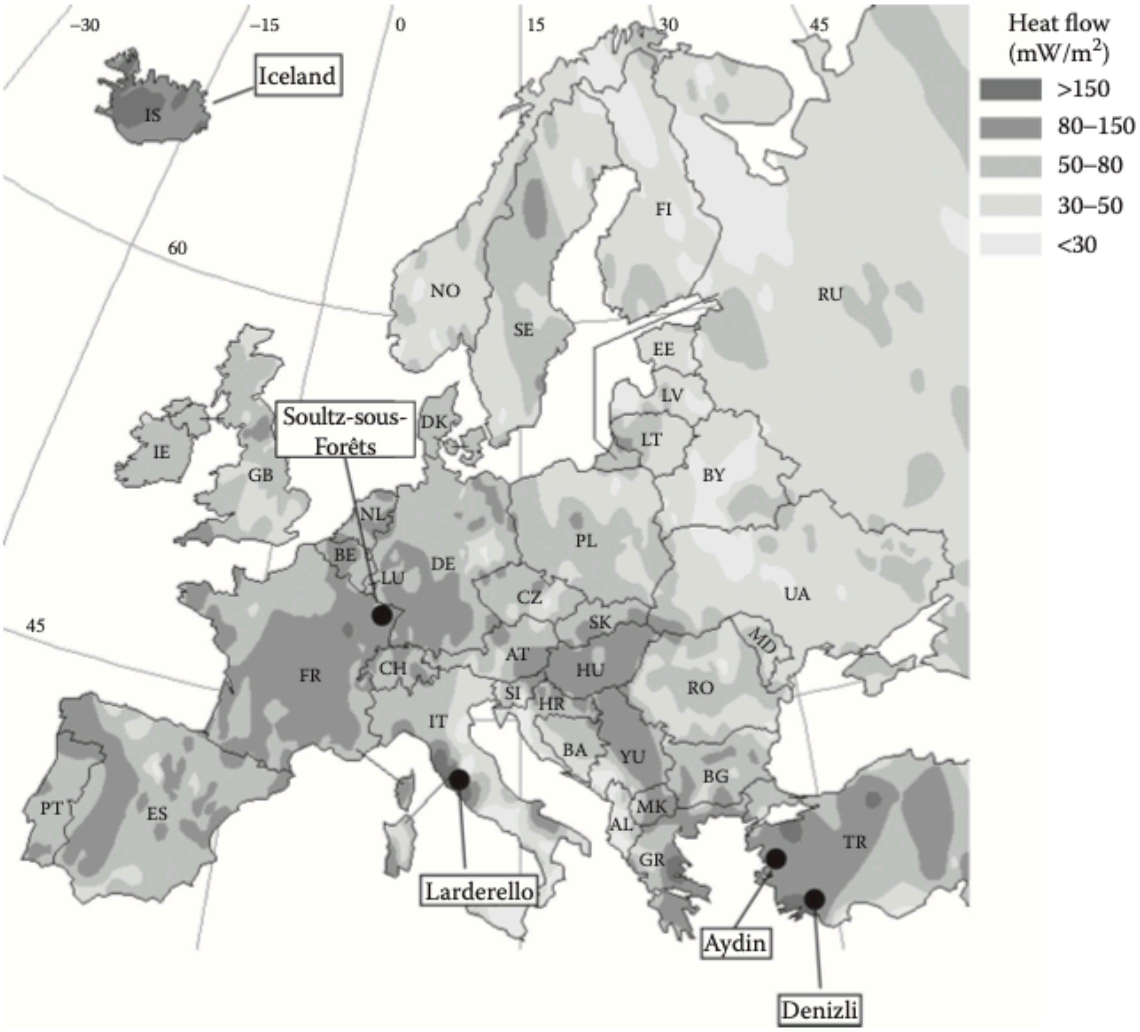
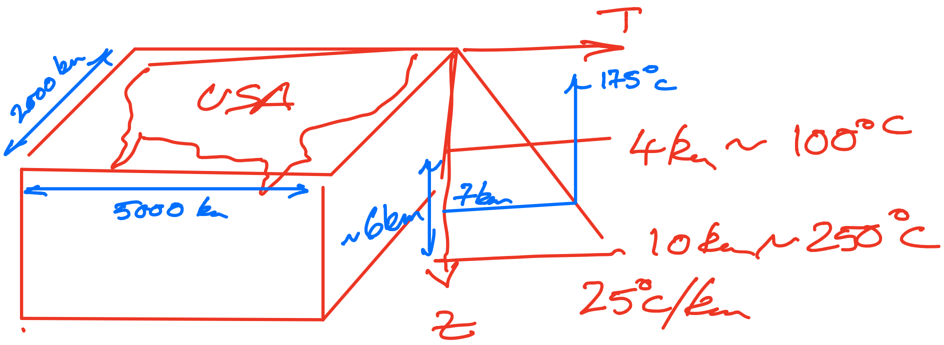


FIGURE 2.10 Heat flow map of Europe. (Modified from the European Community Nr. 17811.)

Simple Calculation

b. Example Hand-Calculation [10%] Simple calculation to demonstrate the technique.

Geothermal - US-Hydrothermal 10^4 EJ; US-EGS 10^7 EJ?? What is the origin?



$$\text{Energy} = \underset{\underset{\sim 10{,}000\ km^2}{A}\times(10\,km-4\,km)}{V}\ \overset{2500\ kg/m^3}{\rho}\ \underset{1000\ J/kg.K}{c}\ \overset{(175°C-100°C)\ \sim 100K}{\Delta T}$$

$$E = \underbrace{(10^4 \times 6)\,km^3 \cdot 2500}_{1.5\times 10^4}\,\cancel{kg}/m^3 \cdot 1000\,J/\cancel{kg.K} \cdot 100\,\cancel{K} \times \frac{1\,m^3}{10^{-9}\,km^3}$$

$$= 10^4 \cdot (1.5\times 10^4) \cdot 10^3 \cdot 10^2 \cdot 10^9 \sim 1.5\times 10^{22}\,J$$

$$\sim 1.5\times 10^4\,EJ$$

OTHER ESTIMATES? 10^7 EJ?

Compares with MIT/Tester Report (2006)

The Future of Geothermal Energy

Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century

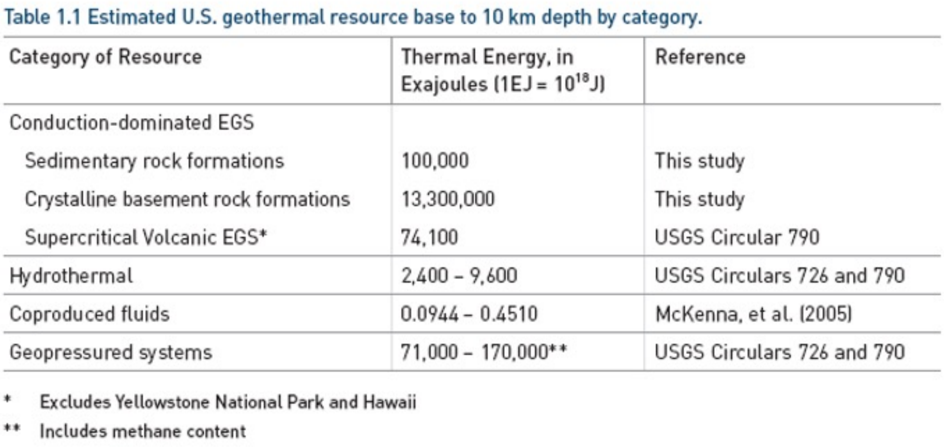


Table 1.1 Estimated U.S. geothermal resource base to 10 km depth by category.

Category of Resource	Thermal Energy, in Exajoules (1EJ = 10^{18}J)	Reference
Conduction-dominated EGS		
Sedimentary rock formations	100,000	This study
Crystalline basement rock formations	13,300,000	This study
Supercritical Volcanic EGS*	74,100	USGS Circular 790
Hydrothermal	2,400 – 9,600	USGS Circulars 726 and 790
Coproduced fluids	0.0944 – 0.4510	McKenna, et al. (2005)
Geopressured systems	71,000 – 170,000**	USGS Circulars 726 and 790

* Excludes Yellowstone National Park and Hawaii

** Includes methane content

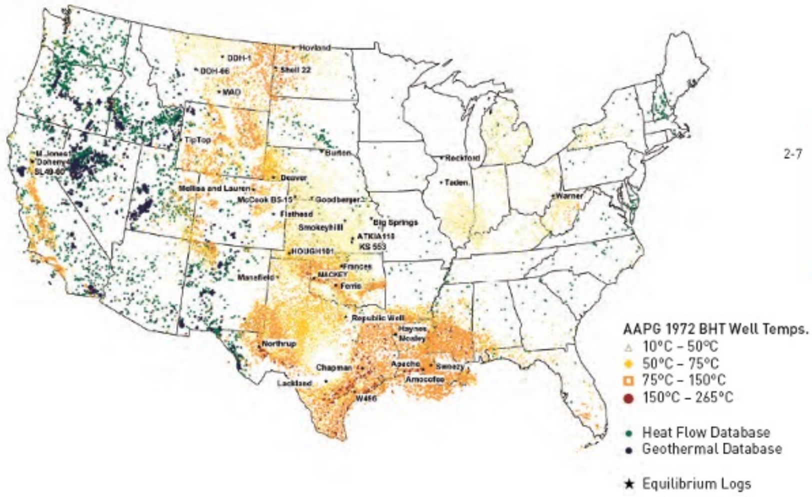


Figure 2.2 All BHT sites in the conterminous United States in the AAPG database. BHT symbols are based on depth and temperature (heat flow is not available for all of the sites, so some were not used for preparation of the Geothermal Map of North America). The named wells are the calibration points. The regional heat flow and geothermal database sites are also shown.

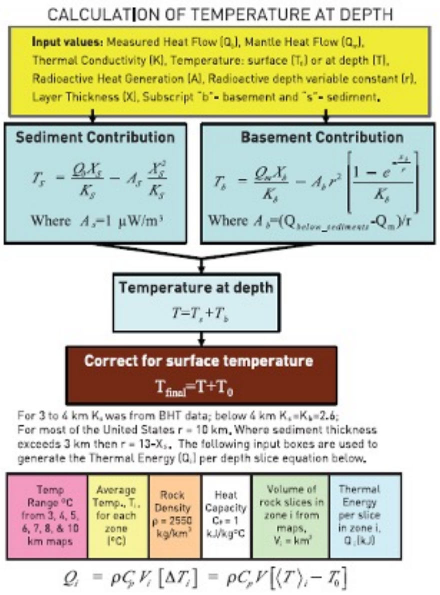


Figure 2.3 Flow chart for calculation of temperature and heat content at depth. Note: 1 kW-sec = 1 kJ and angle brackets denote depth-averaging.

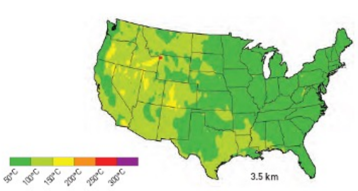


Figure 1.3 Temperatures at a depth of 3.5 km.

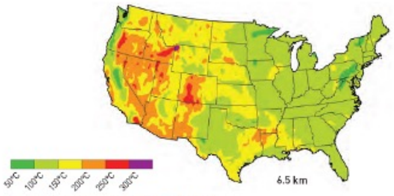


Figure 1.4 Temperatures at a depth of 6.5 km.

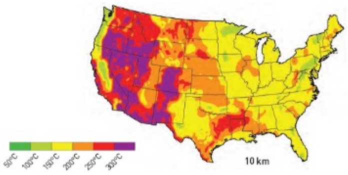
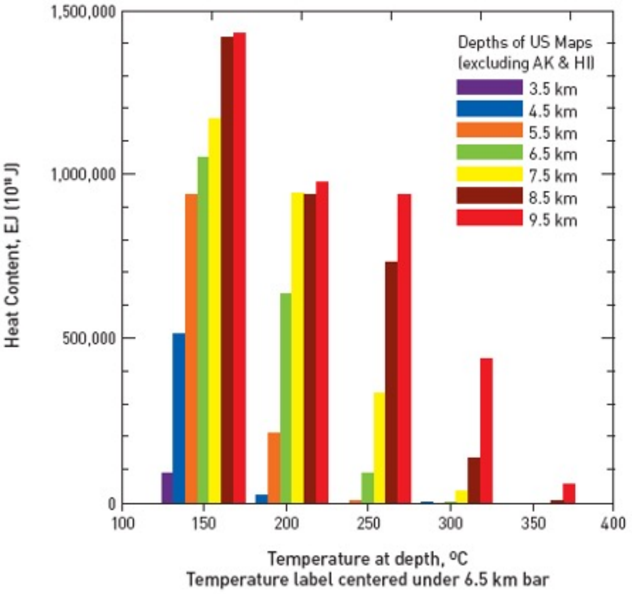


Figure 1.5 Temperatures at a depth of 10 km.



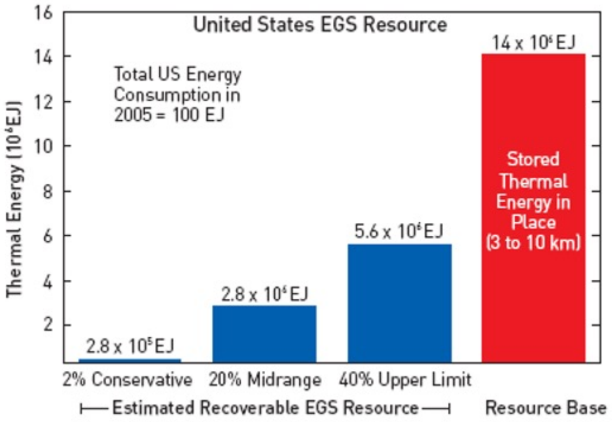


Table 1.2 Estimated land area and subsurface reservoir volumes needed for EGS development. Note: Above 100 MW$_e$, reservoir size scaling should be linear.

Plant size in MW$_e$	Surface area for power plant and auxiliaries in km^2	Subsurface reservoir volume in km^3
25	1	1.5
50	1.4	2.7
75	1.8	3.9
100	2.1	5.0

1. Assuming 10% heat to electric-power efficiency, typical of binary plants.

2. Introduces a factor of 4 to surface area and volumes to deal with redrilling of reservoir at 5-year intervals over a 20-year projected lifetime.

RATES OF RECOVERY ?

How quickly can heat be recovered?

Case Study - N/A

c. Case Study [10%] If appropriate.

Conclusion

4. Conclusion [20%] Summarize important/key points from the presentation.

Geothermal Resources - result of heating by close (40%) and radiogenic heat (60%)
Earth budget controlled by:
  Convection at depth in molten mantle - Free convection - Rayleigh No.
  Conduction across crust - Fourier's law
High gradients at plate boundaries and hot-spot volcanic centers

2. THERMAL CHARACTERISTICS

2.1 Sources of Geothermal Heat

2.2 Thermodynamics

3_1 Thermodynamics and Geothermal Systems

Recap:

Heat supplied to the crust (~70km deep) by convection - but conduction dominates in the crust Hydrothermal regimes concentrated in - destructive, constructive and hot-spot areas

EGS low-grade power ubiquitous

Recovery of thermal energy - requires a heat-transfer mechanism
Generating power requires an energy conversion mechanism - flash to steam

Movies:

Allam Cycle: https://www.youtube.com/watch?v=vFcbev1TkoU Resources: WG3

Thermodynamics: https://en.wikipedia.org/wiki/Laws_of_thermodynamics

General understanding of heat flow and thermodynamics, follows:

2. THERMAL ENERGY

2.1 HEAT & TEMPERATURE

specific heat

a) Absent phase change: $\Delta Q = c \, \Delta T$

ΔQ = Heat ; ΔT = Temperature

SI units: °C or K

Unit of thermal energy = 1 calorie ~ 4.2 J

(1 calorie ≡ 1 gram H_2O ↑ 1°C)

b) With phase change: $\Delta Q = L$

Latent heat

Heat is absorbed but no ΔT.

Latent heat of Fusion (ice → water)

Latent heat of Evaporation (water → gas)

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COEFFICIENTS FOR WATER

c (specific heat) = $4.186\ \text{J/g}\,^\circ\text{C} = 4.2\ \text{kJ/kg}\,^\circ\text{C}$

L_{fusion} (latent heat) = $334\ \text{kJ/kg}$

L_{evap} (latent heat) = $2260\ \text{kJ/kg}$

How much heat needed to melt ice versus heating water?

$$\left.\begin{aligned} \Delta Q &= c\,\Delta T \\ \Delta Q &= L \end{aligned}\right\} \quad L = c\,\Delta T \longrightarrow \Delta T = L/c \sim 80\,^\circ\text{C}$$

How much heat needed to evaporate water versus melt ice?

$$\frac{\Delta Q_{\text{evap}}}{\Delta Q_{\text{melt}}} = \frac{L_{\text{evap}}}{L_{\text{fusion}}} = \frac{2260}{334} \sim 7$$

2.2 HEAT TRANSFER

Three modes: Conduction; Convection; Radiation.

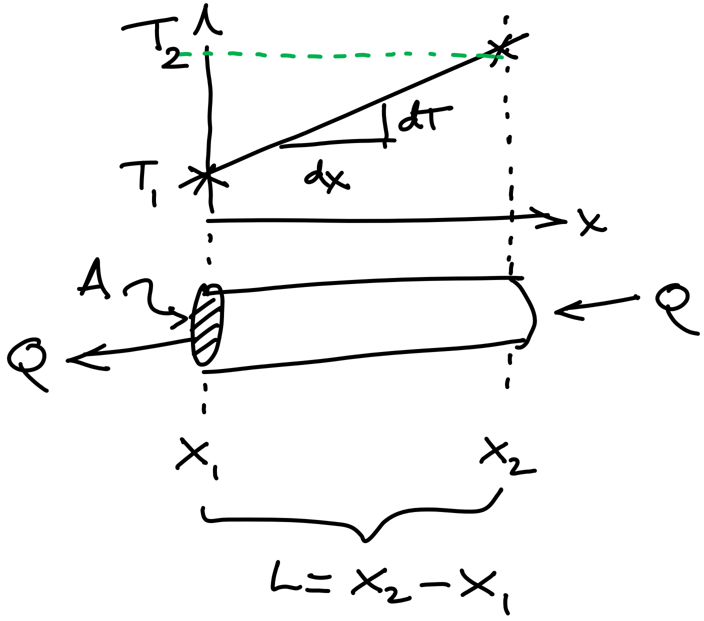
CONDUCTION:

$$Q = Ak\frac{(T_1 - T_2)}{L} \doteq -Ak\frac{\partial T}{\partial x}$$

k = thermal conductivity (Fourier's Law)

Requires that flow is at a 'steady state'.

Flux is a vectoral quantity, hence $Q = -k\frac{\partial T}{\partial x}$



Typical k Magnitudes ($W\,m^{-1}\,K^{-1}$)

Steel: ~30 – 50

Water: 0.6

Rock: ~1 – 3

Styrofoam: ~0.03

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List of thermal conductivities - Wikipedia, the free encyclopedia

CONDUCTION (Cont'd)

Non-steady behavior (transient)

$$\frac{\partial}{\partial t}(\rho c T) + \frac{\partial}{\partial x} q_{Thermal} = 0$$

$$q_{thermal} = -k \frac{\partial T}{\partial x}$$

$$\rho c \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = 0$$

Dimensional Analysis:

$$\rho c \frac{T}{t} \frac{1}{T_0} \doteq k \frac{T}{x^2} \frac{1}{T_0} \Rightarrow 1 \sim \frac{k}{\rho c} \frac{t}{x^2}$$

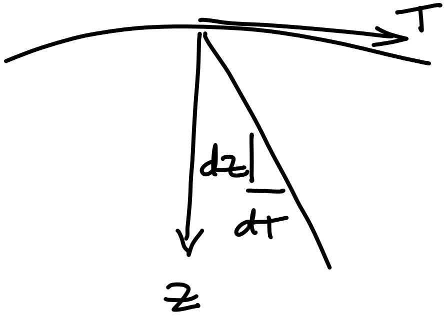
$$\sim \kappa \frac{t}{x^2}$$

Thermal diffusivity (m^2/s)

KELVIN'S PROBLEM / RUTHERFORD'S SOLUTION

How much heat is generated within the earth from radioactive decay?

Assume this is the only heat source:



$$Q = -A\,k\,\frac{\partial T}{\partial z} \quad \left\{ \begin{array}{l} A = 4\pi r^2 \\ k = 1\ \mathrm{W\,m^{-1}\,K^{-1}} \\ \frac{\partial T}{\partial z} \sim 30^\circ/\mathrm{km} \end{array} \right.$$

$$q = -k\,\frac{\partial T}{\partial z} \cong \underbrace{30\ \mathrm{mW/m^2}\ \left(\mathrm{Solar} \equiv 1.4\ \mathrm{kW\,m^{-2}}\right)}_{\times 10^6}$$

How long does it take for one quantum of heat to traverse the crust ~ 60 km thick. (A change at the surface)

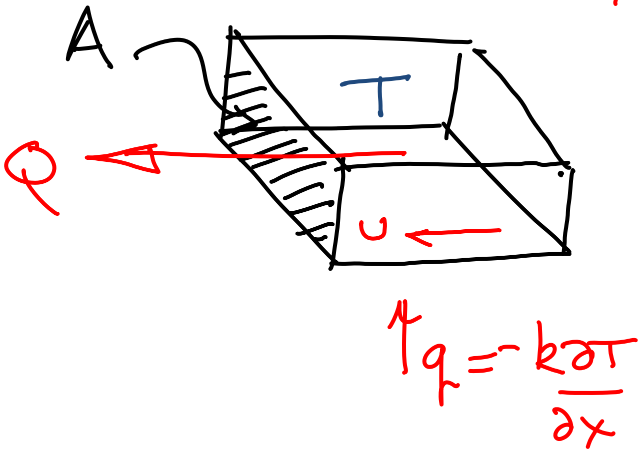
$$\frac{\kappa t}{x^2} \sim 1 \Rightarrow t \sim \frac{x^2}{\kappa} \sim \frac{(60\times10^3)^2\ \mathrm{m}^2}{30\ \mathrm{m^2/y}} \sim 120\times10^6\ \mathrm{y}$$

CONVECTION

Heat carried by bulk motion of fluid.

$$Q = A(\rho u)(cT)$$

Flow velocity

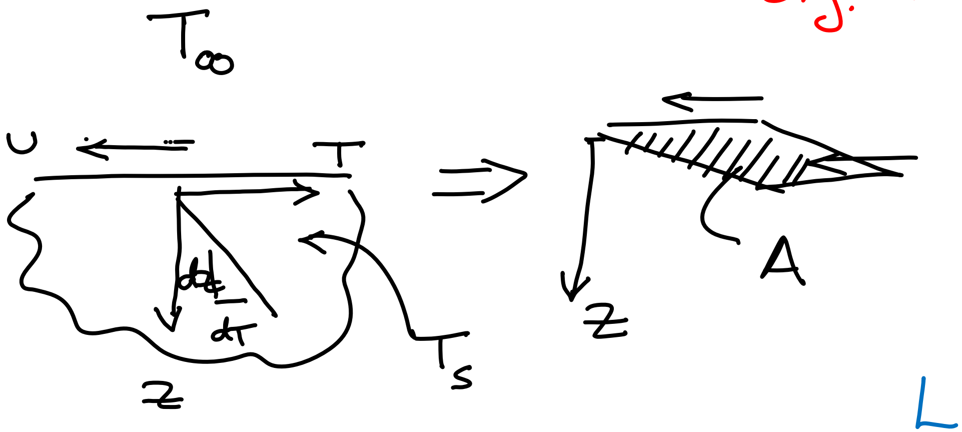


Forced convection:

1. Driven by flow
2. More rapid than conduction since provides fresh cool fluid to elevate thermal gradients → $q = -k\partial T/\partial x$.

CONVECTION (Cont'd)

Convection is an efficient method of heat transfer – from static body to a flowing fluid e.g. Wind chill.



$$\frac{Q}{A} = N_u \, k \frac{(T_s - T_\infty)}{L}$$

L = characteristic length
e.g. radius of bar or fin

$$N_u = f(P_r, R_e) \begin{cases} P_r = \dfrac{c\mu}{k} \\ R_e = \dfrac{\rho u L}{\mu} \end{cases}$$

RADIATION

Transport by EM waves and also works in a vacuum (space).

– Lucky for us.

Power (P_e) per unit area per unit time is:

$$P_e = \varepsilon \sigma T^4$$

ε = emissivity $(0 < \varepsilon < 1)$

$\sigma = 5.67 \times 10^{-8}\ W.m^{-2} K^{-4}$

(Stefan – Boltzmann coeff)

Emissivity: $P_e = \varepsilon \sigma T^4$

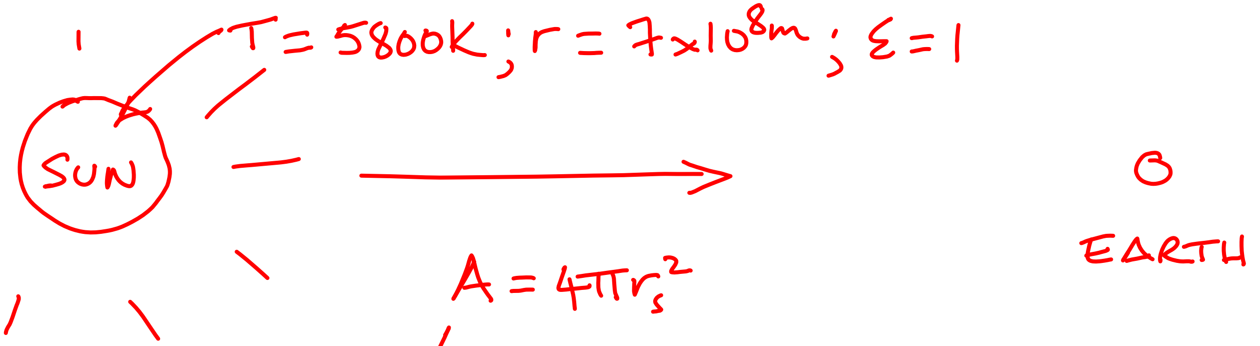
Absorptivity: $P_a = \varepsilon \sigma T_0^4$

$$\text{Net } P = P_e - P_a = \varepsilon \sigma (T^4 - T_0^4)$$

RADIATION (Cont'd)

A 'black body' absorbs all radiation

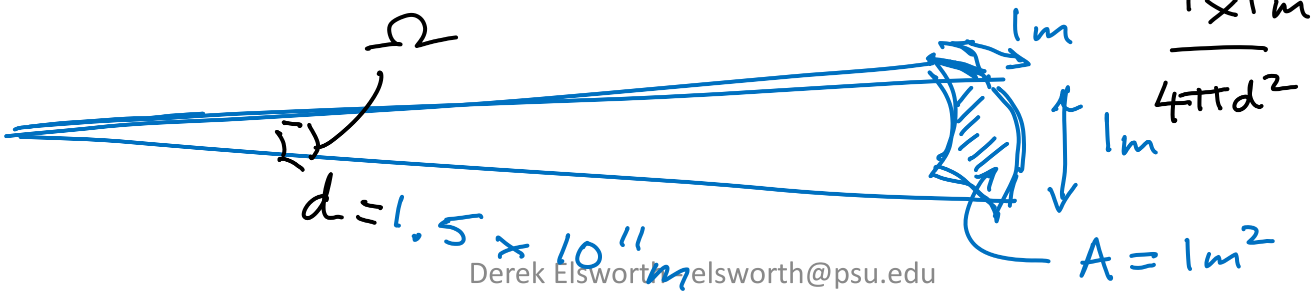
Heat output of the sun.



$T = 5800K$; $r = 7\times10^{8}m$; $\varepsilon = 1$

$A = 4\pi r_s^2$

$P_s = \sigma \varepsilon T^4 A = \underline{\underline{4\times10^{26}W}}$ (total from sun)



$d = 1.5\times10^{11}m$

$\frac{1\times1m}{4\pi d^2} = \Omega$

= Fraction of Sun's surface area.

Thermal energy from sun on 1 m^2 of Earth.

$$P_e = P_s \times \text{Fraction of sun}$$

$$= P_s \, \Omega$$

$$= 4 \times 10^{26}\,\text{W} \times 3.5 \times 10^{-24}$$

$$\sim 1.4\ \text{kW/m}^2$$

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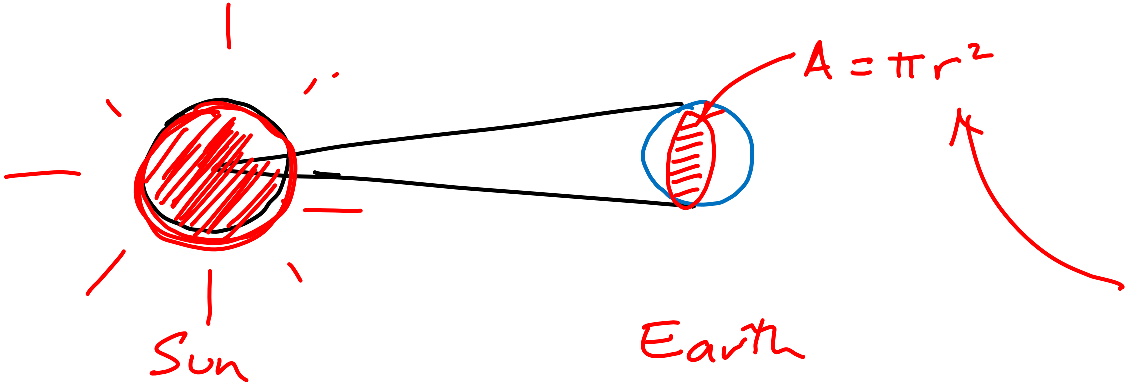
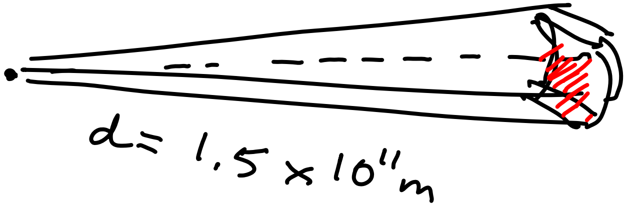
How much radiative energy does the Earth receive?



$r = 6380$ km

Note: that @ large distance subtended angle is v. small. (Ω)



Fraction of radiation is

$$\Omega = \frac{1}{4\pi d^2}$$

$$P_e = P_s \, \Omega \, A_e$$

$$= 4 \times 10^{6} \text{ W} \times 3.5 \times 10^{-24} \times A_e$$

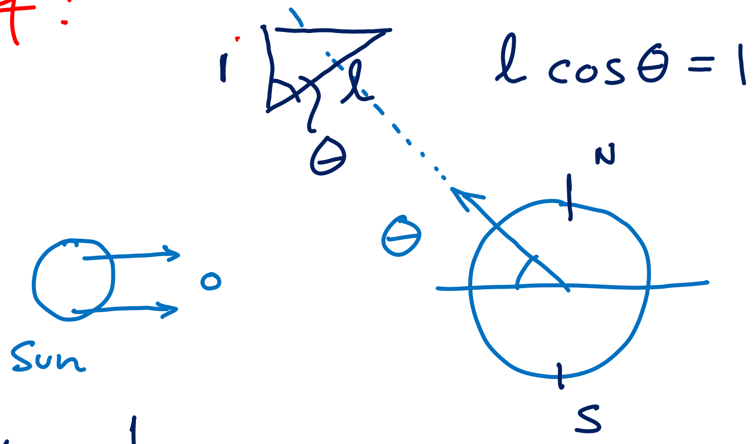
$$\boxed{P_e = 180 \times 10^{6} \text{ GW}}$$

Worldwide fossil fuel combustion = 10 TW

How does the incoming solar radiation change as a function of:

a) Latitude:

Radius of sun = 7×10^8 m
Radius of earth = 6.4×10^6 m

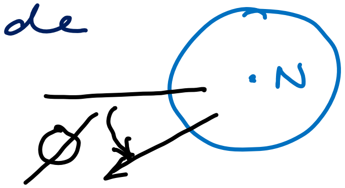


Incident radiation varies as $\frac{1}{l} = \cos\theta$

Note: θ relative to equatorial plane (not equator)

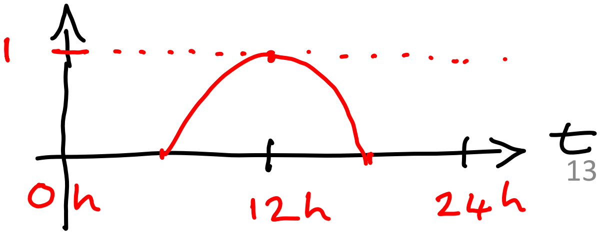
b) Longitude: (Represents time of day.)

Similar argument where ø is longitude relative to noon hour:

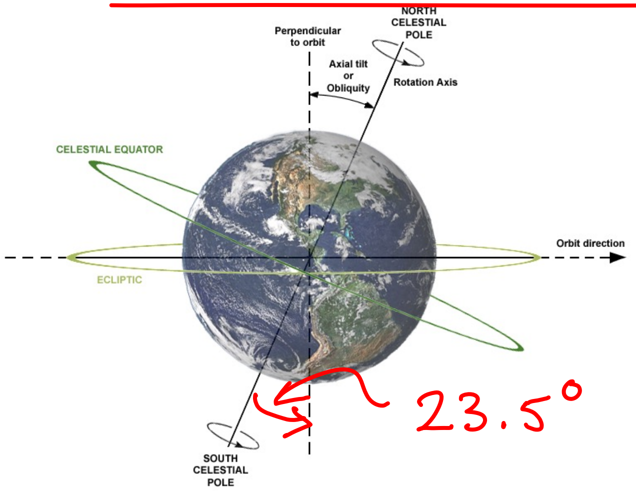


$$P_e = P_{s\,max}\,\Omega\,\cos\phi$$

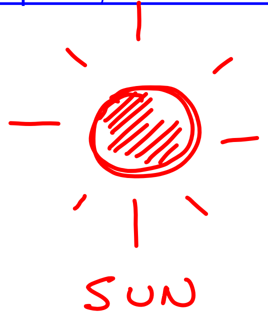
$$= P_{s\,max}\,\Omega\,\frac{(noon - t)}{24}\times 2\pi$$

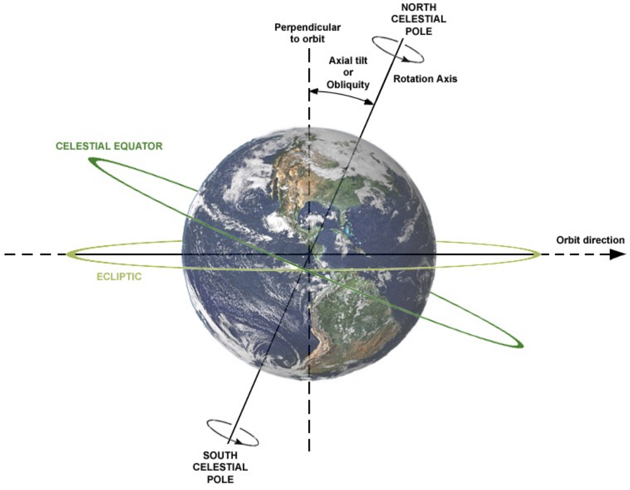


VARIATION OF RADIATION WITH LOCATION & SEASON



Axial tilt - Wikipedia, the free encyclopedia





JUNE 21
(SOLSTICE)

MAR 21
SEPT 21
(EQUINOX)

DECEMBER 21
(SOLSTICE)

UNIVERSITY PARK = 41°N

$P_{e_{max}} \simeq 1.4\ kWm^{-1} \cos\theta$

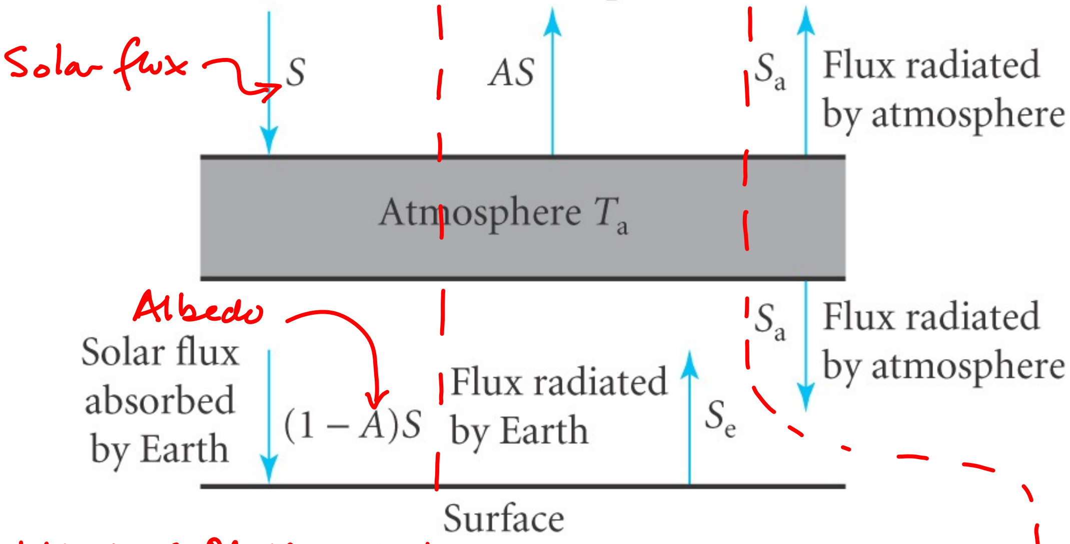
$\theta_{summer} = 41° - 24° = 17°\ N$ $\sim 1.33\ kWm^{-1}$

$\theta_{winter} = 41° + 24° = 65°\ N$ $\sim 0.6\ kWm^{-1}$

But average radiation (annual) is for $\theta = 41°$ and 12h/day

[$P_{e_{av}} \sim 1.06\ kWm^{-1}$] (i.e. 50%)

GREENHOUSE EFFECT



TO EARTH	ATMOSPHERE
INCOMING RADIATION	INCOMING RADIATION
$(1-A)S\pi R^2$	$(1-A)S\pi R^2$
EARTH AS BLACK BODY	BLACK BODY (ATMOS.)
$4\pi R^2\sigma T^4$	$4\pi R^2\sigma T_a^4$
EQUATE	EQUATE
$T = 255$ K (−18C)	$T_a \sim 255$K

ATMOSPHERE AS BLACK BODY

SUN ATMOSPHERE

$$(1-A)S\pi R^2 + 4\pi R^2\sigma T_a$$

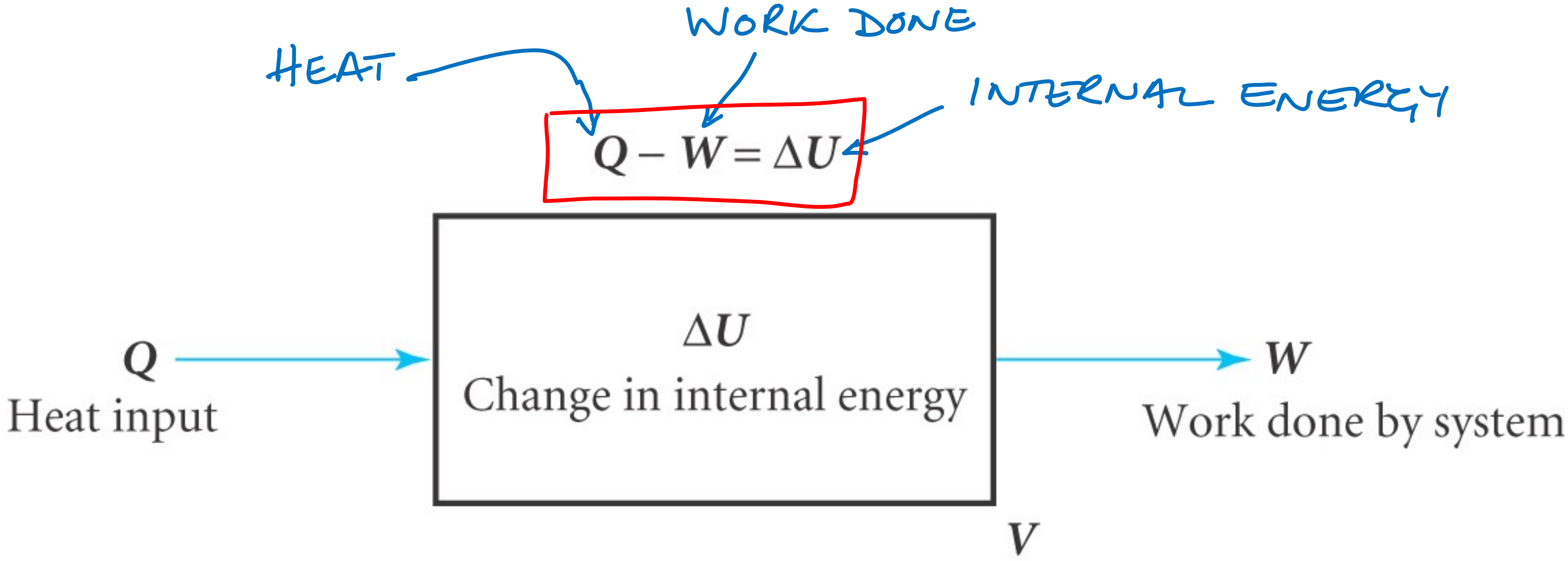
$$4\pi R^2\sigma \boxed{T_E}$$

(EARTH)

Solve

$T_E \sim 303$K (30°c)

2.3 FIRST LAW OF THERMODYNAMICS



$$\boxed{Q - W = \Delta U}$$

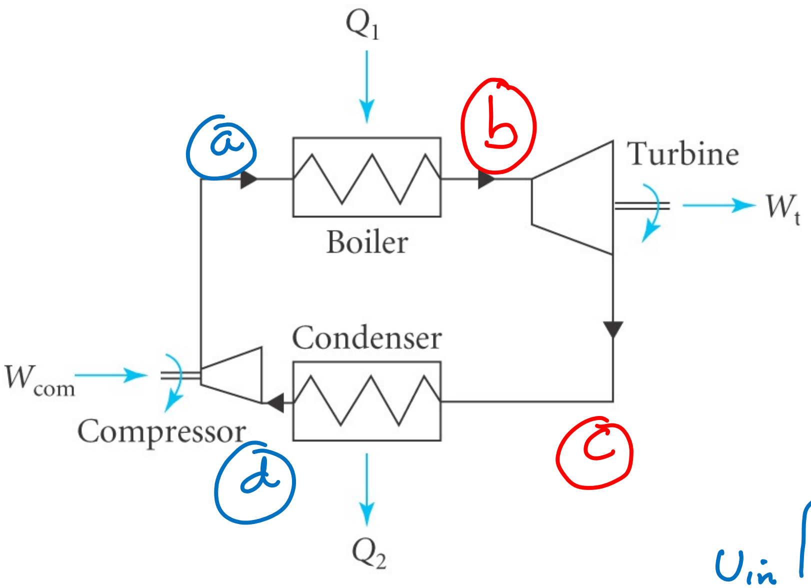
STATEMENT THAT:

ENERGY IS NEITHER CREATED OR DESTROYED

BUT MAY BE REDISTRIBUTED

CONVENTION (POSITIVE): $\begin{cases} Q - \text{heat flows into system \&} \\ W - \text{work done by system.} \end{cases}$

2.4 CLOSED CYCLE FOR A STEAM PLANT



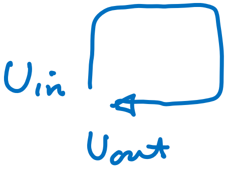
Typical circuit for power conversion.

Work input @ compressor (W_{com})

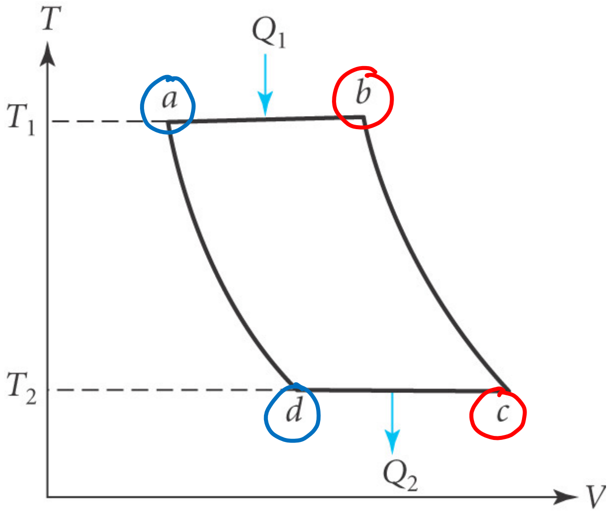
Heat input @ boiler (Q_1)

Work output @ turbine (W_t)

Heat output @ condenser (Q_2)



$\Delta U = 0$ since working fluid begins circuit with the same int. energy it ends



FIRST LAW: $(Q_1 - Q_2) - (W_t - W_{com}) = 0$

EFFICIENCY, $\eta = \frac{\text{net work output}}{\text{heat input}}$

$$\eta = \frac{(W_t - W_{com})}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \doteq 1 - \frac{T_2}{T_1}$$

2.5 USEFUL THERMODYNAMIC QUANTITIES

T = temperature

P = pressure

$v = \frac{1}{\rho}$ = specific volume

u = specific internal energy

h = specific enthalpy

s = specific entropy

six key quantities but they are interdependent — any two define system state

"specific" = per unit mass

ENTHALPY: $h = u + pv$

DESCRIBES:

1. Heat transfer at constant pressure: (e.g. boilers and condensers)
2. Adiabatic (no heat change) compression of gases: (e.g. compressors & turbines)

zero since $pv \equiv$ constant

via $\Delta h = \Delta u + \cancel{\Delta pv}$

$Q - \cancel{W}^{0} = \Delta u \quad \therefore \quad Q = \Delta h$

$\cancel{Q}^{0} - W = \Delta u \quad \therefore \quad W = -\Delta h$

ENTROPY (degree of disorder)

Change in entropy $$\Delta S = \frac{\text{Reversible heat supplied}}{\text{System temperature}} = \frac{\Delta Q_{rev}}{T}$$

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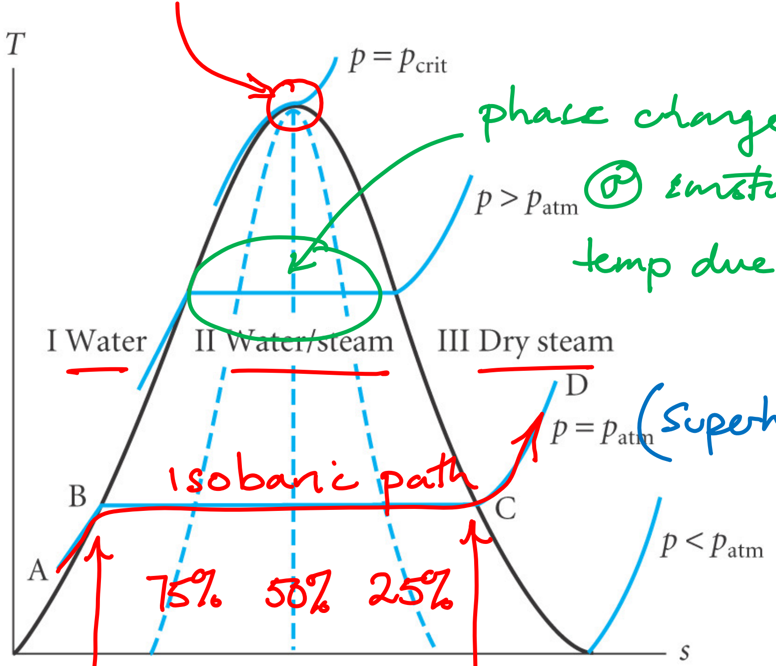
2.6 THERMAL PROPERTIES OF WATER & STEAM

Water and other fluids are heat and energy transfer media in many conversion processes.



critical point

phase change @ constant temp due to latent heat

(superheated region)

isobaric path

75% 50% 25%

100% water

100% steam

Desire to define fluid properties (T, p, v, u, h, s) throughout all regions I, II, and III.

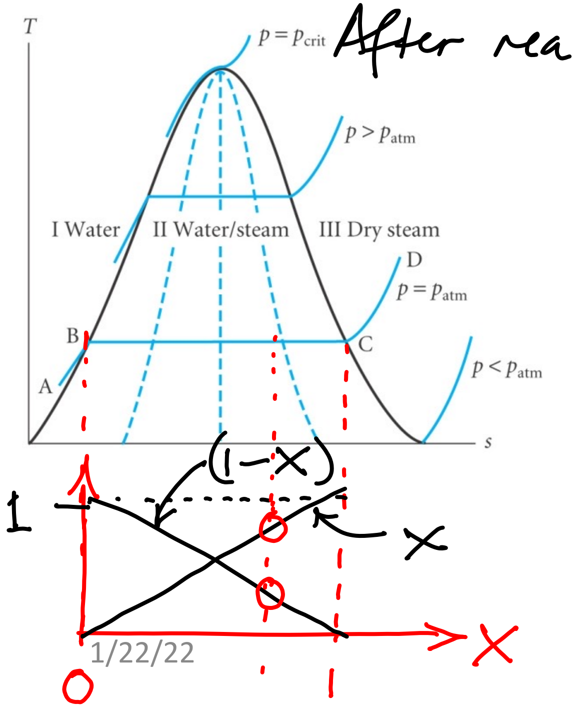
In this figure: v, u, h = f(T, s, p)

SCALING STEAM PROPERTIES IN THE TWO-PHASE REGION II

TOTAL MASS: $m = m_f + m_g$

TOTAL VOLUME: $\forall = \forall_f + \forall_g = \frac{m_f}{\rho_f} + \frac{m_g}{\rho_g} = m_f v_f + m_g v_g$

SPECIFIC VOLUME: $v = \frac{\forall}{m} = \frac{m_f v_f + m_g v_g}{m}$



After rearrangement: $v = (1-x)v_f + x\, v_g$

$x = \frac{m_g}{m}$

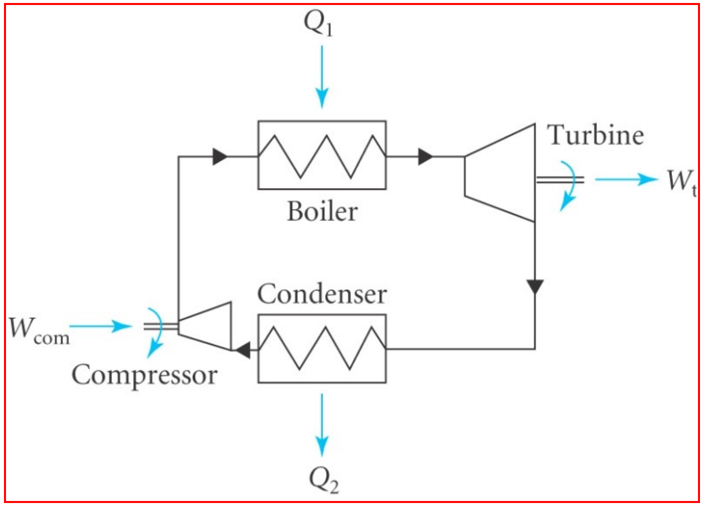
Also: $u = (1-x)u_f + x\, u_g$

$h = (1-x)h_f + x\, h_g$

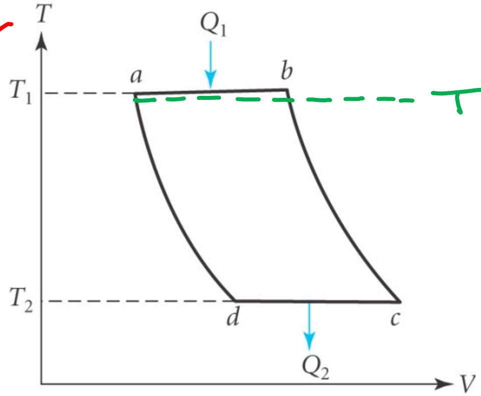
$s = (1-x)s_f + x\, s_f$

This merely scales properties proportionally to mass present of each phas

2.7 DRAWBACKS OF CARNOT CYCLE



T–V space

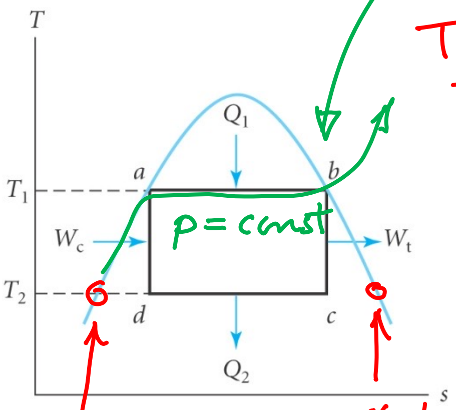


T_1 = constant

∴ boiler must be @ constant pressure

∴ cannot operate in dry steam region

T – s space



100% water

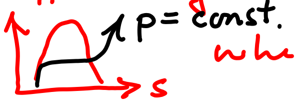
100% steam

∴ condenser cycle begins with some water (c) and 'cools' to some steam (d).

Hence less efficient than going 100% steam → 100% water

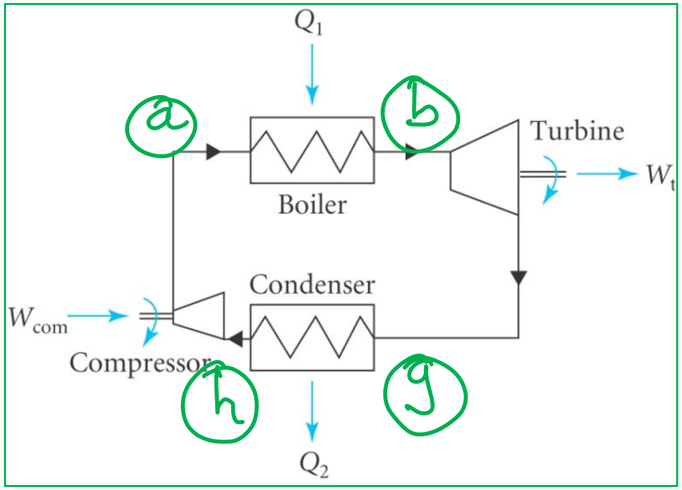
2.8 RANKINE CYCLE FOR STEAM POWER PLANTS

(2.7: Carnot efficiency, $\eta_c = 1 - \frac{T_2}{T_1}$, is max possible efficiency but (for constant T_1 reservoir → this requires isobaric boiler



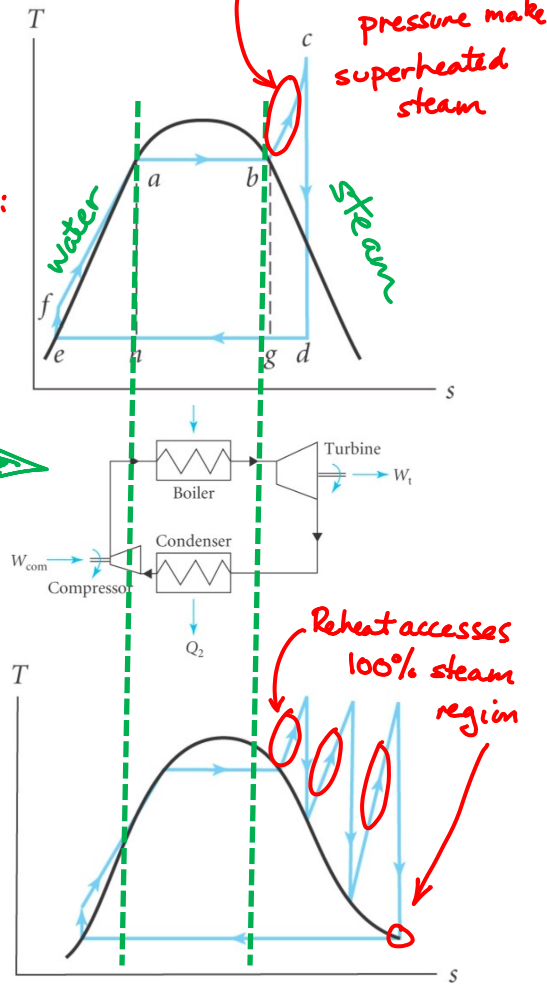
which is unusual)

Rankine cycle is more common — two flavors



① Without reheat:

② With reheat:



Heat at constant pressure makes superheated steam

Reheat accesses 100% steam region

3_2 Thermodynamics and Geothermal Systems

Recap:

Heat supplied to the crust (~70km deep) by convection - but conduction dominates in the crust
Hydrothermal regimes concentrated in - destructive, constructive and hot-spot areas
EGS low-grade power ubiquitous

Recovery of thermal energy - requires a heat-transfer mechanism
Generating power requires an energy conversion mechanism - flash to steam

Movies:

Allam Cycle: https://www.youtube.com/watch?v=vFcbev1TkoU

Resources: WG3

Thermodynamics: https://en.wikipedia.org/wiki/Laws_of_thermodynamics

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?

1. Generation of electricity requires conversion of energy - heat to work to electricity
2. Dissolution and precipitation of minerals (scaling) is controlled by thermodynamics
3. Water in geothermal reservoirs exists in vapor and liquid and may transit between states

Scientific Questions:

2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

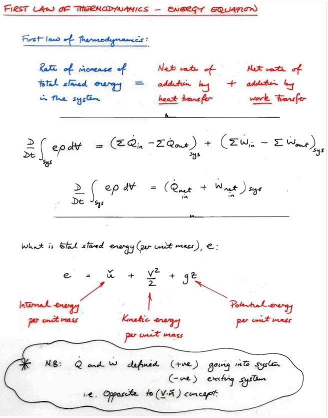
Background on Laws of Thermodynamics:

1. First Law:

a. Conservation of Energy

Energy can neither be created or be destroyed - it is conserved
All forms of energy are equivalent

b. Internal Energy



FIRST LAW OF THERMODYNAMICS – ENERGY EQUATION

First law of Thermodynamics:

Rate of increase of total stored energy in the system = Net rate of addition by heat transfer + Net rate of addition by work transfer

$$\frac{D}{Dt}\int_{sys} e\rho\, d\forall = \left(\Sigma \dot{Q}_{in} - \Sigma \dot{Q}_{out}\right)_{sys} + \left(\Sigma \dot{W}_{in} - \Sigma \dot{W}_{out}\right)_{sys}$$

$$\frac{D}{Dt}\int_{sys} e\rho\, d\forall = \left(\dot{Q}_{\underset{in}{net}} + \dot{W}_{\underset{in}{net}}\right)_{sys}$$

What is total stored energy (per unit mass), e:

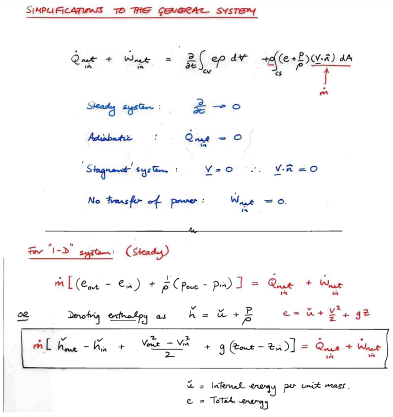
$$e = \check{u} + \frac{V^2}{2} + gz$$

Internal energy per unit mass

Kinetic energy per unit mass

Potential energy per unit mass

* N.B: $\dot{Q}$ and $\dot{W}$ defined (+ve) going into system
(−ve) exiting system
i.e. Opposite to $(\underline{V}\cdot\hat{n})$ concept.



SIMPLIFICATIONS TO THE GENERAL SYSTEM

$$\dot{Q}_{\underset{in}{net}} + \dot{W}_{\underset{in}{net}} = \frac{\partial}{\partial t}\int_{CV} e\rho\, d\forall + \rho\oint_{CS}\left(e + \frac{P}{\rho}\right)\underbrace{(\underline{V}\cdot\hat{n})\, dA}_{\dot{m}}$$

Steady system : $\frac{\partial}{\partial t} \rightarrow 0$

Adiabatic : $\dot{Q}_{\underset{in}{net}} = 0$

'Stagnant' system : $\underline{V} = 0 \quad \therefore \quad \underline{V}\cdot\hat{n} = 0$

No transfer of power : $\dot{W}_{\underset{in}{net}} = 0.$

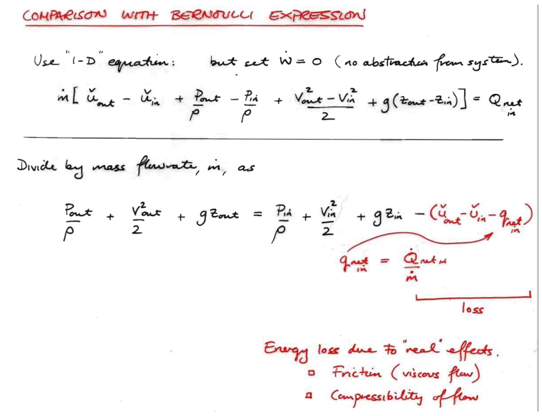
For "1-D" system: (Steady)

$$\dot{m}\left[(e_{out} - e_{in}) + \frac{1}{\rho}(p_{out} - p_{in})\right] = \dot{Q}_{\underset{in}{net}} + \dot{W}_{\underset{in}{net}}$$

OR Denoting enthalpy as $\check{h} = \check{u} + \frac{P}{\rho}$ $\quad e = \check{u} + \frac{V^2}{2} + gz$

$$\boxed{\dot{m}\left[\check{h}_{out} - \check{h}_{in} + \frac{V_{out}^2 - V_{in}^2}{2} + g(z_{out} - z_{in})\right] = \dot{Q}_{\underset{in}{net}} + \dot{W}_{\underset{in}{net}}}$$

$\check{u}$ = Internal energy per unit mass.
e = Total energy



COMPARISON WITH BERNOULLI EXPRESSION

Use "1-D" equation: but set $\dot{W} = 0$ (no abstraction from system).

$$\dot{m}\left[\check{u}_{out} - \check{u}_{in} + \frac{P_{out}}{\rho} - \frac{P_{in}}{\rho} + \frac{V_{out}^2 - V_{in}^2}{2} + g(z_{out} - z_{in})\right] = \dot{Q}_{\underset{in}{net}}$$

Divide by mass flowrate, $\dot{m}$, as

$$\frac{P_{out}}{\rho} + \frac{V_{out}^2}{2} + gz_{out} = \frac{P_{in}}{\rho} + \frac{V_{in}^2}{2} + gz_{in} - \underbrace{\left(\check{u}_{out} - \check{u}_{in} - q_{\underset{in}{net}}\right)}_{loss}$$

$$q_{\underset{in}{net}} = \frac{\dot{Q}_{\underset{in}{net}}}{\dot{m}}$$

Energy loss due to "real" effects.
- Friction (viscous flow)
- Compressibility of flow

$$\Delta E = E_f - E_i$$

which states that the change in internal energy (ΔE) is equal to the internal energy of the system in its final state (E_f) minus the initial internal energy (E_i).

This simple equation is profoundly important. It establishes the significance of knowing the internal energy at the end points of a process that affects a system. It is the difference between these end points that determines how much energy is required to heat a space, generate power, or cool a room. It also emphasizes that the pathway that was followed to get from the initial to the final states has absolutely no significance for the change in internal energy. For example, imagine a volume of gas contained in a cylinder and that the cylinder is a perfect insulator—that is, it will not allow heat to be added to or removed from the gas it contains. Imagine, too, that one end of the cylinder is movable (Figure 3.1). There are an infinite number of ways to get from some specified initial state (the cylinder on the left of the figure) to the final state (the cylinder on the right of the figure), two of which are depicted in the figure. In the sequence A1 → A2, the gas undergoes simple compression in a single step. In this case, the pressure (P_i) and temperature (T_i) of the gas in the initial state are increased to P_f and T_f, respectively, and the internal energy change (ΔE) is equal to $E_f - E_i$. In the sequence B1 to B2 to B3 to B4 to B5, the gas undergoes a series of changes in pressure and temperature before reaching the same P_f and T_f as in the A1 to A2 sequence. Each step results in a change in the internal energy:

$$\Delta E = E_{B2} + E_{B3} + E_{B4} + E_{B5} - E_{B1}$$

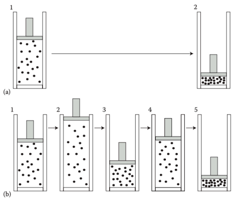


FIGURE 3.1 Diagrammatic representation of a cylinder of gas that follows two pathways (a and b) from one set of pressure and temperature conditions to another. Path (a) represents a single-stage compression, whereas path (b) involves two expansion and two compression stages. For both pathways, the change in the internal energy (E) is the same. The black dots in the cylinder schematically represent the gas molecules. In reality, there are an infinite number of pathways that could be followed that would achieve the same result.

If we were to measure the internal energy at the end of each step in B, we would find that

$$E_{B2} + E_{B3} + E_{B4} + E_{B5} = E_f$$

which results in

$$\Delta E = E_2 + E_3 + E_4 + E_5 - E_1 = E_f - E_i$$

Thus, regardless of the complexity of the path that is followed in getting from one set of conditions to another, or to put it another way, regardless of how much work one does to a system in moving it from one state to another, the internal energy will always be the difference between the initial and final states.

PRESSURE–VOLUME WORK

The conclusion that is inescapable is that any change in the internal energy of a system is solely the result of the work (w) done to the system, or that the system performs, and any heat (q) added to or taken from the system:

$$\Delta E = q + w \tag{3.1}$$

Mechanical work is performed when a force applied to a point, surface, or volume results in displacement of that point, surface, or volume. As an example, consider the changes in the cylinder in Figure 3.1. As the piston moves from its position in B1 to its position in B2, if there is an external force applied to the piston, mechanical work is performed by the gas as its volume increases and forces the piston to move. Hence, the element of mechanical work is defined by

$$dw = -P \times dV \tag{3.2}$$

By convention, mechanical work done *on* a system is positive, whereas work done *by* a system is negative. Work performed is, therefore, equivalent to the difference in volume between the two states:

$$w = -P \times (V_2 - V_1) = -P \times \Delta V \tag{3.3}$$

ENTHALPY

It follows from this discussion that in a process in which no change in volume occurs, no mechanical work is performed and any change in internal energy is solely related to heat added to or removed from the system:

$$\Delta E = q_v \tag{3.4}$$

The subscript v is used to indicate heat at constant volume; similarly, a subscript p would refer to a constant pressure condition. If, however, a change in volume occurs at constant pressure and heat is also added to or removed from the system, the change in internal energy is

$$\Delta E = q_p - (P \times \Delta V) \tag{3.5}$$

The heat added to or removed from the system at constant pressure is called the enthalpy (H) and the change in enthalpy (ΔH) that is realized when moving from one state to another is defined as

$$\Delta H = H_2 - H_1 = [E_2 + (P \times V_2)] - [E_1 + (P \times V_1)] = q_p \tag{3.6}$$

Enthalpy is an important system property in geothermal power applications because it provides a means for establishing the behavior of a system in the subsurface and allows for evaluation of the useful energy that can be extracted from a working fluid. It has units of J/kg. We will consider this topic in more detail in Chapter 10.

c. Pressure-Volume Work (above)

d. Enthalpy (above)

Enthalpy $\check{h} = \check{u} + P/\rho$

and: $\boxed{\dot{m}[(\check{h}_{out} - \check{h}_{in}) + \frac{1}{2}(V^2_{out} - V^2_{in}) + g(z_{out} - z_{in})] = \dot{Q}_{net in} + \dot{W}_{net in}}$

2. <u>Second Law:</u>

Entropy always increases

a. Efficiency

$$\boxed{\text{Efficiency} = -W/Q}$$

b. Carnot Cycle

$$\boxed{P\forall = nRT}$$

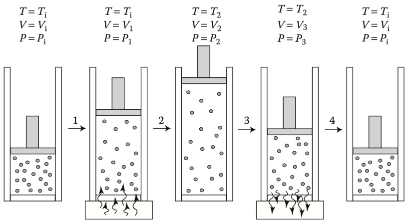


FIGURE 3.2 Diagrammatic representation of a gas cylinder following the steps in a Carnot cycle. Subscripts i and f represent, respectively, initial and final conditions. The arrows at the base of the cylinders in steps 1 and 3 indicate the direction of heat flow, relative to the heat reservoirs that are indicated by the boxes at the bases of the cylinders.

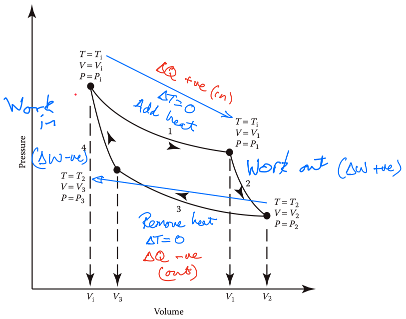


FIGURE 3.3 Pressure versus volume graph for the series of changes for the Carnot cycle depicted in Figure 3.2.

c. Heat Capacity

In general: $C = dq/dT$ or $C\,dT = dq$

Also: $\Delta H = \Delta(E + P \times \forall) = q$

At constant pressure ($\Delta p = 0$): $\Delta H = q_p \rightarrow dH = C_p dT$

At constant volume ($\Delta\forall = 0$): $\Delta E = q_v \longrightarrow dE = C_v dT$

and $dW = C_v dT$

d. Entropy

By definition: $\boxed{dS = dq/T}$

A measure of unattainable heat.

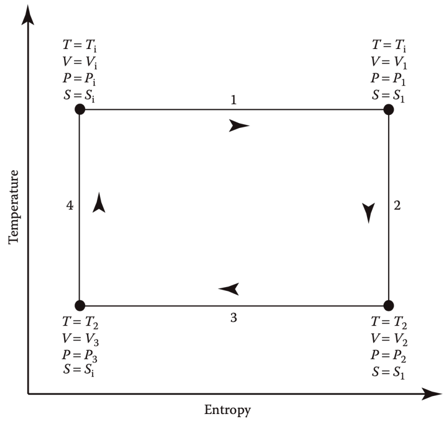


FIGURE 3.4 Temperature versus entropy graph for the same pathways indicated in the pressure versus volume graph in Figure 3.3.

3. Gibbs Function and Gibbs Energy (dG):

Defines the energy available within a system at a reference state ⟶ and therefore the ability of that system to do work, relative to another state

$$\Delta H = \Delta(E + P \times V) = q$$

Then $\Delta H - q = 0$ for example ⟶ $\begin{cases} dq = TdS \\ dq = C\,dT \end{cases}$

(In a closed invariant system)

$$\Delta G_{P,T} = \Delta H_{P_1,T_1} - T \times \Delta S_{P_1,T_1} + \int_{T_1}^{T} \Delta C_p \mathrm{d}T - T \times \int_{T_1}^{T} (\Delta C_p/T)\,\mathrm{d}T + \int_{P_1}^{T} \Delta V \mathrm{d}P \qquad (3.15)$$

where:

$\Delta G_{P,T}$ is the *Gibbs energy* at P and T

$\Delta H_{P_1,T_1}$ is the enthalpy at some standard state, which is usually selected to be 1 bar (0.1 MPa) pressure and 25°C (298 K)

$\Delta S_{P_1,T_1}$ is the entropy at the standard state

ΔC_p is the constant pressure heat capacity

ΔV is the change in volume

ΔG gives the change in energy within the system.

Standard State

$$G_{P,T} - G_{\mathrm{STP}} = (H_{P,T} - H_{\mathrm{STP}}) - T \times (S_{P,T} - S_{\mathrm{STP}})$$

Δ Gibbs Energy = Δ Enthalpy − T × Δ Entropy

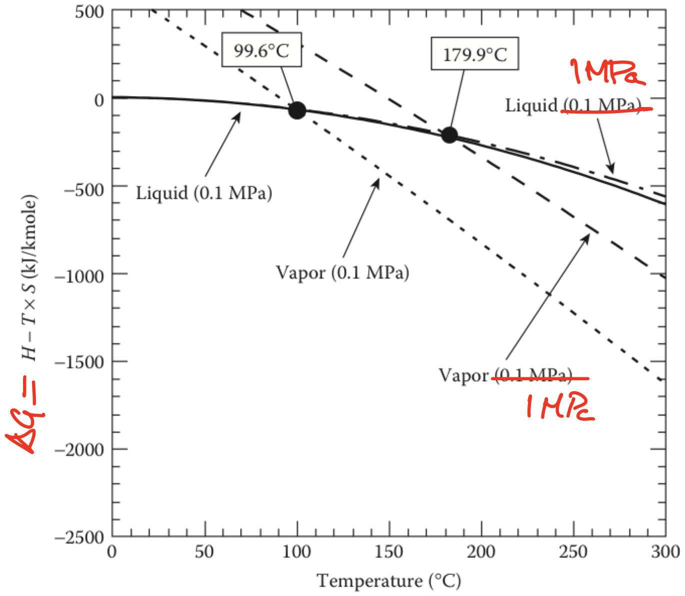


FIGURE 3.5 The isobaric changes in Gibbs energy at 0.1 MPa and 1.0 MPa as a function of temperature, for liquid and vapor H_2O. The temperatures at which the isobaric curves intersect are indicated.

1. At constant pressure ΔT influences vapor more than a fluid
2. At modest pressures (0.1 and 1MPa) liquids (and solids) insensitive to pressure.

4. Thermodynamic Efficiency:

For a closed system – no heat supply

$$\text{Efficiency} = \frac{w}{q_r} = \frac{\Delta q_r}{q_o}$$

If no heat supply then write as temperatures

$$\text{Efficiency} = \frac{T_i - T_2}{T_i}$$

All temperatures in Kelvin!!

Thus – T_i = initial temperature fluid

T_2 = cooled fluid (say 290K).

Efficacy ↑ with temperature of geothermal fluid

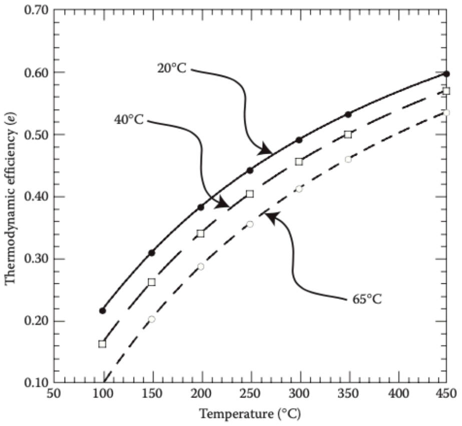


FIGURE 3.6 The thermodynamic efficiency that can be achieved for working fluids that begin at the temperature indicated on the horizontal axis and have an exit temperature as indicated by the arrowed lines. For example, a fluid that began at 200°C and had an exit temperature of 65°C would achieve an efficiency of 0.29, whereas that same fluid would achieve an efficiency of 0.39 if it had an exit temperature of 20°C.

TABLE 3.1

Relationship between Temperatures and Efficiencies for Some Hypothetical Geothermal Reservoir Systems

Reservoir	Reservoir Temperature (°C)	Cooled Temperature (°C)	Efficiency (e)
Low-temperature resource	100	25	0.20
Moderate-temperature resource (winter)	200	10	0.40
Moderate-temperature resource (summer)	200	35	0.33
High-temperature resource	300	25	0.48
High-temperature resource	450	25	0.59

5. Thermodynamic Properties of Water and Water-Rock Interaction:

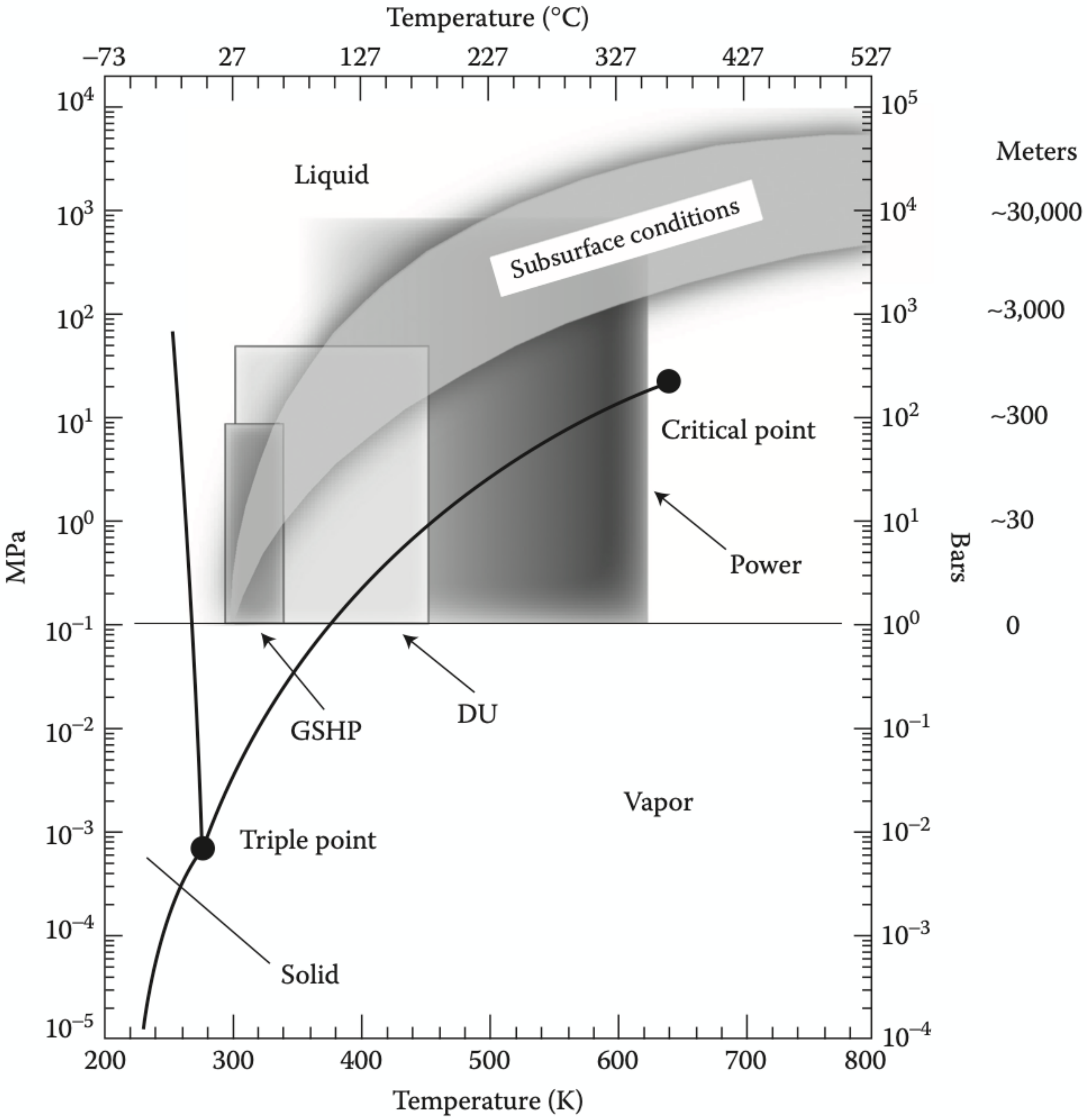


FIGURE 3.7 Phase diagram for water. Temperatures are indicated in degrees Celsius (upper horizontal axis) and Kelvin (lower horizontal axis), and pressures are indicated in megapascals (left vertical axis) and bars (right vertical axis). Also indicated on the right of the figure is the approximate equivalent depth, in meters, below the earth's surface, for the corresponding pressures. The gray band indicates the range of pressure–temperature conditions encountered with depth in the earth. The shaded boxes enclose those sets of conditions appropriate for ground source heat pump applications (medium gray), direct-use applications (light gray), and power generation (gray gradient).

TABLE 3.2
Constant Pressure Heat Capacity (C_p) of Some Common Materials Important for Geothermal Applications at Atmospheric Pressure (1 bar) and 25°C (273 K) and 300°C (573 K); Units Are kJ/kg-K

Material	25°C, 1 bar	300°C, 1 bar
Water[a]	4.18	2.01
Air[b]	1.00	1.04
Potassium feldspar[c]	0.66	1.05

Sources: [a] Bowers, T.S., *Rock Physics and Phase Relations*, ed. T.J. Ahrens, American Geophysical Union, Washington, DC, 45–72, 1995.

[b] Rabehl, R.J., Parameter Estimation and the Use of Catalog Data with TRNSYS. M.S. Thesis, Mechanical Engineering Department, University of Wisconsin-Madison, Madison, WI, 1997.

[c] Helgeson, H. C. et al., *American Journal of Science*, 278-A, 229, 1978.

Energy recovered from water @ 25°C

$$Q = \underbrace{V\rho}_{\text{Mass}} C_V \, \Delta T = M . C_p . \Delta T$$

So for $\Delta T = 1°c$; $M = 1\,kg = 1\,l$;

$$Q = 1 \times 4180\ J/kg\,K \times 1\,K = \underline{4180\,J.}$$

Total enthalpy is $H = M . C_p \, T \nearrow 25+273\,K$

$$H = 1\,kg \times 4180\ J/kg.K \times 298\,K$$

or $\sim Q \times 300$

$\therefore$ change in enthalpy

$\sim 1/300 \sim 0.33\%$

QED

PHASE CHANGE IN SYSTEMS

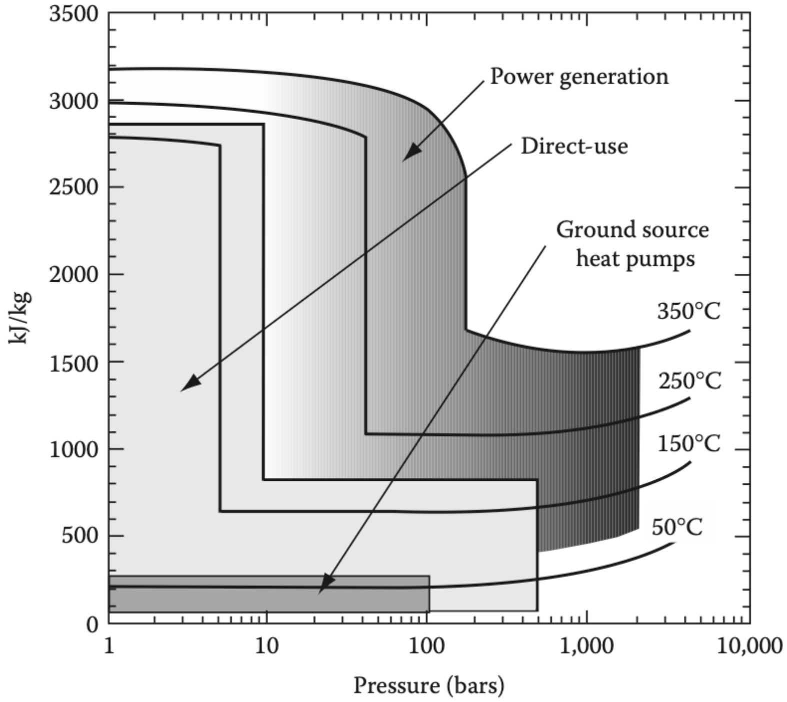


FIGURE 3.8 Enthalpy versus pressure diagram for water, with the corresponding regions for various geothermal applications, color coded as in Figure 3.7.

