Understanding the Potential for Geologic Hydrogen Resources

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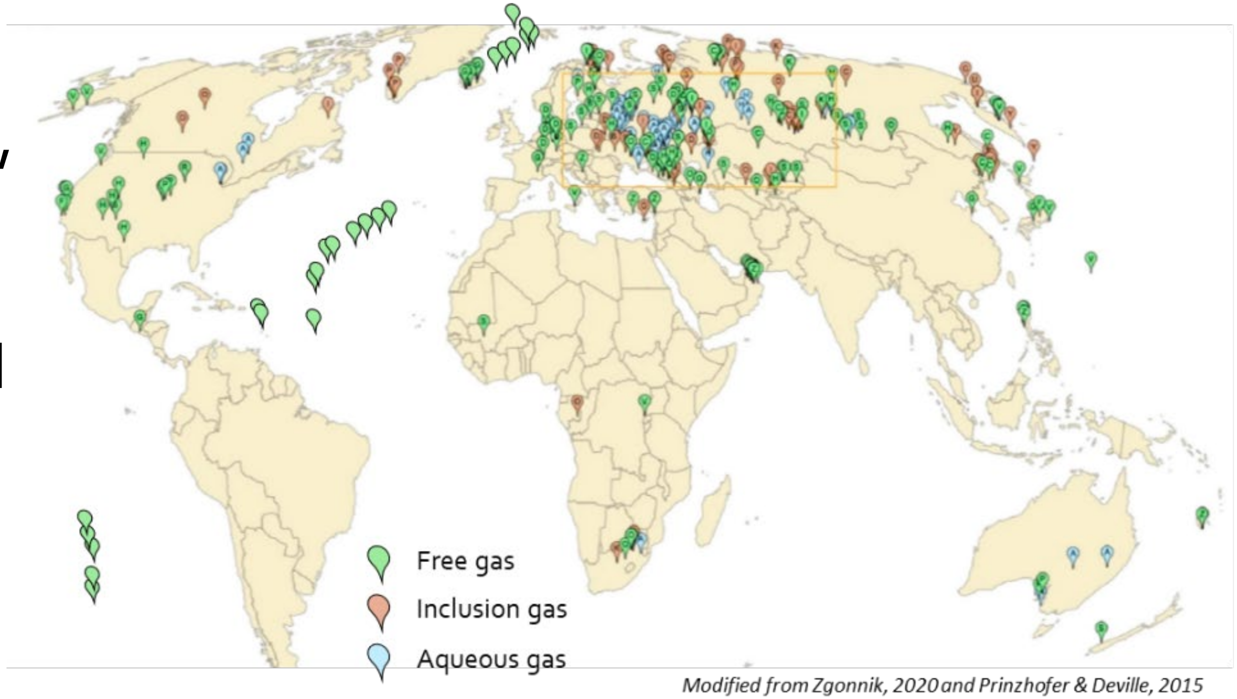
Observations of hydrogen gas on Earth

- Surface observations of high hydrogen concentrations are common
- Associated with mid-ocean ridges, ophiolites, and intracratonic settings
- Deep bore holes and underground mines
- Local flux can be large (~1 Mmcf/day)
- Global annual H2 flux from the subsurface estimated to be ~23 Mt

Surface observations of high hydrogen concentrations (>10%)

