# Future Energy Geomechanics: Deep-Seated Processes

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# Hong Kong – December 2016

University of Waterloo

# Deep Energy Geomechanics…

- Hydraulic Fracture (HF) Geomechanics
  - → 23% of submitted abstracts to ARMA 2017!!
- Deep Geothermal (EGS) Geomechanics
  - → Power, heat from low permeability strata
  - → Using the heat from co-produced water
- Deep Energy Storage Geomechanics
  - → Salt caverns for oil, gas, $H_2$, compressed air
  - → Potential for deep thermal energy storage (heat)
- Deep Waste Disposal Geomechanics
  - → Disposal of waste aqueous liquids
  - → Disposal of particulate waste solids
  - → Deep biosolids disposal (plus $CH_4$ recovery!)

# Shale Gas & Shale Oil Revolution!

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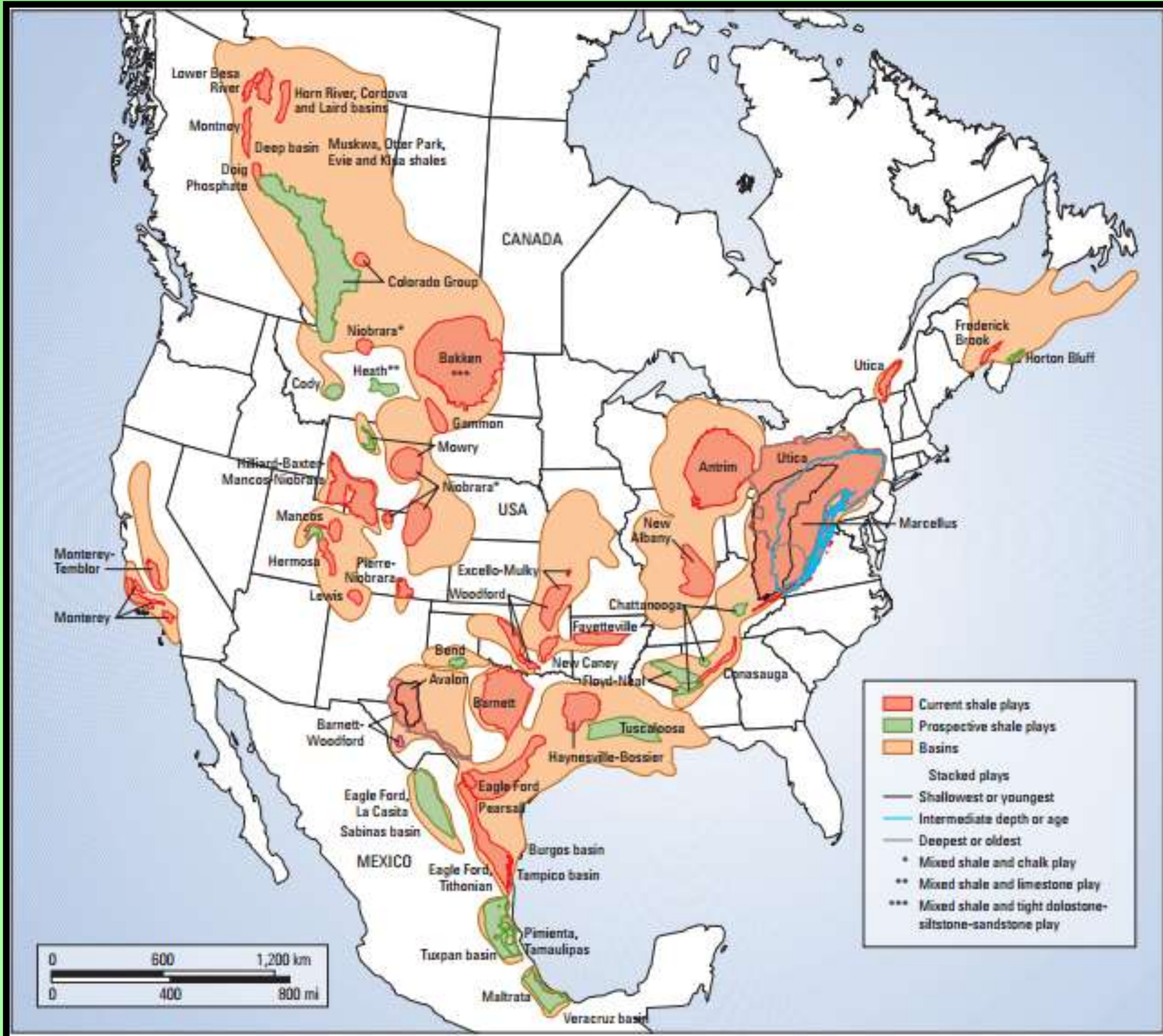
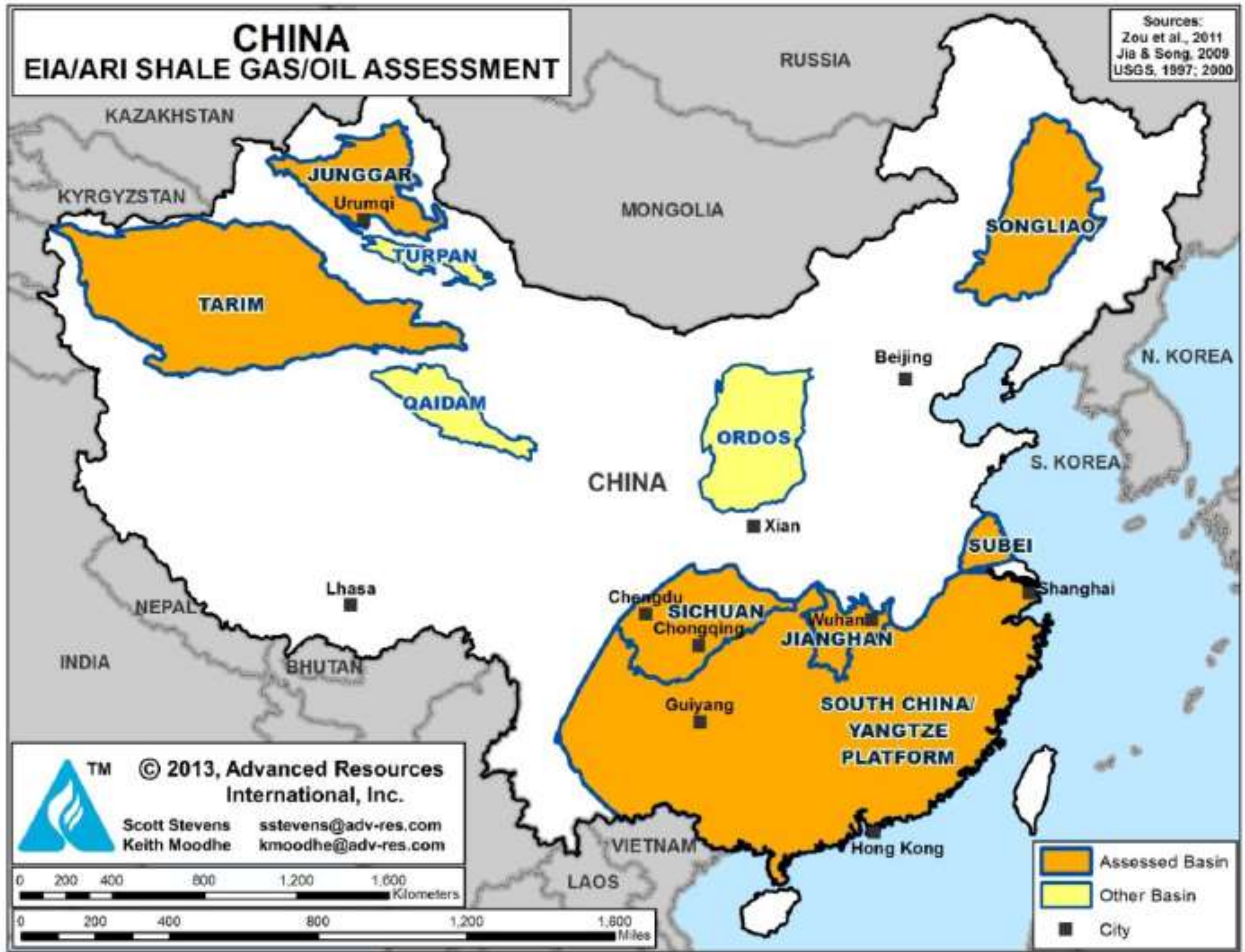



Deep Energy Geomechanics

# Shale Gas Basins of China



# Sichuan…

Everyone agrees the Sichuan shale gas potential is **excellent**, but…

- Difficult geology
- Folds, fractures, faults
- Drilling problems
- $H_2S$ common

We have a lot to learn yet in Sichuan

| SICHUAN BASIN | | | | | |
|---|---|---|---|---|---|
| ERA | PERIOD | EPOCH | FORMATION | AGE (Ma) | THICKNESS (m) |
| CENOZOIC | QUATERNARY | | | 0 - 3 | 0 - 380 |
| | TERTIARY | Upper | | 3 - 25 | 0 - 300 |
| | | Lower | | 25 - 80 | 0 - 800 |
| MESOZOIC | CRETACEOUS | | | 80 - 140 | 0 - 2000 |
| | JURASSIC | Upper | Penglaizhen | 140 - 195 | 650 - 1400 |
| | | Middle | Suining | | 340 - 500 |
| | | | Shaximiao | | 600 - 2800 |
| | | Middle-Lower | Ziliujing | | 200 - 900 |
| | TRIASSIC | Upper | *Xujiahe* | 195 - 205 | 250 - 3000 |
| | | Middle | Leikoupo | 205 - 230 | 900 - 1700 |
| | | Lower | Jialingjiang | | |
| | | | *Feixianguan* | | |
| PALEOZOIC | PERMIAN | Upper | Changxing | 230 - 270 | 200 - 500 |
| | | | Longtan | | |
| | | Lower | Maokou | | 200 - 500 |
| | | | Qixia-Liangshan | | |
| | CARBONIFEROUS | Mississippian | Huanglong | 270 - 320 | 0 - 500 |
| | SILURIAN | Upper | | [illegible] - 570 | 0 - 1500 |
| | | Lower | Longmaxi | | |
| | ORDOVICIAN | | | | 0 - 600 |
| | CAMBRIAN | Upper | Xixiangchi | | 0 - 2500 |
| | | Middle | Yuxiansi | | |
| | | Lower | Qiongzhusi | | |
| PROTEROZOIC | SINIAN | Upper | Dengying | 570 - 850 | 200 - 1100 |
| | | | Doushantuo | | |
| | | Lower | | | 0 - 400 |
| | PRE-SINIAN | | | 850 | |

Source Rock | *Conventional Reservoir*

Source: ARI, 2013.

# Top 10 Countries in Shale Gas

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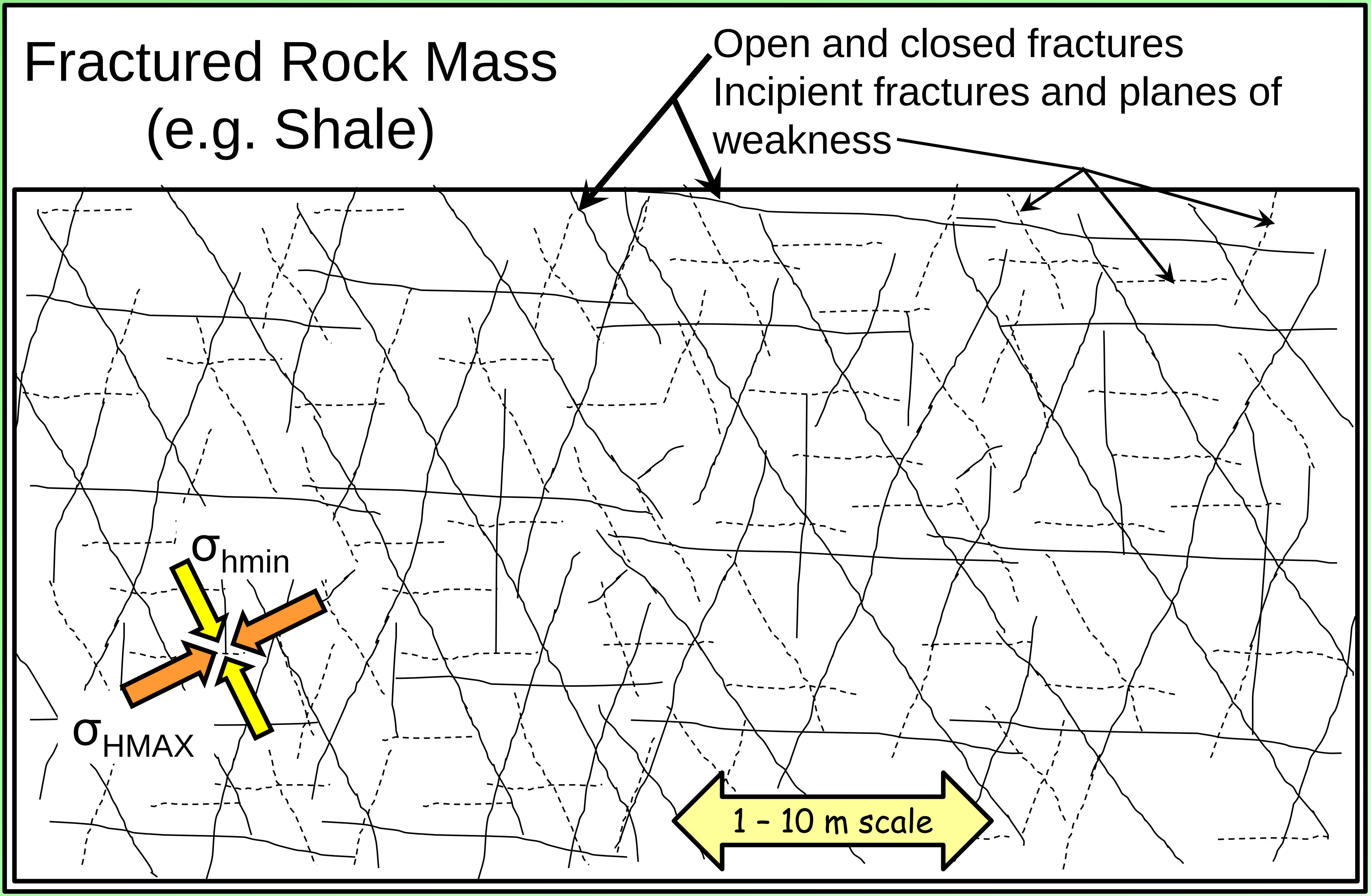
| Rank | Country | (trillion cubic feet) | |
|---|---|---|---|
| 1 | China | 1,115 | |
| 2 | Argentina | 802 | |
| 3 | Algeria | 707 | |
| 4 | U.S.[1] | 665 | (1,161) |
| 5 | Canada | 573 | |
| 6 | Mexico | 545 | |
| 7 | Australia | 437 | |
| 8 | South Africa | 390 | |
| 9 | Russia | 285 | |
| 10 | Brazil | 245 | |
| | World Total | 7,299 | (7,795) |