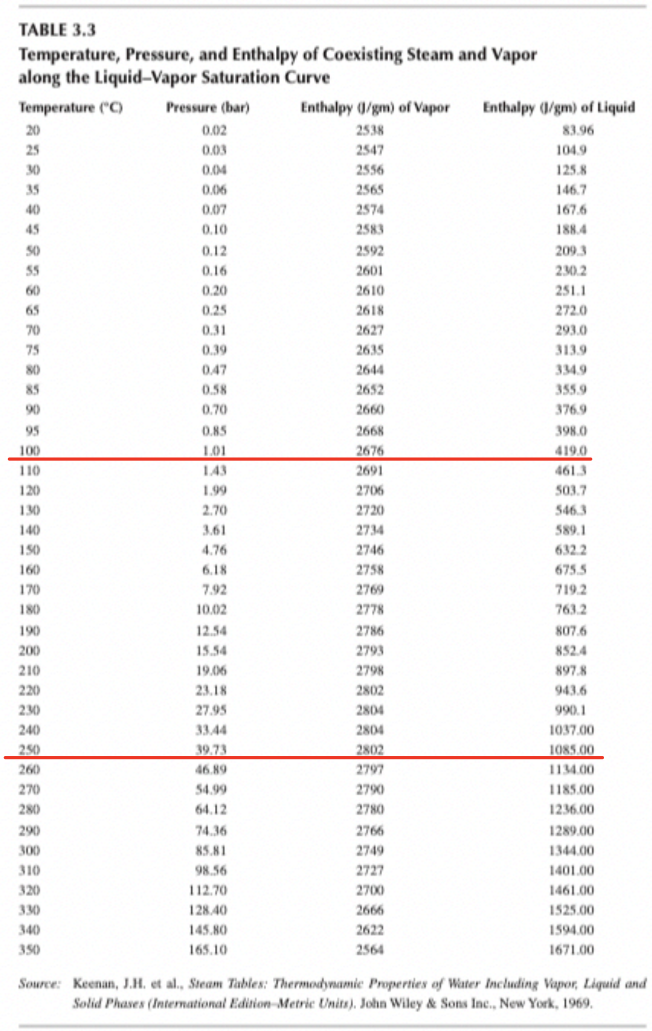


TABLE 3.3
Temperature, Pressure, and Enthalpy of Coexisting Steam and Vapor along the Liquid–Vapor Saturation Curve

Temperature (°C)	Pressure (bar)	Enthalpy (J/gm) of Vapor	Enthalpy (J/gm) of Liquid
20	0.02	2538	83.96
25	0.03	2547	104.9
30	0.04	2556	125.8
35	0.06	2565	146.7
40	0.07	2574	167.6
45	0.10	2583	188.4
50	0.12	2592	209.3
55	0.16	2601	230.2
60	0.20	2610	251.1
65	0.25	2618	272.0
70	0.31	2627	293.0
75	0.39	2635	313.9
80	0.47	2644	334.9
85	0.58	2652	355.9
90	0.70	2660	376.9
95	0.85	2668	398.0
100	1.01	2676	419.0
110	1.43	2691	461.3
120	1.99	2706	503.7
130	2.70	2720	546.3
140	3.61	2734	589.1
150	4.76	2746	632.2
160	6.18	2758	675.5
170	7.92	2769	719.2
180	10.02	2778	763.2
190	12.54	2786	807.6
200	15.54	2793	852.4
210	19.06	2798	897.8
220	23.18	2802	943.6
230	27.95	2804	990.1
240	33.44	2804	1037.00
250	39.73	2802	1085.00
260	46.89	2797	1134.00
270	54.99	2790	1185.00
280	64.12	2780	1236.00
290	74.36	2766	1289.00
300	85.81	2749	1344.00
310	98.56	2727	1401.00
320	112.70	2700	1461.00
330	128.40	2666	1525.00
340	145.80	2622	1594.00
350	165.10	2564	1671.00

Source: Keenan, J.H. et al., *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid and Solid Phases (International Edition–Metric Units)*. John Wiley & Sons Inc., New York, 1969.

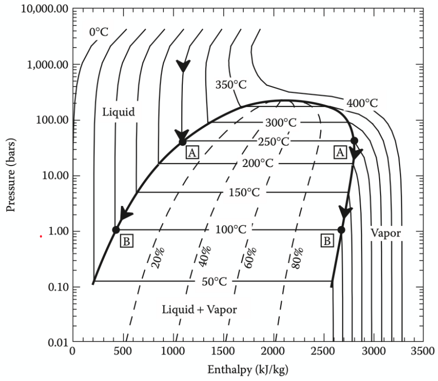


FIGURE 3.9 Pressure versus enthalpy diagram, contoured for temperature. The heavy black line encloses the region where steam and liquid coexist. The dashed lines are lines of constant mass percent steam coexisting with liquid water. The arrowed paths indicate the pressure–enthalpy path followed by a liquid at 250°C that ascends from 1000 bars and exits a wellhead at 1 bar and 100°C.

PHASE CHANGE

① Largest energy recovery with phase change

② Rapid recovery of hot water at depth

$\longrightarrow \Delta p$ but $\Delta H = 0$

Conservation:

1. Mass $\Delta M = 0$
2. Enthalpy $\Delta H = 0$

Example! Water @ 250°C

$p = 40$ bar @ 1500m

(4 MPa)

$$H_{1,250°\mathrm{C}} = x \times H_{1,100°\mathrm{C}} + (1-x) \times H_{\mathrm{v},100°\mathrm{C}}$$

where:

the subscripts l and v stand for liquid and vapor, respectively

x is the fraction of the mass of the system that is liquid

Enthalpies: Liquid @ 250°c/40bar = 1,085 J/kg

100°C/1bar = 0.419 J/kg

Vapor @ 100°c/1bar = 2.676 J/kg

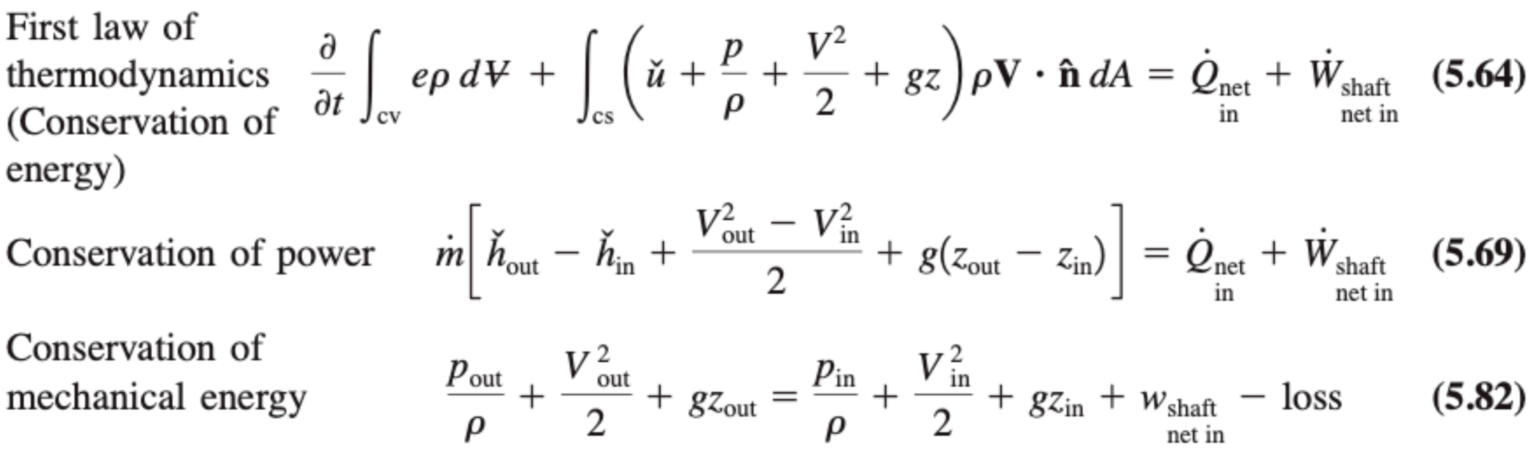
Solve for liquid fraction "x":

$x \sim 70\%$ and $1-x \sim 30\%$

3. For Each Sub-Topic:

a. Detailed Explanation of the Topic [40%] Describe the physical principles in detail and at a pace that is tutorial for an audience.

Summary - in terms of EME 303



First law of thermodynamics (Conservation of energy)

$$\frac{\partial}{\partial t}\int_{\text{cv}} e\rho\, d\forall + \int_{\text{cs}}\left(\check{u} + \frac{p}{\rho} + \frac{V^2}{2} + gz\right)\rho\mathbf{V}\cdot\hat{\mathbf{n}}\, dA = \dot{Q}_{\substack{\text{net}\\ \text{in}}} + \dot{W}_{\substack{\text{shaft}\\ \text{net in}}} \tag{5.64}$$

Conservation of power

$$\dot{m}\left[\check{h}_{\text{out}} - \check{h}_{\text{in}} + \frac{V_{\text{out}}^2 - V_{\text{in}}^2}{2} + g(z_{\text{out}} - z_{\text{in}})\right] = \dot{Q}_{\substack{\text{net}\\ \text{in}}} + \dot{W}_{\substack{\text{shaft}\\ \text{net in}}} \tag{5.69}$$

Conservation of mechanical energy

$$\frac{p_{\text{out}}}{\rho} + \frac{V_{\text{out}}^2}{2} + gz_{\text{out}} = \frac{p_{\text{in}}}{\rho} + \frac{V_{\text{in}}^2}{2} + gz_{\text{in}} + w_{\substack{\text{shaft}\\ \text{net in}}} - \text{loss} \tag{5.82}$$

b. Example Hand-Calculation [10%] Simple calculation to demonstrate the technique.

c. Case Study [10%] If appropriate.

Conclusion:

4. Conclusion [20%] Summarize important/key points from the presentation.

3. FLUID FLOW AND GEOCHEMISTRY

3. FLUID FLOW AND GEOCHEMISTRY

4_1 Subsurface Fluid Flow

Recap:

Thermo - Defines behavior of fluids and minerals in the crust
Importance of First and Second Laws
Phase change is an important mechanism for heat transfer fluids

Movies:

Fractional Fluid Flow: https://www.youtube.com/watch?v=cNDUKylb4Ds

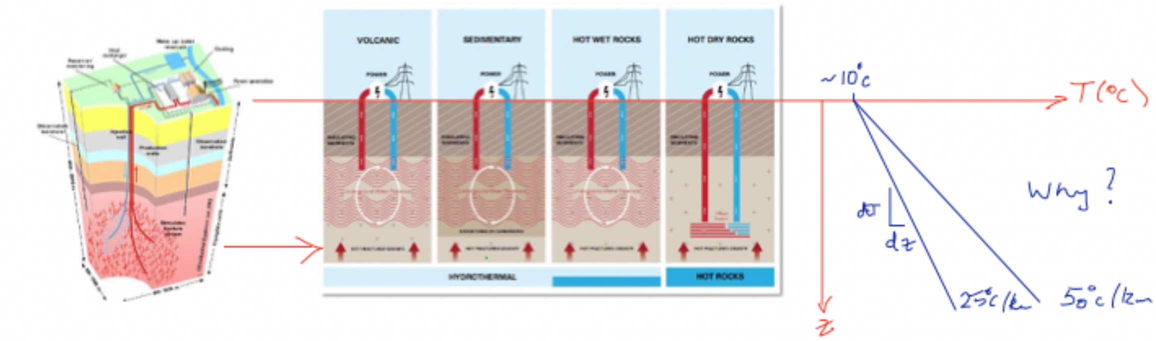
Resources: WG4

Reative Permeabilities: https://www.youtube.com/watch?v=A9c0vRU_Jko&feature=youtu.be

Darcy's Law: https://www.youtube.com/watch?v=mxPuiryMjJs&feature=youtu.be

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Fluids present naturally or introduced.... and function as a heat transfer medium
Convective (rather than conductive) heat transfer often necessary
Fluids may be naturally occurring water/brine or artificially introduced CO2 (v. exotic)

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

What controls fluid movement (modulated by permeability and storage)?

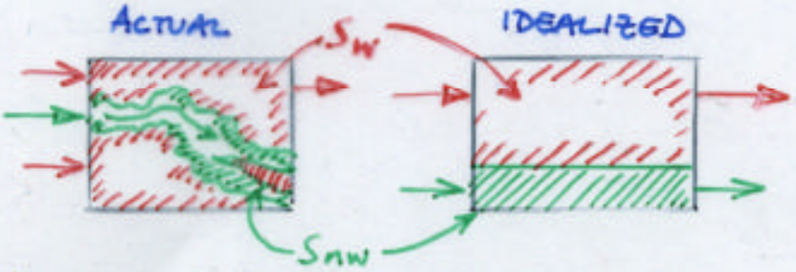
Impacts of multiple phases (vapor/liquid) and changes in permeability?

What rates of thermal recovery may result - and what are the controls?

3. SIMULTANEOUS FLOW OF TWO IMMISCIBLE FLUIDS

Simultaneous Flow of Two Fluids (water & vapor):

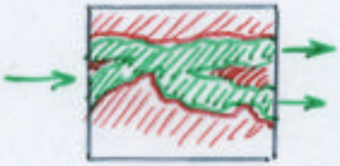
- Capillarity and capillary pressures govern the "equilibrium" penetration of fluids — static behavior
- Once penetrated, the individual phases may transfer and be transported
  - Pure phase (free product)
  - Dissolved form (later).



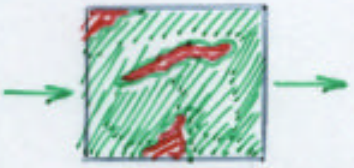
a) Note that flow within phase is not subject to capillarity (capillarity acts at fringes, only)

b) Each fluid establishes its own "tortuous" path → stable channels

No flow of NW
(Discontinuous NW)



Both fluids flow

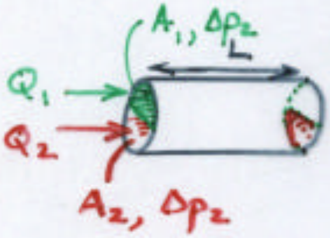


No flow of W
(Discontinuous Wetting)

Increasing saturation of Non-Wetting →

3.1 MOTION EQUATIONS Darcy's Law

Apply Darcy's Law



Establish steady flow at volumetric flow rates, Q_1 and Q_2.

$$\left.\begin{array}{ll} 🟩 & q_1 = \left(\frac{k_1}{\mu_1}\right) \frac{\Delta p_1}{L} \\ & \\ 🟥 & q_2 = \left(\frac{k_2}{\mu_2}\right) \frac{\Delta p_2}{L} \end{array}\right\} \quad q_\alpha = \left(\frac{k_\alpha}{\mu_\alpha}\right) \frac{\Delta p_\alpha}{L} \quad ; \quad q_\alpha = \frac{Q_\alpha}{A_\alpha}$$

Δp_α = effective pressure drop of α^{th} fluid

k_α = "effective" permeability of medium to fluid α.

k_α depends on : a) Porous medium (pore size & distribution and fractures).

b) Saturation, S_w and S_{nw}.

"Relative" permeabilities

$$k_{r_1} = \frac{k_1}{k}(S_1) \quad ; \quad k_{r_2} = \frac{k_2}{k}(S_2)$$

- Relative to single phase permeability of a fully saturating fluid
- Determine from "equilibrium" laboratory flow tests under different saturations.

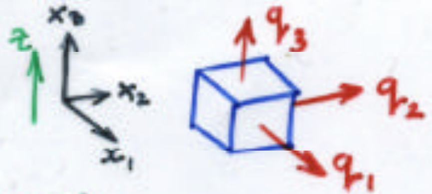
Effective permeability

$$k_1 = k_{r_1} k$$

True permeability (L^2)

Relative permeability

FLUID MOTION EQUATION (DARCY'S LAW)



i = flow direction, x_1, x_2, x_3.

("z" is // to x_3)

$$q_{i_1} = -\frac{k_1}{\mu_1}\left(\frac{\partial p_1}{\partial x_j} + \rho_1 g \frac{\partial z}{\partial x_j}\right) = -k\,\frac{k_{r1}}{\mu_1}\left(\frac{\partial p_1}{\partial x_j} + \rho_1 g \frac{\partial z}{\partial x_j}\right)$$

$$\frac{K_2}{\rho_2 g}$$

$$q_{i_2} = -\frac{k_2}{\mu_2}\left(\frac{\partial p_2}{\partial x_j} + \rho_2 g \frac{\partial z}{\partial x_j}\right) = -k\,\frac{k_{r2}}{\mu_2}\left(\frac{\partial p_2}{\partial x_j} + \rho_2 g \frac{\partial z}{\partial x_j}\right)$$

May also use piezometric head, h, for constant ρ_1 and ρ_2, but must be defined separately for each fluid, h_α

$$h_\alpha = \frac{p_\alpha}{\rho_\alpha g} + z \quad ; \qquad \alpha = 1, 2$$

$$\boxed{\begin{aligned} q_{i_1} &= -k\,\frac{k_{r1}}{\mu_1}\,\rho_1 g\,\frac{\partial h_1}{\partial x_j} \\[2ex] q_{i_2} &= -k\,\frac{k_{r2}}{\mu_2}\,\rho_2 g\,\frac{\partial h_2}{\partial x_j} \end{aligned}}$$

Similarity between:

permeability (L^2)

$$q = -k\,\frac{\rho g}{\mu}\,\frac{dh}{dx_j}$$

$$= -K\,\frac{dh}{dx_j}$$

Hydraulic Conductivity (L/T)

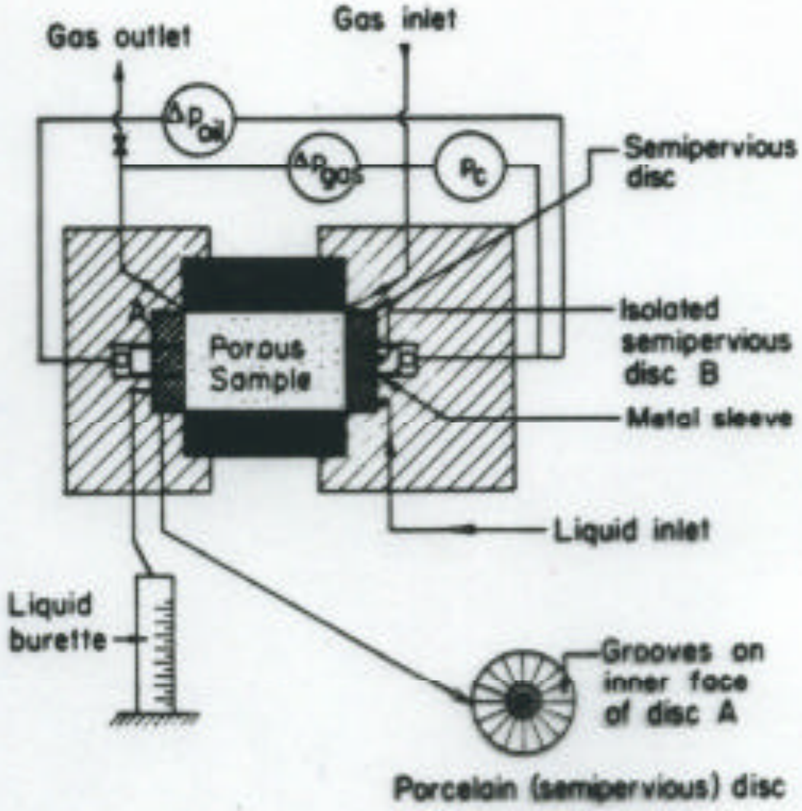


FIG. 9.2.15. Hassler's apparatus for relative permeability determination (after Osoba et al., 1951).

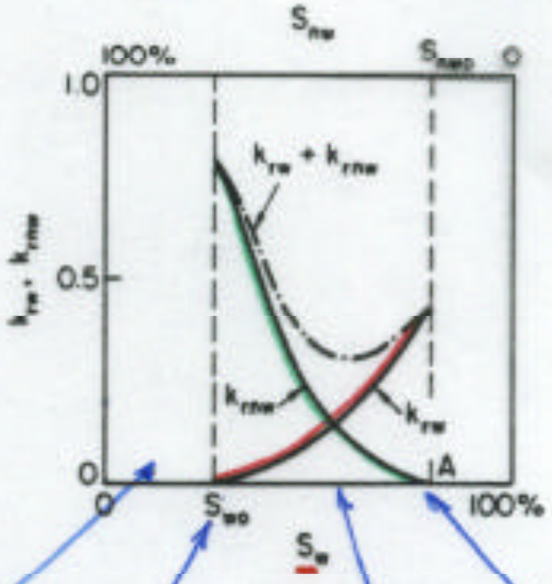
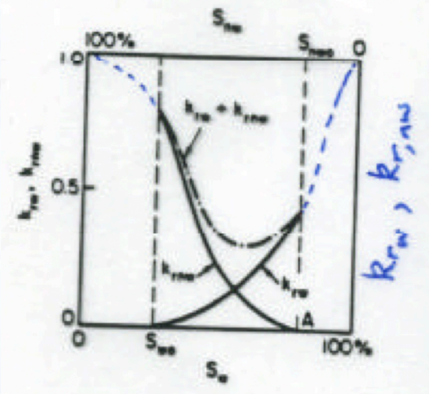


FIG. 9.3.1. Typical relative permeability curves (e.g., wetting fluid = water, nonwetting fluid = oil).

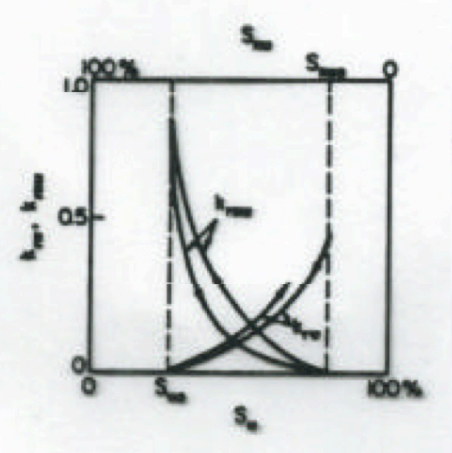
Relative Permeability

3.2 RELATIVE PERMEABILITY



- ☐ $k_{r_{nw}} + k_{r_w} \neq 1 \Rightarrow k_{r_{nw}} + k_{r_w} < 1$.
  Most effective transmission is at 100% saturation (if accessible). Interference.
- ☐ Usually $k_{r_{nw}}$ closer to 1 than k_{r_w}
- ☐ Steep decline of k_{r_w} with increasing S_{nw} indicates larger pores occupied first by nonwetting phase.

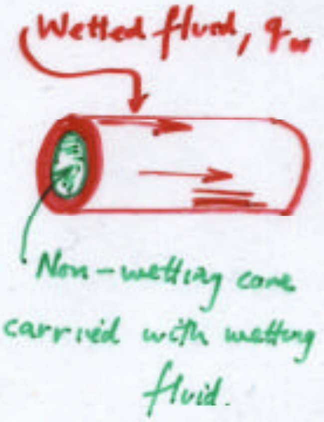
Nonwetting phase occupies larger pores preferentially due to capillary pressure arguments.



- ☐ k to wetting fluid is always <u>larger</u> for open pored unconsolidated material.
- ☐ k to <u>non</u>-wetting fluid is always <u>smaller</u> for open-pored unconsolidated material.

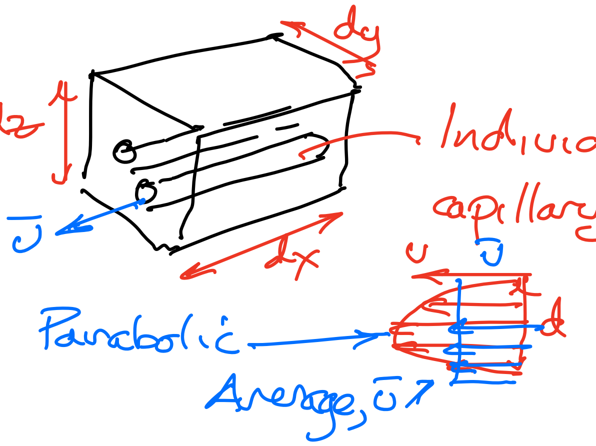
<u>Hysteresis</u>:

1. Wetting fluid surrounds grains and non-wetting fluid ∴ may move nw fluid even if no pressure gradient in nw fluid.



2. Since change in saturation requires change in wetted grain surface – wettability is hysteretic. ∴ permeabilities are hysteretic.

Capillary Relations for Permeability



Average flow velocity, $\bar{u} = \frac{d^2}{32\mu}\frac{dp}{dx}$

Flow volume rate per tube, Q_i : $Q_i = \frac{\pi d^2}{4}\frac{d^2}{32\mu}\frac{dp}{dx}$

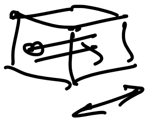
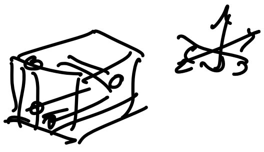
Area

No. of tubes : $n = \frac{V_v}{V_T} = \frac{A_v}{A_T}\cdot\frac{dx}{dx} = \frac{(\pi d^2/4)\times i_{tubes}\times dx}{dy\,dz\,.\,dx}$

$$Q_{TOTAL} = Q_i \times i_{tubes}$$

$$Q_T = \cancel{\frac{\pi d^2}{4}}\,\frac{d^2}{32\mu}\cdot\frac{dp}{dx}\times\frac{\cancel{dx}\,dy\,dz\,.\,n}{\cancel{(\pi d^2/4)}\;\cancel{dx}}$$

$$Q_T = A\frac{k}{\mu}\frac{dp}{dx} = dy\,dz\,.\,\frac{d^2 n}{32\mu}\cdot\frac{dp}{dx}$$

Thus : $k = \frac{d^2 n}{32}$ for  or $\frac{d^2 n}{96}$ for 

Equivalency of Permeability (k)and Hydraulic Conductivity (K)

Permeability (k : m²) intrinsic property of rock

Hydraulic conductivity (K : m/s) – rock + fluid

$$\frac{k}{\mu_f} = \frac{K}{\rho_f g} \quad : \quad \frac{m^2}{Pa.s} \doteq \frac{(m/s)}{kg/m^3 . m/s^2}$$

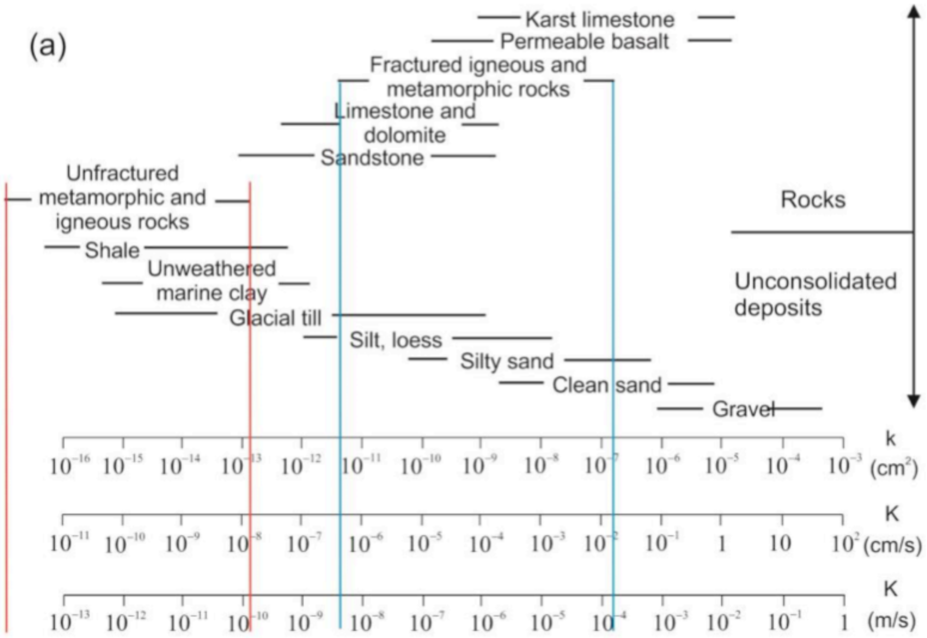


Figure 2. (a) Values of permeability (*k*) and hydraulic conductivity (*K*) for different geological materials. Notice that the *K* values for the fractured igneous and metamorphic rocks (between the blue bars) vary 5 orders of magnitude. Unfractured crystalline rocks have extremely low *K* values and are comparable to shale and clay (modified from Freeze and Cherry 1979).

TABLE 4.1
Permeabilities for Some Representative Geological Materials

	Highly Fractured Rock	Well-Sorted Sand, Gravel	Very Fine Sand and Sandstone	Fresh Granite
κ (cm^2)	10^{-3}–10^{-6}	10^{-5}–10^{-7}	10^{-8}–10^{-11}	10^{-14}–10^{-15}
κ (millidarcy)	10^{8}–10^{5}	10^{6}–10^{4}	10^{3}–1	10^{-3}–10^{-4}

KOZENY–CARMAN EQUATION

The factors that determine permeability were formally quantified by Kozeny (1927) and later modified by Carman (1937, 1956). The final form of the equation they developed is

$$\kappa = \frac{\left[n^3/(1-n)^2\right]}{(5\times S_A)^2} \tag{4.2a}$$

where:
- n is the porosity, as a fraction
- S_A is the specific surface area of the pore spaces per unit volume of solid (cm^2/cm^3)

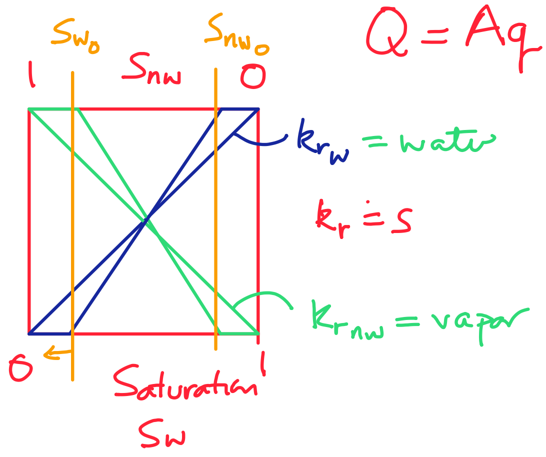
Equation 4.2a is known as the Kozeny–Carman equation. This equation allows the dependence of the permeability on the porosity of a porous sample to be determined. Implicit in this relationship are all of the factors discussed above regarding flow in the porous rocks. Of particular importance for permeability is the tortuosity of the flow path—the more tortuous the network of pores through which fluid must flow, the lower will be the permeability. Tortuosity can be accounted for by recasting Equation 4.2a as

$$\kappa = c_0 \times T \times \frac{\left[n^3/(1-n)^2\right]}{S_A^2} \tag{4.2b}$$

where:
- T is the tortuosity which is equivalent to the ratio of a straight path of length L connecting two points to the actual path followed along some tubular route L_t, that is, L/L_t
- c_0 is a constant characteristic of the system

Generally, $c_0 \times T = 0.2$, thus reducing Equation 4.2a to 4.2b.

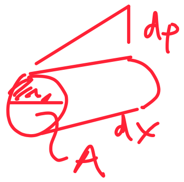
4-2 - RECAP



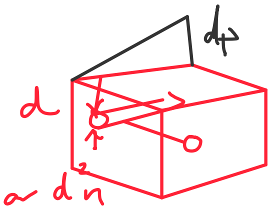
$$k_r \doteq S$$

$$S_w + S_{nw} = 1$$

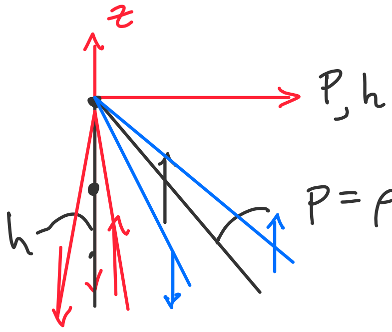
$$Q = Aq = A\,k_{r\alpha}\,\frac{k}{\mu}\,\frac{dp}{dx}$$



$$\overset{m^2}{\frac{k}{\mu}} = \overset{m/s}{\frac{K}{\rho g}}$$



$$k = \frac{d^2 n}{32} \propto \frac{d^2 n}{96}$$



$$P = \rho g \cdot (-z)$$

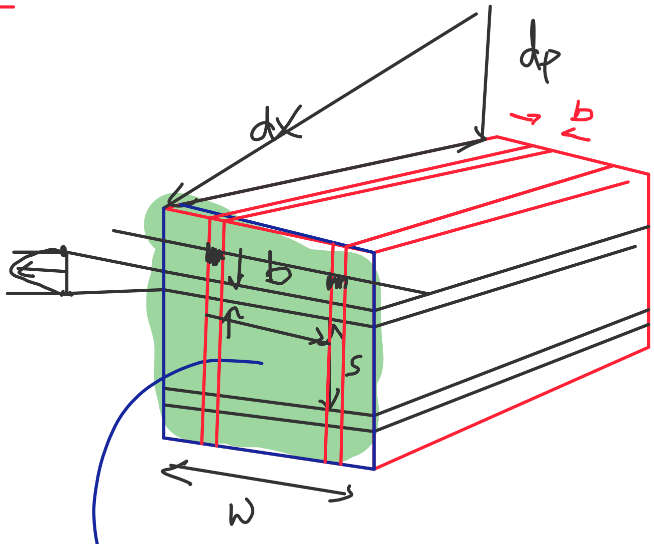
$$h = \cancel{z} + \cancel{\frac{P}{\rho g}} + \cancelto{0}{\frac{v^2}{2g}}$$

Permeability Fractured –

Conservation of Mass & Momentum –

Simple flow models

FRACTURED ROCKS



$$k = \frac{b^2}{12}$$

$$Q = b \cdot \overset{k}{\boxed{\frac{b^2}{12}}} \, \frac{1}{\mu} \, \frac{dp}{dx} \, w$$

$$\text{no. of tubes} = \frac{1}{s}$$

$$k = \frac{b^3}{12s}$$

$$Q = A \, \frac{\overset{(m^2)}{k}}{\mu} \, \frac{dp}{dx}$$

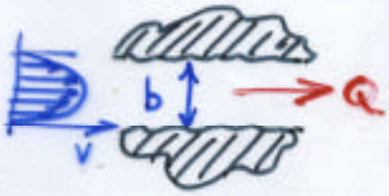
$$\frac{K}{\rho g} = \frac{k}{\mu}$$

$$\underset{(m/s)}{K} = \frac{\rho g}{\mu} \, \frac{b^3}{12s}$$

$$k_{2sets} = \frac{b^3}{12s} + \frac{b^3}{12s} = \frac{2}{12} \, \frac{b^3}{s}$$

PERMABILITY/CONDUCTIVITY OF FRACTURES

Flow in fractures



$$\bar{v} = -\overset{k}{\overbrace{\frac{gb^2}{12\nu}}}\frac{dh}{dx}$$

$\bar{v}$ = average velocity.

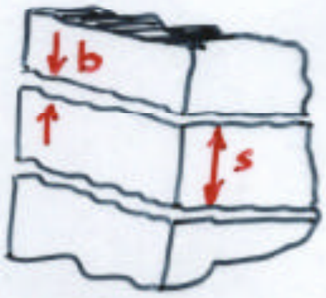
ν = kinematic viscosity of fluid

$\nu = \mu/\rho$

Equivalent flow rate per unit width: for single fracture

$$Q = b\,\frac{gb^2}{12\nu}\frac{dh}{dx}$$

Multiple fractures arranged in parallel:



Total of N fractures per unit height:

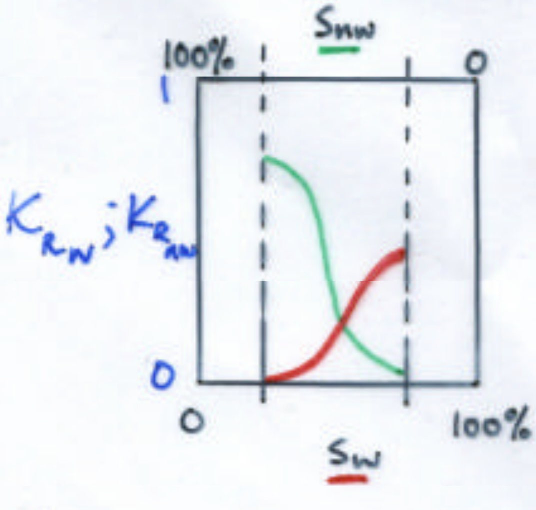
$N = 1/s$

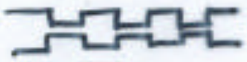
$$Q = \underbrace{\frac{gb^3}{12\nu}\frac{1}{s}}_{K_b}\frac{dh}{dx}$$

Equivalent conductivity for multiple sets : $K_b = \frac{gb^3}{6\nu s}$

Enables b to be evaluated if K known (measured).

Relative permeability of fractures



- Similar behaviour to porous medium
- Distribution of apertures 

  Large apertures saturate first

Capillary pressure or head $h_c = \frac{2\sigma}{b\gamma_w}$

Fracture Permeability - Nomograph

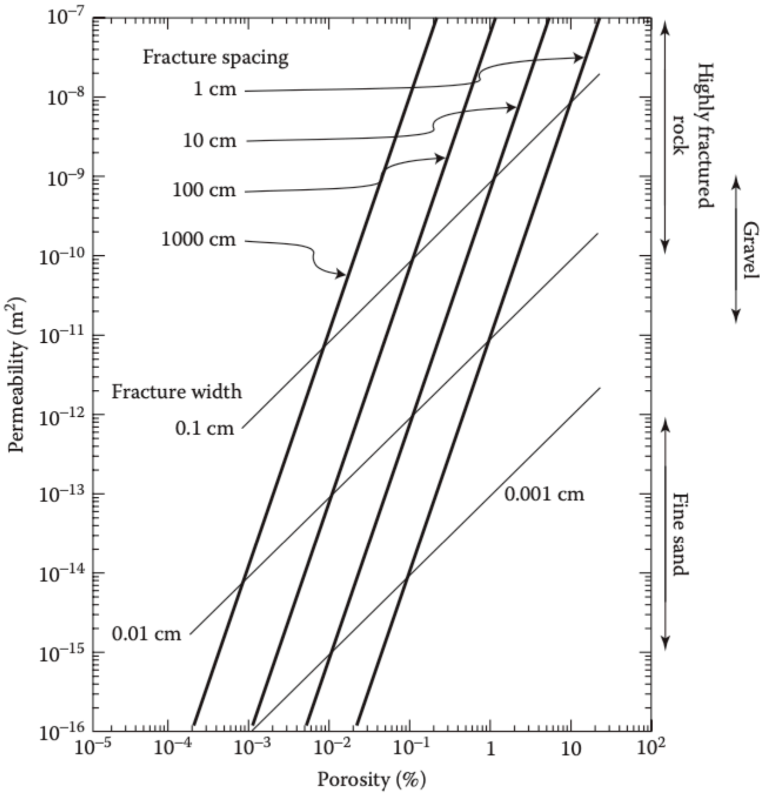


FIGURE 4.6 Theoretical relationship between fracture permeability (air) and fracture porosity. The bulk porosity and permeability for a given fracture width (or aperture) and spacing of those fractures is found by locating the intersection of the width and spacing of interest. It is clear that permeability is a function of both fracture width and spacing, both of which affect bulk porosity. (Modified from Reservoir Characterization Research Lab, University of Texas, Austin, TX, available at http://www.beg.utexas.edu/indassoc/rcrl/rckfabpublic/petrovugperm.htm; Lucia, F.J., *American Association of Petroleum Geologists*, 79, 1275–1300, 1995.)

Crustal Permeability at Depth

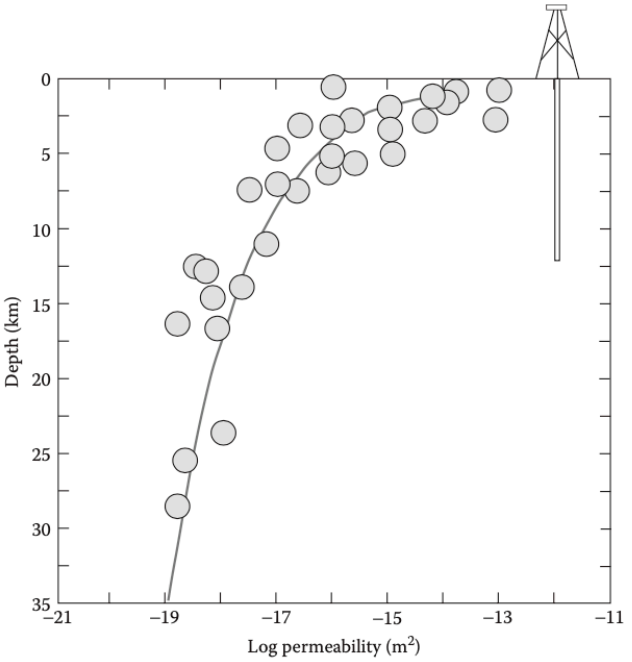
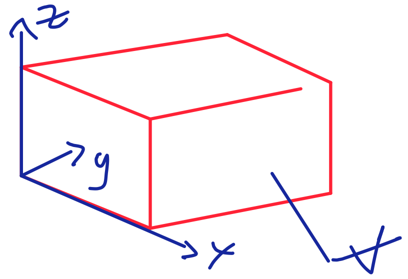


FIGURE 4.8 The variation of permeability as a function of depth. For reference, the depth of the deepest drilled oil well in the world is also portrayed. (Modified from Manning, C.E. and Ingebritsen, S.E., *Reviews of Geophysics*, 37, 127–150, 1999.)

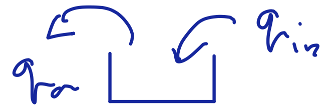
Conservation of Mass/Momentum



$n\forall_T \cancel{S}$ $\to 1$

$q = \cancel{k_r}\frac{k}{\mu}\frac{dp}{dx}$, $k_r \to = 1$

$$\frac{\partial}{\partial t}(\rho \cancel{\forall_v}) + \frac{\partial}{\partial x}\rho \cancel{q_x} = 0$$



$$n = \frac{\forall_v}{\forall_T}$$

$$\frac{\partial}{\partial t}(\rho n) - \frac{\partial}{\partial x}\frac{k}{\mu}\frac{dp}{dx}\rho = 0$$

$$\frac{\partial p}{\partial p}\rho\frac{\partial n}{\partial t} + n\frac{\partial \rho}{\partial t}\frac{\partial p}{\partial p}\checkmark - \frac{\partial^2 p}{\partial x^2}\rho\frac{k}{\mu}$$

$$\cancel{\frac{\rho}{\rho}}\frac{\partial n}{\partial p}\underline{\frac{\partial p}{\partial t}} + \frac{n}{\rho}\frac{\partial \rho}{\partial p}\underline{\frac{\partial p}{\partial t}} - \frac{\partial^2 p}{\partial x^2}\frac{k}{\mu}\frac{\cancel{\rho}}{\cancel{\rho}}$$

$$\left(\frac{\partial n}{\partial p} + \frac{n}{\rho}\frac{\partial \rho}{\partial p}\right)\frac{\partial p}{\partial t} = \frac{k}{\mu}\frac{\partial^2 p}{\partial x^2}$$

Compressibility of reservoir ($\frac{1}{Pa}$)

$n \cdot \underbrace{\frac{1}{\rho}\frac{\partial \rho}{\partial p}}$

$C_{water} \to E_{water} \sim 2$ GPa

$C_{vapor} \to E_{gas} \sim P$

$E = 10$ GPa $= 10\times10^9$ Pa

$C = \frac{1}{E}$

$$(C_m + n\,C_{fluid})\frac{\partial p}{\partial t} = \frac{k}{\mu}\frac{\partial^2 p}{\partial x^2} + \frac{k}{\mu}\frac{\partial^2 p}{\partial^2 y} + \cdot$$

<u>Heads</u>, h

$$\frac{K}{\rho g} = \frac{k}{\mu}$$

$$h = \frac{P}{\rho g} + z$$

$$S_w + S_{nw} = 1$$

$$P_c = P_{nw} - P_w$$

$$(C_m + c_f n)\frac{\partial \textcircled{p}}{\partial t} = \frac{\overset{\checkmark}{k}}{\mu}\frac{\partial^2 p}{\partial x^2} \longleftarrow \text{Petroleum, Geotherm}$$

$$S_s \frac{\partial \textcircled{h}}{\partial t} = \overset{\checkmark}{K}\frac{\partial^2 h}{\partial x^2} \longleftarrow \text{Groundwater}$$

3.3 Mass Conservation in Multiphase Flow

Continuity equation: $\frac{\partial}{\partial t}(n S_\alpha \rho_\alpha) + \frac{\partial}{\partial x_i}(\rho_\alpha q_{i\alpha}) = 0$ $\alpha = 1, 2$ or $\alpha = 1, 2, 3.$

For an incompressible fluid and medium $\frac{\partial}{\partial t}(n \text{ and } \rho) = 0$

Substitute q_α from relative permeability relation:
Results in 4 equations:

$$n \frac{\partial S_1}{\partial t} - \frac{\partial}{\partial x_i}\left[k \frac{k_{r1}}{\mu_1}\left(\frac{\partial p_1}{\partial x_j} + \rho_1 g \frac{\partial z}{\partial x_j}\right)\right] = 0$$

$$n \frac{\partial S_2}{\partial t} - \frac{\partial}{\partial x_i}\left[k \frac{k_{r2}}{\mu_2}\left(\frac{\partial p_2}{\partial x_j} + \rho_2 g \frac{\partial z}{\partial x_j}\right)\right] = 0$$

$$S_1 + S_2 = 1$$

$$p_2 - p_1 = p_c(S_1)$$

Solve for 4 unknowns: S_1, S_2, p_1, p_2

with $h_1 = z + \frac{p_1}{\rho_1 g}$; $h_2 = z + \frac{p_2}{\rho_2 g}$

Solve using numerical techniques.

SIMPLIFIED RELATIONS FOR FLOW

HYDROLOGY

$$K\frac{\partial^2 h}{\partial x^2} = S_s\frac{dh}{dt}$$

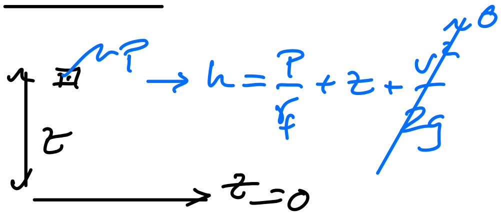
K = hydraulic conductivity
coefficient of permeability
(m/s).

S_s = specific storage

$$S_s = \rho g(\alpha + n\beta)$$

Reservoir rock compressibility ~(1/10 GPa)

Fluid compressibility



$$h = \frac{P}{\gamma} + z + \cancel{\frac{v^2}{2g}}^{\approx 0}$$

PETROLEUM ENG/GEOTHERMAL RES. ENG.

$$\frac{K}{\rho g}\frac{\partial^2 h}{\partial x^2} = \frac{S_s}{\rho g}\frac{dh}{dt}$$

with $\frac{K}{\rho g} \equiv \frac{k}{\mu}$; $P = h\cdot\rho g = h\gamma$

Substituting:

$$\frac{k}{\mu}\frac{\partial^2 p}{\partial x^2} = \bar{\beta}\frac{\partial p}{\partial t}$$

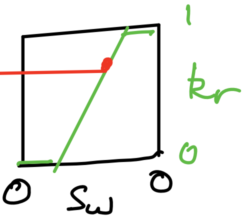
$$\bar{\beta} = (\alpha + n\beta)$$

QED

STEADY STATE FLOW ($\partial p/\partial t = 0$)

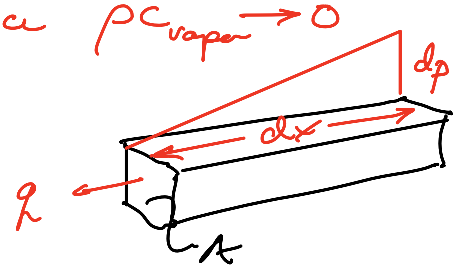
$k_r \sim 1$

$$q = -k_r(S_{water})\frac{k}{\mu}\frac{dp}{dx}$$



Less interested in q_{vapor} since $\rho c_{vapor} \to 0$

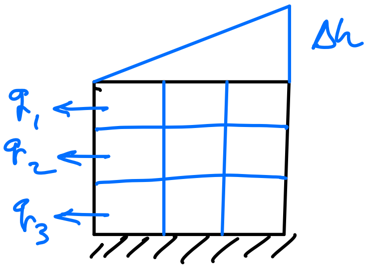
$$Q = qA = A\frac{k}{\mu}\frac{dp}{dx}$$



$$\text{Power} = Q\rho c\Delta T = \frac{\cancel{m^3}}{s}\cdot\frac{\cancel{kg}}{\cancel{m^3}}\frac{J}{\cancel{kg}\cdot\cancel{K}}\cdot\cancel{K} = \frac{J}{s} = W$$

GEOMETRY OF FLOW

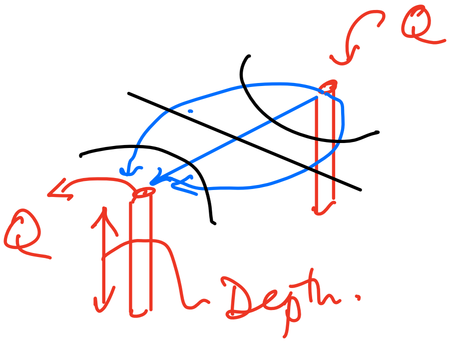
Flow Nets

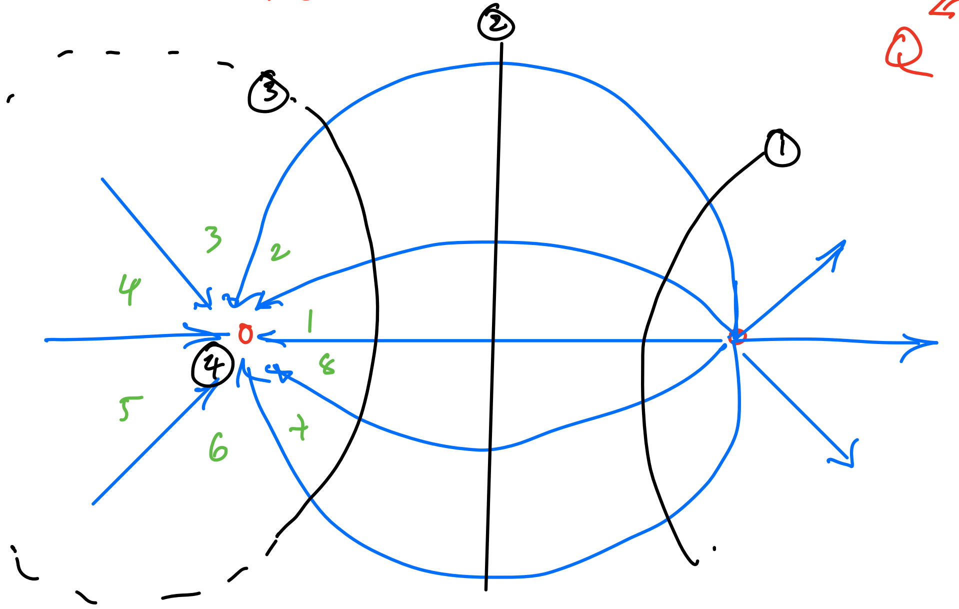


$$Q = \frac{N_f}{N_d} \cdot K \Delta h \doteq \frac{-}{-} \frac{m}{s} \cdot m \times \left(\begin{matrix}\text{length}\\ \text{into page}\end{matrix}\right)$$

$m^3/s.$

$$Q = \frac{N_f}{N_d} \cdot \frac{K}{\rho g}(\Delta h \rho g) = \frac{N_f}{N_d} \cdot \frac{k}{\mu} \Delta p$$





$$\frac{N_f}{N_d} \sim \frac{7}{4} \sim \frac{1}{2}$$

$$\boxed{Q \sim \text{Depth} \times \frac{N_f}{N_d} \times \frac{k}{\mu} \cdot \Delta p}$$

$$\boxed{\text{Power} \sim Q \rho c \Delta T}$$

QED.

Recall economic limit of $Q = 100\ l/s \sim 0.1\ m^3/s.$
for ~5 MW.

Check. $0.1 \frac{m^3}{s} \times 1000 \frac{kg}{m^3} \times 4000 \frac{J}{kg.K.} \times 100\ K$

~ 40 MW Thermal.

What is limiting k for $100\ l/s$?

3. FLUID FLOW AND GEOCHEMISTRY

3.1 Subsurface Fluid Flow

3.2 Simple Quantitative Models

3.3 Chemistry of Geothermal Fluids

5_1 Simple Quantitative Models - of Geothermal Reservoirs

Recap:

Fluid Flow - Defines rates of fluid transmission - controlled by Darcy's Law
Reservoirs may be liquid or vapor or mixed (multiphase) - Relative permeability
Geometry of flow matters (flow nets)

Movies:

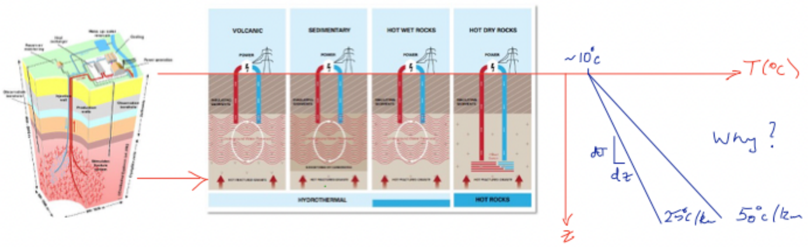
??:

Resources: AG2&3

Mass/Energy Balance: https://www.youtube.com/watch?v=P-wSRZIPJcg&feature=youtu.be

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



What changes in P&T result in a reservoir during production?
How do these changes impact rates and longevity of production of hot fluids?
What simple models describe these systems? Describing output (Power) and duration?
What are intrinsic differences between Lumped (box) and Distributed Parameter models?

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Define rates of fluid flow and energy production with time - thus productivity and longevity

1. Overall behavior of geothermal reservoirs - under production - Mechanisms of depletion
2. Lumped parameter models - pressure and heat recovery
3. Distributed parameter models - radial flow
4. Thermal breakthrough
5. Limits of heat rate recovery

1. Overall behavior of geothermal reservoirs - under production - Mechanisms of depletion

General form of reservoir:

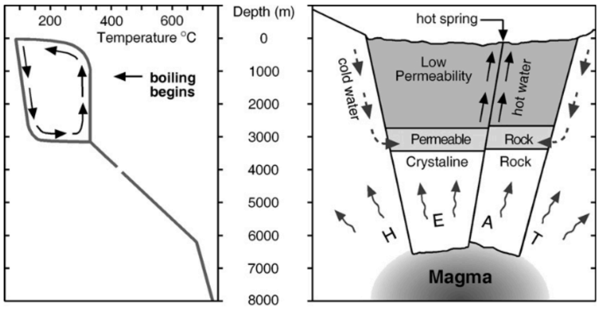


FIGURE 2.2 Model of the large-scale circulation of fluid in the natural state of a geothermal system. *Source: White, D.E., 1967 "Some principles of geyser activity, mainly from Steamboat Springs, Nevada" Am. J. Sci. 265, pp641–684.*

Pressure versus Depth

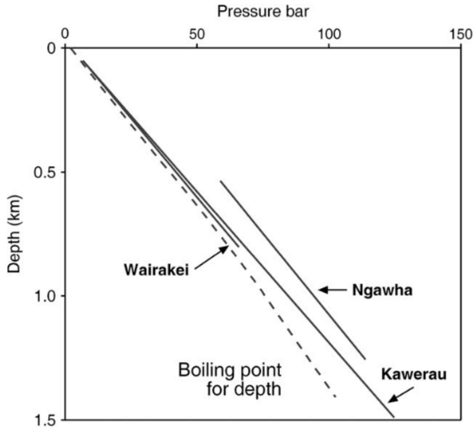


FIGURE 2.6 Pressure distribution with depth in three New Zealand geothermal fields. *Source: Grant 1981.*

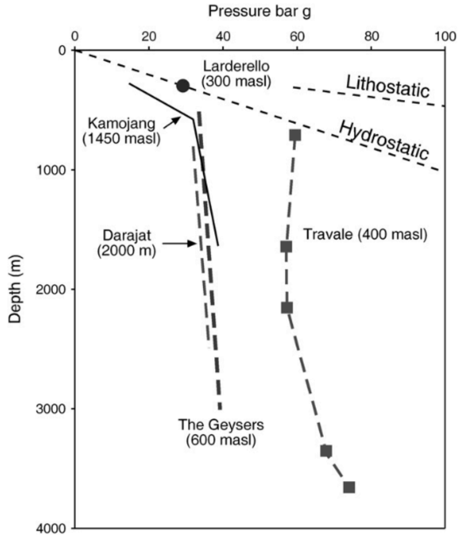
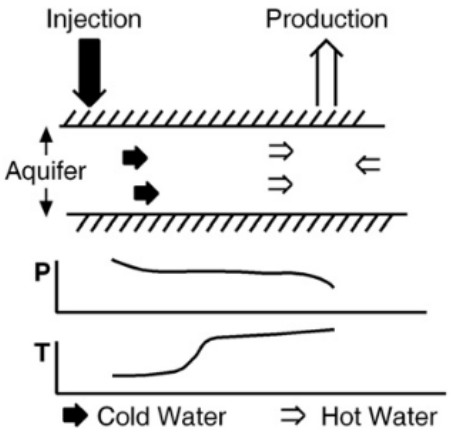


FIGURE 2.7 Reservoir pressure in vapor-dominated systems (Travale is part of greater Larderello). *Source: Allis, 2000.*

Impact of Depletion and Reinjection



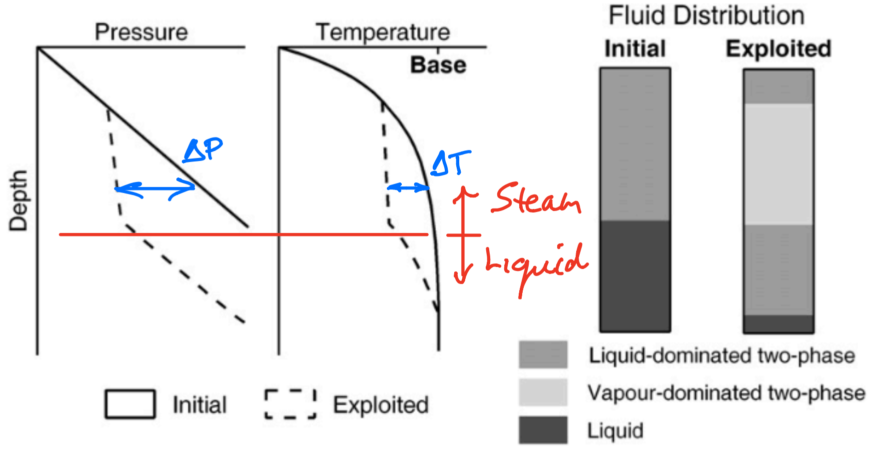


FIGURE 2.9 Fluid distribution in natural and exploited states of a liquid-dominated reservoir.

2. Lumped parameter models - pressure and heat recovery

Relative importance of Δp and ΔT.

$$h = \underset{\cancel{\rho}cT/\cancel{\rho}}{\underset{\downarrow}{u}} + P/\rho$$

Say $\Delta T = 100^\circ C$

$\Delta p = 10\,MPa \rightarrow 0$

$$u = c\Delta T = 4.1\times10^{3}\,J/kgK \times 10^{2}\,K$$

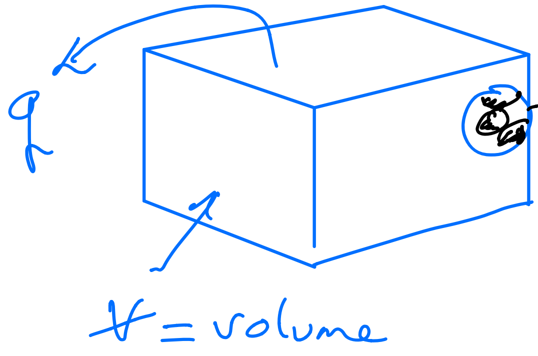
$$= \underline{4\times10^{5}\,J/kg}$$

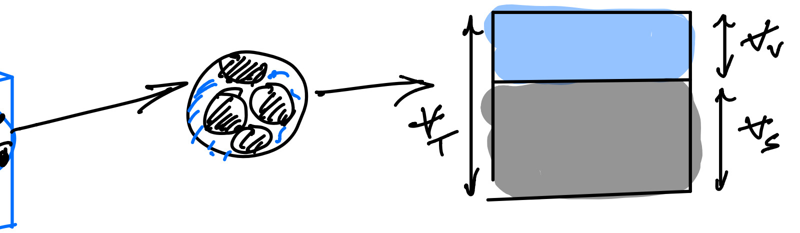
$$\Delta P/\rho = 10^{7}\,\frac{N}{m^2} \times \frac{1\,m^3}{10^3\,kg} = 10^4\,J/kg.$$

Relative importance of P & T

1. Heat is regenerable by resupply.
2. Pressure ~ $\frac{1}{40}$th ~ Thermal energy

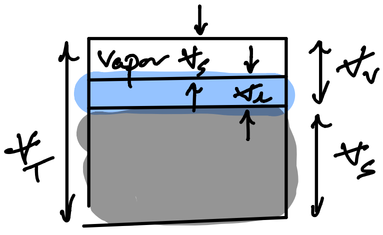
SIMPLE BOX MODELS





Porosity, $\phi = \frac{\mathcal{V}_v}{\mathcal{V}_T}$

Saturation, $S = \frac{\mathcal{V}_\ell}{\mathcal{V}_v}$



q = volumetric production rate

m^3/s

W = mass rate = $q\rho$ = kg/s

MASS BALANCE : $\forall \frac{d}{dt}(\phi\rho) = -W$

HEAT BALANCE : $\forall \frac{d}{dt}[(1-\phi)\rho_m U_m + \phi\rho U] = -WH$

Assuming isothermal depletion then

$$\forall\left[\rho\frac{\partial\phi}{\partial t} + \phi\frac{\partial\rho}{\partial t}\right] = -W$$

$$\forall\left[\rho\frac{\partial\phi}{\partial P}\underline{\frac{\partial P}{\partial t}} + \phi\frac{\partial\rho}{\partial P}\underline{\frac{\partial P}{\partial t}}\right] = -W$$

$$\forall\rho\left[\frac{\partial\phi}{\partial P} + \phi\frac{1}{\rho}\frac{\partial\rho}{\partial P}\right]\frac{\partial P}{\partial t} = -W$$

$$\frac{\partial\phi}{\partial P} = \frac{\partial\forall_v}{\partial P}\frac{1}{\forall_T} = C_m \qquad \phi . C$$

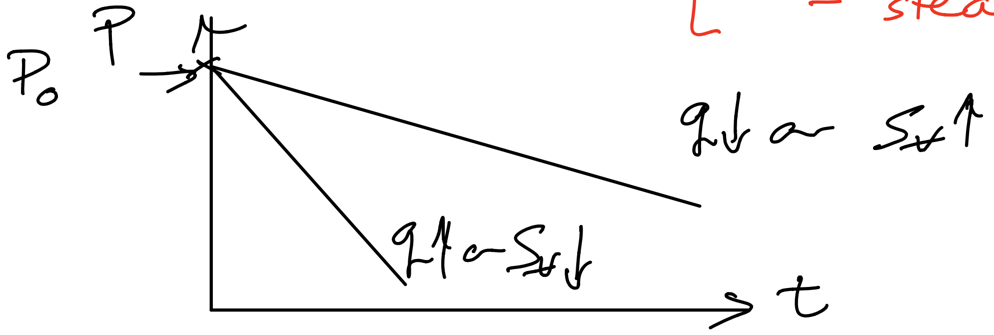
$$\rho\underline{\forall[C_m+\phi C]}\frac{\partial P}{\partial t} = -q\rho = -W$$

$$S_\forall = \forall[C_m+\phi C]$$

$C_m \sim 1/10GPa$

C – water ~ $1/2GPa$

– steam ~ 1/pressure



NOTE: If steam reservoir then $C_{steam} >> C_m$ or C_{liquid}

then use ideal gas law

$$S_V = V\phi c = V\phi/p = \frac{V\phi}{\rho RT}$$

Thus - pressure drop modulated as:

$$\frac{dP}{dt} = -\frac{q}{S_V} = -\frac{M}{S_M}$$

$$S_V = V[c_m + \phi c]$$

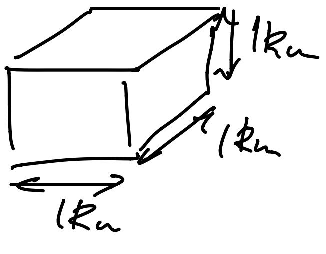
$$S_M = \rho S_V = \rho V[c_m + \phi c]$$

Definition of S_V

$$S_V = \frac{q\,dt}{dp} = \frac{V_{fluid}}{dp}$$

$$S_M = \frac{\text{Mass of fluid}}{dp}.$$

dp = 10 MPa (1000 m of water)



$$M_f = \rho V c\, dp = \underset{kg/m^3}{1000} \cdot \underset{m^3}{\cancel{10}^9} \cdot \frac{1}{\cancel{10}^9} \cdot 10^7$$

$$= \underline{\underline{10^{10}\ kg}}$$

Total mass of 1km cube of water is $10^9 \times 1000$ kg/m

$\Rightarrow 10^{12}$ kg ∴ $\frac{1}{100}$ th.

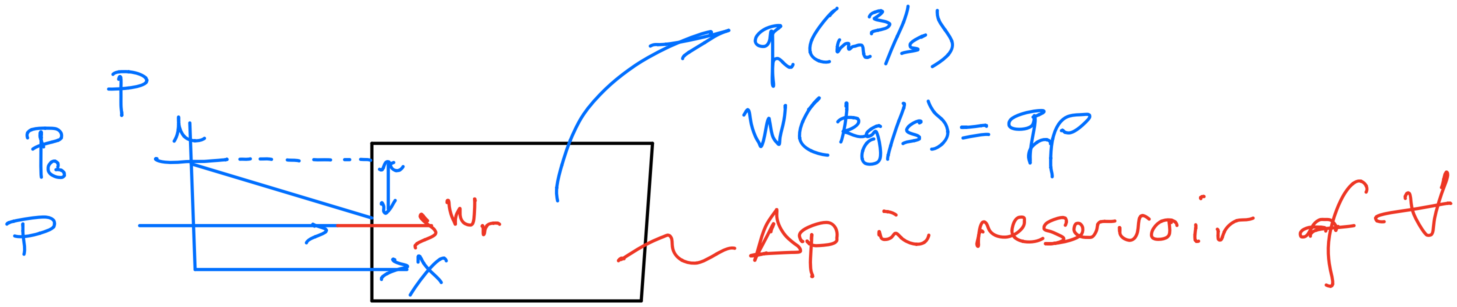
Convert pore space — water → steam.

then Mass water $= 10^{12} \times \cancel{\phi} \rightarrow 20\%$

$\sim 10^{11}$ kg.

Compressibility provides small release from storage!!

TRANSIENT RESPONSE



Reservoir — Δp due to withdrawal

Mass change is $W = S_M \Delta p$ in dt (1)

Balance recharge with withdrawal: $(W - W_r)\Delta t$ (2)

Conservation of mass fr (1) and (2)

$$S_M \frac{dp}{dt} + (W - W_r) = 0$$

Assume steady state when $W = W_r \rightarrow \frac{dP}{dt} = 0$

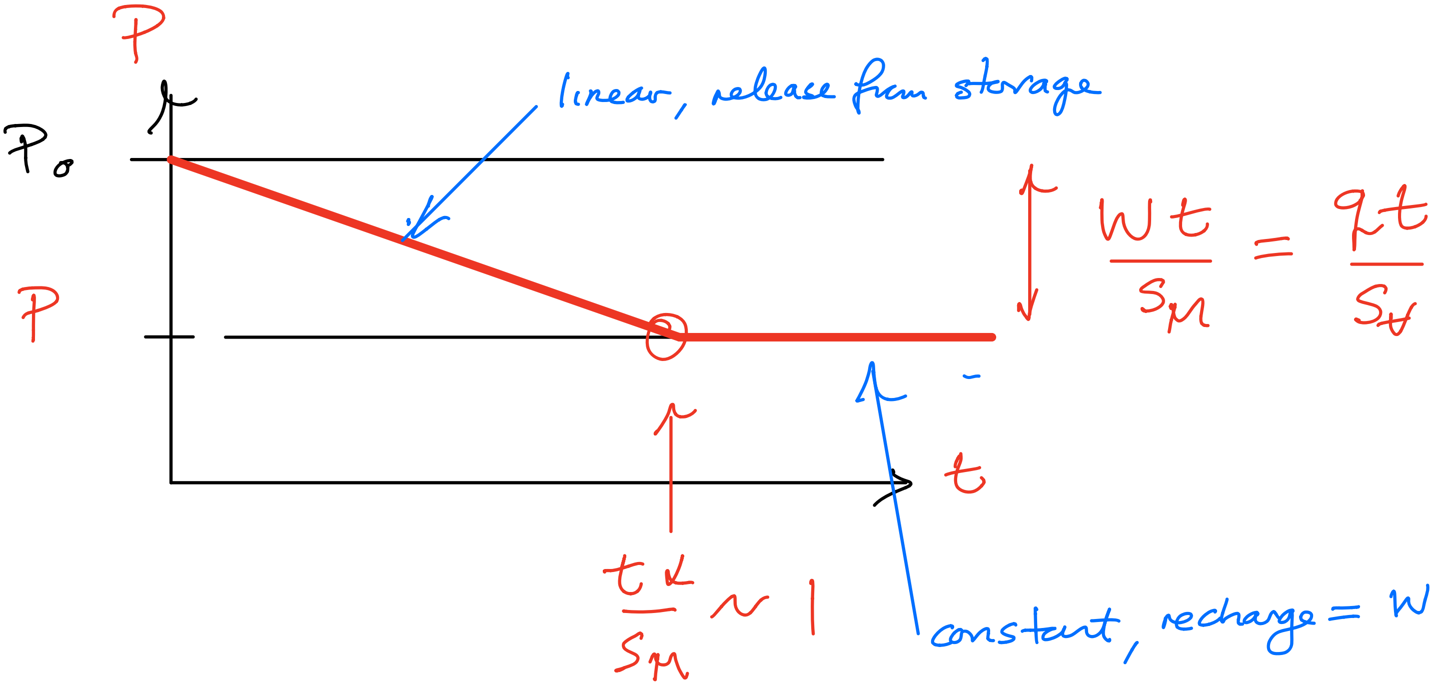
Set $W_r = \alpha (P_0 - P)$

Thus:

$$W = \alpha (P_0 - P) - S_M \frac{dP}{dt}$$

Solve:

$$P_0 - P = \frac{W}{\alpha}\left(1 - e^{-t\alpha/S_M}\right)$$



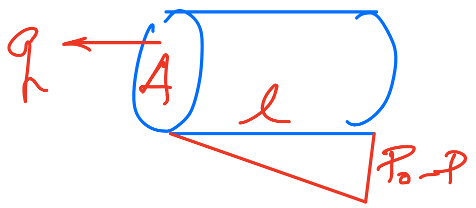
Energy recovery, $E = W c \Delta T$

Paramaterization

S_M — straightforward — n, ρ, V, c.

α — steady state — $\alpha = W/(P_0 - P)$

$$\alpha = \frac{W}{(P_0-P)} = \frac{q\rho}{(P_0-P)} = \frac{\rho \cdot Ak/\mu\,\cancel{(dP)}}{l \cdot \cancel{(P_0-P)}}$$



3. Distributed parameter models - radial flow

3.3. PRESSURE TRANSIENT MODELS

The simplest model is a vertical well, circular in cross section, that fully penetrates a uniform horizontal aquifer of infinite radial extent that is sealed above and below, as shown in Figure 3.1. There is no spatial variation of rock properties (especially permeability). The only spatial variations of pressure (and temperature and saturation, if relevant) that need to be considered are those pertaining to radial distance from the well. The fluid in the aquifer is in vertical equilibrium with depth at all times, so there are no effects due to gravity.

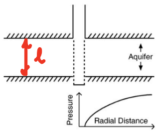


FIGURE 3.1 Basic well model for pressure transients.

3.3.1. Single-Phase Aquifer Fluid

Darcy's law in the radial (axial) form is:

$$v_r = -\frac{k}{\mu}\frac{\partial P}{\partial r} \tag{3.21}$$

In similar form, the conservation of mass equation is:

$$\varphi\frac{\partial\rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) = 0 \tag{3.22}$$

or

$$\varphi c\rho\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\rho\frac{k}{\mu}r\frac{\partial P}{\partial r}\right) \tag{3.23}$$

It is assumed that the compressibility is constant and that changes in the viscosity may be ignored in comparison with changes in pressure. This gives:

$$\frac{\varphi\mu c}{k}\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right) \tag{3.24}$$

This is the diffusivity equation, with the hydraulic diffusivity:

$$\kappa = \frac{k}{\varphi\mu c} \tag{3.25}$$

Many solutions of this equation are available from the literature on heat conduction, which obeys the same equation.

If a well begins withdrawal at time $t = 0$, at a constant rate q or $W = \rho q$, the pressure in the aquifer is given as a function of radial distance and time by:

$$\Delta P = P - P_o = -\frac{q\mu}{4\pi kh}E_1\left(\frac{\varphi\mu c r^2}{4kt}\right) = -\frac{W\nu}{4\pi kh}E_1\left(\frac{\varphi\mu c r^2}{4kt}\right) \tag{3.26}$$

where

$$E_1(x) = \int_x^\infty \frac{1}{y}e^{-y}dy \tag{3.27}$$

$E_1(x)$ is tabulated by Abramowitz and Stegun (1965). (The function $E_1(x)$ is denoted by $-Ei(-x)$ in the petroleum literature.) For small values of the argument x, or long time:

$$E_1(x) \sim -\ln(x) - \gamma \tag{3.28}$$

where $\gamma = 0.5772$ is Euler's constant. Using this asymptotic for Eq. (3.26) gives:

$$P - P_o = -\frac{W\nu}{4\pi kh}\left\{\ln(t) + \ln\left(\frac{4k}{\varphi\mu c r^2}\right) - \gamma\right\} \tag{3.29}$$

The pressure at any point changes linearly with the logarithm of the time. In Eq. (3.26) the parameters of the aquifer and fluid enter in two groups:

$$\frac{\mu}{4\pi kh}$$

and

$$\frac{\varphi\mu c}{k} = \frac{\varphi ch}{(kh/\mu)} \tag{3.30}$$

By suitable observation of the pressure change, it may be possible to fit an observed history to theory and identify the two parameter groups kh/μ, the transmissivity or mobility-thickness, and φch, the storativity. (k/μ is called the mobility.) If the fluid viscosity μ is known, the permeability-thickness kh can be identified. Thus, in principle, two parameter groups are identifiable. One, the storativity, measures the aquifer's capacity to store fluid, and the other, the transmissivity, measures its ability to transmit fluid.

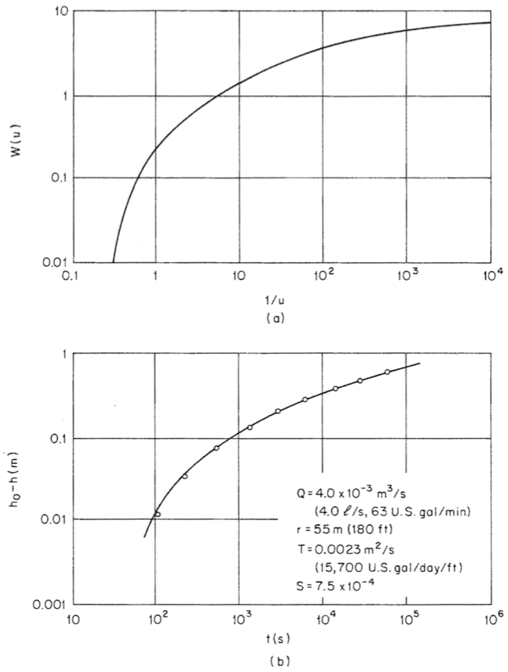
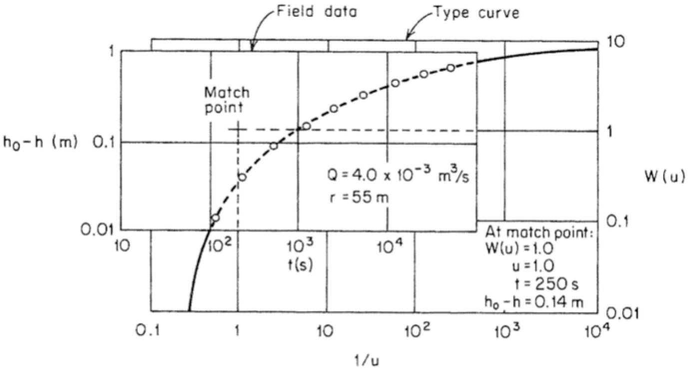


Figure 8.5 (a) Theoretical curve of $W(u)$ versus $1/u$. (b) Calculated curve of $h_0 - h$ versus t.



$$T = \frac{QW(u)}{4\pi(h_0-h)} = \frac{(4.0 \times 10^{-3})(1.0)}{(4.0)(3.14)(0.14)} = 0.0023\ \text{m}^2/\text{s} \quad (15{,}700\ \text{U.S. gal/day/ft})$$

$$S = \frac{4uTt}{r^2} = \frac{(4.0)(1.0)(0.0023)(250)}{(55.0)^2} = 7.5 \times 10^{-4}$$

Figure 8.22 Determination of T and S from $h_0 - h$ versus t data using the log-log curve-matching procedure and the $W(u)$ versus $1/u$-type curve.

Conversions: $T = K\ell = \frac{k}{\mu}\cdot\rho g\cdot\ell$

$(h_0 - h) = (P_0 - P)/\gamma$

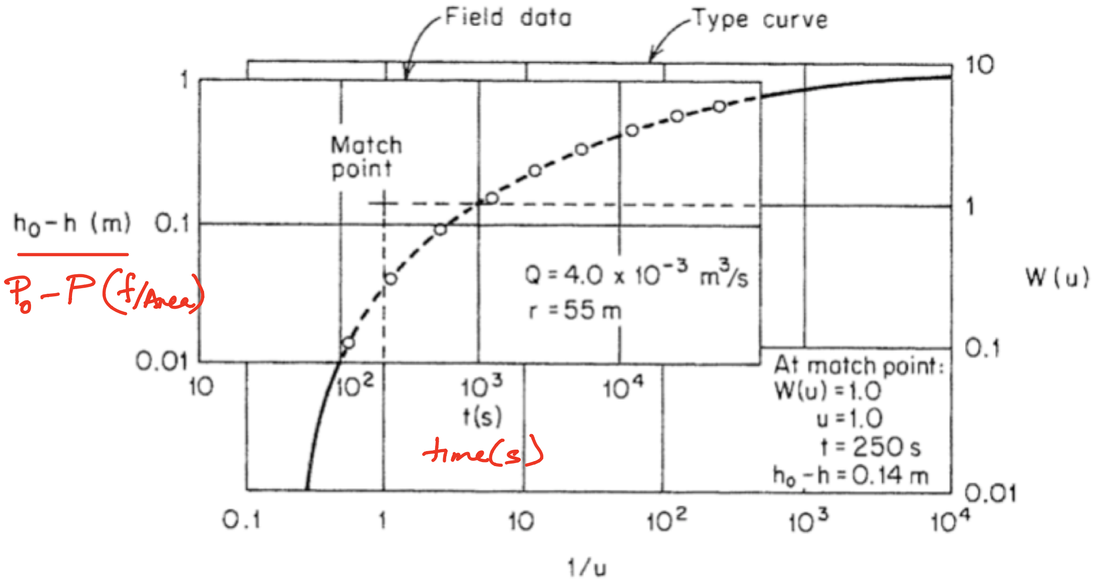
$Q = q$

$S = S_s\cdot\ell = \rho g c\ell.$

Plot $(P_0 - P)$-vs-time

Find matchpoints: $\frac{1}{u} = W(u) = 1$

$P_0 - P$ and t.