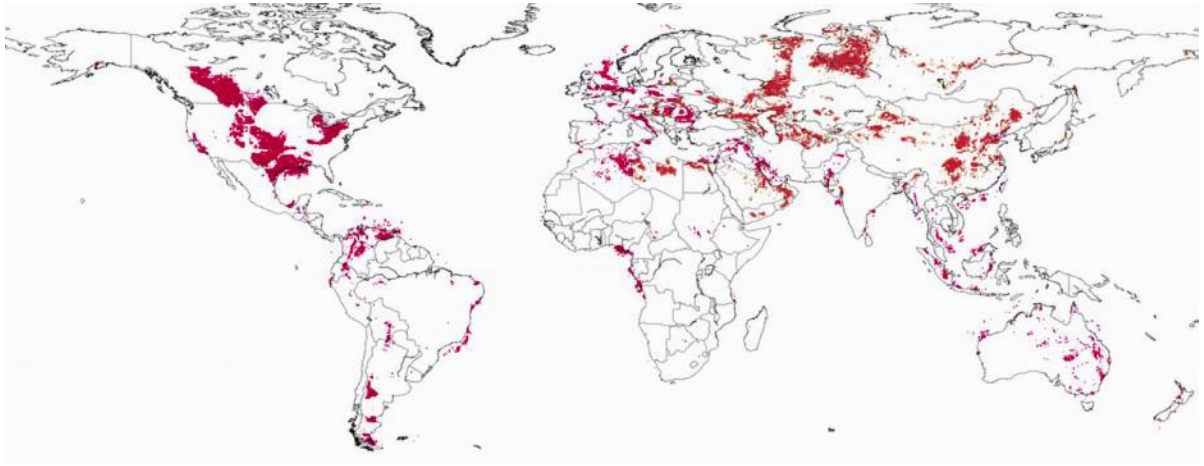


Modified from Zgonnik, 2020 and Prinzhofer & Deville, 2015

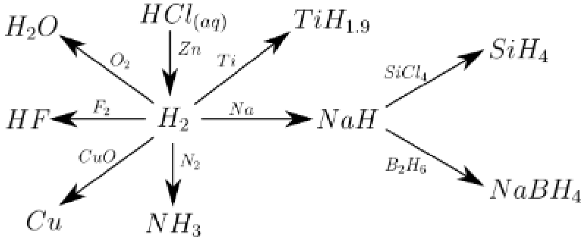
Observations of hydrogen gas on Earth

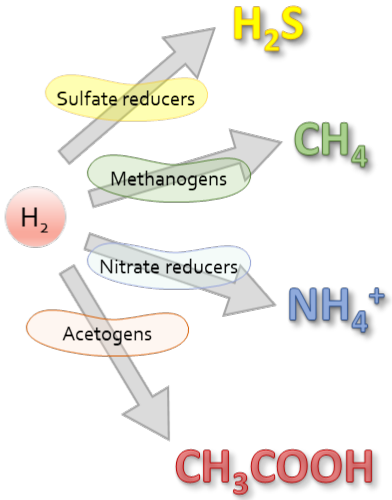
- Millions of oil and gas wells drilled worldwide
- Hydrogen above trace levels (>~1 %) reported in only a few dozen fields
- Hydrogen is diffusive and reactive (both biologic and abiotic reactions)
- Economic accumulations of hydrogen gas *probably* can't form

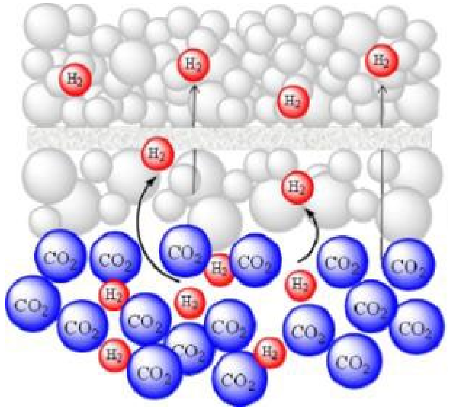
Global distribution of oil and gas wells



Modified from Scarpelli et al., 2020

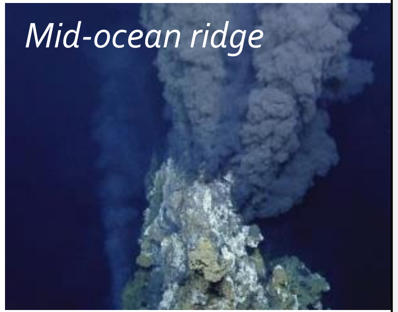






Limitations to oil and gas well observations

- Petroleum exploration is not targeted at hydrogen
- Hydrogen not always analyzed in natural gases
- Geologic settings where hydrogen generation is most likely to occur are not where oil and gas is found
  - Ophiolites
  - Mid-ocean ridges
  - Precambrian cratons
- Hydrogen migrating upward through thermally mature organic-rich rocks is likely consumed by hydrocarbon forming reactions