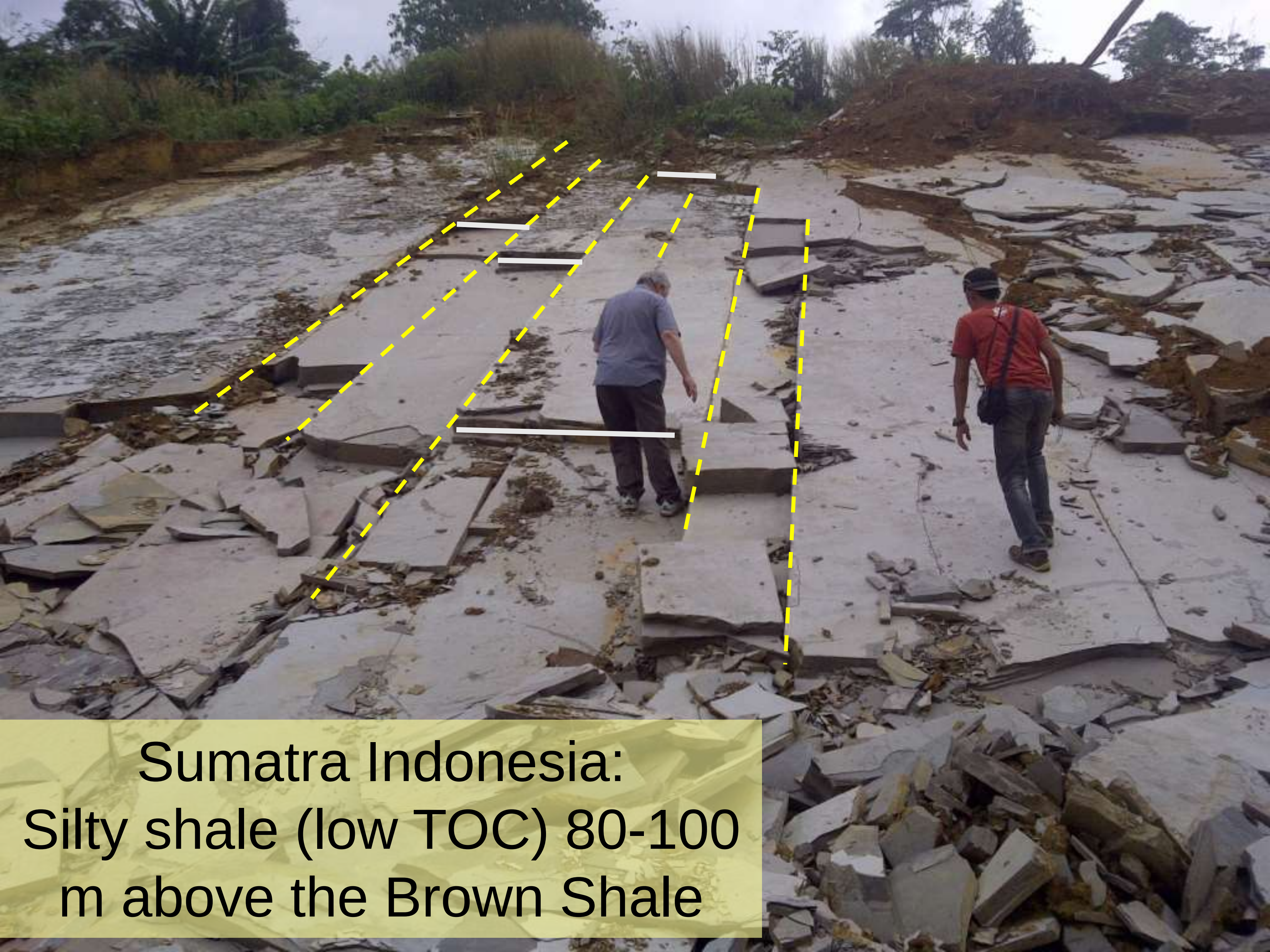
EIA June 2013

# Unlocking O&G with HF…


From: http://geology.com/rocks/shale.shtml

# Naturally Fractured Rock





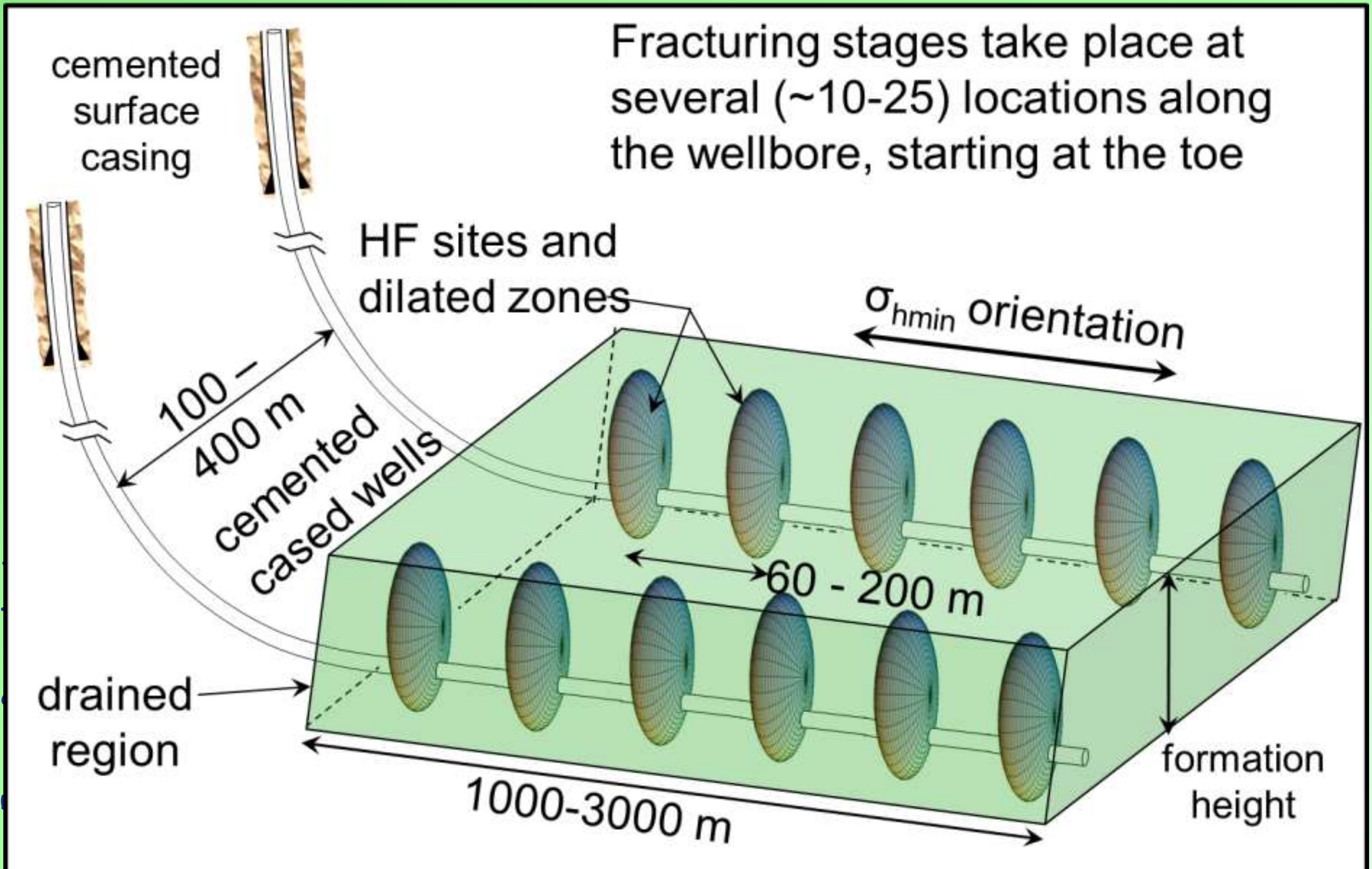
Sumatra Indonesia:
Silty shale (low TOC) 80-100 m above the Brown Shale

# Natural Fractures: Challenges



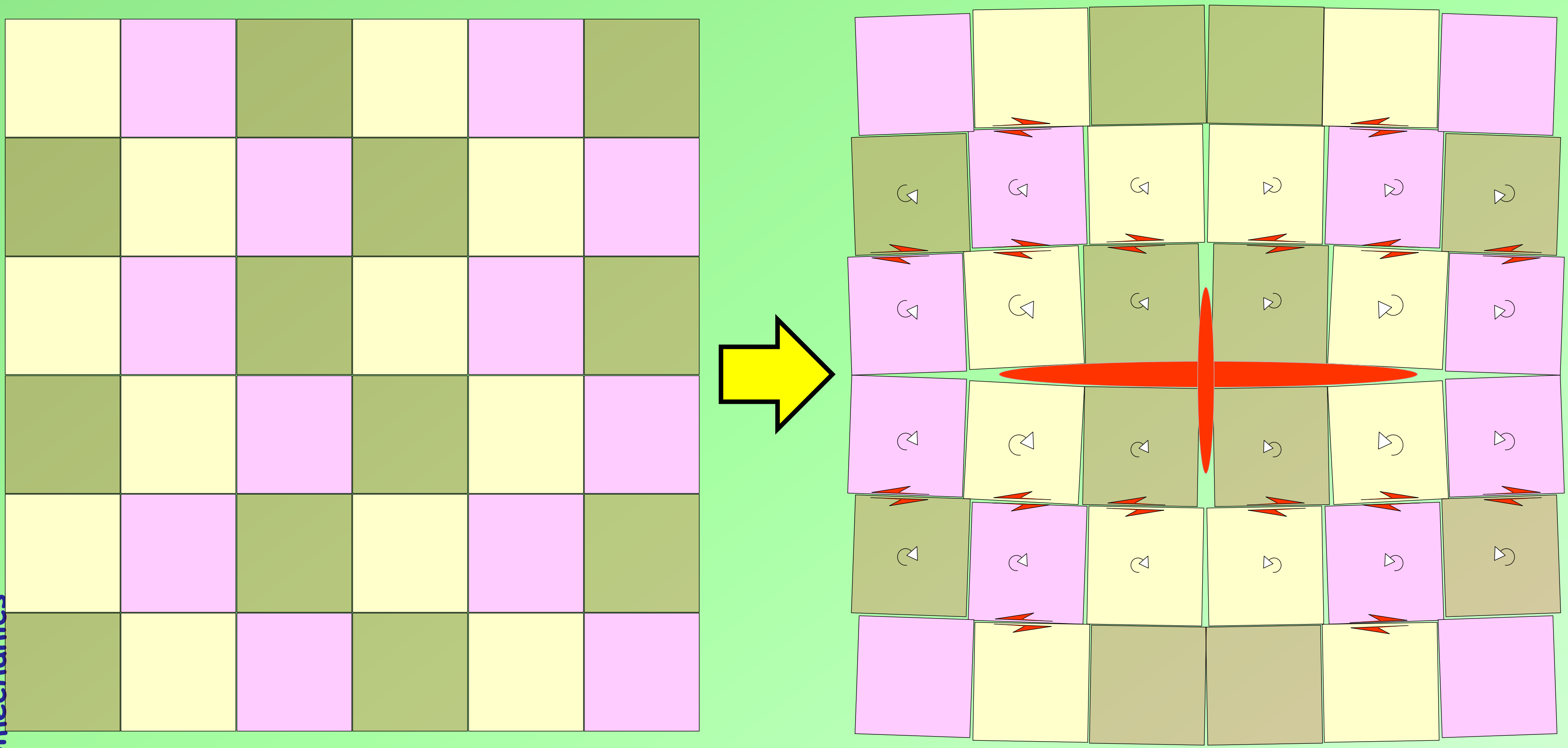
- Naturally existing fractures are largely closed
- When we do HF, we want to open and connect many natural fractures to the new HF
- So, the properties of the natural fractures are very important but we don't know how to incorporate them into models:
  - Fracture cohesion, frictional behavior, ductility
  - Fabric (frequency, orientation, joint sets, etc. etc.)
  - Compressibility of fractures and the effect on the permeability
  - Effect of changing stresses on fracture aperture
  - And so on
- A great deal of research is needed in this area

# The HF-Well Array at Depth…



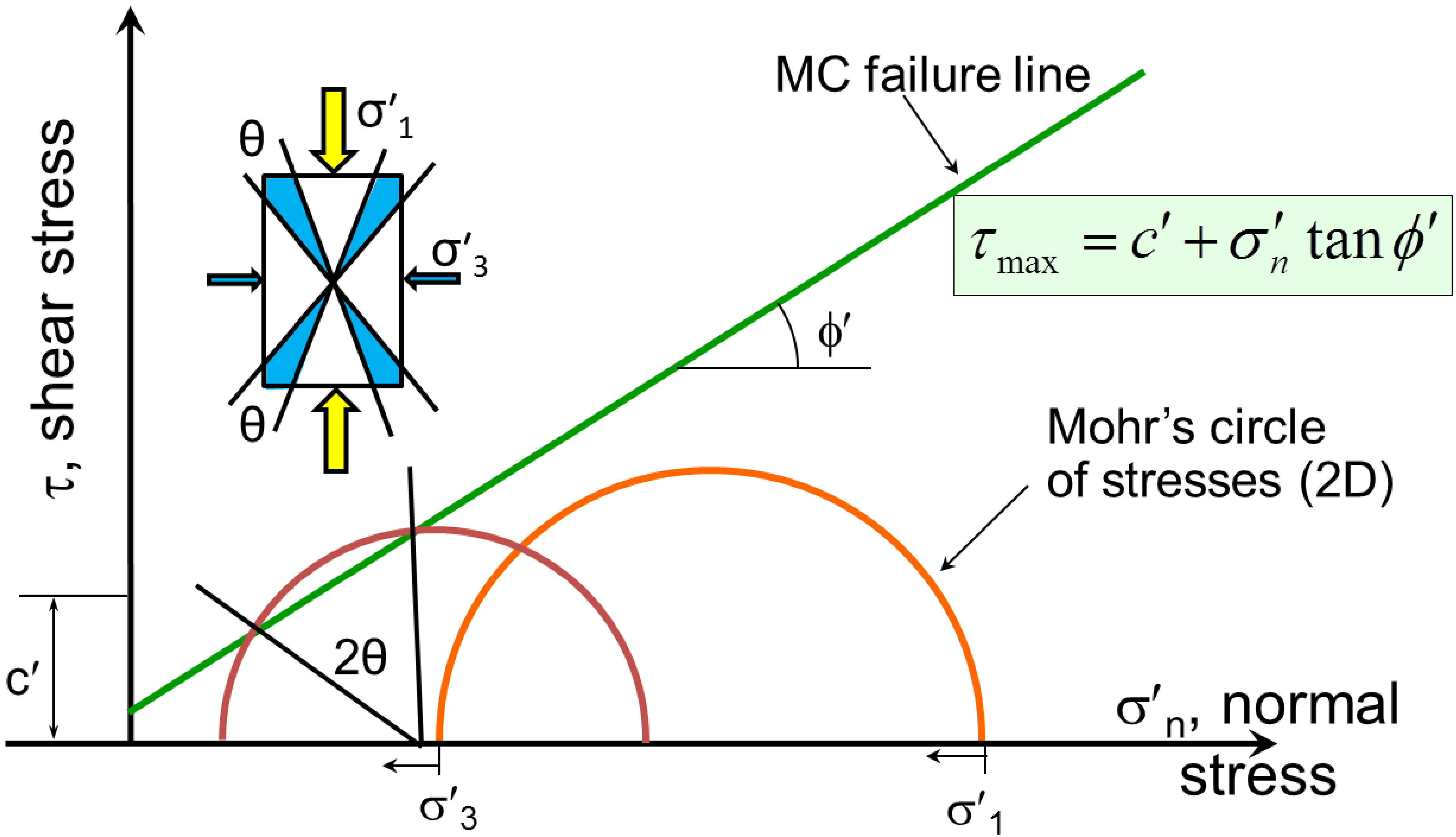
# The Complex Mechanics…





It turns out to be very difficult to “design” each HF stage to give optimal results

# Which Joints Slip?




Increasing p and reducing $\sigma'_n$ leads to slip of critically oriented joint (blue areas).