Evaluate reservoir properties

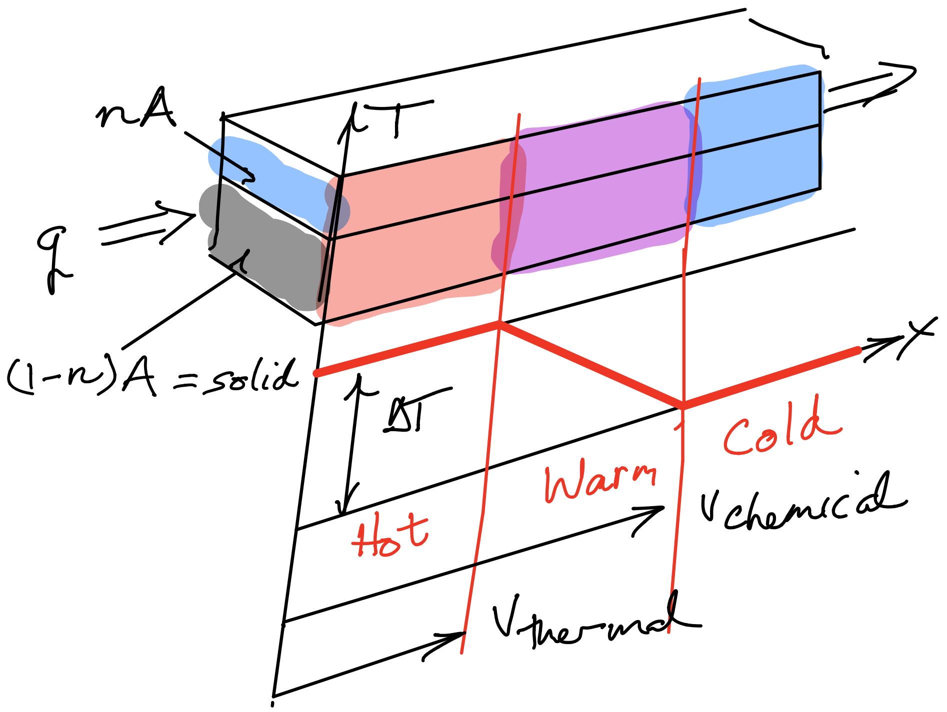
$$T = \frac{k}{\mu} \cancel{\rho} \cancel{g} \, l = \frac{q \, W(u) \, \cancel{\rho g}}{4\pi (P_o - P)}$$

$$\boxed{k = \frac{\mu}{l} \cdot \frac{q \, W(u)}{4\pi (P_o - P)}}$$

$$S = \cancel{\rho g} \, c \, \cancel{l} = 4 u t \frac{k}{\mu} \cancel{\rho g} \frac{\cancel{l}}{r^2}$$

$$\boxed{c = 4 u t \frac{k}{\mu} \frac{1}{r^2}}$$

4. Thermal breakthrough



Hot fluid injected
Cold reservoir
(backwards?)

$$\frac{q}{A\phi} = V_{chemical}$$

Thermal energy injected: $H_{th} = \rho c q \Delta T \, dt$

Thermal energy absorbed: $H_{ab} = (\rho C)_{reservoir} \Delta T \, V_{therm} A \, dt$

Equating:

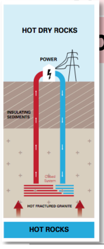
$$\rho c \, (V_{chem} \cancel{A} \phi) \cancel{\Delta T} \cancel{dt} = (\rho c)_r \cancel{\Delta T} \, V_{thermal} \cancel{A} \cancel{dt}$$

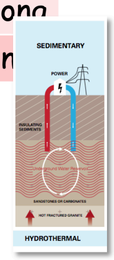
$$\frac{V_{thermal}}{V_{chemical}} = \frac{\phi \rho c}{\phi \rho c + (1-\phi)\rho_m c_m} = \left[1 + \frac{(1-\phi)}{\phi} \underset{\overset{\uparrow}{\sim \frac{1}{2}}}{\frac{\rho_m c_m}{\rho c}}\right]^{-1}$$

n	Vchem/Vthermal
10%	5.5
20%	3.0
30%	2.2
100%	1

Contrasts Between EGSs & SGRs

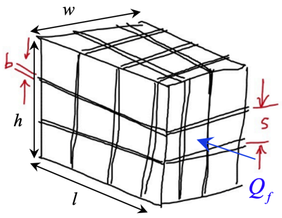
EGS (Order of Mag.)	Property	SGRs (Order of Mag)
Fractured-non-porous	General	Porous-fractured
<<1%,<1%	Porosity, n_0 -> n_{stim}	~10-30%, ~same
microD -> mD	Permeability, k_0 -> k_{stim}	>mD -> >>mD
10^6	K_f/k_{matrix}	10^6 ->1
10-100m	Heat transfer length, s	1m -> 1cm
>>100/1. >100/1	*$Heat_{solid}/Heat_{fluid}$	~10/1-2/1, same
?	Chemistry	?
V. Strong	TM Perm. Feedbacks	Less strong
oderate, late time	TC Perm. Feedbacks	Stron





$$*\frac{\text{Heat in solid}}{\text{Heat in fluid}}=\frac{\cancel{V}(1-n)\rho_R c_R \Delta T}{\cancel{V}(n)\rho_W c_W \Delta T}=\frac{(1-n)}{n}\frac{\rho_R c_R}{\rho_W c_W}$$

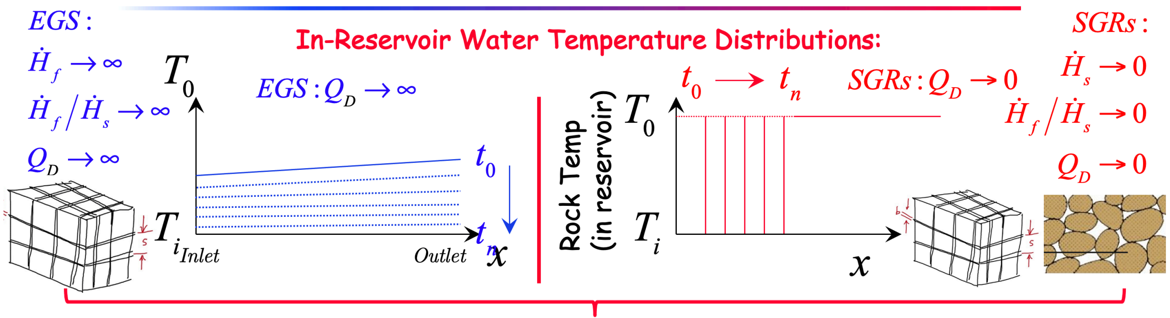
Thermal Drawdown EGS -vs- SGRs



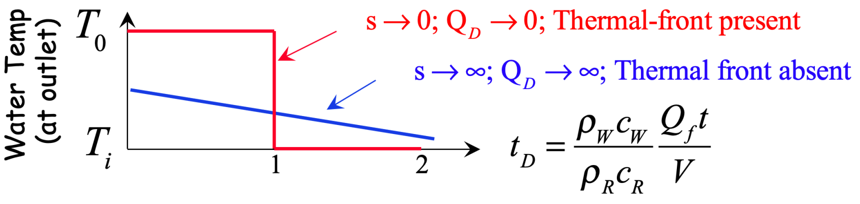
$$\dot{H}_{solid} \sim A\lambda_R \frac{dT}{dx} \sim \frac{V\lambda_R \Delta T}{s^2}$$

$$\dot{H}_{fluid} \sim Q_f \rho_W c_W \Delta T$$

$$\frac{\dot{H}_f}{\dot{H}_s} \sim \frac{\rho_W c_W}{\lambda_R}\frac{Q_f s^2}{V} = Q_D$$

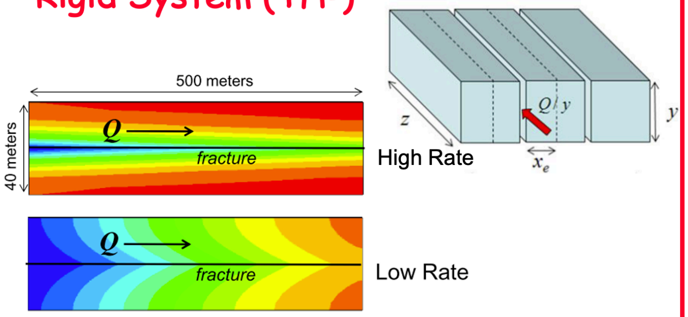


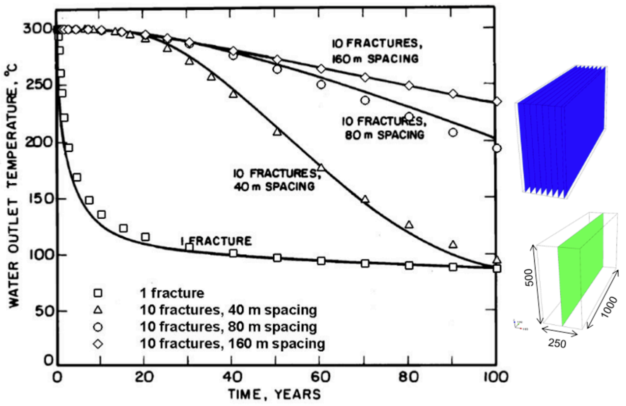
Thermal Output:



Thermal Short-Circuiting

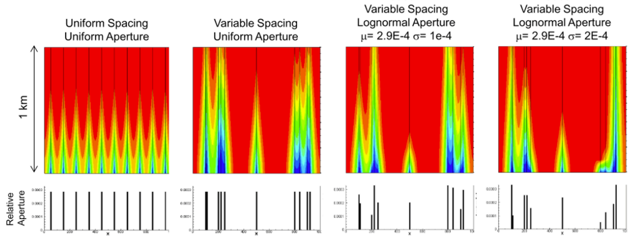
Rigid System (TH-)

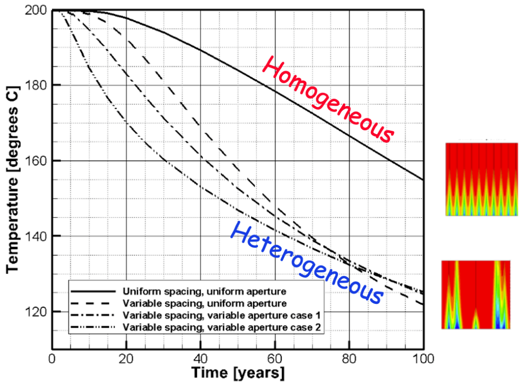




Deformable System (THM)

- Positive dQ->dT->dU->dQ
- Correlated initial aperture and length

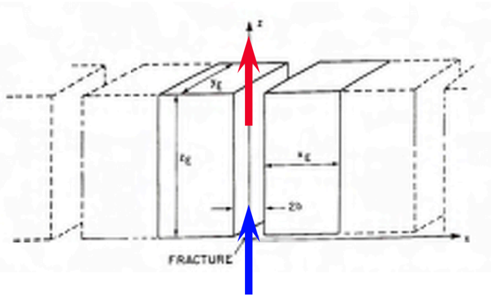




[Doe, et al, 39th Stanford Geotherm. Wkshp., 2014]

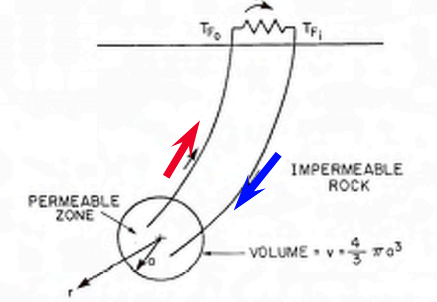
Thermal Recovery at Field Scale

Parallel Flow Model

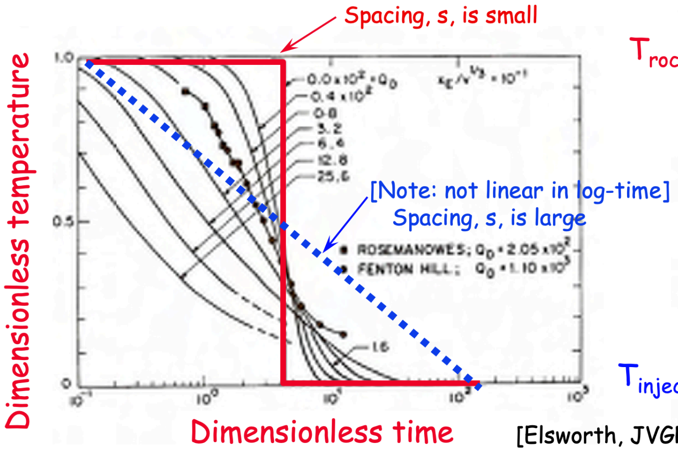


[Gringarten and Witherspoon, Geothermics,1974]

Spherical Reservoir Model



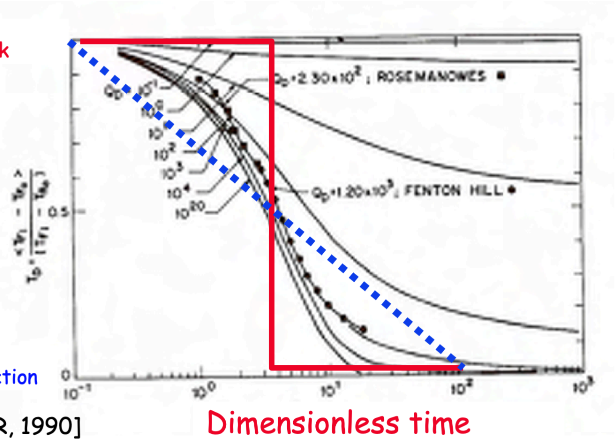
[Elsworth, JGR, 1989]



T_{rock}

$T_{injection}$

[Elsworth, JVGR, 1990]



3. FLUID FLOW AND GEOCHEMISTRY

3.1 Subsurface Fluid Flow
3.2 Simple Quantitative Models
3.3 Chemistry of Geothermal Fluids

6_1 Chemistry of Geothermal Fluids

Recap:

1. Overall behavior of geothermal reservoirs - under production - Mechanisms of depletion
2. Lumped parameter models - pressure and heat recovery
3. Distributed parameter models - radial flow
4. Thermal breakthrough
5. Limits of heat rate recovery

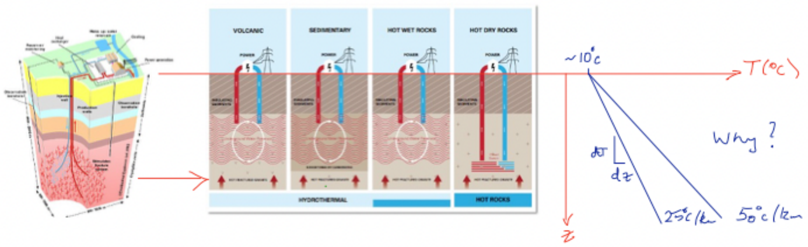
Movies:

??:

Resources: WG5

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



What chemical reactions and dissolution and precipitation impact:

1. Piping and wells
2. Surface facilities
3. Subsurface reservoirs - injection and recovery

Scientific Questions:

2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Define rates of fluid flow and energy production with time - influenced by chemistry

1. Chemistry of geothermal fluids
2. Units of concentration
3. Chemical equilibrium and Law of Mass Action
   - A. Chemical activity
   - B. Affinity
4. Solubility
5. Kinetics and reaction rates
6. Reservoir/Plan response

1. Chemistry of geothermal fluids

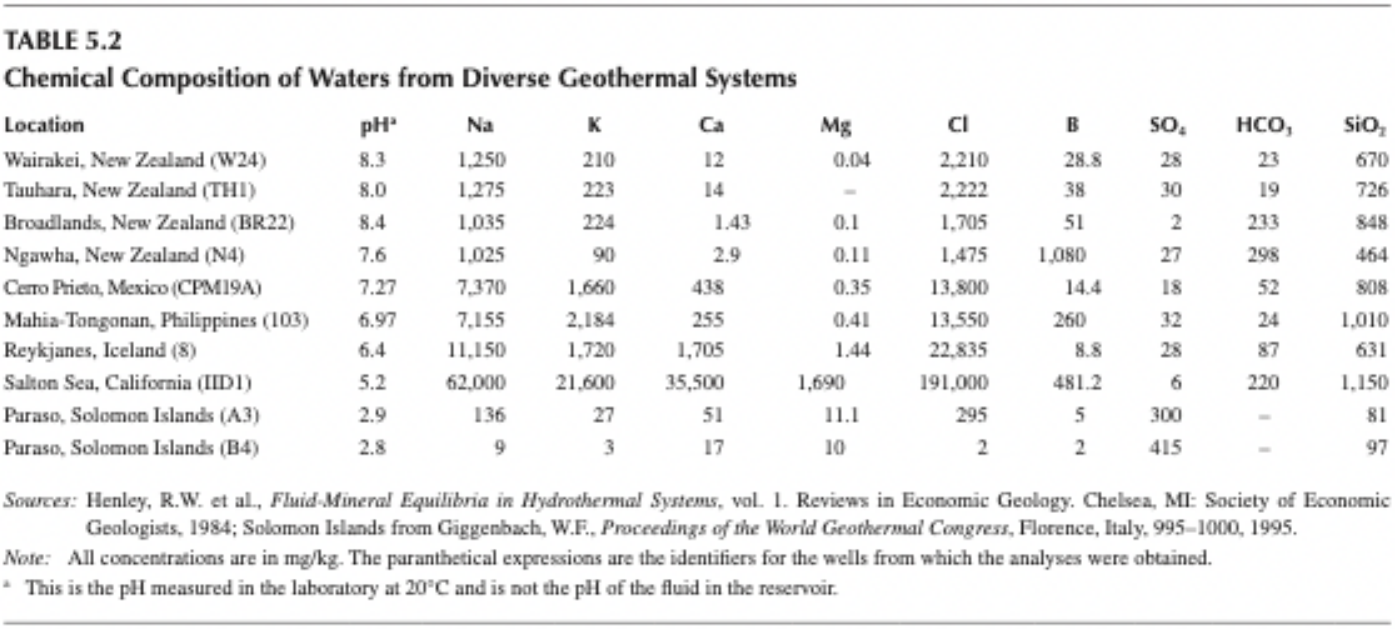


TABLE 5.2

Chemical Composition of Waters from Diverse Geothermal Systems

Location	pH[a]	Na	K	Ca	Mg	Cl	B	SO_4	HCO_3	SiO_2
Wairakei, New Zealand (W24)	8.3	1,250	210	12	0.04	2,210	28.8	28	23	670
Tauhara, New Zealand (TH1)	8.0	1,275	223	14	–	2,222	38	30	19	726
Broadlands, New Zealand (BR22)	8.4	1,035	224	1.43	0.1	1,705	51	2	233	848
Ngawha, New Zealand (N4)	7.6	1,025	90	2.9	0.11	1,475	1,080	27	298	464
Cerro Prieto, Mexico (CPM19A)	7.27	7,370	1,660	438	0.35	13,800	14.4	18	52	808
Mahia-Tongonan, Philippines (103)	6.97	7,155	2,184	255	0.41	13,550	260	32	24	1,010
Reykjanes, Iceland (8)	6.4	11,150	1,720	1,705	1.44	22,835	8.8	28	87	631
Salton Sea, California (IID1)	5.2	62,000	21,600	35,500	1,690	191,000	481.2	6	220	1,150
Paraso, Solomon Islands (A3)	2.9	136	27	51	11.1	295	5	300	–	81
Paraso, Solomon Islands (B4)	2.8	9	3	17	10	2	2	415	–	97

Sources: Henley, R.W. et al., *Fluid-Mineral Equilibria in Hydrothermal Systems*, vol. 1. Reviews in Economic Geology. Chelsea, MI: Society of Economic Geologists, 1984; Solomon Islands from Giggenbach, W.F., *Proceedings of the World Geothermal Congress*, Florence, Italy, 995–1000, 1995.

Note: All concentrations are in mg/kg. The paranthetical expressions are the identifiers for the wells from which the analyses were obtained.

[a] This is the pH measured in the laboratory at 20°C and is not the pH of the fluid in the reservoir.

2. Units of concentration

By mass per liter of water: $mg/L \doteq 10^{-3} g/L \doteq ppm$

$\mu g/L \doteq 10^{-6} g/L \doteq ppb$

Equivalent weight: $\dfrac{\text{Formula weight}}{\text{Electrical charge (of ion)}}$

Milliequivalents per liter: $\dfrac{\text{Concentration in mg/L}}{\text{Formula weight}}$

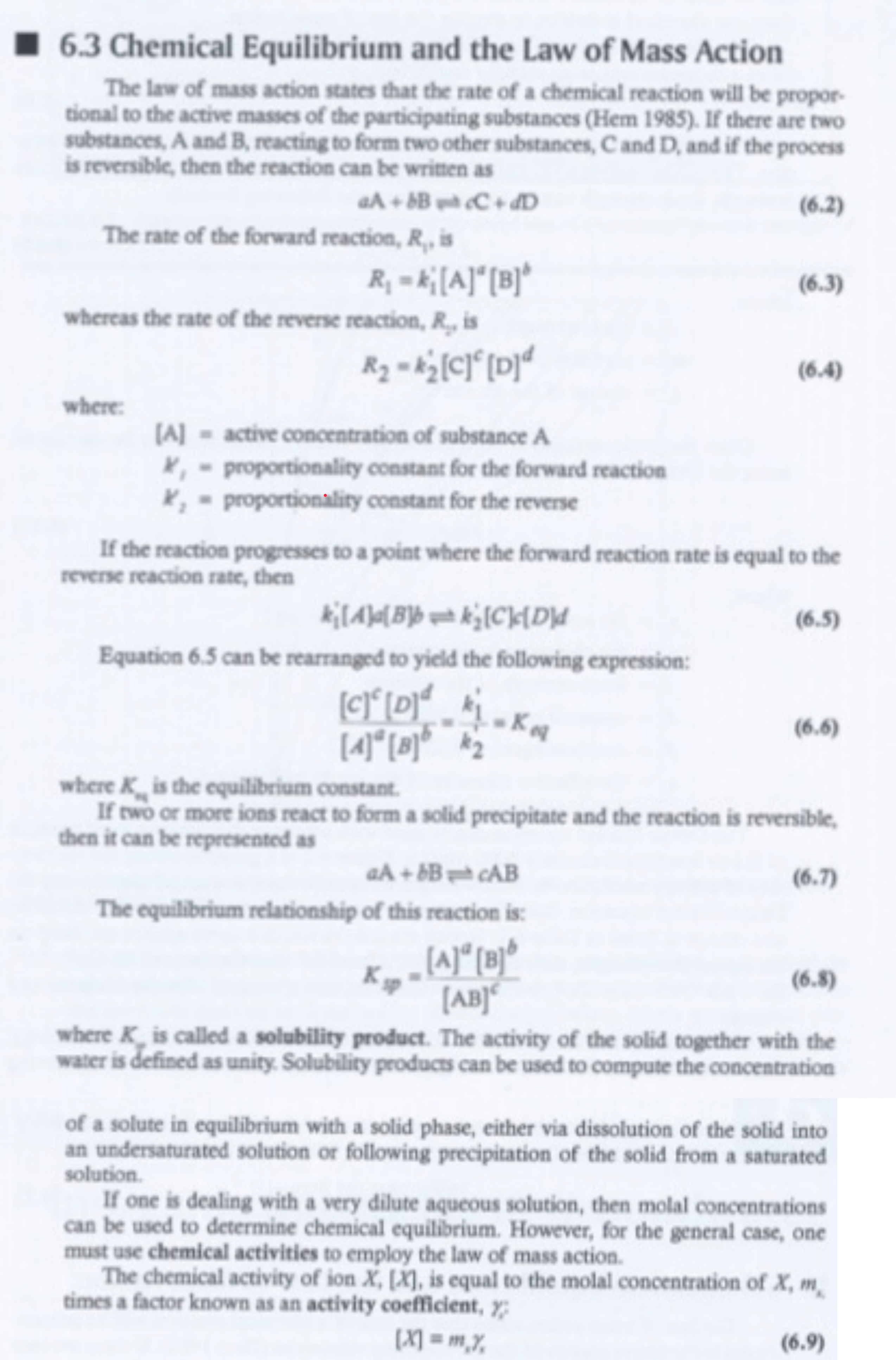
1-Molal : 1 mole solute in 1000 g (1 Liter) of solvent

1-Molar : 1 mole solute in 1000 g (   ) of solution

For dilute solution (less than seawater)

$$\text{Molality} = \frac{(mg/L) \times 1}{\text{Formula wt.}}$$

3. Chemical equilibrium and Law of Mass Action



6.3 Chemical Equilibrium and the Law of Mass Action

The law of mass action states that the rate of a chemical reaction will be proportional to the active masses of the participating substances (Hem 1985). If there are two substances, A and B, reacting to form two other substances, C and D, and if the process is reversible, then the reaction can be written as

$$aA + bB \rightleftharpoons cC + dD \tag{6.2}$$

The rate of the forward reaction, R_1, is

$$R_1 = k_1'[A]^a[B]^b \tag{6.3}$$

whereas the rate of the reverse reaction, R_2, is

$$R_2 = k_2'[C]^c[D]^d \tag{6.4}$$

where:

[A] = active concentration of substance A
k'_1 = proportionality constant for the forward reaction
k'_2 = proportionality constant for the reverse

If the reaction progresses to a point where the forward reaction rate is equal to the reverse reaction rate, then

$$k_1'[A]a[B]b \rightleftharpoons k_2'[C]c[D]d \tag{6.5}$$

Equation 6.5 can be rearranged to yield the following expression:

$$\frac{[C]^c[D]^d}{[A]^a[B]^b} = \frac{k_1'}{k_2'} = K_{eq} \tag{6.6}$$

where K_{eq} is the equilibrium constant.

If two or more ions react to form a solid precipitate and the reaction is reversible, then it can be represented as

$$aA + bB \rightleftharpoons cAB \tag{6.7}$$

The equilibrium relationship of this reaction is:

$$K_{sp} = \frac{[A]^a[B]^b}{[AB]^c} \tag{6.8}$$

where K_{sp} is called a **solubility product**. The activity of the solid together with the water is defined as unity. Solubility products can be used to compute the concentration of a solute in equilibrium with a solid phase, either via dissolution of the solid into an undersaturated solution or following precipitation of the solid from a saturated solution.

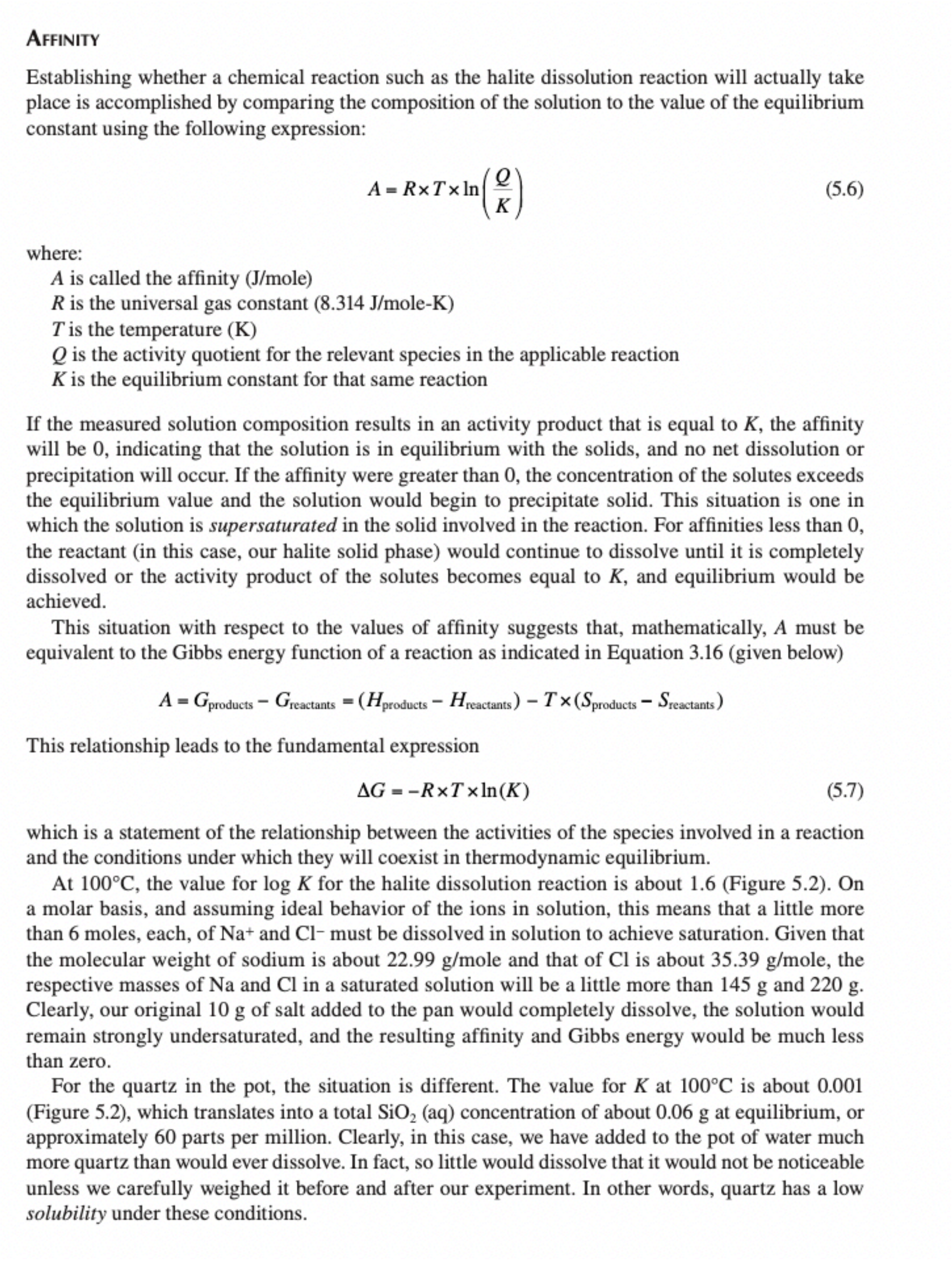
If one is dealing with a very dilute aqueous solution, then molal concentrations can be used to determine chemical equilibrium. However, for the general case, one must use **chemical activities** to employ the law of mass action.

The chemical activity of ion X, $[X]$, is equal to the molal concentration of X, m_x times a factor known as an **activity coefficient**, γ_x:

$$[X] = m_x\gamma_x \tag{6.9}$$

A. Chemical activity (see above)

B. Affinity



AFFINITY

Establishing whether a chemical reaction such as the halite dissolution reaction will actually take place is accomplished by comparing the composition of the solution to the value of the equilibrium constant using the following expression:

$$A = R \times T \times \ln\left(\frac{Q}{K}\right) \tag{5.6}$$

where:

A is called the affinity (J/mole)
R is the universal gas constant (8.314 J/mole-K)
T is the temperature (K)
Q is the activity quotient for the relevant species in the applicable reaction
K is the equilibrium constant for that same reaction

If the measured solution composition results in an activity product that is equal to *K*, the affinity will be 0, indicating that the solution is in equilibrium with the solids, and no net dissolution or precipitation will occur. If the affinity were greater than 0, the concentration of the solutes exceeds the equilibrium value and the solution would begin to precipitate solid. This situation is one in which the solution is *supersaturated* in the solid involved in the reaction. For affinities less than 0, the reactant (in this case, our halite solid phase) would continue to dissolve until it is completely dissolved or the activity product of the solutes becomes equal to *K*, and equilibrium would be achieved.

This situation with respect to the values of affinity suggests that, mathematically, *A* must be equivalent to the Gibbs energy function of a reaction as indicated in Equation 3.16 (given below)

$$A = G_{\text{products}} - G_{\text{reactants}} = (H_{\text{products}} - H_{\text{reactants}}) - T \times (S_{\text{products}} - S_{\text{reactants}})$$

This relationship leads to the fundamental expression

$$\Delta G = -R \times T \times \ln(K) \tag{5.7}$$

which is a statement of the relationship between the activities of the species involved in a reaction and the conditions under which they will coexist in thermodynamic equilibrium.

At 100°C, the value for log *K* for the halite dissolution reaction is about 1.6 (Figure 5.2). On a molar basis, and assuming ideal behavior of the ions in solution, this means that a little more than 6 moles, each, of Na^+ and Cl^- must be dissolved in solution to achieve saturation. Given that the molecular weight of sodium is about 22.99 g/mole and that of Cl is about 35.39 g/mole, the respective masses of Na and Cl in a saturated solution will be a little more than 145 g and 220 g. Clearly, our original 10 g of salt added to the pan would completely dissolve, the solution would remain strongly undersaturated, and the resulting affinity and Gibbs energy would be much less than zero.

For the quartz in the pot, the situation is different. The value for *K* at 100°C is about 0.001 (Figure 5.2), which translates into a total SiO_2 (aq) concentration of about 0.06 g at equilibrium, or approximately 60 parts per million. Clearly, in this case, we have added to the pot of water much more quartz than would ever dissolve. In fact, so little would dissolve that it would not be noticeable unless we carefully weighed it before and after our experiment. In other words, quartz has a low *solubility* under these conditions.

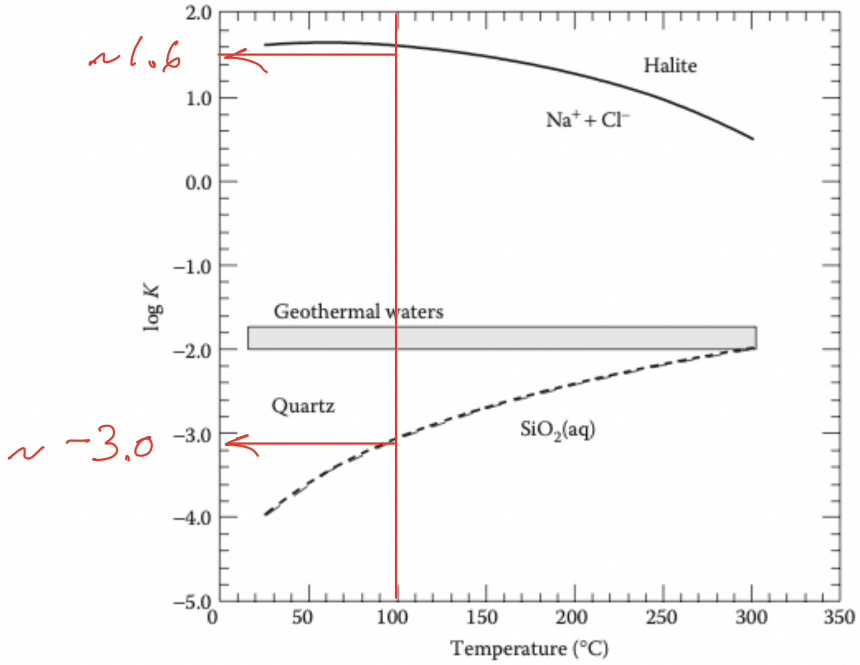


FIGURE 5.2 Variation of the equilibrium constant for halite and quartz dissolution, as a function of temperature. The gray box encloses the range of aqueous SiO_2 compositions for the geothermal waters listed in Table 5.1.

$\log K = 1.6$

$K = 10^{1.6} \sim 40.$

$\log K = -3$

$K \sim 0.001$

4. Solubility

10g of NaCl @ 100°c

$\log K = 1.6$

$K = 40$

$[Na]'[Cl]' = 40 \quad \therefore \sim\sqrt{40} \sim 6$ moles

Na : 23g/mole × 6 ~ 150g } saturat

Cl : 35g/mole × 6 ~ 210g

10g in 1 liter ∴ undersaturated

10g of SiO_2 @ 100°c

$\log K = -3$

$K \sim 0.001$

$[SiO_2]' = 0.001$

Si : 28g/mole } ~ 60g/mole

O : 16g/mole × 2

60 g/mole × 0.001 ~ 0.6 g
@ saturation

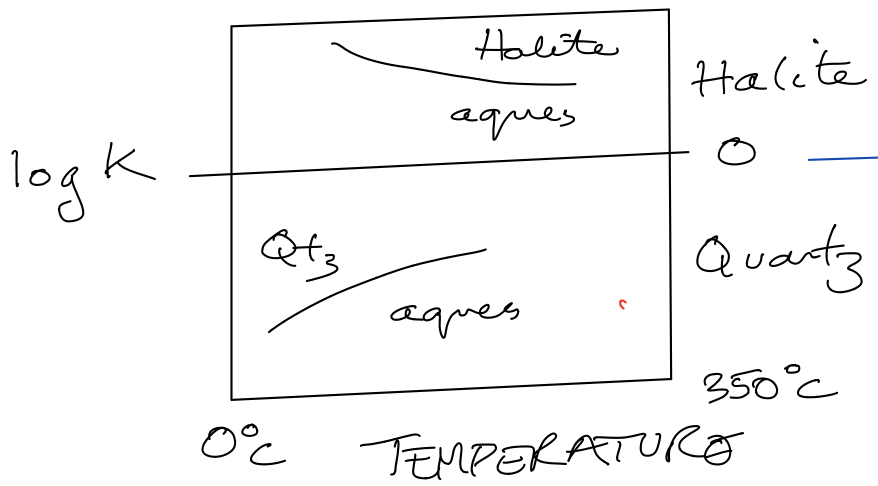
∴ 10g is much more than would dissolve.

Consequences of Affinity and Gibbs Energy

(+ve)

$$\Delta G = -R \times T \times \ln(K)$$

+ve (8.314 J/m.K)



log K (+ve)
∴ ΔG and Affinity (−ve)
Undersaturated

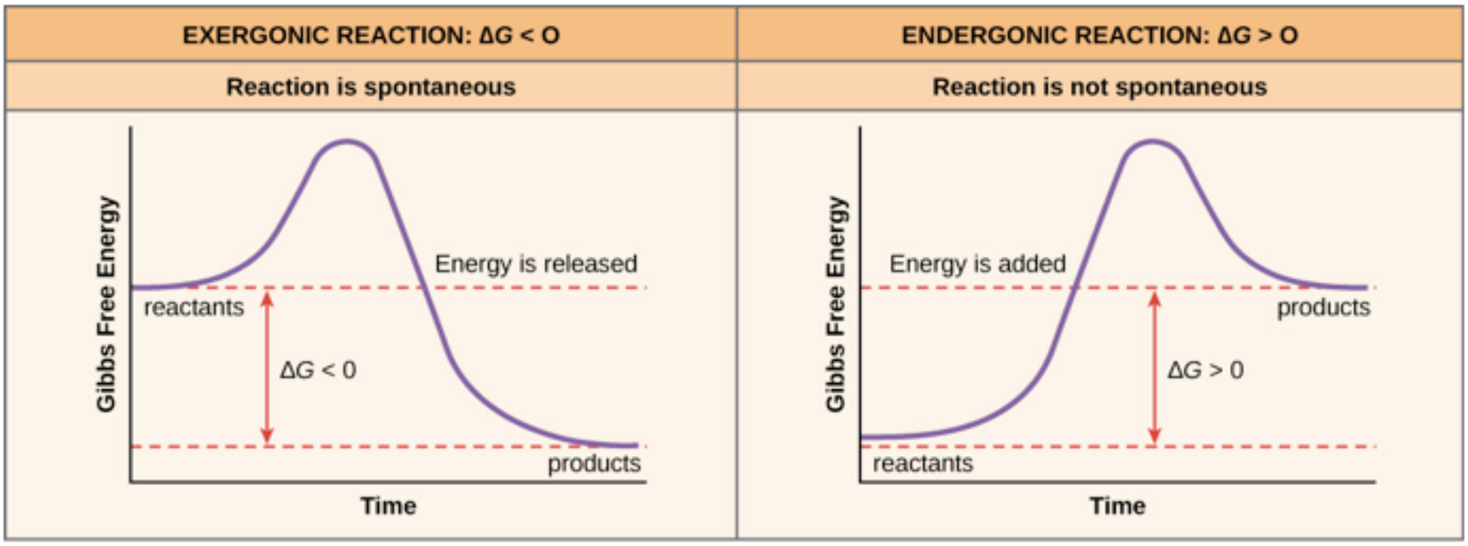
log K (−ve)
∴ ΔG and Affinity (+ve)

Saturated

RELEVANCE OF GIBBS ENERGY

$$\Delta G = \Delta H - T\Delta S$$

	$\Delta H < 0$	$\Delta H > 0$
$\Delta S > 0$	Spontaneous at all T $(\Delta G < 0)$	Spontaneous at high T (when $T\Delta S$ is large)
$\Delta S < 0$	Spontaneous at low T (when $T\Delta S$ is small)	Non-spontaneous at all T $(\Delta G > 0)$



PROGRADE VS RETROGRADE SOLUBILITY

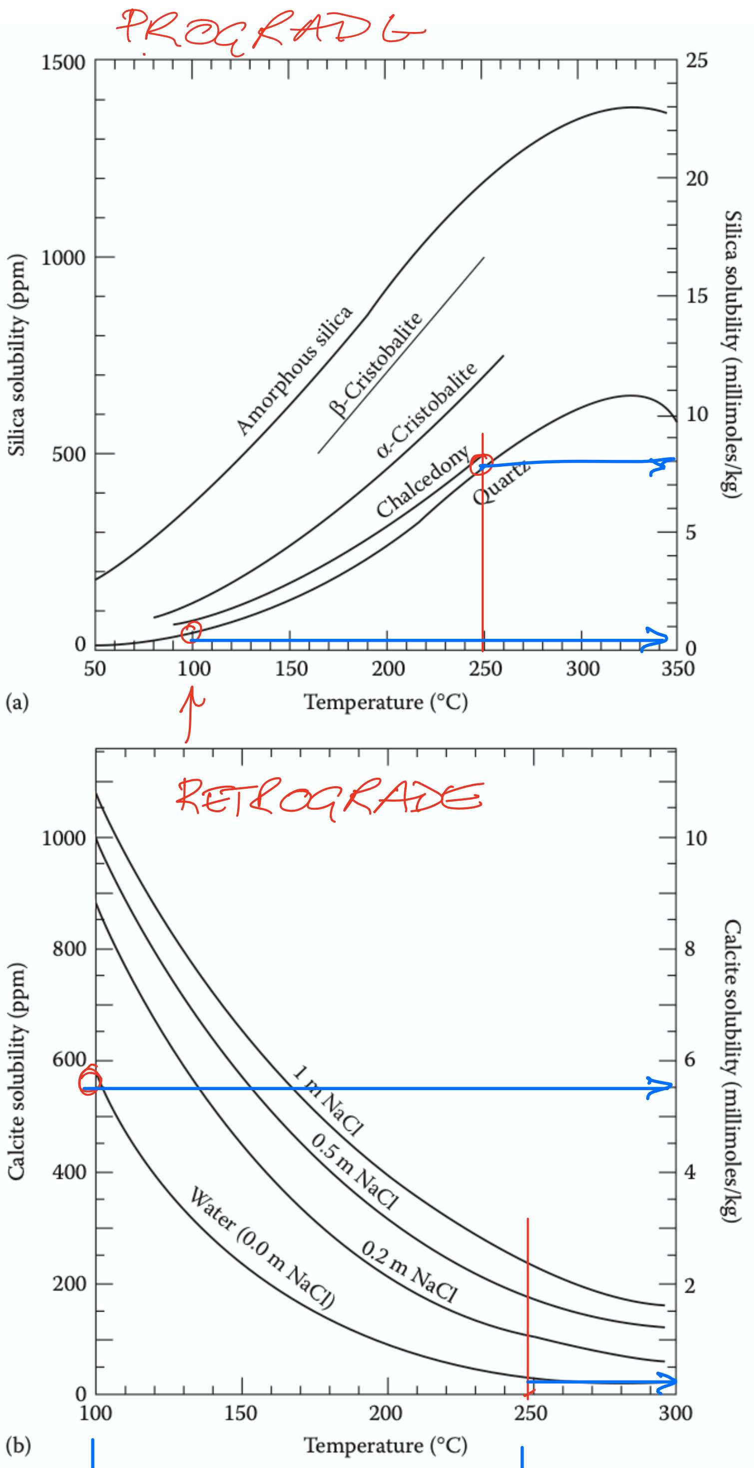
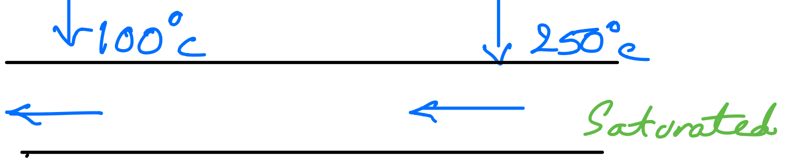


FIGURE 5.3 Comparison of the solubility of (a) quartz and (b) calcite, as a function of temperature and composition of the solvent (for calcite).

$CaCO_3(s) \rightarrow Ca^{2+} + CO_3^{2-}$

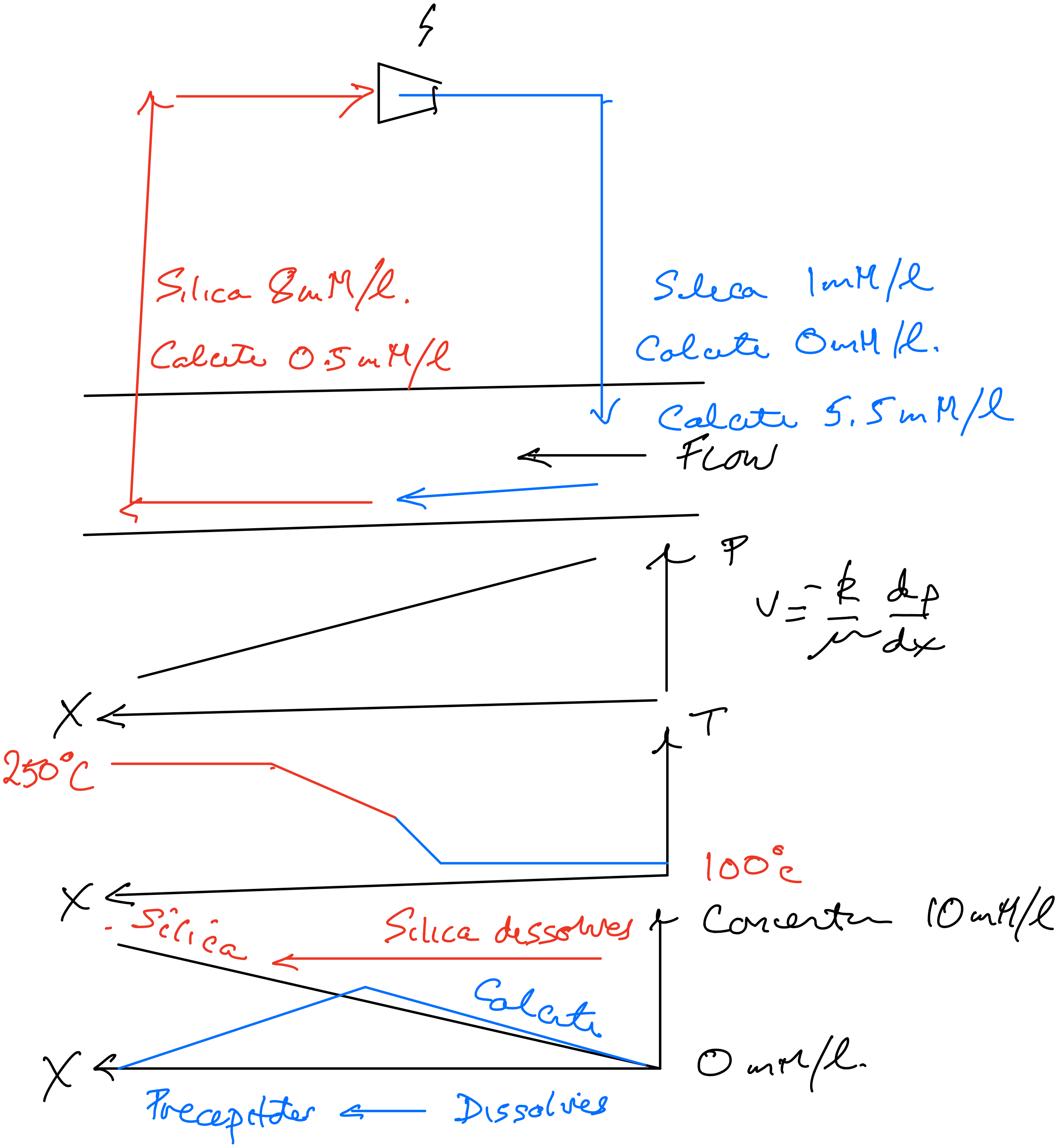
$CO_3^{2+} + H_2O \rightarrow HCO_3^{-} + H^{+}$

Sensitive to pH and presence of other ions.



Precipitation	< 1 mM	~ 8 mM/liter Silica
Dissolution	5.5 mM	< 0.5 mM/liter Calcite

IMPLICATIONS OF DISSOLUTION/PRECIPITATION



[3:3] Mass Transport

Recap

$$\underline{S}\,\underline{\dot{c}} + [\underline{K}_d + \underline{K}_a]\,\underline{c} = \underline{q} + \underline{R}$$

Reactive transport

- Sorption
- First-order reactions
- Multiple reactions

Reaction Rates

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (c_i \mathbf{u}) - \nabla \cdot (D_i \nabla c_i) = R_i \tag{1}$$

For the reaction:

$$A + B \underset{k_2}{\overset{k_1}{\rightleftharpoons}} C \tag{2}$$

$$\begin{aligned} \text{Forward rate} &= k_1[A][B] \\ \text{Reverse rate} &= k_2[C] \end{aligned} \tag{3}$$

At equilibrium:

$$\text{Forward rate} = \text{Reverse rate}$$

$$k_1[A][B] = k_2[C] \tag{4}$$

$$\therefore \quad [A][B] = \frac{k_2}{k_1}[C] \tag{5}$$

For closed system and one mole each of [A] and of [B], with $k_1 = 1$ and $k_2 = 10$, then:

$$\frac{[A][B]}{[C]} = \frac{(1-X)^2}{X} = \frac{10}{1} \tag{6}$$

And $(1-X) = [A] = [B] = 0.916$ and X=$[C] = 0.0839$.

Implementation:

$$\begin{aligned} R_A &= -k_1[A][B] &+& \; k_2[C] \\ R_B &= -k_1[A][B] &+& \; k_2[C] \\ R_C &= +k_1[A][B] &-& \; k_2[C] \end{aligned} \tag{7}$$

Generalized:

$$R_i = -k_i^f \prod_{j=1}^{N} [c_j^f]^{\alpha_j^r} + k_i^r \prod_{j=1}^{N} [c_j^r]^{\alpha_j^r} \tag{8}$$

Heats of reaction:

$$H_i = R_i \Delta H_i \tag{9}$$

And heat balance requires:

$$\rho c \frac{\partial T}{\partial t} + \nabla \cdot (T \mathbf{u}) - \nabla \cdot (\lambda \nabla T) = H_i \tag{10}$$

REACTION RATES

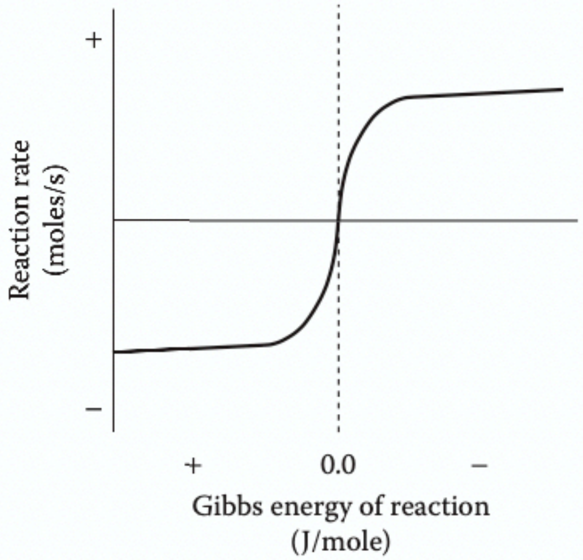


FIGURE 5.5 Variation of the reaction rate plotted as a function of the Gibbs energy of a reaction.

Graphically, this relationship appears as shown in Figure 5.5. Hence, any equation describing this behavior must be able to account for the far-from-equilibrium behavior as well as the behavior close to equilibrium.

One such general reaction rate equation, written in a form that uses the measured dissolution rate for reference, is given by

$$R = S_A \times k \times T_{\text{fac}} \times \alpha \times \phi \times \prod a_i \times \left(\frac{1-Q}{K}\right)^{\omega} \tag{5.8}$$

where:

R is the rate (moles/s)

S_A is the effective surface area exposed to the fluid (cm^2)

k is the far-from-equilibrium rate constant (moles/cm^2-s)

T_{fac} is the temperature correction factor for the rate constant k (usually an Arrhenius function)

α is a power function that accounts for changes in the rate close to equilibrium conditions

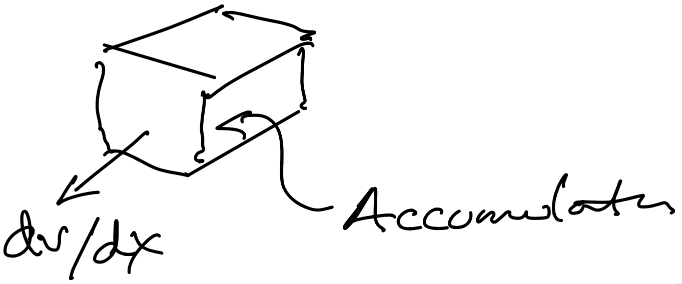
φ is a function that modifies the rate for precipitation relative to that for dissolution

a_i accounts for the dependence of the rate on the activities of specific components in solution (often this is mainly a reflection of the activity of the hydrogen ion, H$^+$)

Q/K is the same as in Equation 5.6

ω is the power dependence that accounts for the particular dissolution or precipitation mechanism (for details see discussions in the works of Lasaga et al. [1994] and Glassley et al. [2003])

CONSERVATION RELATIONS



$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial x} = 0$$

MASS

WATER FLOW – Conserve fluid mass

Darcy's law $v_d = -\frac{k}{\mu}\frac{dp}{dx}$

Compressibility $C = \frac{1}{\rho}\frac{\partial \rho}{\partial p}$

$$C\frac{\partial p}{\partial t} + \quad - \frac{k}{\mu}\frac{\partial^2 p}{\partial x^2} = q_f$$

SOLUTE FLOW – Conserve mass of solute

Fick's Second law $v_m = -D\,\partial c/\partial x$

Advective flux $v_d = v_f c$

$$\frac{\partial c}{\partial t} + v_f\frac{\partial c}{\partial x} - D\frac{\partial^2 c}{\partial x^2} = R$$

HEAT FLOW – Conserve thermal energy, U

Fourier's law $v_h = -k\frac{\partial T}{\partial x}$

Advective flux $v_h = v_f \rho c T$

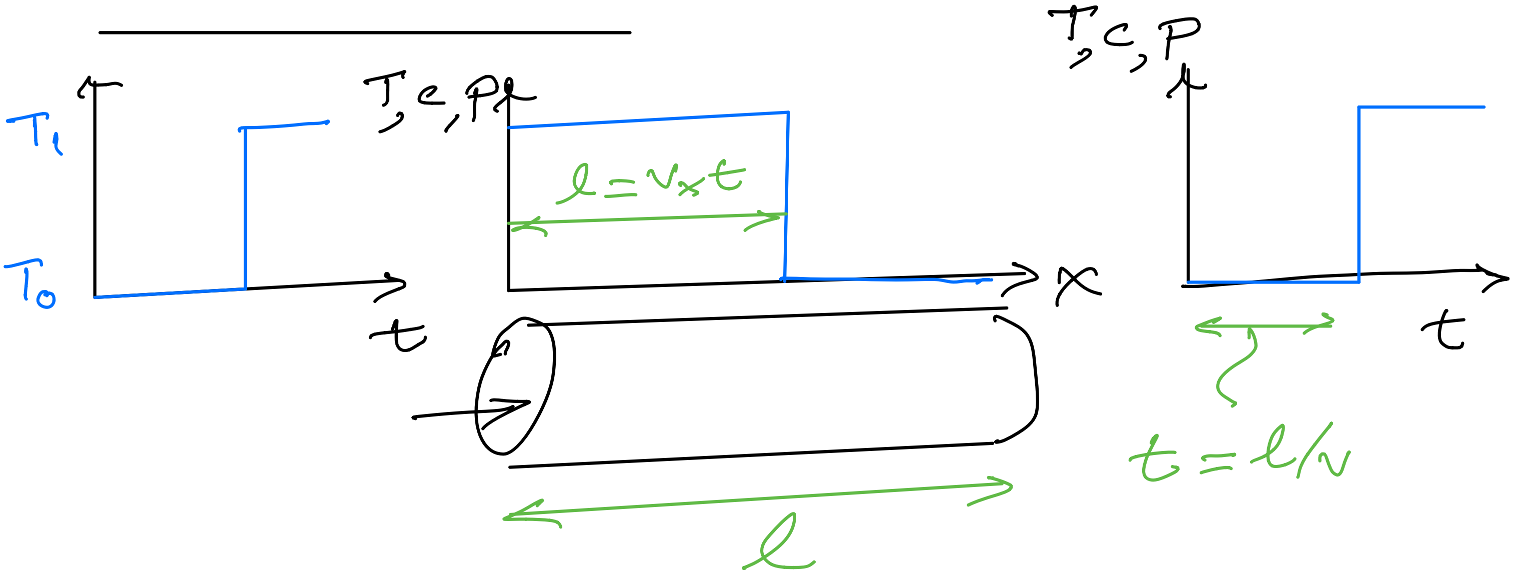
$$\overline{\rho c}\frac{\partial T}{\partial t} + \rho c_w u \frac{\partial T}{\partial x} - k\frac{\partial^2 T}{\partial x^2} = q_{th}$$

$(1-\phi)\rho c_m + \phi \rho c_w \rightarrow \overline{\rho c}$

SIMILAR EQUATIONS

$$\underbrace{A\frac{\partial T}{\partial t}}_{\text{Accumulatn}} + \underbrace{B\frac{\partial T}{\partial x}}_{\text{Advectn}} + \underbrace{C\frac{\partial^2 T}{\partial x^2}}_{\text{Diffusn}} = D$$

SIMILAR SOLUTIONS



APPROACHES TO REACTIVE TRANSPORT MODELING

1. Pseudo-reactive using linear isotherms
    - Retardation approach → gives chromatographic effect
    - Adsorption of monolayer of components at sorption sites
    - No pore clogging or dissolution
    - Multi-component retardation possible, but no reaction/interactio

2. First order reaction with a single component
    - Reaction rate law defines rate of precipitation/dissolution
    - Dissolution/precipitation may be used to update pore volume/surface area/permeability

3. Reaction with multiple reacting components
    - Complex interacting solutes
    - Precipitation / dissolution

General approaches of 2. & 3.

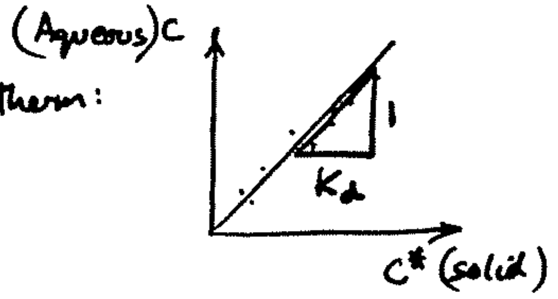
1. Determine $\partial c/\partial t$ in transport (spatial)
2. Determine $\partial c/\partial t$ in species due to reaction.

PSEUDO-REACTIVE SYSTEM — "RETARDATION" APPROACH

concentration on mineral surfaces

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - \frac{v_x}{n}\frac{\partial c}{\partial x} - \frac{\rho_b}{n}\frac{\partial c^*}{\partial t}$$

Linear isotherm:

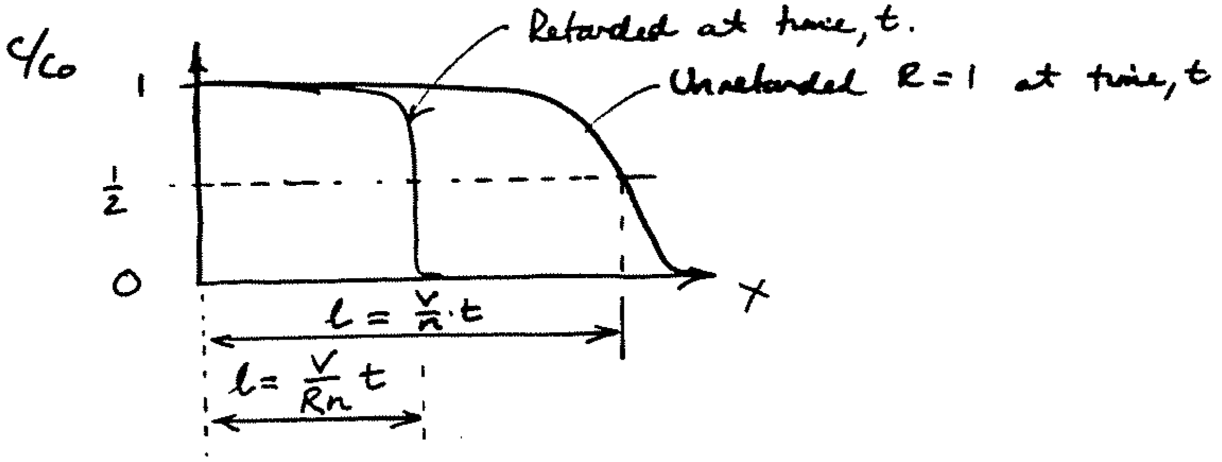


$$\frac{\partial c^*}{\partial t} = \frac{\partial c^*}{\partial c}\frac{\partial c}{\partial t} \Rightarrow K_d\frac{\partial c}{\partial t}$$

Replacing $\rho_b/n \, \frac{\partial c^*}{\partial t}$ yields a modified transport equation

$$\underbrace{\left(1 + \frac{\rho_b}{n}K_d\right)}_{R = \text{retardation coefficient}}\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - \frac{v_x}{n}\frac{\partial c}{\partial x}$$

$$\frac{\partial c}{\partial t} = \frac{D}{R}\frac{\partial^2 c}{\partial x^2} - \frac{v_x}{Rn}\frac{\partial}{\partial x}$$



FIRST ORDER REACTION — SINGLE COMPONENT

Dissolution / Precipitation of Quartz

$$H_4SiO_4\,(aq) = SiO_2\,(q) + 2H_2O\,(\ell) \qquad (1)$$

Stochiometric reaction

$$\left(\frac{\partial c}{\partial t}\right)_{Rxn} = -k(c - c_{eq}) \qquad (2)$$

Rate law

equilibrium concentration — no precip./dissol.

Transport Equation (one component) for fluid phase.

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - \frac{v_x}{n}\frac{\partial c}{\partial x} + \left(\frac{\partial c}{\partial t}\right)_{Rxn}$$

Translate to FE statement:

$$\int_V \underline{b}^T\underline{b}\,d\forall\,\dot{\underline{c}} + D\int_V \underline{a}^T\underline{a}\,d\forall\,\underline{c} + \frac{v_x}{n}\int_V \underline{b}^T\underline{a}\,d\forall\,\underline{c} - k_1\int \underline{b}^T\underline{b}\,d\forall\,(\underline{c} - \underline{c}_{eq}) = \underline{q}$$

$$\underline{K}_0\,\dot{\underline{c}} + D\,\underline{K}_{II}\,\underline{c} + \frac{v_x}{n}\underline{K}_I\,\underline{c} - k_1\,\underline{K}_0(\underline{c} - \underline{c}_{eq}) = \underline{q}$$

Separate terms for solution (implicit time stepping $(\lambda = 1)$):

$$\left[\frac{1}{\Delta t}\underline{K}_0 + D\underline{K}_{II} + \frac{v_x}{n}\underline{K}_I - k_1\underline{K}_0\right]\underline{c}^{t+\Delta t} = \underline{q}^{t+\Delta t} + \frac{1}{\Delta t}\underline{K}_0\underline{c}^t$$

Mass Accumulation + Diffusion + Advection + Dissol./Precip

$$-k_1\underline{K}_0\,\underline{c}^t$$

Solve for $\underline{c}$ with time

These are *fluid* concentrations of any species (quartz)

Similar to retardation approach.

2.4. THE RATE LAW

We can show experimentally that for the general irreversible reaction

$$\underset{\text{reactants}}{A + 2B + \ldots} \rightarrow \underset{\text{products}}{P + 2Q \ldots}$$

we can write the rate law,

$$\frac{d[A]}{dt} = -k[A]^a[B]^b[P]^p[Q]^q \ldots \tag{2-1}$$

where

$\frac{d[A]}{dt}$ = time rate of change in molar concentration of species A,
k = reaction rate constant, and
$a, b, p, q, \ldots$ = constants

In this book, [ ] is used to signify concentration in moles/liter. We may use concentration units other than moles/liter in the rate law but in doing so we should use the same concentration unit for each species and realize that both the numerical value and units of the reaction rate constant will differ from those found when molecular concentrations are used.

Using our knowledge of the stoichiometry of the reaction, that is, the relative number of moles of species reacting and the relative number of moles of products being formed as the reaction proceeds, we can state that

$$\frac{d[A]}{dt} = \frac{1}{2}\frac{d[B]}{dt} \ldots = \frac{-d[P]}{dt} = \frac{-1}{2}\frac{d[Q]}{dt} \ldots \tag{2-2}$$

because 1 mole of A reacts for every 2 moles of B that react, and so forth, and 1 mole of P is formed for every mole of A that reacts, and so forth. We can determine the *reaction order* from the rate law. The *overall* reaction order is

$$a + b + p + q \ldots \tag{2-3}$$

while the order *with respect to* A is a, the order with respect to B is b, and so forth. If the reaction is irreversible, then $p, q, \ldots$, the exponents of the product concentration, are usually zero. For example, if

$$\frac{d[A]}{dt} = -k[A][B]^2$$

then we would say that the reaction was first order with respect to A, second order with respect to B, and third order overall. It is important to note that reaction order is generally not determined by the stoichiometry of the overall reaction. Laboratory experimentation is necessary to determine the order.

The following example illustrates several points that are important for a good understanding of the rate law.

Integrated forms of the rate law are very useful for analyzing rate data to determine reaction rate constants and reaction order. Let us first consider the irreversible reaction

$$\text{A} \rightarrow \text{products}$$

which has the rate law

$$\frac{d[\text{A}]}{dt} = -k[\text{A}]^n$$

To determine the behavior of [A] as a function of time, we must integrate the rate expression with respect to time. We will do this for several values of the reaction order, n. When $n = 0$, the reaction is zero order, and

$$\frac{d[\text{A}]}{dt} = -k[\text{A}]^0 = -k \tag{2-4}$$

Upon integrating, we obtain

$$[\text{A}] = [\text{A}]_0 - kt \tag{2-5}$$

where $[\text{A}]_0$ = the concentration of A at $t = 0$, that is, the initial concentration of A. The *half-life*, $t_{1/2}$, or time for 50 percent of the initial concentration to react can be obtained from Eq. 2-5 by setting $[\text{A}] = 0.5\ [\text{A}]_0$ when $t = t_{1/2}$. Then

$$t_{1/2} = \frac{0.5[\text{A}]_0}{k}$$

When $n = 1$, the reaction is *first order*, both with respect to A and overall, and we can write,

$$\frac{d[\text{A}]}{dt} = -k[\text{A}] \tag{2-6}$$

Rearranging Eq. 2-6 and solving the integral,

$$\int_{[A]_0}^{[A]} \frac{d[\text{A}]}{[\text{A}]} = -\int_0^t k\, dt$$

we find

$$\ln{[\text{A}]} = \ln{[\text{A}]_0} - kt \tag{2-7}$$

or

$$[\text{A}] = [\text{A}]_0 e^{-kt} \tag{2-8}$$

Examination of Eq. 2-7 suggests that the rate constant k may be determined experimentally from a plot of ln [A] versus t, which has a slope of $-k$. Also, from Eq. 2-8, when $[\text{A}] = 0.5\ [\text{A}]_0$, we find the half-life to be

$$t_{1/2} = \frac{0.693}{k}$$

If the reaction is greater than first order, then we can write

$$\frac{d[\text{A}]}{dt} = -k[\text{A}]^n \tag{2-9}$$

PROCESS COUPLINGS [T-H-M-C]

$$\begin{bmatrix} \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & R_{42} & \cdots & R_{44} \end{bmatrix} \begin{Bmatrix} \underline{u} \\ \underline{p} \\ \underline{T} \\ \underline{c} \end{Bmatrix} + \begin{bmatrix} \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & S_{44} \end{bmatrix} \begin{Bmatrix} \dot{\underline{u}} \\ \dot{\underline{p}} \\ \dot{\underline{T}} \\ \dot{\underline{c}} \end{Bmatrix} = \begin{Bmatrix} \dot{\underline{f}} + \ldots \\ \underline{q}_F + \ldots \\ \underline{q}_T + \ldots \\ \underline{q}_M + \ldots \end{Bmatrix}$$

or

or

$$\frac{\partial c_i}{\partial t} = D_i \frac{\partial^2 c}{\partial x^2} - \frac{v_x}{n} \frac{\partial c}{\partial x} + \left(\frac{\partial c_i}{\partial t}\right)_{R \times N}$$

Reaction with Multiple Reacting Components

See for example: Steefel & MacQuarrie in "Reactive Transport in Porous Media"
Ed Lichtner, P.C., Steefel, C.I. and Oelkers, E.H.
Mineralogical Soc. of Amer. 1996.

Basic Approach

1. Write a single equation for each species considered, as:

$$\frac{\partial c_i}{\partial t} = D_i \frac{\partial^2 c_i}{\partial x^2} - \frac{v_x}{n} \frac{\partial c_i}{\partial x} + R_i c_i$$

Reaction rate: $R_i c_i = \frac{\partial c_i}{\partial t} = -k_i(c - c_{eq})$

or $\frac{\partial c_i}{\partial t} = -k_i[c]$

Components are not necessarily independent

2. Solve sequentially as:

   1. Solve transport equation → Evaluate $\underline{c}_i$ @ all nodes with $R_i = 0$

   2. Evaluate reaction term $\frac{\partial \underline{c}_i}{\partial t} = -k_i(\underline{c}_i - \underline{c}_{eq_i})$

   $$\underline{c}_i^{n+1} \quad \underline{c}_i^{n} + \Delta t \left(\frac{\partial \underline{c}_i}{\partial t}\right)_{R+N}$$

   Repeat Step ①

REACTION ALGORITHMS FOR MULTICOMPONENT SYSTEMS

Mathematical descriptions of reaction systems

The multicomponent, multi-species systems typical of those which occur in porous media require some special treatment, both because they involve multiple unknowns and because they are usually nonlinear. The mathematical description used, however, will depend on what form the reactions in the system are assumed to take. It is instructive to derive a general approach to handle multicomponent, multi-species reactive systems. Formulations for arbitrarily complex reaction systems characterized by both equilibrium and non-equilibrium reactions have been presented by Lichtner (1985), Lichtner (this volume), Friedly and Rubin (1992), Sevougian et al. (1993), and Chilakapati (1995). A clear discussion of one possible way of doing so is given by Chilakapati (1995). His approach begins with the most general case, a set of ordinary differential equations for each species in the system and reactions between the species described by kinetic rate laws. A system containing N_{tot} species and N_r reactions can be expressed as

$$\mathbf{I} \cdot \frac{d\mathbf{C}}{dt} = \nu \cdot \mathbf{R}. \tag{1}$$

The raised dot indicates matrix multiplication. $\mathbf{I}$ is the identity matrix of dimension $N_{tot} \times N_{tot}$, $\mathbf{C}$ is the vector of solute concentrations of length N_{tot}, ν is a matrix of dimension $N_{tot} \times N_r$, and $\mathbf{R}$ is a vector of length N_r. For example, the matrix ν and the vector $\mathbf{R}$ have the form

$$\nu = \begin{bmatrix} \nu_{1,1} & \nu_{1,2} & \cdots & \nu_{1,N_r} \\ \nu_{2,1} & \nu_{2,2} & \cdots & \nu_{2,N_r} \\ \vdots & \cdots & \cdots & \vdots \\ \nu_{N_{tot},1} & \nu_{N_{tot},2} & \cdots & \nu_{N_{tot},N_r} \end{bmatrix} \qquad \mathbf{R} = \begin{bmatrix} R_1 \\ R_2 \\ \cdots \\ R_{N_r} \end{bmatrix}. \tag{2}$$

The multiplication of the identity matrix by the derivatives of the individual species concentrations results in an ODE of similar form for each of the species in the system.

As an example, consider an aqueous system consisting of Ca^{+2}, H^+, OH^-, CO_3^{-2}, HCO_3^-, H_2CO_3, and $CaCO_3(s)$ (calcite). We ignore H_2O for the sake of conciseness. In addition, we assume that the following reactions occur, without yet specifying whether they are to be considered equilibrium or kinetically-controlled reactions,

$$CaCO_3 \rightleftharpoons Ca^{+2} + CO_3^{-2} \qquad R_1 \tag{3}$$

$$HCO_3^- \rightleftharpoons CO_3^{-2} + H^+ \qquad R_2 \tag{4}$$

$$H_2CO_3 \rightleftharpoons CO_3^{-2} + 2H^+ \qquad R_3 \tag{5}$$

$$H^+ + OH^- \rightleftharpoons H_2O \qquad R_4. \tag{6}$$

In the above equations R_i symbolizes the rate expression for reaction i. We also make no assumptions at this stage about whether the set of reactions included are linearly independent (although the reactions listed above are). We have shown the reactions to be reversible here (thus the symbol $\rightleftharpoons$) but the results below apply whether the reactions are irreversible or reversible since at this stage, one can think of the reaction rates as simply time-dependent expressions of the mole balances inherent in a balanced chemical reaction. The reversibility or lack thereof only determines whether the sign of the reaction rate can change. The term *reversible* is generally used by thermodynamicists to refer to equilibrium reactions (Lichtner, this volume), although we prefer to use it to refer to reactions which are sufficiently close to equilibrium that the backward reaction is important. It is quite possible in a steady-state flow system, for example, for backward reactions to be important and yet not to be at equilibrium (e.g. Nagy et al., 1991; Nagy and Lasaga, 1992; Burch et al., 1993). According to this definition, the term *irreversible* is used for those reactions which proceed in only one direction (i.e. those that can be represented with a unidirectional arrow, $\longrightarrow$).

For our example aqueous system, the rates for the individual species can be written

$$\frac{d[\mathrm{H_2CO_3}]}{dt} = -R_3 \tag{7}$$

$$\frac{d[\mathrm{HCO_3^-}]}{dt} = -R_2 \tag{8}$$

$$\frac{d[\mathrm{CaCO_3}]}{dt} = -R_1 \tag{9}$$

$$\frac{d[\mathrm{OH^-}]}{dt} = -R_4 \tag{10}$$

$$\frac{d[\mathrm{H^+}]}{dt} = R_2 + 2R_3 - R_4 \tag{11}$$

$$\frac{d[\mathrm{Ca^{+2}}]}{dt} = R_1 \tag{12}$$

$$\frac{d[\mathrm{CO_3^{-2}}]}{dt} = R_1 + R_2 + R_3. \tag{13}$$

In matrix form the system of equations becomes

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{d[\mathrm{H_2CO_3}]}{dt} \\ \frac{d[\mathrm{HCO_3^-}]}{dt} \\ \frac{d[\mathrm{CaCO_3}]}{dt} \\ \frac{d[\mathrm{OH^-}]}{dt} \\ \frac{d[\mathrm{H^+}]}{dt} \\ \frac{d[\mathrm{Ca^{+2}}]}{dt} \\ \frac{d[\mathrm{CO_3^{-2}}]}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 2 & -1 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} \tag{14}$$

As written in Equation (14), the stoichiometric reaction matrix, ν, is referred to as being in *canonical* form (Smith and Missen, 1982; Lichtner, 1985; Lichtner, this volume). The system of equations is partitioned into the first four rows where the associated species (H_2CO_3, HCO_3^-, $CaCO_3$(s), and OH^-) are involved in only one reaction while in the remaining three rows the species are involved in multiple reactions. The first four species are referred to as secondary or non-component species, while the last three are the primary or component species (Lichtner, this volume). These are also referred to as *basis* species because they form a basis which spans the concentration space. In this example, we have written all of the carbonate reactions using the species CO_3^{-2} precisely so as to restrict all of the other carbonate species to involvement in a single reaction. This is an essential first step in obtaining either the canonical formulation (Lichtner, 1985; Lichtner, this volume) or to writing the reactions in *tableaux* form (Morel and Hering, 1993), both of which assume that one is dealing with a set of linearly independent reactions, but it is not essential for what follows below. The procedure will also work if, for example, the formation of H_2CO_3 involved H^+ and HCO_3^- rather than 2 H^+ and CO_3^{-2}, although we will not obtain the conserved quantities (total H^+, total CO_3^{-2}, etc.) found in the tableaux method without additional manipulations.

The system of ODEs could be solved directly in the form of Equation (14) if the reactions are all described with kinetic rate laws. Alternatively, one can apply a Gauss-Jordan elimination process to the matrix ν and simultaneously to the identity matrix **I** until there are no pivots left (Chilakapati, 1995). The resulting transformed set of ODEs is now

$$\mathbf{M} \cdot \frac{d\mathbf{C}}{dt} = \nu^{*} \cdot \mathbf{R} \tag{15}$$

which partitions the system of equations into N_r ODEs associated with reactions and N_c conservation laws with zero right-hand sides (i.e. no associated reactions). The number of conservation laws or mole balance equations is equal to

$$N_c = N_{tot} - \text{rank of } \nu = N_{tot} - N_r. \tag{16}$$

N_r, therefore, refers to the number of *linearly independent* reactions between the species in the system. For the sake of clarity, we make the first N_r rows of the matrix **M** the ODEs with associated reactions and the next N_c rows the conservation equations, so that the left hand of Equation (15) takes the form

$$\begin{bmatrix} M_{1,1} & \cdots & M_{1,N_r+N_c} \\ \vdots & \cdots & \vdots \\ M_{N_r,1} & \cdots & M_{N_r,N_r+N_c} \\ M_{N_r+1,1} & \cdots & M_{N_r+1,N_r} \\ \vdots & \cdots & \vdots \\ M_{N_r+N_c,1} & \cdots & M_{N_r+N_c,N_r+N_c} \end{bmatrix} \cdot \begin{bmatrix} \frac{dC_1}{dt} \\ \vdots \\ \frac{dC_{N_r}}{dt} \\ \vdots \\ \frac{dC_{N_r+N_c}}{dt} \end{bmatrix} \tag{17}$$

In our example, the Gauss-Jordan elimination is carried out on the the matrix ν on the right hand side of Equation (14) and the same row transformations are applied to the identity matrix, **I**, yielding

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 2 & 1 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{d[H_2CO_3]}{dt} \\ \frac{d[HCO_3^-]}{dt} \\ \frac{d[CaCO_3]}{dt} \\ \frac{d[OH^-]}{dt} \\ \frac{d[H^+]}{dt} \\ \frac{d[Ca^{+2}]}{dt} \\ \frac{d[CO_3^{-2}]}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} \tag{18}$$

The stoichiometric reaction matrix, ν^{*}, now consists of a nonsingular 4 by 4 matrix (N_r by N_r) and three rows of zeros corresponding to the N_c conservation equations. Writing out the ODEs in Equation (18), we find

$$\frac{d[H_2CO_3]}{dt} = -R_3 \tag{19}$$

$$\frac{d[HCO_3^-]}{dt} = -R_2 \tag{20}$$

$$\frac{d[CaCO_3]}{dt} = -R_1 \tag{21}$$

$$\frac{d[OH^-]}{dt} = -R_4 \tag{22}$$

Table 1. Tableaux for carbonate system, neglecting H_2O as a species and component.

		Components		
		H^+	Ca^{+2}	CO_3^{-2}
Species	H_2CO_3	2		1
	HCO_3^-	1		1
	$CaCO_3$		1	1
	OH^-	-1		
	H^+	1		
	Ca^{+2}		1	
	CO_3^{-2}			1

and

$$\frac{d}{dt}\left([H^+] + 2[H_2CO_3] + [HCO_3^-] - [OH^-]\right) = 0 \tag{23}$$

$$\frac{d}{dt}\left([Ca^{+2}] + [CaCO_3]\right) = 0 \tag{24}$$

$$\frac{d}{dt}\left([CO_3^{-2}] + [H_2CO_3] + [HCO_3^-] + [CaCO_3]\right) = 0. \tag{25}$$

From the example, it is apparent that we have eliminated the reactions in the equations originally corresponding to the species H^+, Ca^{+2}, and CO_3^{-2} by making use of the relations in the first four equations. The last three equations are mole balances for *total* H^+, Ca^{+2}, and CO_3^{-2}

$$TOTH^+ = [H^+] - [OH^-] + [HCO_3^-] + 2[H_2CO_3] \tag{26}$$

$$TOTCa^{+2} = [Ca^{+2}] + [CaCO_3] \tag{27}$$

$$TOTCO_3^{-2} = [CO_3^{-2}] + [H_2CO_3] + [HCO_3^-] + [CaCO_3]. \tag{28}$$

Note that the canonical form of the stoichiometric reaction matrix is identical to the *tableaux* form popularized by Morel and coworkers (Morel and Hering, 1993; Dzombak and Morel, 1990). By transposing the last three rows of the matrix **M** in Equation (17), we can write the matrix in tableaux form (Table 1).

The procedure has yielded expressions for the total concentrations of the N_c *primary* or *component* species. A more general form is given by

$$TOT_j = C_j + \sum_{i=1}^{N_r} \nu_{ij} X_i \tag{29}$$

where C_j and X_i refer to the concentration of the primary and secondary species respectively. Note that the number of secondary species is equal to N_r, the number of linearly independent reactions in the system (i.e. the rank of the matrix ν). Equation (27) and Equation (28) are recognizable as the total concentrations of calcium and carbonate respectively. The total concentration of H^+ is written in exactly the same form as the other equations, although its physical meaning is less clear because it may take on negative values due to the negative stoichiometric coefficients in the expression. The mole balance equation for total H^+ is just the *proton condition* equation referred to in many aquatic chemistry textbooks. Oxidation-reduction reactions are also easily handled with this method. If the redox reactions are written as whole cell reactions, there is no need in any application not involving an electrical current (see Lichtner, this volume) to introduce the electron as an unknown. Writing the reactions as whole cell reactions allows redox reactions to be treated exactly like any other reaction.

CONVECTIVE HEAT FLOW

Assume – Thermal equilibrium of fluid and rock ∴ $T_R = T_F$
and only 1 variable

– Not necessary to make this assumption (convenient).

$\rho_f c_f n + (1-n)\rho_r c_r$

$$D^* \frac{\partial^2 T}{\partial x^2} - \rho_f c_f q_D \frac{\partial c}{\partial x} = (\overline{\rho c})\frac{\partial T}{\partial t}$$

$D^* = D_r(1-n) + D_f(n)$

Darcy flux $q_D = -\frac{k}{\mu}\frac{dp}{dx}$

FE Equations:

$$D^* \frac{\partial^2 T}{\partial x^2} = D^* \int_V \underline{a}^T \underline{a}\, d\forall\, \underline{T} = \underline{K}_2 \underline{T}$$

$$\rho_f c_f q_D \frac{\partial T}{\partial x} = \rho_f c_f q_D \int_V \underline{b}^T \underline{a}\, d\forall\, \underline{T} = \underline{K}_1 \underline{T}$$

$$\overline{\rho c}\, \frac{\partial T}{\partial t} = \overline{\rho c} \int_V \underline{b}^T \underline{b}\, d\forall\, \dot{\underline{T}} = \underline{K}_0 \dot{\underline{T}}$$

ASSEMBLED EQUATIONS: (Implicit, $\lambda = 1$)

$$[\underline{K}_2 + \underline{K}_1]\,\underline{T}^{t+\Delta t} + \underline{K}_0 \dot{\underline{T}}^{t+\Delta t} = \underline{q}^{t+\Delta t}$$

$$\dot{\underline{T}} = \frac{1}{\Delta t}\left[\underline{T}^{t+\Delta t} - \underline{T}^{t}\right]$$

GATHERING TERMS:

$$\left[\underline{K}_2 + \underline{K}_1 + \frac{1}{\Delta t}\underline{K}_0\right]\underline{T}^{t+\Delta t} = \underline{q}^{t+\Delta t} + \frac{1}{\Delta t}\underline{K}_0 \underline{T}^{t}$$

$\underline{K}_1$ may change if q_D changes in time.