Mineral exploration generally does not look at gas composition and is typically much shallower than the probable locations for hydrogen accumulations

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BOOK CHAPTER

Hydrogen exploration: a review of global hydrogen accumulations and implications for prospective areas in NW Europe

Author(s): N. J. P. Smith ; T. J. Shepherd ; M. T. Styles ; G. M. Williams

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Abstract

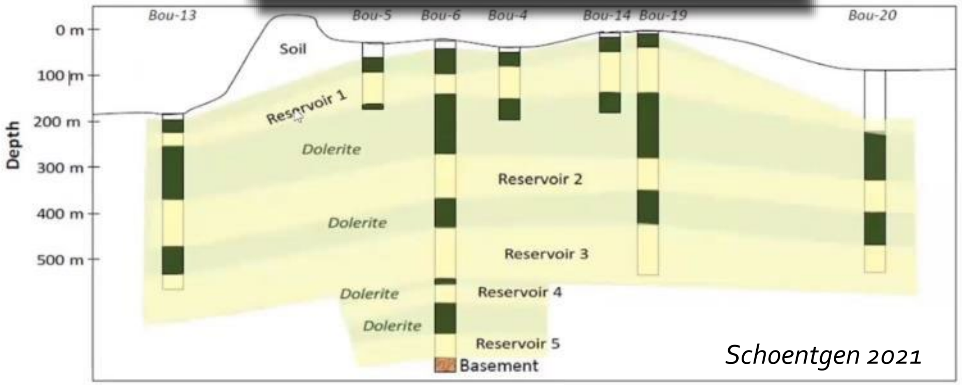
From a geological perspective, hydrogen has been neglected. It is not as common as biogenic or thermogenic methane, which are ubiquitous in hydrocarbon basins, or carbon dioxide, which is ... drogen ... th the oceans ... with abiogenic ... eoretically ... hiolites ... rust basins ... and the Mid-Atlantic ridge and its fracture zones. The subsurface areas of these environments are relatively poorly known, compared to hydrocarbon basins.

Hydrogen shows may indicate larger reserves in the subsurface, in a similar way to the beginnings of hydrocarbon exploration in the 19th century. The main source of hydrogen is ultramafic rocks, which have experienced serpentinization, although other generation processes have been identified, including biogenic production of hydrogen during very early stages of maturation and radiolysis. There are two main tectonic settings where serpentinization has operated. The main accessible onshore areas are where ophiolites are found tectonically emplaced within fold belts. Potentially much larger investigation areas lie in the subsurface of some ophiolites. These areas generally lie outside hydrocarbon provinces. However, where thrusting has emplaced ophiolites over a hydrocarbon-bearing foreland basin, tests involving sub-thrust conventional hydrocarbon exploration plays could also be employed to search for hydrogen. The other main tectonic setting is in highly extended basins, for example failed rifts or aulacogens, where thick sediments overlie thinned or absent crust above probably serpentinized mantle. These structures occur offshore on continental margins and extend onshore into long-lived rifts which have been reactivated and rejuvenated repeatedly.