# Optimizing the HF Design…?

- Maximize accessed volume, minimize cost…
- Current HF design models are extremely weak
- Insufficient information is collected in practice…
  - MS is one source
  - Deformation measurements: geomechanics calibration
  - Post-HF assessment
  - Long-term well behavior (RF + rate)
- Research into a deeper understanding of HF mechanics in naturally fractured rock masses
- Better monitoring, model calibration and verification

# Multi-Well Pad – $120,000,000

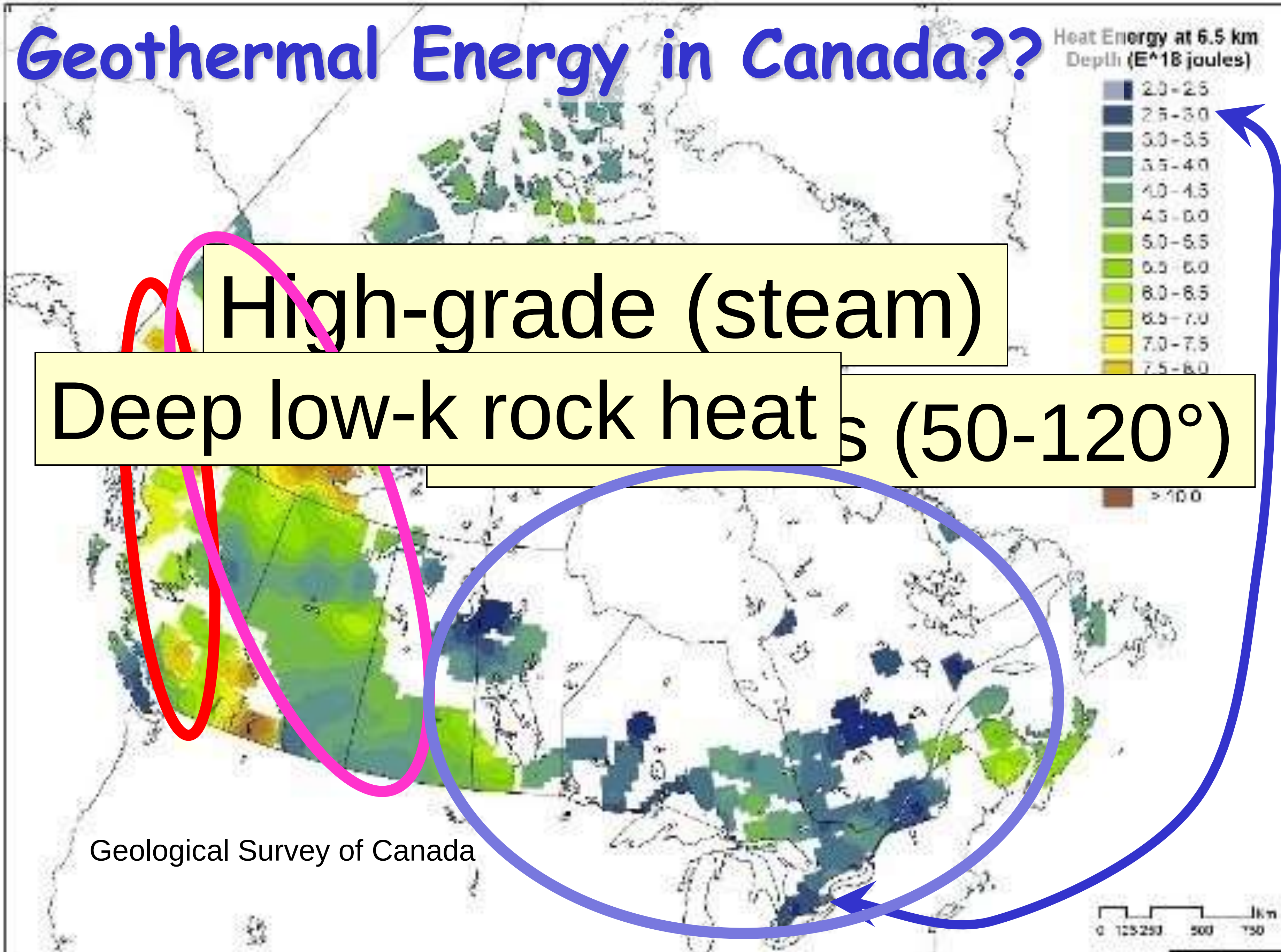
# Deep Geothermal Geomechanics

# Geothermal Methods…



- High T Geothermal? Few good sites!
- Shallow local geothermal with heat pumps is used, but it is costly
- Heat storage in porous aquifers???
- EGS – Enhanced Geothermal Systems
  - "Intermediate-grade" thermal energy
  - "Heat mining" at depths of > 4 km (T > 90°C)
  - Large volumes of rock, but little water…
- Let's look at EGS possibilities…

# Geothermal Energy in Canada??




Geological Survey of Canada

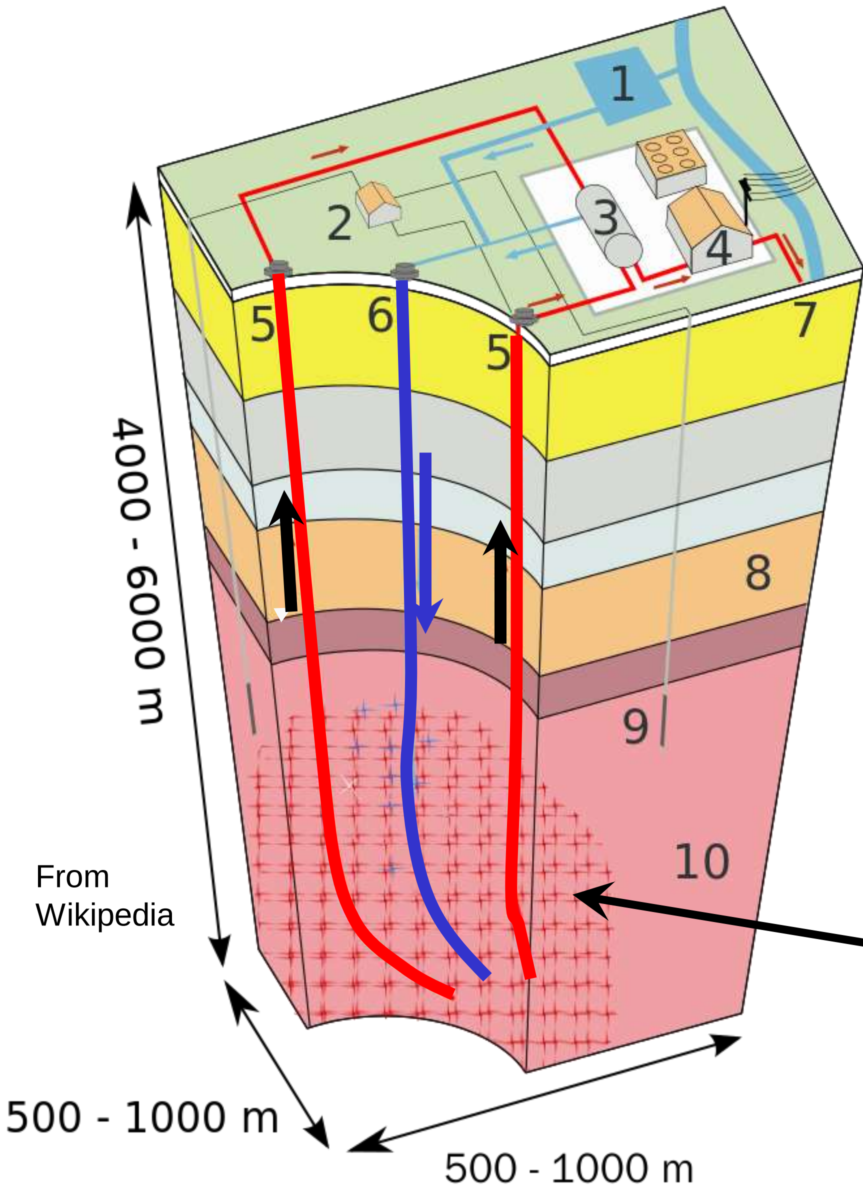
Pembina

# Deep EGS



- Enhanced Geothermal Systems – EGS
- Issues…
  - → Cost of deep drilling to access heat because of a low geothermal gradient
  - → No surface disposal of fluids from depth
  - → Scaling of pipes in the primary loop must be controlled
  - → Access to a large enough rock volume
  - → Must be at least 20 MW, more is better
- Steady, reliable, small footprint…

# The EGS Concept…




From Wikipedia

1 Water lagoon
2 Pump house
3 Heat exchanger
4 Turbine hall
5 Production well
6 Injection well
7 Hot $H_2O$ to district heating
8 Porous sediments
9 Observation well
10 Crystalline bedrock

Geothermie_Prinzip.svg: *Geothermie_Prinzip01.jpg: "Siemens Pressebild" http://www.siemens.comderivative

# To Implement EGS

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- Has to be deep enough to access elevated temperatures for power + heat
- In most of Canada, this means depths greater than 4 km
- Wells must be drilled economically
  - ➔ As widely apart as feasible
- Hydraulically fractured for communication
- …and a binary circulation system used…
- District heating is the major application

# 7 km Deep Drilling Rig…

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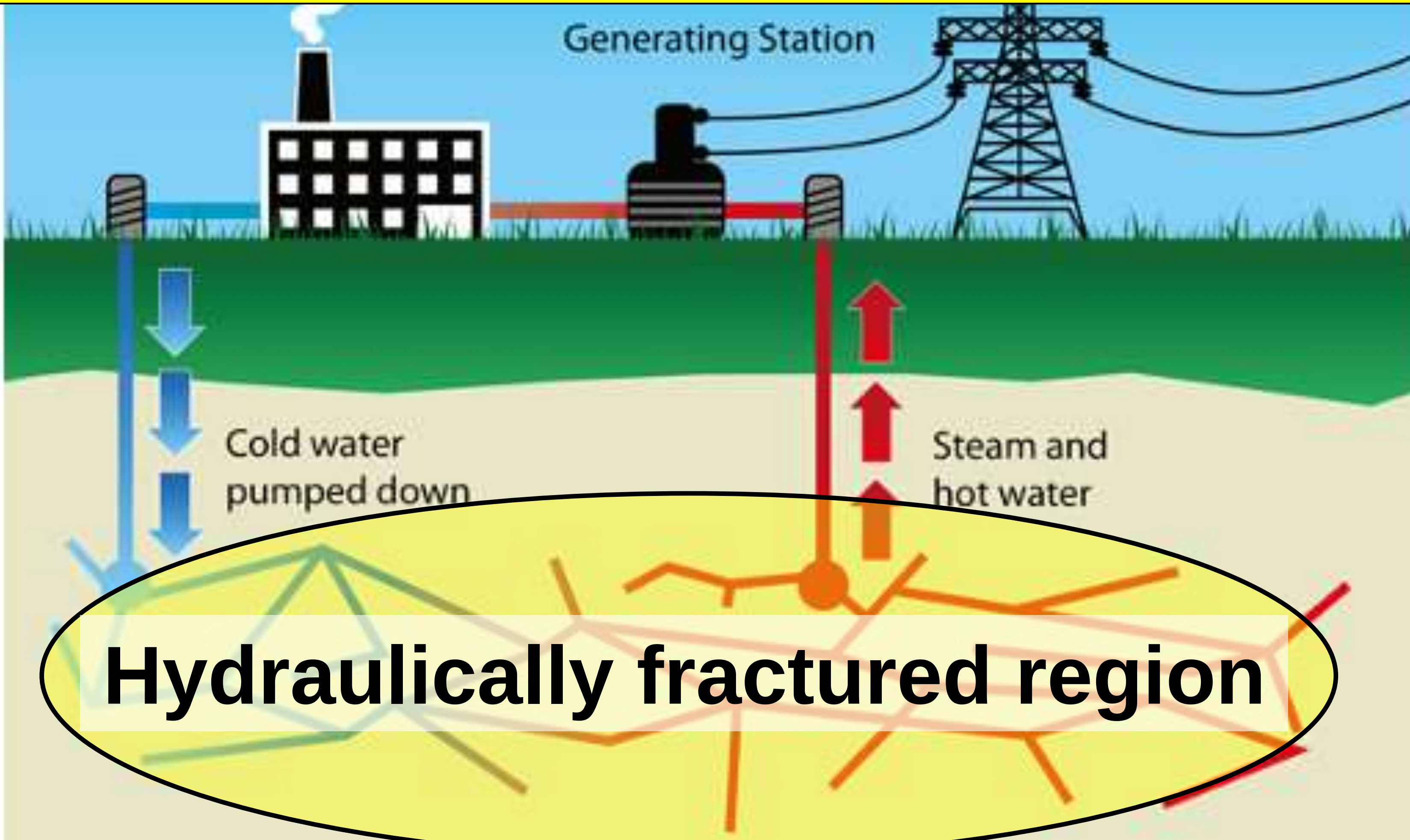
7 km deep