SYSTEM TYPES

SOLID MECHANICS	FLOW SYSTEM	TRANSPORT
○ Conservation of momentum: (Equilibrium), $VW_I = VW_E$	○ Conservation of mass: $\underline{\nabla}^T \underline{q} = 0$	○ Conservation of mass $\underline{\nabla}^T \underline{q} = 0$
○ Continuity (Compatibility): $\underline{\varepsilon} = \underline{a}\,\underline{u}$	○ Continuity: $\underline{h}_{,} = \underline{a}\,\underline{h}$	○ Continuity: $\underline{c}_{,} = \underline{a}\,\underline{c}$
○ Constitutive relation: $\underline{\sigma} = \underline{D}\,\underline{\varepsilon}$	○ Constitutive reln. $\underline{v} = \underline{D}\,\underline{h}_{,}$	○ Constitutive: diffusion - $\underline{v}_1 = \underline{D}\,\underline{c}_{,}$ advective - $\underline{v}_2 = \underline{A}\,\underline{c}$
○ Initial Conditions	○ ICs	○ ICs
○ Boundary Conditions	○ BCs	○ BCs

— SOLVE SYSTEM EQUATIONS —

6. Reservoir/Plan response - Sauty (1980) and EnvSE 408 Section 3.2

Short-timescale Chemo-mechanical Effects and Their Effect on the Transport Properties of Fractured Rock

By

Derek Elsworth, Hide Yasuhara,
Amir Polak[2], and Jishan Liu[3]

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Penn State University
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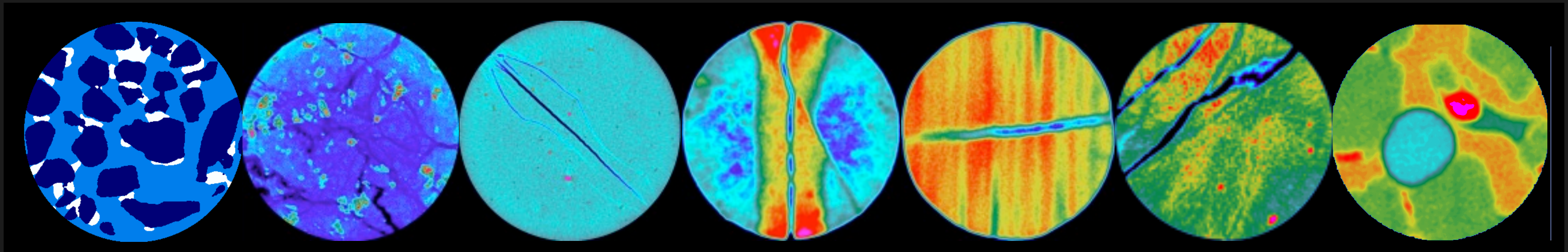
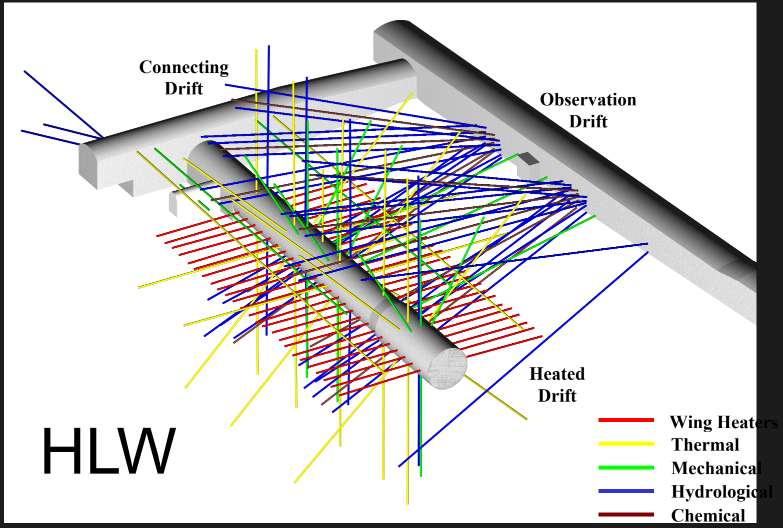
[3]University of Western Australia

Supported By: DOE-BES-DE-FG02-00ER15111
& DOE-Geothermal-DE-FG36-04GO14289



What is the importance?

HDR/EGS/Conventional



HLW

CO_2 Sequestration

and Petroleum Recovery

What are the roles of:

Stress fields and paths [M]

Thermal fields and paths [T]

Chemical potential fields and paths [CB]

In the evolution of fluid transport [H] behavior?

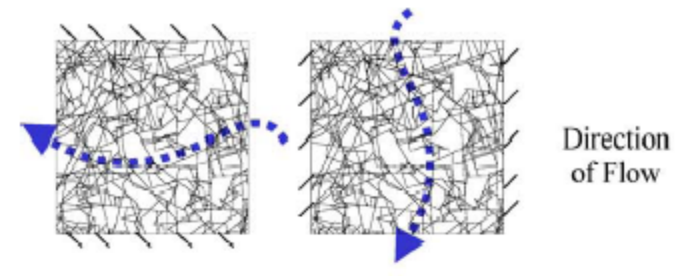
Specifically….. where fractures are present – what is the transmission sensitivity?… and …

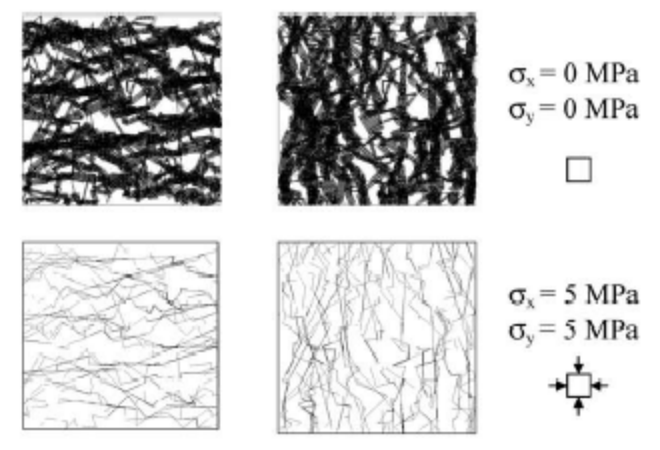
Specifically….. whether fracture permeabilities increase or decrease with net dissolution/precipitation, pressure-solution, …..? ……And how quickly do they do this?

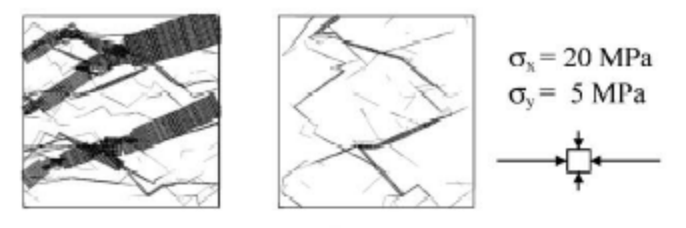
………… and what are the controls on these processes?

Typical Modes of Analysis for THMC Systems:

THM - GeoMechanics

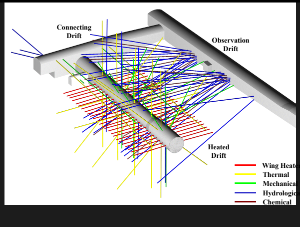


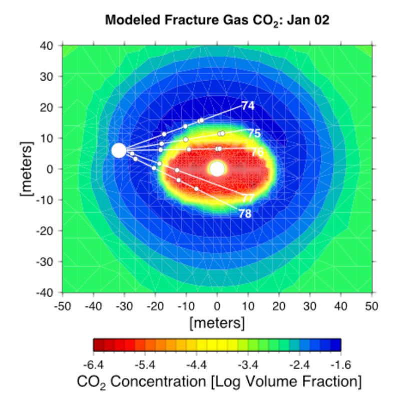


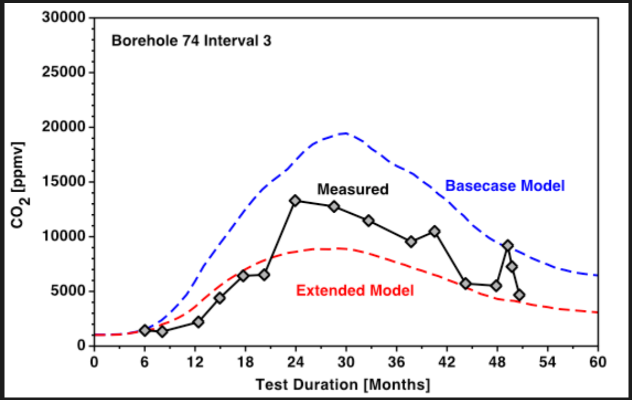


e.g. K.-B. Min (2004)

THC - GeoChemistry







[Courtesy: E. Sonnenthal]

What is the form of the THMC linkage C-to-M?.... And is it important?

Road Map

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- Conclusions

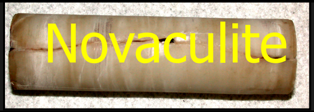
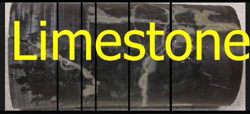
Experimental Configurations

Q_{fluid}

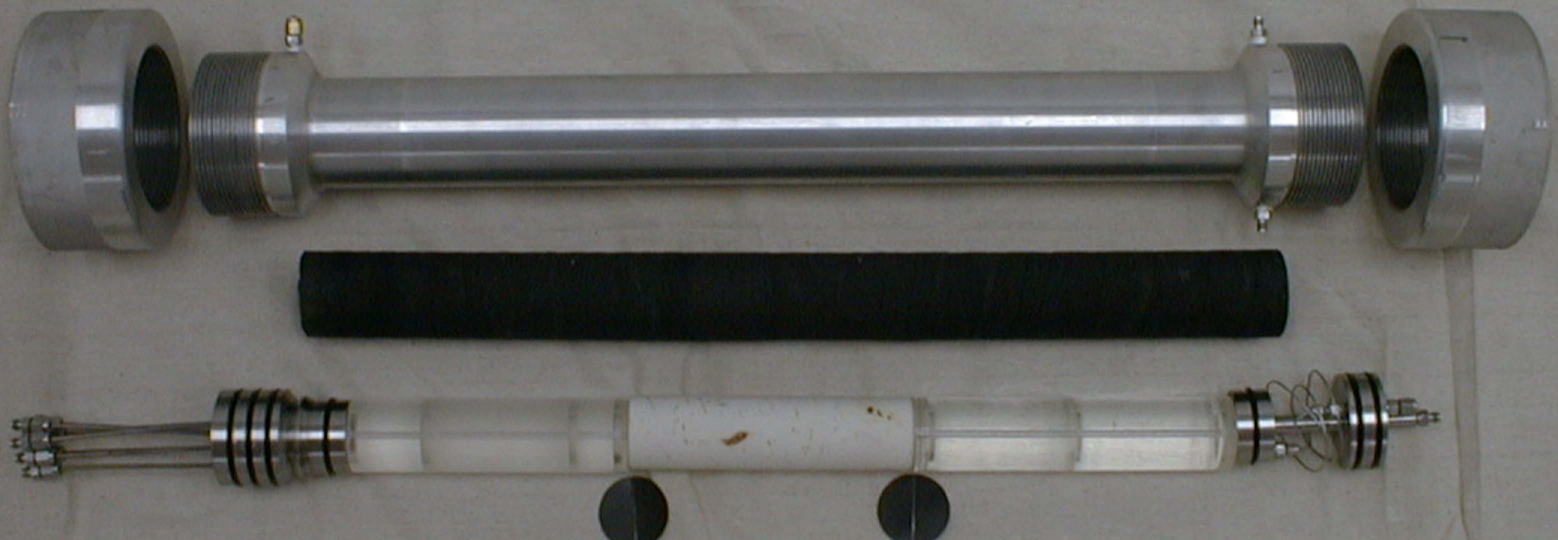
Q_{mass}

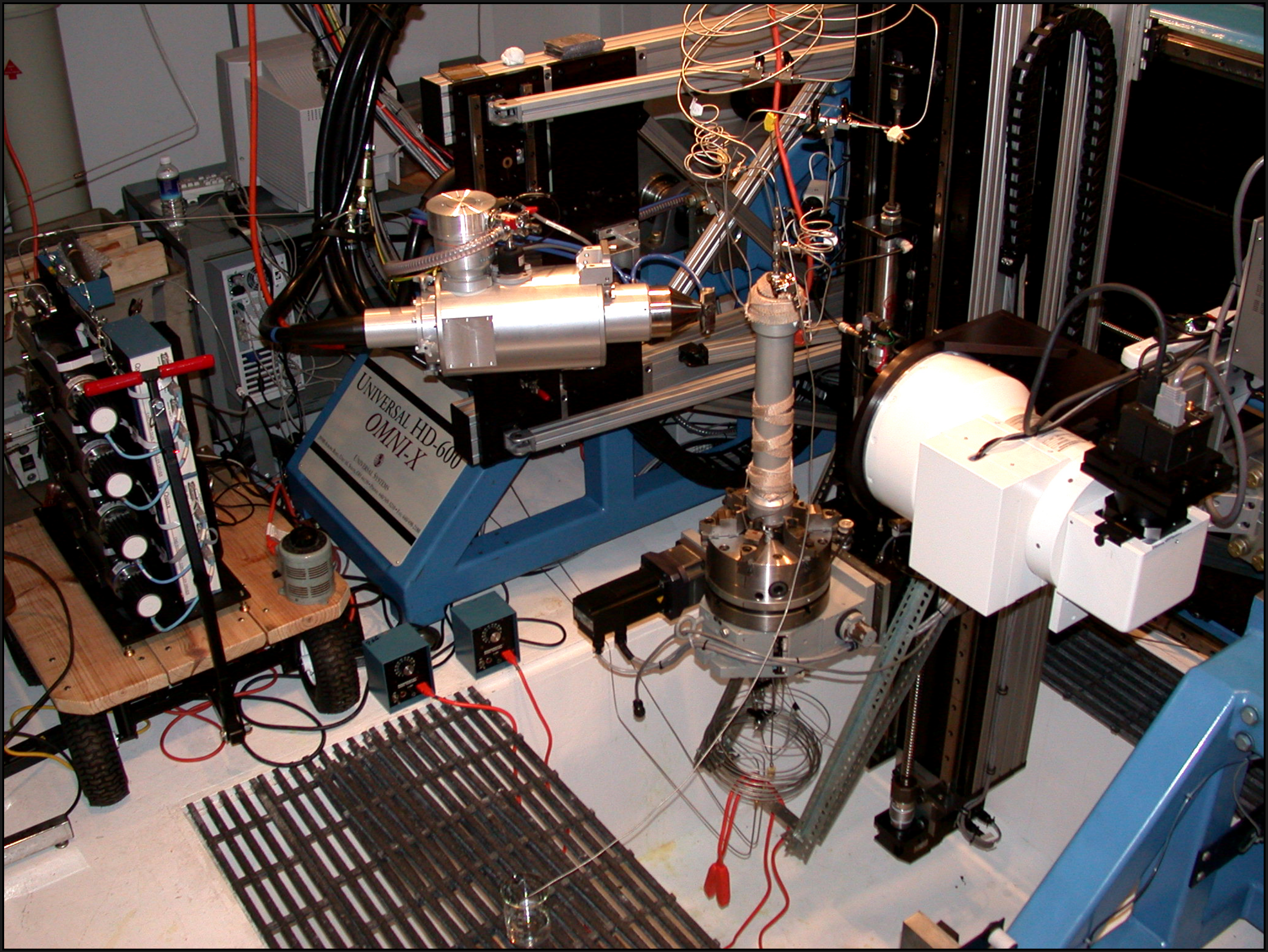
x-ray CT

Δk

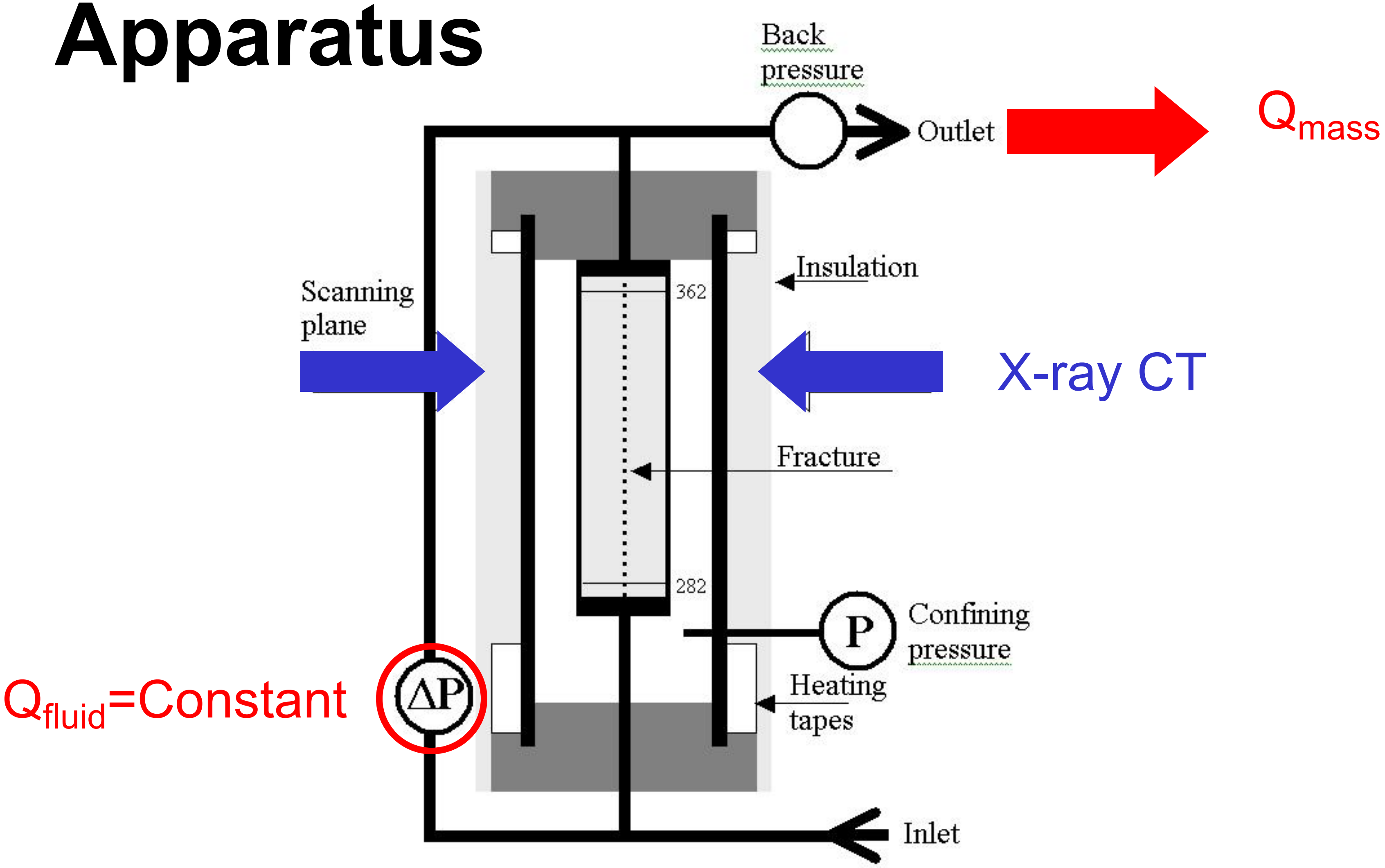
		 Novaculite	 Limestone
Matrix Porosity		<0.01%	<0.01%
Temperatures, ° C		20-150	20
Effective Stress, MPa		3.5	3.5
Permeants		DI	G/w & DI
Diss. Rate, k_+ [Mol.m^{-2}.s^{-1}]		$\sim10^{-9}$	$\sim10^{-6}$
Precip. Rate, k_- [Mol.m^{-2}.s^{-1}]		$\sim10^{-7}$	

Experimental Arrangement

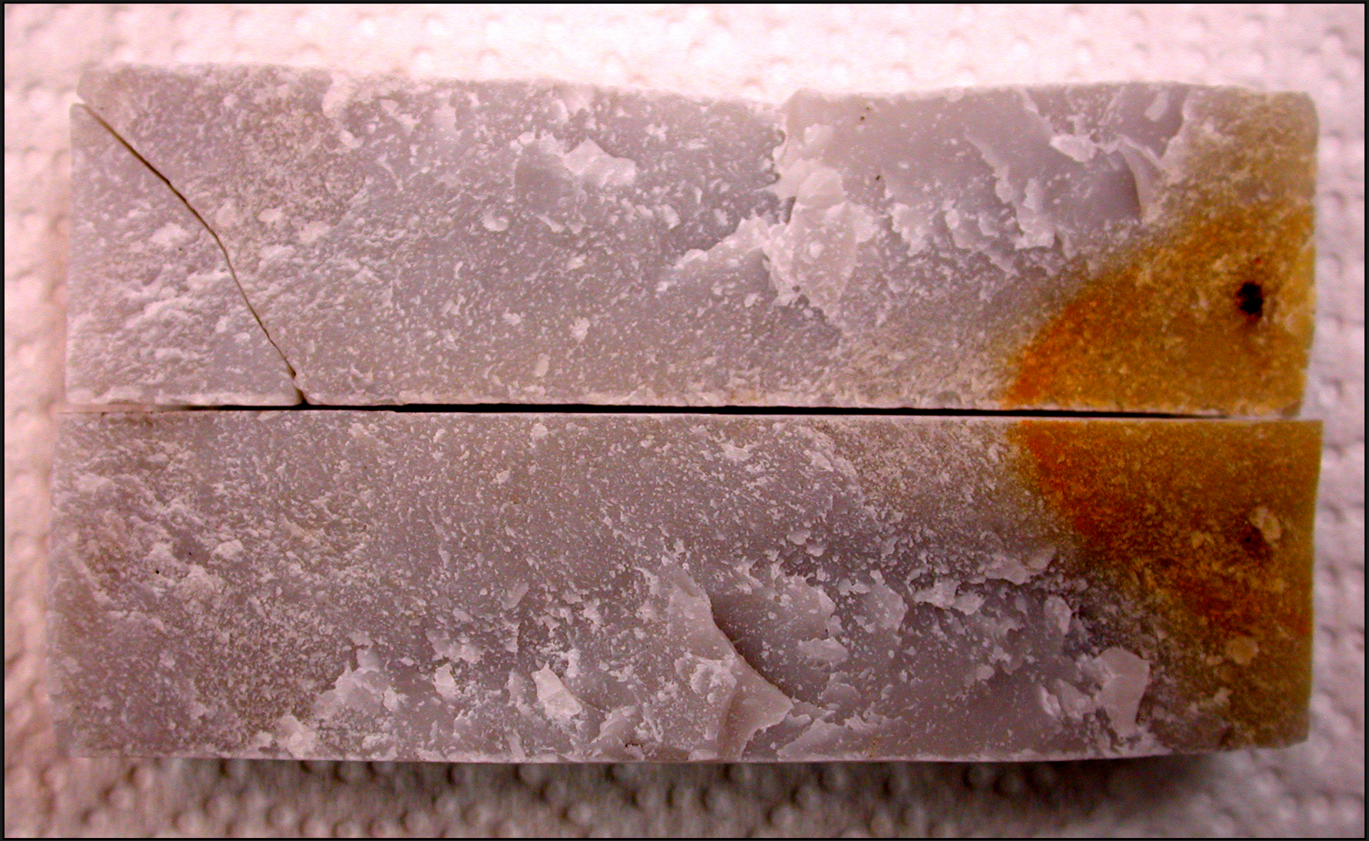



Universal HD-600
OMNI-X

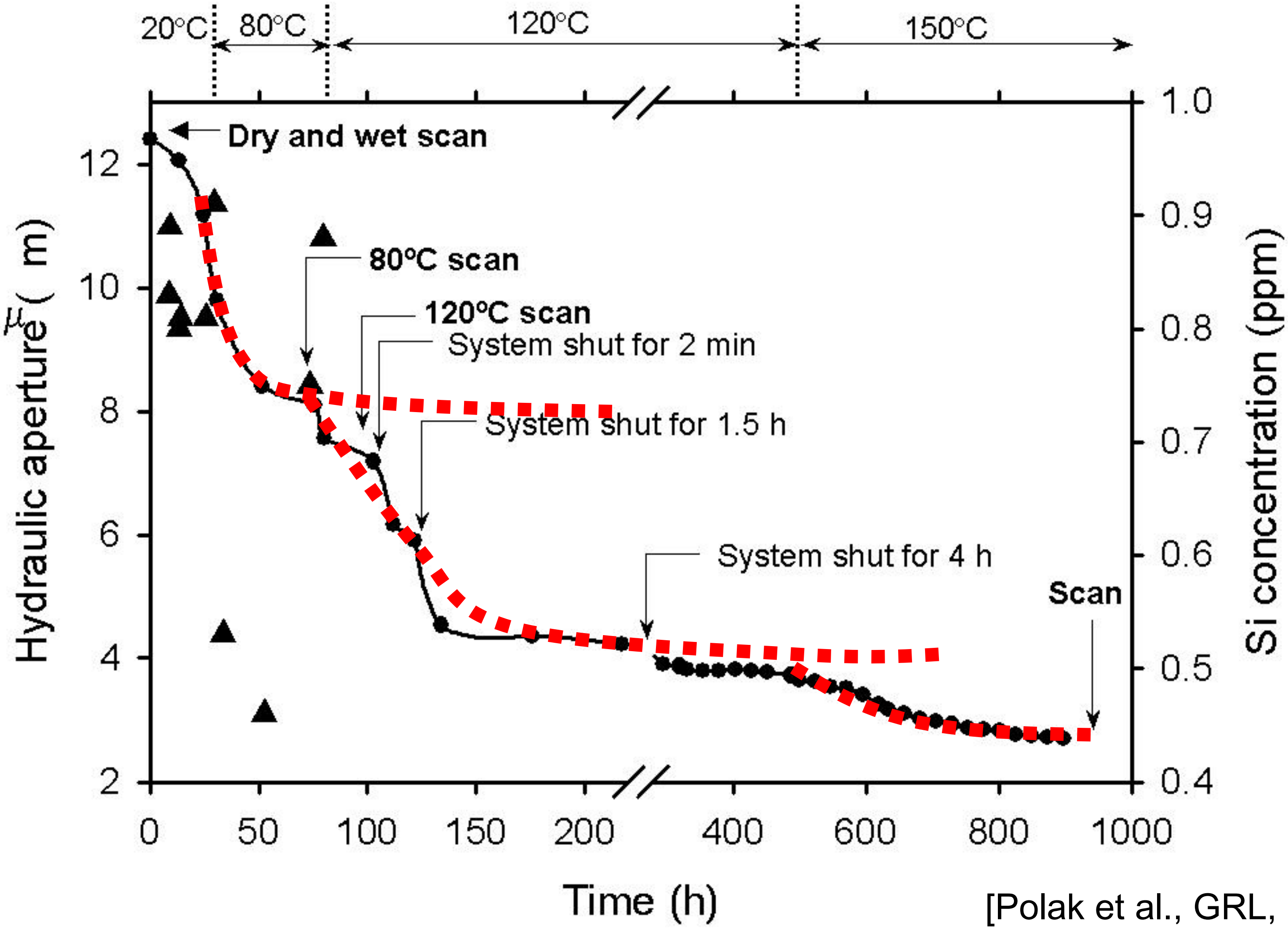
Apparatus


Back pressure
Outlet
Qmass
Insulation
Scanning plane
362
X-ray CT
Fracture
282
P
Confining pressure
Qfluid=Constant
ΔP
Heating tapes
Inlet

Arkansas Novaculite (99.5% Si; n<0.01%)



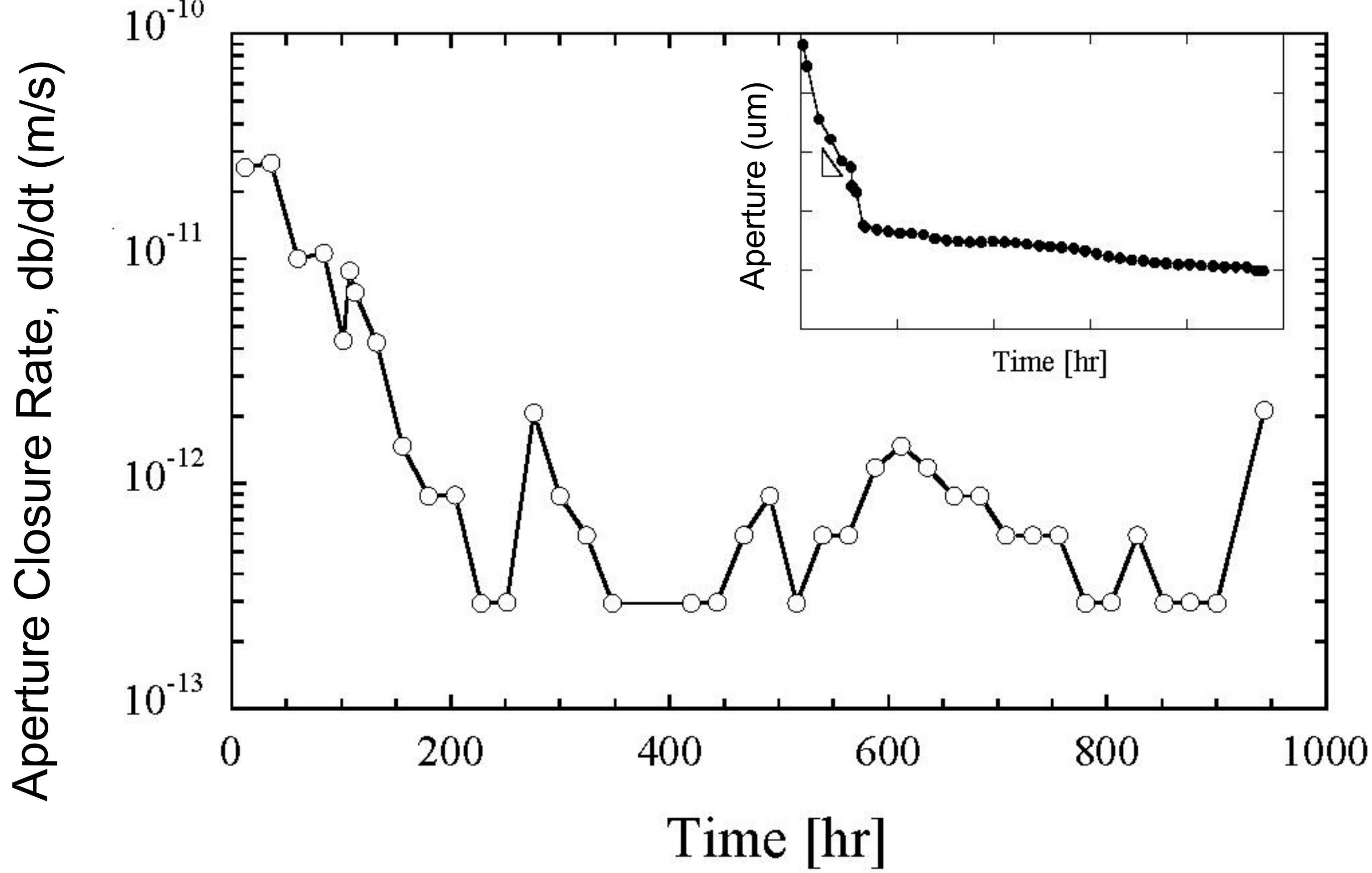
Typical Response



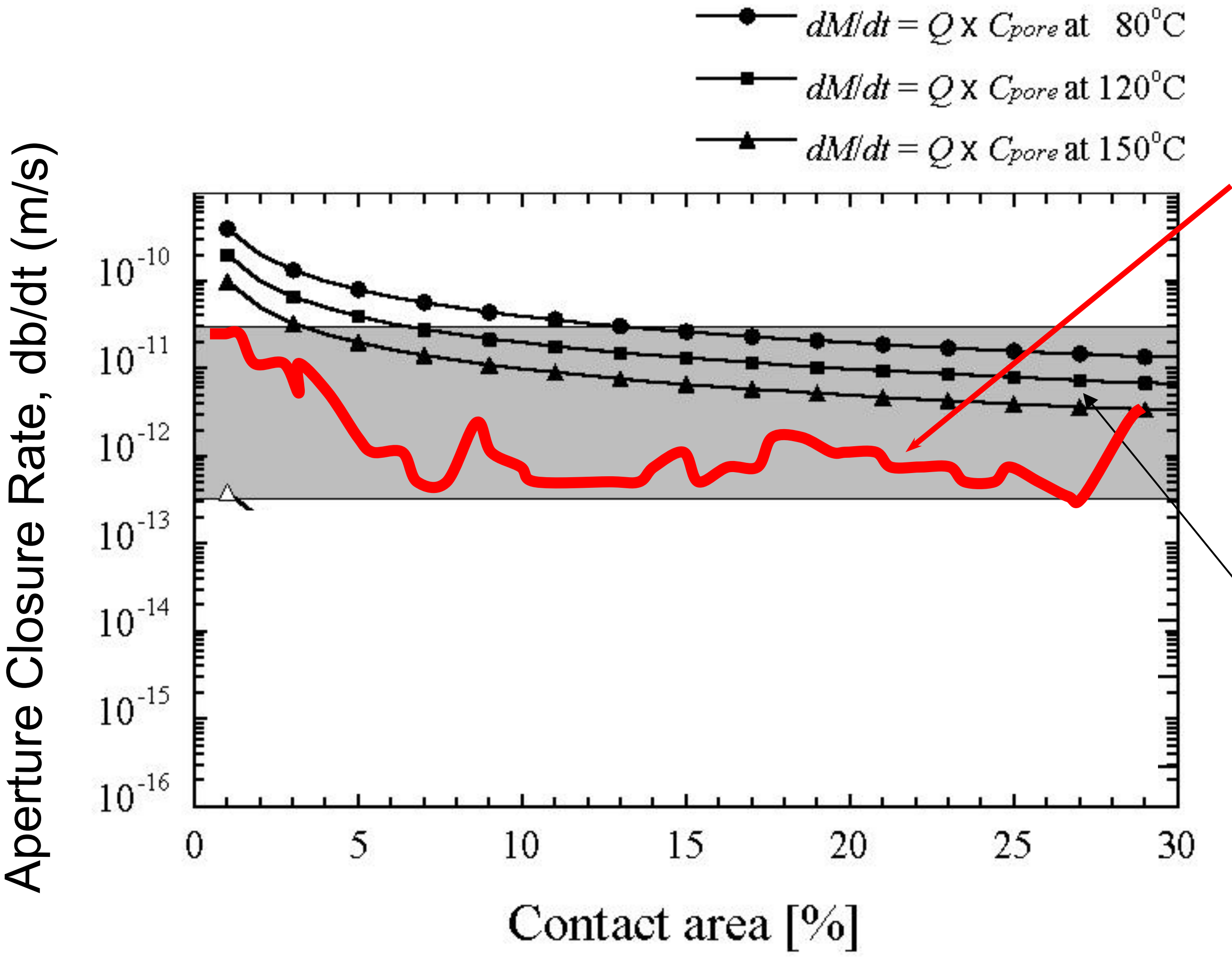
[Polak et al., GRL, 2003]

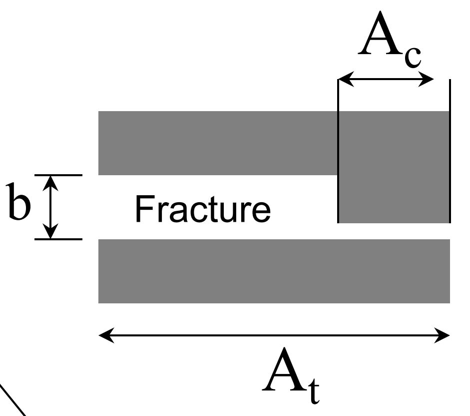
Hydraulic Measurements of db/dt

$$k = \frac{b^2}{12} \rightarrow b = \sqrt{12k} \rightarrow \frac{db}{dt}$$



Mineral-Mass Measurements of db/dt

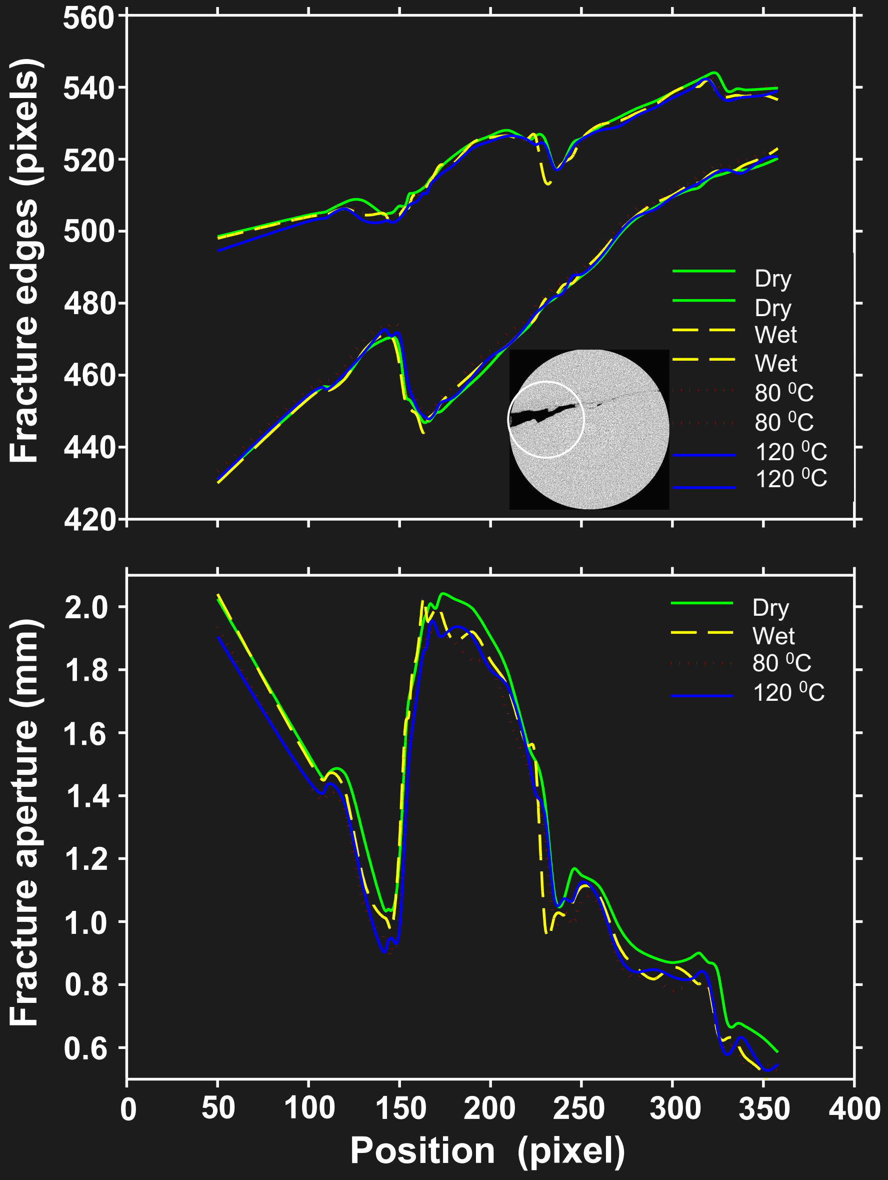




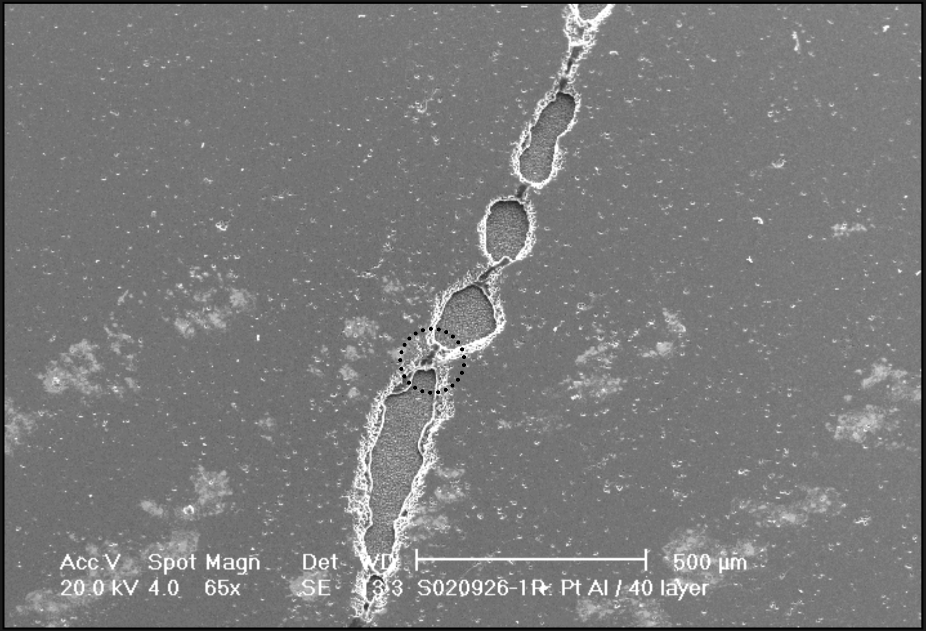
$$\frac{db}{dt} = \frac{dM}{dt}\cdot\frac{1}{A_c\rho_g} = \frac{Q\cdot C_p}{A_c\rho_g}$$

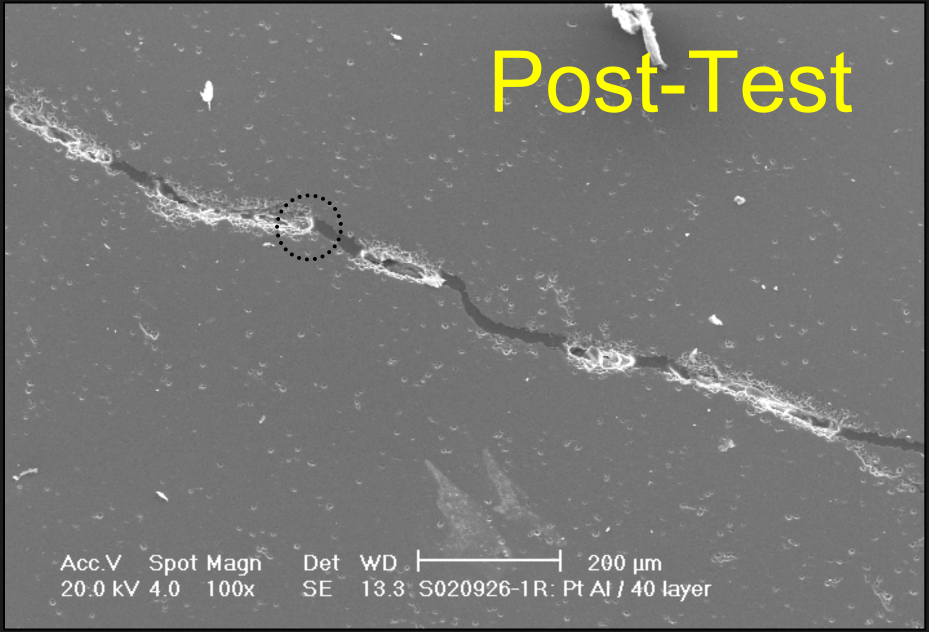
Imaging-Derived Aperture Changes

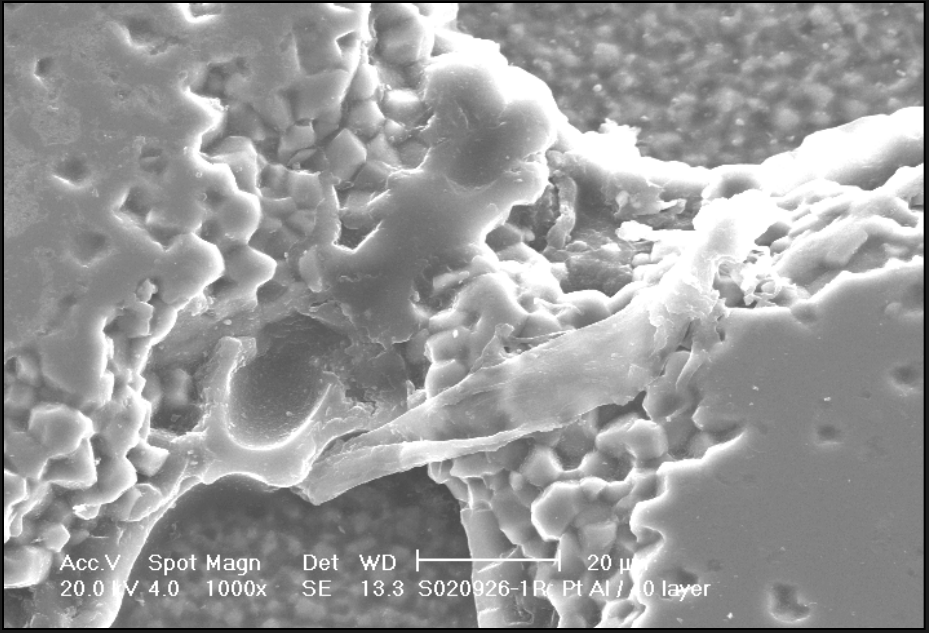
- Observed mean aperture change of 10 µm
- Resolution of 37 µm too low
- In areas of large absent chip, aperture changes are of the order 100 µm
- This amplification results from core rotation around a fulcrum

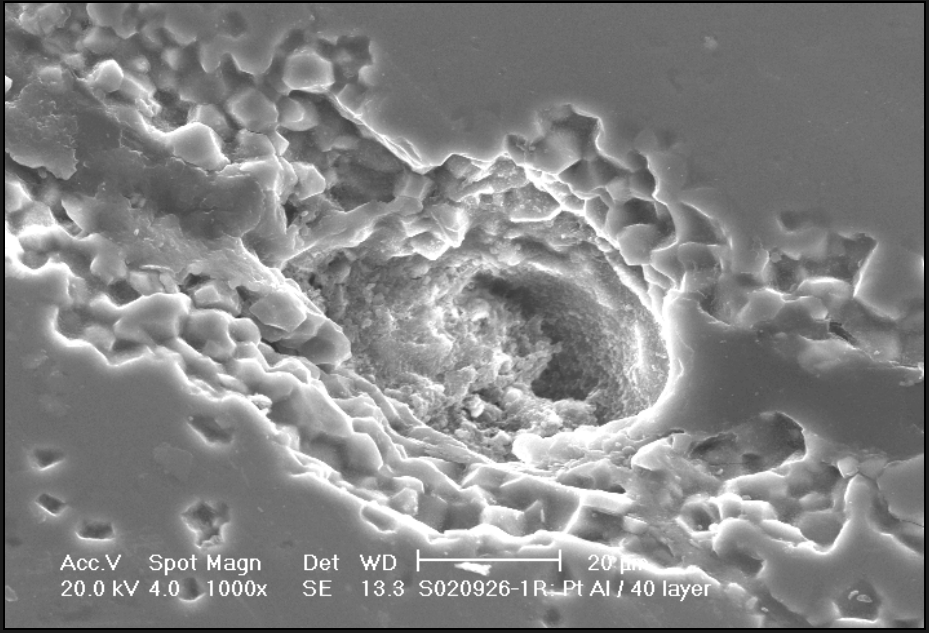


Post-Test


Acc.V Spot Magn Det WD 500 µm
20.0 kV 4.0 65x SE 13.3 S020926-1R: Pt Al / 40 layer


Acc.V Spot Magn Det WD 200 µm
20.0 kV 4.0 100x SE 13.3 S020926-1R: Pt Al / 40 layer


Acc.V Spot Magn Det WD 20 µm
20.0 kV 4.0 1000x SE 13.3 S020926-1R: Pt Al / 40 layer


Acc.V Spot Magn Det WD 20 µm
20.0 kV 4.0 1000x SE 13.3 S020926-1R: Pt Al / 40 layer

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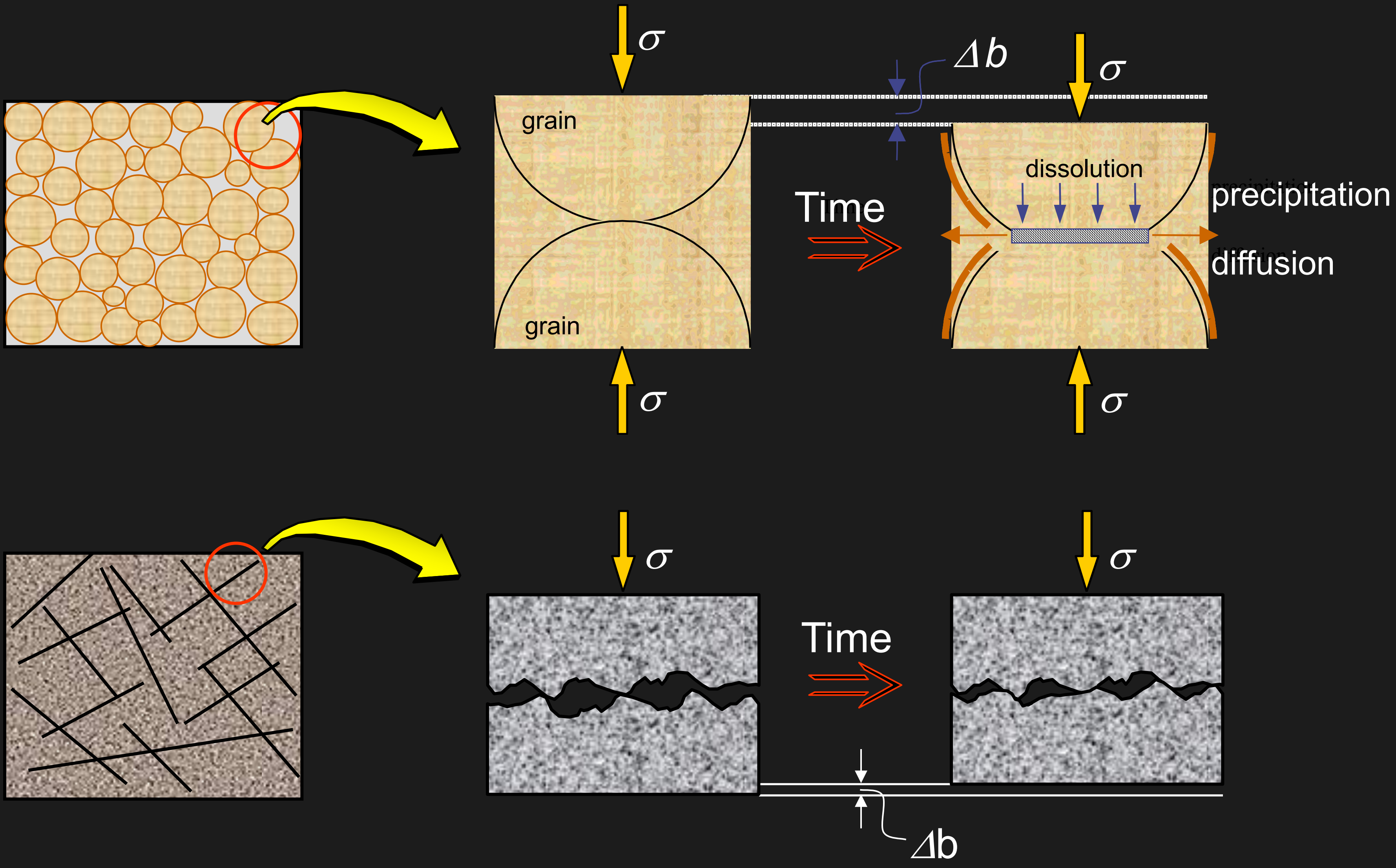
Dissolution Processes
Approaches to Determine Δk or Δb



Component Model

- Interface Dissolution

$$\left.\begin{aligned} \frac{dM_{diss}}{dt} &\approx \dot{\varepsilon}_{diss}\,\frac{d}{\omega}\,\rho_g\left(\frac{\pi}{4}d_c^2\,\omega\right) \\ &= \frac{3\pi V_m^2\,\sigma_{eff}\,k_+\rho_g\,d_c^2}{4RT} \\ \frac{dM_{diss}}{dt} &= \frac{3\pi V_m^2\,(\sigma_a-\sigma_c)k_+\rho_g\,d_c^2}{4RT} \end{aligned}\right\} \qquad \sigma_c = \frac{E_m\left(1-T/T_m\right)}{4V_m}$$

- Interface Diffusion

$$J = -D_b\,\frac{dC}{dx} \qquad J_m = -2\pi r\varpi D_b\left(\frac{dC}{dr}\right)_{r=d_c}$$

$$J_m = \frac{dM_{diff}}{dt} = \frac{2\pi\,\omega\,D_b}{\ln\left(d_c/2a\right)}\left(C_{\mathrm{int}}-C_{pore}\right)$$

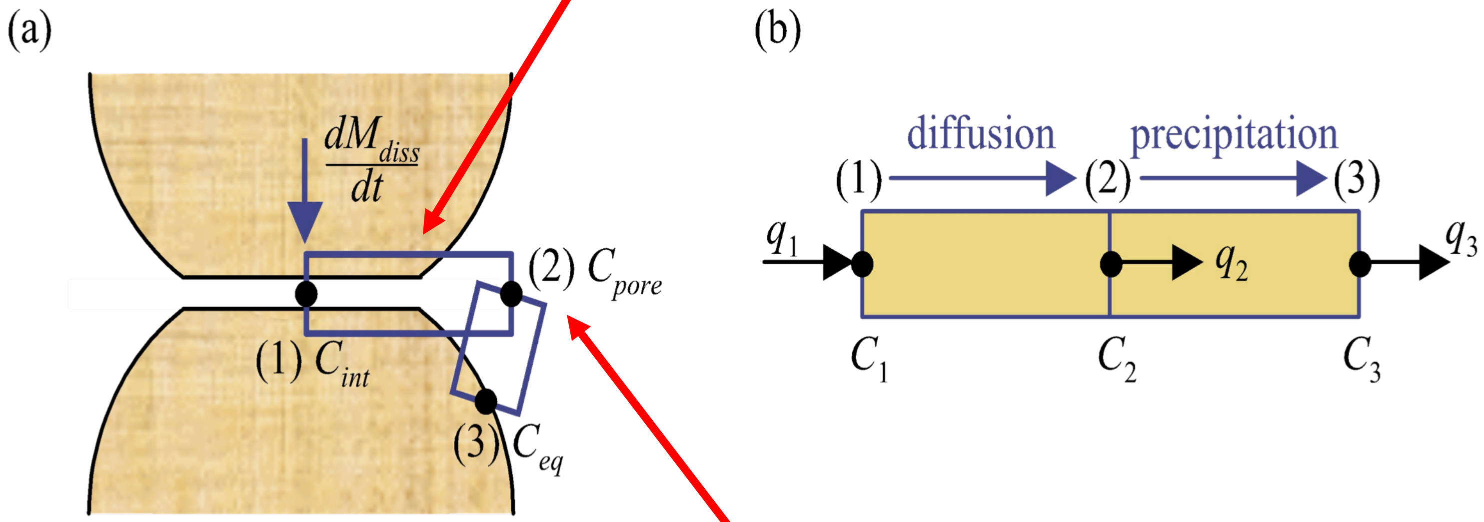
- Pore Precipitation

$$\frac{dM_{prec}}{dt} = V_{pore}\,\frac{A}{M}\,k_-\left(C_{pore}-C_{eq}\right)$$

[Yasuhara et al., JGR, 2003]

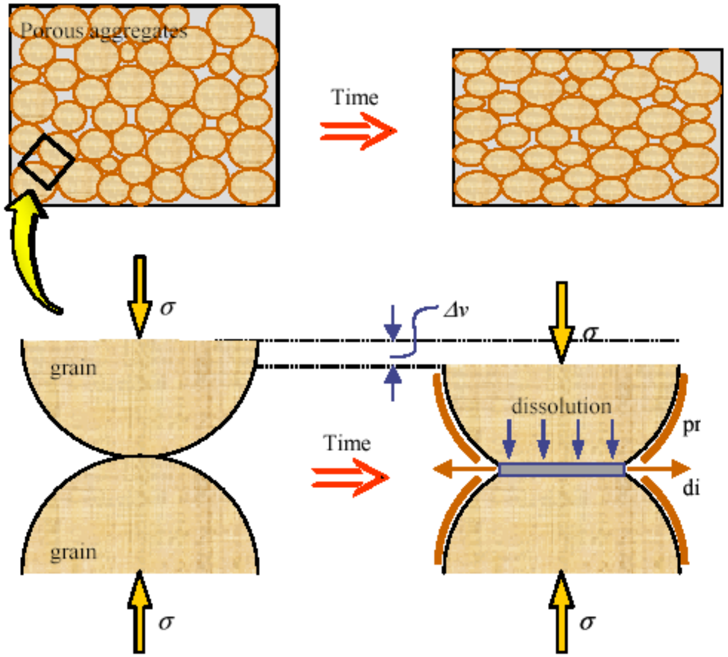
Mass Transfer Modes – Essential Components

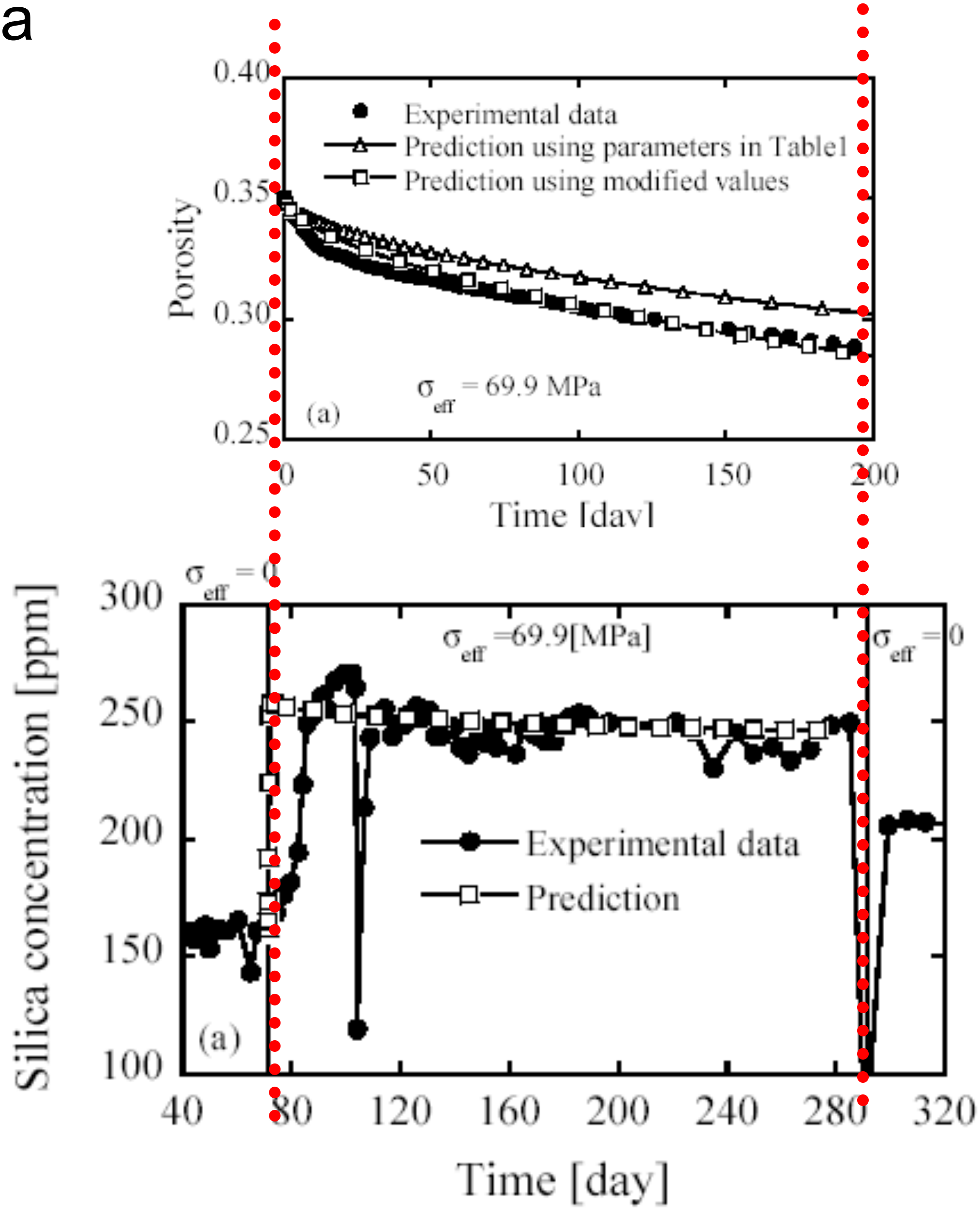
Contact geometry evolves with interpenetration



Pore concentration allows mass balance for arbitrarily open or closed systems

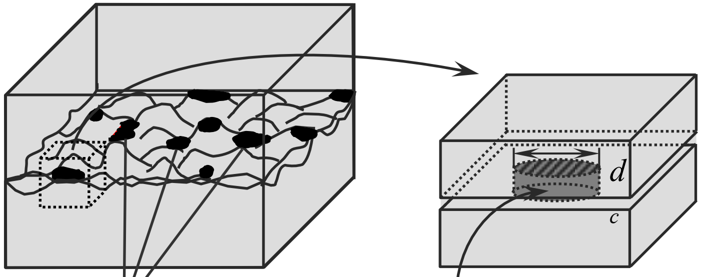
Matching Compaction Data





[Experimental data from Elias and Hajash, 1992]

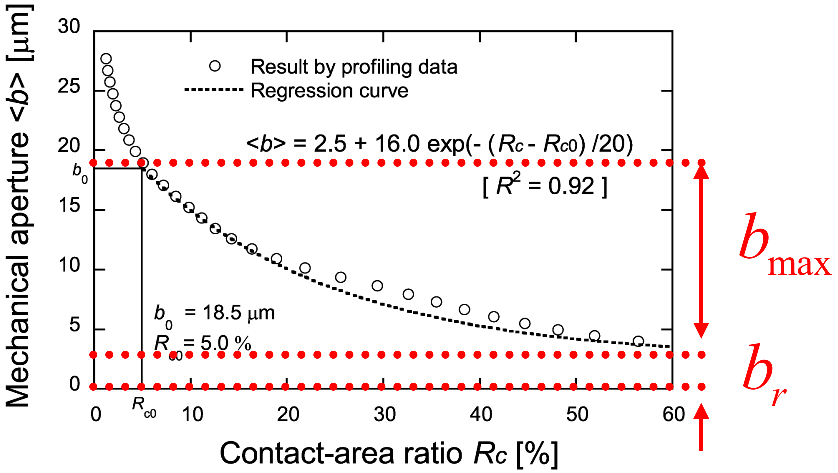
Constraint on Fracture Apertures and Fluid Concentrations

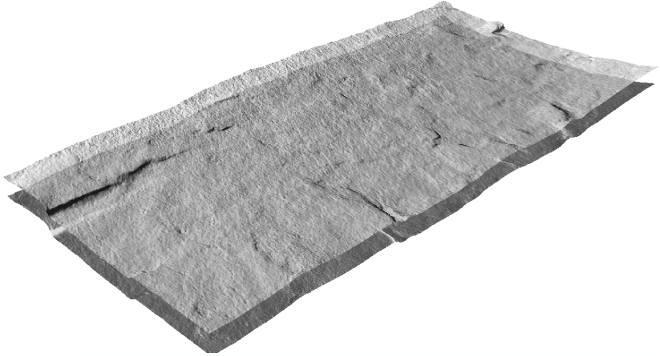


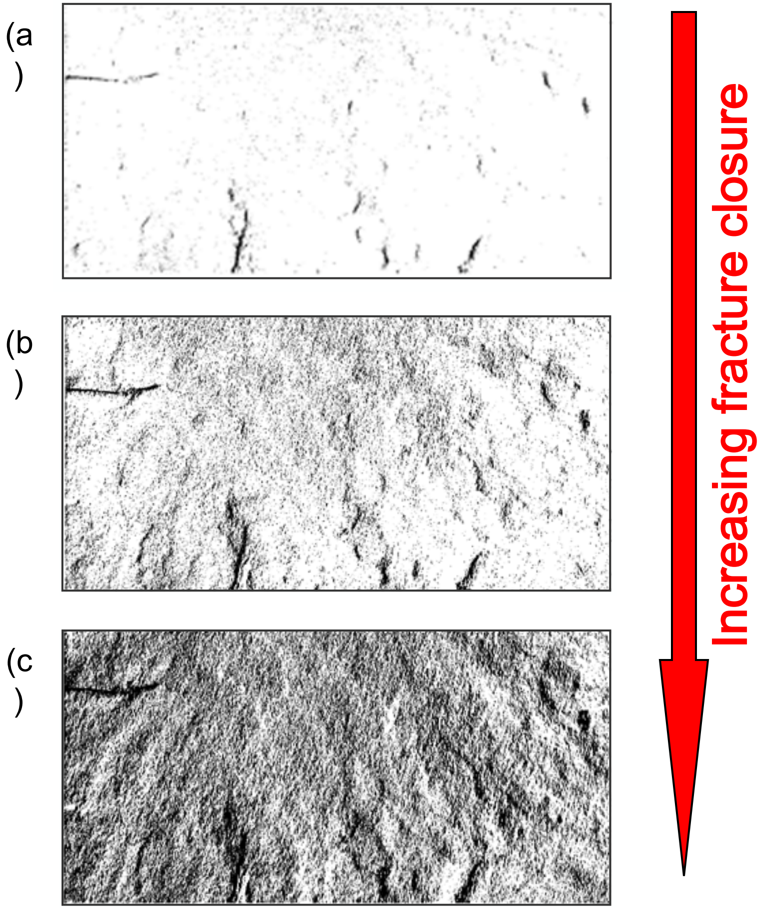
Asperity contacts

Local contact area, A^l_c

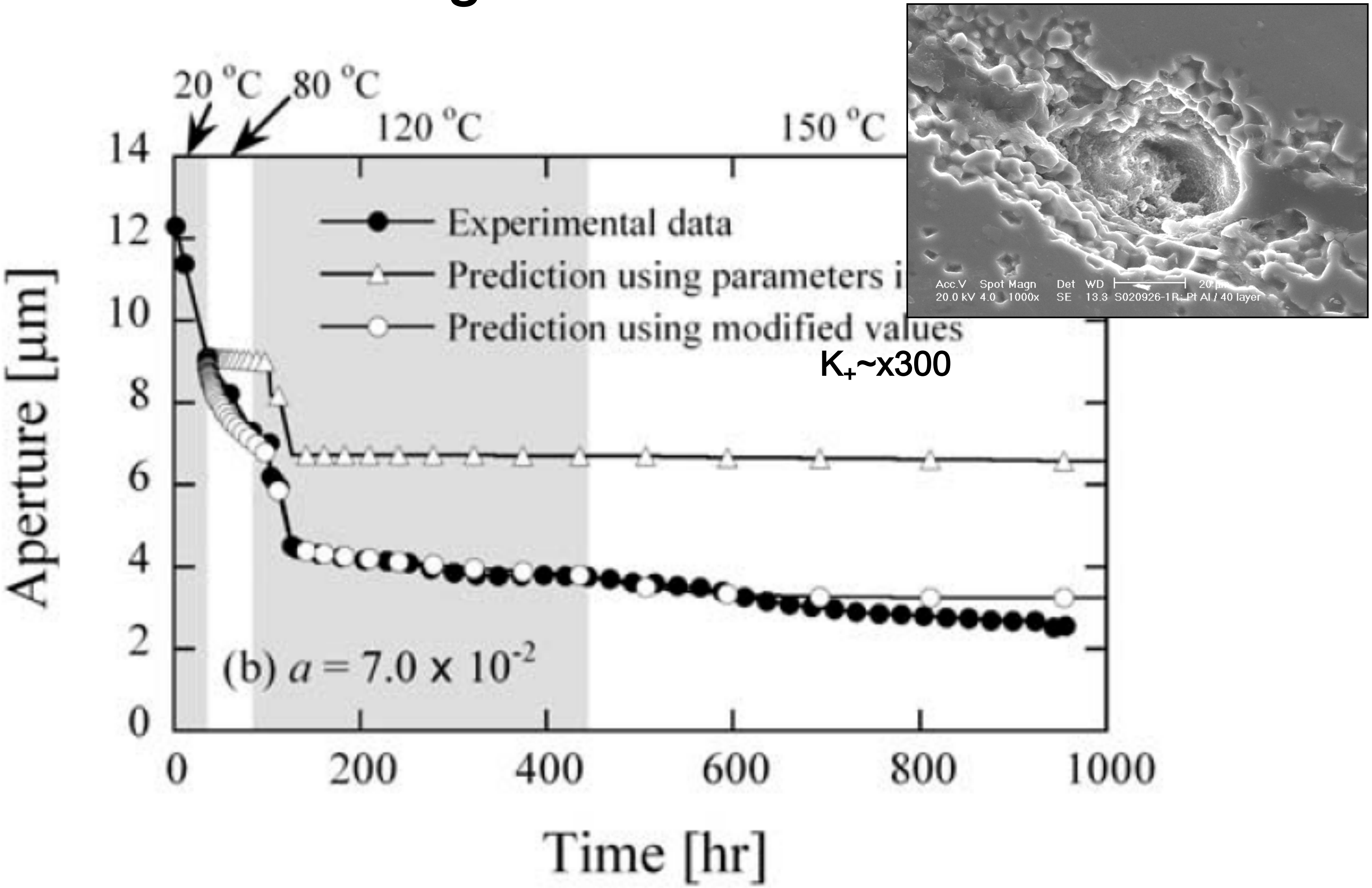
$$<b>= b_r + b_{\max} Exp[(R_c - R_{c0})/a]$$







Modeling Results - Novaculite



K_{+}~x300

[Yasuhara et al., JGR, 2004]

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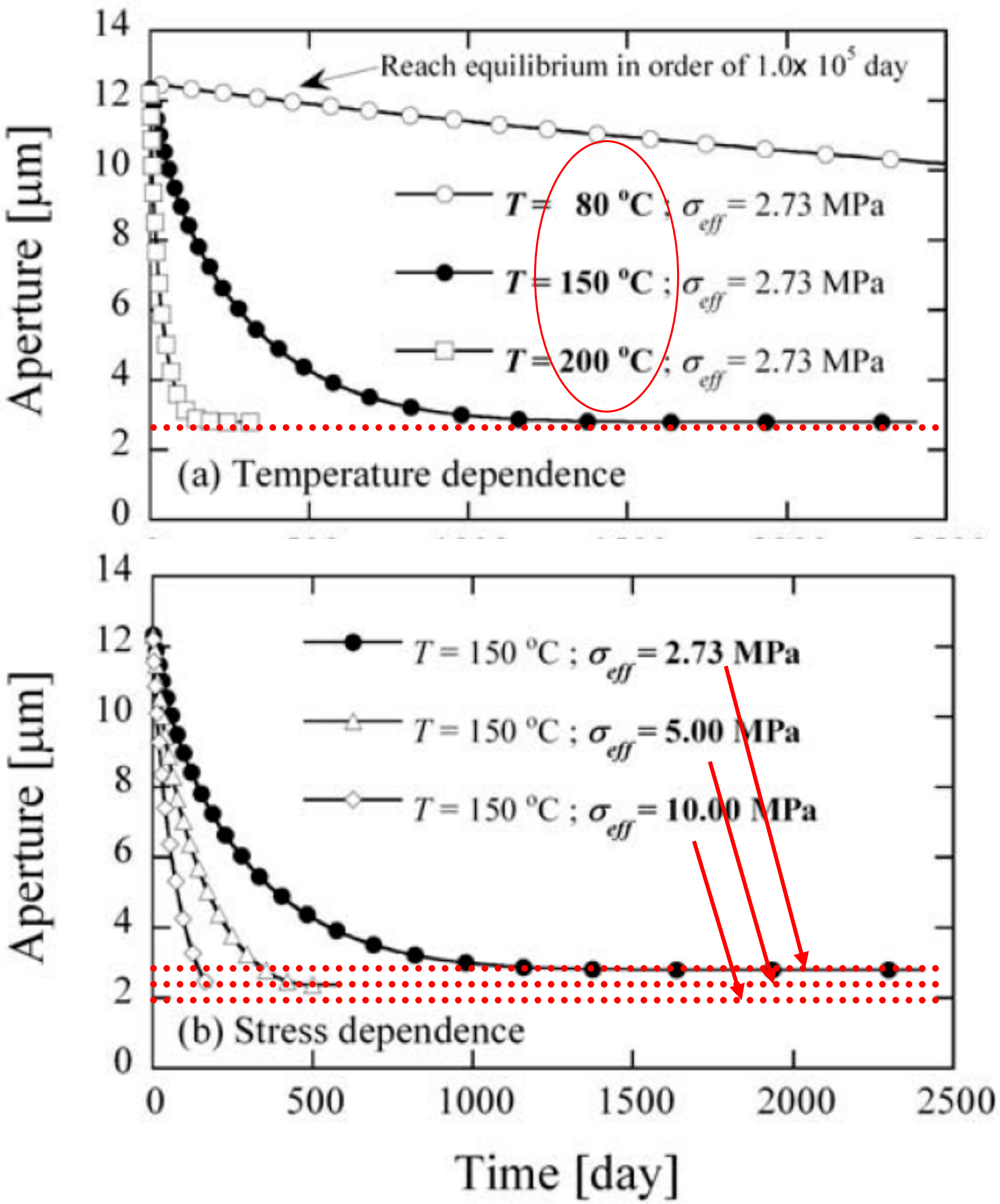
Projected Response of Novaculite

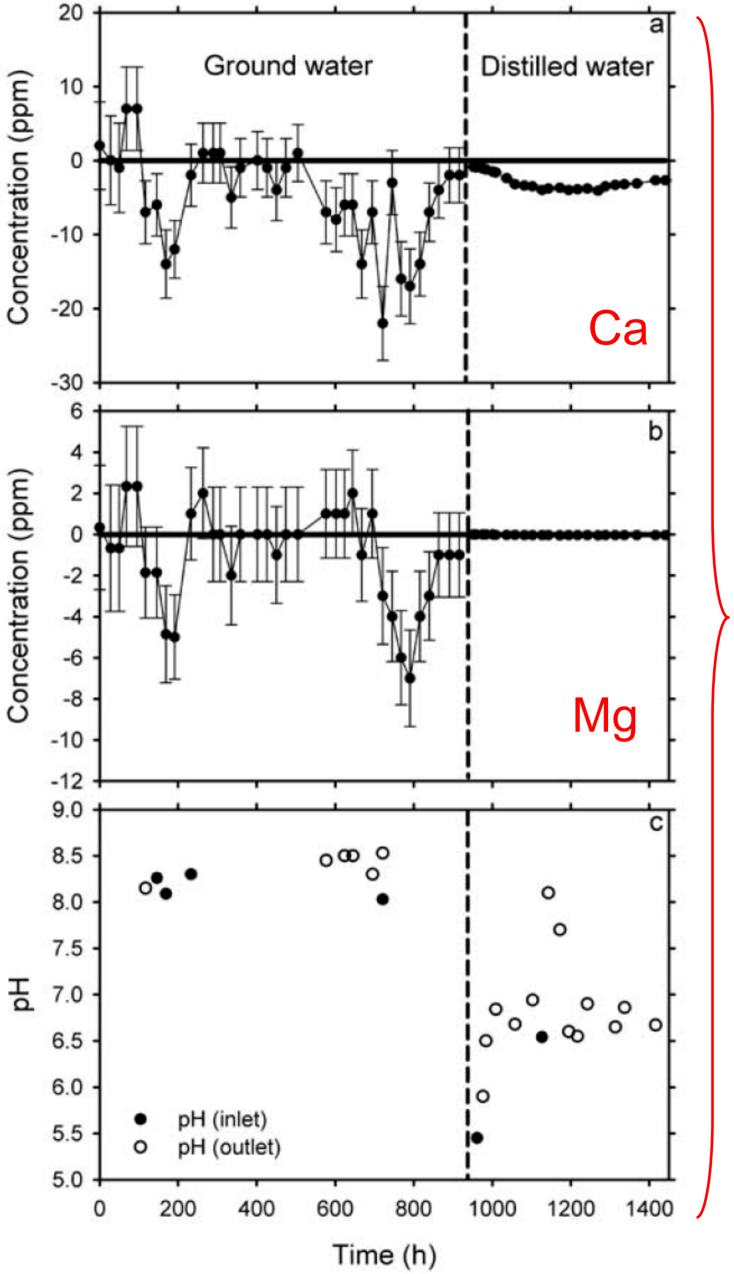
Define projected behavior for varied temperatures

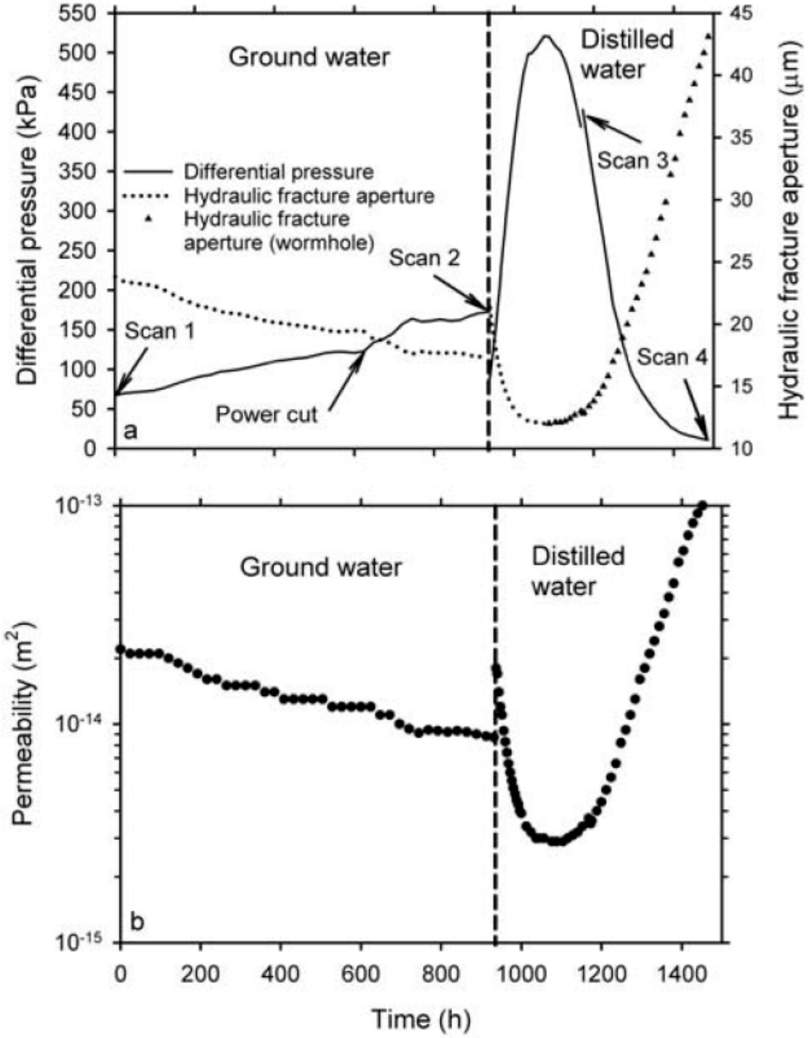
….and mean stress magnitudes



[Yasuhara et al., JGR, 2004]

Fractured Limestone – Features of Response

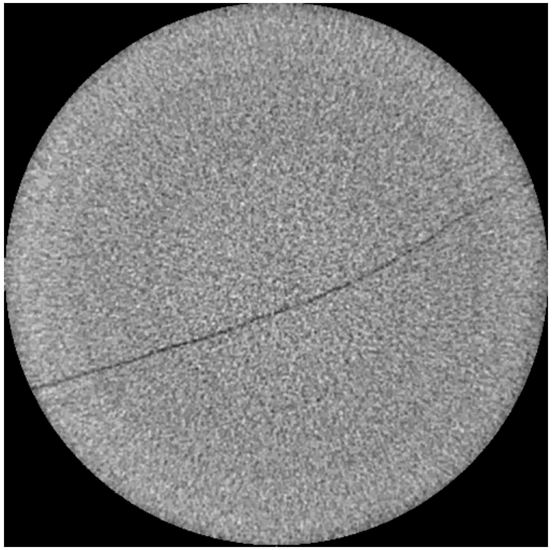




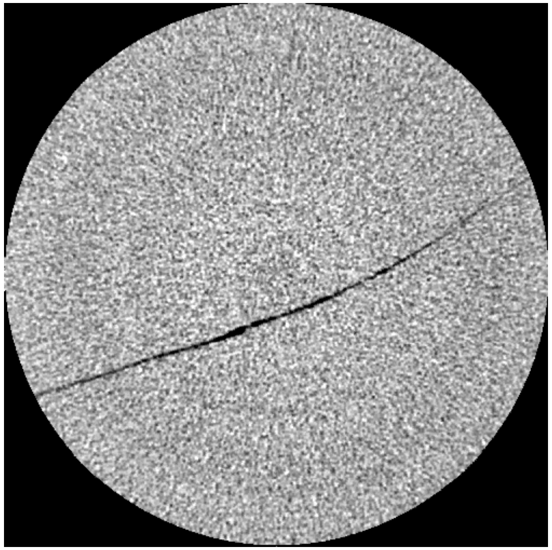
[Polak et al., WRR, 2004]