We haven't been looking for hydrogen in the right places with the right tools

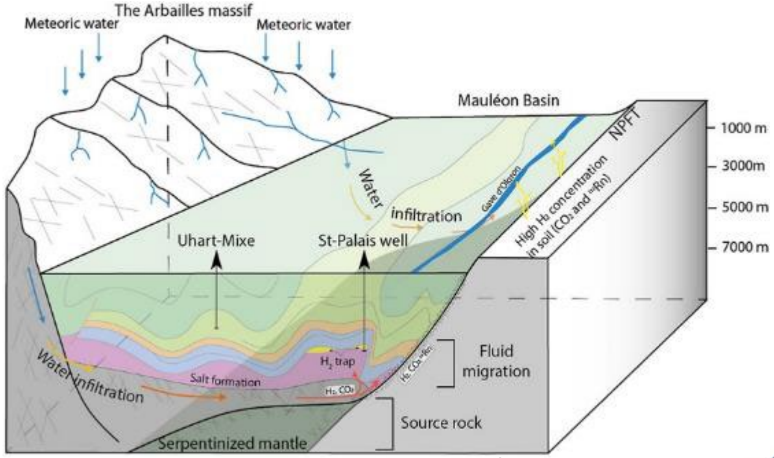
Recent hydrogen resource activity

- Natural hydrogen accumulation discovered in Mali in 2012
- Research and exploration
  - Africa: *Mali, Morocco, Djibouti, and Namibia*
  - Europe: *Pyrenees, Aquitaine Basin, Corsica, the Alps, and Iceland*
  - S. America: *Brazil and Colombia*
  - Australia: *Amadeus and Perth Basins*
- Early in 2021 570,000 km² (~⅓) South Australia leased for natural hydrogen exploration
- 1st wildcat well in US drilled for hydrogen in NE being flow tested, and exploration in NE, KS, and AZ
- 2022 USGS initiated the first and only funded research project in N. America dedicated to understanding hydrogen resource potential



Schoentgen 2021

Geologic model for hydrogen accumulation in the French Pyrenees



Lefeuvre et al., 2022

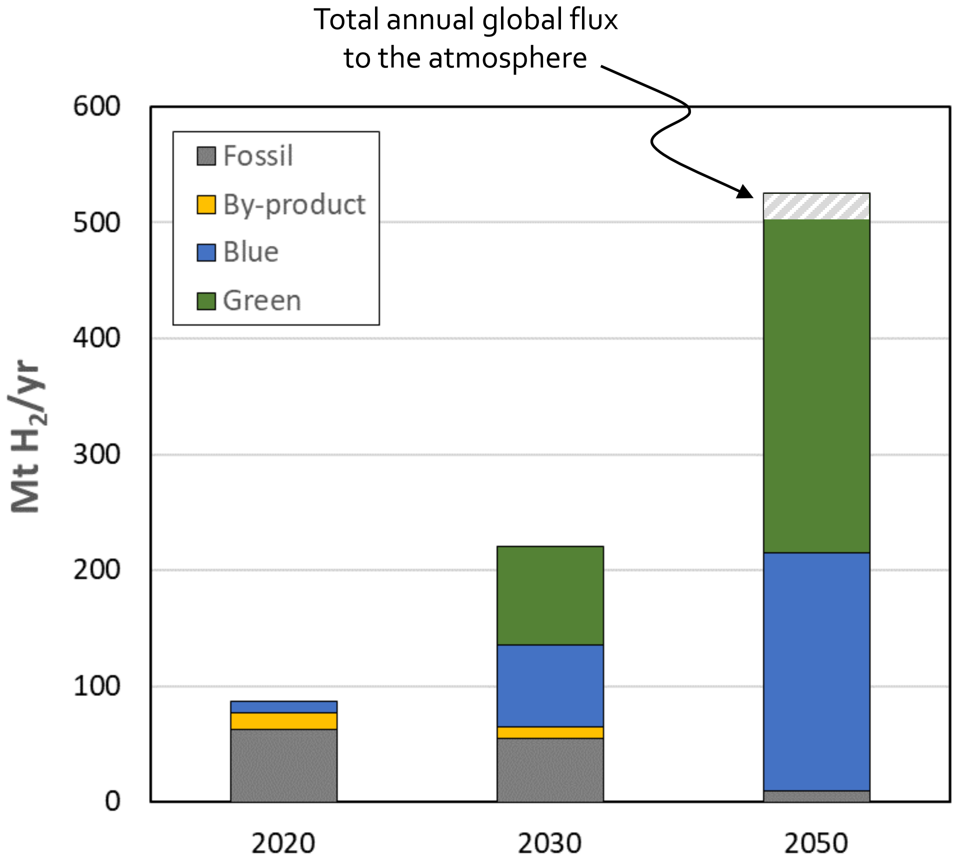
How much hydrogen could be in the Earth?