40 MW

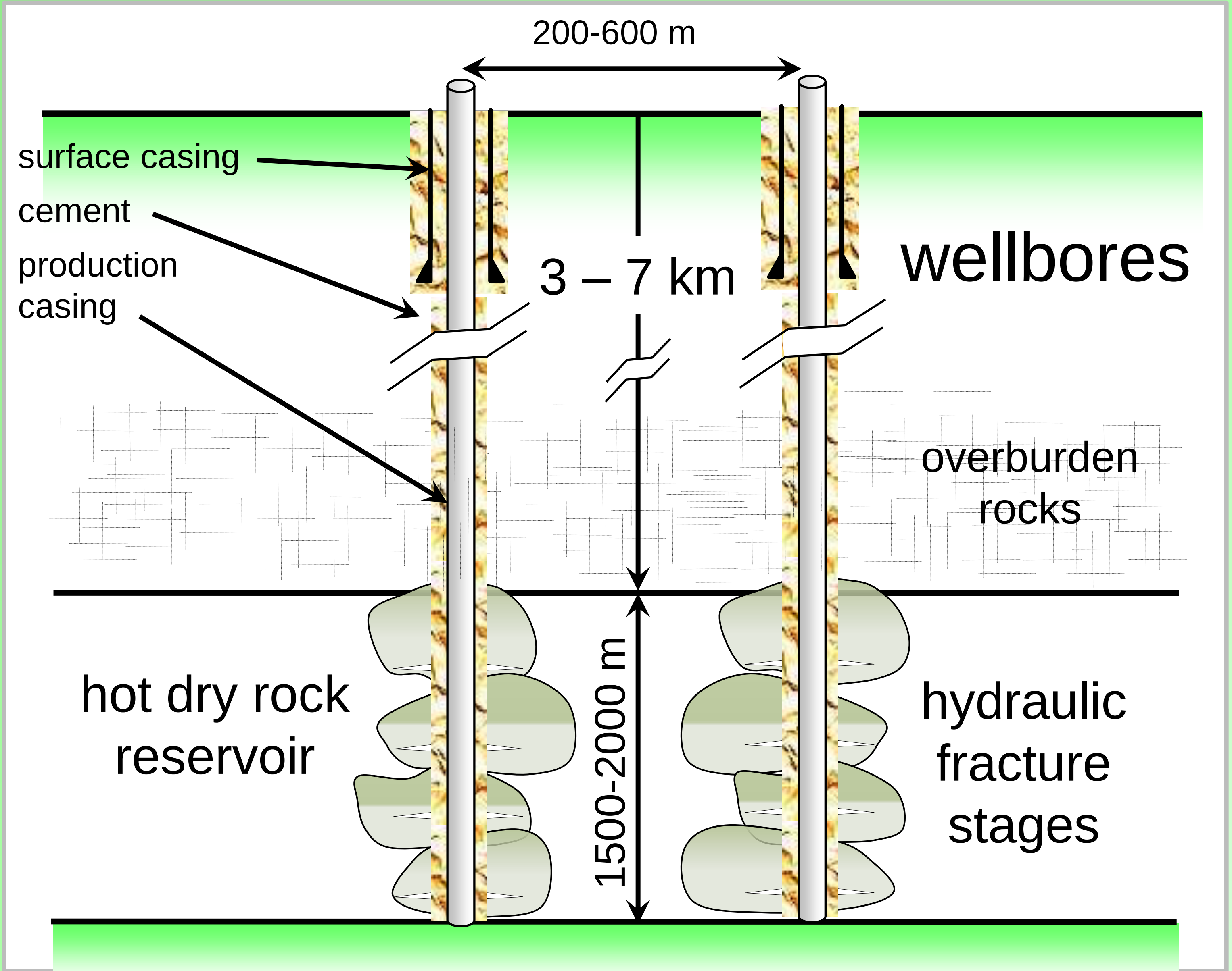
granite

# …not just power, …also district heating!



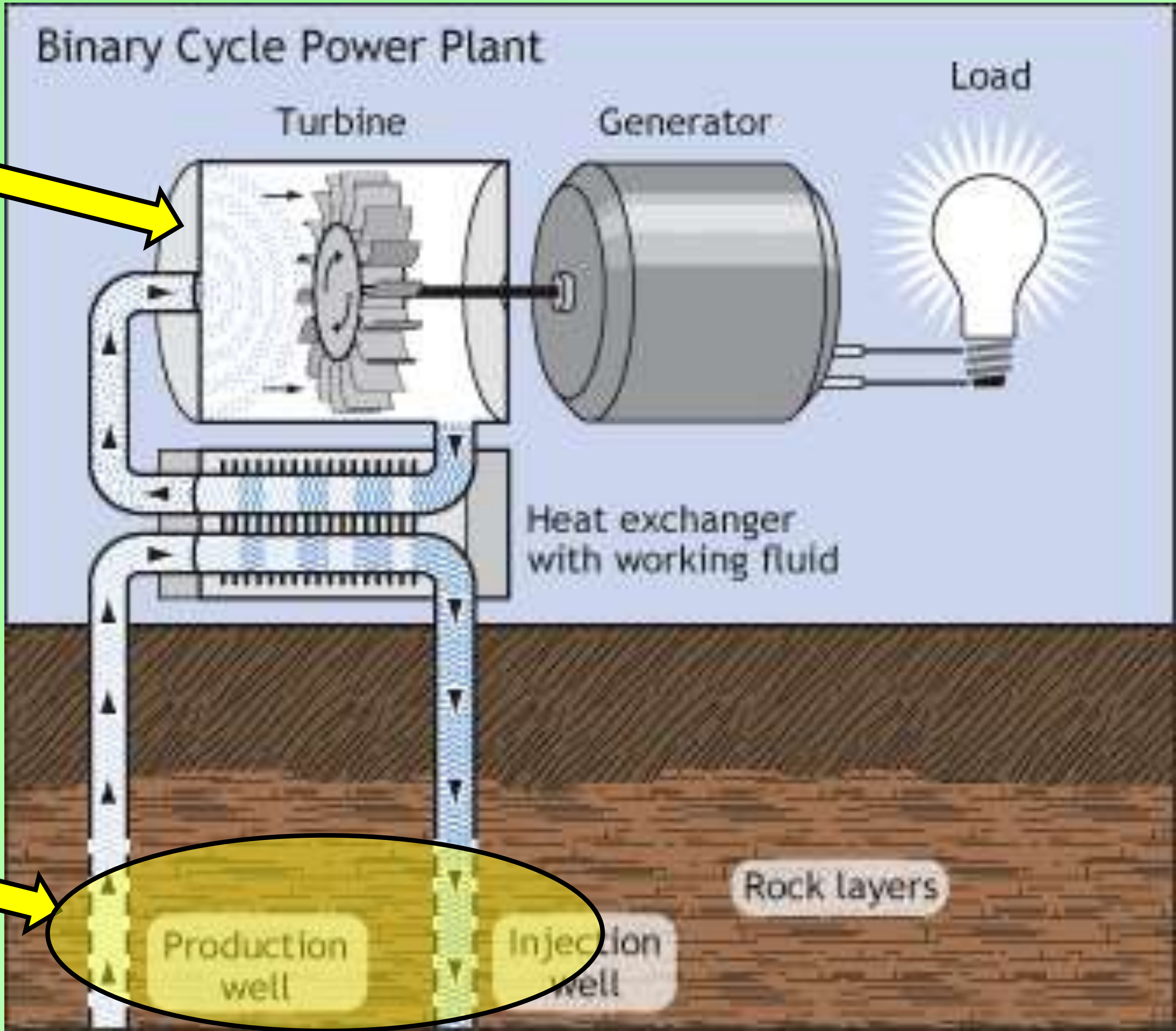

http://ieet.org/index.php/IEET/more/grasso20

# Interwell Communication…



# The Binary EGS Cycle

**Special low ΔT turbine**




https://serendipitousscavenger.wordpress.com/tag/enhanced-geothermal-systems/

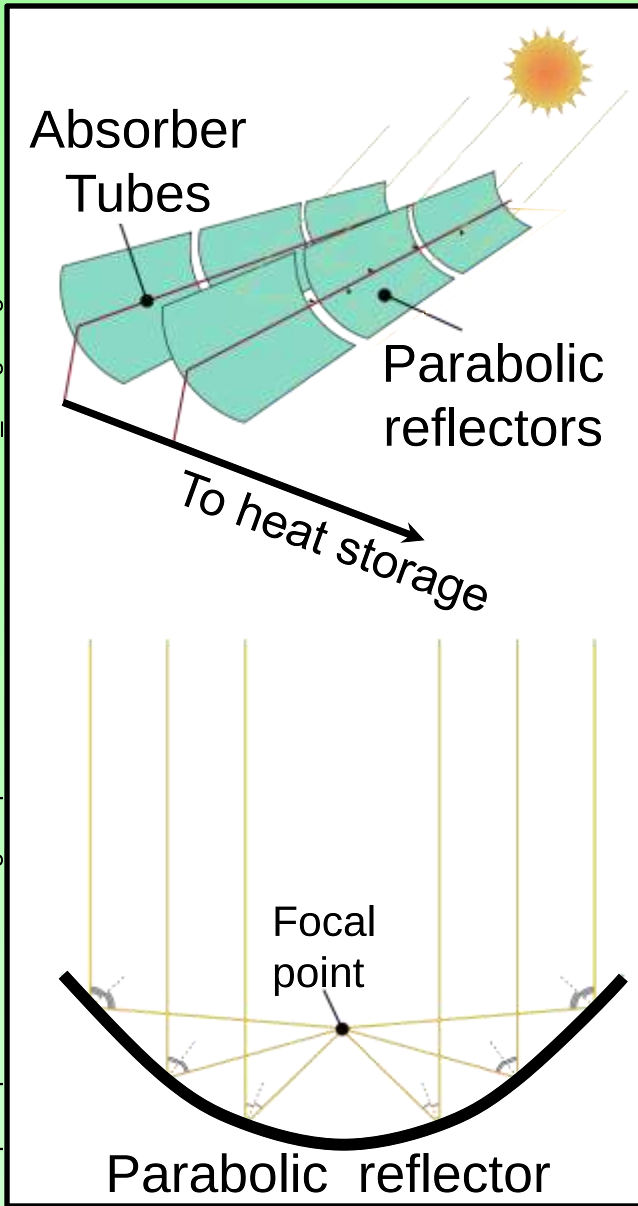
**Fractured region**

# Energy Storage & EGS

- Is it possible to store energy in a geothermal system?
- The only feasible means seems to be storing energy as heat… From where?
- Here is a concept to be studied…
- Solar energy can be "stored" as heat in a large volume of rock at depth (if ΔT is suitable)
- And if the time scale is annual, there are potential economic advantages in Canada…

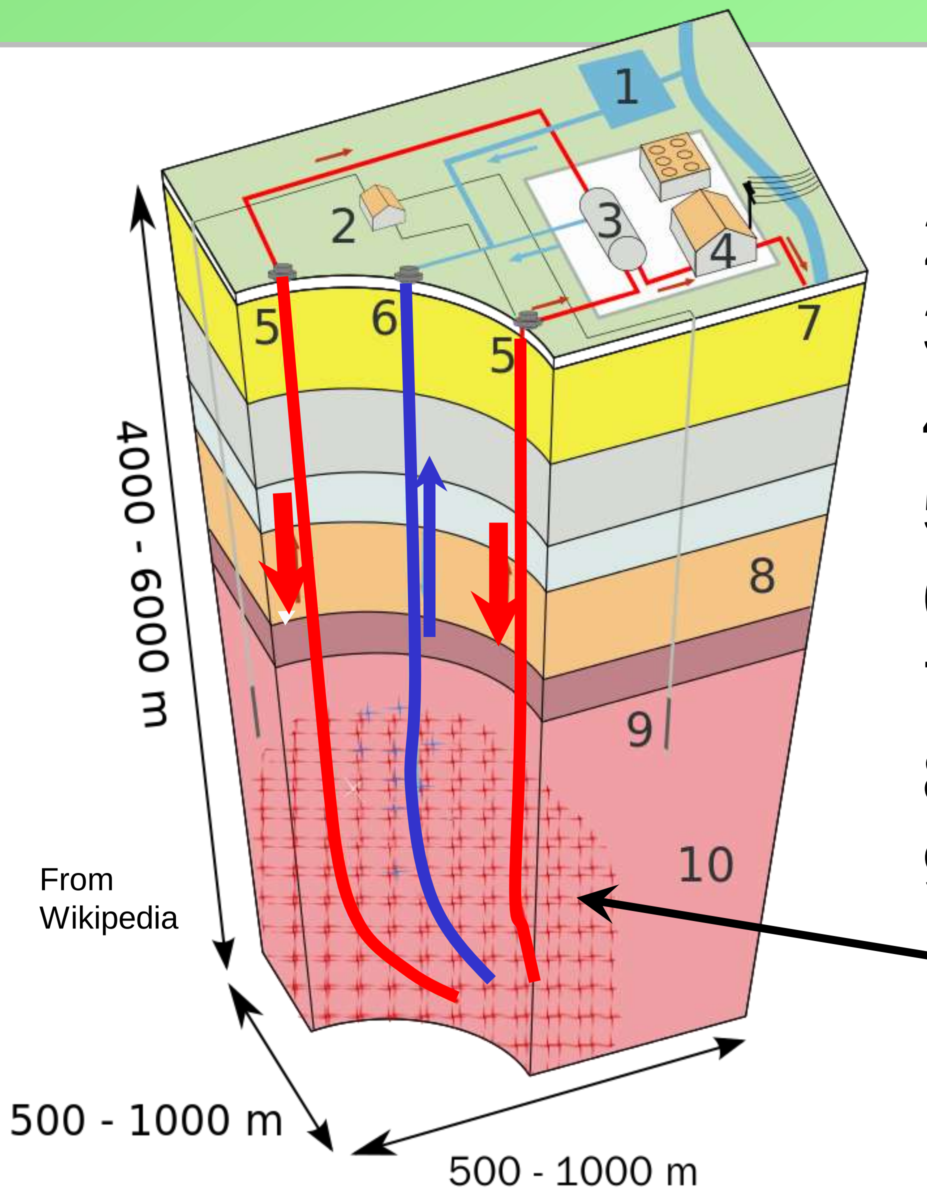
# Solar Energy…

- Photovoltaic solar panels are 10-15% efficient (will improve somewhat)
- Thermal collection can be 70-75% efficient, T > 200°C (good ΔT)
- The problem is: **Where do we store the thermal energy?**




https://upload.wikimedia.org/wikipedia/commons/b/b5/Parabolic_trough.svg

# Operate EGS in Reverse!

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Geothermie_Prinzip.svg: *Geothermie_Prinzip01.jpg: "Siemens Pressebild"
http://www.siemens.comderivative

# Geomechanics Challenges…

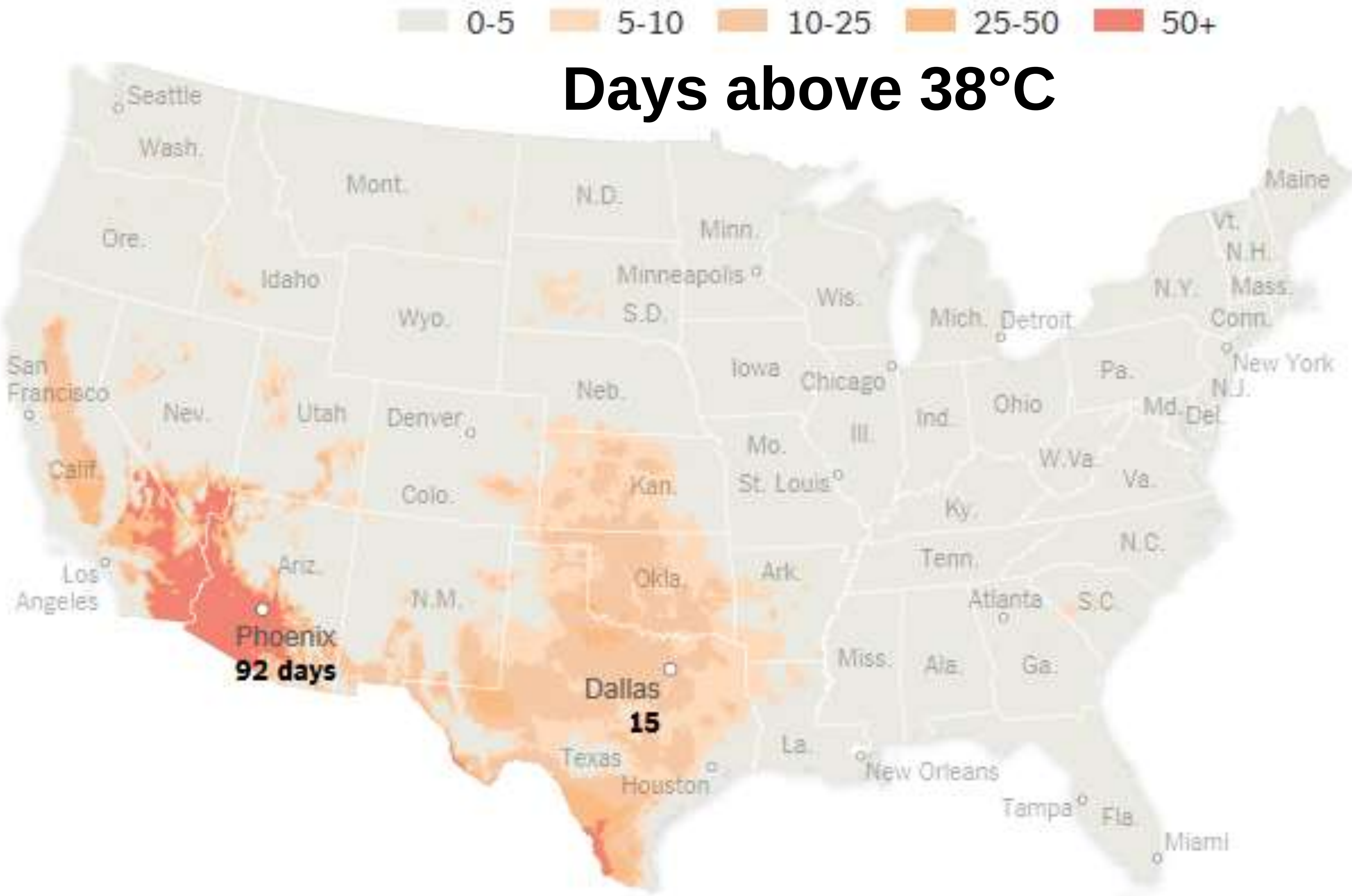
- First, deep economic drilling in hard rocks
- Second, establishing primary fluid flow communication through hydraulic fracturing
  - ➔ Stress fields, simultaneous 2-well fracking
- Third, thermoelastic modeling in naturally fractured rocks: many nonlinearities…
  - ➔ Joint aperture changes = ($\Delta T$, $\Delta p$, [$\sigma'$], $\beta_T$, …)
- Fourth, the possibility of annual thermal recharging of the heat at depth
  - ➔ Solar thermal heat recirculation
- Fifth, predicting, measuring and controlling induced seismicity

# CAES
# Compressed Air Energy Storage in Salt Caverns, Porous Reservoirs

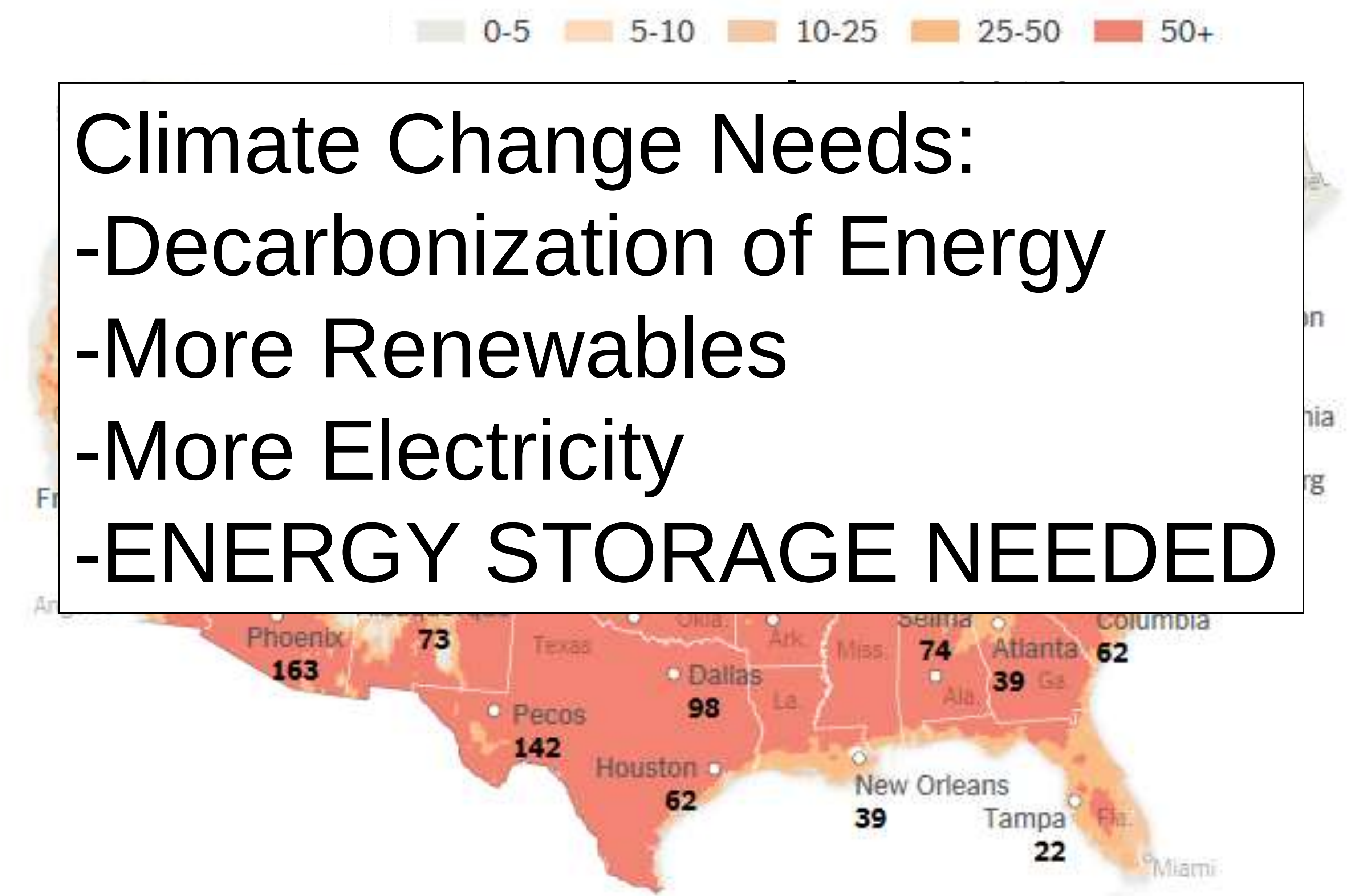
# Why CAES…?