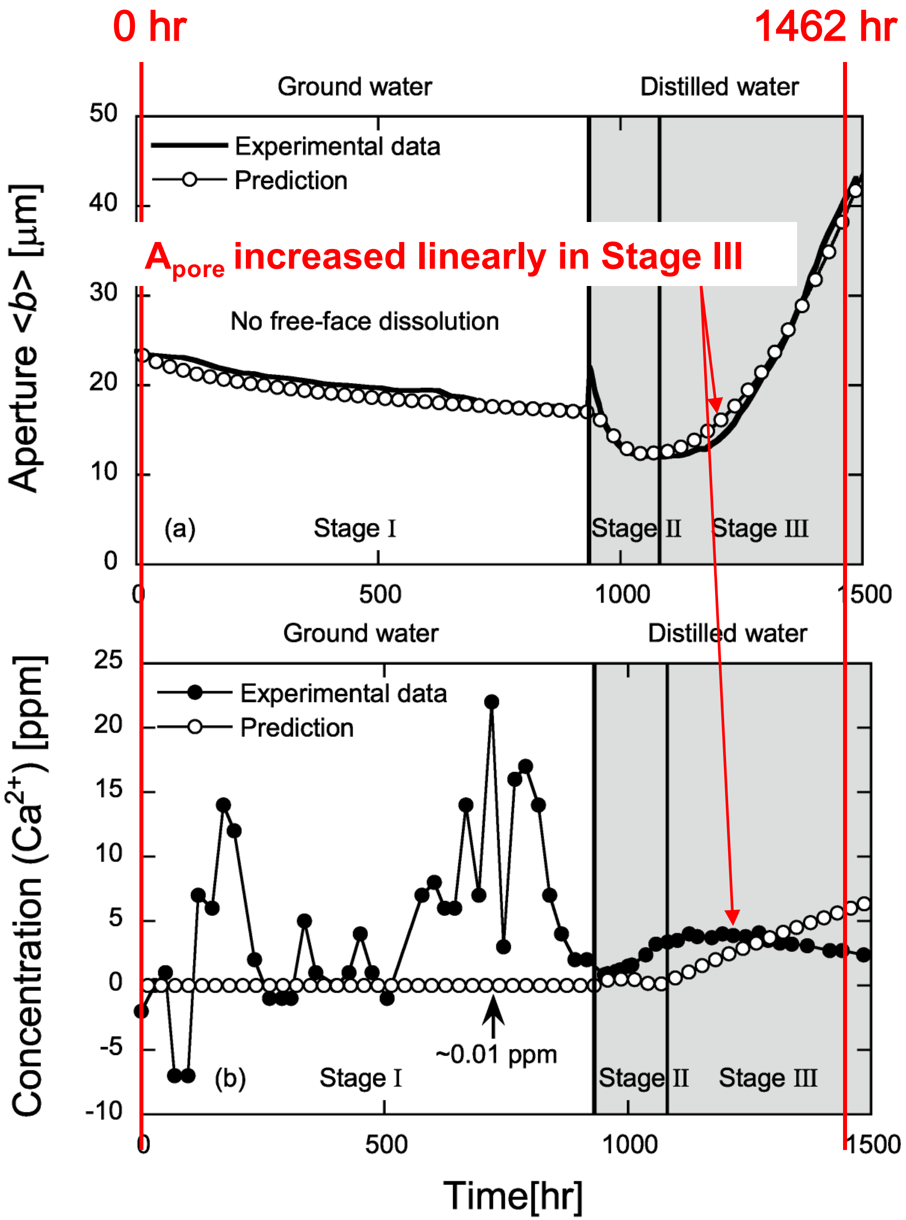
Fractured Limestone – Features of Response

0 hr



1462 hr



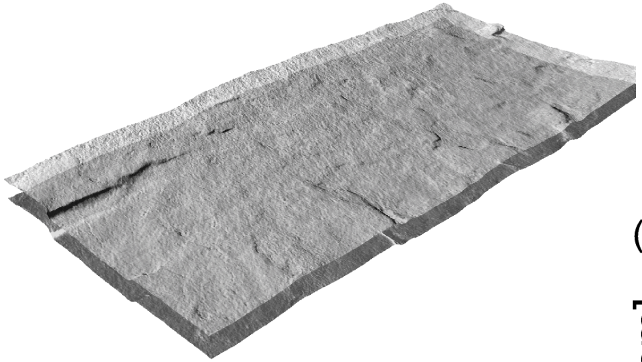


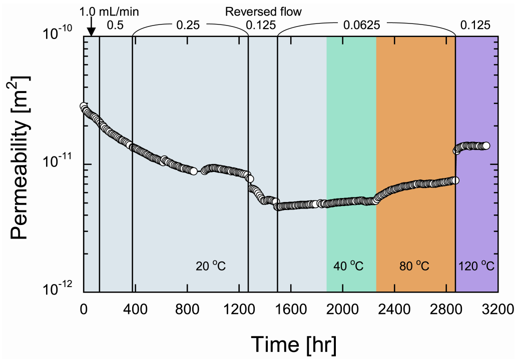
0 hr

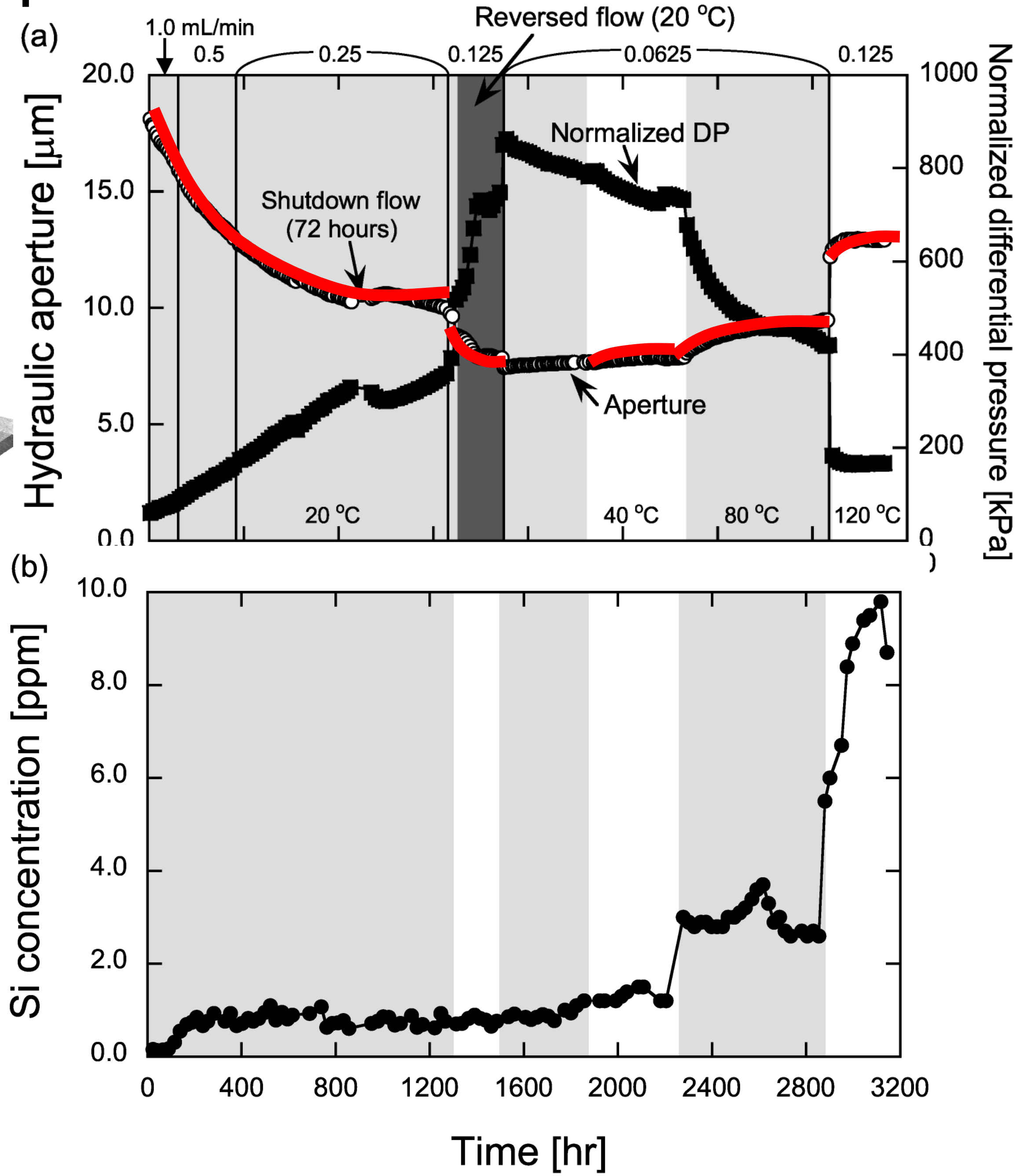
1462 hr

A_{pore} increased linearly in Stage III

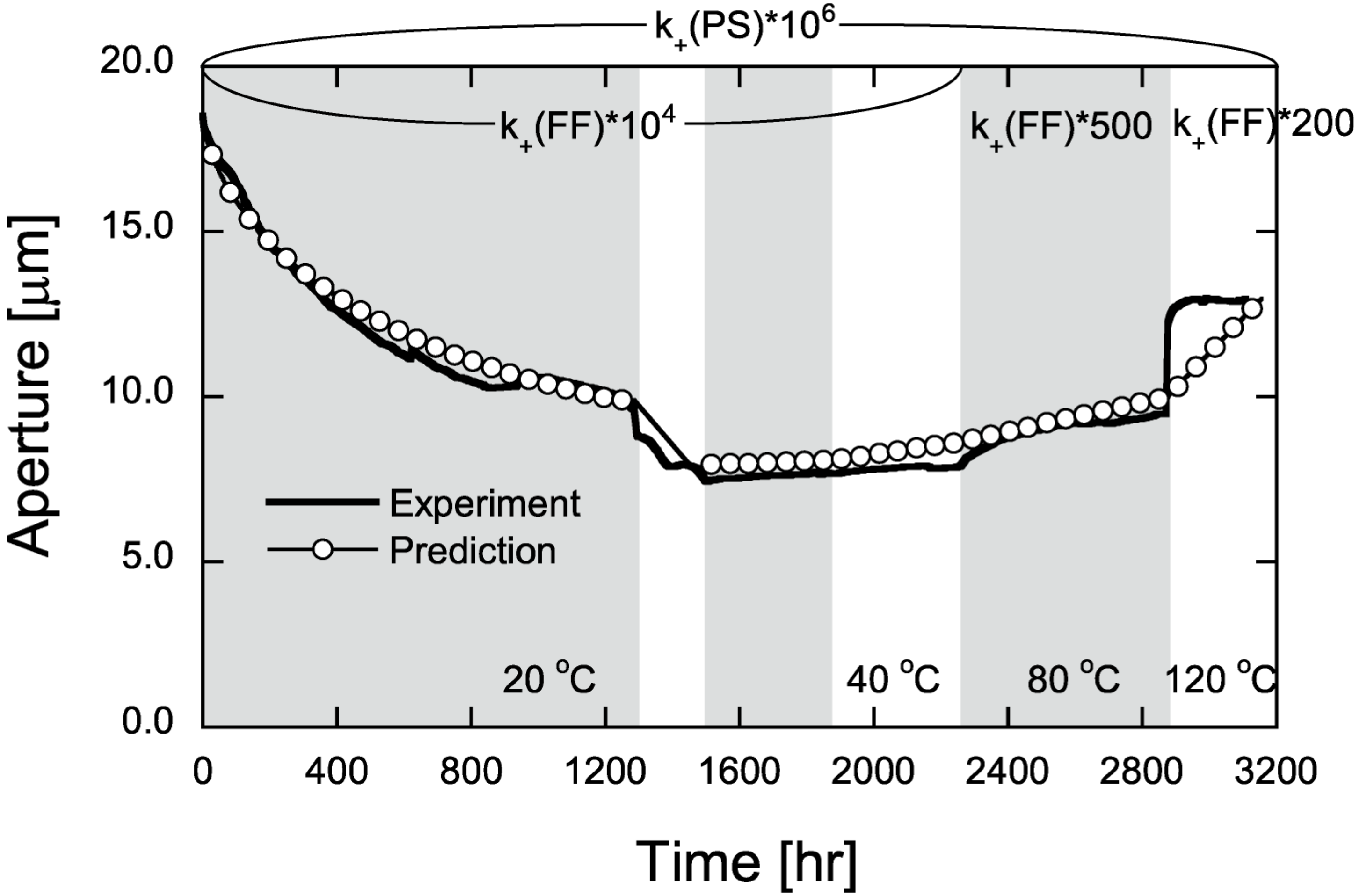
Novaculite – 20 week response







…..and Lumped Parameter Prognostic Model for Novaculite …



…..and CT Observations……

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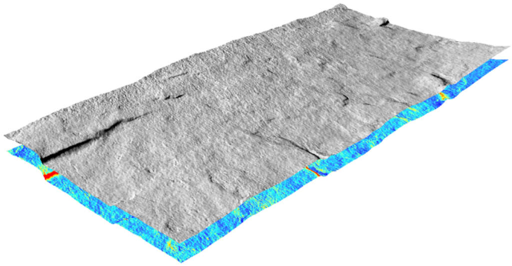
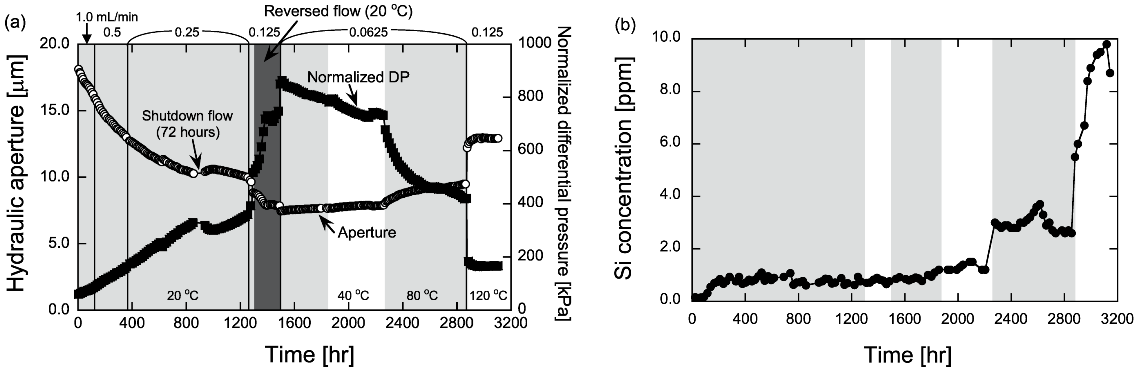
Distributed Parameter Models – Applied to Novaculite …

1. Set initial aperture distribution





2. Apply I.C. and B.C.

→ Obtain velocity distr. in a fracture by solving Reynolds' equation

$$\nabla\left(\frac{b^3}{12\mu}\nabla p\right)=0$$

3. Dissolution at contact area and free-face (reaction)

→ Obtain concentration distribution + Modify aperture distribution due to dissolution

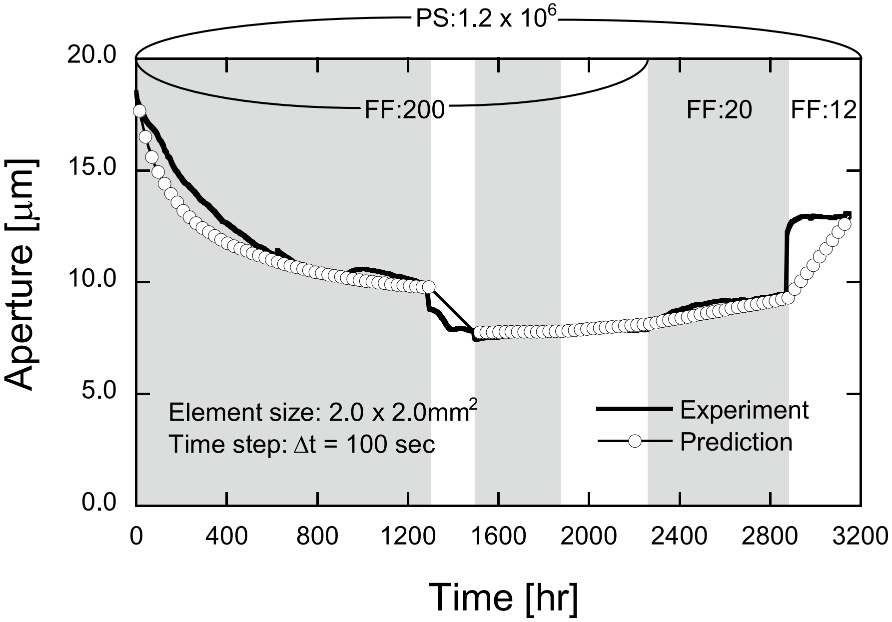
$$\frac{dM^{PS}}{dt}=\frac{3\pi V_m^2\rho_g k_+\left(\sigma_a-\sigma_c\right)A_e}{4RT};\qquad \frac{dM^{FF}}{dt}=2A_e k_+\frac{C_{eq}-C_i}{C_{eq}}$$

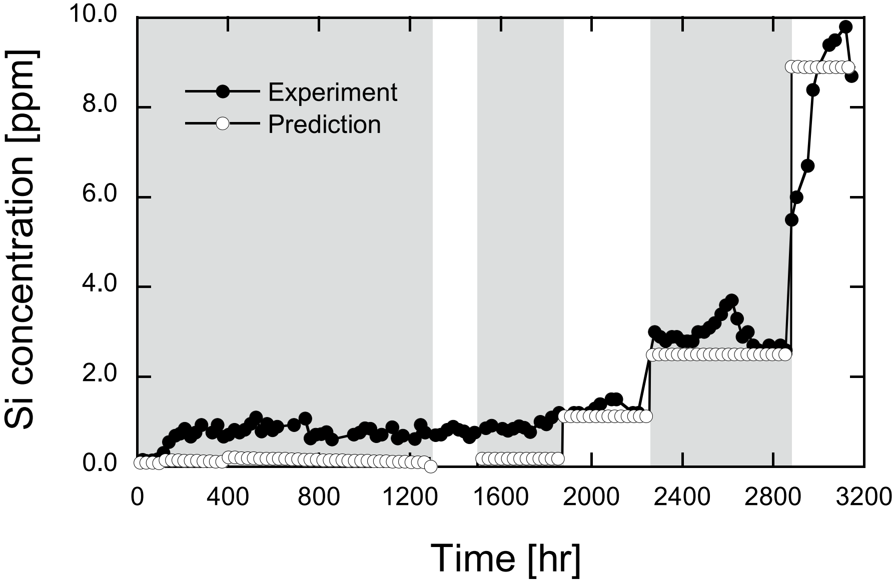
4. Lagrangian-Eulerian method (Advection-diffusion)

→ Obtain concentration distribution within and out of domain

Iteration

Distributed Parameter Model – Results for Novaculite …

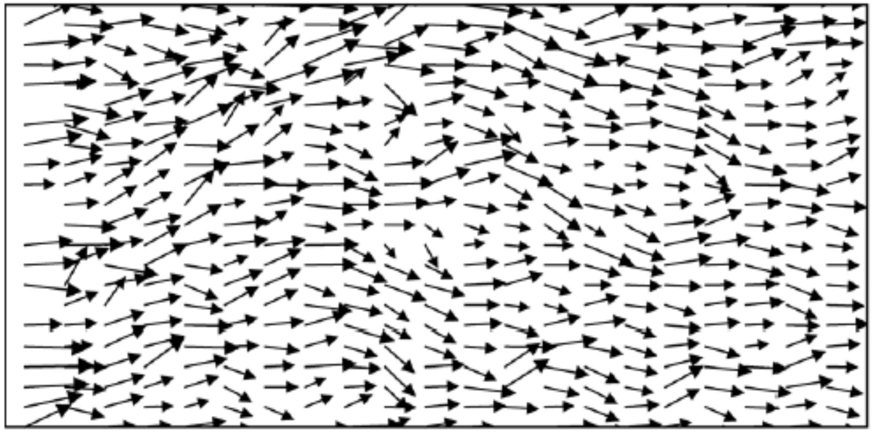




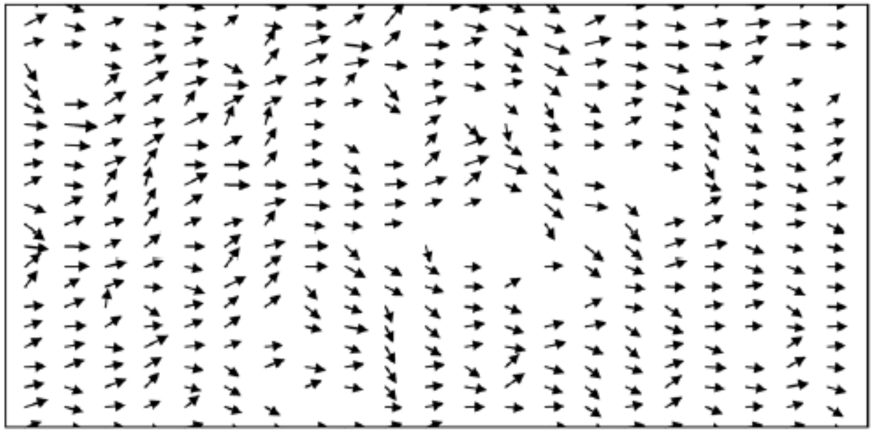
- Numerical model is capable of better replicating experiment – multiplier on k_+ is greatly reduced over lumped parameter case.

Reynolds' Flow Vectors and Measured/Predicted Aperture Distribution in Sample

(a) 0 hr

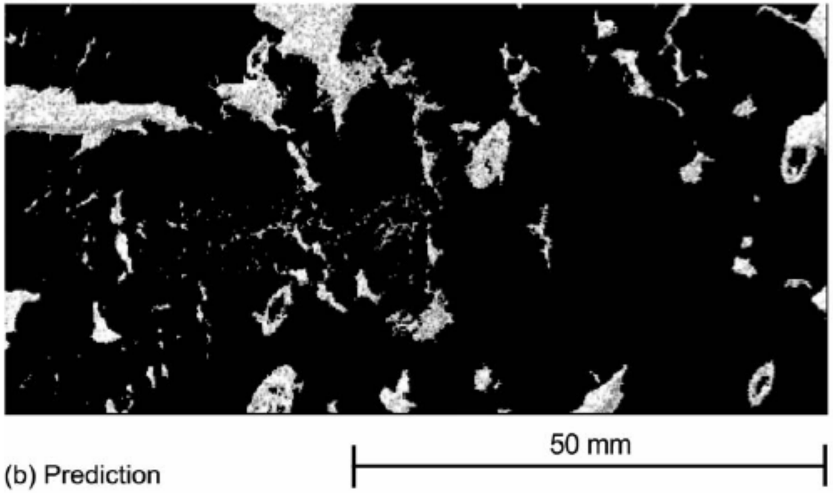


(b) 3150 hr

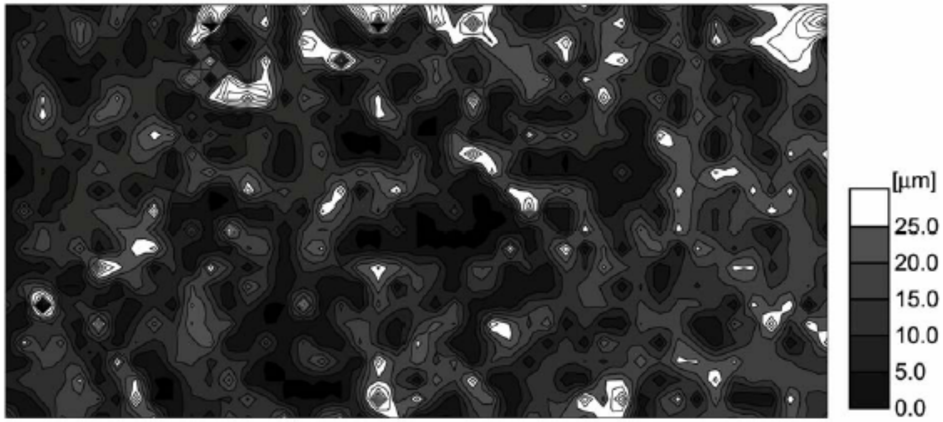


Wood's metal cast CT image

(a) CT image



(b) Prediction



Observations

1. Transport properties change in sometimes surprising modes as controlled by:
    - Stress
    - Thermal
    - Chemical-potential
    - Advective flux

    Fields and paths

2. Coupled Mechanical and Chemical feedbacks can be both significant and relatively rapid – especially for systems far-from-equilibrium

3. Locations of mass redistribution exert a fundamental control on the form and strength of permeability change

4. These fields and paths exert strong control on bulk transport [and mechanical] properties – related mechanical properties are manifest as a creep-like response (visco-elastic/plastic)

5. Understanding these complex interactions seem a prerequisite to predicting behavior at prototype scales

4. RESOURCE EXPLORATION AND CHARACTERIZATION

4. RESOURCE EXPLORATION AND CHARACTERIZATION

4.1 Geology

4.2 Geophysics

4.3 Drilling

7_1 Exploration and Characterization - Geological Setting

Recap:

1. Dissolution/precipitation important within reservoirs and external plant
2. Equilibrium chemistry defines modes of precipitation/dissolution
3. Reaction rates determine rates of precipitation/dissolution

Movies: You now know enough to benefit from these

Reservoir Characteristics - Interpreting Temperature and Pressure Measurements from Wells
Rick Allis, Utah Geological Survey
https://www.youtube.com/watch?v=fCIumFc3n5Y&t=2312s
.

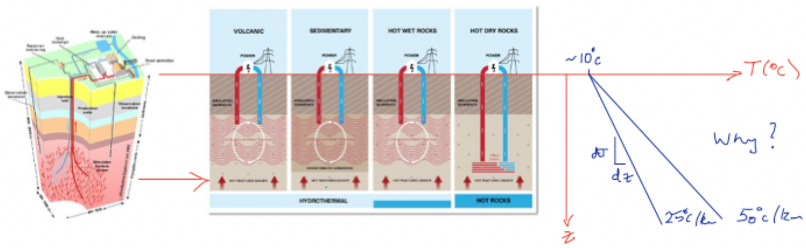
Predicting and Detecting Natural and Induced Flow Paths for Geothermal Fluids in Deep Sedimentary Basins - Stuart Simmons, EGI, University of Utah
https://www.youtube.com/watch?v=ZOJWIWzWLDg&t=2997s

Others as on the syllabus - at the Penrose SedHeat Meeting:
https://www.youtube.com/channel/UCBHQHy4hVyBJQFogrKvKUAg/videos

Resources: WG6

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
Therefore prospect for:
 (i) High Mass_rate/permeability/overpressure and
 (ii) High T at shallow depth
Less crucial in "engineered" systems - "EGS" and "GSHP"

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

1. What geological habits/characteristics are indicative of geothermal reservoirs?
2. What methods are available to discover them and characterize the resource?
   A. Geology/Geophysics
   B. Drilling/Instrumentation
   C. Well completion/Testing

GEOLOGY

1. What geological habits/characteristics are indicative of geothermal reservoirs?
    A. Analysis of geology at a variety of scales - plate boundary to local
        a. Reports
        b. Surface features - remote sensing and imagery
        c. Drilling records
    B. Initiate local investigation
        a. Geochemical signatures
        b. Geophysical investigation
        c. Drilling and sampling
        d. Well completion then well testing

Classification of Geothermal Systems - Regional Perspective (WG6)

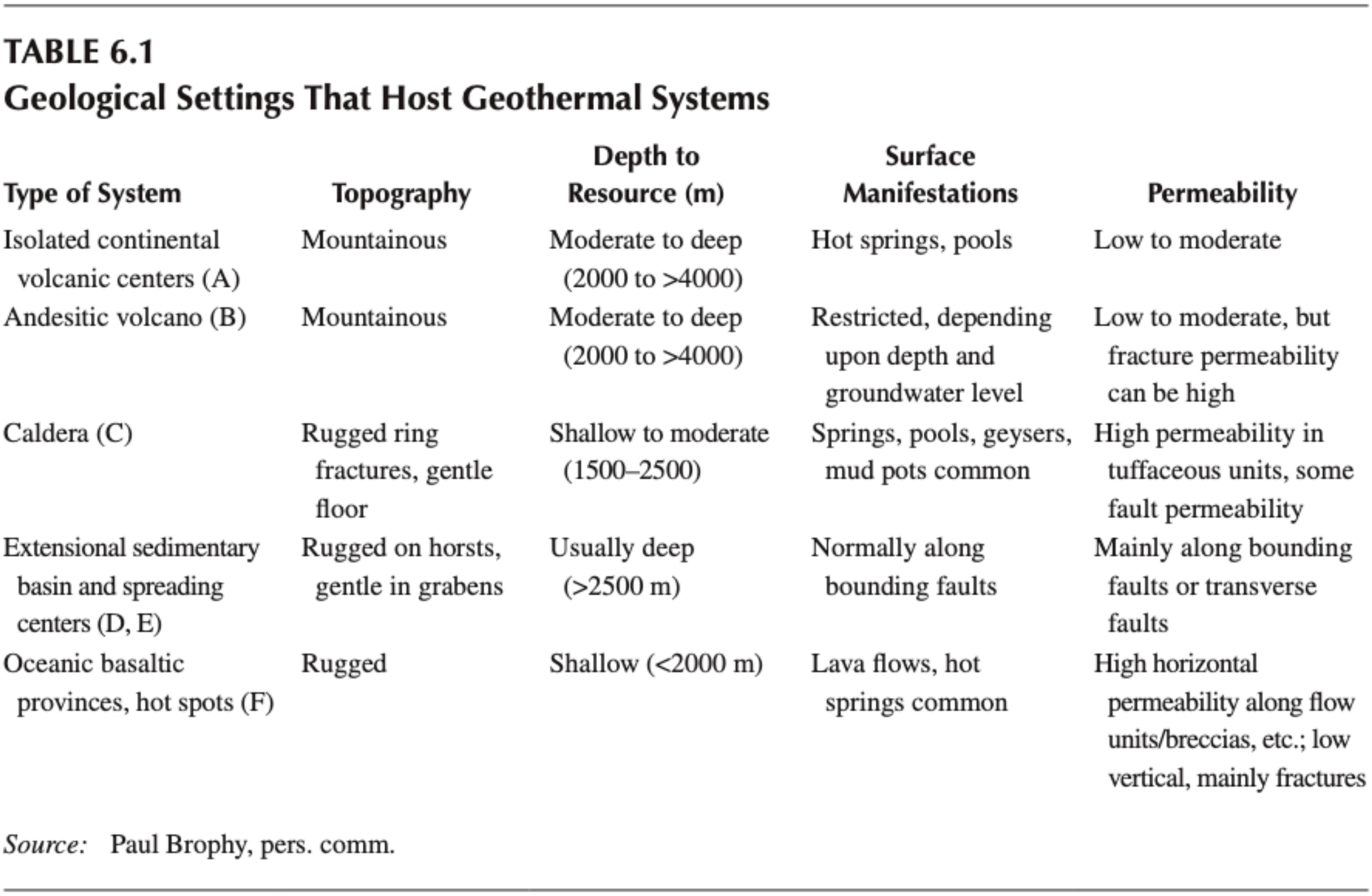
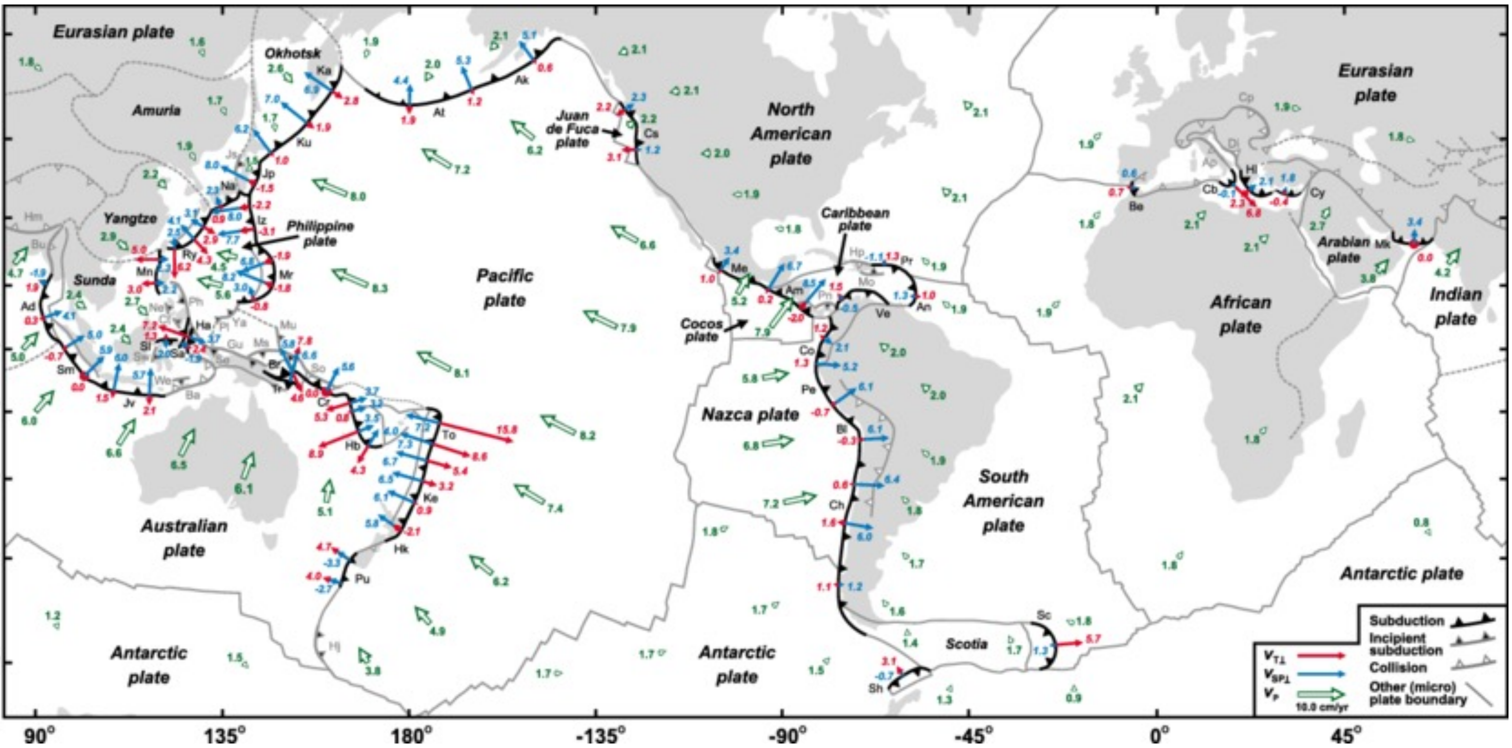
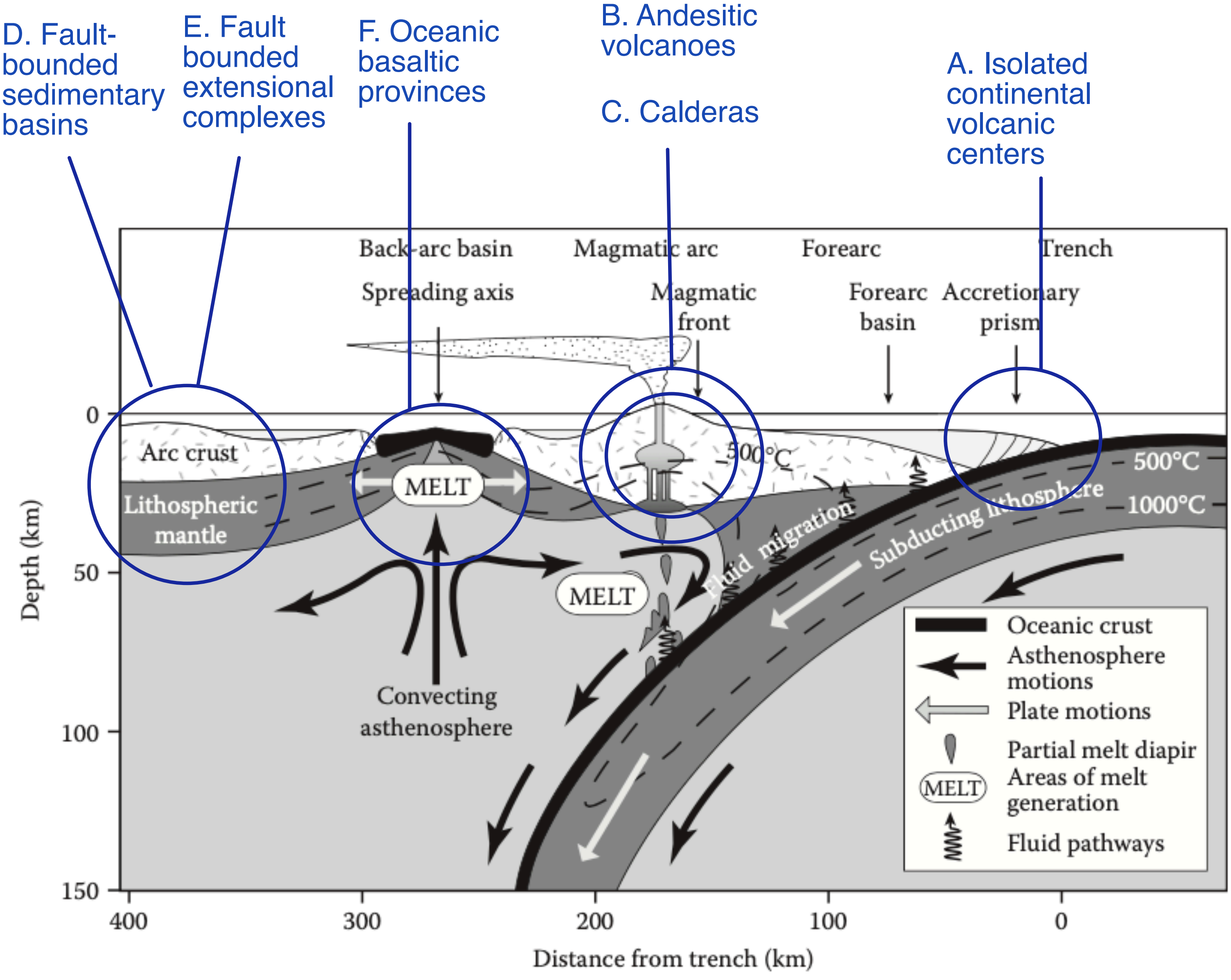


TABLE 6.1
Geological Settings That Host Geothermal Systems

Type of System	Topography	Depth to Resource (m)	Surface Manifestations	Permeability
Isolated continental volcanic centers (A)	Mountainous	Moderate to deep (2000 to >4000)	Hot springs, pools	Low to moderate
Andesitic volcano (B)	Mountainous	Moderate to deep (2000 to >4000)	Restricted, depending upon depth and groundwater level	Low to moderate, but fracture permeability can be high
Caldera (C)	Rugged ring fractures, gentle floor	Shallow to moderate (1500–2500)	Springs, pools, geysers, mud pots common	High permeability in tuffaceous units, some fault permeability
Extensional sedimentary basin and spreading centers (D, E)	Rugged on horsts, gentle in grabens	Usually deep (>2500 m)	Normally along bounding faults	Mainly along bounding faults or transverse faults
Oceanic basaltic provinces, hot spots (F)	Rugged	Shallow (<2000 m)	Lava flows, hot springs common	High horizontal permeability along flow units/breccias, etc.; low vertical, mainly fractures

Source: Paul Brophy, pers. comm.

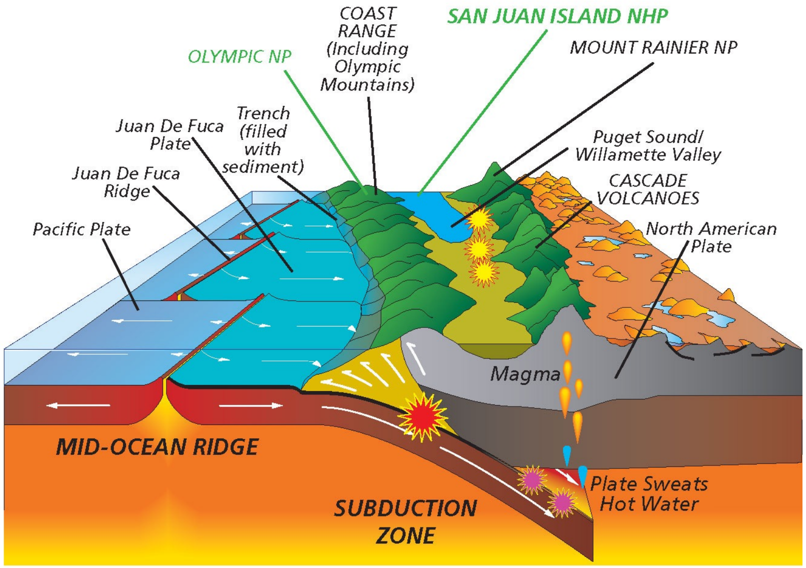

Eurasian plate
Okhotsk
Amuria
Yangtze
Sunda
Philippine plate
Pacific plate
Juan de Fuca plate
North American plate
Caribbean plate
Cocos plate
Nazca plate
South American plate
Scotia
African plate
Arabian plate
Indian plate
Australian plate
Antarctic plate
Subduction
Incipient subduction
Collision
Other (micro) plate boundary
$V_{T\perp}$
$V_{SP\perp}$
V_P
10.0 cm/yr
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
90°
135°
180°
-135°
-90°
-45°
0°
45°


D. Fault-bounded sedimentary basins
E. Fault bounded extensional complexes
F. Oceanic basaltic provinces
B. Andesitic volcanoes
C. Calderas
A. Isolated continental volcanic centers
Back-arc basin
Magmatic arc
Forearc
Trench
Spreading axis
Magmatic front
Forearc basin
Accretionary prism
Arc crust
Lithospheric mantle
MELT
500°C
500°C
1000°C
Subducting lithosphere
Fluid migration
MELT
Convecting asthenosphere
Oceanic crust
Asthenosphere motions
Plate motions
Partial melt diapir
MELT
Areas of melt generation
Fluid pathways
Depth (km)
0
50
100
150
400
300
200
100
0
Distance from trench (km)

A. Isolated continental volcanic centers (e.g. The Geysers)

B. Andesitic volcanoes (e.g. Cascade volcanoes incl. Newberry, Montserrat, BWI)

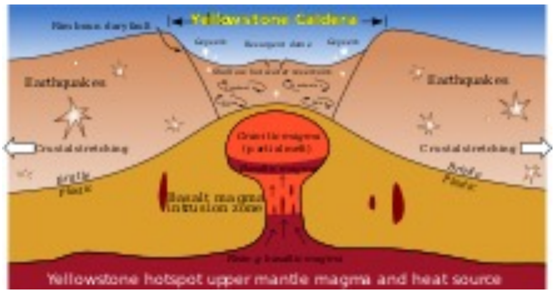
C. Calderas (e.g. Valles Caldera, NM (Fenton Hill), Yellowstone, Crater lake, OR, Long Valley, CA)

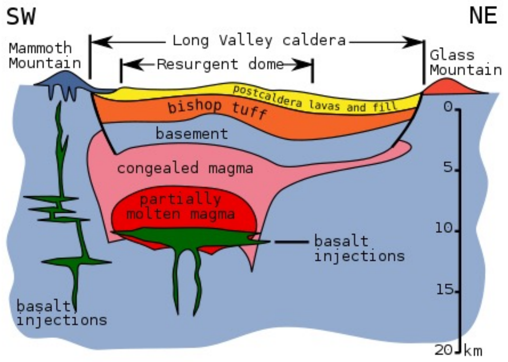


Cascadia earthquake sources

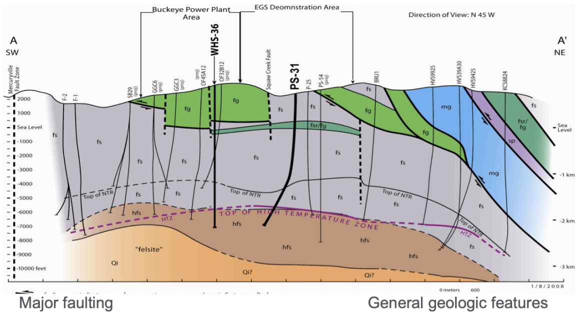
Source	*Affected area*	*Max. size*	*Recurrence*
Subduction Zone	West. WA, OR, CA	M 9	500-600 years *(1700)*
Deep Juan De Fuca Plate	West. WA, OR	M 7+	30-50 years *(1949, 1965, 2001)*
Crustal faults	WA, OR, CA	M 7+	hundreds of years? *(CE 900, 1872)*

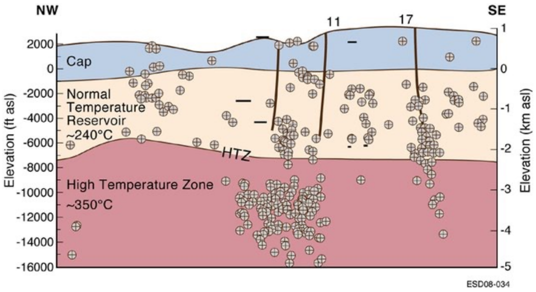
C. Yellowstone & Long Valley





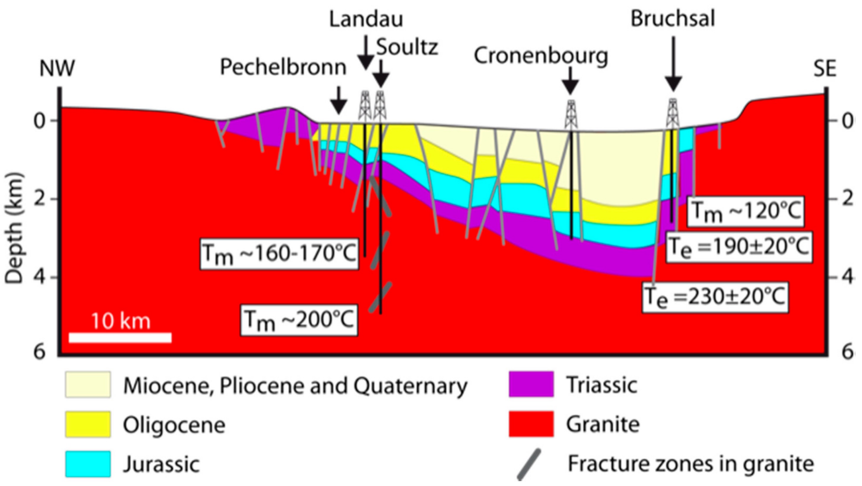
A. The Geysers

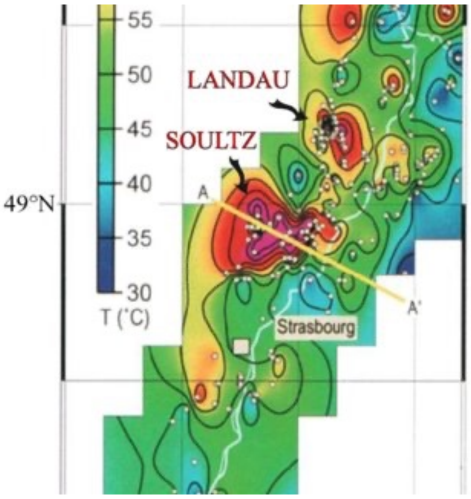


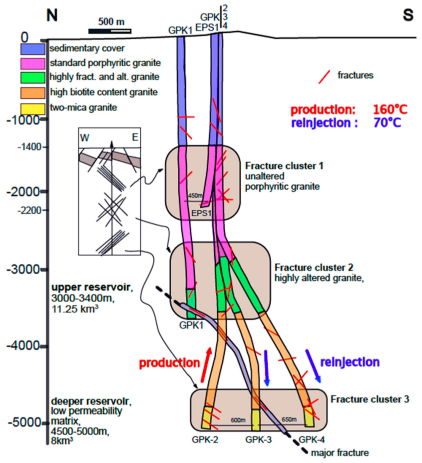


B. Soufrière Hills Volcano, BWI

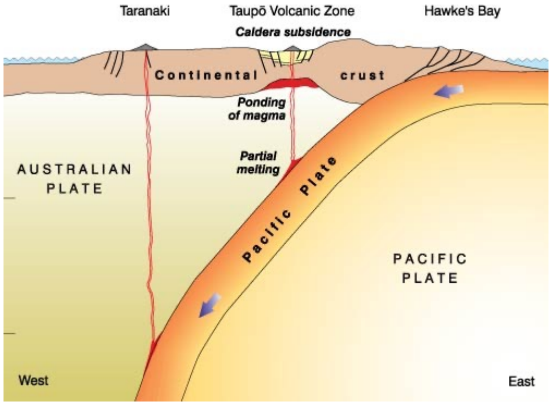
D. Fault-bounded sedimentary basins (e.g. Rhine graben France/German and Soultz EGS, Salton Sea, CA)

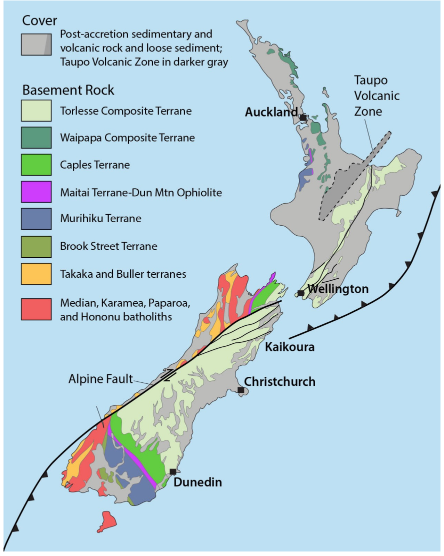




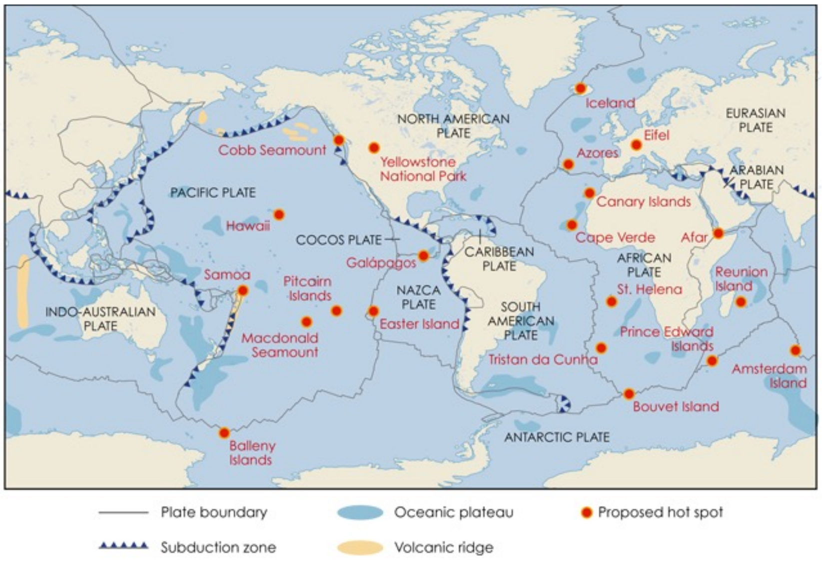


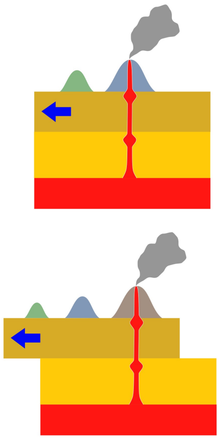
E. Fault bounded extensional complexes (e.g. Taupo Volcanic Zone, NZ, East Africa Rift)

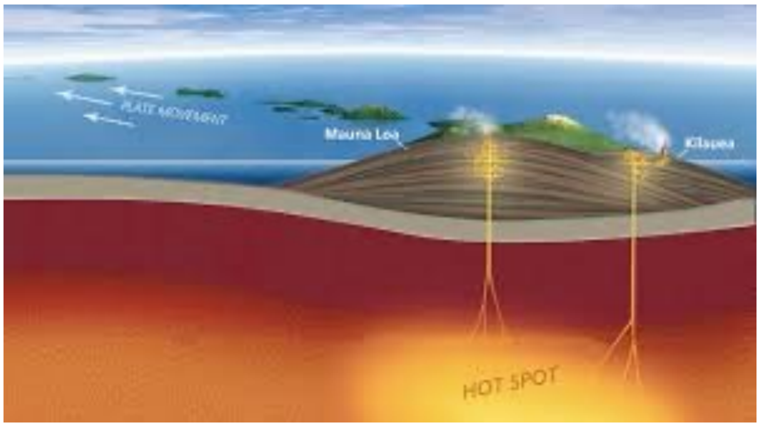




F. Oceanic basaltic provinces (e.g. Hawaii, Canary Islands, Azores, Iceland)





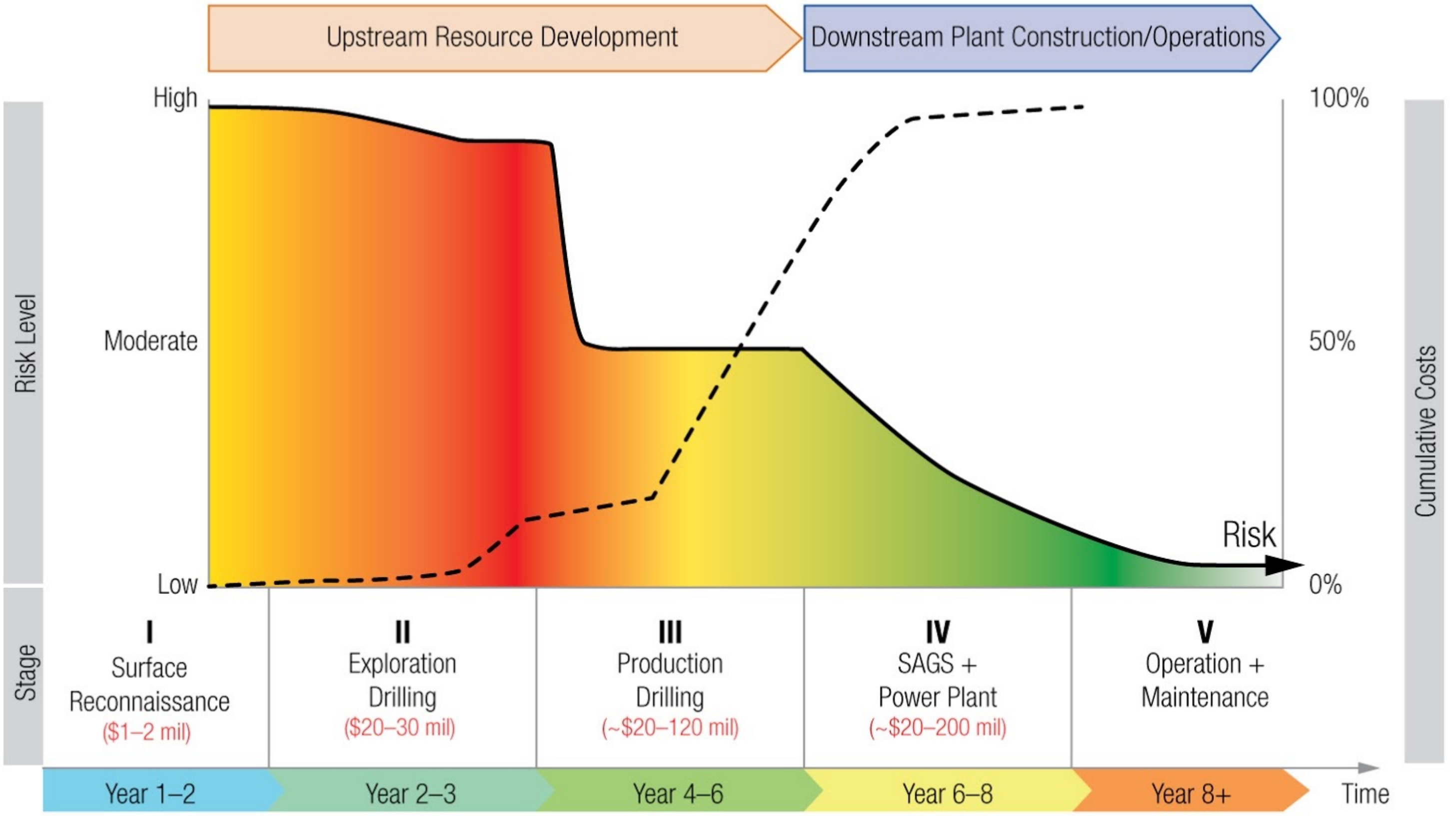


These geological settings control the location of largely hydrothermal resources

What determines the optimal placement of wells? What methods are available to de-risk exploration

What about EGS in widespread locations and sedimentary aquifers ......

Figure 1 | A Conceptual Representation of Risks and Costs during the Different Stages of a Geothermal Development



Source: Adapted from Geothermal Handbook (ESMAP 2012).

4. RESOURCE EXPLORATION AND CHARACTERIZATION

4.1 Geology
4.2 Geophysics
4.3 Drilling

7_2 Exploration and Characterization - Geophysics

Recap:

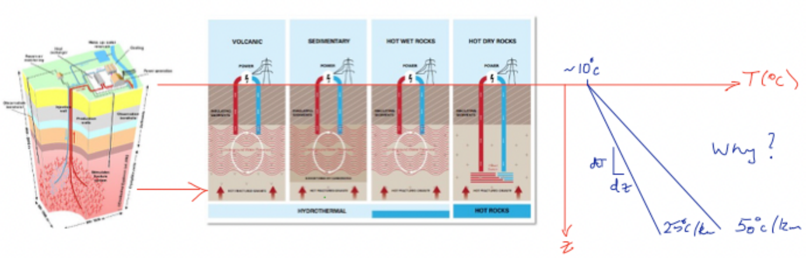
1. Geological setting provides information on global location of resources
2. Location specific structure will differ in various environments

Movies: https://www.energy.gov/eere/forge/sandia-national-laboratories-west-flank

Resources: WG7

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
Therefore prospect for:
  (i) High Mass_rate/permeability/overpressure - define fast flow paths, and
  (ii) High T at shallow depth
Less crucial in "engineered" systems - "EGS" and "GSHP"

Scientific Questions:

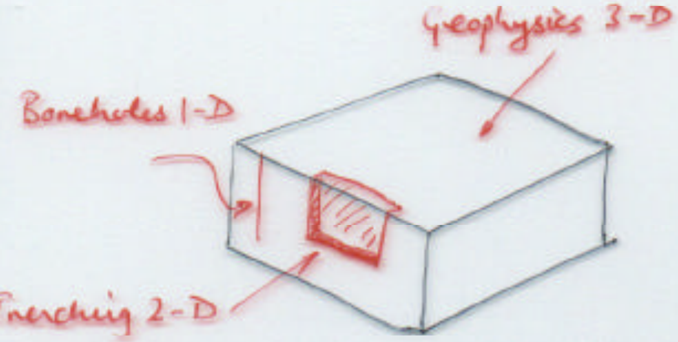
2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

1. How do we locally define the reservoir and the distribution of:
   A. Temperatures - as shallow as possible
   B. Permeable pathways - as distributed as possible or high flow rates

GEOPHYSICS

1. Geomagnetic methods
2. Geoelectric methods DC/AC/EM
3. Seismic methods
4. Gravity methods
5. Borehole methods - Well logging

GEOPHYSICAL METHODS OF INVESTIGATION



Investigation Scales

small scale – representativeness of sample
– large scale structures
v. imp for groundwater since large scale structure controls flow/ transport behavior.
– use of pump tests.

large scale – – big picture
– correlation with real behavior through boreholes.

Geophysical Methods: Fast/ large volume/area coverage → inexpensive.

1. Geomagnetic methods
2. Geoelectric methods
    2.1 Direct Current
    2.2 Electromagnetic (Radar)
3. Seismic methods
    3.1 Refraction
    3.2 Reflection
4. Gravity methods

Miscellaneous: Well logging.

DIAGRAM OF DELIVERABLES FOR A PHASE II
MONITORING WELL DESIGN PROJECT

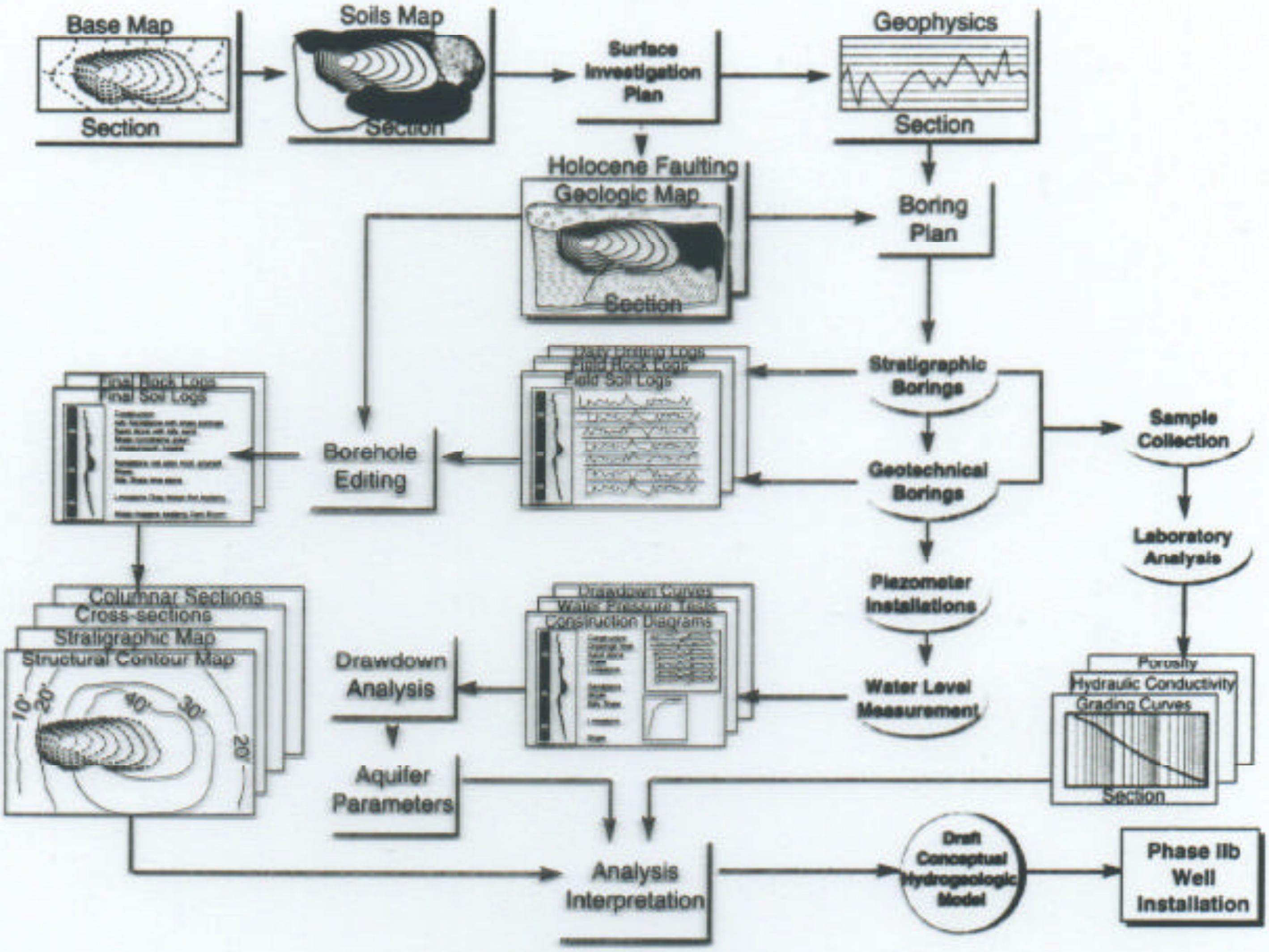
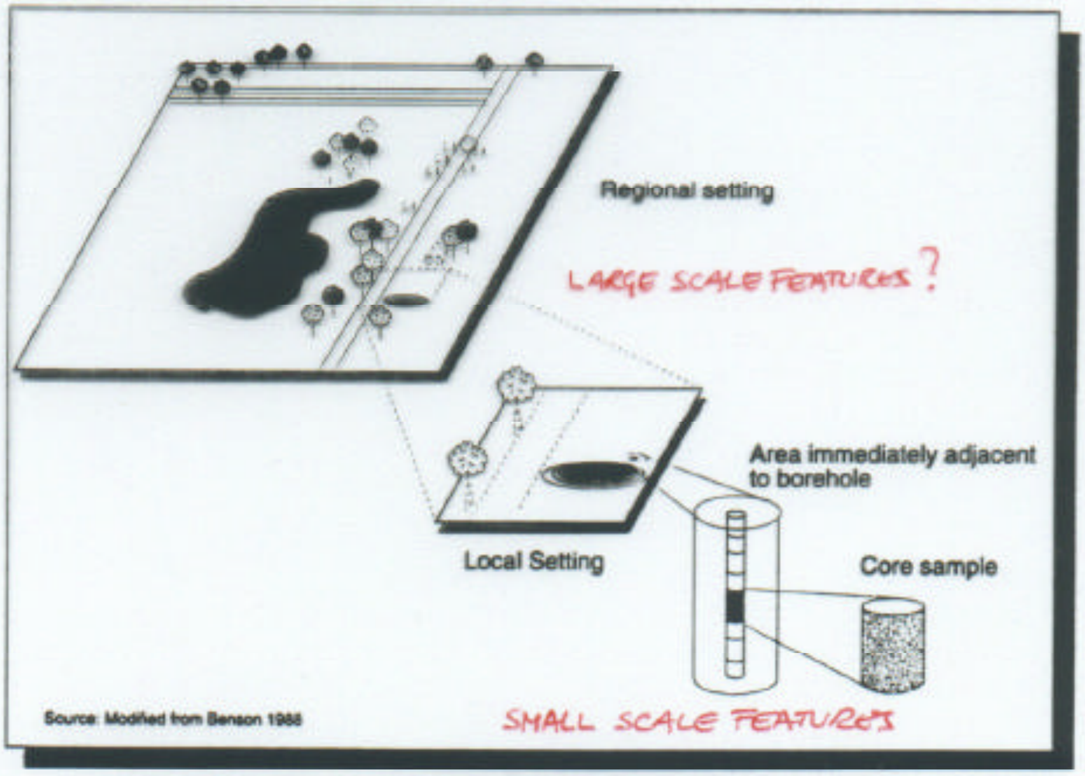


Figure 3-3a Phase II Flow Diagram

CONCEPTS OF SCALE



Source: Modified from Benson 1988

Figure 3-12 Regional to Core Sample Scales

1. GEOMAGNETIC METHODS

- ☐ Measure change in Earth's mag. field
  - ∴ Locates ferrous targets

- ☐ Response proportional to
  1. Mass of target, M.
  2. $\frac{1}{r^3}$ separation of target.

- ☐ Susceptibility to urban utilities
  - ∴ rural areas better

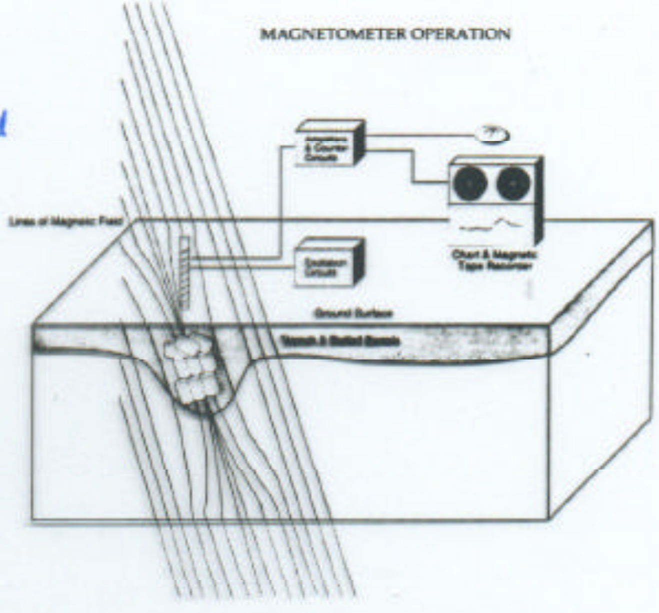
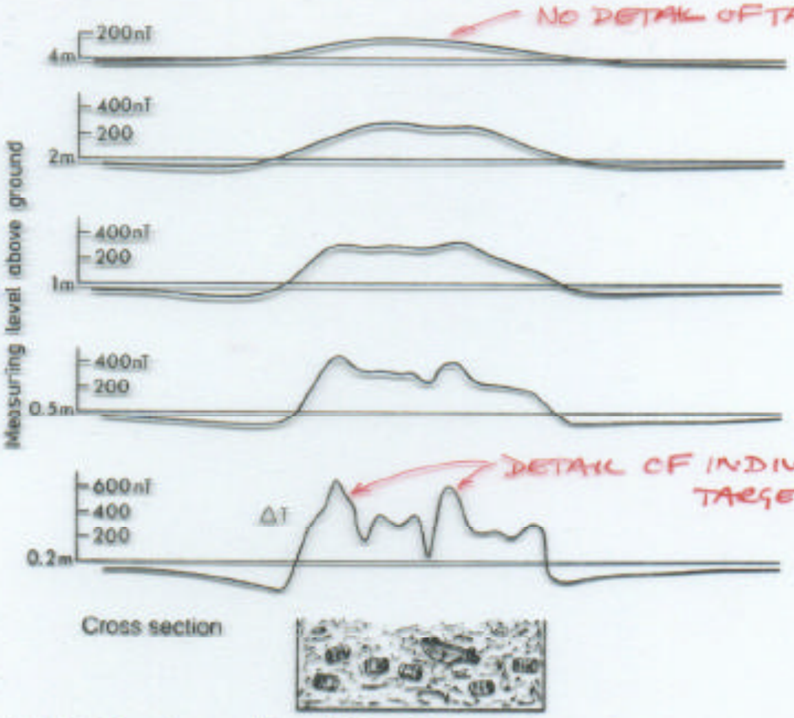


Figure 3-20 Magnetometry

- ☐ Measurement in nTeslas
  - i.e. 10^{-9} Teslas
- ☐ Resolution ↓ with ↑ target depth since $1/r^3$

Max Depths

- 1 drum @ 10ft.
- Multi-drums @ 30ft.



NO DETAIL OF TARGETS

DETAIL OF INDIVIDUAL TARGETS

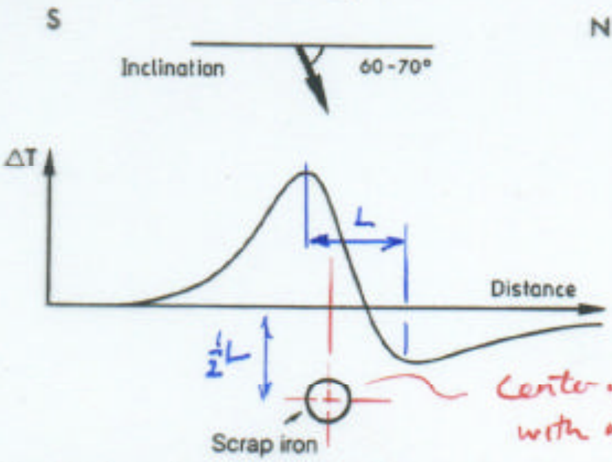
Fig. 2.1. Magnetic anomalies at different heights above ground

---

Anomoly influenced by inclination of Earth's mag. field. (60° in U.S.)

Max to South

Depth = $\frac{1}{2}$L.



Center not coincident with max or min.

Fig. 2.2. Magnetic section of the total intensity DT over a globe-shaped concentration of scrap iron at 65° latitude

Since

Two types of magnetometers

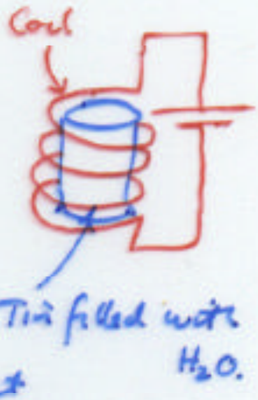
1. Permanent Magnet Magnetometers

{ Magnetic field balance
Torsion magnetometer

- Measures ↑ and → magnetic components
- Accuracy 1 nT
- Slow but v. accurate

2. Proton Magnetometers

- Measures total field, T, or variations, ΔT.
- Principle:
  - Apply a strong 1 second duration magnetic field
  - Causes hydrogen protons to spin (changes spin)
  - Shut off magnetic field and measure spin frequency.



- Fast, but records only max field component
- Accuracy $\frac{1}{2}$ nT

2. GEOELECTRIC METHODS

- ☐ D.C. METHODS
  - ☐ PROFILING
  - ☐ SOUNDING
- ☐ ELECTROMAGNETIC (GPR)

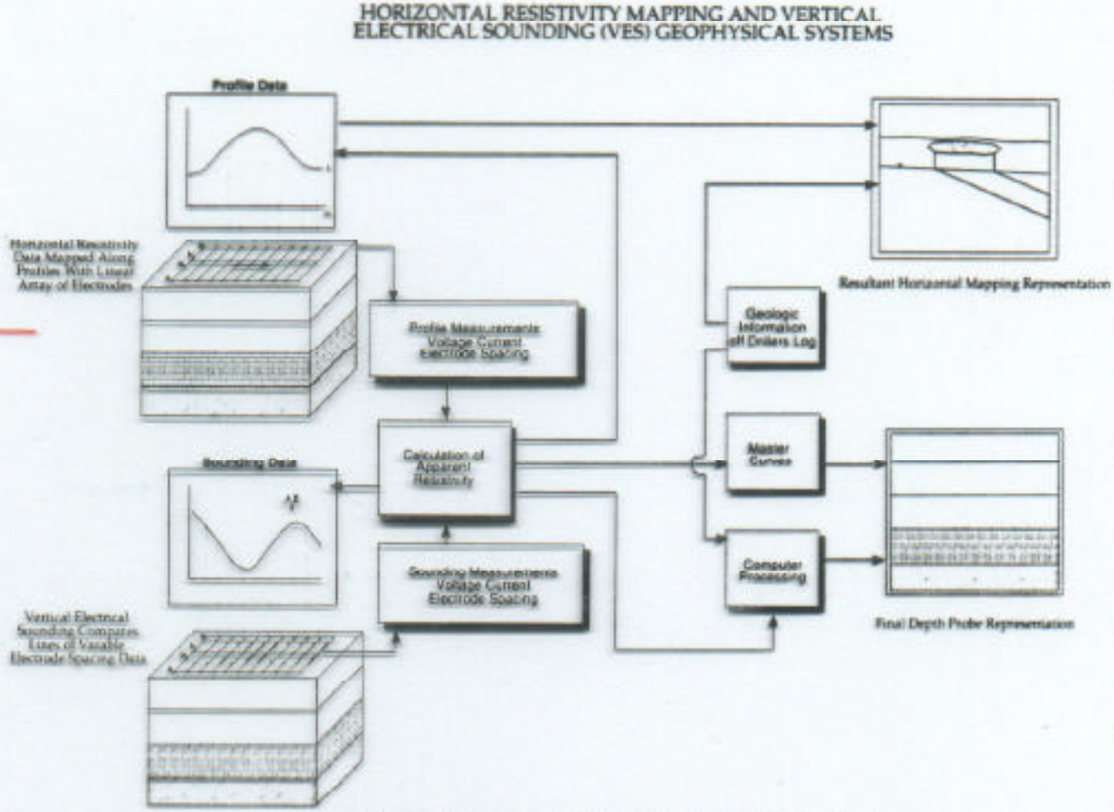


Figure 3-27 Resistivity Geophysical Method

DC. METHODS

- ☐ Uses electrical conductivity/resistivity contrasts.
- ☐ Apply D.C. field.
- ☐ Measure modified field

Ohm's Law

$U = I \cdot R$

R = resistance $[\Omega]$

$R = \frac{b}{q} \rho$

ρ = Specific resistivity $[\Omega m]$

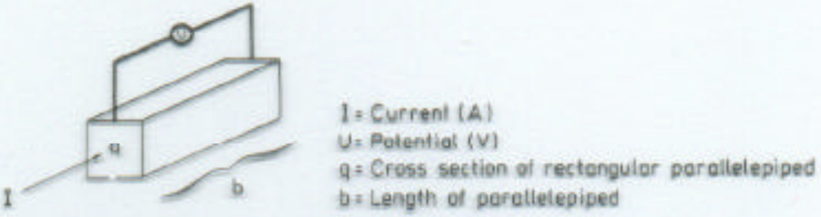


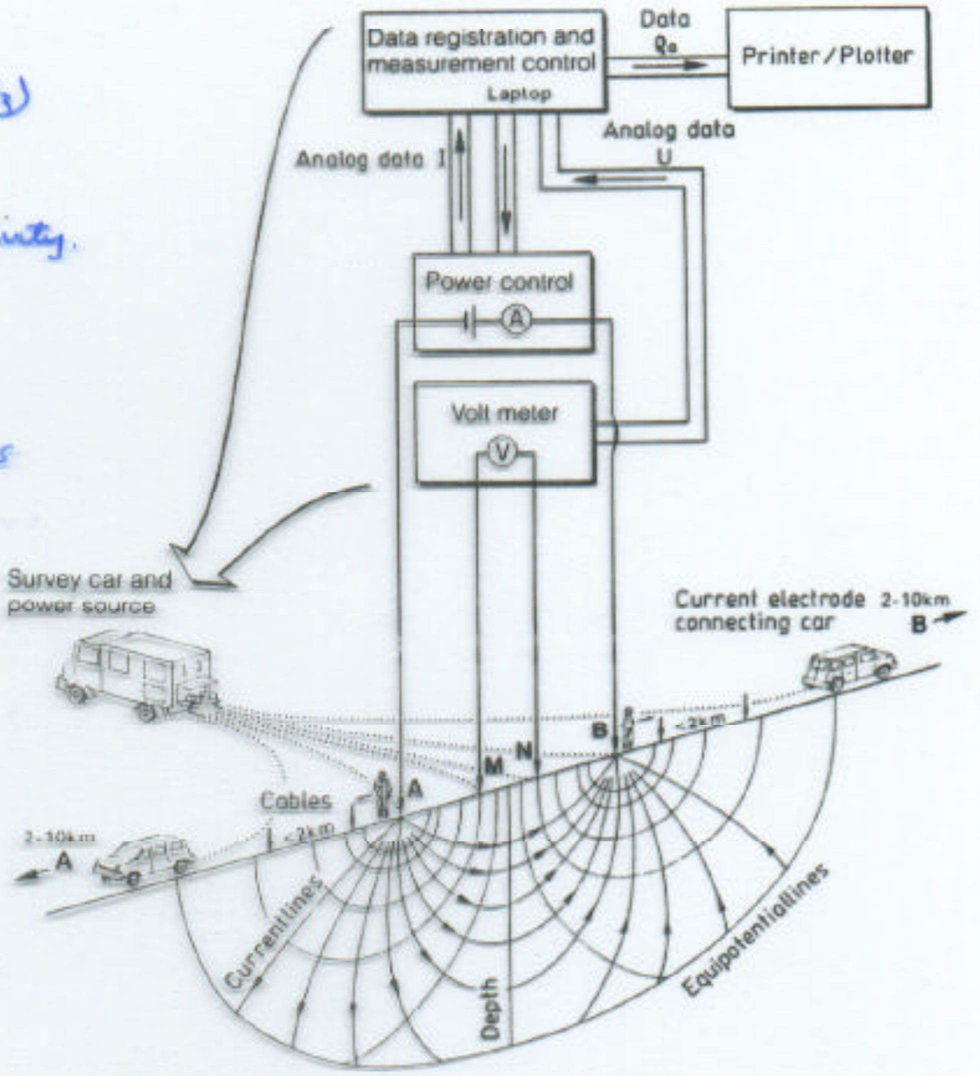
Fig. 2.3. Current flow through a limited conductor

Method

Apply 1. DC

2. AC @ low frequency (< 100Hz)

- Two stakes with high conductivity.
- Causes potential field
- Measure field by increasing spacing of input electrodes to ↑ depth penetration.
- Infer distribution of conducting layers.



I = Current (A)
U = Potential (V)
A, B = Current electrodes
M, N = Potential electrodes: non-polarizable

Fig. 2.4. Principle of measurement and potential field for geoelectric DC surveys

Data Reduction

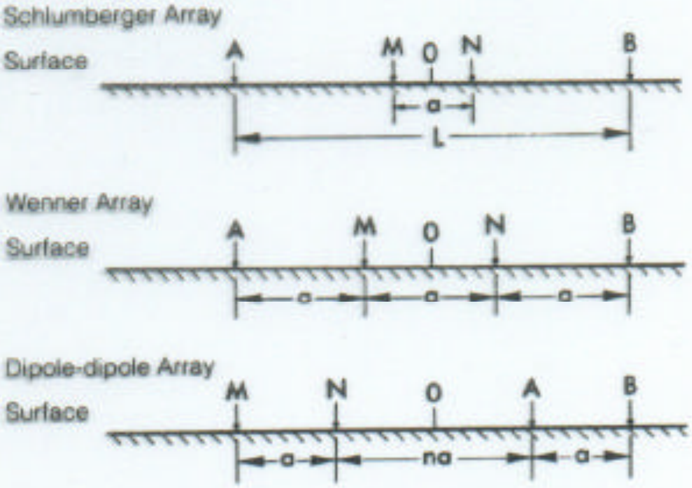
Plot $\frac{U}{I}$ at variable separation.

$\frac{U}{I} \approx R$ but are really specific resistivities, ρ_a, since measured at top of half-space.

Correct to specific resistivities as:

$$\rho_s = K\left(\frac{U}{I}\right)$$

	K
Schlumberger	$\frac{\pi}{a}\left[\left(\frac{1}{2}L\right)^2 - \left(\frac{1}{2}a\right)^2\right]$
Wenner	$2\pi a$
Dipole-dipole	$\pi a \cdot n(n+1)(n+2)a$



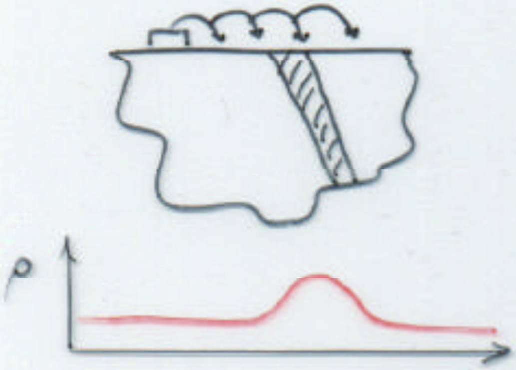
L = AB = Separation current electrodes
a = MN = Separation potential electrodes
0 = Point of measurement

Fig. 2.5. Arrays for geoelectric mapping and sounding

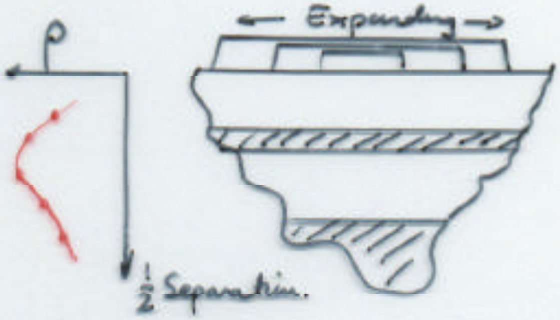
Connect the magnitudes to ρ_s:

Method depends on resistivity contrast between layers

Mapping



Sounding



Mapping

- Locate rim of disposal sites / or drums / or plumes

- Fixed array separation ∴ locate changes in ρ_s or absolute magnitude of ρ_s
- Separation between electrodes chosen for sampling depth.
  Wenner array commonly used.
- Require contrasts in ρ_s

Garbage	< 20 Ωm	
Gravel/sandstone	1000 Ωm	Contrast ok
Clays	3–30 Ωm	No contrast.