- Grid management
  - Short term (hour - day)
- Decarbonization
  - Storage (day - week)
- Climate Issues

# 1991-2010 average



# By 2100




Climate Change Needs:

-Decarbonization of Energy

-More Renewables

-More Electricity

-ENERGY STORAGE NEEDED

# Versatile Energy Storage…

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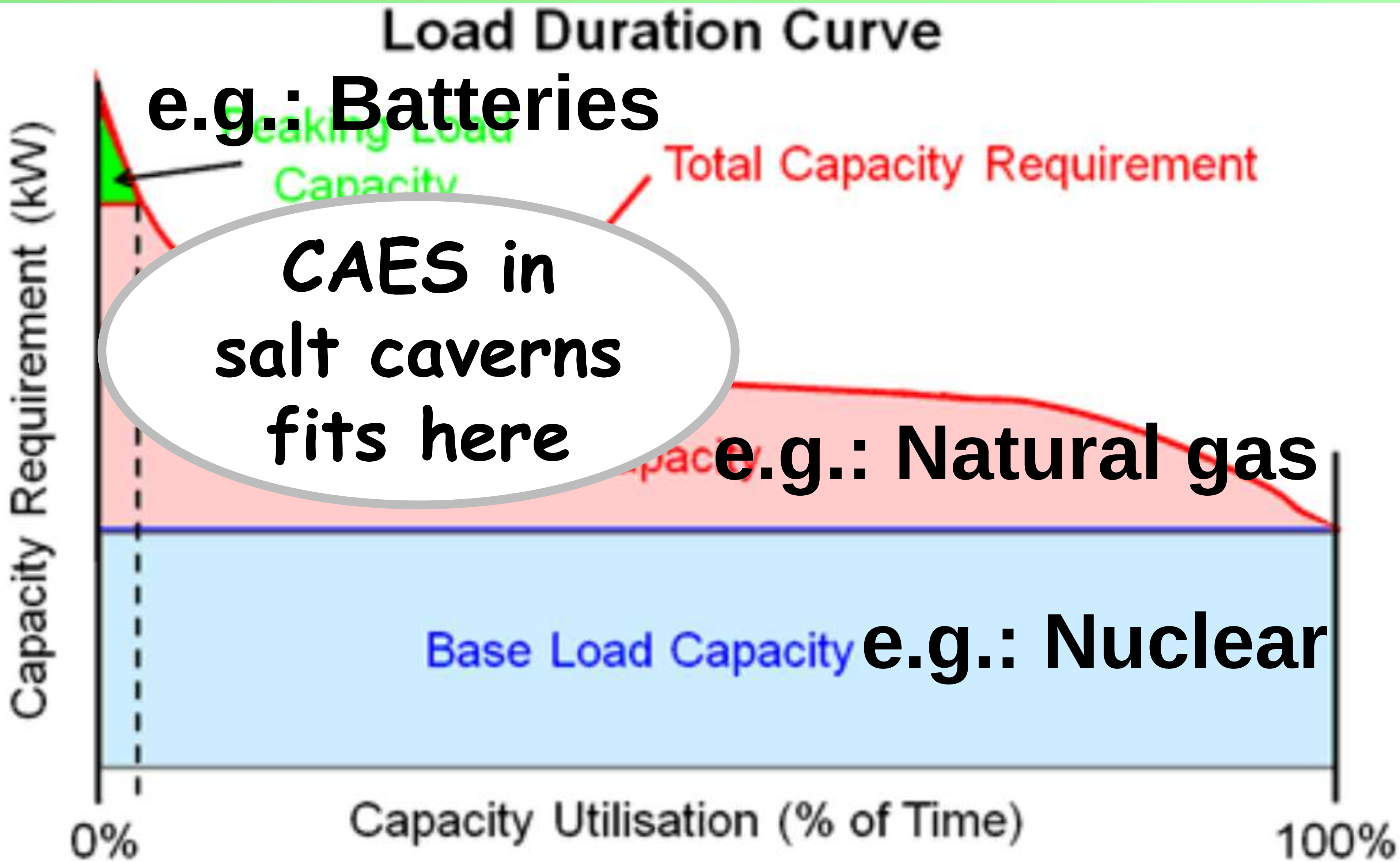
- Frequency regulation and maintaining grid stability, security, resilience
- Energy harvesting (sun, wind, excess base load…) for later use (hours to day)
- A grid-scale buffer for emergencies
- Increased grid efficiency
  - Peak shaving to reduce base load needs
  - Power provision in sharp demand change periods
  - Rapid response time (spinning reserves)
  - …and so on…

# Different Types of Load



# Some Energy Storage Concepts

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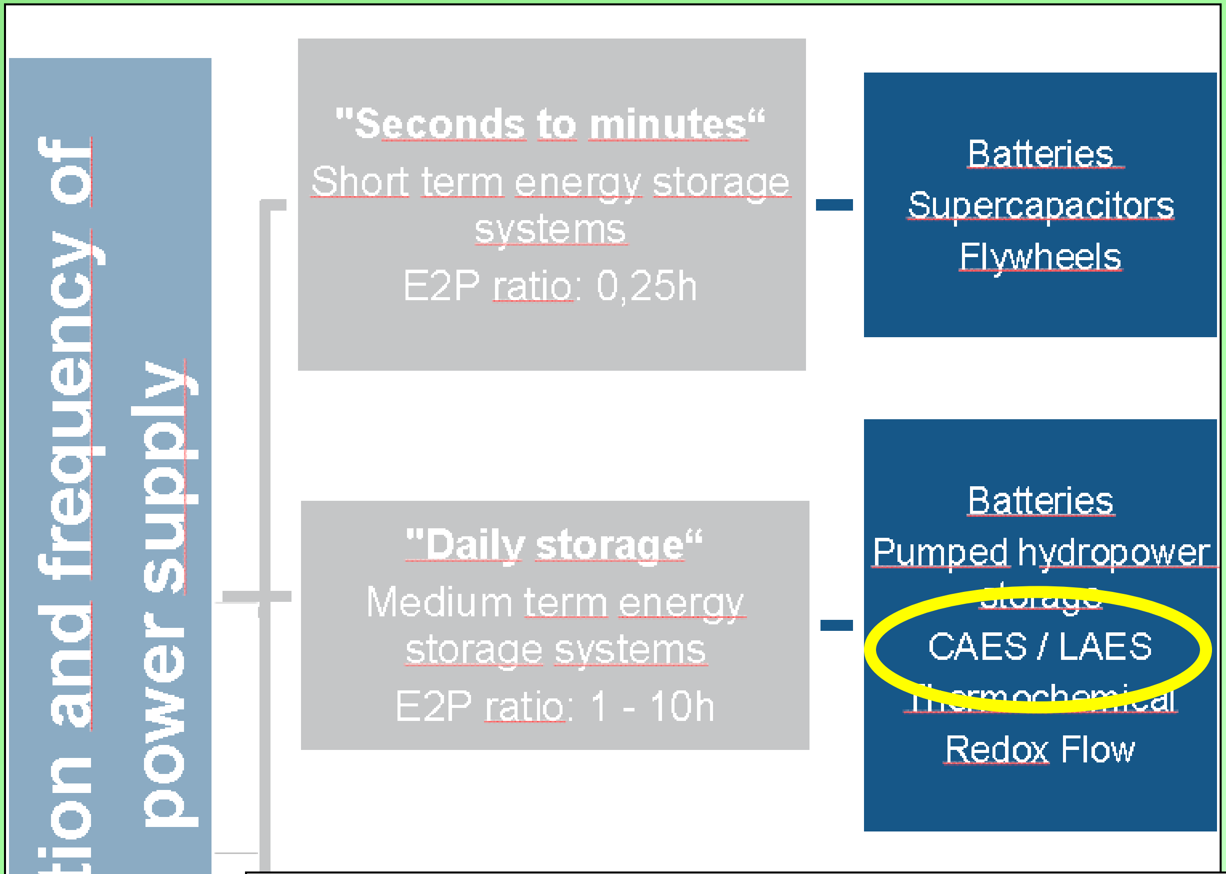
- Batteries (DC-AC issues)
  - ➔ Large battery banks, 1,000,000 electrical cars…
- Chemical storage
  - ➔ Advanced electrolysis to create H2 (storage?)
  - ➔ Other forms of non-battery chemical storage…
- Heat storage (not for electricity)
- Mechanical energy storage
  - ➔ Flywheels, elevation of huge mass…
- Superconducting magnets, capacitors…
- …scale, cost, efficiency, safety… issues

# CAES is Considered "Daily"



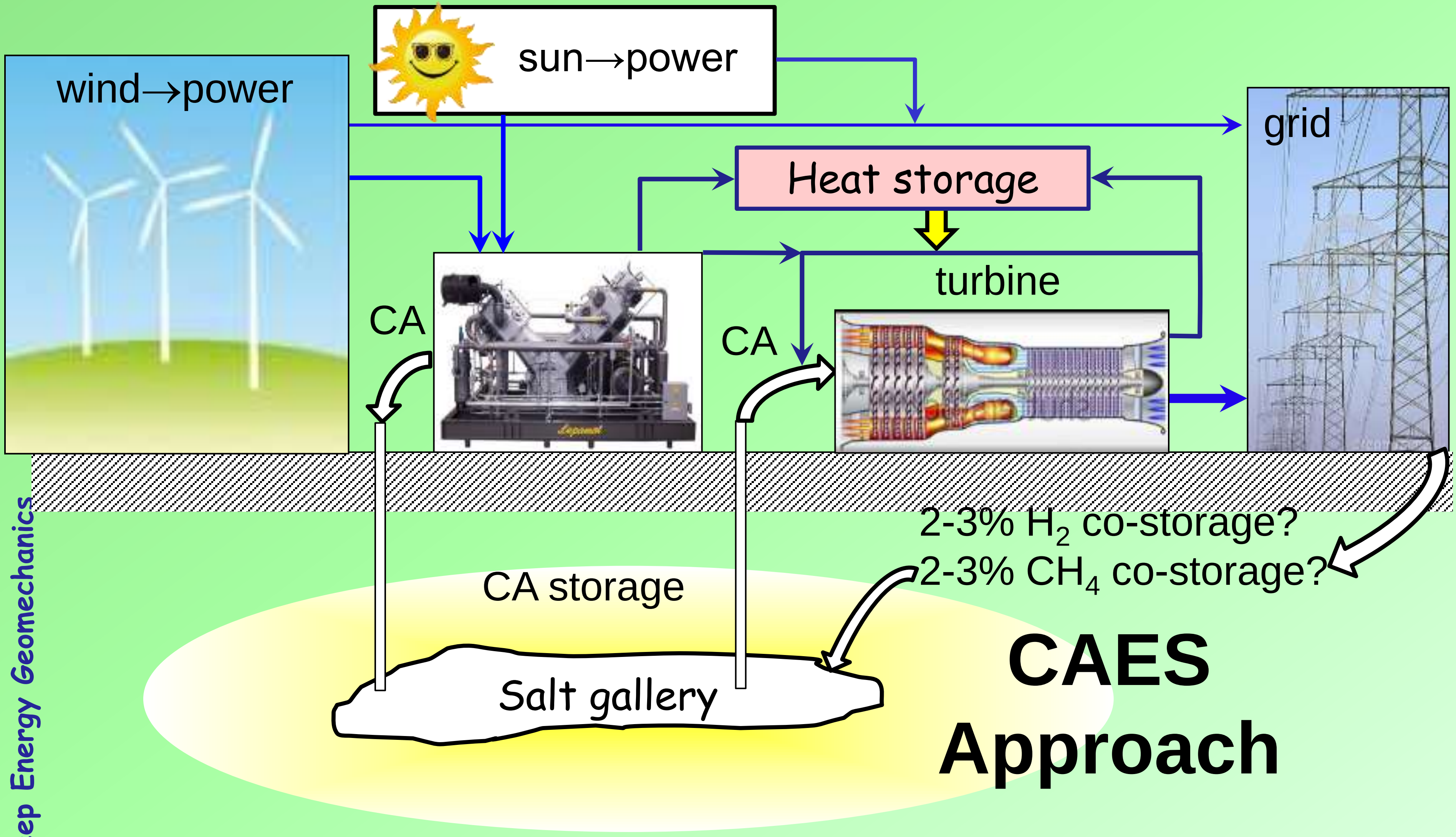



CAES time frame is considered to be daily

**…and it can be large-scale 100-500 MW per project**

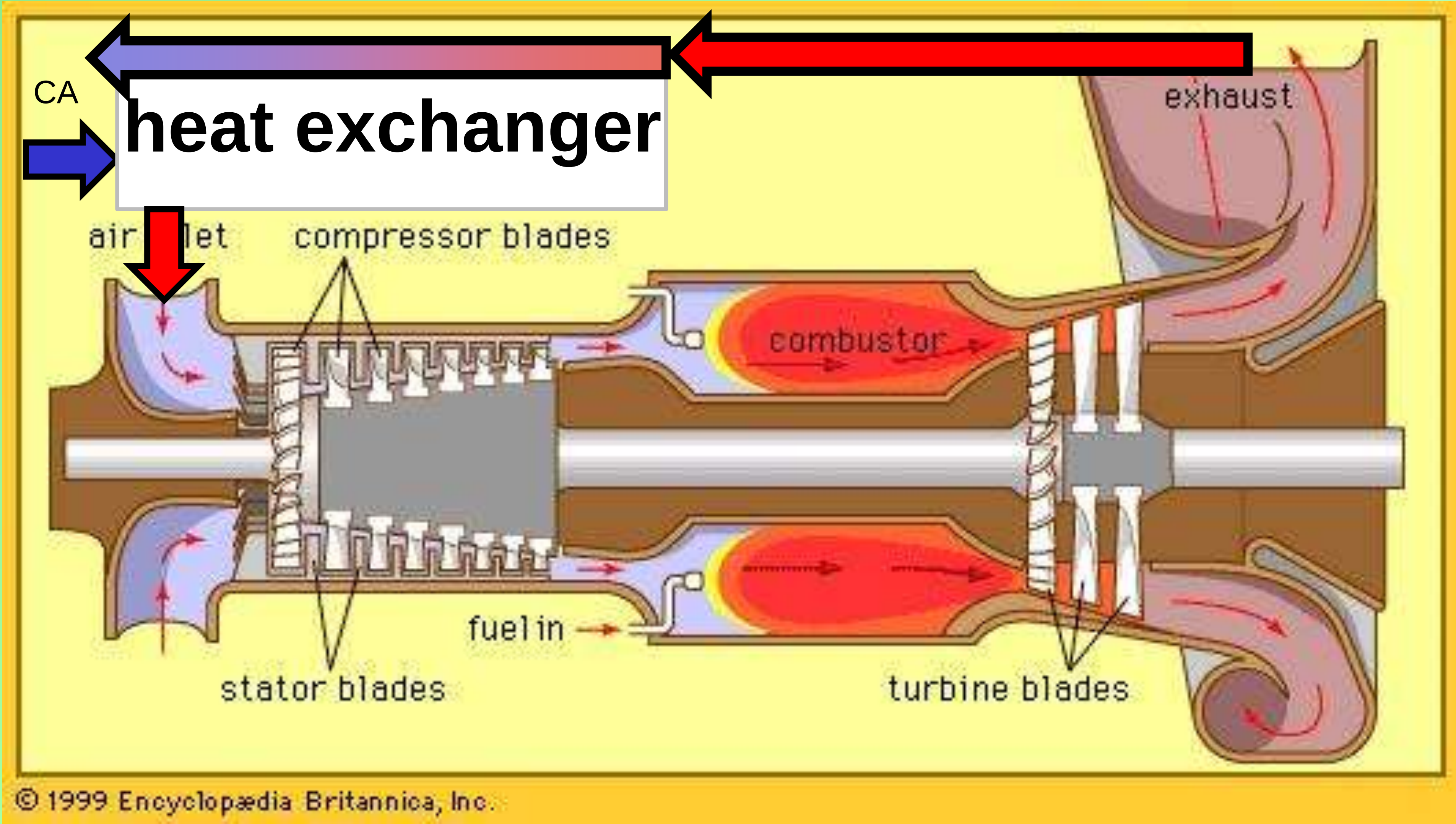
# The CAES Concept…





# Combustion Gas Heats CA

- Heat Efficiency

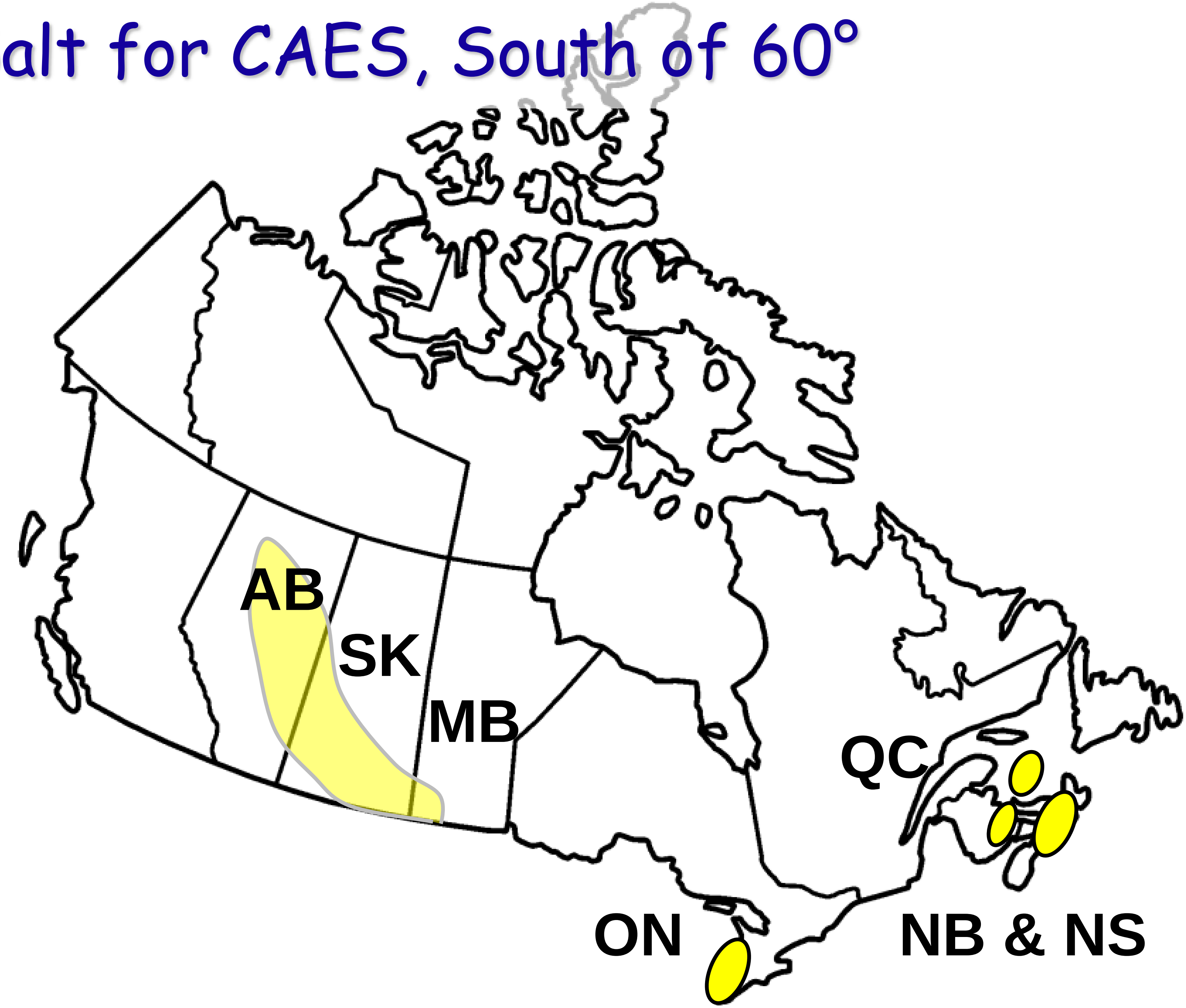


# Salt – Halite - NaCl



- Soluble, $\rho$ = 2.16, low $\varphi$ = 0.002–0.02
- Macrocrystalline – 3–25 mm
- Exhibits **creep behavior** at engineering T-$\sigma$ conditions
- *A* valuable resource…
  - Industrial use, de-icing, etc.
  - NaCl strata and domes trap valuable oil & gas
  - Dry storage in mined salt repositories (Kansas)
  - Underground storage of fluids ($CH_4$, $C_2H_4(OH)_2$…)
  - Waste disposal – toxic & non-toxic solid wastes
  - **Power storage – CAES**

# Salt for CAES, South of 60°



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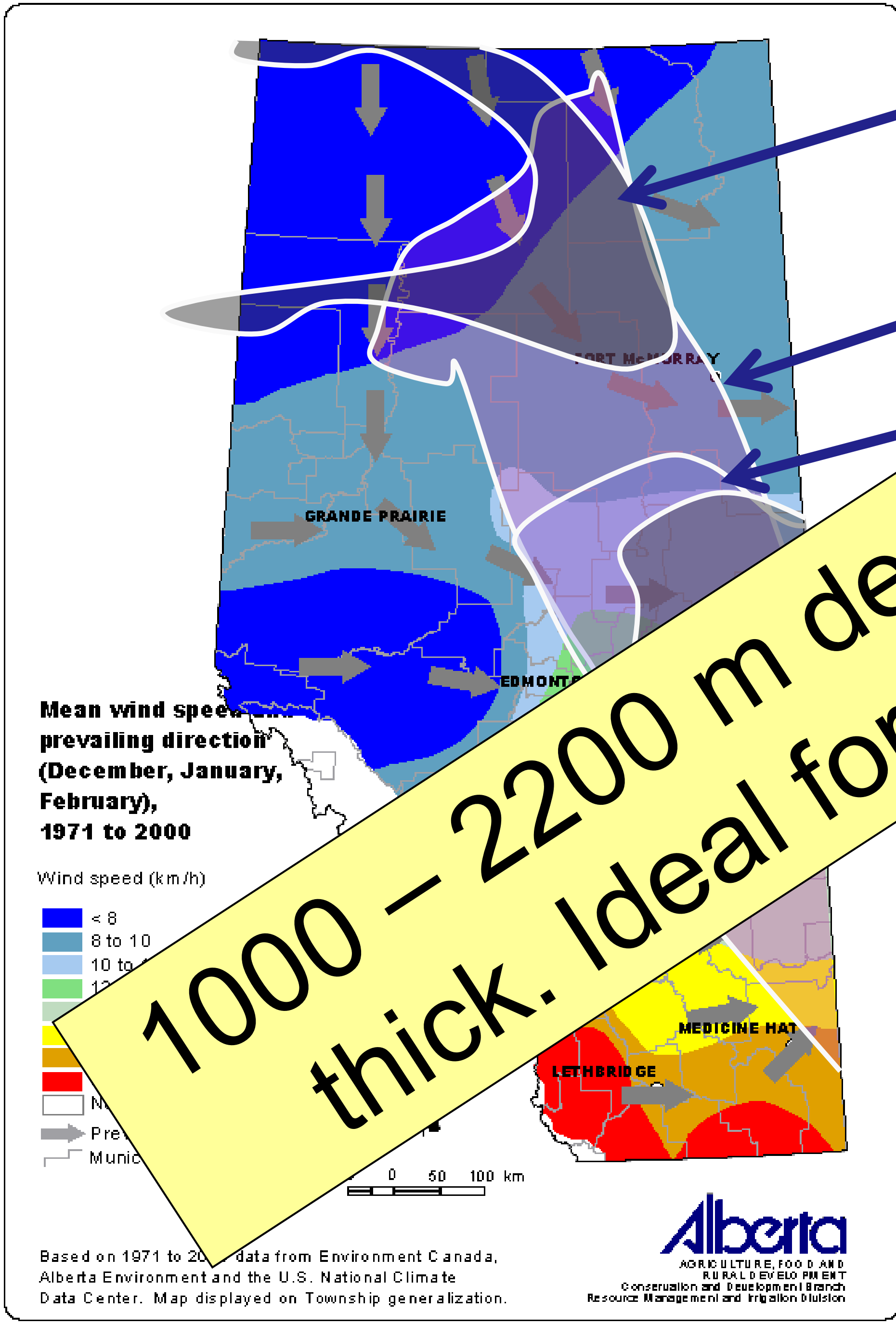



Cold Lake Fm

Prairi

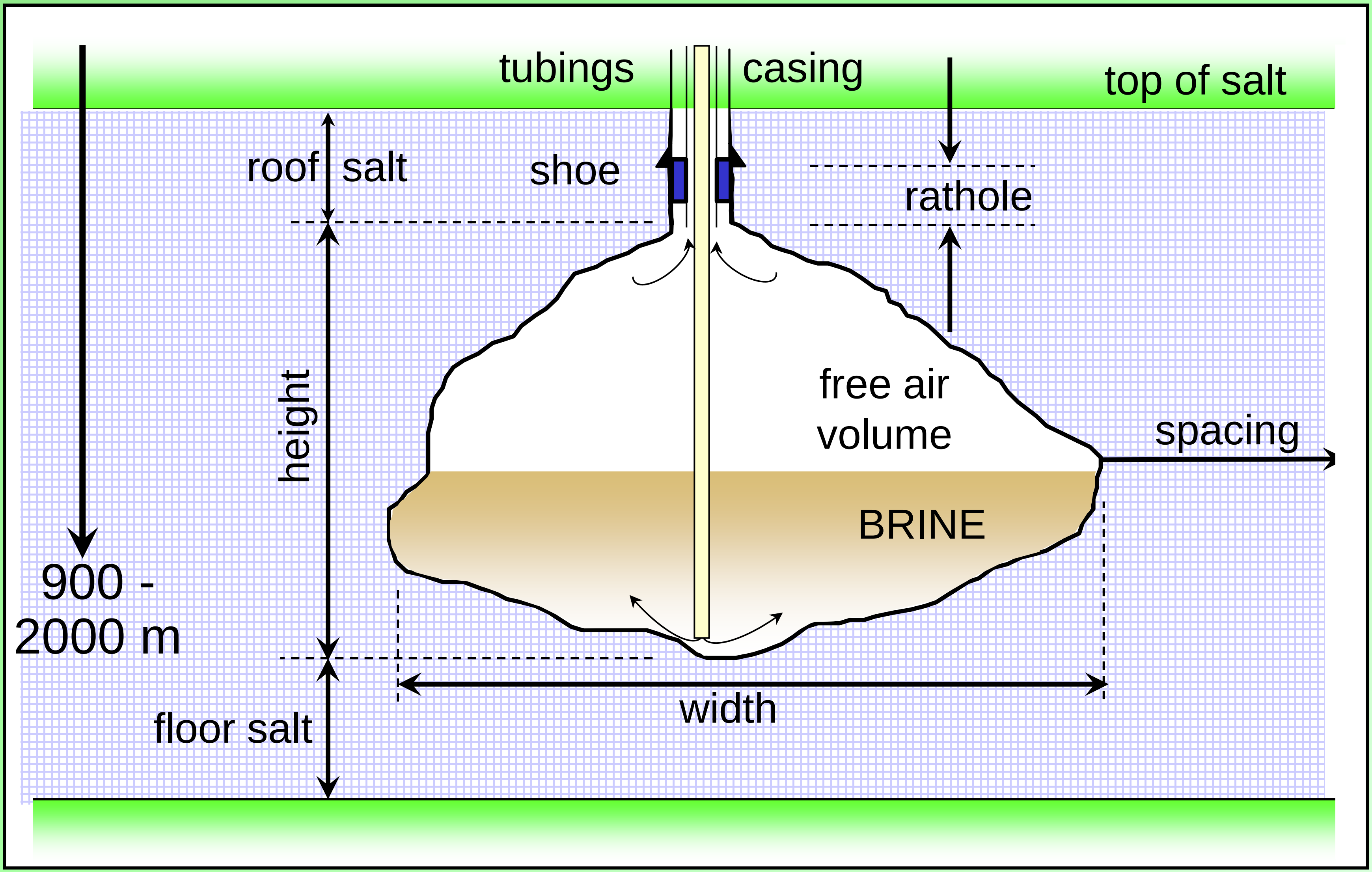
Fm

1000 – 2200 m deep. Up to 200 m thick. Ideal for CAES caverns

**Wind in Dec Superposed with NaCl Strata**

# CAES - Constant P Mode





# Thick Salt & Good Wind!

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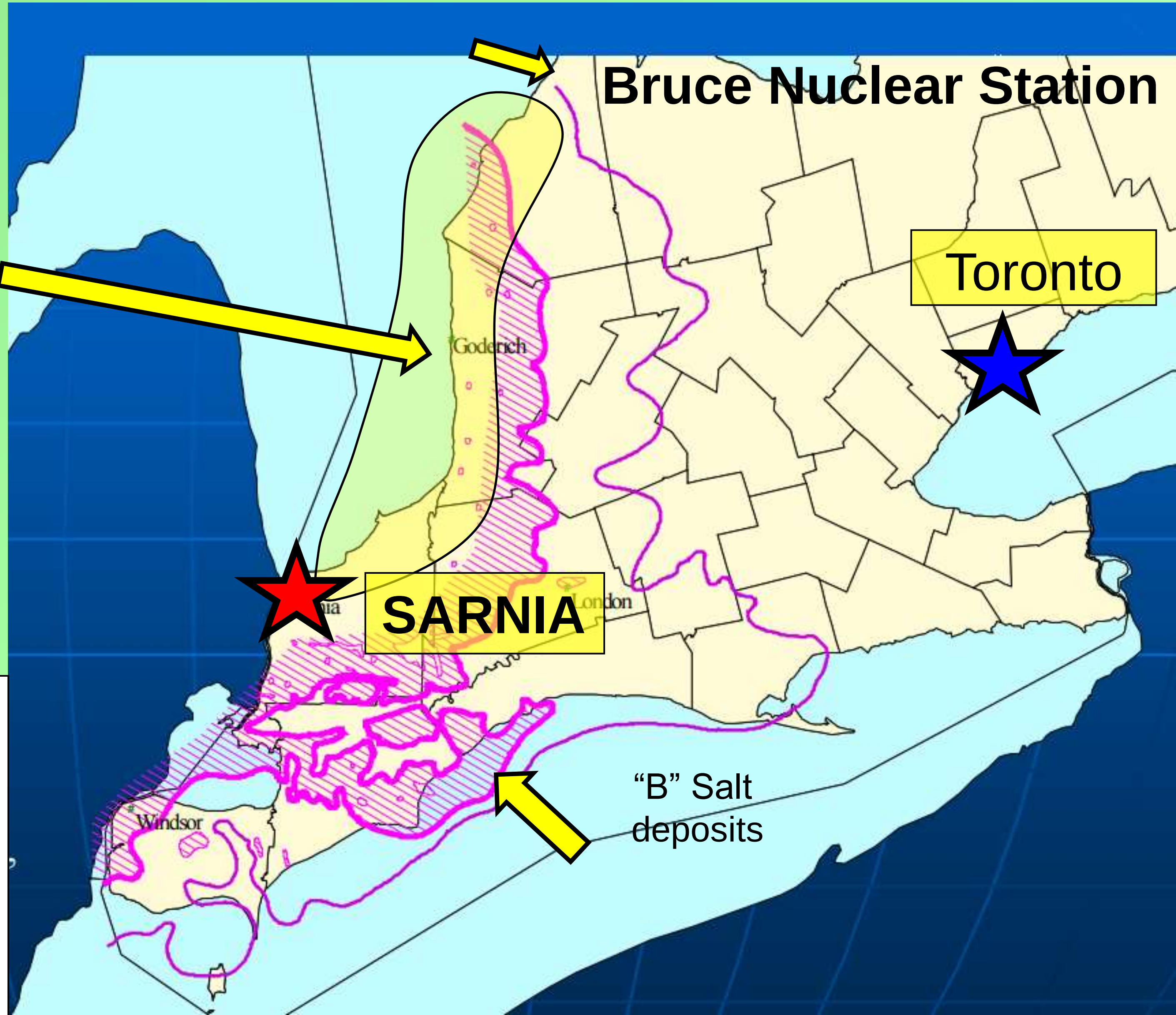
**Lake Huron Coast = best windy sites in SW Ontario**