SOUNDING

Determine:

1. Apparent resistivities of strata
2. Thickness and depth of interfaces

Mainly Schlumberger array

1. Increase separation logarithmically
2. Plot $\rho_a = \frac{U}{I}$ with half spacing $L/2$
3. Match with model type curves, or invert numerically.

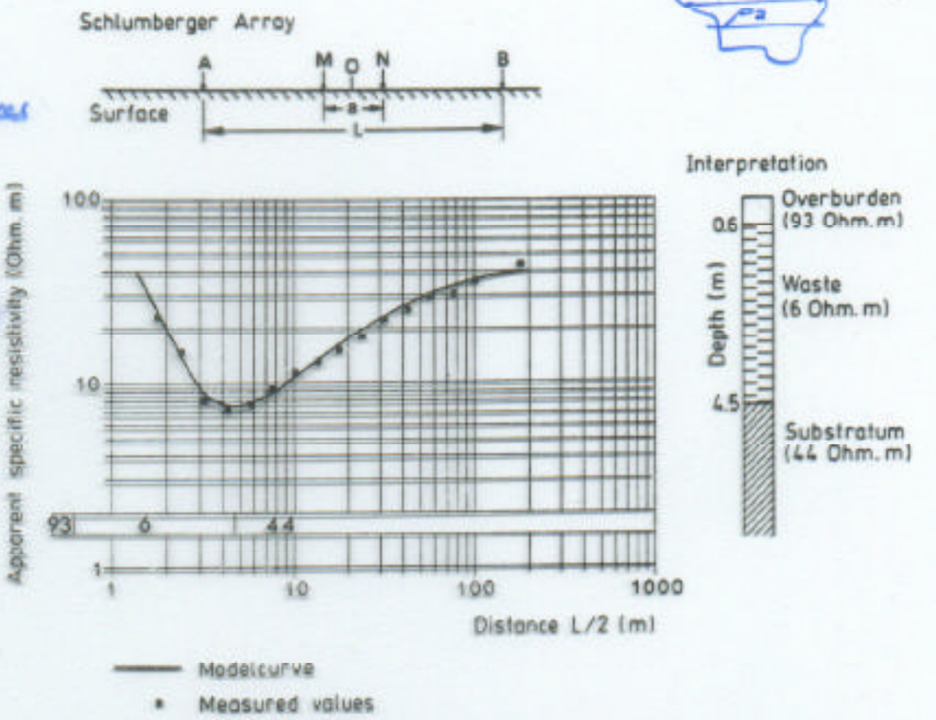


Fig. 2.6. Geoelectric sounding curve (VES) of a Schlumberger array with digital interpretation and computed model curve of the minimum type "H"

Problems

1. Omitted beds

   Thin layers or layers masked by very conductive beds

2. Equivalence

   Non-unique curves since equivalence of behavior

Table 2.1. Specific resistivities

Rock type/Material	Specific resistivity [Ωm]
Rock type	
clay, marl, rich	3 – 30
clay, marl, meagre	10 – 40
clay, sandy, silt	25 – 150
sand, with clay	50 – 300
sand, gravel in ground water	200 – 400
sand, gravel, dry	800 – 5000
rubble, dry	1000 – 3000
limestone, gypsum	500 – 3500
sandstone	300 – 3000
salt beds and salt domes	> 10000
granite	2000 – 10000
gneis	400 – 6000
Deposited refuse	
domestic garbage	12 – 30
debris and dumped soil	200 – 350
industrial mud	40 – 200
scrap metal	1 – 12
pieces of broken glass and porcelain	100 – 550
casting sand	400 – 1600
wastepaper (wet)	70 – 180
contaminated plume of domestic-garbage dump	1 – 10
used oil	150 – 700
tar	300 – 1200
cleaning clothes and materials	30 – 200
used lacquer and paint	200 – 1000
barrels (empty)	5 – 20

Equivalence

- Non-unique solution
- Match with borehole data
- Effect of saturant may influence results.

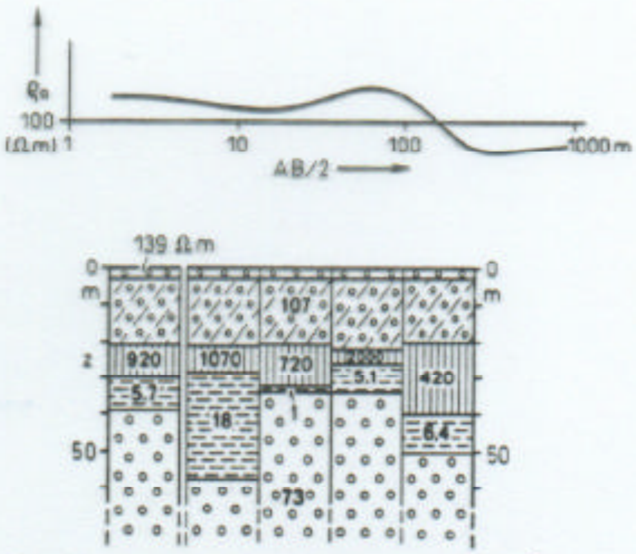


Fig. 2.7. Equivalent digital interpretations of a Schlumberger sounding curve. Left column = mathematically best model. The selection of the most suitable model has to consider neighboring curves and the known geology

Fracture detection methods

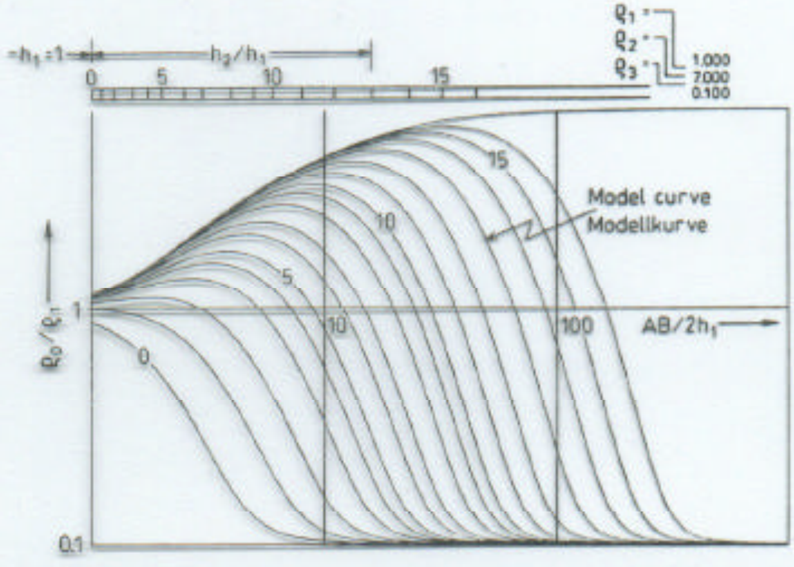
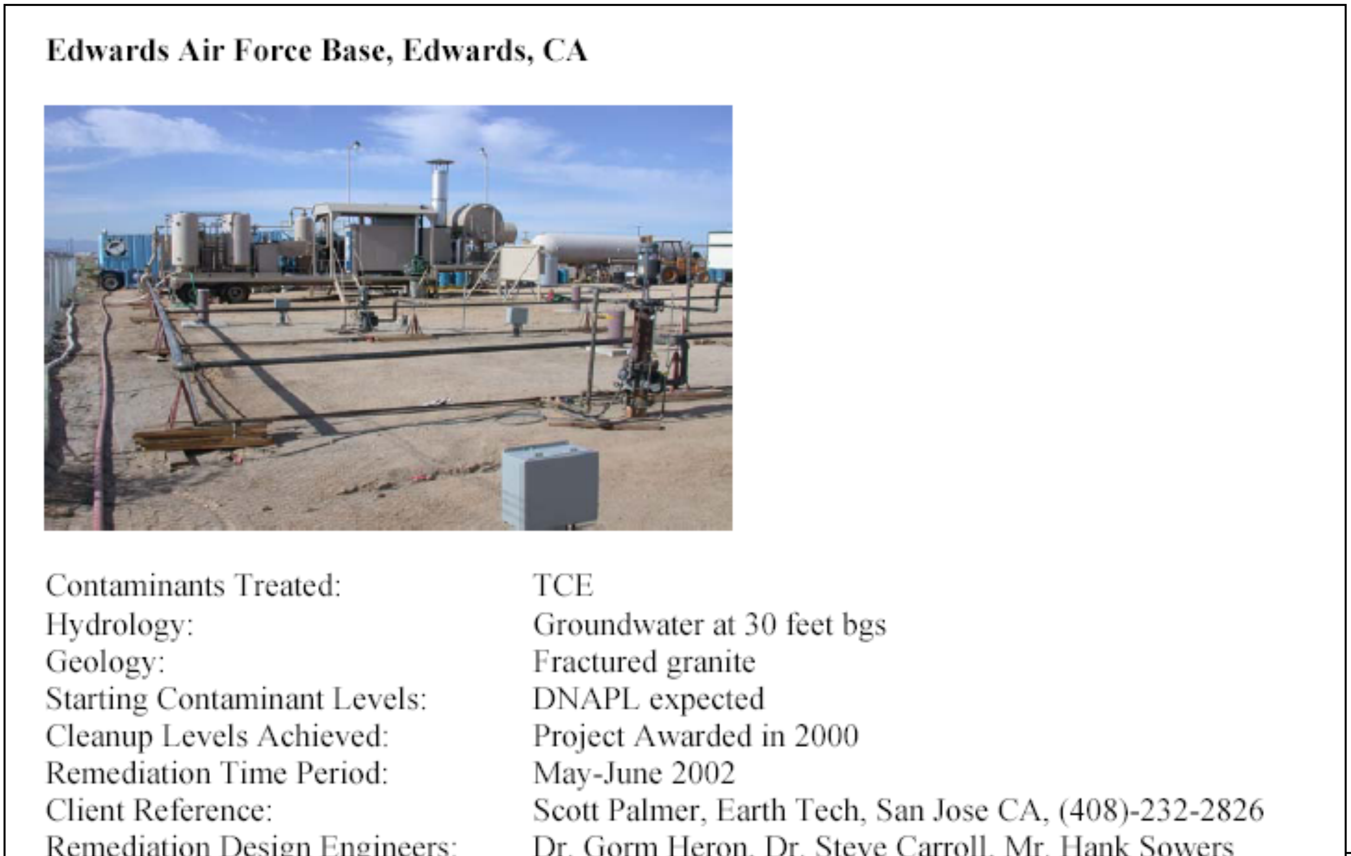


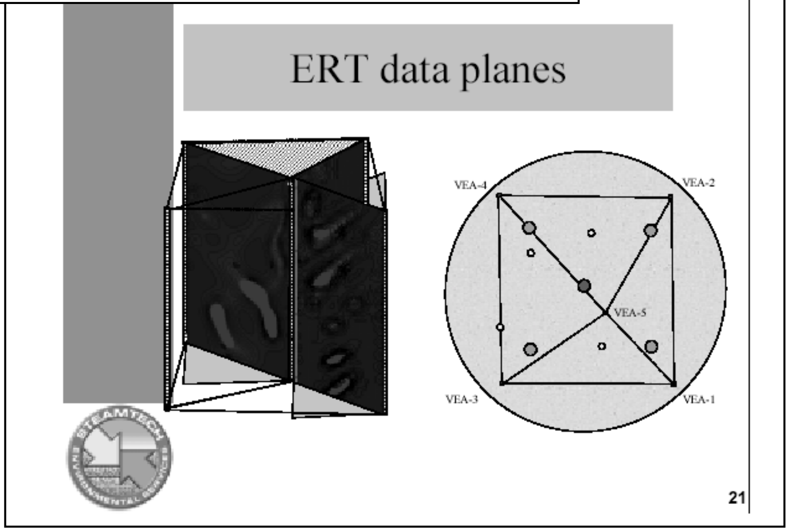
Fig. 2.8. Three-layer master curves in a log-log graph of the INGESO atlas. The resistivities of the three beds are in the ratios 1:7:0.1; first layer : second layer : third layer. The sounding curve, which has been drawn on log-log graph paper in the field, is laid on top of the master curve and moved around until one of the master curves tallies with the field curve. The thickness of the second layer, which has here seven times the ρ_a-value of the first layer (see the resistivity values at the top right) can be found by the number of the curve no. 13. On the thickness beam at the top left, which is divided from 0 to 16, the thickness h_2 can be directly determined

Edwards AFB, CA – Thermal Remediation Monitoring with ERT

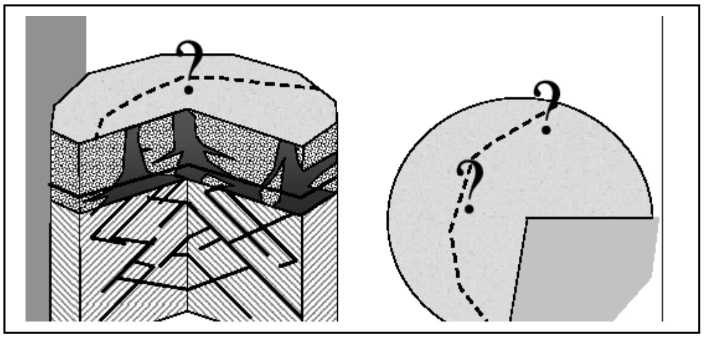


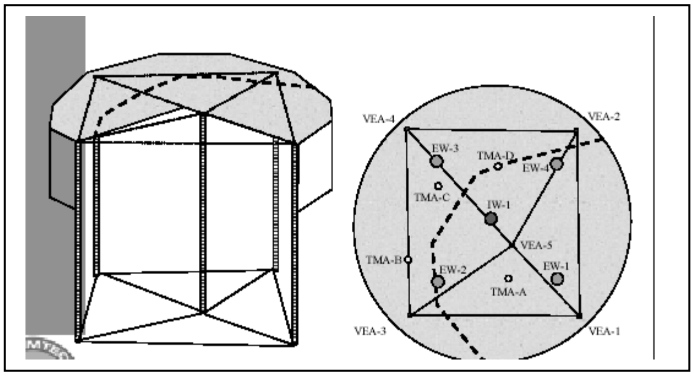
Edwards Air Force Base, Edwards, CA

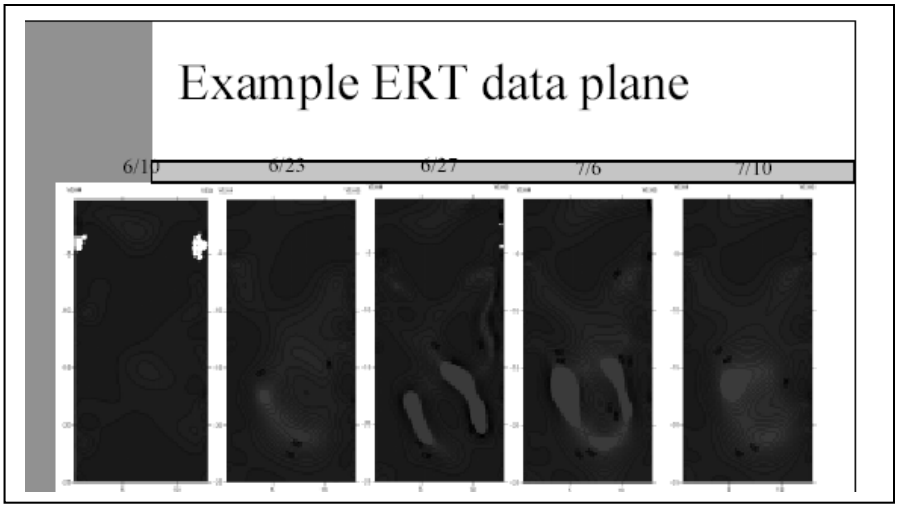
Contaminants Treated:	TCE
Hydrology:	Groundwater at 30 feet bgs
Geology:	Fractured granite
Starting Contaminant Levels:	DNAPL expected
Cleanup Levels Achieved:	Project Awarded in 2000
Remediation Time Period:	May-June 2002
Client Reference:	Scott Palmer, Earth Tech, San Jose CA, (408)-232-2826
Remediation Design Engineers:	Dr. Gorm Heron, Dr. Steve Carroll, Mr. Hank Sowers



ERT data planes







Example ERT data plane

Magnetotellurics

Measure electrical resistivity from current generated by the Earth's (natural) magnetic field.

e.g. West Flank Coso:
https://www.energy.gov/eere/forge/sandia-national-laboratories-west-flank

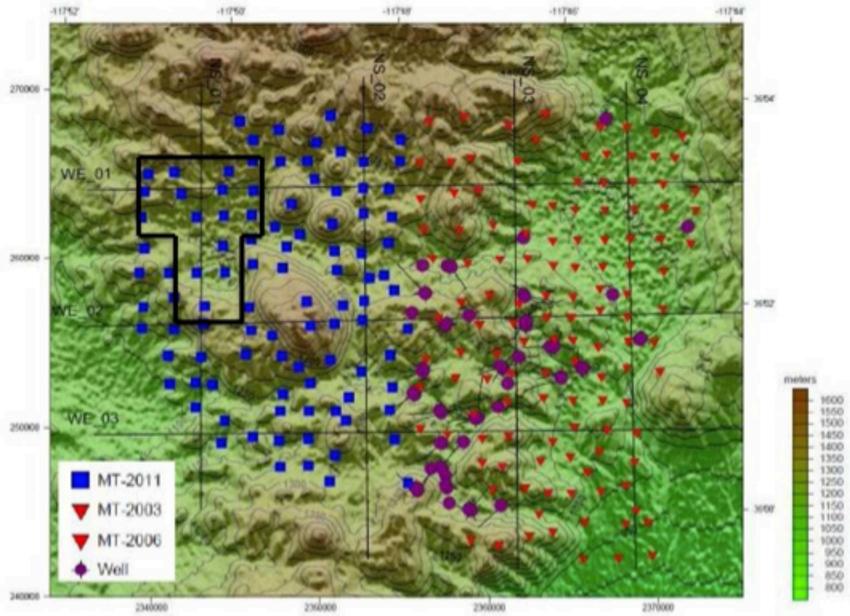


Figure 23. MT survey points throughout the Coso Volcanic Field starting in 2003 through 2011. The West Flank FORGE test area polygon is pictured for reference.

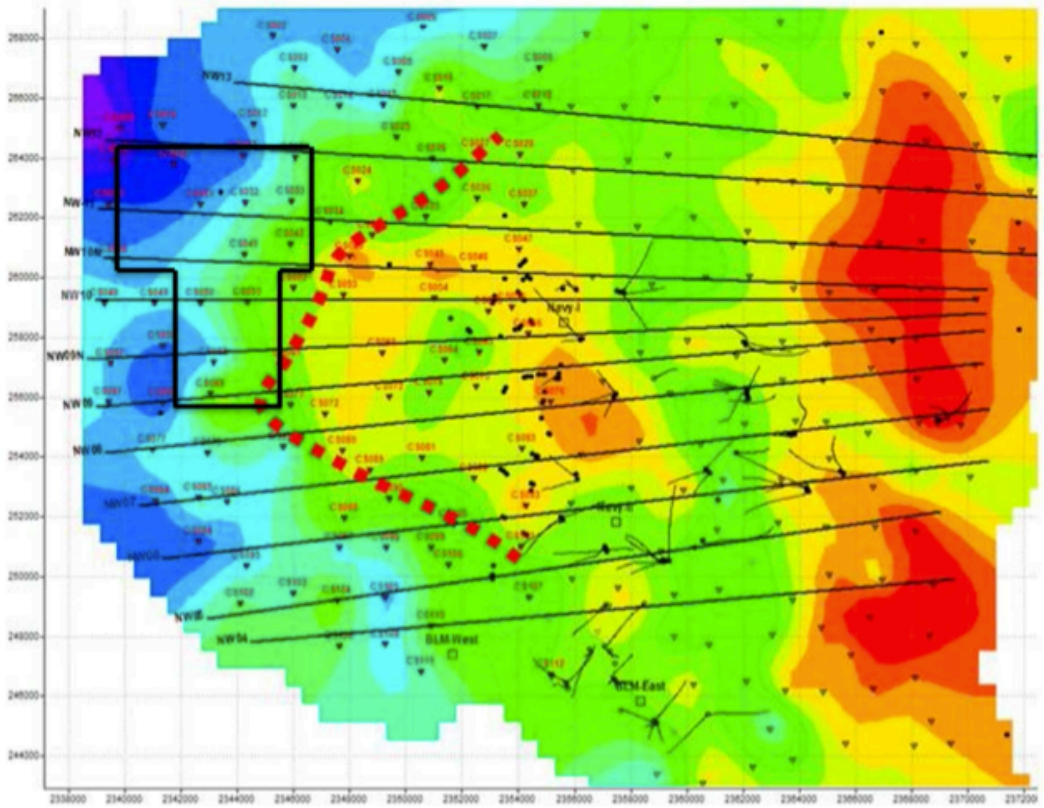


Figure 24. Map of MT conductance at ~600 meters depth of a 1D inversion. The red dashed line is the mapped extent of the hydrothermal system at Coso. The West Flank FORGE test polygon is drawn on top for reference.

INDUCED POLARIZATION (INDUCED POTENTIAL)

- Apply DC current as Wenner or Schlumberger.
- Cut current and measure voltage decay with time 1s – 8s
- Reverse current to erase remnant charge

Effective depth penetration, D

$D \sim a(n+1)\frac{1}{2}$

Dipole lengths n = 1 to 6

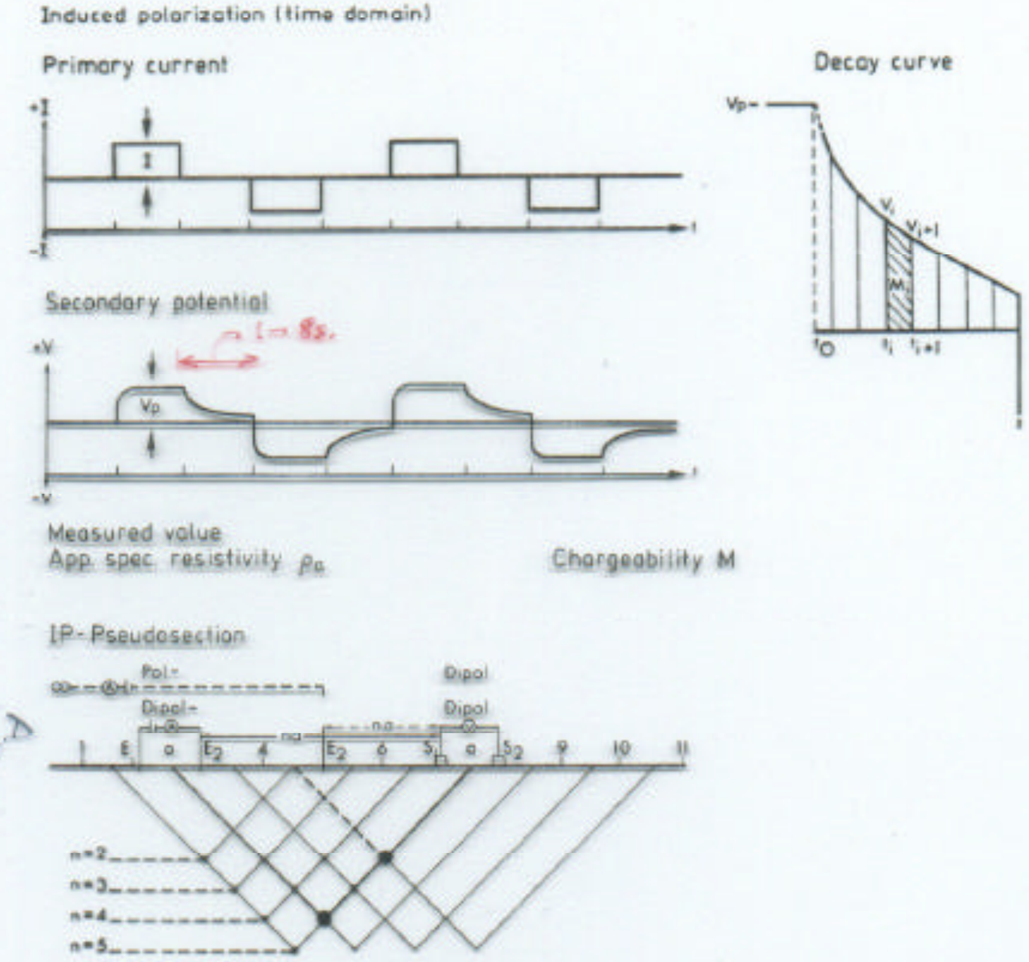


Fig. 2.9. Principle of induced polarization (IP)

SELF POLARIZATION

- Measures natural geo-electric field
- Results from chemical reactions (natural battery) eg Redox.

  30mV – 200 mV

  - sometimes results from rapid fluid flow < 10mV.

2.2 ELECTROMAGNETIC METHODS

NOTE: $v = f\lambda$

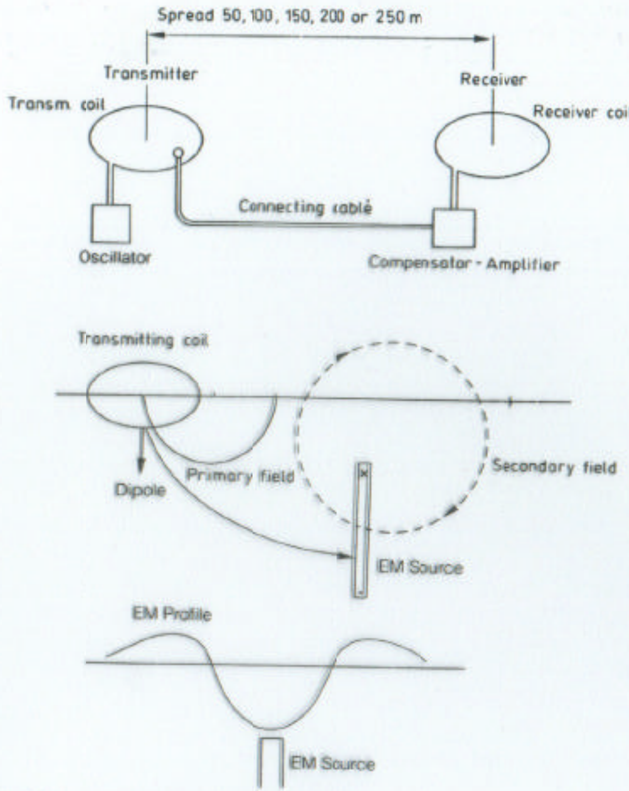
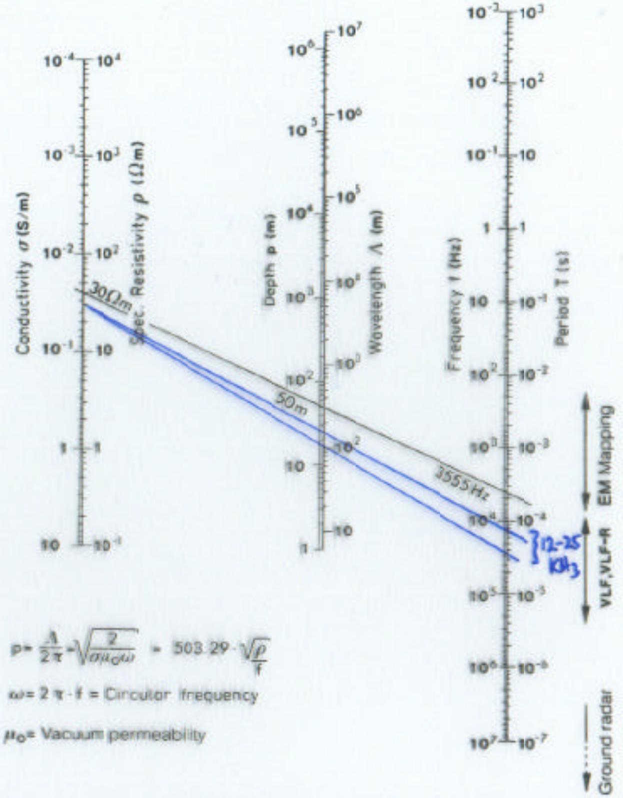


Fig. 2.11. Principle of electromagnetic mapping



Fi. 2.12. Nomogram showing the relations of specific resistivity (left column), depth of penetration (middle column) and frequency (right column) of a homogenous plane wave

EM Mapping (Longitudinal profile)

- ☐ Primary EM field by primary coil
- ☐ Induces secondary EM field in body of different specific resistivity ρ_x
- ☐ Resolve interpretation ambiguities using multiple frequencies. (perhaps 12)

EM by Distant Transmitter (VLF)

- ☐ Permanent transmitters around globe (12 - 2.5kHz) (Submarine navigation)
- ☐ Measure induced secondary fields & interpret.
- ☐ Set frequency ∴ depth of penetration ~15m for $\rho_a < 30\ \Omega m$.

TIME - DOMAIN ELECTROMAGNETICS (TDM)

- Similar to IP but decay of EM signal is measured with time.

- Transmitter loop of 5m to 100m diameter but achieve large depth penetration 50 - 1000m.

Applied to determine brine pools and salt water intrusion.

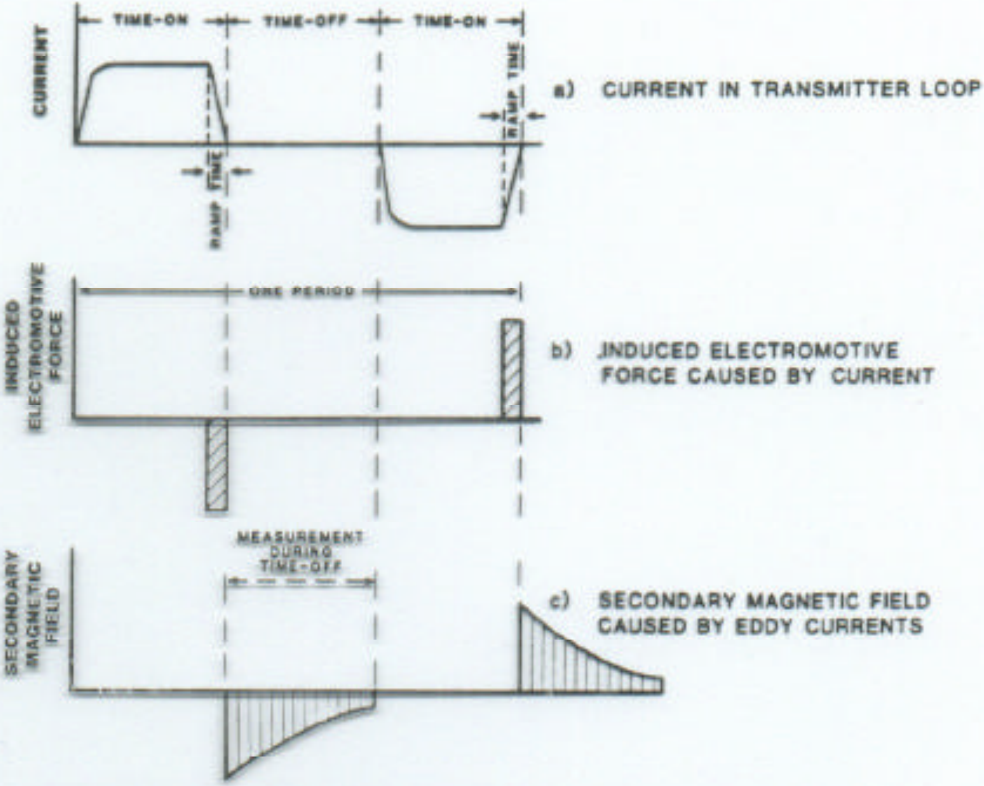
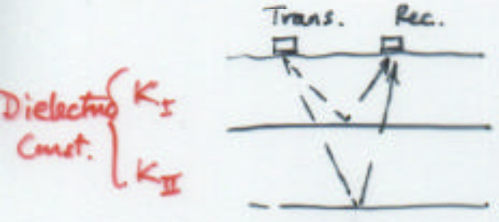


Fig. 2.15. System wave forms employed by the TDEM method

GROUND-PENETRATING RADAR (GPR)



Records travel time that must be scaled to a velocity → depth.

- Shallow depth penetration for EM waves 8 MHz – 4 GHz
  Reflection from interfaces with dielectric constant contrast, K

- Dielectric constant, $K = \frac{\text{Capacitance of material}}{\text{Capacitance of vacuum}} = \varepsilon$ (non-dimensional)

- Depth penetration – Limited in low conductivity (high resistivity)
  Clays 0.2 m
  Salt, ice, dry granite > 300m
  Typically 3-10m.

- High dielectric contrast of water (80) greatly influences response
  - Changing saturation (record infiltration in real time)
  - Type of saturant (LNAPL or DNAPL)

- Depth penetration controlled by frequency
  ↑ frequency → reduce penetration and increase resolution
  (see nomogram)

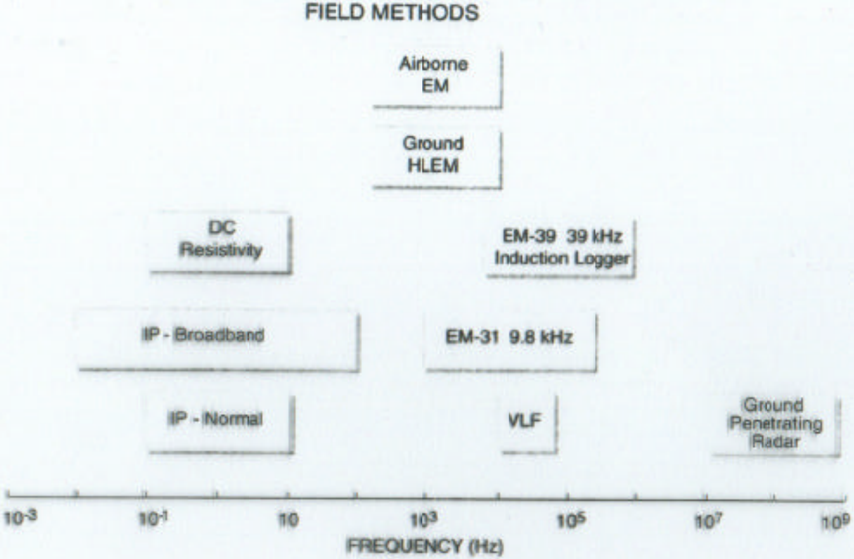


Figure 3-22 Frequencies Used By Electrical Geophysical Methods

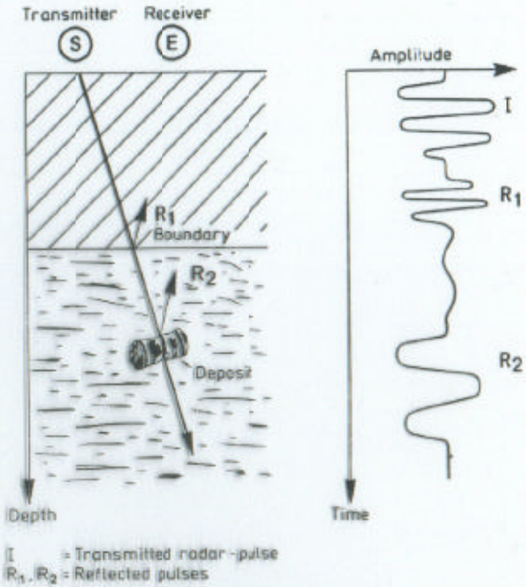


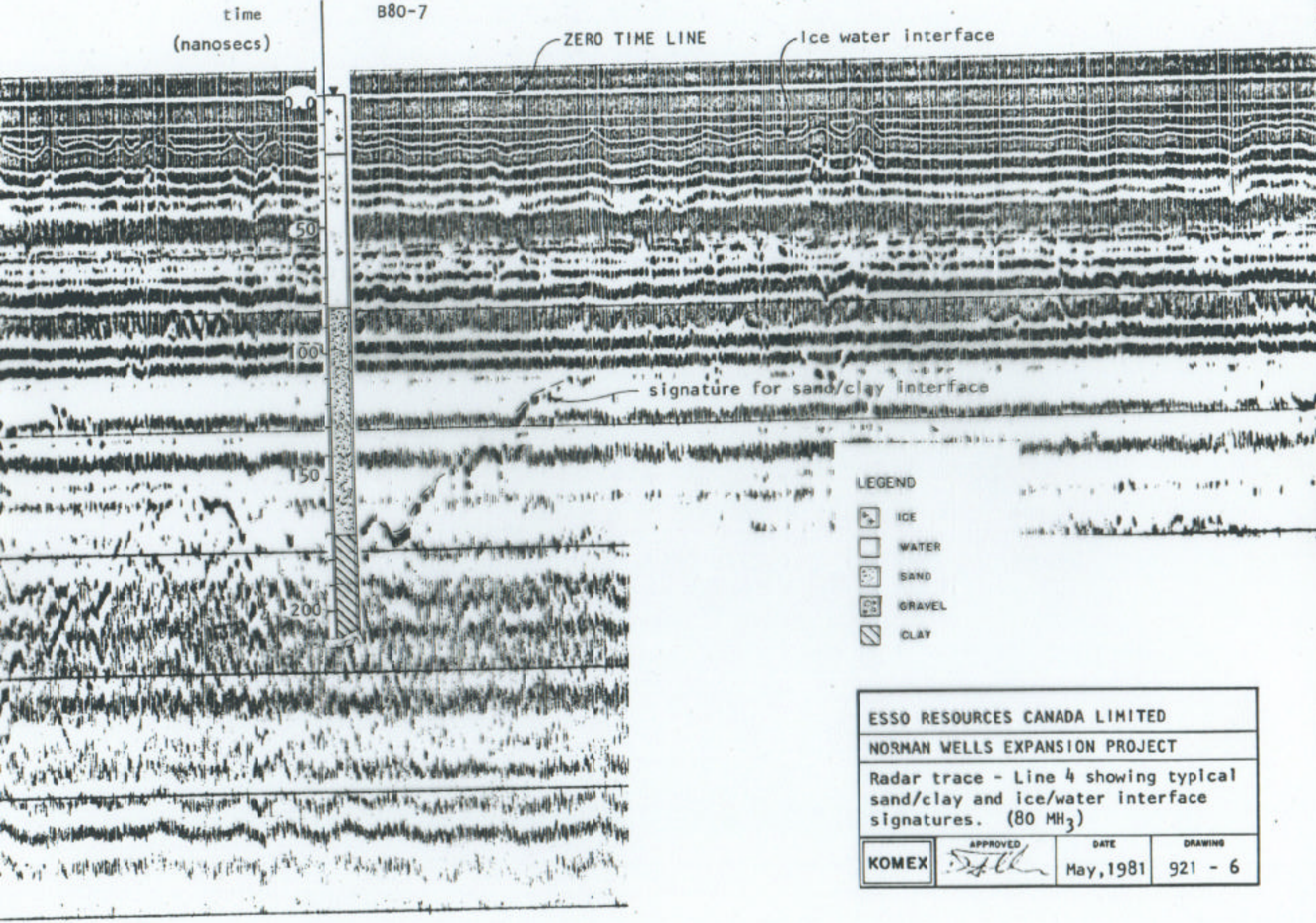
Fig. 2.17. Principle of ground radar measurements

Table 2.3. Dielectric constants (K), electric conductivity (σ), electric velocity and attenuation (a) at a frequency of 100 MHz. Davis and Anan (1989)

Material	K	σ(mS/m)	v (m/ns)	a (dB/m)
Air	1	0	0,3	0
Freshwater	80	0,01	0,33	$2 \cdot 10^{-1}$
Seawater	80	$3{,}0 \cdot 10^{4}$	0,01	0,1
Dry sand	4	0,01	0,15	0,01
Wet sand, Aquifer	25	$0{,}1^{-1}$	0,06	0,03
Limestone	6	$0{,}5^{-2}$	0,12	0,04
Fat clay	5–35	0,05	0,06	1,0–300
Granite	5	0,1–1	0,13	0,01
Rock salt	6	0,1–1	0,13	0,01
Slate	5–15	0,03	0,09	1,0–100

Velocity of EM wave enables calculation of reflector depth

Dielectric const defines the potential for attenuation



ESSO RESOURCES CANADA LIMITED

NORMAN WELLS EXPANSION PROJECT

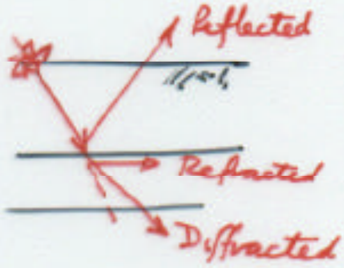
Radar trace - Line 4 showing typical sand/clay and ice/water interface signatures. (80 MH_3)

KOMEX	APPROVED	DATE	DRAWING
		May, 1981	921 - 6

3. SEISMIC METHODS

- ☐ Measures elastic properties of rocks ($V_s = ?$) evidenced through seismic velocity
- ☐ Locates interfaces between different V_s

At interfaces; seismic waves are
- Diffracted
- Refracted
- Reflected



Procedure

1. Arrange geophones along single line
2. Provide initial shock input. Hammer/Drop hammer/Explosive/Air gun.
3. Record first (primary) and sometimes secondary (shear wave) arrivals

↓

Evaluate
1. Bed thickness
2. Seismic velocity

1. Primary compressional wave (P wave)
2. Shear wave (slower) S-wave.

S wave attenuated by fluid saturated materials eg fluid filled fractures.

Typically:

1. V_s increases with depth (due to ↑E)
2. Weathered surface zones have ↓V_s
3. Two methods of interpretation

3.1 Seismic Refraction

3.2 Seismic Reflection.

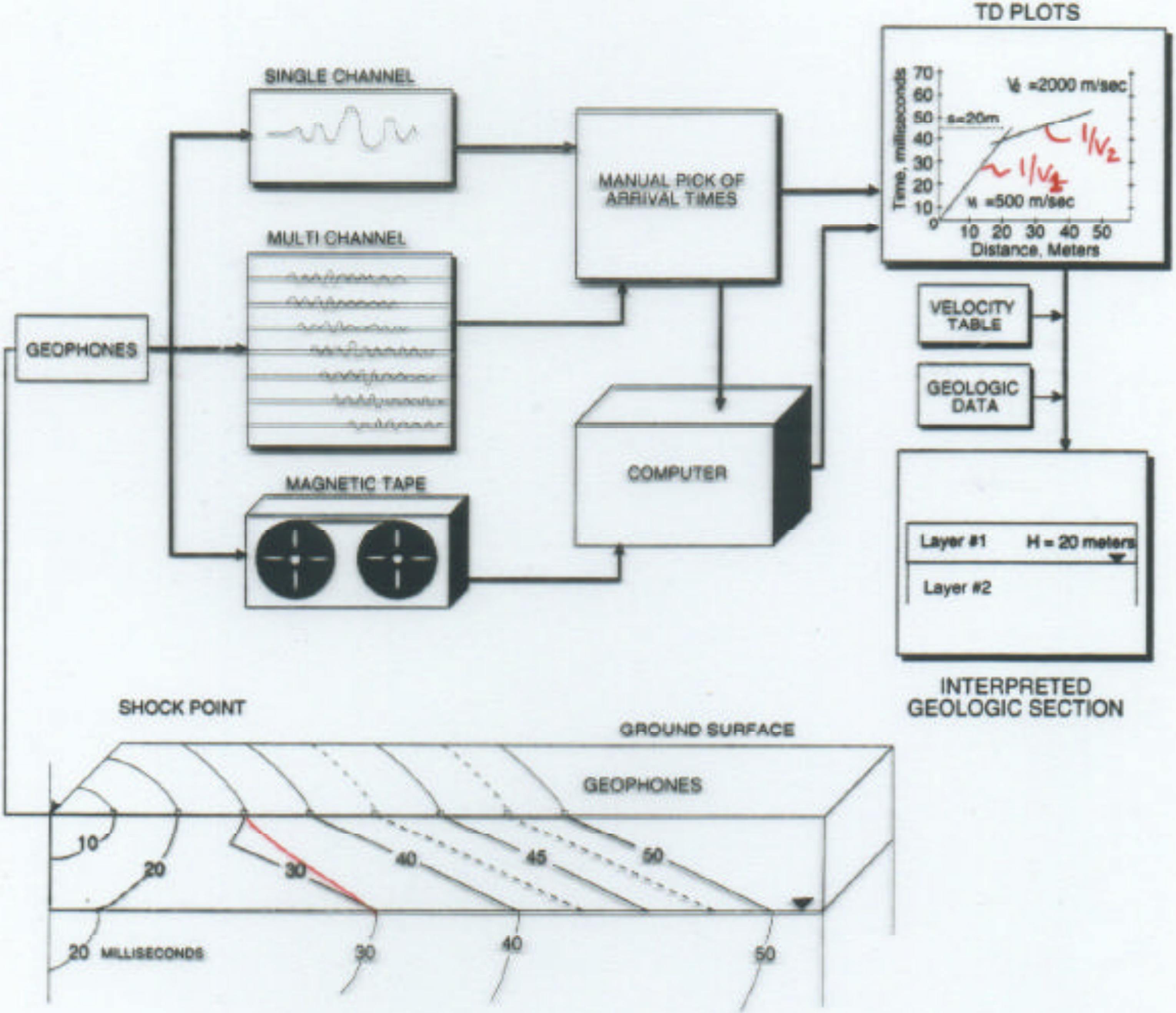
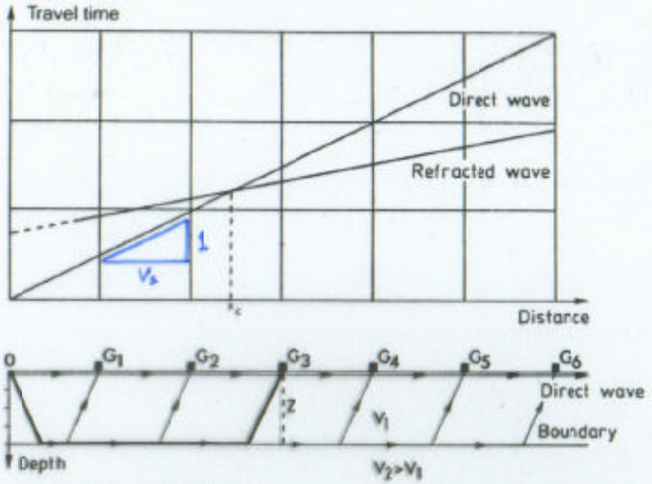


Figure 3-15 Seismic Geophysical Method

3.1 SEISMIC REFRACTION



$G_1 - G_6$ = Geophones
V_1, V_2 = Seismic velocities
x_c = Critical distance

Fig. 2.18. Principle of seismic refraction

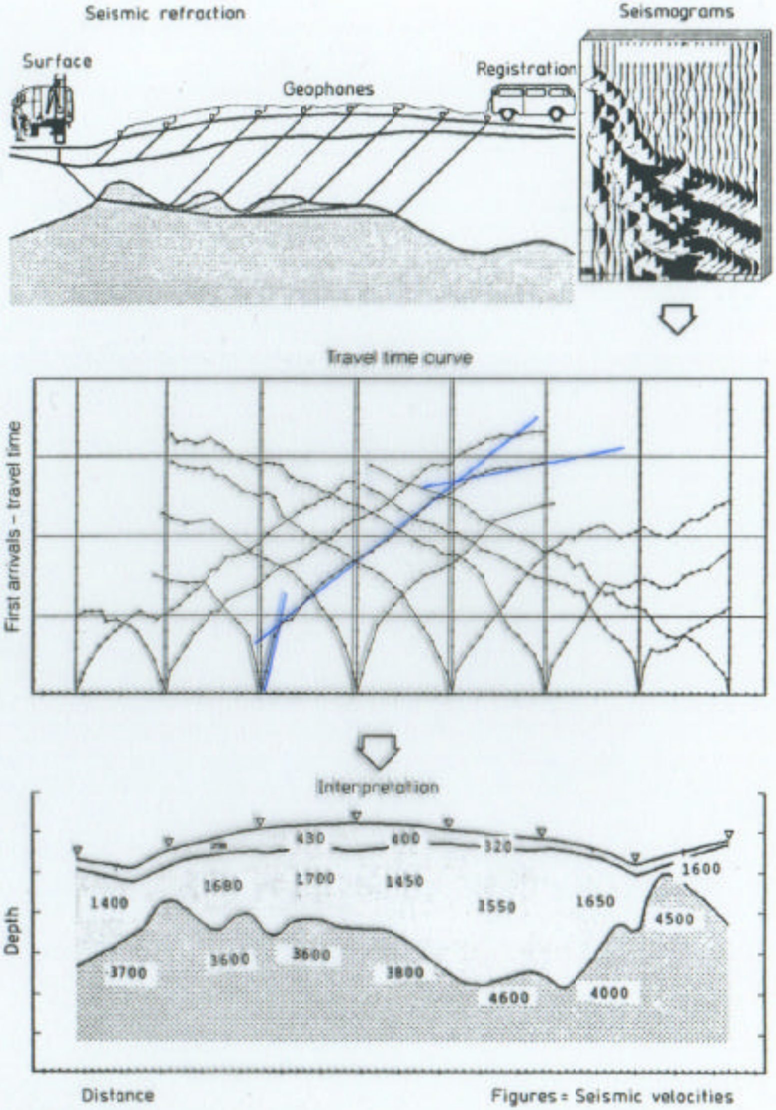


Fig. 2.19. Pattern of seismic refraction

1. Fire shot and plot
   time distance graph of first arrivals.
2. Evaluate unit velocities of units
   from slope of curve
3. Evaluate layer depths from inflection points

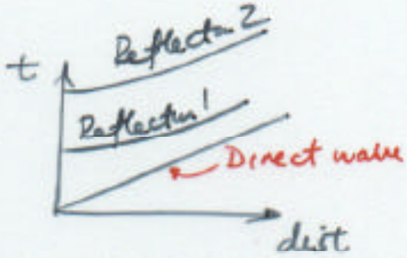
String length defines depth penetration
String length ~~x~~/ 5 = desired penetration depth
typical depths of < 50m

Ambiguities – weathering
water table

3.2 SEISMIC REFLECTION

Source impulse creates shock front reflected by interfaces.

Reflection occurs @ interfaces with "seismic impedence" changes. Seismic impedence = $\underset{\text{density}}{\rho} V_s$



Measure arrival times and plot as time – distance.

Advantages over Refraction

1. Increased depth penetration with small string length

Disadvantages

1. Reflected wave arrives so quickly that surface waves are present and must be filtered out.

To use @ depth < 50 m, need:

① Receivers with high sampling rate and high frequency source

② Sophisticated filtering and data analysis methods.

REFLECTION

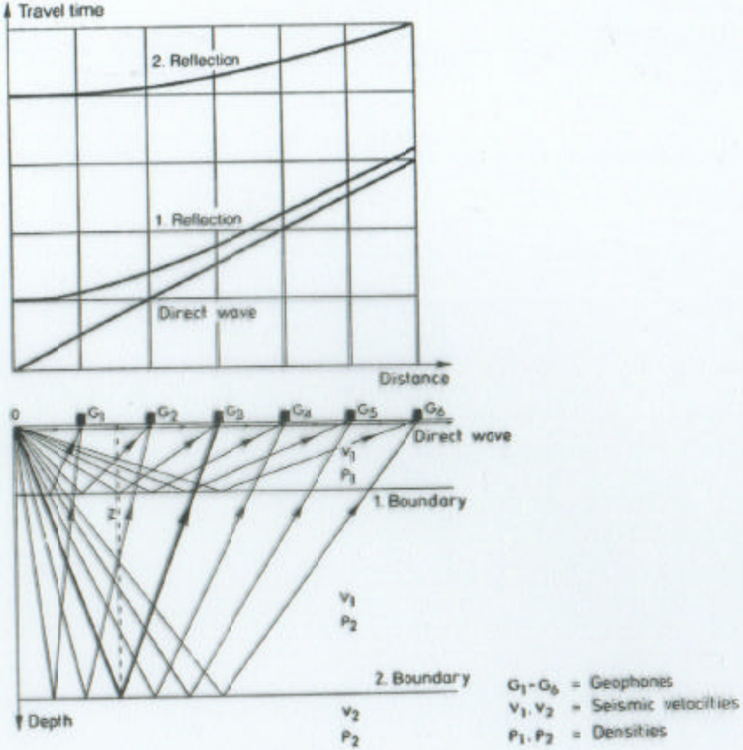


Fig. 2.21. Principle of seismic reflection

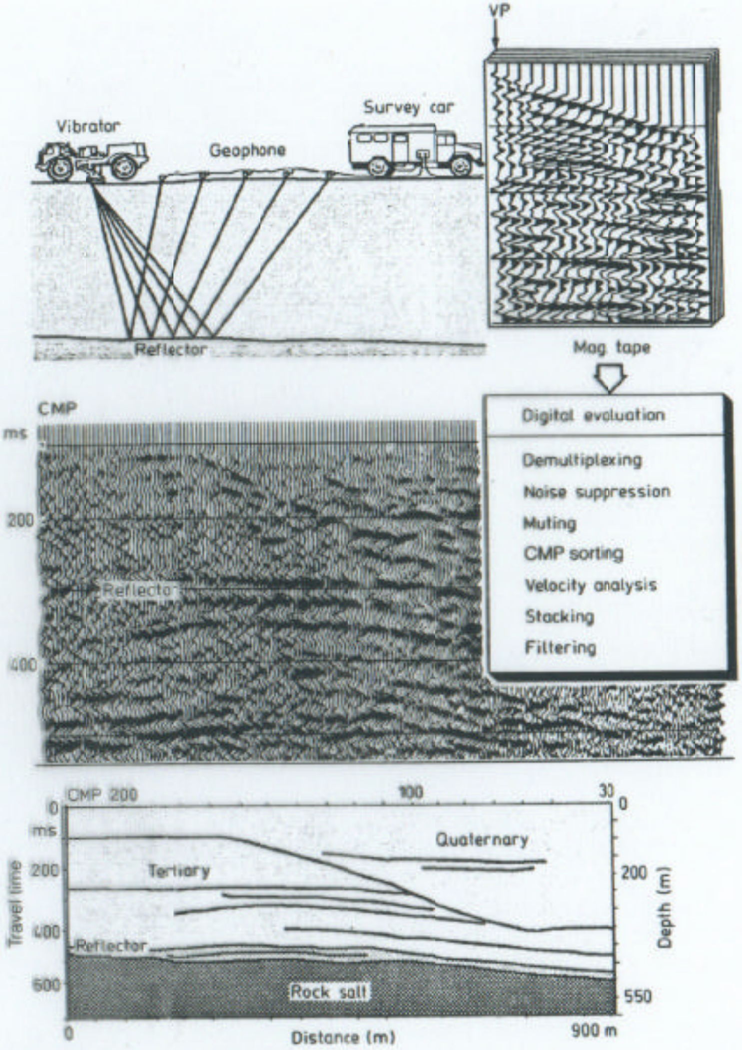


Fig. 2.22. Pattern of seismic reflection

4. GRAVITY METHODS

Detects changes in density according to Newton's Law of gravitational attraction

$$g = \frac{F}{m_2} = \frac{GM_e}{R^2}$$

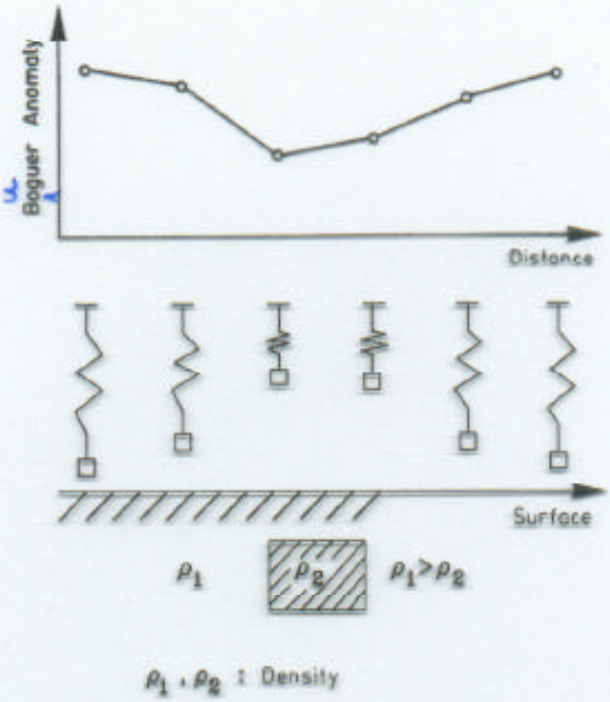


Fig. 2.23. Principle of gravity measurements

G = gravitational constant 6.67×10^{-8} degree $\frac{cm^2}{g^2}$

g = grav. accn.

Gravitometers measure variation in $g = 9.8\ m/s^2$ of $10^{-5}\ m/s^2$

Gravity depends on:

1. Latitude (Non-perfect sphere) ⬭
2. Elevation (R) [Free air correction]
3. Topography (m_2) [Terrain correction]
4. Earth tides [Isostatic correction]
5. Density variations in subsurface [Bouguer correction]

Density is the only important factor in gravity measurements, but effect is much less than all other factors

Limited applicability to Environmental Surveys:

1. Small signal
2. High cost.

5. WELL LOGGING

- Applicable to materials in vicinity of wellbore
- Variety of logging signals available
- Recorded continuously with depth.

Methods

Gamma Ray	- Measures natural gamma radiation - Pick up clay layers to .3m resolution
Density Log	- Artificial source ^{137}Cs @ probe base and gamma detector @ top - Adsorption of gamma radiation by rock is proportional to density (Compton effect)
Neutron Log	- Artificial Neutron source - Measure backscattering to determine moisture content (presence of Hydrogen) → porosity log.
Electric Log	- Apparent resistivity in sidewall rock (Multiple pt. arrays) - May simultaneously measure self potential - Records mixed resistivity ∴ correct for mud/water effects
Salinometer	- Resistivity of borehole fluid.
Temperature	
Sonic velocity	
Caliper	
Flowmeter	
Deviation	

Table 2.4. Logging methods, measured parameters and objects of investigation

Symbol	Parameter	Result	Object
GR	count of natural gamma radiation	natural radioactivity of rocks	petrography clay content
D	counts of compton scattered rays	density of rocks	fracturing, porosity
N	counts of secondary neutron-neutron rays	lithology	stratigraphy porosity
EL, ES	apparent resisitivity	true resistivity	hydraulics, lithology
ML, MLL	apparent resistivity at borehole wall	true resistivity small scale	lithology, hydraulics
IEL	app. conductivity, focused induction	true conductivity	lithology
FEL, LL	focused electric log	true resistivity of rock	lithology
SP	self-potential (probe-to-surface)	sources of electric potentials	oxidizing bodies
SAL	resistivity of borehole fluid	salinity	total salt content of fluid
TEMP	temperature of borehole fluid	geothermal field	thermal gradient
SONIC SV	travel time of seismic waves	seismic velocity	seismic velocity
CAL	borehole diameter	shape of borehole walls	correction of other logs
FLOW	revolutions of a spinner	velocity of fluid flow	zones of in- and outflow of water
DV	compass and dipmeter	inclination + azimuth of borehole	spatial drill path
OPT	video signals, photography	state of borehole walls	direct view of lithology

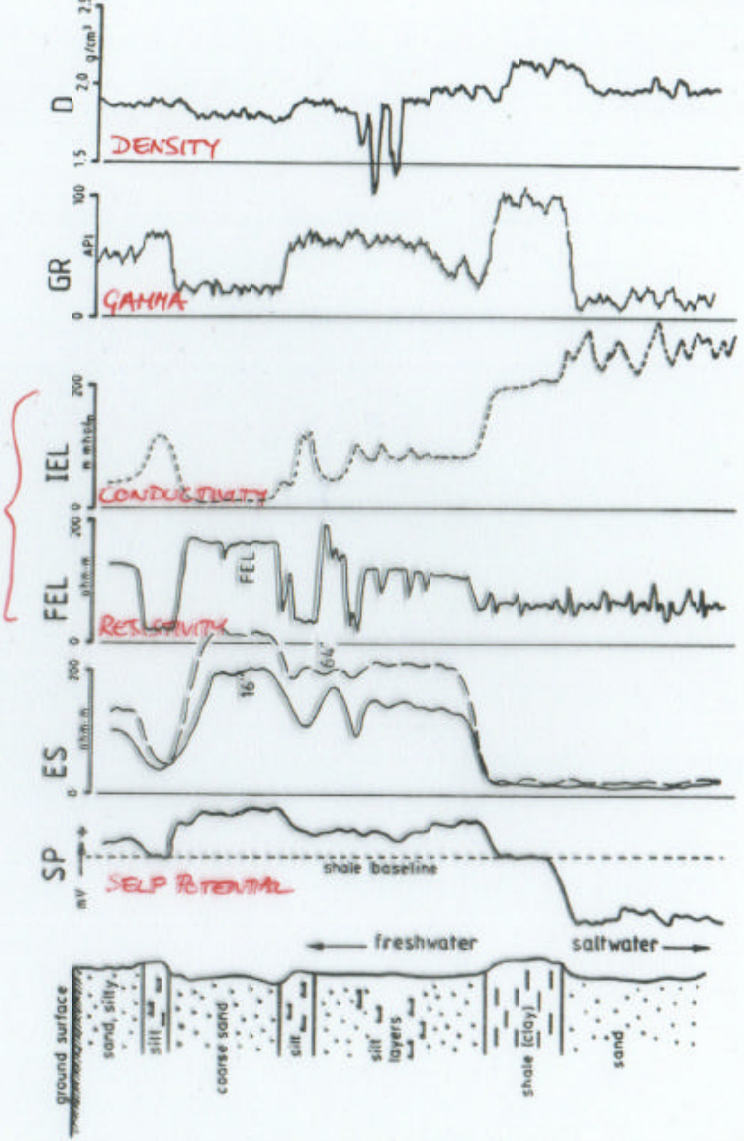


Fig. 2.24. Comparison of different logs with the lithology of cores.
SP = self-potential survey; ES = electrical survey measures resistivity in 16" and 64" point array; FEL = focused electrical log for thin layers; IEL = induction electric log measures electric conductivity; GR = gamma ray measures natural radiation; D = density log by artificial gamma source and detector

Table 2.4. Logging methods, measured parameters and objects of investigation

Symbol	Parameter	Result	Object
GR	count of natural gamma radiation	natural radioactivity of rocks	petrography clay content
D	counts of compton scattered rays	density of rocks	fracturing, porosity
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ML, MLL	apparent resistivity at borehole wall	true resistivity small scale	lithology, hydraulics
IEL	app. conductivity, focused induction	true conductivity	lithology
FEL, LL	focused electric log	true resistivity of rock	lithology
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FLOW	revolutions of a spinner	velocity of fluid flow	zones of in- and outflow of water
DV	compass and dipmeter	inclination + azimuth of borehole	spatial drill path
OPT	video signals, photography	state of borehole walls	direct view of lithology

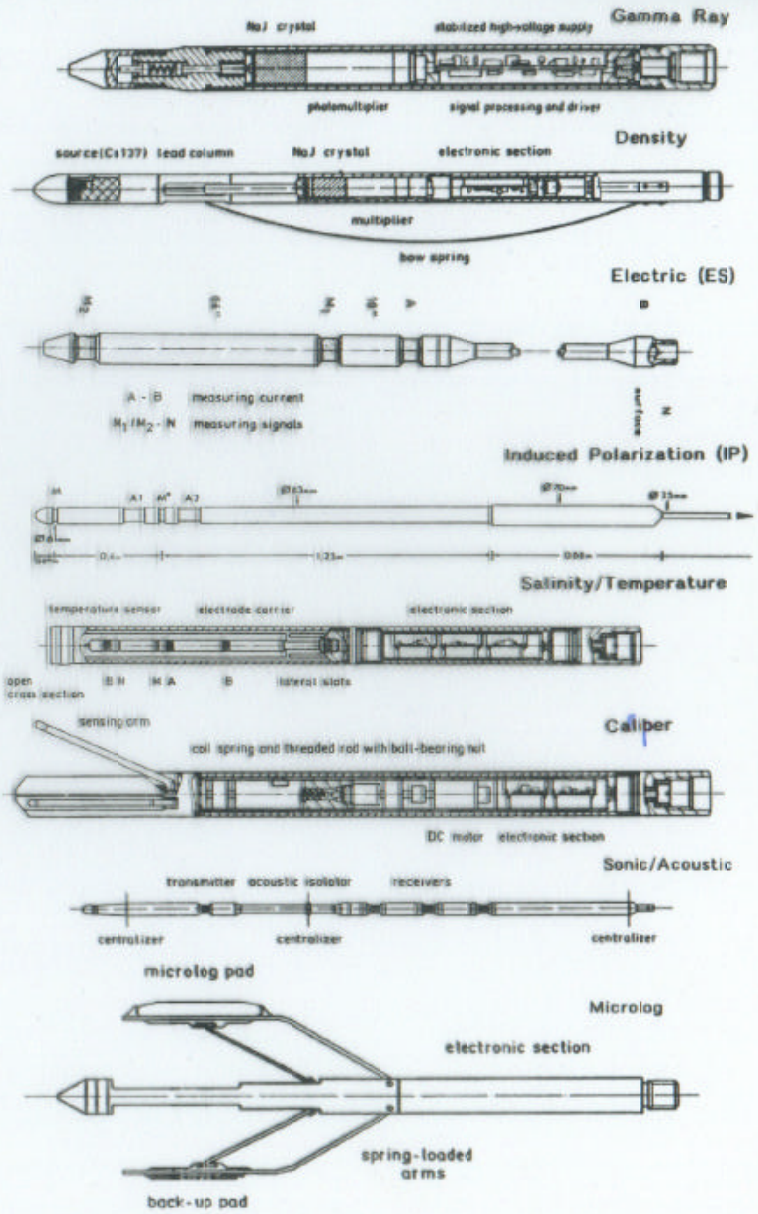


Fig. 2.25. Probes for geophysical well logging

This table is intended as a general guide. The application ratings given are based upon actual experience at a large number of sites. The rating system is based upon the ability of each method to produce results under general field conditions when compared to other methods applied to the same task. One must consider site-specific conditions before recommending an optimum approach.

In some cases a method rated 3 or NA may in fact solve the problem due to unique circumstances. For example, seismic refraction is rated NA for evaluating organic contaminants. However, in some cases where the contaminant flow is controlled by bedrock, the seismic method may provide an effective evaluation by mapping bedrock depth.

Organic Vapor Analysis

Application	GPR	EM	Res.	Seis.	MD	Mag.	OVA
Evaluation of natural geologic and hydrologic conditions							
Depth and thickness of soil and rock layers and vertical variations	1[a]	2	1	1	NA	NA	NA
Mapping lateral variations in soil and rock (fractures, karst features, etc.)	1[a]	1	2	2 (Refr.) 1 (Refl.)	NA	NA	NA
Depth of water table	3	2	1		NA	NA	NA
Evaluation of subsurface contamination and post-closure monitoring							
Inorganics (high TDS and electrically conducive)							
Early warning contaminant detection	3	1	2	NA	NA	NA	NA
Detailed lateral mapping	3	1	2	NA	NA	NA	NA
Vertical extent	3	2	1	NA	NA	NA	NA
Changes of plume with time (flow direction and rate)	3	1	2	NA	NA	NA	NA
Post cleanup/closure monitoring	3	1	2	NA	NA	NA	NA
Organics (typically nonconducive)							
Early warning contaminant detection	3	3	3	NA	NA	NA	1
Detailed lateral mapping	2[a]	2	3	NA	NA	NA	1
Vertical extent	2[a]	3	2	NA	NA	NA	2
Changes of plume with time (flow direction and rate)	3	3	3	NA	NA	NA	1
Post cleanup/closure monitoring	3	3	3	NA	NA	NA	1
Location of buried wastes and delineation of trench boundaries							
Bulk waste trenches—without metal	1	1	2	3	NA	NA	NA[d]
Bulk waste trenches—with metal	1	1	2	3	1[c]	1[b]	NA[d]
Depth of trenches and landfills	2	3	2	2	NA	NA	NA[d]
Detection of 55-gal steel drums	2[a]	2	NA	NA	1[c]	1	NA[d]
Estimates of depth and quantity of 55-gal steel drums	2[a]	3	3	NA	2	1	NA[d]
Location of utilities							
Buried pipes and tanks	1	1[c]	NA	NA	1[c]	1[b]	NA[c]
Potential pathways of contaminant migration via conduits and permeable trench backfill	1	2	NA	NA	2	2	NA[d]
Abandoned wells with metal casing	3	NA	NA	NA	2	1[b]	NA[d]

1 = Primary choice under most field conditions.
2 = Secondary choice under most field conditions.
3 = Limited field application under most field conditions.
NA = Not applicable.

[a] Shallow.
[b] Assumes ferrous metals to be present.
[c] Assumes metals to be present.
[d] Assumes no vapors present.

Note: Many site-specific conditions may dictate the choice of a method rated 2 or 3 in preference to a 1.

Magnetic detector

Source: Benson, 1988

Table 3-3 Applications of Selected Field Investigation Techniques for Waste Disposal Sites

APPLICATIONS	METHODS										
	SEISMIC	SEISMIC MONITORING	SONAR	GRAVITY	MAGNETIC	RESISTIVITY	ELECTROMAGNETIC	RADAR	TIME-DOMAIN REFLECTOMETRY	RADIOMETRICS	BOREHOLE LOGGING
DEPTH TO BEDROCK	●					○	○	●			
FAULT DETECTION	●				●		●				●
FRACTURES IN ROCK		○						○		○	●
BURIED CHANNELS	●			○		●	●	●			
GROUND WATER SURFACE	○					○	○	●	○		●
SOIL WATER CONTENT	○					○	○	●	●	●	●
WATER DEPTH			●					●			
SUB-BOTTOM STRATIGRAPHY	●		●					●			
SEA BED SCOUR			●								
ICE THICKNESS							○	●			
PERMAFROST MAPPING	●					●	●	●	○		
PEAT THICKNESS	○					●	●	●			
SOIL STRATIGRAPHY	●					○	○	●		○	●
SAND & GRAVEL MAPPING	○					●	●	●			
LEACHATE PLUMES						●	●	○		●	●
SALT WATER INTRUSION						●	●	○	○		○
BURIED DRUMS					●	○	●	○			
BURIED PIPES & CABLES					○		●	○			
BURIED CAVITIES & TUNNELS	●			○	○		●	●			
VOIDS AROUND PIPES		○						○			
SUBSIDENCE (SLOPES & TUNNELS)	●	●		○			○	●	○		
PHYSICAL PROPERTIES	●	○		○	○	○	○	○	●	●	●
ELECTRICAL GROUNDING						●	●				
RIPPABILITY	●										
RADIOACTIVE HAZARDS											

SOURCE: Modified From MultiVIEW Geoservices Inc.

● OFTEN APPLICABLE
○ SOMETIMES APPLICABLE

Figure 3-12 Summary geophysical techniques

4. RESOURCE EXPLORATION AND CHARACTERIZATION

8_1 Exploration and Characterization - Drilling

Recap:

1. Geophysics provides 3D view of the reservoir/site at high granularity
2. Uses only proxies for permeability and temperature - and no samples or p,T,x measurements
3. Geophysics low cost but only slightly reduces investment risk

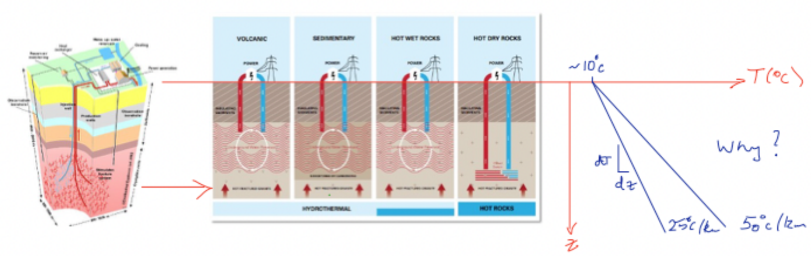
Movies: (GSHP Installation) https://www.youtube.com/watch?v=IMO9jvwIHFg

West Flank Coso: https://www.osti.gov/servlets/purl/1455367/

Resources: WG9

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
Therefore prospect for:
 (i) High Mass_rate/permeability/overpressure - define fast flow paths, and
 (ii) High T at shallow depth
Less crucial in "engineered" systems - "EGS" and "GSHP"

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

1. How do we locally define the reservoir and the distribution of:
    - A. Temperatures - as shallow as possible
    - B. Permeable pathways - as distributed as possible or high flow rates

    .... by direct access.....

DRILLING

1. Soil - Trenching/Augering/Tricone drilling
2. Rock - Tricone drilling/Core drilling

Table 1. Advantages and Disadvantages of Auger, Rotary, and Cable Tool Drilling

Type	Advantages	Disadvantages
Auger	• Minimal damage to aquifer • No drilling fluids required • Auger flights act as temporary casing, stabilizing hole for well construction • Good technique for unconsolidated deposits • Continuous core can be collected by wire-line method	• Cannot be used in consolidated deposits • Limited to wells less than 150 ft in depth • May have to abandon holes if boulders are encountered
Rotary	• Quick and efficient method • Excellent for large and small diameter holes • No depth limitations • Can be used in consolidated and unconsolidated deposits • Continuous core can be collected by wire-line method	• Requires drilling fluids, which alter water chemistry • Results in a mud cake on the borehole wall, requiring additional well development, and potentially causing changes in chemistry • Loss of circulation can develop in fractured and high-permeability material • May have to abandon holes if boulders are encountered
Cable Tool	• No limitation on well depth • Limited amount of drilling fluid required • Can be used in both consolidated and unconsolidated deposits • Can be used in areas where lost circulation is a problem • Good lithologic control • Effective technique in boulder environments	• Limited rigs and experienced personnel available • Slow and inefficient • Difficult to collect core

Source: EPA (1989).

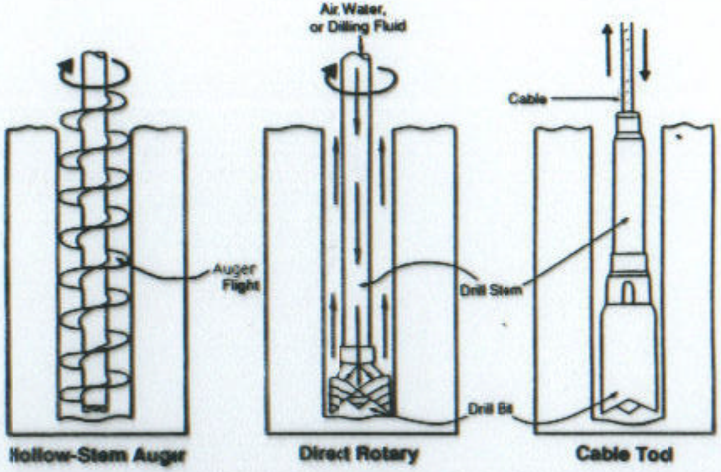


Figure 2. Illustration and advantages and disadvantages of auger, rotary, and cable tool drilling. *Source:* EPA (1989).

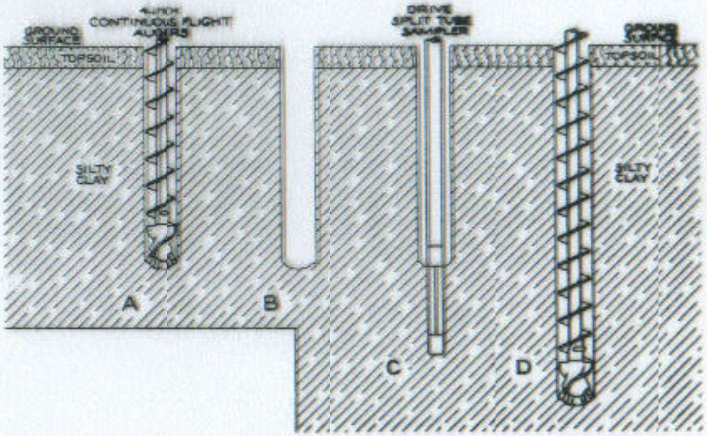


Figure 3. Continuous flight auger drilling. A. Advance auger to sampling interval; B. Remove flight augers; C. Advance split-spoon sampler; D. Advance auger to next sample interval. *Source:* University of Missouri, Rolla (1981).

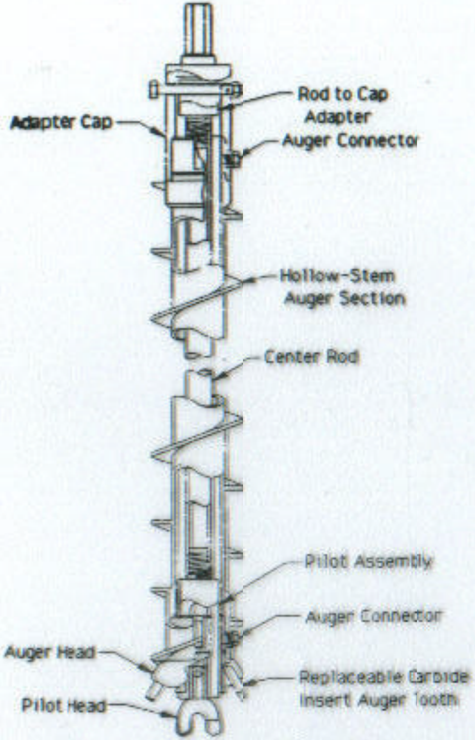


Figure 5. Components of a consolidated mining equipment hollow-stem auger. *Source:* University of Missouri, Rolla (1981).

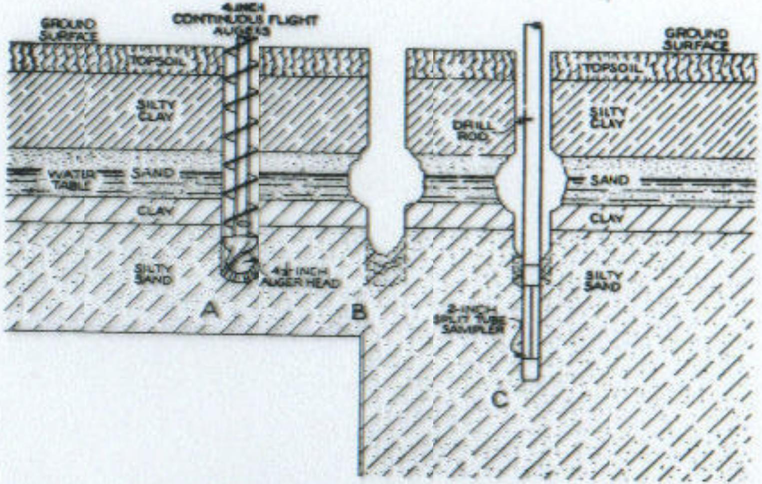


Figure 4. Continuous flight auger drilling though caving material. A. Auger to sample interval; B. Saturated sand stratum flows causing borehole to "bell"; C. Sampler must advance through sand "flow" slough to sample in-placesilty sand. *Source:* University of Missouri, Rolla (1981).

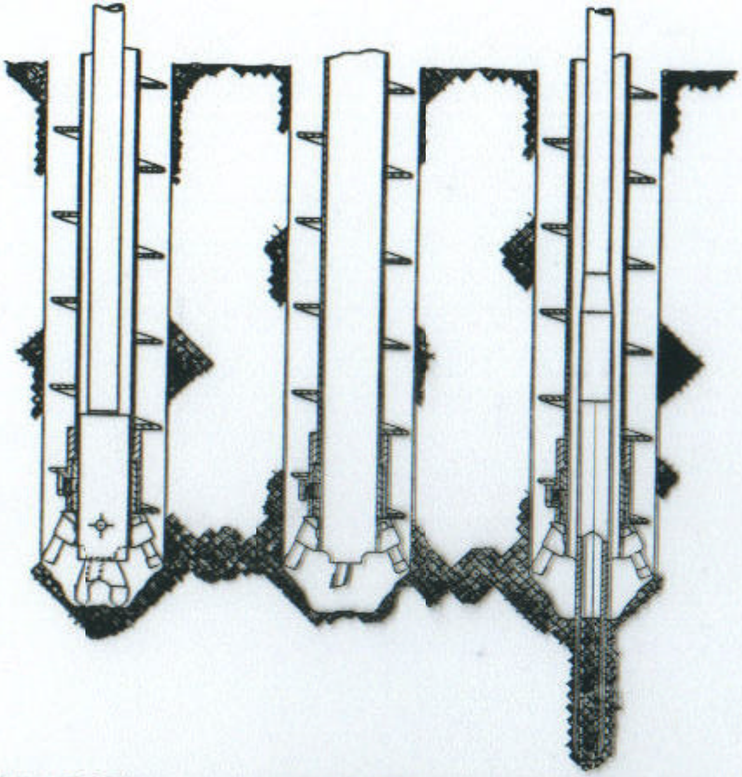


Figure 6. Driving a soil sampler through he hollow-stem auger. *Source:* University of Missouri, Rolla (1981).

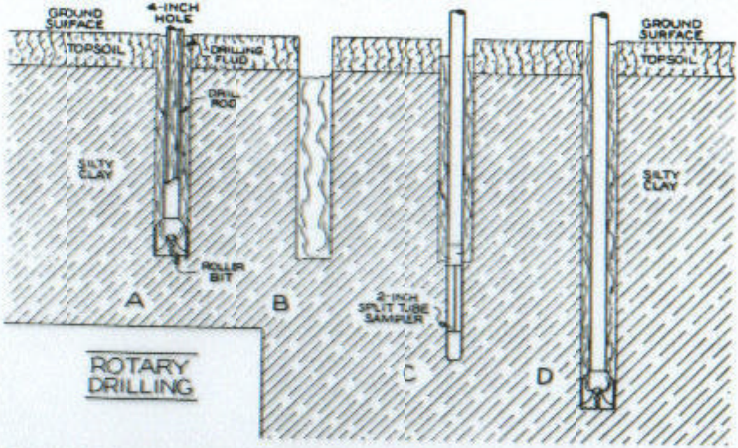


Figure 7. Rotary drilling. A. Mud rotary driling advance to sampler interval; B. Drilling mud holds borehole walls up; C. Split-spoon sampler advanced; D. New drill rod attached and borehole advanced. *Source:* University of Missouri, Rolla (1981).

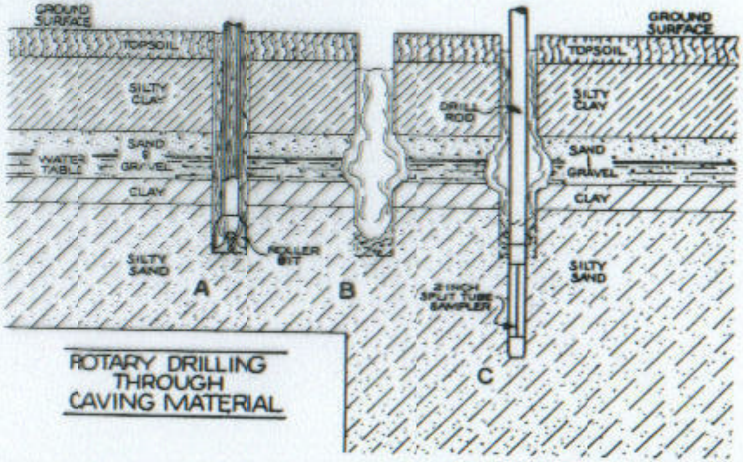
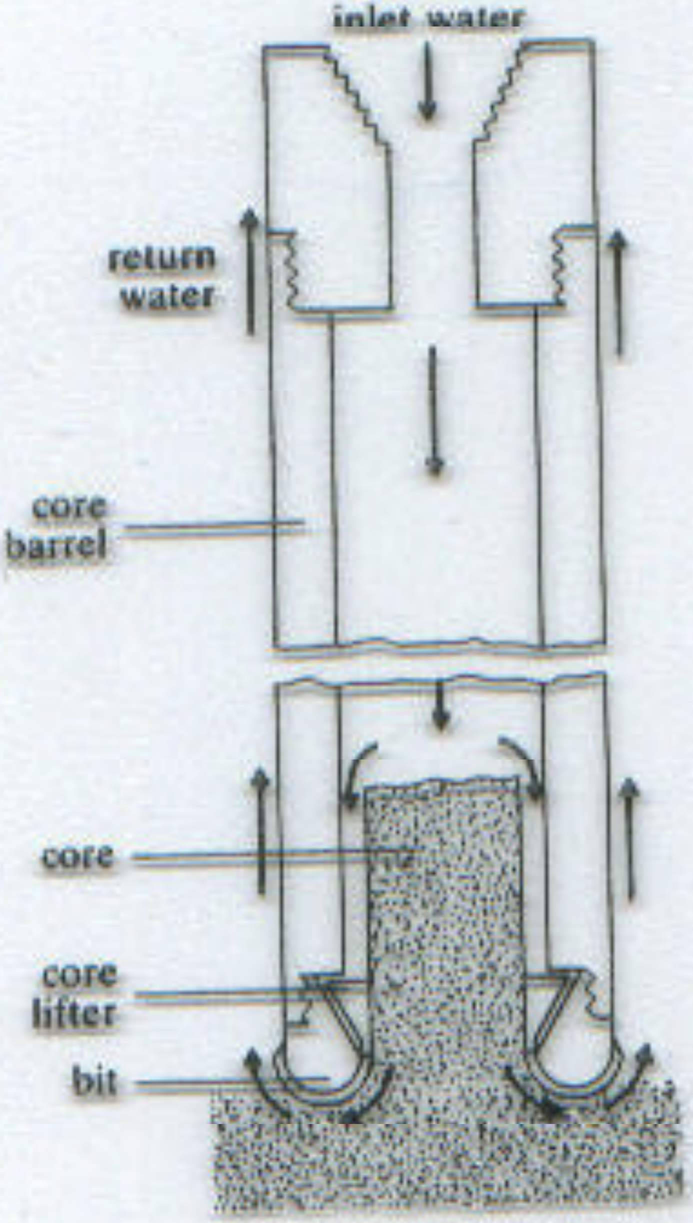


Figure 8. Rotary drilling hrough caving material. A. Rotary drilling advances borehole to below water table; B. Drilling mud holes borehole walls open to minimize "flow" and caving; C. Split spoon advanced at desired sample depth. *Source:* Unversity of Missouri, Rolla (1981).


inlet water
return water
core barrel
core
core lifter
bit

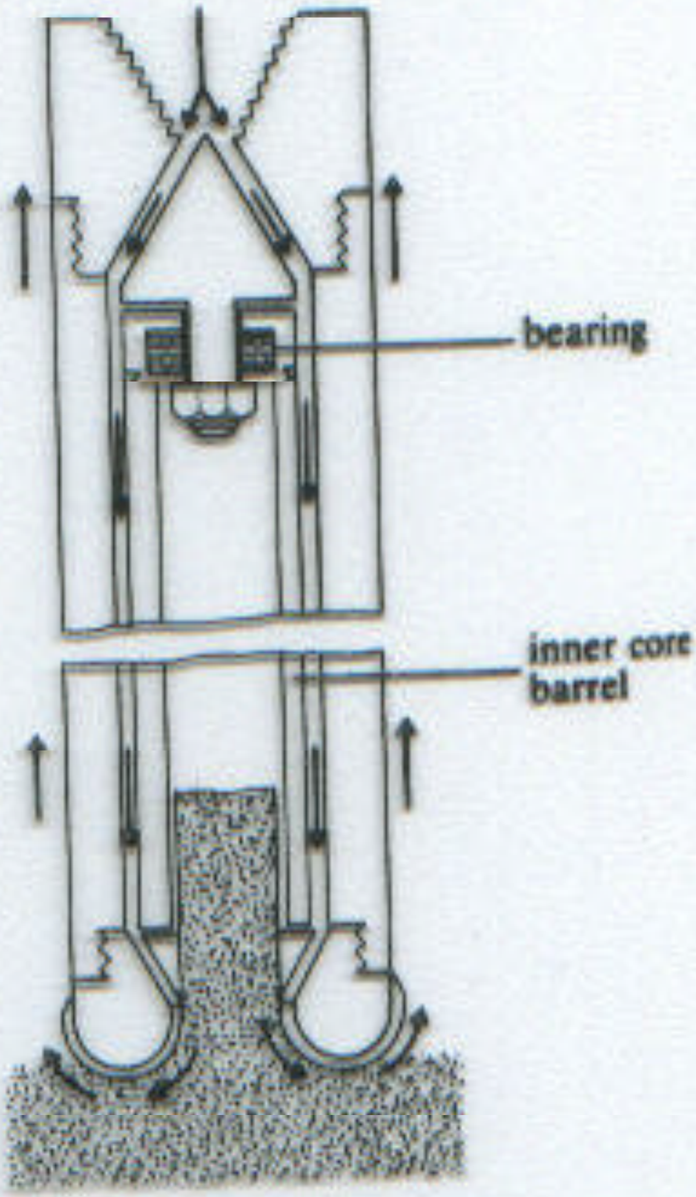

bearing
inner core barrel

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
HAND AUGERS – A hand auger is advanced by turning it into the soil until the bucket or screw is filled. The auger is then removed from the hole. The sample is dislodged from the auger, and drilling continues. Motorized units are also available.	• Shallow soil investigations (0 to 15 ft) • Soil samples collected from the auger cutting edge • Water-bearing zone identification • Contamination presence examination; sample analysis • Shallow, small diameter well installation • Experienced user can identify stratigraphic interfaces by penetration resistance differences as well as sample inspection • Highly mobile, and can be used in confined spaces • Various types (i.e., bucket, screw, etc.) and sizes (typically 1 to 9 inches in diameter) • Inexpensive to purchase	• Limited to very shallow depths (typically < 15 ft) • Unable to penetrate extremely dense or rocky or gravelly soil • Borehole stability may be difficult to maintain, particularly beneath the water table • Potential for vertical cross-contamination • Labor intensive
SOLID-FLIGHT AUGERS – A cutter head (≥ 2-inch diameter) is attached to multiple auger flights. As the augers are rotated by a rotary drive head and forced down by either a hydraulic pulldown or a feed device, cuttings are rotated up to ground surface by moving along the continuous flighting.	• Shallow soils investigations (< 100 ft) • Soil samples are collected from the auger flights or using split-spoon or thin-walled samplers if the hole will not cave upon retrieval of the augers • Vadose zone monitoring wells • Monitor wells in saturated, stable soils • Identification of depth to bedrock • Fast and mobile; can be used with small rigs • Holes up to 3-ft diameter • No fluids required • Simple to decontaminate	• Low-quality soil samples unless split-spoon or thin-wall samples are taken • Soil sample data limited to areas and depths where stable soils are predominant • Unable to install monitor wells in most unconsolidated aquifers because of borehole caving upon auger removal • Difficult penetration in loose boulders, cobbles, and other material that might lock up auger • Monitor well diameter limited by auger diameter • Cannot penetrate consolidated materials • Potential for vertical cross-contamination
HOLLOW-STEM AUGERS – Hollow-stem augering is done in a similar manner to solid-flight augering. Small-diameter drill rods and samplers can be lowered through the hollow augers for sampling. If necessary, sediment within the hollow stem can be cleaned out prior to inserting a sampler. Wells can be completed below the water table using the augers as temporary casing.	• All types of soil investigations to <100 ft below ground • Permits high-quality soil sampling with split-spoon or thin-wall samplers • Water-quality sampling • Monitor well installation in all unconsolidated formation • Can serve as a temporary casing for coring rock • Can be used in stable formations to set surface casing • Can be used with small rigs in confined spaces • Does not require drilling fluids	• Difficulty in preserving sample integrity in heaving (running sand) formations • If water or drilling mud is used to control heaving will invade the formation • Potential for cross-contamination of aquifers where annular space not positively controlled by water or drilling mud or surface casing • Limited auger diameter limits casing size (typical augers are: 6¼-in OD with 3¼-in ID, and 12-in OD with 6-in ID) • Smearing of clays may seal off interval to be monitored

Table 9-3. **Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).**

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
DIRECT MUD ROTARY – Drilling fluid is pumped down the drill rods and through a bit attached to the bottom of the rods. The fluid circulates up the annular space bringing cuttings to the surface. At the surface, drilling fluid and cuttings are discharged into a baffled sedimentation tank, pond, or pit. The tank effluent overflows into a suction pit where drilling fluid is recirculated back through the drill rods. The drill stem is rotated at the surface by top head or rotary table drives and down pressure is provided by pull-down devices or drill collars.	• Rapid drilling of clay, silt, and reasonably compacted sand and gravel to great depth (>700 ft) • Allows split-spoon and thin-wall sampling in unconsolidated materials • Allows drilling and core-sampling in consolidated rock • Abundant and flexible range of tool sizes and depth capabilities • Sophisticated drilling and mud programs available • Geophysical borehole logs	• Difficult to remove drilling mud and wall cake from outer perimeter of filter pack during development • Bentonite or other drilling fluid additives may influence quality of ground-water samples • Potential for vertical cross-contamination • Circulated cutting samples are of poor quality; difficult to determine sample depth • Split-spoon and thin-wall samplers are expensive and of questionable cost effectiveness at depths > 150 ft • Wireline coring techniques for sampling both unconsolidated and consolidated formations often not available locally • Drilling fluid invasion of permeable zones may compromise integrity of subsequent monitor well samples • Difficult to decontaminate pumps
AIR ROTARY – Air rotary drilling is similar to mud rotary drilling except that air is the circulation medium. Compressed air injected through the drill rods circulates cuttings and groundwater up the annulus to the surface. Typically, rotary drill bits are used in sedimentary rocks and down-hole hammer bits are used in harder igneous and metamorphic rocks. Monitor wells can be completed as open hole intervals beneath telescoped casings.	• Rapid drilling of semi-consolidated and consolidated rock to great depth (>700 ft) • Good quality/reliable formation samples (particularly if small quantities of drilling fluid are used) because casing prevents mixture of cuttings from bottom of hole with collapsed material from above • Allows for core-sampling of rock • Equipment generally available • Allows easy and quick identification of lithologic changes • Allows identification of most water-bearing zones • Allows estimation of yields in strong water-producing zones with short "down time"	• Surface casing frequently required to protect top of hole from caving • Drilling restricted to semi-consolidated and consolidated formations • Samples reliable, but occur as small chips that may be difficult to interpret • Drying effect of air may mask lower yield water producing zones • Air stream requires contaminant filtration • Air may modify chemical or biological conditions; recovery time is uncertain • Potential for vertical cross-contamination • Potential exists for hydrocarbon contamination from air compressor or down-hole hammer bit oils
AIR ROTARY WITH CASING DRIVER – This method uses a casing driver to allow air rotary drilling through unstable unconsolidated materials. Typically, the drill bit is extended 6 to 12 inches ahead of the casing, the casing is driven down, and then the drill bit is used to clean material from within the casing.	• Rapid drilling of unconsolidated sands, silts, and clays • Drilling in alluvial material (including boulder formations) • Casing supports borehole, thereby maintaining borehole integrity and reducing potential for vertical cross-contamination • Eliminates circulation problems common with direct mud rotary method • Good formation samples because casing (outer wall) prevents mixture of caving materials with cuttings from bottom of hole • Minimal formation damage as casing pulled back (smearing of silts and clays can be anticipated)	• Thin, low pressure water-bearing zones easily overlooked if drilling not stopped at appropriate places to observe whether or not water levels are recovering • Samples pulverized as in all rotary drilling • Air may modify chemical or biological conditions; recovery time is uncertain

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
DUAL-WALL REVERSE ROTARY – Circulating fluid (air or water) is injected through the annulus between the outer casing and drill pipe, flows into the drill pipe through the bit, and carries cuttings to the surface through the drill pipe. Similar to rotary drilling with the casing driver, the outer pipe stabilizes the borehole and reduces cross-contamination of fluids and cuttings. Various bits can be used with this method.	• Very rapid drilling through both unconsolidated and consolidated formations • Allows continuous sampling in all types of formations • Very good representative samples can be obtained with reduced risk of contamination of sample and/or water-bearing zone • Allows for rock coring • In stable formations, wells with diameters as large as 6 inches can be installed in open hole completions	• Limited borehole size that limits diameter of monitor wells • In unstable formations, well diameters are limited to approximately 4 inches • Equipment available more common in the southwest U.S. than elsewhere • Air may modify chemical or biological conditions; recovery time is uncertain • Unable to install filter pack unless completed open hole
CABLE TOOL DRILLING – A drill bit is attached to the bottom of a weighted drill stem that is attached to a cable. The cable and drill stem are suspended from the drill rig mast. The bit is alternatively raised and lowered into the formation. Cuttings are periodically removed using a bailer. Casing must be added as drilling proceeds through unstable formations.	• Drilling in all types of geologic formations • Almost any depth and diameter range • Ease of monitor well installation • Ease and practicality of well development • Excellent samples of coarse-grained media can be obtained • Potential for vertical cross-contamination is reduced because casing is advanced with boring • Simple equipment and operation	• Drilling is slow, and frequently not cost-effective as a result • Heaving of unconsolidated materials must be controlled • Equipment availability more common in central, north central, and northeast sections of the U.S.
ROCK CORING – A carbide or diamond-tipped bit is attached to the bottom of a hollow core barrel. As the bit cuts deeper, the rock sample moves up into the core tube. With a double-wall core barrel, drilling fluid circulates between the two walls and does not contact the core, allowing better recovery. Clean water is usually the drilling fluid. Standard core tubes are attached to the bottom of a drill rod and the entire string of rods must be removed after each core run. With wireline coring, an inner core barrel is withdrawn through the drill string using an overshot device that is lowered on a wireline into the drill string.	• Provides high-quality, undisturbed core samples of stiff to hard clays and rock • Holes can be drilled at any angle • Can detect location and nature of rock fractures • Can use core holes to run a complete suite of geophysical logs • Variety of core sizes available • Core holes can be utilized for hydraulic tests and monitor well completion • Can be adapted to a variety of drill rig types and operations	• Relatively expensive and slow rate of penetration • Can lose a large quantity of drilling water into permeable formations • Potential for vertical cross-contamination

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
CONE PENETROMETER -- Hydraulic rams are used to push a narrow rod (e.g., 1.5-inch diameter) with a conical point into the ground at a steady rate. Electronic sensors attached to the test probe measure tip penetration resistance, probe side resistance, inclination and pore pressure. Sensors have also been developed to measure subsurface electrical conductivity, radioactivity, and optical properties (fluorescence and reflectance). Cone penetrometer tests (CPT) are generally performed using a special rig and a computerized data collection, analysis, and display system. To facilitate interpretation of CPT data from numerous tests, CPT data from at least one test per site should be compared to a log of continuously sampled soil at an adjacent location. References: Robertson and Campanella (1986), Lark et al. (1990), Smolley and Kappmeyer (1991), Christy and Spradlin (1992), Edge and Cordry (1989), and, Chiang et al. (1992).	• Efficient tool for stratigraphic logging of soft soils • Measurement of some soil/fluid properties (e.g., tip penetration resistance, probe side friction, pore pressure, electrical conductivity, radioactivity, fluorescence), with proper instrumentation, can be obtained continuously rather than at intervals; thus improving the detectability of thin layers (i.e., subtle DNAPL capillary barriers) and contaminants • There are virtually no cuttings brought to the ground surface, thus eliminating the need to handle cuttings • Process presents a reduced potential for vertical cross-contamination if the openings are sealed with grout from the bottom up upon rod removal • Porous probe samplers can be used to collect groundwater samples with minimal loss of volatile compounds • Soil gas sampling can be conducted • Fluid sampling from discrete intervals can be conducted using special tools (e.g., the Hydropunch™ manufactured by Q.E.D. Environmental Systems of Ann Arbor, Michigan)	• Unable to penetrate dense geologic conditions (i.e., hard clays, boulders, etc.) • Limited depth capability (depends on • Soil samples cannot be collected for examination or chemical analyses, unless special equipment is utilized • Only very limited quantities of groundwater can be sampled • Limited well construction capability • Limited availability

Table 1. Well-Drilling Selection Guide

Drilling Method	Drilling Fluid	Casing Advance	Type of Material Drilled	Nominal Drilling Depth, in ft 1_/	Nominal Range of Borehole Sizes, in in.	Samples Obtainable 2_/	Coring Possible	Reference Section
Power Auger (Hollow Stem)	None, Water, Mud	Yes	Soil, Weathered rock	<150	5 - 22	S, F	Yes	6.2
Power Auger (Solid Stem)	Water, Mud	No	Soil, Weathered Rock	<150	2-10	s	Yes	6.3
Power Bucket Auger	None, Water (below water table	No	Soil, Weathered rock	<150	18 -48	S	Yes	6.4
Hand Auger	None	No	Soil	<70 (Above Water Table Only)	2 - 6	S	Yes	6.5
Direct Fluid Rotary	Water, Mud	Yes	Soil, Rock	>1000	2 - 36	S, R	Yes	7.3
Direct Air Rotary	Air, Water, Foam	Yes	Soil, Rock	>1500	2 - 36	S, R, F	Yes	7.4
DTH Hammer	Air, Water, Foam	Yes	Rock, Boulders	<2000	4 - 16	R	Yes	7.5.1
Wireline	Air, Water, Foam	Yes	Soil, Rock	>1000	3-6	S, R, F	Yes	7.6
Reverse Fluid Rotary	Water, Mud	Yes	Soil, Rock	<2000	12 - 36	S, R, F	Yes	7.8
Reverse Air Rotary	Air, Water, Foam	Yes	Soil, Rock	>1000	12 - 36	S, R, F	Yes	7.7
Cable Tool	Water	Yes	Soil, Rock	<5000	6-8	S, R, F (F- Below Water Table)	Yes	8
Casing-Advancer	Air, Water, Mud	Yes	Soil, Rock, Boulders	<2000	2 -16	S, R, F	Yes	9
Direct-Push Technology	None	Yes	Soil	<100	1.5 - 3	F	Yes	10
Sonic (Vibratory)	None, Water, Mud, Air	Yes	Soil, Rock, Boulders	<500	4 -12	S, R, F	Yes	11
Jet Percussion	Water	No	Soil	<50	2 - 4	S	No	12
Jetting	Water	Yes	Soil	<50	4	S	No	12

1/ Actual achievable drilled depths will vary depending on the ambient geohydrologic conditions existing at the site and size of drilling equipment used. For example, large, high-torque rigs can drill to greater depths than their smaller counterparts under favorable site conditions. Boreholes drilled using air/air foam can reach greater depths more efficiently using two-stage positive-displacement compressors having the capability of developing working pressures of 250 to 350 psi and 500 to 750 cfm (particularly when submergence requires higher pressures). The smaller rotary-type compressors are only capable of producing a maximum working pressure of 125 psi. and produce 500 to 1200 cfm. Likewise, the rig mast must be constructed to safely carry the anticipated working loads expected. To allow for contigencies, it is recommended that the rated capacity of the mast be at least twice the anticipated weight load or normal pulling load. 2/ Soil = S (Cuttings), Rock = R (Cuttings), Fluid = F (Some samples might require accessory sampling devices to obtain.)

SAND2016-6071C

ARMA-AAPG-SEDHEAT WORKSHOP

June 24 – 25, 2016

Drilling Challenges in Geothermal Reservoirs

Douglas Blankenship
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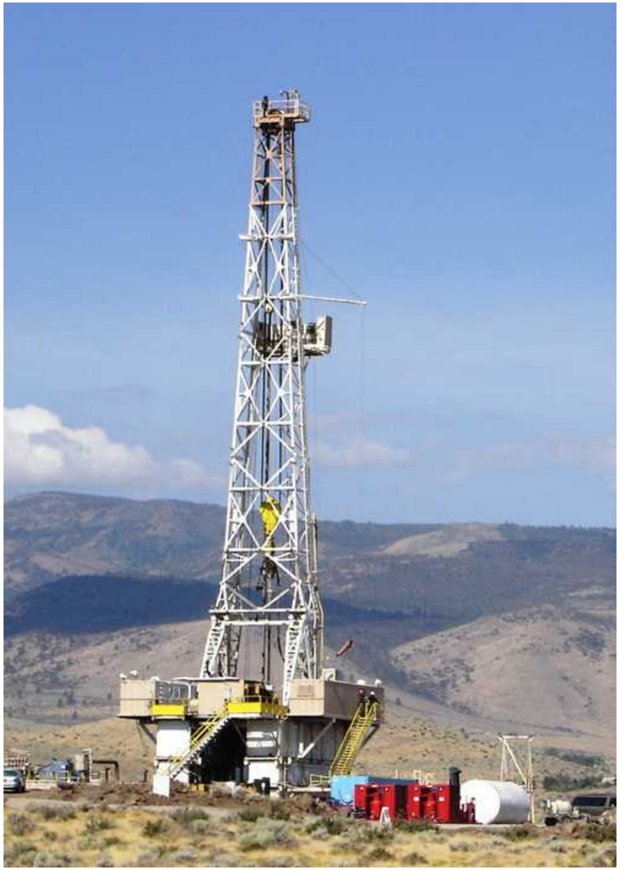
History

- First Oil Well in US – Drake's 1859

- First Geothermal Projects
  - Larderallo, Italy 1913
    - 250 kw, expanded in 1935
    - Sold electricity to the electric railway system
  - Geysers, USA 1921
    - 250 kw, just for use at the Geysers Resort
    - Commercially developed in 1962, PG&E sold into grid system
  - Wairakei, New Zealand 1958

Relative Size by Active Rig Count

- Oil and Gas Rigs Worldwide 1,448*
  - USA 424
  - Canada 69
  - International 955
- Geothermal Rigs Worldwide ~15-20



* From Baker Hughes Rotary Rig Count, June 2016

Geothermal Drilling vs O&G

- Hot
  - By definition
- Often
  - High matrix strength
  - Abrasive
  - Fractured
  - Underpressurized formations
  - Corrosive fluids
- Larger diameters
  - 12 ¼” dia. bottom-hole common

Drilling Costs can Exceed 50% of a Developer’s Capital Investment

Different Purposes For Wells

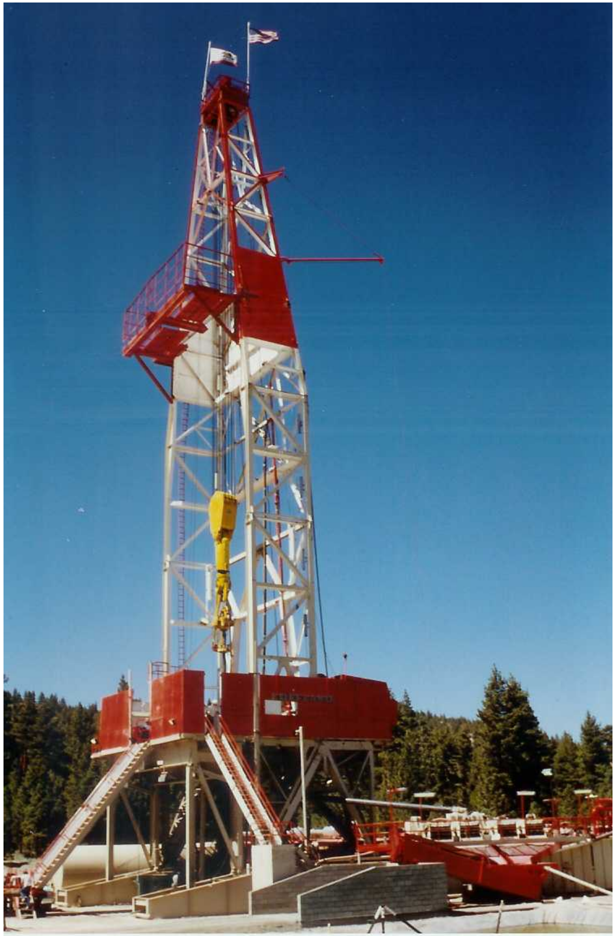
- Gradient Holes
- Test or Exploration Wells
    - Core Holes
    - Slim Holes
- Production Wells
- Injection Wells

Different Drilling Processes

- Cable Tool/Auger
- Continuous Coring
- Rotary
  - Mud
  - Air, Mist, Foam

Basic Components of the Drilling System

- Bits
- Drilling Fluids
- BOP
- Casing
- Cement



Bits in Geothermal

- Used to extend the hole
  - Roller / Drag Bits (e.g., PDCs) /Hammers/Diamond Impregnated
- Roller bits most common in geothermal drilling
  - "Old" technology – Source of Howard Hughes fortune (Hughes Tool Company founded in 1909 by dad)
  - Durable in hard fractured formations but slow and inefficient rock reduction tool
  - Significant research over past couple decades (bearings, cutting structure, …) but footage/day remains low in geothermal.
- Bits are part of the bottom-hole-assembly
  - Collars / stabilizers / reamers/ jars / …

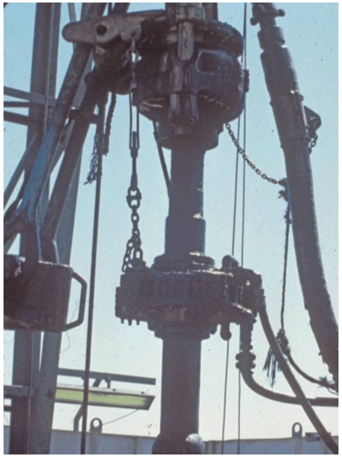
Rock Reduction in Broader Industry

- Polycrystalline diamond compact (PDC)
  - ~2/3 of world footage drilled with PDC's and all high $$$ O&G wells
  - Efficient, high performance tools
  - Viable for geothermal with recent advances
- Percussive hammers (air)
  - Extensive use in mining industry
  - Efficient, robust tool for hard rock limitations have been addressed
- High speed motors / turbines with impregnated diamond bits
  - Excellent results in O&G in drilling high strength rock

Rock reduction systems used in other industries can be applied to geothermal drilling to substantively improve daily drilling rates

Drilling Fluids

- A circulation system (fluid/pumps/cleaning)
  - Clean the hole of cuttings
  - Cool and clean the bit
  - Wellbore stability
  - Lubricate the drill string
  - Form filter cake
  - Well Control

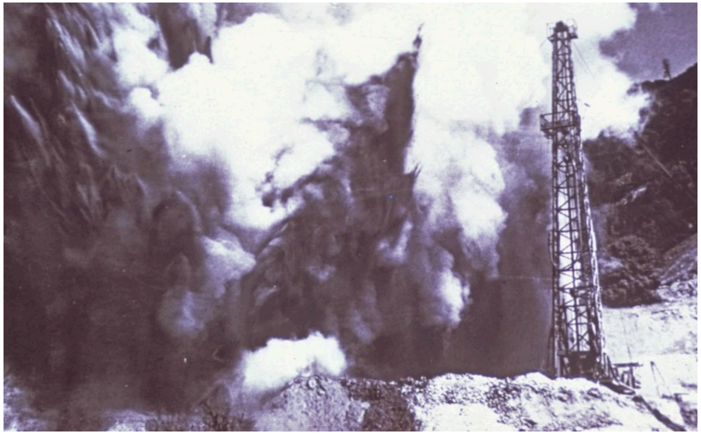


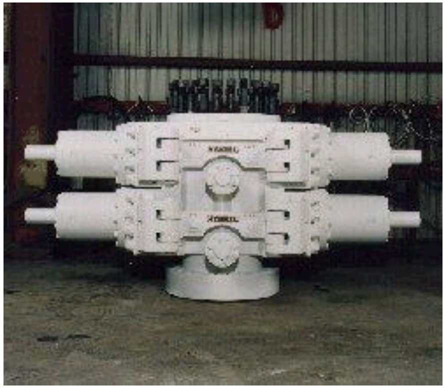
Drilling Fluids in Geothermal

- Water-based muds
  - Bentonite primary viscosifier, polymers used but degrade at HT
  - Water uptake in solids greater at high temperatures, cleaning important
  - Mud coolers often used
- Air/Foam/Mist drilling common in geothermal
  - Prevents fouling of fractures
  - Probably not a big issues with EGS
- Clean water
  - Used with high lost circulation and drilling without returns

Blow Out Prevention Equipment – Well Control

Blowout prevention equipment (BOPE) in geothermal drilling is necessary





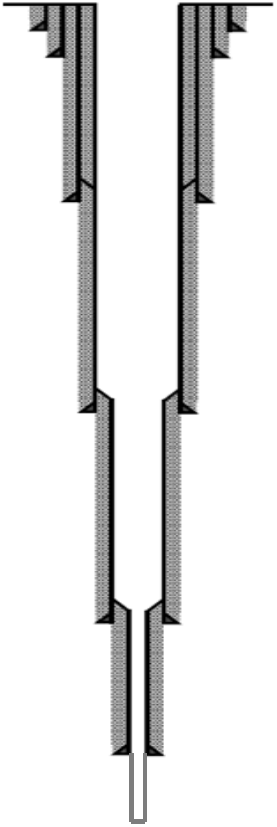
Blow Out Prevention in Geothermal

- BOPE is used to control “kicks” and potential outflow
  - Different components (rotating head, annual preventer, pipe rams, blind rams, shear rams)
  - Deepwater Horizon demonstrated why they are not called blow out stoppers
- Protects against unexpected steam or gas flow
  - Circulating hot water to surface which can flash
    - Higher temperatures or pressures than expected
  - Loss of drilling fluid in the well can result in flashing
    - Lost Circulation
- Some air drilled wells are advanced while producing

Mud is the first line of defense; BOPE and cemented casing are the second.

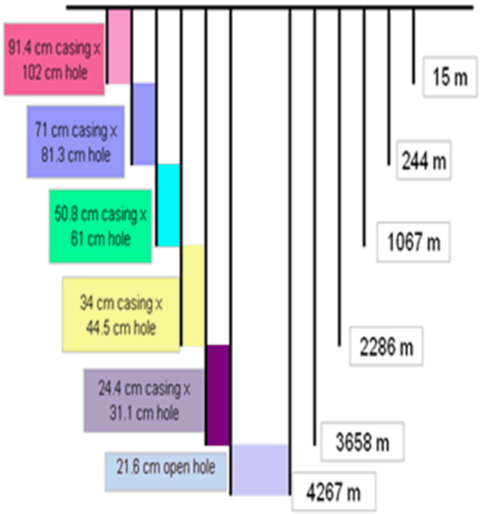
Casing and Cement

- Driven by Well Design
  - Well design is a bottom up process
- Casing and Cement
  - Provides aquifer protection
  - Part of the well control system
  - Isolates troublesome formations
  - Can define production zones
  - Provides fluid pressure control
- Geothermal casing is cemented to surface
  - Eliminates trapped water
  - Restrains unacceptable growth



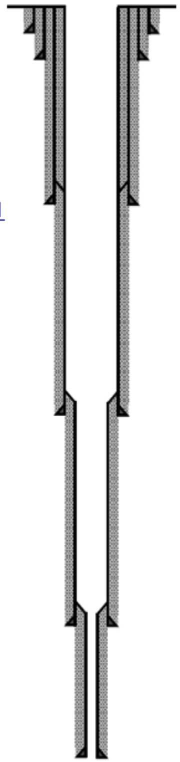
Cement and Casing

- Casing and Cement need to
  - Retain strength at high temp.
  - Withstand corrosive fluids
- Cementing to surface often problematic
  - Inside out common
  - Outside in being used (reverse circulation)
- Geothermal specific cements have been developed by DOE
  - e.g., “ThermaLock”



So what are Well Cost Drivers?

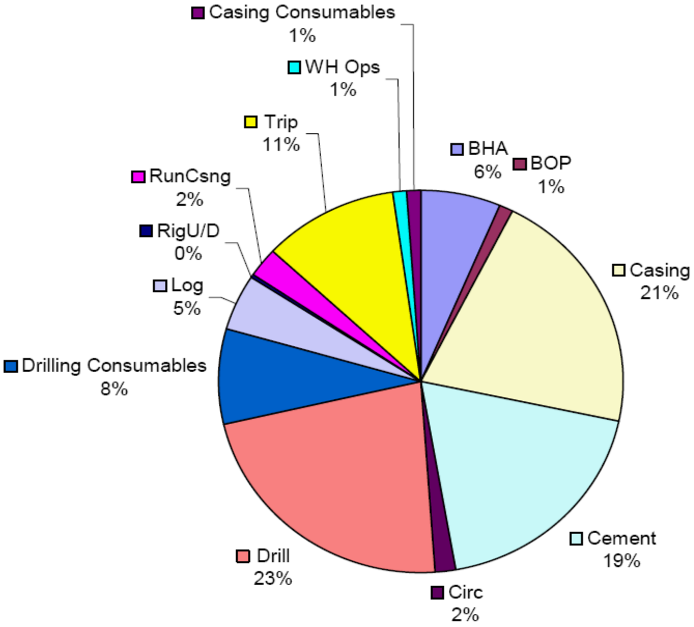
- An exercise
  - 6 km (20,000 ft) well
  - Analytical flow calculations performed to determine wells ability to meet MIT report recommended flow rates (80 kg/s @200 °C, 5 MWe)
  - ThermaSource Inc. performed “drilling on paper” exercise describing operational steps, tools, materials and costs
  - Drilling script provided by ThermaSource is subsequent basis for well construction analysis

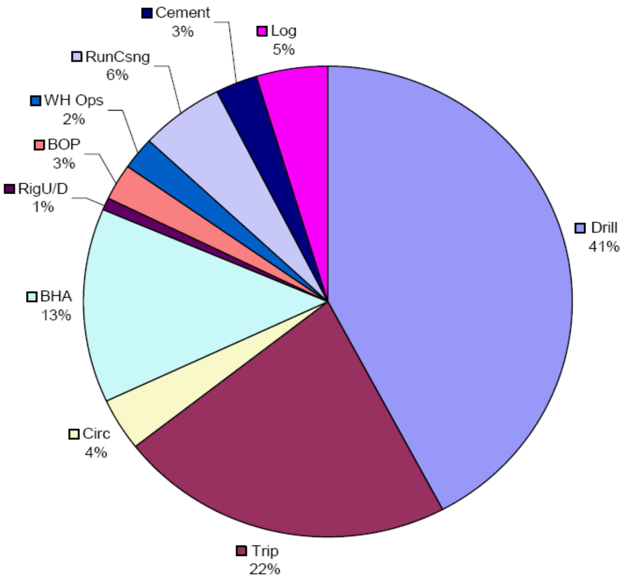


HOLE Information	CASING Information
CONDUCTOR 48 in to 50 ft	CONDUCTOR PIPE 40 in, Line Pipe to 50 ft
SURFACE HOLE 36 in to 500 ft	SURFACE CASING 30 in, 310 ppf, X-56 Line Pipe to 500 ft
	PRODUCTION L-1 TIE-BACK 13-3/8 in, 72 ppf, N-80 Vam Top, Seamless
INTERMEDIATE HOLE 1 26 in to 5000 ft	INTERMEDIATE CASING 1 20 in, 169 ppf, N-80, BTC, Seamless
PRODUCTION HOLE 1 17-1/2 in to 10000 ft Seamless	PRODUCTION LINER 1 13-5/8 in, 88.2 ppf, P-110, BTC, *Top of 13-5/8 in Production Liner 1 at 4800 ft*
PRODUCTION HOLE 2 12-1/4 in to 17000 ft	PRODUCTION LINER 2 53.5 ppf, P-110, BTC, Seamless *Top of 9-5/8 in Production Liner 2 at 9800 ft*
PRODUCTION HOLE 3 8-1/2 in to 20000 ft	PRODUCTION LINER 3 7 in, 32 ppf, P-110, BTC, Seamless *Top of 7 in Production Liner 3 at 16800 ft*

SAND2008-7866 (2008)

EGS Well Construction Costs





Well cost (%) breakdown by task.

Well construction task time percentages.

Phase	Drill	Trip	Circ	Drilling Consumabl	BOP	BHA	Casing	RunCsng	Casing Consumables	Cement	WH Ops	Log	RigU/D	Grand Total	Cost/ft
1 Surface	$109,728	$36,070	$6,278	$193,155	$81,620	$148,916	$170,000	$31,392		$258,171	$43,949	$130,813	$24,183	$1,234,276	$2,469
2 INT-1	$987,550	$203,561	$14,116	$582,450	$62,785	$153,840	$950,000	$94,177		$1,258,078	$75,341	$165,691	$12,557	$4,560,146	$912
3 PROD-1	$909,173	$309,909	$34,045	$354,380	$0	$291,501	$1,123,200	$94,177		$758,349		$200,569	$12,557	$4,087,861	$818
4 PROD-2	$1,786,996	$768,065	$132,817	$352,590	$0	$252,146	$705,600	$125,569		$577,114		$241,261	$6,278	$4,948,436	$707
5 PROD-3	$852,750	$833,203	$155,906	$185,492	$0	$264,786	$217,600	$125,569		$368,342		$270,326	$6,278	$3,280,253	$1,093
6 PL1-TB	$6,278	$100,455	$12,557		$81,620	$213,468	$1,128,000	$43,949		$690,428	$69,063		$6,278	$2,352,097	
General									$255,000					$255,000	
Grand Total	$4,652,477	$2,251,263	$355,720	$1,668,067	$226,024	$1,324,657	$4,294,400	$514,834	$255,000	$3,910,481	$188,354	$1,008,660	$68,132	$20,718,069	

SAND2008-7866 (2008)

Well Cost Exercise

- Results consistent with proprietary drilling records
- Drilling, casing and cementing costs are obvious
- Other costs such as tripping and BHA handling are not trivial
- Task and consumable cost structure changes with depth and design
- Relative impact of new technologies and methods will be dependent on well specification
- Non-hole making tasks are significant cost drivers
  - Tripping and BHA handling are not trivial contributors

There is no economic silver bullet! Reducing well construction cost will require multiple focus areas

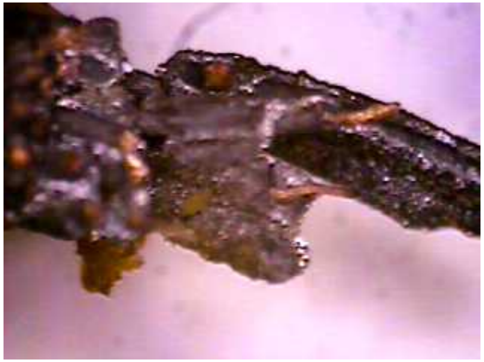
Geothermal in Sedimentary Systems

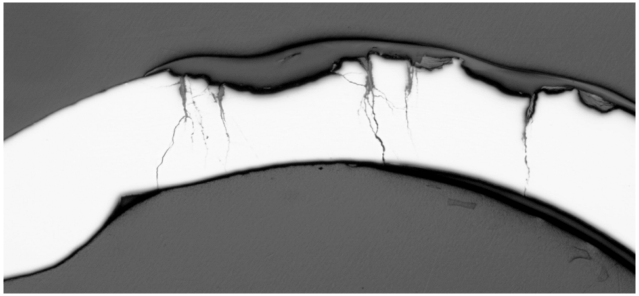
- Drilling will be closer to the O&G experience, but not the same.
  - Large diameter wells, High temperatures, Casing approaches, …
- Higher ROPS likely, but cost will be comparable
  - Many drivers on cost that are agnostic of application
  - Economic pressures will remain (leverage co-production?)
- Completion schemes will likely be different than “traditional” geothermal
  - Simple slotted liners may not be viable

High Temperature Challenges in Geothermal Drilling and Resource Exploration

High Temperature Failures

- A high temperature environment by itself can be a primary failure mode with electronic components, seals and circuit boards
- High temperature can also accelerate other failure modes
  - Intermetallic growth and voiding
  - Materials outgassing
  - Corrosion from wellbore fluids
  - Hydrogen darkening of optical fiber
  - Stress induced failures from CTE mismatch





Standard Open Hole Logging Tools

- Temperature, Pressure, Spinner (Flow)
- Spontaneous potential
- Resistivity (induction and laterolog)
- Gamma (total and U, K, Th spectrum)
- Gamma density (can include photoelectric factor)
- Sonic (porosity, stress estimate from dipole tool)
- Neutron porosity (can include formation sigma)
- NMR (pore size, porosity, permeability estimate)
- Borehole imagers (microresistivity and ultrasonic)

Other Logging/Monitoring Tools

- Cased Hole
  - Multi-arm caliper
  - Casing inspection (ultrasonic, EM and Hall effect imagers)
  - Cement Bond Log (sonic and ultrasonic)

- Seismic
  - Vertical seismic profile

- Fiber optic
  - Distributed temperature sensing (DTS)
  - Seismic

MWD/LWD

- Measurement While Drilling (MWD)
  - Pressure and temperate
  - Shock and vibration
  - Direction and inclination
  - RPM, weight on bit, torque on bit
  - Data is transmitted in real time (EM or mud pulse telemetry)

- Logging While Drilling (LWD)
  - Most of the open hole logging measurements
  - Measurements are stored for later download

Commercial HT Tools

- Most open hole logging tools are available in a HT versions up to 260°C
  - Dipole sonic tools, microresistivity imagers and NMR tools are the exception
  - Dewar heat shields are typically used above 177°C
  - Logging time can be between 4 and 12 hours

- MWD/LWD systems are typically limited to 180°C
  - Halliburton claims a 230°C system with directional, drill string dynamics, pressure and gamma information

Significant costs incurred if tools are run over their max temperature!

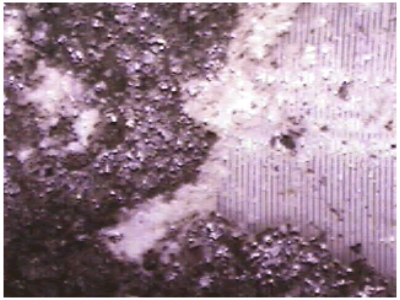
Electronics

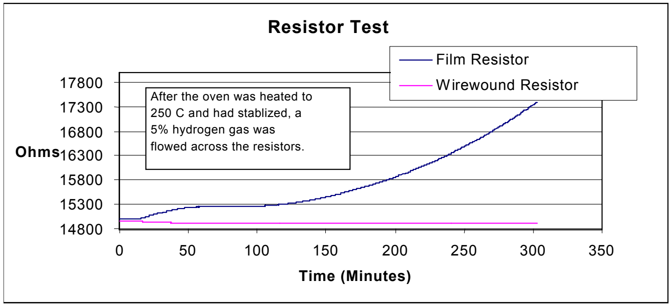
- Most commercial HT tools use automotive or MIL-SPEC components and heat shields
- High temperature SOI devices provide limited analog and digital capability up to 300°C
- SiC power devices and GaN RF devices offer additional functionality at temperatures exceeding 300°C
- Barriers to adoption
  - Cost
  - Component selection
  - Packaging
  - Everything else (solder, sensors, seals, cables…)

275°C Amplifier

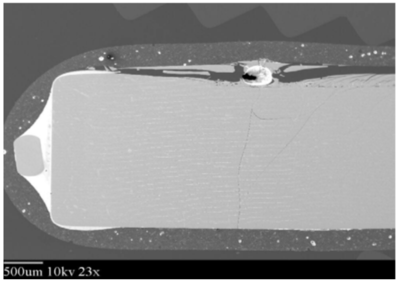
Passive Components

- Wirewound resistors are typically used at high temperature
  - Become large as values increase
  - Coatings can degrade over time
- Metal film resistors can be susceptible to the downhole environment
- Only ceramic capacitors can be used above 225°C
  - Values are low for stable dielectrics
  - Fail shorted
- Currie Temperature becomes and issue for magnetic components as operating temperatures increase



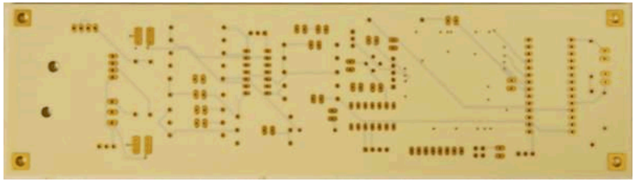


After the oven was heated to 250 C and had stablized, a 5% hydrogen gas was flowed across the resistors.



Packaging and Circuit Substrates

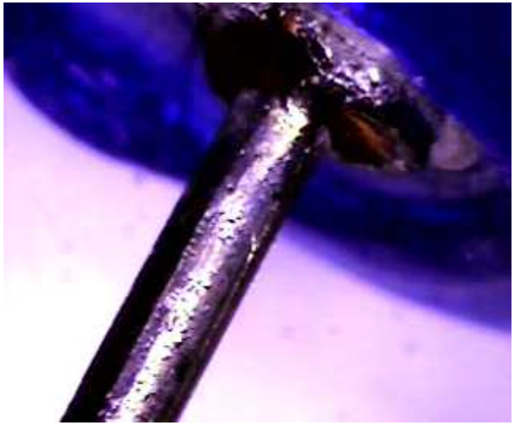
- Polyimide boards begin to fail above 250°C
- Ceramic boards show promise for applications above 300°C, but are difficult to manufacture for large aspect ratio boards (ex. 18” X 1”)
- Small multi-chip modules show promise for HT packaging
  - Die attach CTE mismatch must be solved for a wide range of systems
    - Die – Si, SiC, GaN
    - Substrate - Al_2O_3, AlN, Si_3N_4
  - Die bond pads must be matched to bond wire to avoid issues with intermetallic formation and Kirkendall voiding

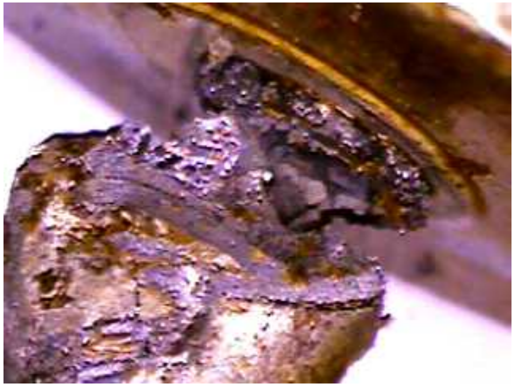


Hybrid Circuit in Metal Package (courtesy Quartzdyne, Salt Lake City, UT)

Solder and Wire

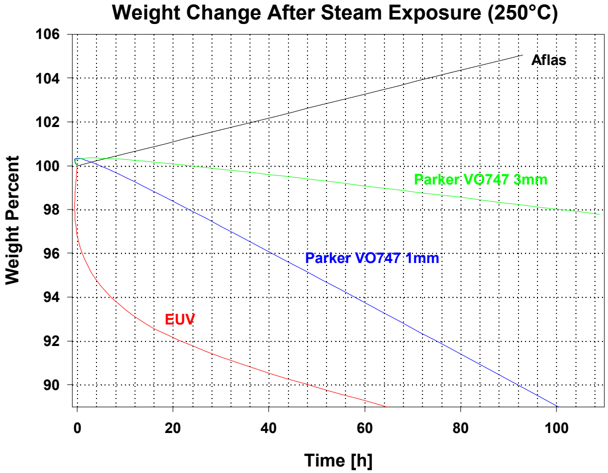
- Most HT solder alloys consist of high concentrations of Pb with either Sn or In
- High temperatures increase intermetallic growth rate
  - Cu-Sn, Au-Sn, Au-In
  - Leads to brittle failures and voiding
- AuSn solder can help, but is expensive and difficult to work with
- HT electronics assembly requires specialized tools





Seals and Insulation

- Polymers typically fail quickly in geothermal environments
  - Temperature, pressure, corrosive chemicals
- Seals are typically changed after a single HT logging run
- Insulation and encapsulants cannot be replaced easily
- Example materials:
  - Teflon
  - Kalrez
  - PEEK
  - Kapton



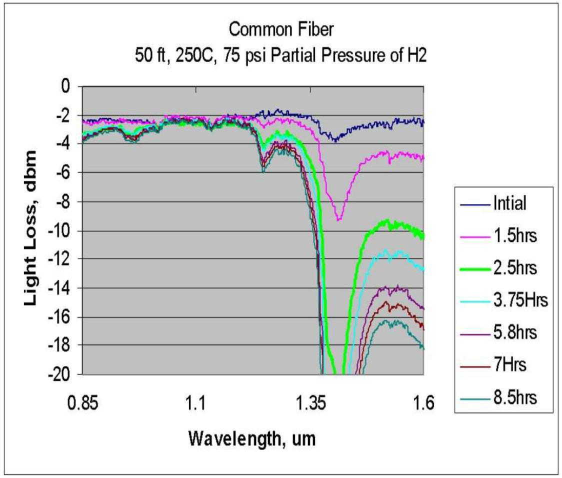
Sensors

- Pressure and temperature sensors are available up to 300°C
- Some accelerometers can function up to 275°C, but geophones are limited to ~200°C
- GM tubes and NaI crystals are limited to ~200°C
  - PM tubes available for 175°C
  - No commercial high temperature photodetectors

Widebandgap materials may provide a pathway to new high temperature sensor designs

Fiber Optics

- H_2 darkening is a major cause of fiber optic sensor failure in geothermal wells
- Fiber embrittlement is also an issue
- Pure silica core fiber and hermetic carbon coatings help at lower temps, but still fail at 300°C
- H_2 scavenging gels can be used, but also only buy a little more time



Special HT Considerations for MWD/LWD and Drilling Tools

- Downhole power for MWD/LWD systems is typically provided by mud driven generators and batteries
  - Batteries are not readily available between 200°C and 300°C
  - Supercapacitors may provide a solution
- Elastomeric seals in downhole motors begin to fail above 177°C
- Bearings in rollercone bits can fail at temperature
- Shock and vibration mitigation becomes difficult due to lack of reliable elastomers

Thoughts for Discussion

- Understand what kind of wells will be needed for EGS
  - Well construction, completion, reservoir construction and operations are all interrelated.
- Leverage technologies **and** practices employed by other industries.
  - What can be adopted or adapted to geothermal conditions
- Continue development of enabling technologies and known needs
  - Continue with the obvious

Thoughts - Understanding Needs

- Well field design
  - Number of wells (Injectors/producers)
  - Hole orientation
  - Extended reach directional drilling (“horizontal”)
  - Multilaterals?
- Casing design
  - Cost reduction strategies
  - Identify tool/supply deficiencies
  - Optimize cementing practices
- Completions definition
  - What approach is needed to meet EGS needs and what is the state of the technology?
  - Should consider reservoir creation strategy, stimulation applications, production applications, intervention applications

Thoughts - Leveraging from Others

- Woo larger and similar industry service providers
  - O&G is obvious
  - Mining has similar mindset (lower margin)
- Adopt capabilities where possible
  - Active monitoring of drilling efficiency
  - Bit technologies
- Adapt to fit needs
  - Reverse circulation cementing
  - Expandable casing
- Look at wide bandgap development for power electronics, SSL and harsh environment sensing

Thoughts - Development Needs

- Enabling Technologies
  - High temperature electronic components for logging and drilling tools
  - HT hard rock directional drilling tools
  - HT production and intervention tools
  - Improved telemetry (copper and fiber)
  - HT pumps
  - HT smart completions
  - HT H_2 tolerant fiber
- Known needs
  - Increase daily footage (not instantaneous ROP)
  - Leaner casing designs / new casing materials
  - Reduce tripping time
  - HT tools
  - Zonal Isolation

Application of Site Investigation to the West Flank of Coso FORGE Site

https://www.osti.gov/servlets/purl/1455367/

5. GEOTHERMAL ENERGY RECOVERY AND CONVERSION

5. GEOTHERMAL ENERGY RECOVERY AND CONVERSION

1. **Hydrothermal**
2. SedHeat
3. EGS
4. Direct Use
5. Ground Source Heat Pumps
6. Thermal Storage

9_1 Geothermal - Hydrothermal

Recap:

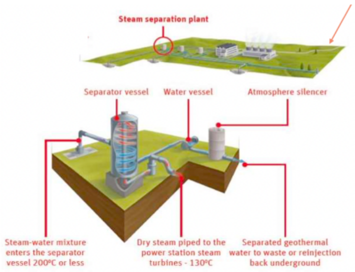
1. Geothermal Resource Characterizations by:
    a. Environment/Geological Habit
    b. Geophysics
    c. Drilling - for exploration and production
2. Designed to reduce risk of projects - drilling is one of the most significant costs

Movies*:* (IGA): https://www.youtube.com/watch?v=ZjtmFfBTBBg
(Indonesia): https://www.youtube.com/watch?v=WBpjzBg1nRw

Resources: WG10

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
How is hot water/steam recovered. And once recovered - used to generate power?

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Hydrothermal

1. Plant layout
2. Recovery from wells
3. Friction losses in wellbores
4. Thermodynamics of energy conversion
    A. Single-flash production
    B. Double-flash production
    C. Binary production

Introduction

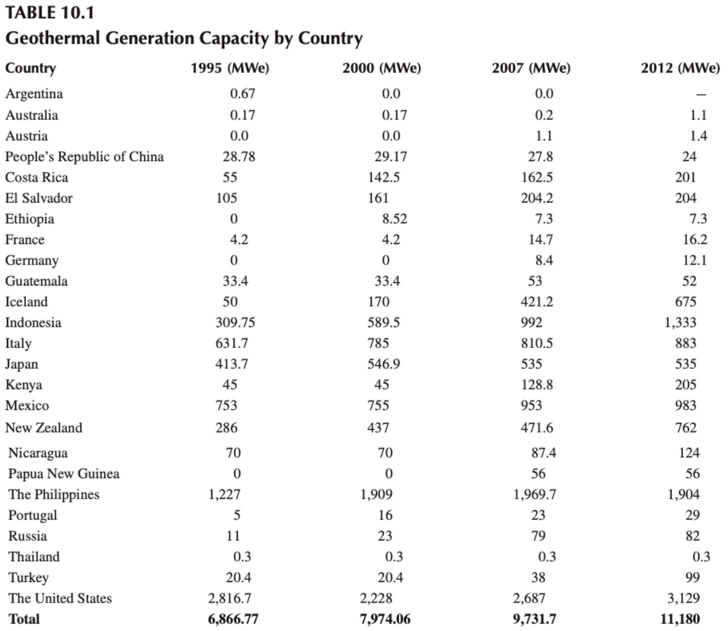
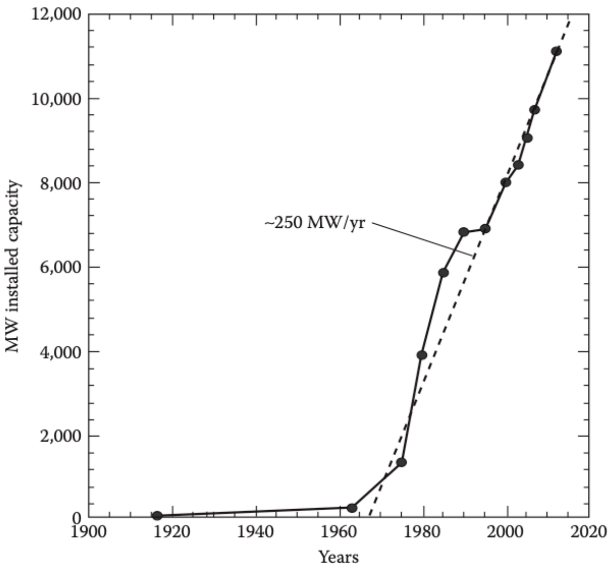
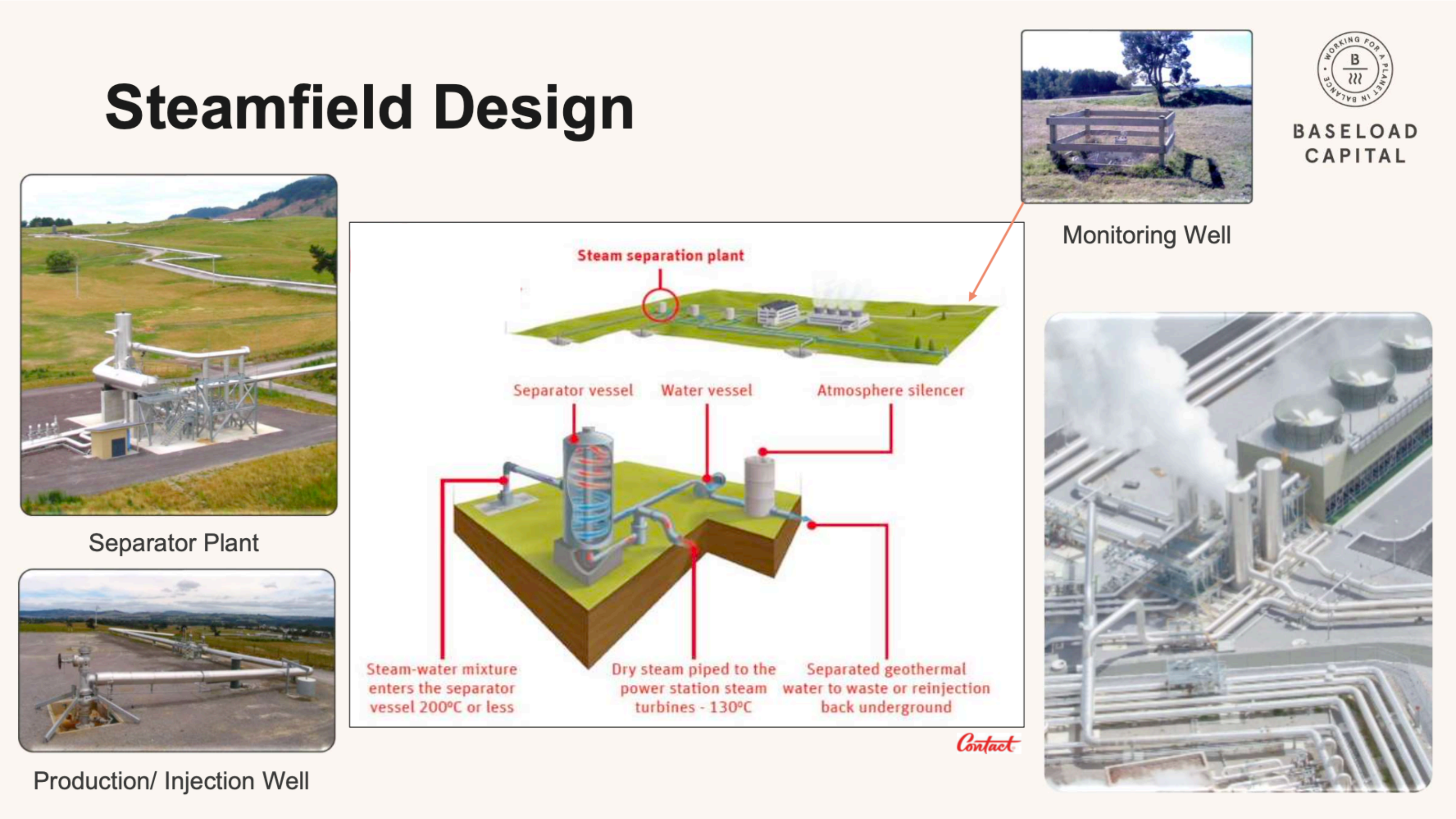


TABLE 10.1
Geothermal Generation Capacity by Country

Country	1995 (MWe)	2000 (MWe)	2007 (MWe)	2012 (MWe)
Argentina	0.67	0.0	0.0	–
Australia	0.17	0.17	0.2	1.1
Austria	0.0	0.0	1.1	1.4
People's Republic of China	28.78	29.17	27.8	24
Costa Rica	55	142.5	162.5	201
El Salvador	105	161	204.2	204
Ethiopia	0	8.52	7.3	7.3
France	4.2	4.2	14.7	16.2
Germany	0	0	8.4	12.1
Guatemala	33.4	33.4	53	52
Iceland	50	170	421.2	675
Indonesia	309.75	589.5	992	1,333
Italy	631.7	785	810.5	883
Japan	413.7	546.9	535	535
Kenya	45	45	128.8	205
Mexico	753	755	953	983
New Zealand	286	437	471.6	762
Nicaragua	70	70	87.4	124
Papua New Guinea	0	0	56	56
The Philippines	1,227	1,909	1,969.7	1,904
Portugal	5	16	23	29
Russia	11	23	79	82
Thailand	0.3	0.3	0.3	0.3
Turkey	20.4	20.4	38	99
The United States	2,816.7	2,228	2,687	3,129
Total	**6,866.77**	**7,974.06**	**9,731.7**	**11,180**



1. Plant Layout



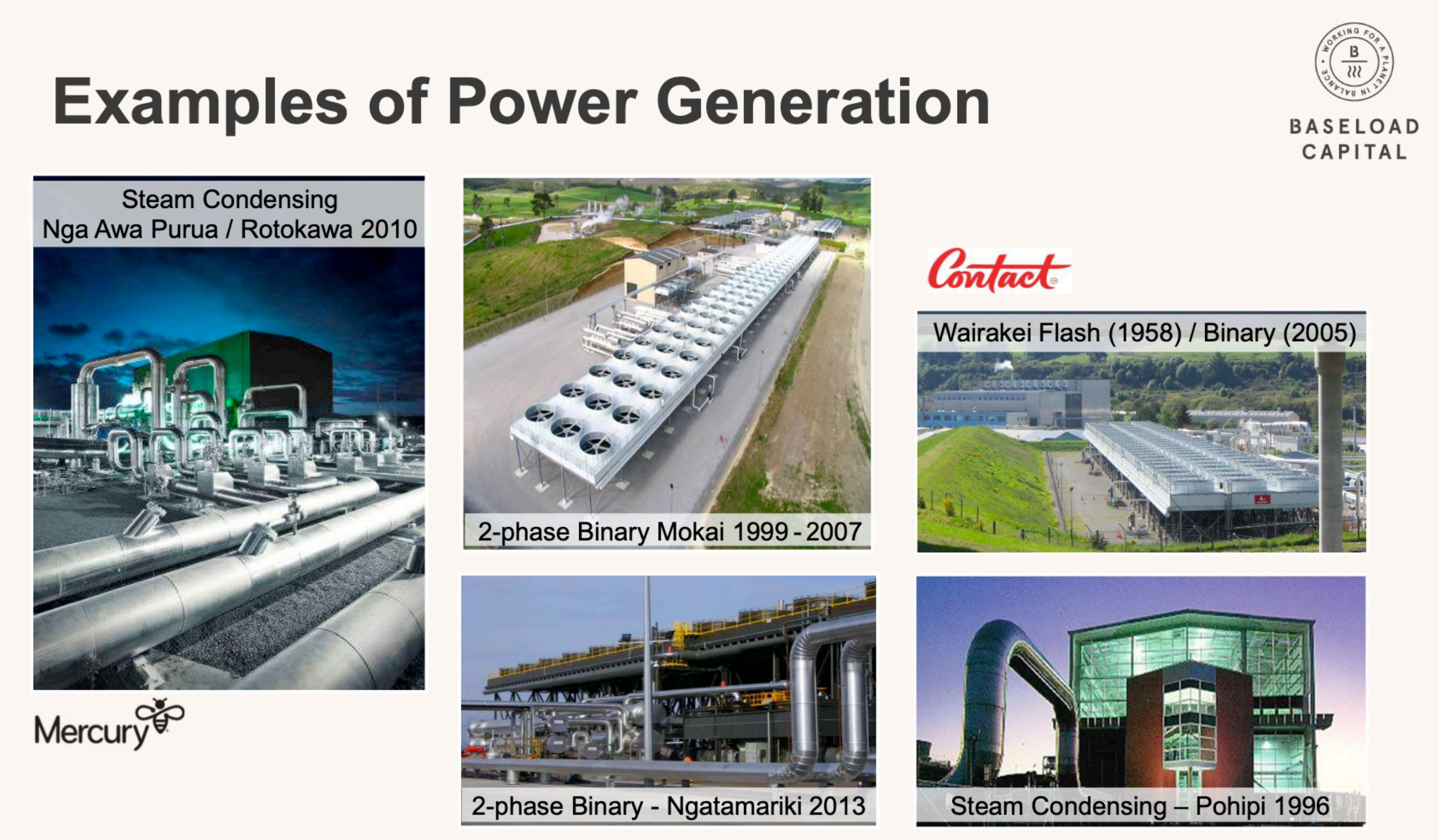
Steamfield Design

BASELOAD CAPITAL

Separator Plant

Production/ Injection Well

Monitoring Well



Examples of Power Generation

BASELOAD CAPITAL

Steam Condensing
Nga Awa Purua / Rotokawa 2010

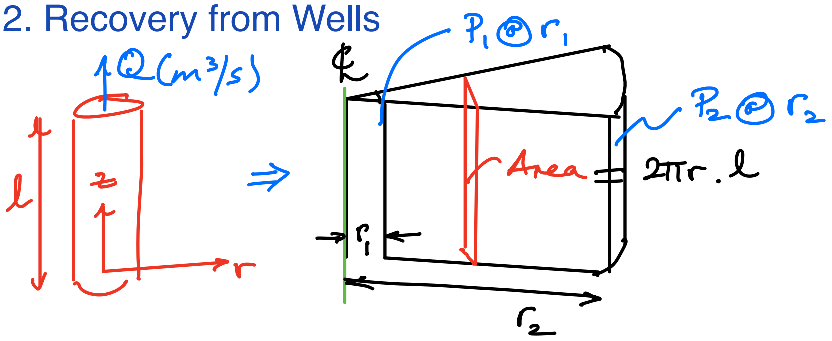
2-phase Binary Mokai 1999 - 2007

Wairakei Flash (1958) / Binary (2005)

2-phase Binary - Ngatamariki 2013

Steam Condensing – Pohipi 1996

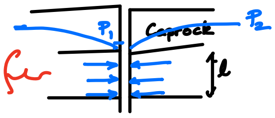
2. Recovery from Wells



Darcy's law: $q = -\frac{k}{\mu}\frac{dp}{dr}$

Area = $2\pi r . l$

Assumed radial flow – confined aquifer



$$Q = A . q = 2\pi r l . \times \frac{k}{\mu}\frac{dp}{dr}$$

$$Q\int_{r_1}^{r_2}\frac{dr}{r} = 2\pi l . \frac{k}{\mu} . \int_{P_1}^{P_2} dp$$

$$Q(\ln r_2 - \ln r_1) = 2\pi l . \frac{k}{\mu}(P_2 - P_1)$$

$$\boxed{Q = 2\pi l \frac{k}{\mu}\frac{(P_2 - P_1)}{\ln(r_2/r_1)}}$$

Choose some numbers:

Hydrothermal – $k \sim 10^{-15}\ m^2$ (mD)

μ @ 200°c $\sim 10^{-4}$ Pa.s

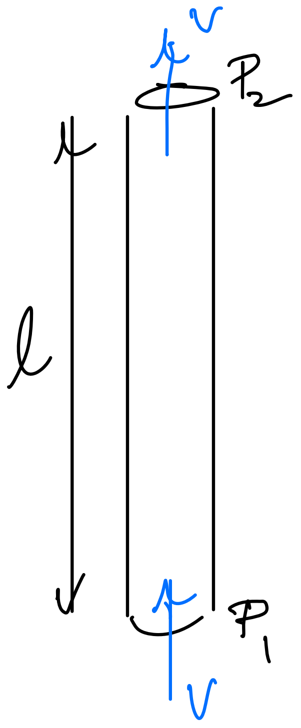
$l \sim 1000\ m$

$\Delta P_{max} \sim$ depth to base of caprock $\times\ \gamma_{water}$

$r_2 \sim$ well spacing/2

$r_1 \sim 0.1\ m$ = 4" radius.

3. Friction losses in wellbores



$$V = \frac{Q}{A}$$

$$l = (z_2 - z_1)$$

$$\frac{P_1}{\gamma} + z_1 + \cancel{\frac{v^2}{2g}} + h_p = \frac{P_2}{\gamma} + z_2 + \cancel{\frac{v^2}{2g}} + \sum h_L$$

$$\frac{(P_1 - P_2)}{\gamma} + (z_1 - z_2) + h_p = \sum h_L$$

$$h_p = \frac{W}{g\underbrace{\boxed{\rho Q}}_{\dot{m}}} \; ; \qquad h_L = f \cdot \frac{l}{D} \cdot \frac{v^2}{2g}$$

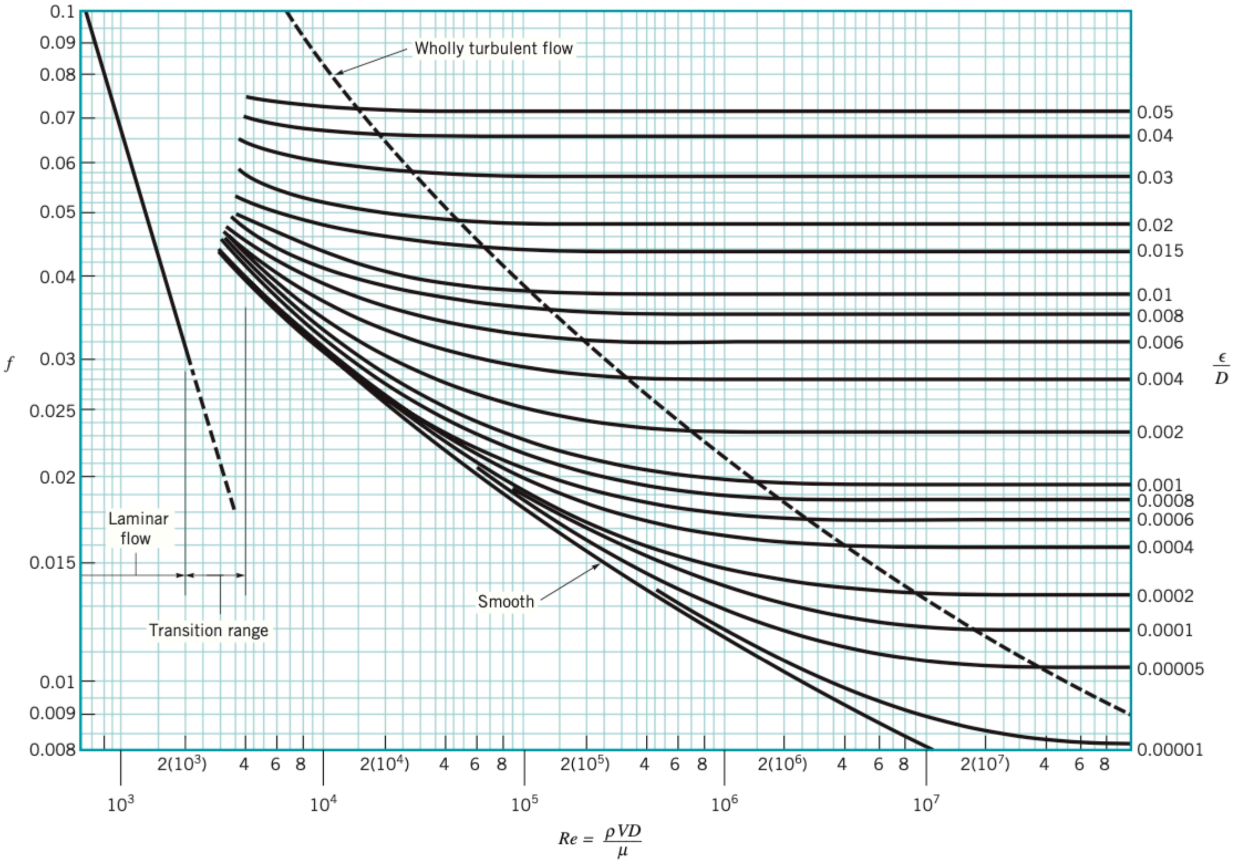
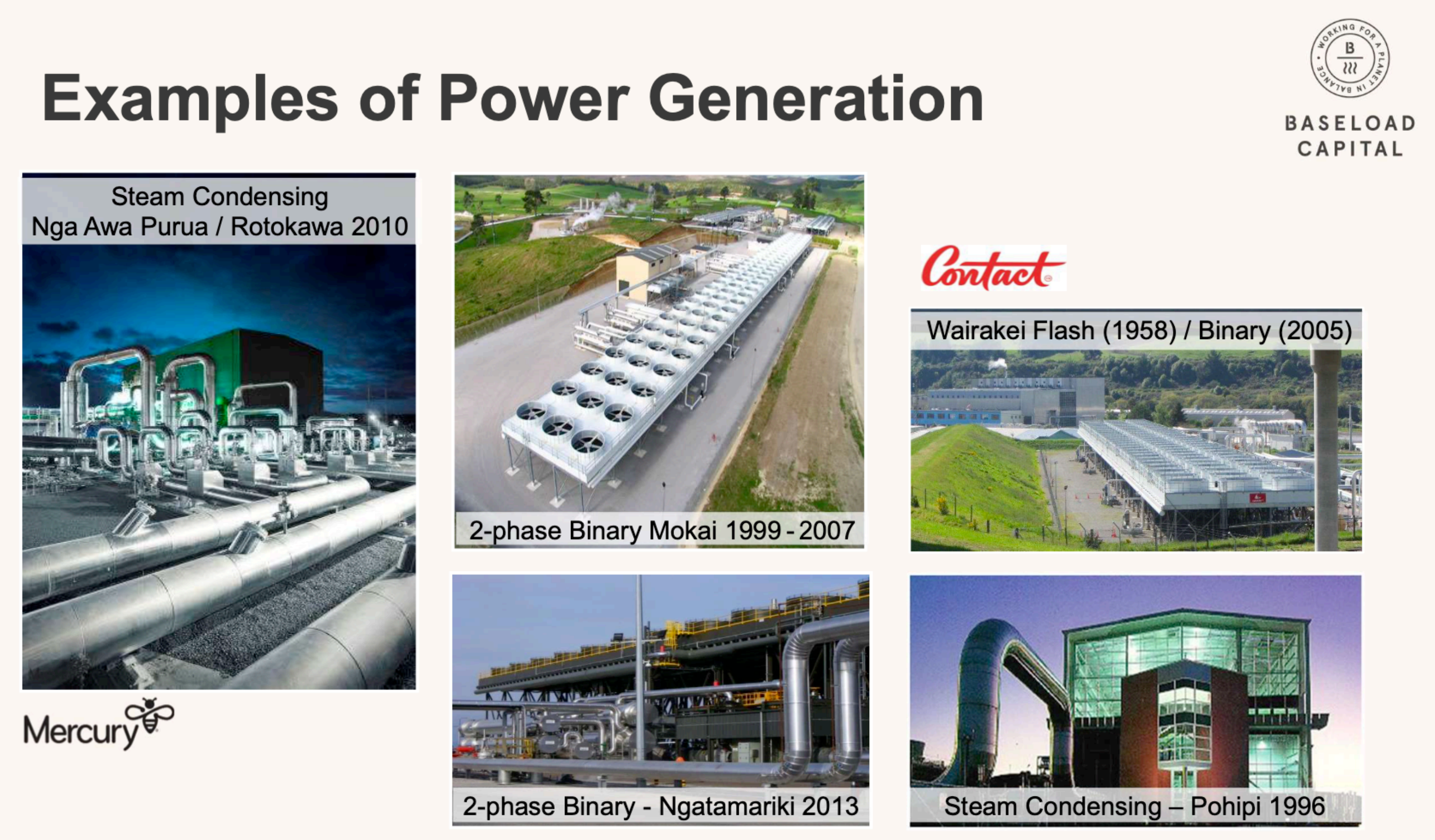


FIGURE 8.20 Friction factor as a function of Reynolds number and relative roughness for round pipes—the Moody chart. (Data from Ref. 7 with permission.)



Examples of Power Generation

BASELOAD CAPITAL

Steam Condensing
Nga Awa Purua / Rotokawa 2010

Mercury

2-phase Binary Mokai 1999 - 2007

Contact

Wairakei Flash (1958) / Binary (2005)

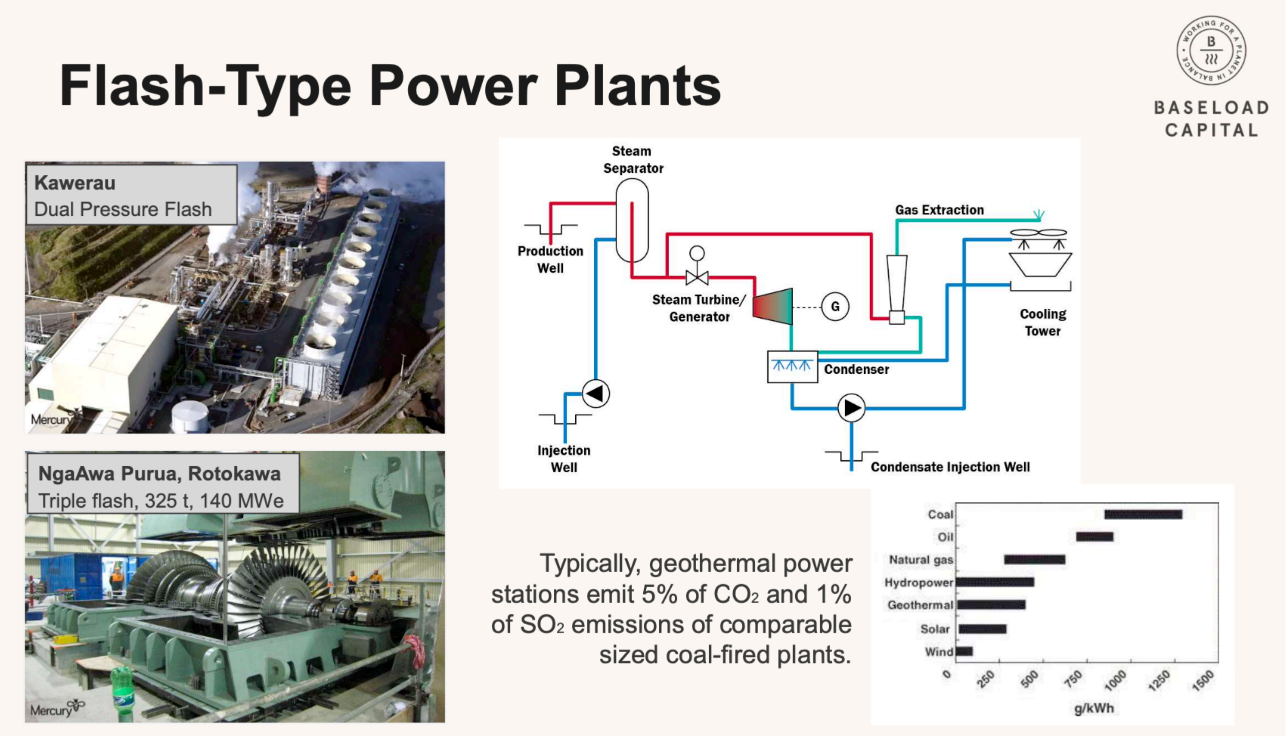
2-phase Binary - Ngatamariki 2013

Steam Condensing – Pohipi 1996

IN GENERAL

$$P_{electrical} = \underbrace{Eff_{generator}}_{\sim 0.90 \text{ Kinetic} \rightarrow \text{Electrical}} \times \overbrace{Eff_{turbine}}^{f(0.85;\ \text{steam content})} \times P_{thermal}$$

A. Single-flash production



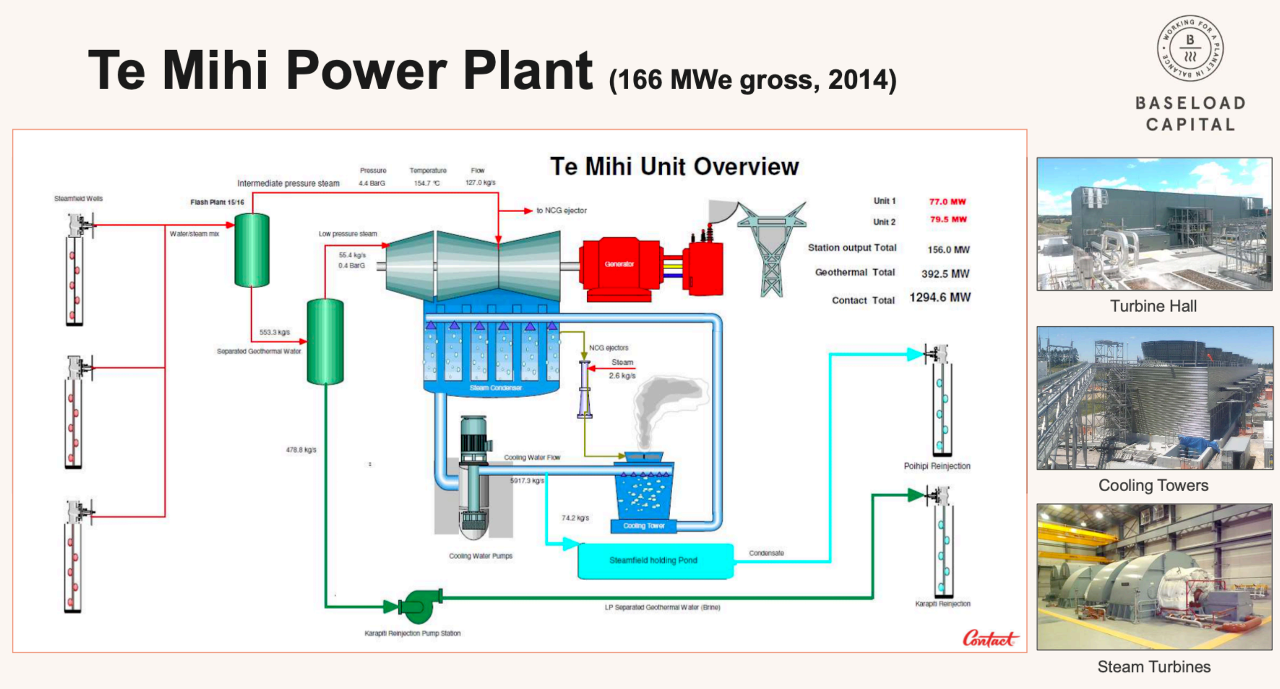
Flash-Type Power Plants

BASELOAD CAPITAL

Kawerau
Dual Pressure Flash

NgaAwa Purua, Rotokawa
Triple flash, 325 t, 140 MWe

Typically, geothermal power stations emit 5% of CO_2 and 1% of SO_2 emissions of comparable sized coal-fired plants.