Salina B Salt – thickest, but not the deepest

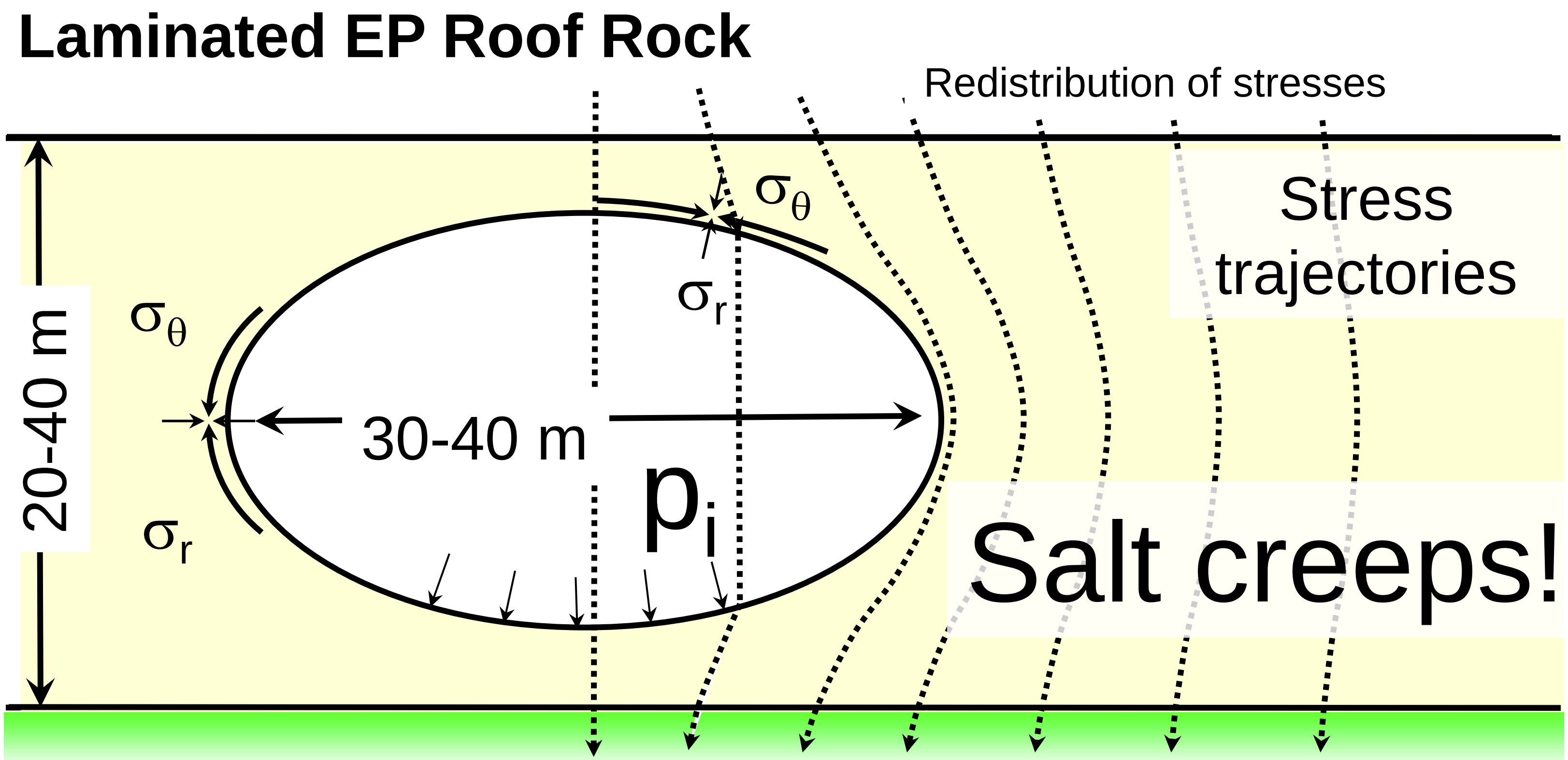
anics

# Salt - Asse Salt Mine (DE)



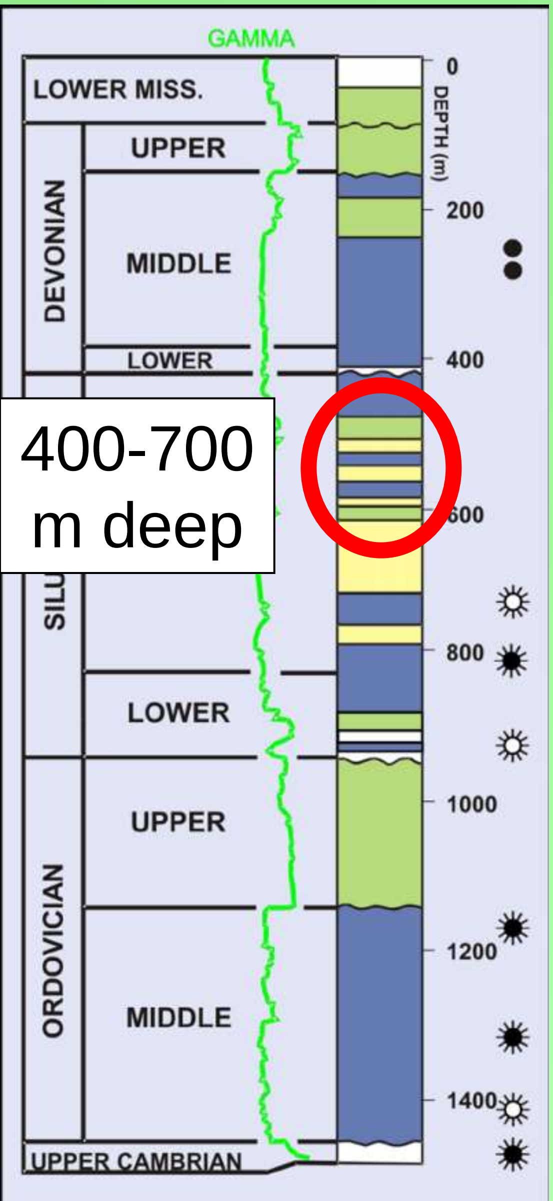
# Gallery Stress Redistribution



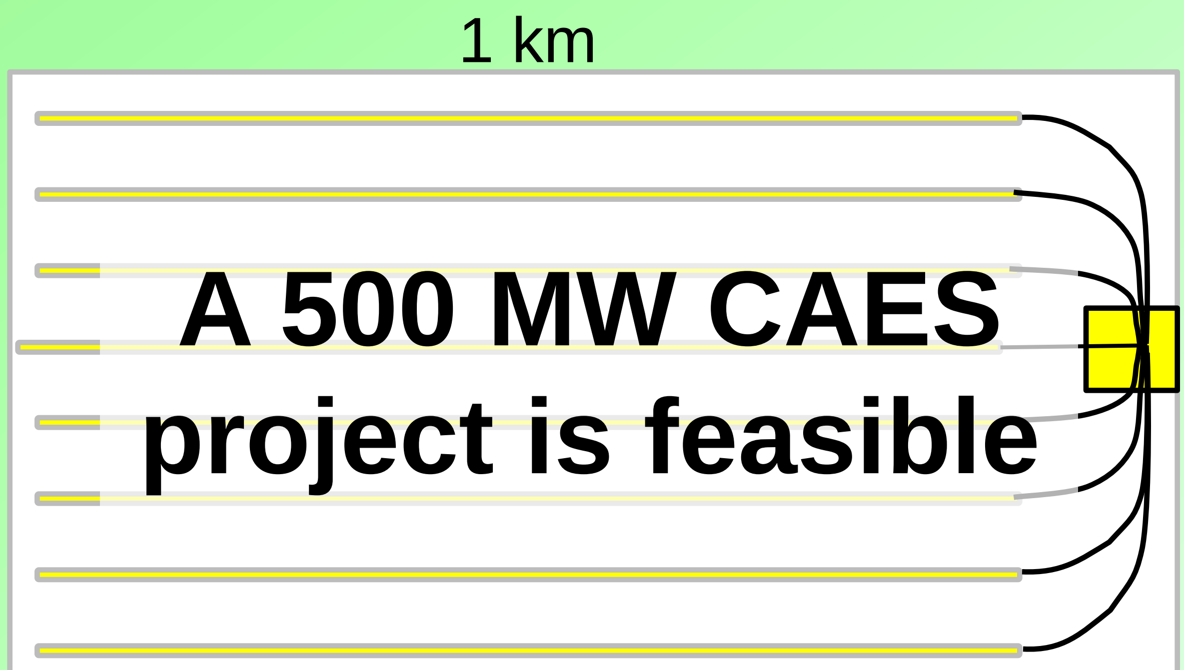



30 year life, up to 10,000 Δp cycles?

# In Our Study… AB & ON




- The thinly bedded salts of ON will require the use of long **<u>Galleries</u>** for economies of scale
- The solutioning of such galleries is a novel aspect

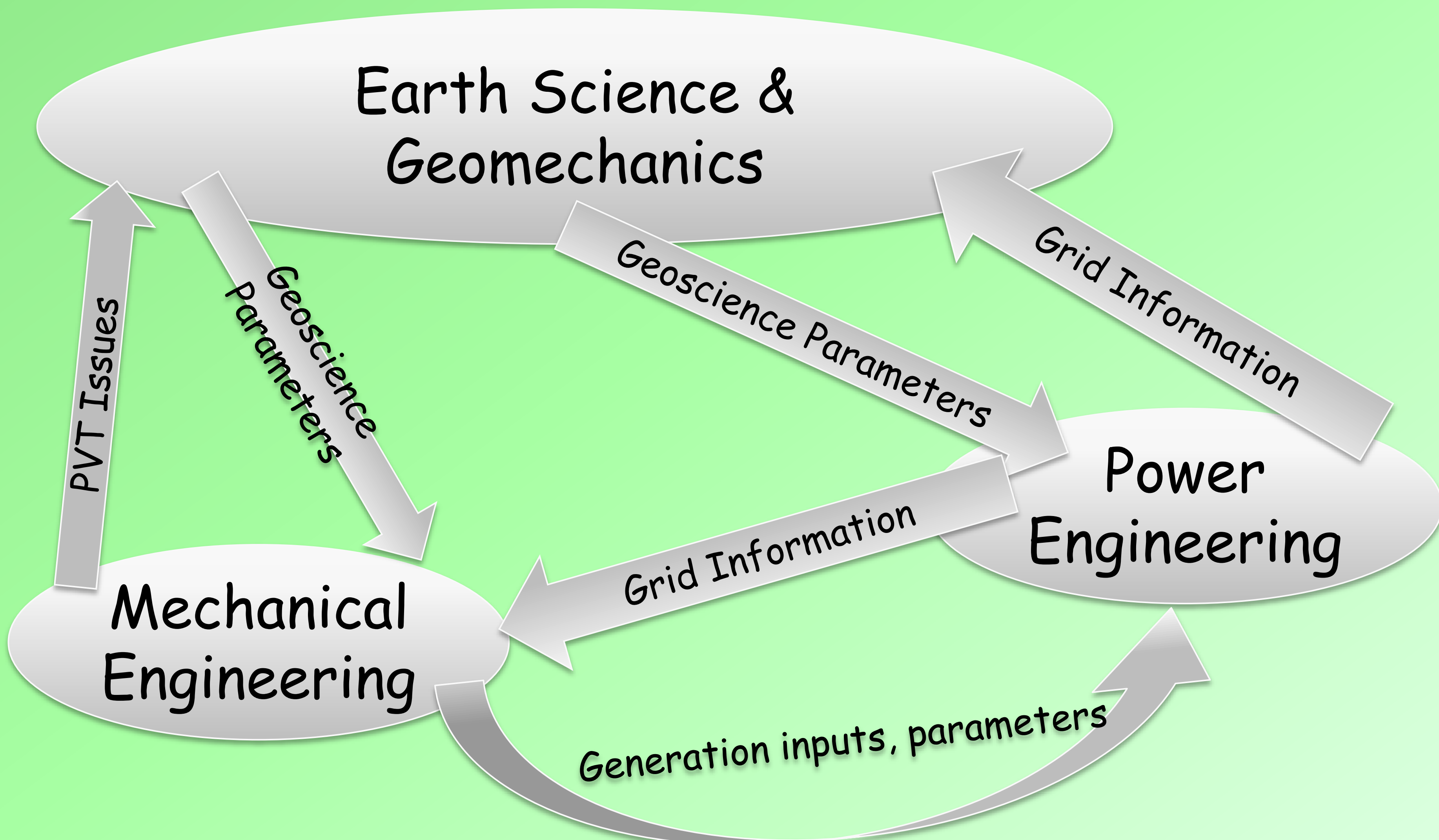


# Geomechanics Challenges…



- Long (800 m) galleries in thinly bedded salt is a new idea
- Stability issues
  - ➔ Long-term roof span stability in non-salt rocks
  - ➔ Cyclic loading and permeability/gas effects
  - ➔ Modeling rock mass behavior is needed
- A new advantage for long galleries…
  - ➔ Roof instability in an axisymmetric cavern with a vertical well leads to likely well impairment
  - ➔ But not in a gallery, the roof span is smaller…
- Porous reservoir use is an inferior option
- …but salt is not everywhere…

# CAES Discipline Integration



# Deep Disposal of Wastes

# Deep Disposal?

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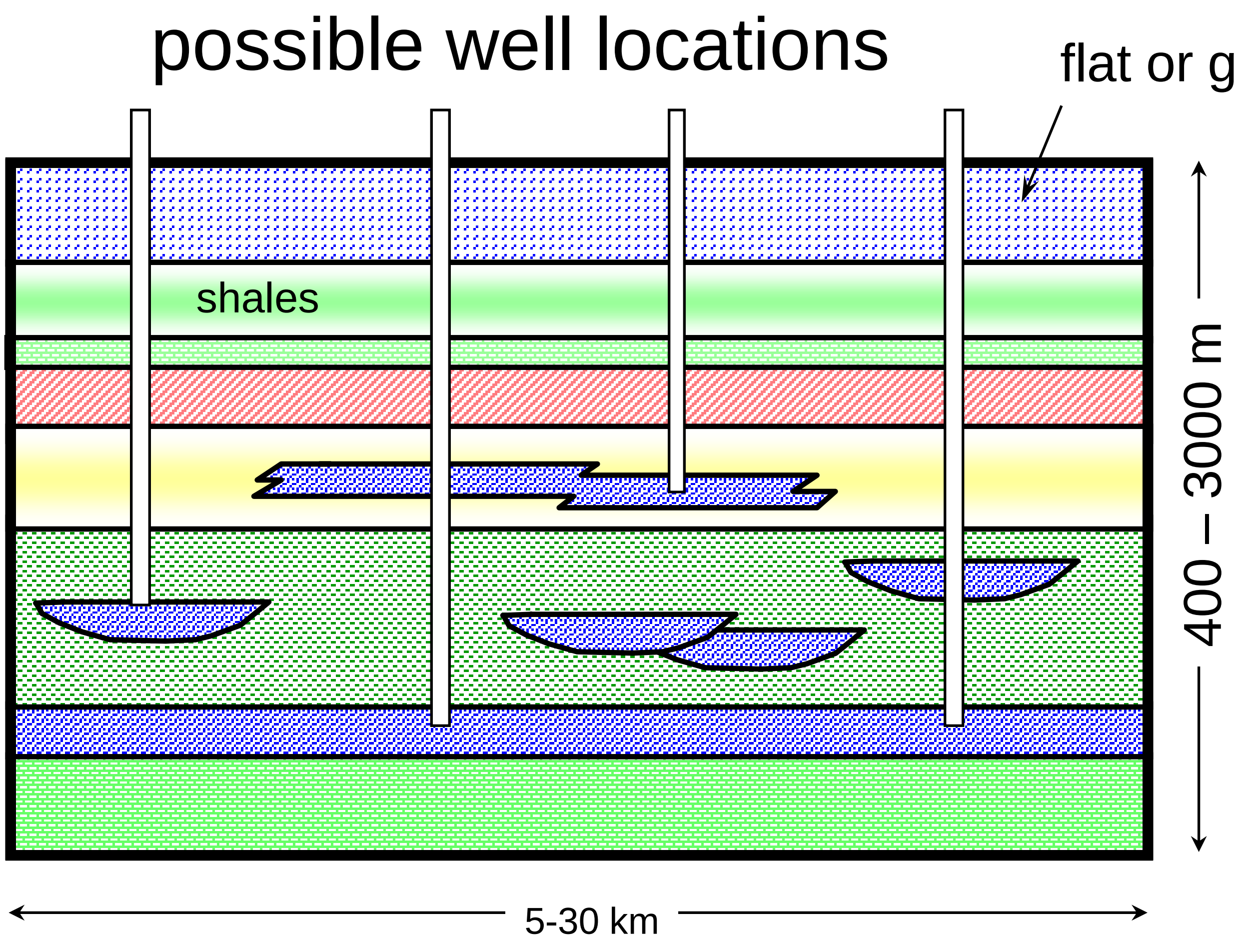
- Industrial activity (energy) generates wastes…
- Recycling – treatment – disposal…
- Waste aqueous liquids and solids can be placed deep in sedimentary strata, giving…
  - ➔ Permanent entombment, high security
  - ➔ Protection of the surface environment (no landfills)
  - ➔ Reasonable costs
- The process of solid waste disposal is one of continuous hydraulic fracturing…
- Issues include site suitability, operations management, monitoring…
- +20 years experience now exist…