Te Mihi Power Plant (166 MWe gross, 2014)

BASELOAD CAPITAL

Te Mihi Unit Overview

Unit 1	77.0 MW
Unit 2	79.5 MW
Station output Total	156.0 MW
Geothermal Total	392.5 MW
Contact Total	1294.6 MW

Turbine Hall

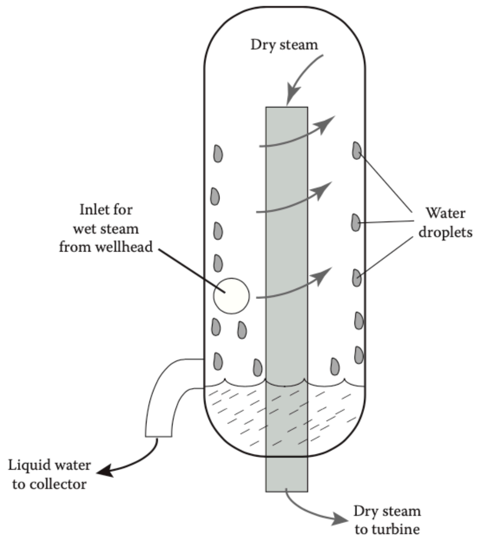
Cooling Towers

Steam Turbines

Physics of energy conversion

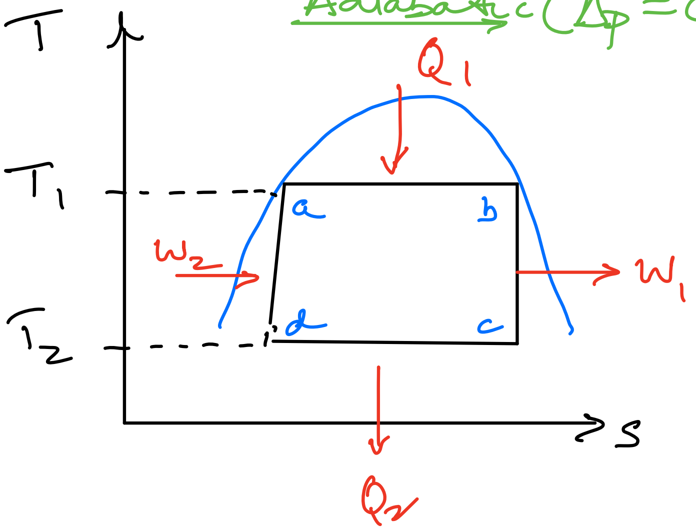
Turbine: $Eff_{turbin} \sim 0.85 \times \left(\frac{1+X_s}{2}\right)$

X_s = steam fraction: $\frac{100\% \rightarrow 1.0 ✓}{0\% \rightarrow 0.0}$



CARNOT CYCLE

Adiabatic ($\Delta p = 0$; $\Delta T = 0$)



Isentropic

($\Delta s = 0$)

① $$\boxed{\eta_c = 1 - \frac{T_2}{T_1}}$$

② $\underline{Q + W = \Delta h}$ $\begin{cases} Q = h_b - h_a & (W=0) \\ W = h_b - h_c & (Q=0) \end{cases}$

③

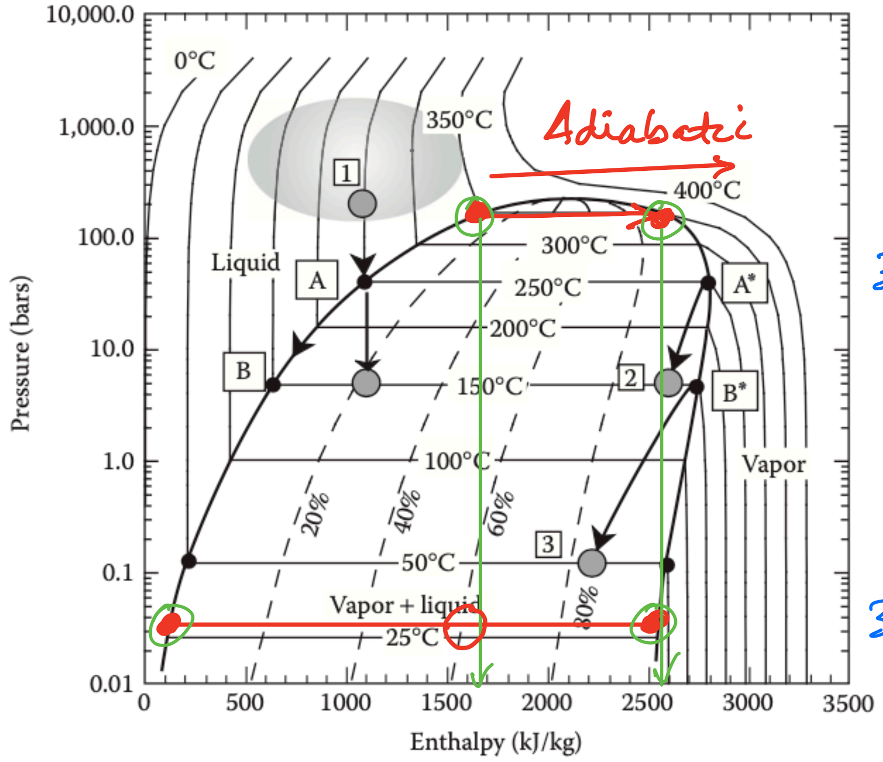
$$h = (1-x)\, h_l + x\, h_g$$

$$s = (1-x)\, s_l + x\, s_g$$

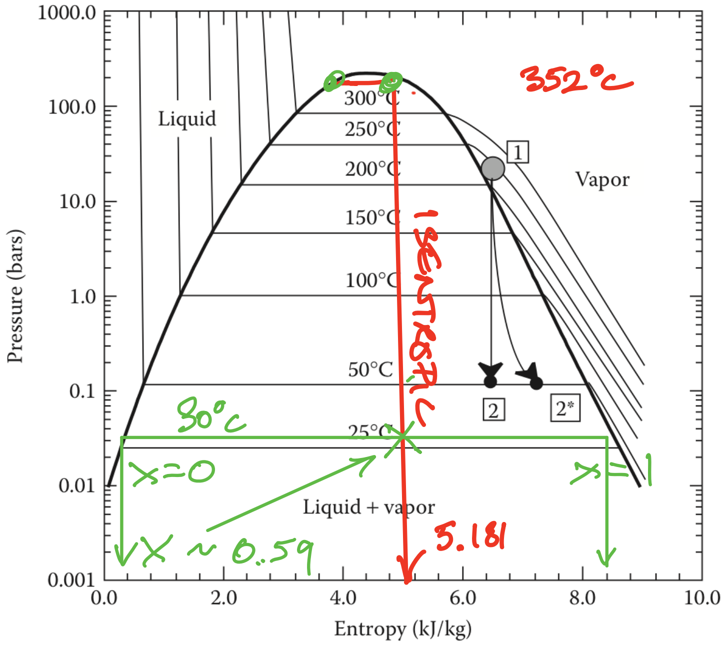
CONSIDER: Reservoir ⓑ: $T = 352°c$, $p = 170$ bar

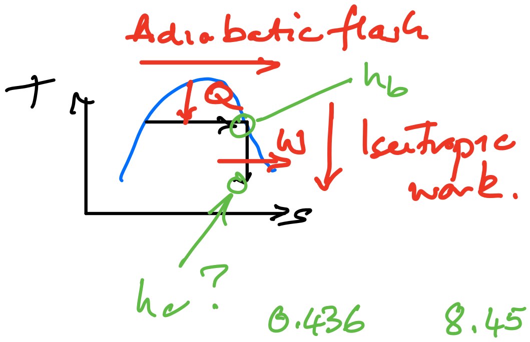
Discharge ⓒ: $T = 30°c$; $p = 0.04$ b

$$\eta_c = 1 - \frac{273+30}{273+352} \cong 0.52$$



T	h_ℓ (kJ/kg)	h_g (kJ/kg)
352°c	1690	2548 $= h_b$
30°c	126	2556





$$s_c = (1-x)\, s_\ell + x\, s_g$$

5.181 0.436 8.452

?

$$\boxed{x \sim 0.59}$$

$$\therefore\ h_c = (1-x)\, h_\ell + x\, h_g$$

$$\boxed{h_c \sim 1560 \text{ kJ/kg}}$$

$$W = h_b - h_c = 2548 - 1560 \simeq 988 \text{ kJ/kg.}$$

EFFICIENCY CONSTRAINTS

$$\text{POWER}_{\text{ELEC}} = \eta_{\text{generator}} \times \eta_{\text{turbine}} \times \text{POWER}_{\text{THERM}}$$

$$\eta_{\text{TURBINE}} \simeq 0.85 \times \left(\frac{1+\cancelto{0.59}{X}}{2}\right)$$

$$\simeq 0.85 \times 0.8 = 0.68 \sim \underline{\underline{0.7}}$$

$$\eta_{\text{GENERATOR}} \sim 90-100\%.$$

Viable well for payback is 100 kg/s.

100 kg/s $\quad$ 352°C → 30°C

$$\text{POWER}_{\text{THERMAL}} = 988\ \text{kJ/kg} \times 100\ \text{kg/s}$$

$$= 100{,}000\ \text{kJ/s}$$

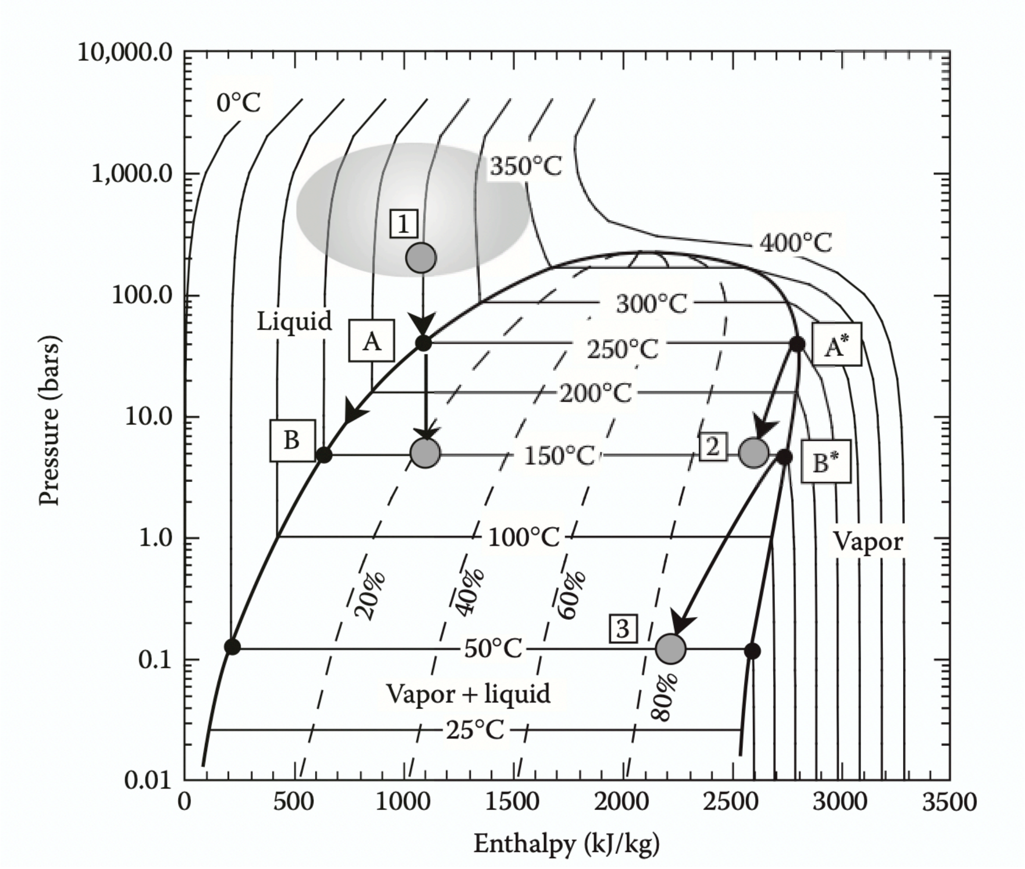
$$= 100\ \text{MW}_{\text{TERMAL}}$$

@ 60% efficiency → 60 MW.

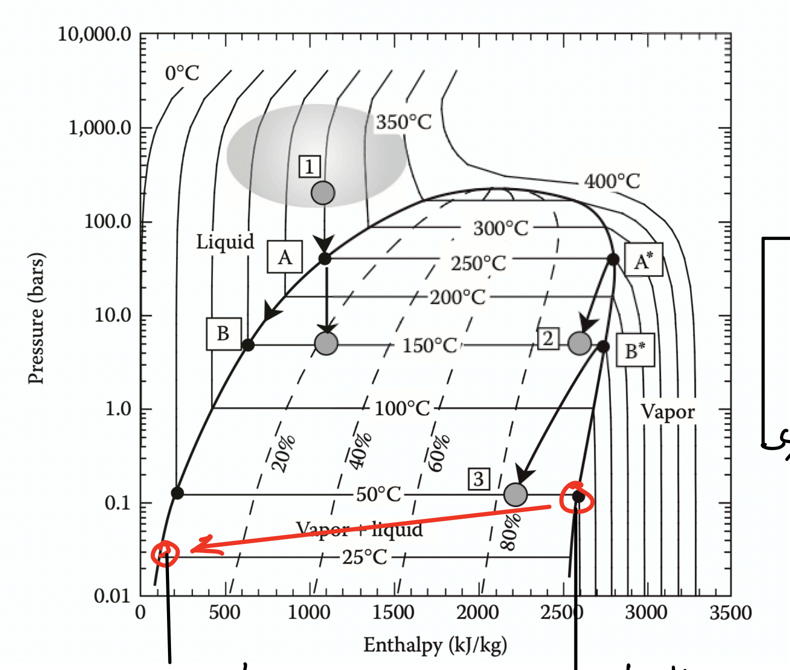
Possible ΔT → 30°C is higher than expected.

∴ track along $X \simeq 60\%$ steam @ higher $T_c \uparrow$

B. Dual-flash plants



Condensing water for reinjection



105 kJ/kg

2592 kJ/kg

2592 − 105 ~ 2487.

Turbin exit 50°c

Cool to 25°c

$\Delta H_{inj} = \dot{M}_{inj} \times 2487 \, kJ/kg$

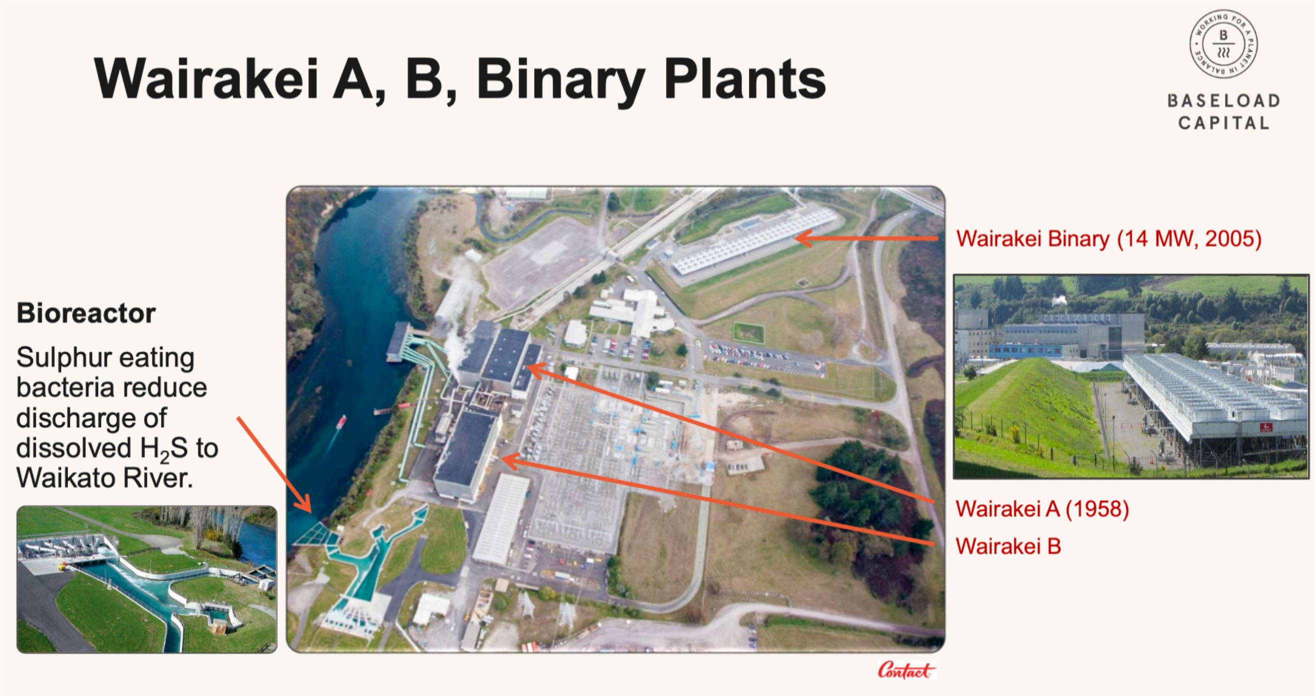
$\Delta H_{condt} = \dot{M}_c \, c \, \Delta T$

?

4.2 kJ/kg.K

25°c

C. Binary plants



Wairakei A, B, Binary Plants

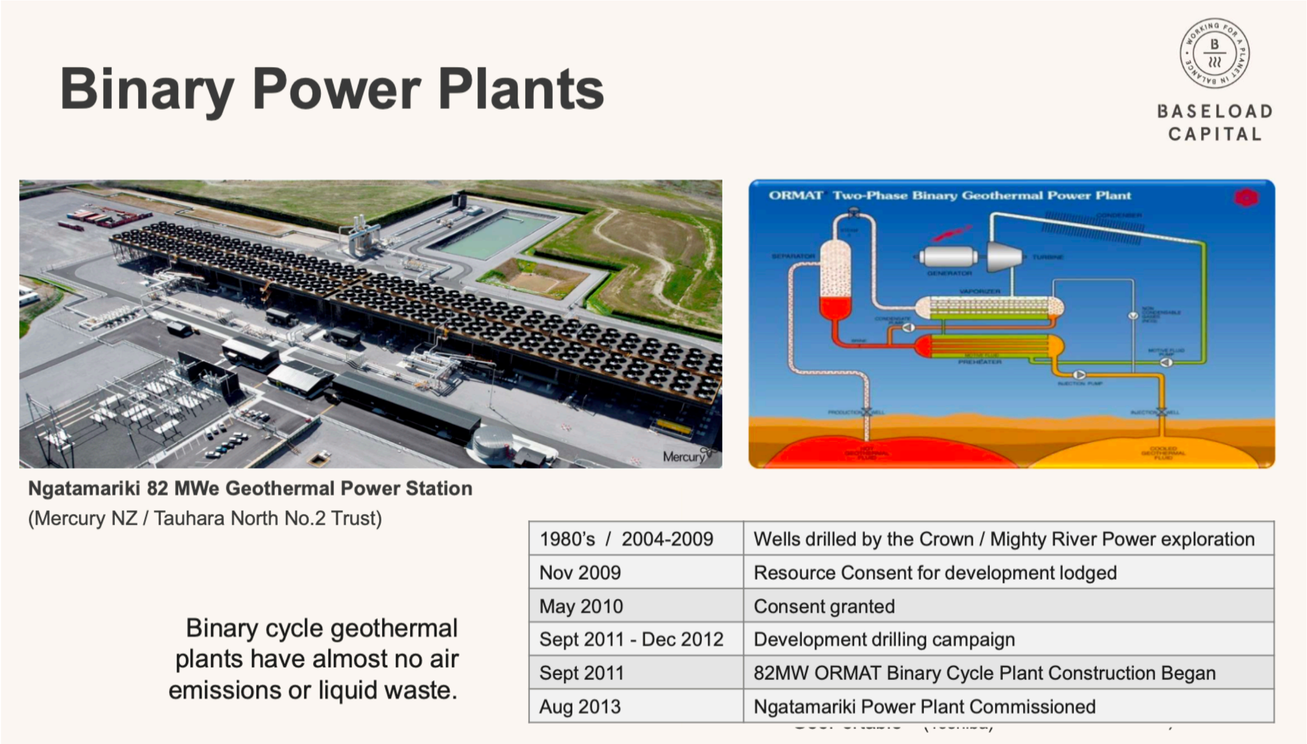
Bioreactor

Sulphur eating bacteria reduce discharge of dissolved H_2S to Waikato River.

Wairakei Binary (14 MW, 2005)

Wairakei A (1958)

Wairakei B

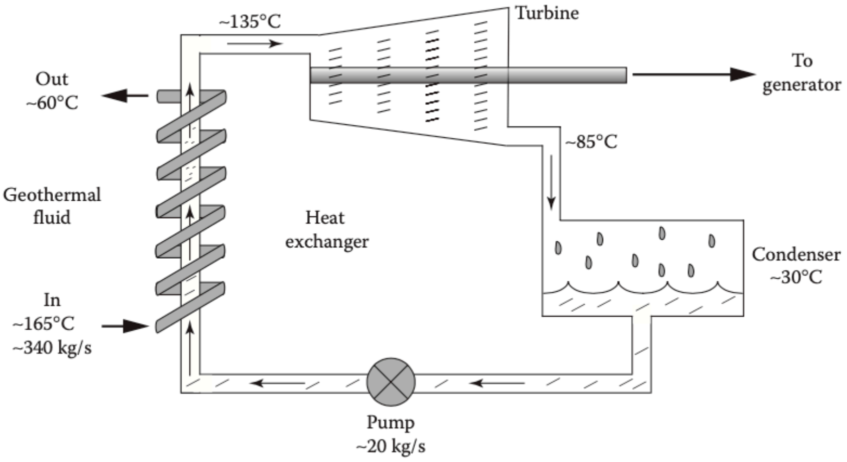


Binary Power Plants

Ngatamariki 82 MWe Geothermal Power Station
(Mercury NZ / Tauhara North No.2 Trust)

Binary cycle geothermal plants have almost no air emissions or liquid waste.

1980's / 2004-2009	Wells drilled by the Crown / Mighty River Power exploration
Nov 2009	Resource Consent for development lodged
May 2010	Consent granted
Sept 2011 - Dec 2012	Development drilling campaign
Sept 2011	82MW ORMAT Binary Cycle Plant Construction Began
Aug 2013	Ngatamariki Power Plant Commissioned



ISOPENTANE FLASH

BP ~ 28°C

C ~ 2.3 kJ/kg.°c

Heat of vap ~ 344 kJ/kg.

∴ Heat input to condense

$$\Delta H = c \dot{M} \Delta T$$

$$= 2.3 \frac{kJ}{kg.K} \cdot 20 \frac{kg}{s} \cdot 50°c$$

~ 2.3 MW @ 100% Effic

5. GEOTHERMAL ENERGY RECOVERY AND CONVERSION

1. Hydrothermal
2. **SedHeat**
3. EGS
4. Direct Use
5. Ground Source Heat Pumps
6. Thermal Storage

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5. Ground Source Heat Pumps
6. Thermal Storage

12_1 Geothermal - Direct Use

Recap:

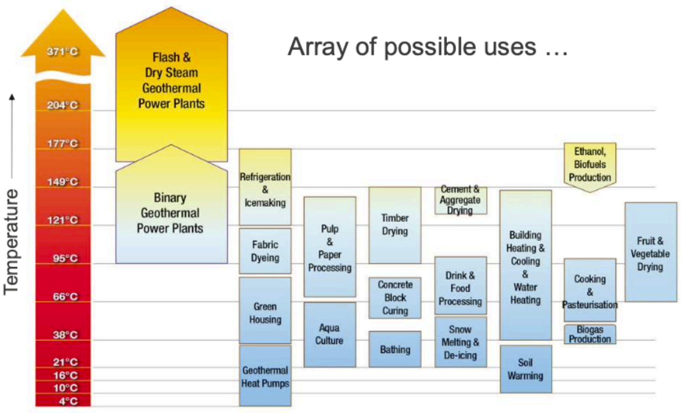
1. EGS challenges:
    a. Creating a low-impedance high-heat-transfer long-lived heat exchanger
    b. Minimizing environmental effects, esp. seismicity

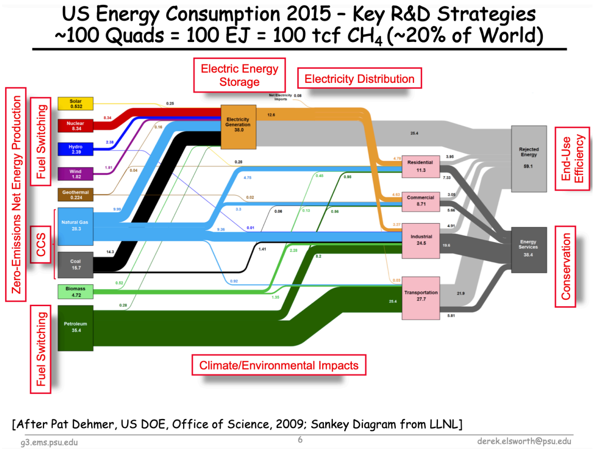
Movies: (Great Lakes SedHeat Network): https://igws.indiana.edu/glsn/speakers
(P. Fulton): https://psu.zoom.us/rec/share/iuFAh64nqxbLUhZH18NtNC49ieLkSzubs4xwjUmmQoLtRhSr63DjdxdVzX9K_uoh.PYzJEaPv1juZxyn0
(Mozoun): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/2_v_alyammahimozoun.mp4
(Brent): https://www.youtube.com/watch?v=6FrNdtsvW9U
(Tim): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/6_v_bruggemantimothy.mp4

Resources: WG12

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?





US Energy Consumption 2015 – Key R&D Strategies
~100 Quads = 100 EJ = 100 tcf CH_4 (~20% of World)

[After Pat Dehmer, US DOE, Office of Science, 2009; Sankey Diagram from LLNL]

g3.ems.psu.edu 6 derek.elsworth@psu.edu

Utilize low quality heat without the penalty of conversion to electricity
Utilize the 50% "rejected power" from the Sankey diagram
Opportunities:
1. Low temperature resource
2. Cascade of successively lower heat uses

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Direct Use

1. What are the "highest" uses at each stage?

5. GEOTHERMAL ENERGY RECOVERY AND CONVERSION

1. Hydrothermal
2. SedHeat
3. EGS
4. Direct Use
5. **Ground Source Heat Pumps**
6. Thermal Storage

13_1 Geothermal - GSHPs

Recap:

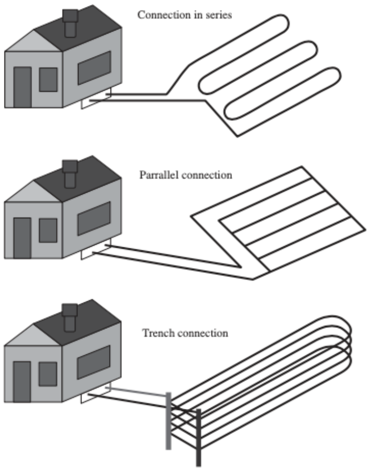
1. Direct Use:
    a. Utilizes low heat/quality resource to fill a significant need
    b. Potentially utilizes the ~50% rejected heat in the Sankey diagram

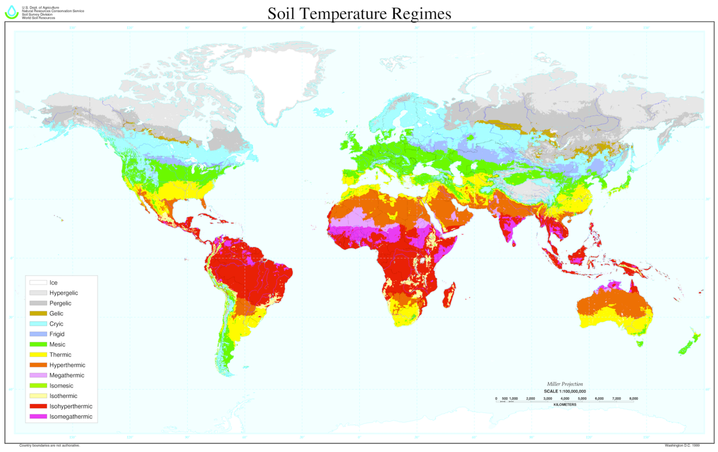
Movies: (Great Lakes SedHeat Network): https://igws.indiana.edu/glsn/speakers
(Jerrod): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/3_v_anthonyjerrod.mp4
(Shreya): https://drive.google.com/file/d/1MuDdfXslJnNfs1g8YcSj5PVVkrDgfZ5v/view

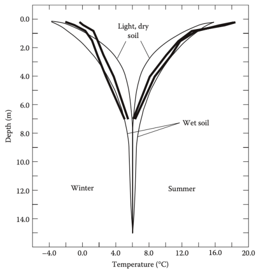
Resources: WG11 & MR 5+6

Motivation:

1. **Motivation [10%]** Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?







Soil Map: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/worldsoils/?cid=nrcs142p2_054019

Utilize low quality heat without the penalty of conversion to electricity
Distributed power opportunity for off-grid and remote use
Broadly geographically available (in US) due to climatic zonations

Scientific Questions:

2. **Scientific Questions to be Answered/Outline [10%]** What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

GSHPs

1. Mechanisms of heat flow in the shallow earth?
2. Mechanism of utilizing low quality heat -> high(er) quality heat?
3. Rate-limiting processes?

1. Mechanisms of heat flow in the shallow earth?

?

TABLE 11.2
Thermal Conductivity (W/m-K) and the Constant Pressure Heat Capacity (C_p [J/mole-K]) of Some Common Materials at 25°C

Material	k_{th}	C_p	Q	m³
Quartz[a]	6.5	44.5	1960	128.5
Alkali feldspar[a]	2.34	203	2000	130
Calcite[a]	2.99	82	2103	120
Kaolinite[a]	0.2	240	2408	105
Water	0.61	75.3	4181	60

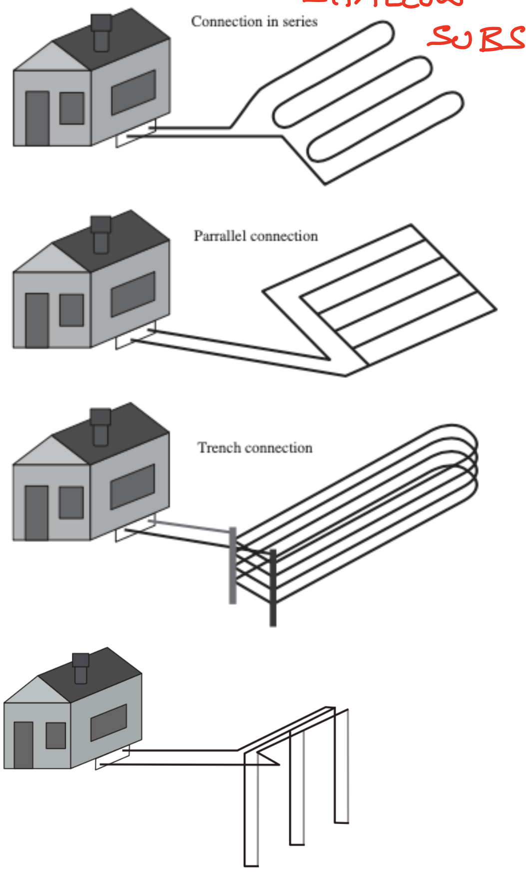
Source: [a] C_p computed from Helgeson, H.C. et al., *American Journal of Science*, 278-A, 229, 1978.

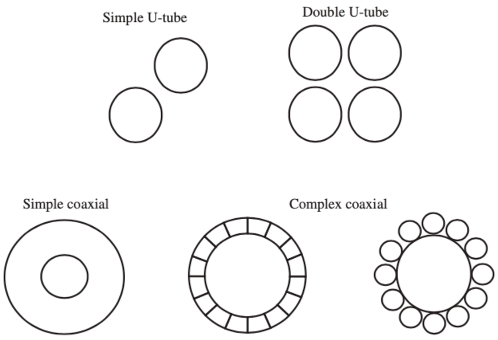
Note: The amount of heat, *Q* (kJ/m³-K), that must be supplied or removed, per cubic meter of material, for 1°C of temperature increase or decrease at about 25°C is shown. The number of cubic meters of each material needed to supply 7 kW of heat is shown in the column m³ (see text for details).

$$Q = \rho C_p \Delta T \forall$$

Note: Use J/kg.K

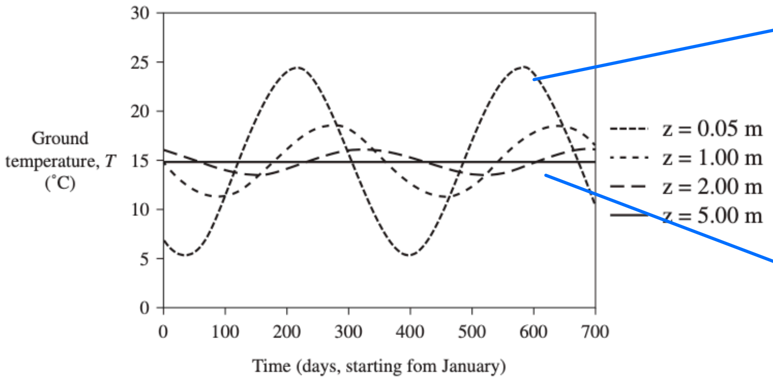
RECOVER HEAT FROM SHALLOW SUBSURFACE

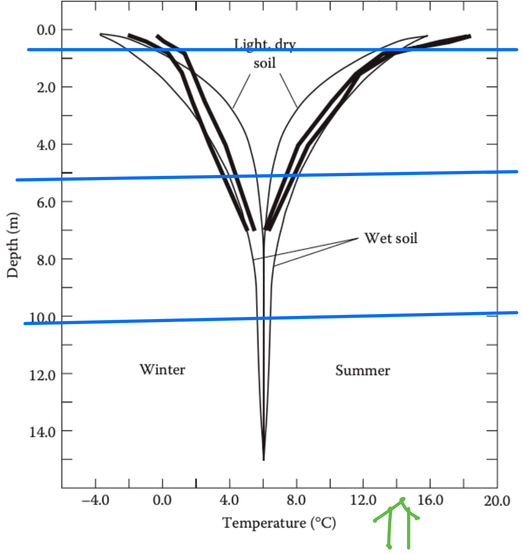




This defines amount of heat supplied but not the RATE.

INSOLATION 200 – 1500 W/m²





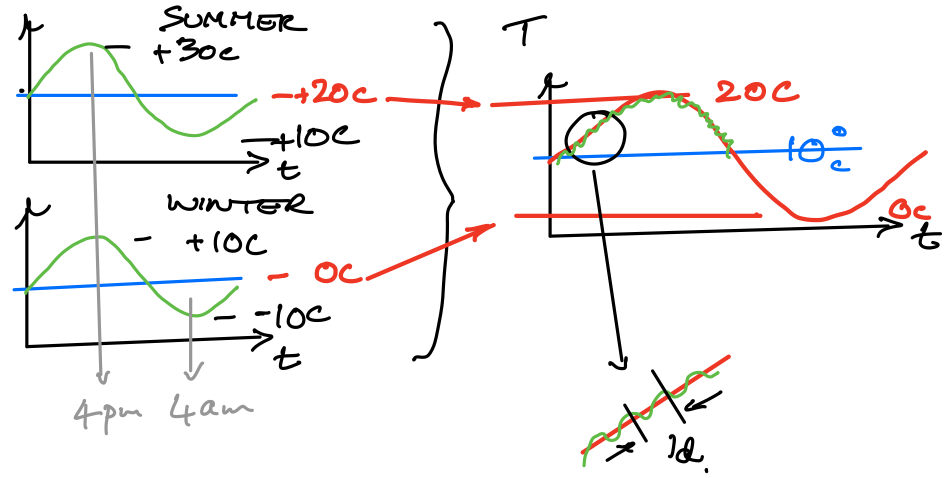
GEOTHERMAL FLUX ≐ 87 mW/m²

TEMPERATURE CHANGES IN SHALLOW SUBSURFACE

$200\ W/m^2 >> 87\ mW/m^2$ ∴ Insolation dominates

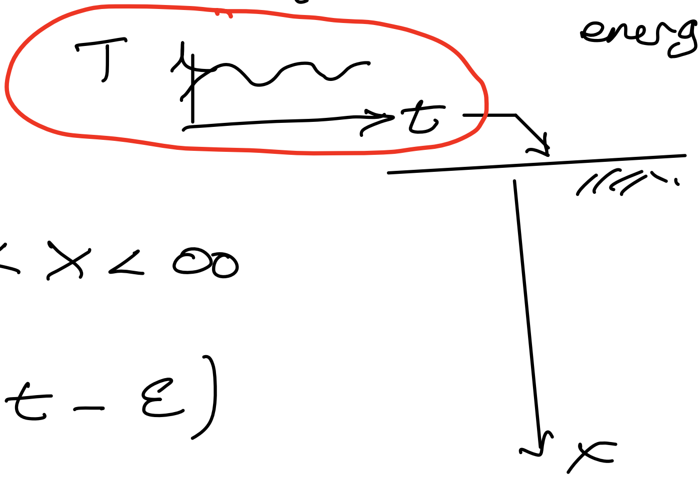
Insolation   Geothermal   – sets deep temperature as average

DIURNAL (AIR)   ANNUAL



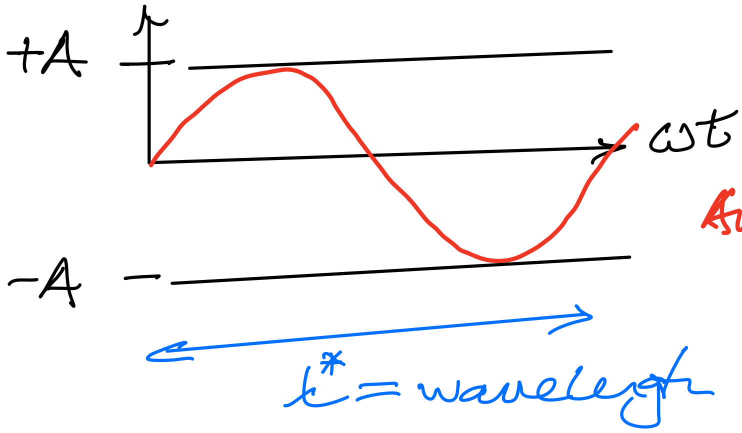
Solve: $\rho c \frac{\partial T}{\partial x} = \lambda \frac{\partial^2 T}{\partial x^2}$

{ 1. Fourier's Law
2. Conservation of energy



ICs: $T = 0 \quad 0 < x < \infty$

BCs: $T = A\cos(\omega t - \varepsilon)$



Amplitude $= A \doteq K$ or C

Ang. Frequency $= \omega \doteq \frac{1}{sec}$

n = frequency $= \frac{\omega}{2\pi}$

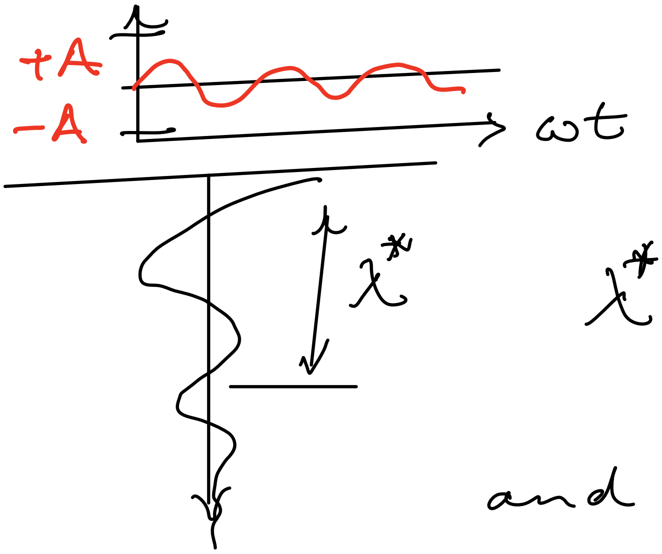
SOLUTION (dynamic steady state)

$$T = A e^{-kx} \cos(\omega t - kx - \varepsilon)$$

with $k = \left(\frac{\omega}{2K}\right)^{1/2}$ = wave number = $\frac{1}{m}$

$K = \frac{\lambda}{\rho c}$ = thermal diffusivity m^2/s

Wavelength (in space not time ωt)



$$\lambda^* = \frac{2\pi}{k} = \frac{4\pi K}{n}$$

and n = frequency = $\frac{\omega}{2\pi}$

Set $kx = 2\pi$ (i.e. one wavelength)

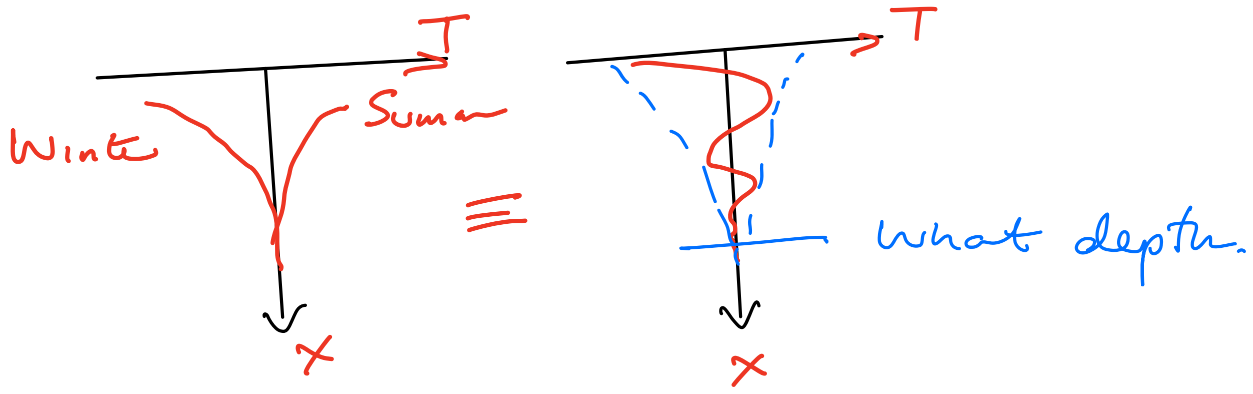
Then $2\pi = kx = \left(\frac{\omega}{2K}\right)^{1/2} x$ & $\boxed{\omega} = 2\pi n$

$$2\pi = \left(\frac{2\pi n}{2K}\right)^{1/2} x$$

or $$x = (2\pi)^{1/2} \cdot \left(\frac{2K}{n}\right)^{1/2}$$

$$x = \left(\frac{4\pi K}{n}\right)^{1/2} = \lambda^{*}$$

Depth for no temperature change



$$T = A e^{-kx} \left(\qquad \right)$$

And $e^{(-2\pi)} \approx 0.0019 \approx 0.002$

$$\simeq 0.2\% \equiv 0$$

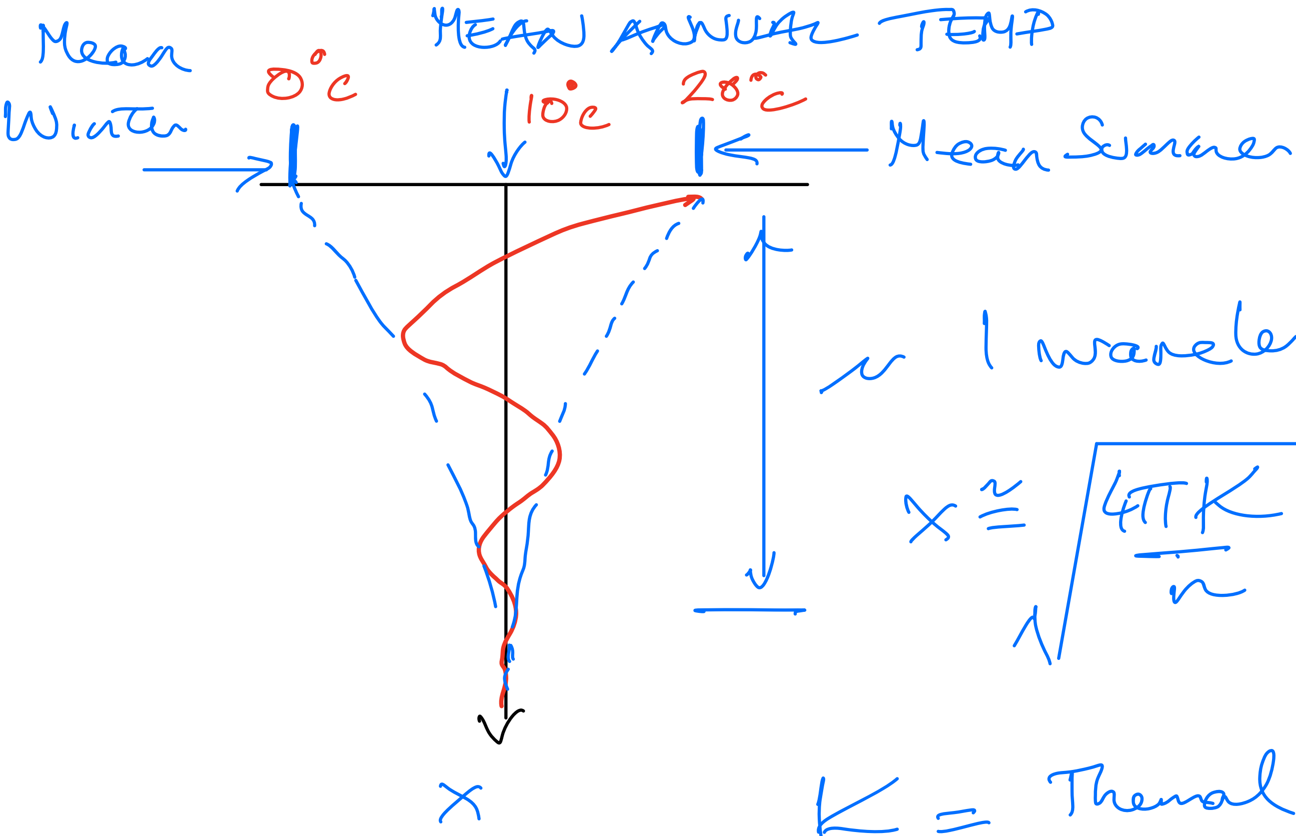
$$-2\pi = -kx \quad \therefore \quad x = \left(\frac{4\pi K}{n}\right)^{1/2}$$

If $K = 30\ m^2/yr.$

Wavelength	Freq
2.7cm	1/min
1m	1/day
20m	1/year

$$\boxed{\left(4\pi\,\frac{30}{1}\right)^{1/2} = \sqrt{360\ m^2/yr\ yr.} \quad \sim \underline{\underline{20\,m}}}$$

TEMPERATURE PROFILES



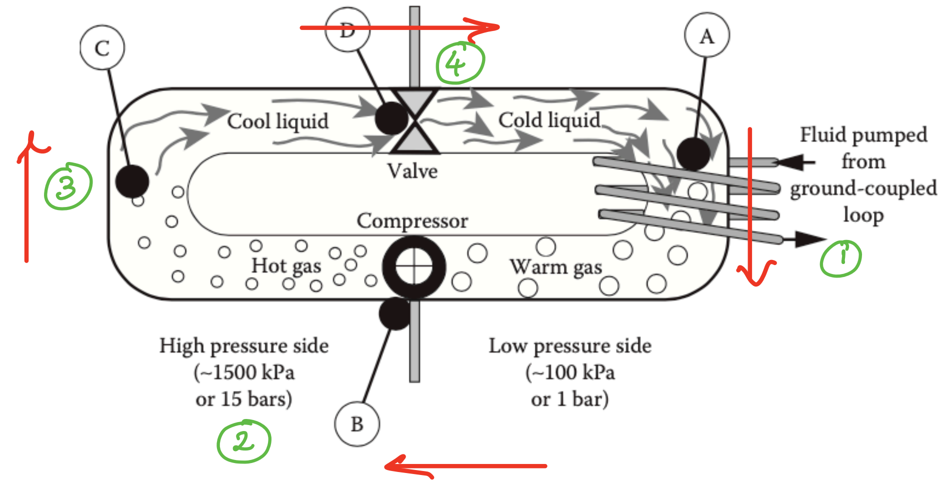
~ 1 wavelength

$$x \simeq \sqrt{\frac{4\pi K}{n}}$$

$$K = \frac{\text{Thermal cond}}{\rho c}$$

2. Mechanisms of utilizing low quality heat -> high(er) quality heat?

THERMODYNAMICS OF HEAT PUMPS



COIL FROM GROUND

ΔT ~ ±10°C

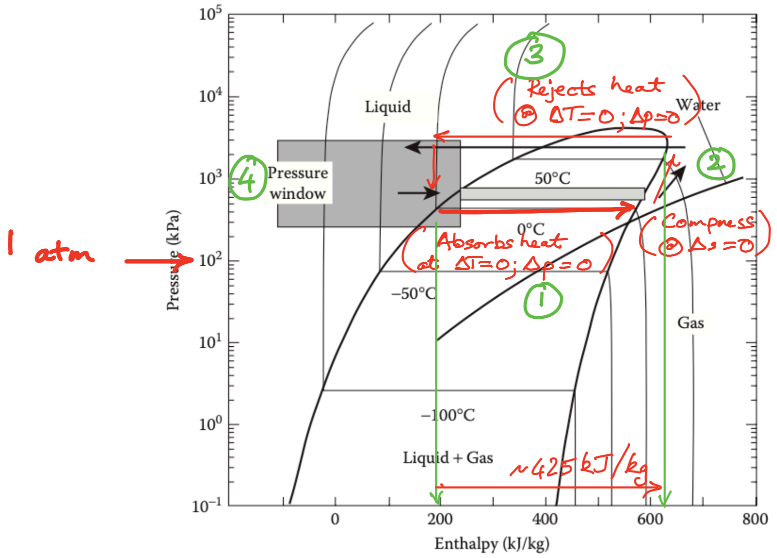
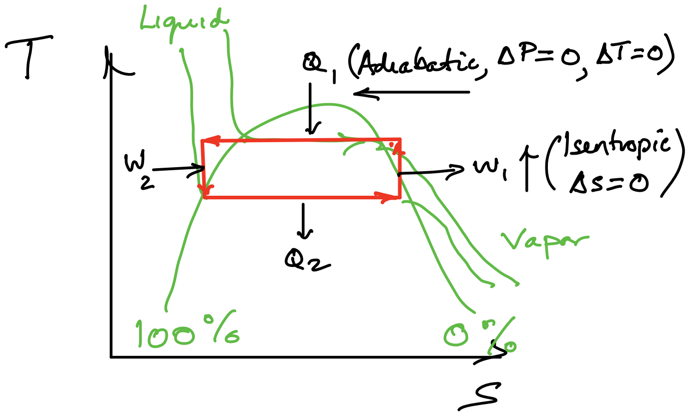


FIGURE 11.4 Enthalpy–pressure diagram for propane showing the two-phase liquid–gas region. For reference, the low-temperature limb of the liquid boundary for the water system is also shown (see Figure 3.8 for details of the water system).



CARNOT CYCLE – Same as deep geothermal.

PRINCIPLE – Heat gained leg ① >> Energy of compression leg ②

Allows +ΔH in leg ① (from ground – low quality)

└→ Rejected to building leg ③

└→ @ energy cost of Δp in ②

TUNE 2-PHASE FLUID ⟶ 0 – 50°C BP

or for PA, 0 – 20°C or ~10°C.

i.e. Capable of liquid → vapor @ 10°C

and ② p > atm

FOR PROPANE $\Delta H \sim 425$ kJ/kg (of propane)

Geothermal water $C = 4.18$ kJ/kg.K.

TABLE 11.1
Thermodynamic Properties of Some Compounds Potentially Useful as Refrigerants

Name	Formula	Molecular Weight (g/mol)	Density (kg/m³)	Melting Temperature (°C)	Boiling Temperature (°C)	Heat of Vaporization (kJ/kg)	Constant Pressure Heat Capacity (kJ/kg-K)
R134a	$H_2FC\text{-}CF_3$	102.03	1206	−101	−26.6	215.9	0.853
Propane	C_3H_8	44.096	582	−187.7	−42.1	425.31	1.701
Isopentane	C_5H_{12}	72.15	626	−160	28	344.4	2.288

EFFICIENCY: For 1 kg of geothermal water/s and a 1.5 kW compressor

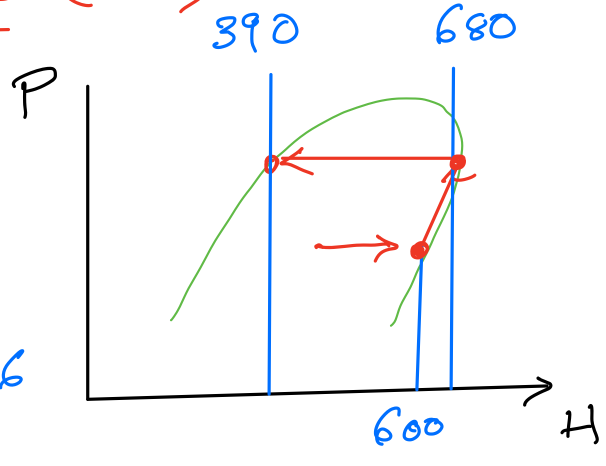
$$\frac{E_{total}}{E_{consumed}} = \frac{4180\ \text{J/s} + 0.8 \times 1500\ \text{J/s}}{1500\ \text{J/s}}$$

$$\sim 3.6$$

COEFFICIENT OF PERFORMANCE (COP)

$$COP = \frac{\text{Delivered heat}}{\text{Comp. elec. demand}}$$

$$= \frac{680 - 390\ \text{kJ/kg}}{680 - 600\ \text{kJ/kg}} \doteq 3.6$$



Note - assumes 100% efficeny of compressor (not 0.8).

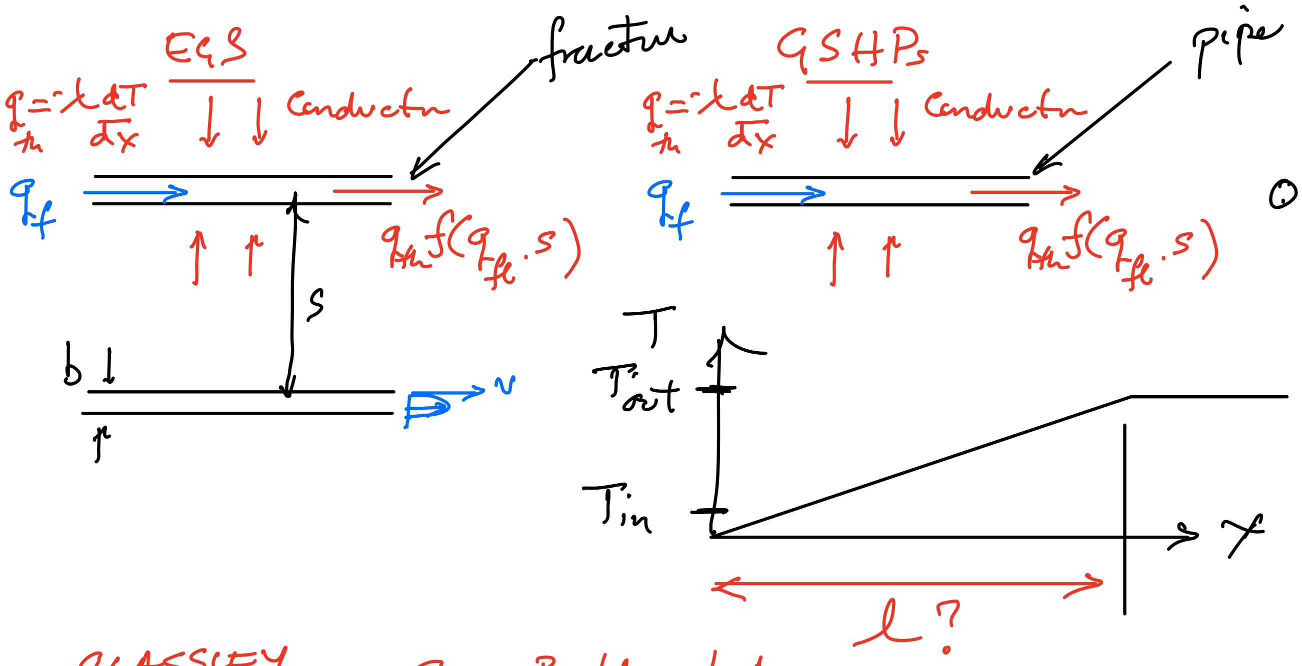
GSHPs

1. Mechanisms of heat flow in the shallow earth?
2. Mechanism of utilizing low quality heat -> high(er) quality heat?
3. Rate-limiting processes?

HEAT FLOW IN GEOTHERMAL (WATER) SYSTEM.

Similar to EGS — Rate limited

Engineered — Engineered (constructed).



GLASSLEY

C_H = Building heating load ~ 12kW (not elec load of 1kW).

Heating loop:

$$L_H(\mathrm{m}) = \frac{\{(C_H) \times [(\mathrm{COP}-1)/\mathrm{COP}] \times [R_P + (R_S \times F_H)]\}}{(T_L - T_{\min})} \tag{11.4}$$

For a cooling loop, the corresponding equation is

Energy Efficiency Ratio ≡ COP cooling

$$L_C(\mathrm{m}) = \frac{\{(C_C) \times [(\mathrm{EER}+3.412)/\mathrm{EER}] \times [R_P + (R_S \times F_C)]\}}{(T_{\max} - T_H)} \tag{11.5}$$

where:

- R_P is the resistance to heat flow of the pipe (which is equivalent to 1/thermal conductivity of the pipe)
- R_S is the resistance to heat flow of the soil (which is equivalent to 1/thermal conductivity of the soil)
- F_H (F_C) is the fraction of time the heating (cooling) system will be operating
- T_L (T_H) is the minimum (maximum) soil temperature at the depth of installation
- $T_{\min}$ ($T_{\max}$) is the minimum (maximum) fluid temperature for the selected heat pump

Check units:

$$CoP \doteq -$$

$$T \doteq K$$

$$R \doteq 1/(W/(m.K)) \doteq \frac{m.K}{W}$$

$$L_H(m) \doteq \frac{\cancel{W}(-) \times m\cancel{K}/\cancel{W}}{\cancel{K}} \doteq m \checkmark$$

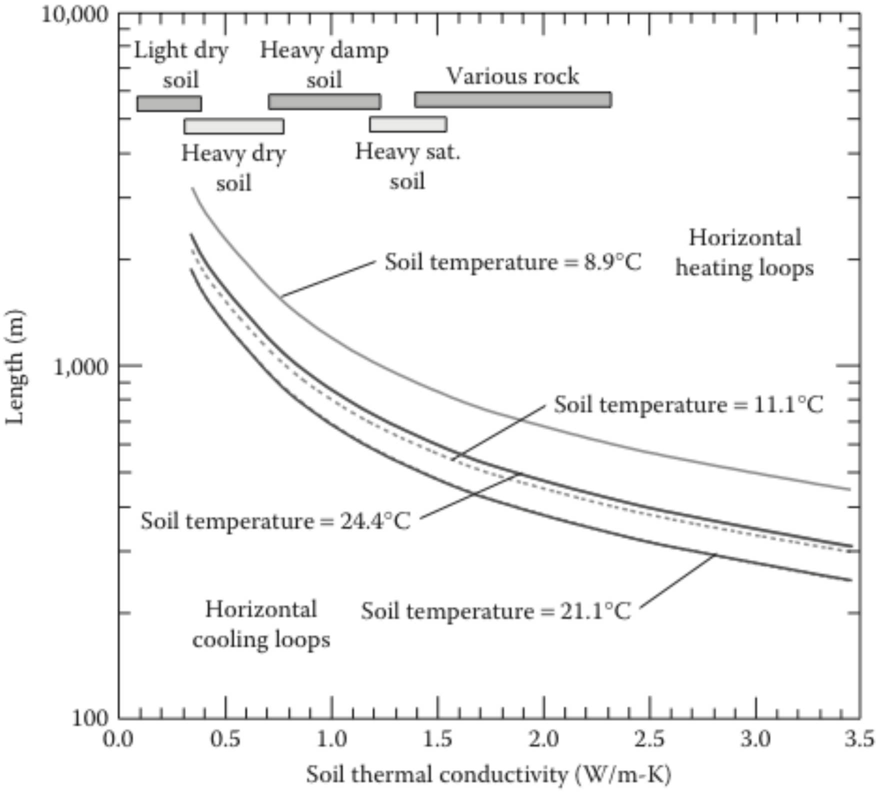
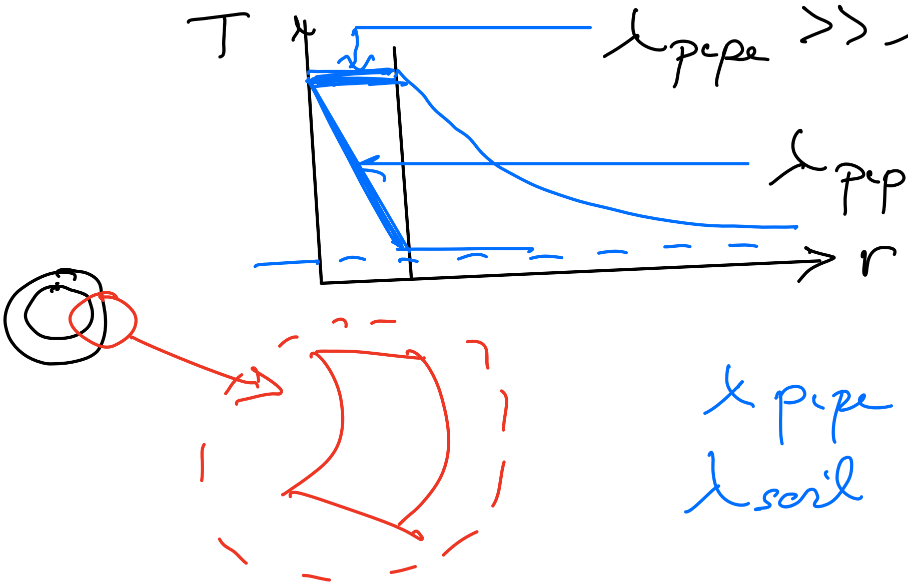


FIGURE 11.7 Computed loop length for heating and cooling, closed-loop GHP systems. In these calculations, it was assumed that the COP of the heat pump was 3.24 and the EER was 7.8. Pipe thermal conductivity was assumed to be 14.8 W/m-K, the heating and cooling run time fractions were 0.5 and 0.6, respectively, and the heat pump fluid T_{max} and T_{min} were 37.8°C and 4.4°C, respectively. For reference, the range of thermal conductivities for light, dry soil (Light dry soil); heavy, dry soil (Heavy dry soil); heavy, damp soil (Heavy damp soil); heavy, saturated soil (Heavy sat. soil); and crystalline rocks (Various rock) are also shown.

Suggests a length of ~ 1000m !!

RATIONAL BASIS FOR DESIGN



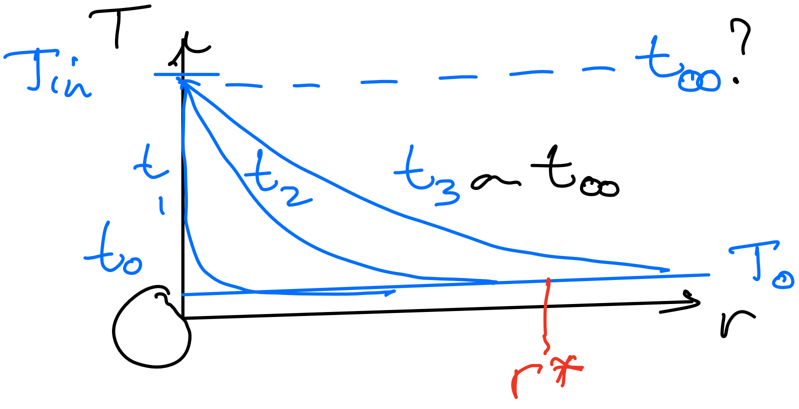
$\lambda_{pipe} >> \lambda_{soil}$ ✓

$\lambda_{pipe} << \lambda_{soil}$ ✗

$\lambda_{pipe} \sim 15\ W/mK$ ✓

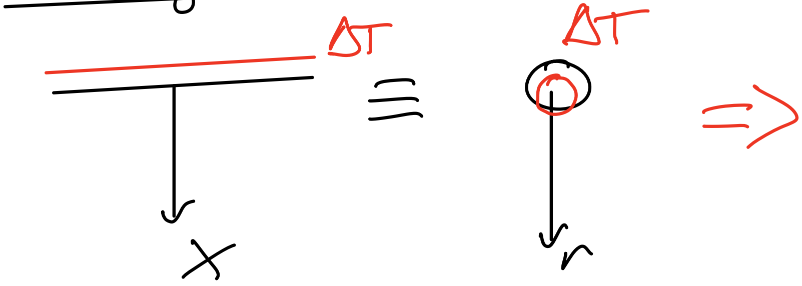
$\lambda_{soil} \sim 1\ W/mK.$

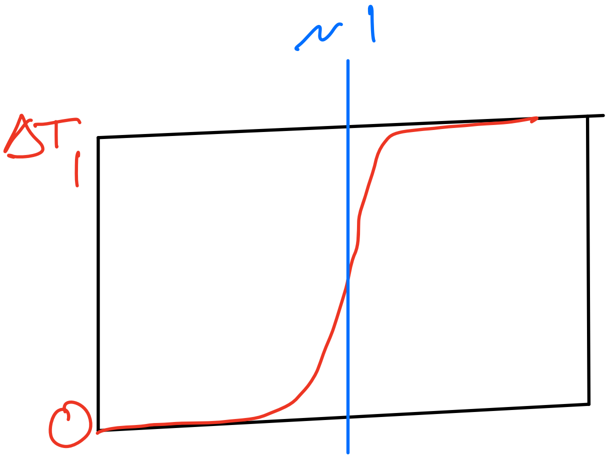
STEADY STATE OF TRANSIENT BEHAVIOR?



(to first order)

Analogous to :





$$t_D = \frac{Kt}{r^{*2}}$$

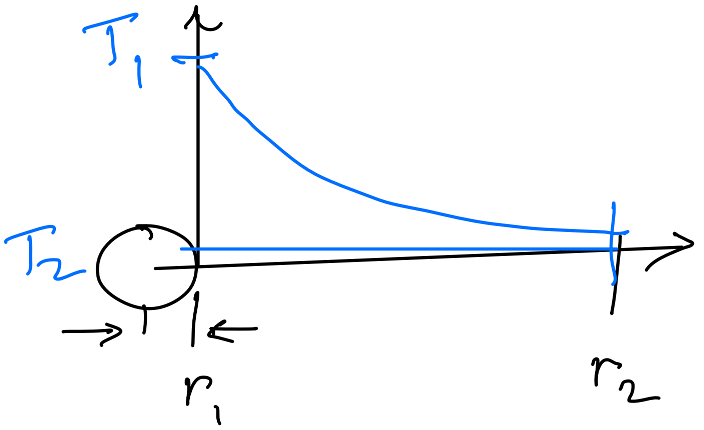
STEADY HEAT FLOW AROUND PIPE

1. What does it look like
2. What is heat flux to pipe?
3. How long does it take (more than $\frac{1}{2}$ y?)

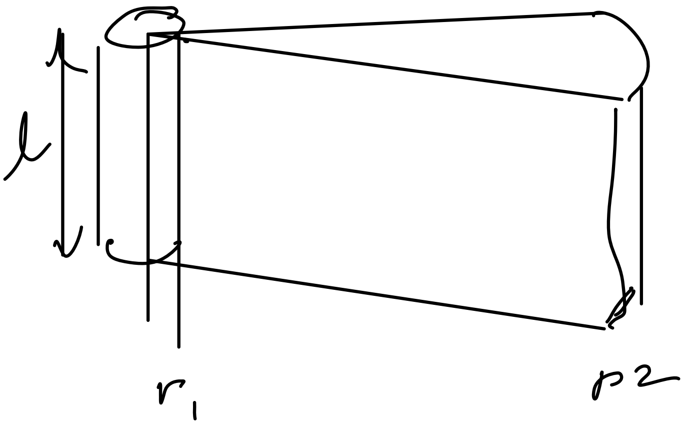
Same as water flow to well

Darcy's Law $q = -K\frac{dh}{dr}$ or $-\frac{k}{\mu}\frac{dp}{dr}$

Fourier's Law $q = -\lambda\frac{dT}{dr}$.



$$Q_f = 2\pi l \frac{k}{\mu}\frac{(P_2-P_1)}{\ln(r_2/r_1)}$$



$$Q_h = 2\pi l \lambda\frac{(T_2-T_1)}{\ln(r_2/r_1)}$$

This gives steady flux.

But – 1. Is steady reached?

2. If so, what is r_2?

IS STEADY FLUX REACHED?

$$t_D \sim 1 = \frac{Kt}{r_2^2} \longrightarrow r_2 \approx \sqrt{\underset{\substack{\uparrow \\ 10\pi\, m^2/yr}}{K}\;\underset{\substack{\uparrow \\ \frac{1}{2} yr.}}{t}}$$

$$r_2 \sim \sqrt{16} \sim \underline{4\, m}$$

Steady flow to pipe if $r_2 \sim 1m$

$r_1 \sim 1\,cm = 10^{-2} m$

Thermal load for house? $\sim 10\, kW$

(not 1 kW for elec)

$$\underline{Q = 10^4 W}$$

Soil conductivity $\sim \lambda = 1\, W/(m.K)$

Temperature drop $\sim 10°C = \Delta T$.

$\ln(4/10^{-2}) \sim 6.0$

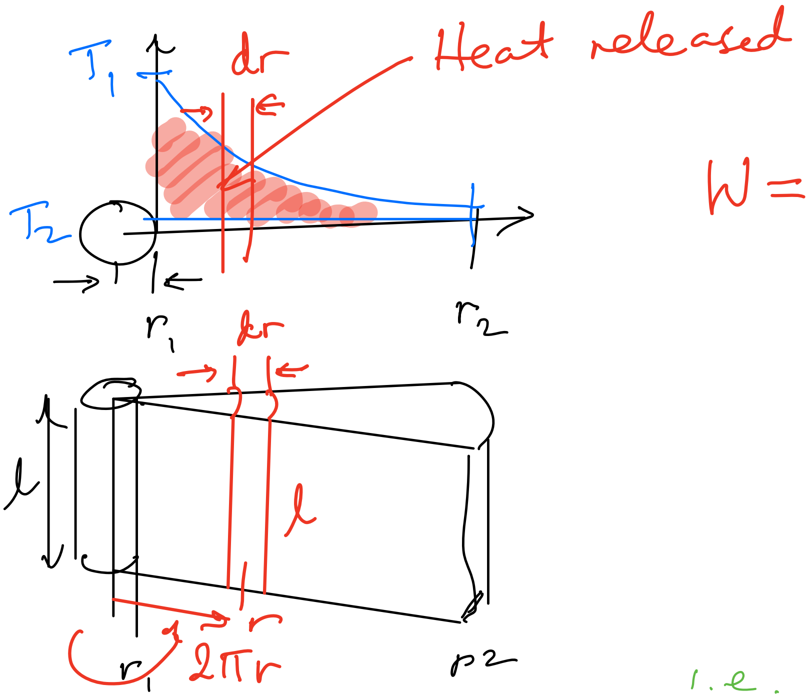
$$\boxed{Q_{th} = 2\pi l \lambda \frac{(T_2 - T_1)}{\ln(r_2/r_1)}}$$

$$l = \frac{Q \ln(r_2/r_1)}{2\pi \cdot \lambda \cdot \Delta T}$$

$$l = \frac{10^4 W \cdot \cancel{6}}{\cancel{2\pi} \quad 1\, W/(mK) \cdot 10\, K}$$

$\ell \sim 10^3 m$ QED.

HOW MUCH HEAT RELEASED FROM STORAGE IN GETTING TO STEADY STATE?



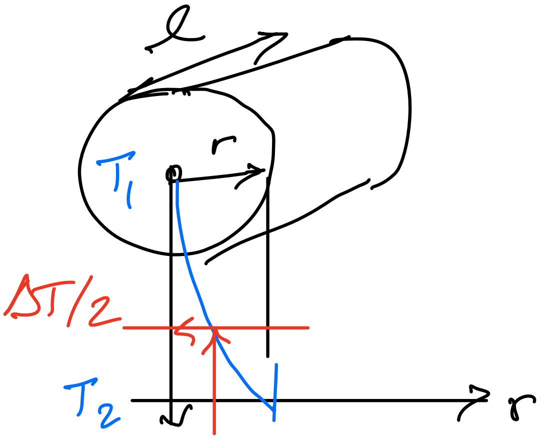
$$W = \forall \rho c T$$

$$W = \int \frac{2\pi r\,dr\,\ell}{\forall}\, \rho c\, T$$

recover fn $T = f(r)$

i.e. set Q = known fn(r_1/r_2) then determ fn r_3.

Estimate:



$10^\circ c/2$

1000m

$$W = \forall \rho c T \doteq \pi r^2 \cdot \ell \cdot \rho c \cdot T$$

4m 2000kg/m³ 1000J/kg·K

$$W = (50\,\mathrm{m}^2)(1000\,\mathrm{m})(2000\,\mathrm{kg/m^3}) \times (1000\,\mathrm{J/kg\cdot K}) \times 5\,^\circ\mathrm{C}$$

$$W = 10^2\ 10^3\ 10^3\ 10^3 \times 5 = 5\times10^{11}\ \mathrm{J\ in\ \tfrac{1}{2}y}.$$

$$= \underline{5\times10^{11}}\ \mathrm{J\ in\ \tfrac{1}{2}y}$$

$$\tfrac{1}{2}y = \sim 10^5\,\mathrm{s} \times 100\,\mathrm{d} \cong 10^7\,\mathrm{s}$$

Power is $\dfrac{W}{1/2y} = \dfrac{5\times10^{11}\,\mathrm{J}}{10^7\,\mathrm{s}} \sim 5\times10^4\,\dfrac{\mathrm{J}}{\mathrm{s}}$

Power from storage = 50 kW

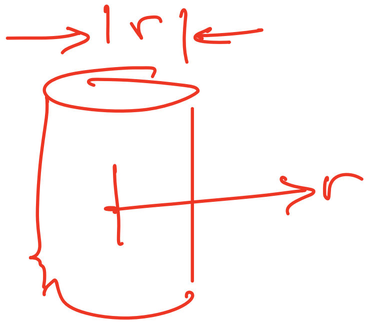
Power for steady state = $\underline{10\ \mathrm{kW}}$

Assumed house load for Steady state

<u>Conclusion</u>: Radius of cooling in soil less than 4 m. since storage supplies × 5 of steady flow

QED.

How long to cool a can of seltzer or cook a steak?



$$t_D = \frac{Kt}{r^2} \sim 1$$

$$K = \frac{\lambda}{\rho c} \sim \frac{0.5\, W/(m.K)}{10^3\, kg/m^3 \cdot 4.1\, kJ/kg\cdot K}$$

$$K \sim 0.1\times 10^{-6}\, m^2/s$$

$$t \sim (r^2/K) \sim (2\times 10^{-2} m)^2/0.1\times 10^{-6}$$

$$\sim \frac{4\times 10^{-4}}{0.1\times 10^{-6}} \sim 40\times 10^{2}\, s$$

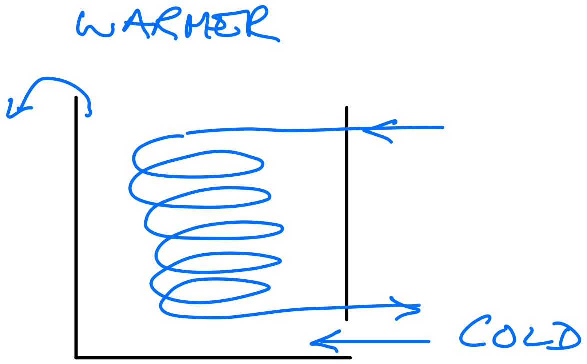
$$\underline{4000 s \sim 60 \text{ min} \sim 1 \text{ hr.}}$$

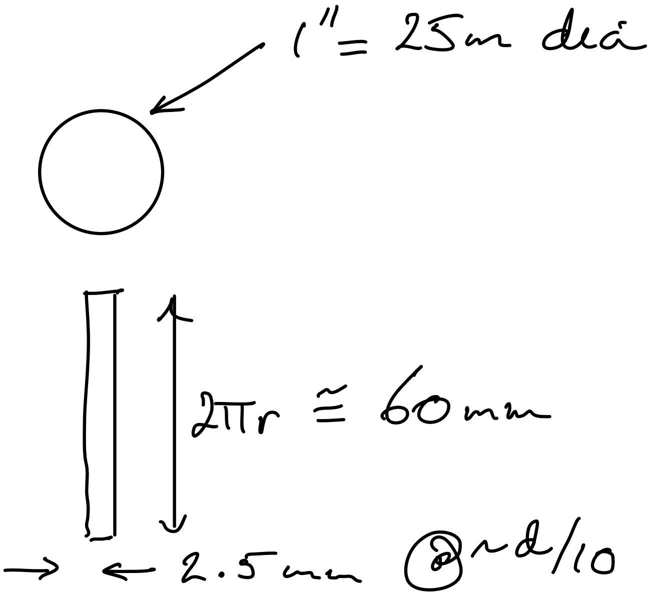
Note scaling with r^2

Cooking a steak. Double the thickness

Quadruple to cooking time

USE OF B/H HEAT EXCHANGER OR CRYPT





$$\overset{10\,kW}{\cancel{Q}} = A\lambda\frac{dT}{dx} = \frac{L\times(60\times10^{-3}m)\;1\,.\,10}{2.5\times10^{-3}m}$$

$$\frac{10^4\,(2.5\times10^{-3}m)}{(60\times10^{-3}m)\times1\times10} \doteq \frac{\cancel{N.m}}{\cancel{s}}\;\frac{\cancel{m}\quad\cancel{K}\,m}{\cancel{m}\quad\cancel{Nm/s}\,.\,\cancel{K}}$$

$$L \cong 10^4\overset{\sim 1/20}{\cancel{\left(\frac{2.5}{60}\right)}}\frac{1}{10}$$

$$L \sim \frac{10^3}{20} \sim 50m \quad QED.$$

Volume of water needed to maintain temp

is. $10kW = 10^4 W = \dot{M}\,c\,\Delta T$

$\dot{M} \sim 10^4 J/s/(c\,\Delta T) \sim 10^4/(4.1\times10^3).10$

$\dot{M} \sim 0.25$ kg/s

10^5 secs $\approx 0.25 \times 10^5$ kg $\equiv 25 \times 10^3$ kg/d.

5. GEOTHERMAL ENERGY RECOVERY AND CONVERSION

1. Hydrothermal
2. SedHeat
3. EGS
4. Direct Use
5. Ground Source Heat Pumps
6. **Thermal Storage**

14_1 Geothermal - Aquifer Thermal Storage

Recap:

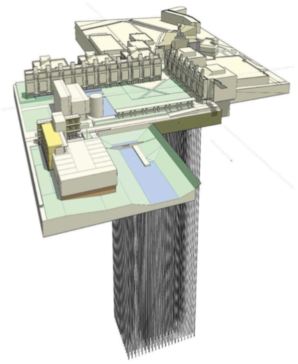
1. GSHPs:
    a. Utilize low quality heat without the penalty of conversion to electricity
    b. Distributed power opportunity for off-grid and remote use
    c. Broadly geographically available (in US) due to climatic zonations

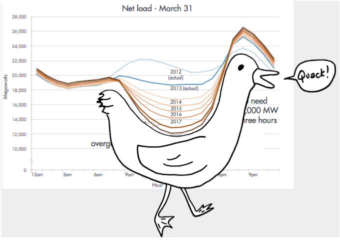
Movies*:* (Great Lakes SedHeat Network): https://igws.indiana.edu/glsn/speakers
(Mark): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/7_v_collmark_LATE.mp4
(Ryan): https://psu.zoom.us/rec/play/zA3PZ8P2YeJQJgVwg1bQWsnq2JwndddprhgG0smGb-WjvHyyauBeRyWwzK1lCkJyH9ZuRn1UNTyx2N8_.SXQtIdwyrRyQNzu9?startTime=1616982757000
(Brandon): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/15_v_lindgrenbrandon.mp4
(John): https://personal.ems.psu.edu/~fkd/courses/eme_497/videos/20_v_pavlakovicjohn.mp4

Resources: MR 4

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?





Provide diurnal or inter-seasonal storage
Avoid issues of intermittency/dispatchability in renewables - load shifting
Address off-grid and local/distributed needs

Scientific Questions:

2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

Aquifer Thermal Storage

1. Modes and layouts - closed-versus-open systems
2. Mechanisms of storage
    A. Open
    B. Closed