# Ideal Disposal Lithostratigraphy




Shale barriers to flow

Permeable zones blunt upward migration

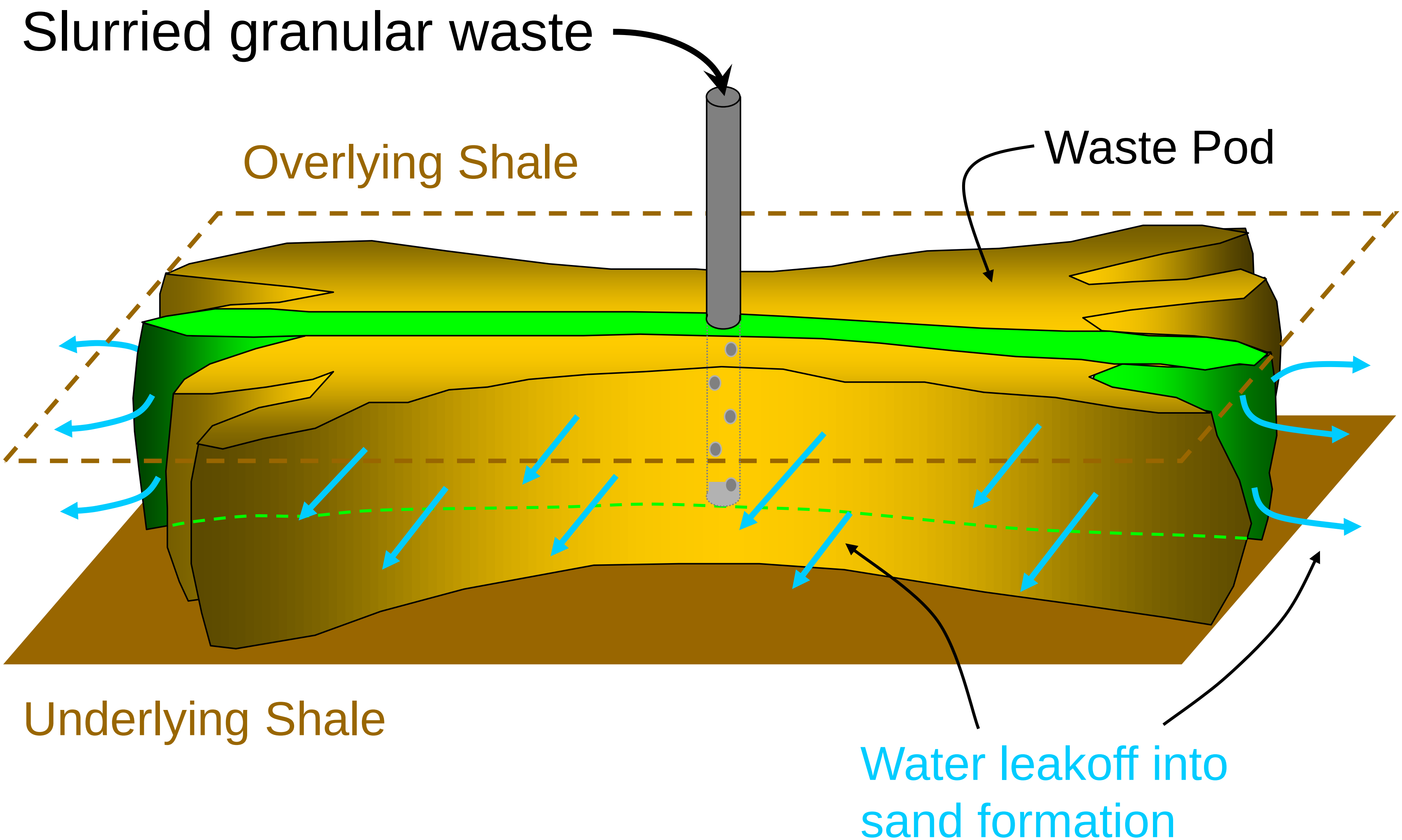
Zones with good storage

High k zones

No O&G reserves

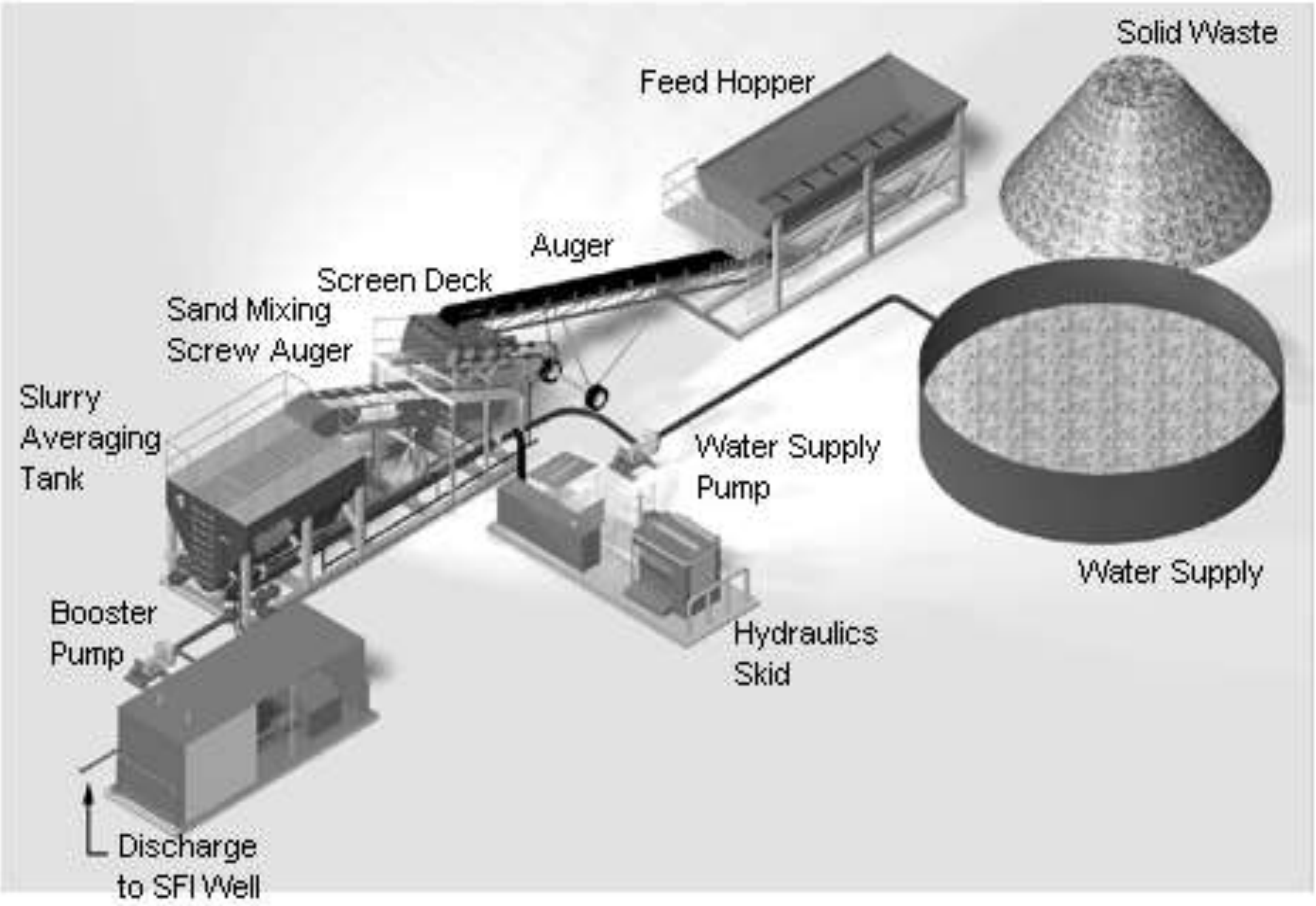
not to scale

# Waste Pod Growth



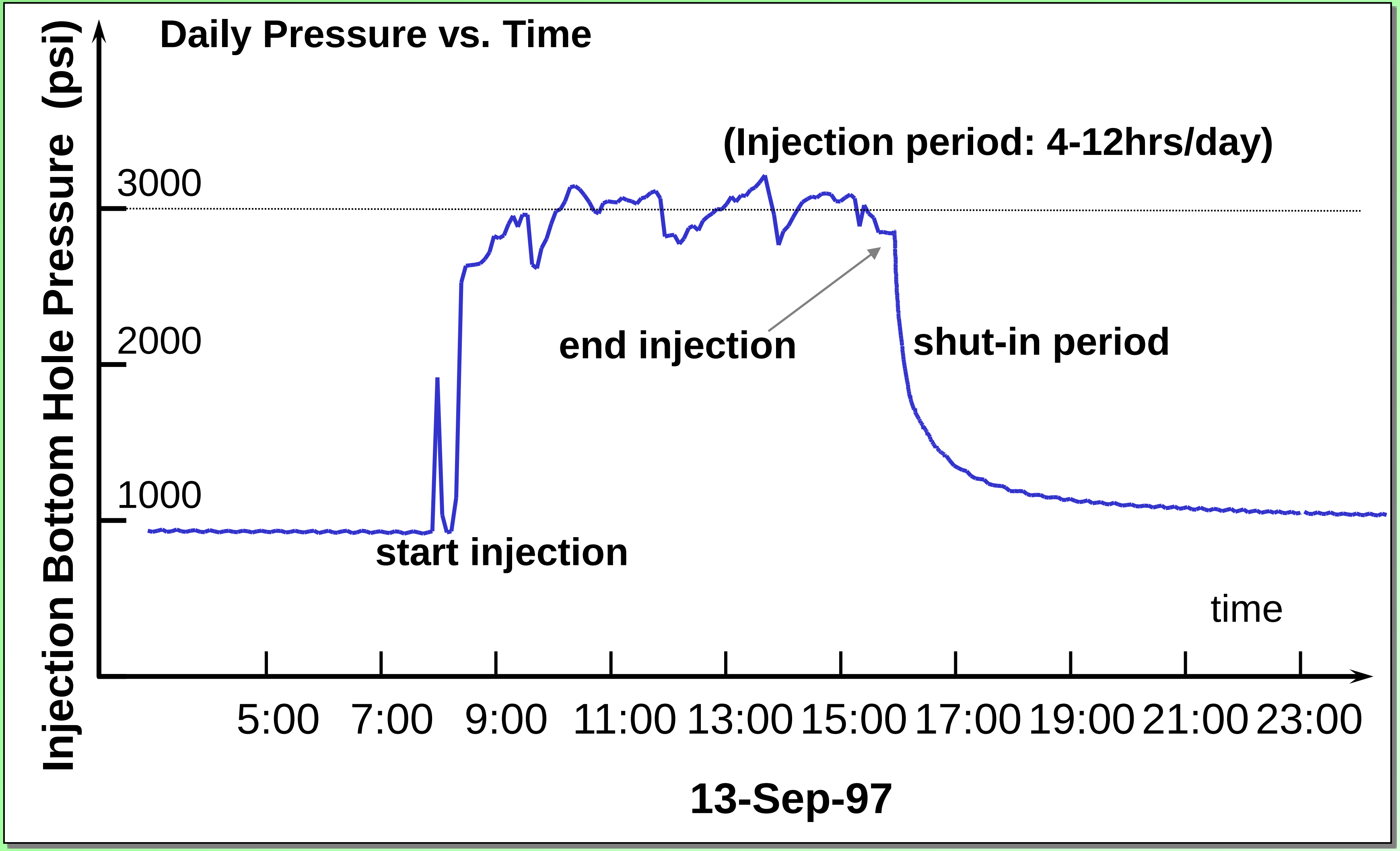
# Schematic of Injection System





# Deep Injection near Los Angeles

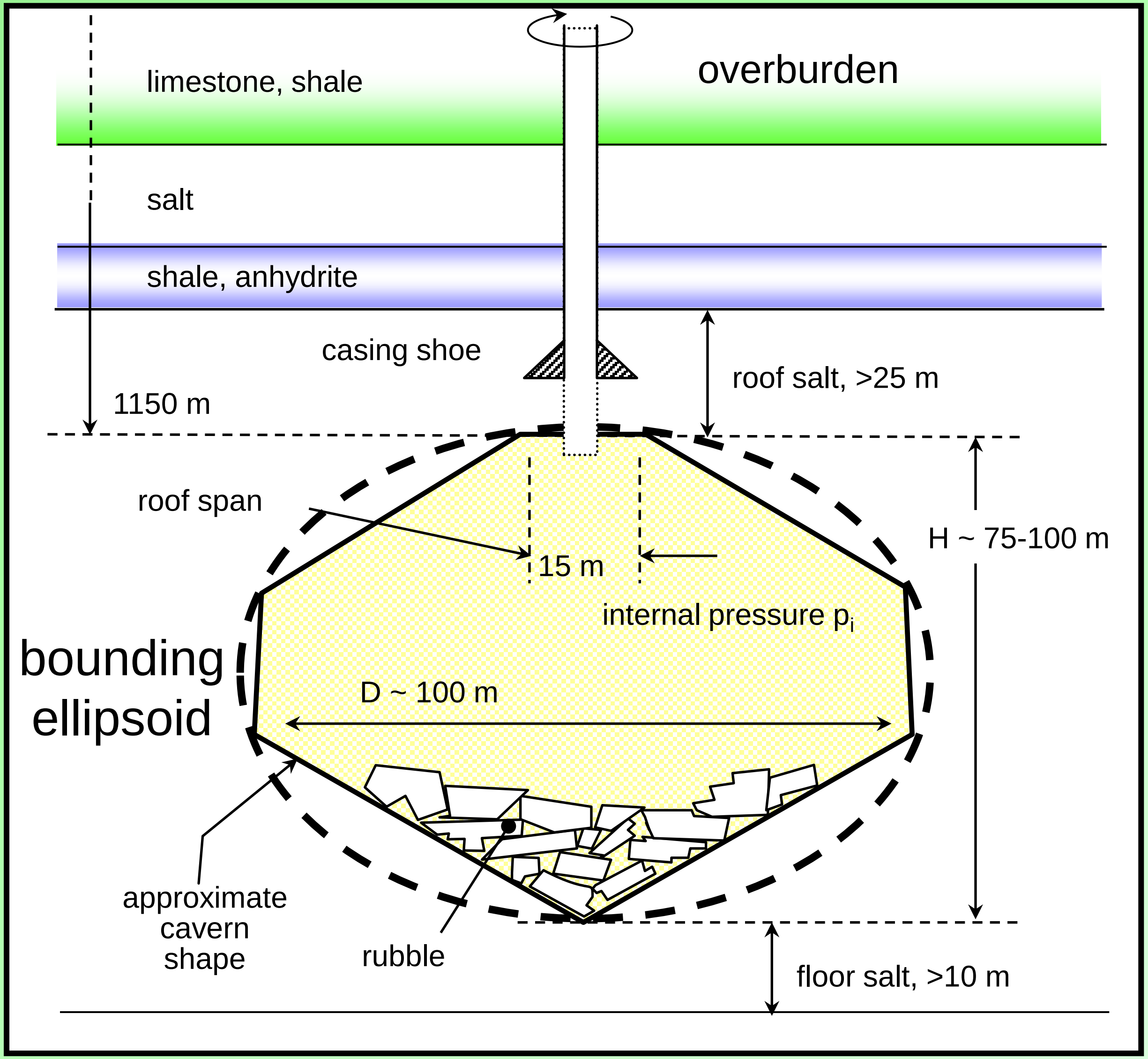
# One Day's Injection Record




Deep Energy Geomechanics

# Salt Cavern Waste Disposal

- Integrity
- Stability
- Security
- Safety
- Longevity
- …
- …




Deep Energy Geomechanics


Waste Placement
in a Salt Cavern

# Deep Disposal Geomechanics

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- Site selection and capacity
- Monitoring of "everything" to assure good containment and process control
- Massive stress changes induce changes in the formation response to injection
- Well integrity must be assured, monitored
- Simulation is challenging (we are trying DEM methods to achieve better understanding)
- In salt caverns… …closure rates, excess brine disposal, and some other geomechanics issues
- Challenges remain, and many geomechanics issues arise

# Geomechanics in deep, naturally fractured rock masses presents challenges and opportunities

# Conclusions - A



- Geomechanics must be **integrated** with…
- Geological, geophysical sciences (e.g.: fabric)
- Petroleum engineering (e.g.: multiphase flow)
- Thermal sciences (e.g.: thermoelastic stresses)
- Environmental sciences (e.g. well integrity)
- Need for decarbonization (climate change…)

Interdisciplinary integrations present great challenges and great opportunities for geomechanics research and development

# Conculsions - B

- Deep Geomechanical Processes involve…
- A urgent need for better **monitoring**, especially deformations (fiber optics, tilt…)
- Models that can simulate the **evolution** of naturally fractured rock mass properties
- Understanding of large-scale stress changes and induced **seismicity** (prediction, control…)
- Impacts of **cyclic loading** on rocks – daily to annual cycles
- Geomechanics is the **key discipline** in most deep energy-related processes

# Acknowledgements


- Conference organizers, especially Quentin
- Yin Shunde, one of the best graduate students I have ever had the pleasure of helping (he taught me a great deal)
- Colleagues and funding agencies over 30 years…


*Deep Energy Geomechanics*