Context

- Annual global demand projected to be >500 Mt/yr by 2050
- Total flux of hydrogen from the subsurface estimated to be ~23 Mt/yr
- If we could find and produce all of this, it would only meet <5% of global demand

Resource potential depends on:

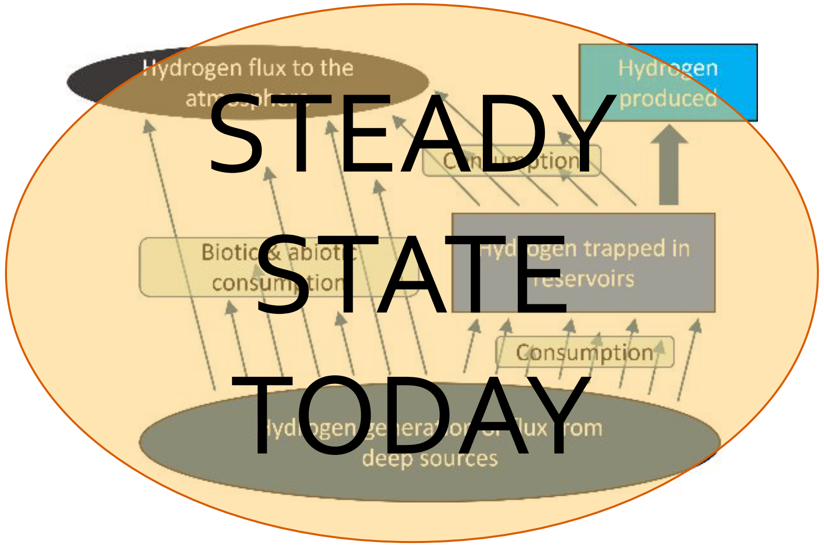
- Trapping efficiency
- Residence time
- Hydrogen consumption (biotic & abiotic)
- Exploration/production success

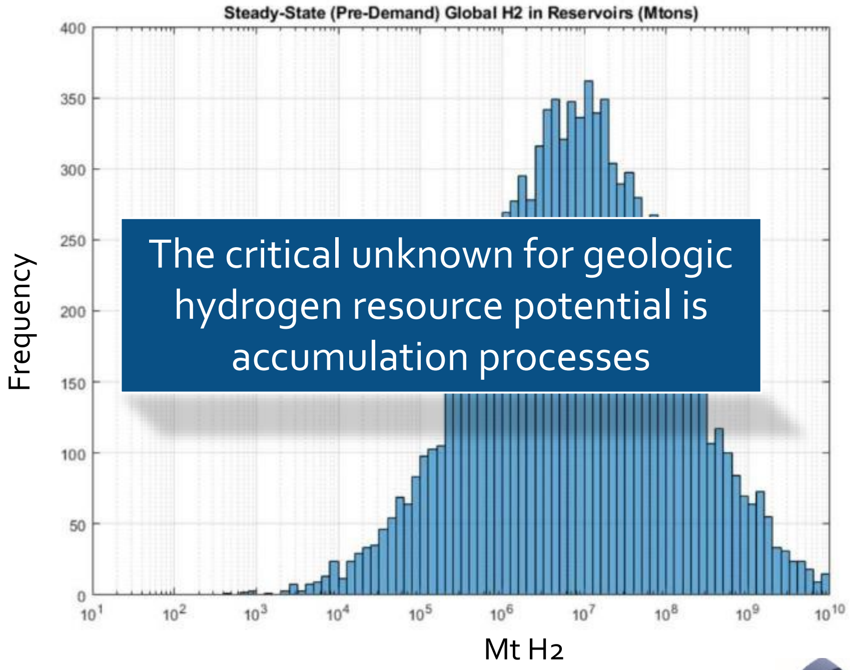


IEA Global Hydrogen Review 2021

Geologic hydrogen resource model

- Simple box model for global hydrogen resources
- Inputs constrained by known hydrogen behavior (e.g., flux to atmosphere, etc.) and analogues (e.g., petroleum, helium, etc.)
- Assume steady state today
- In-place hydrogen amounts may range from thousands to billions of Mt with mean predictions of 10's of millions
- Most hydrogen is likely inaccessible – too deep, too far offshore, too small accumulations
- A few percent recovery would still supply all projected H2 demand (~500 Mt/yr) for 100's of years



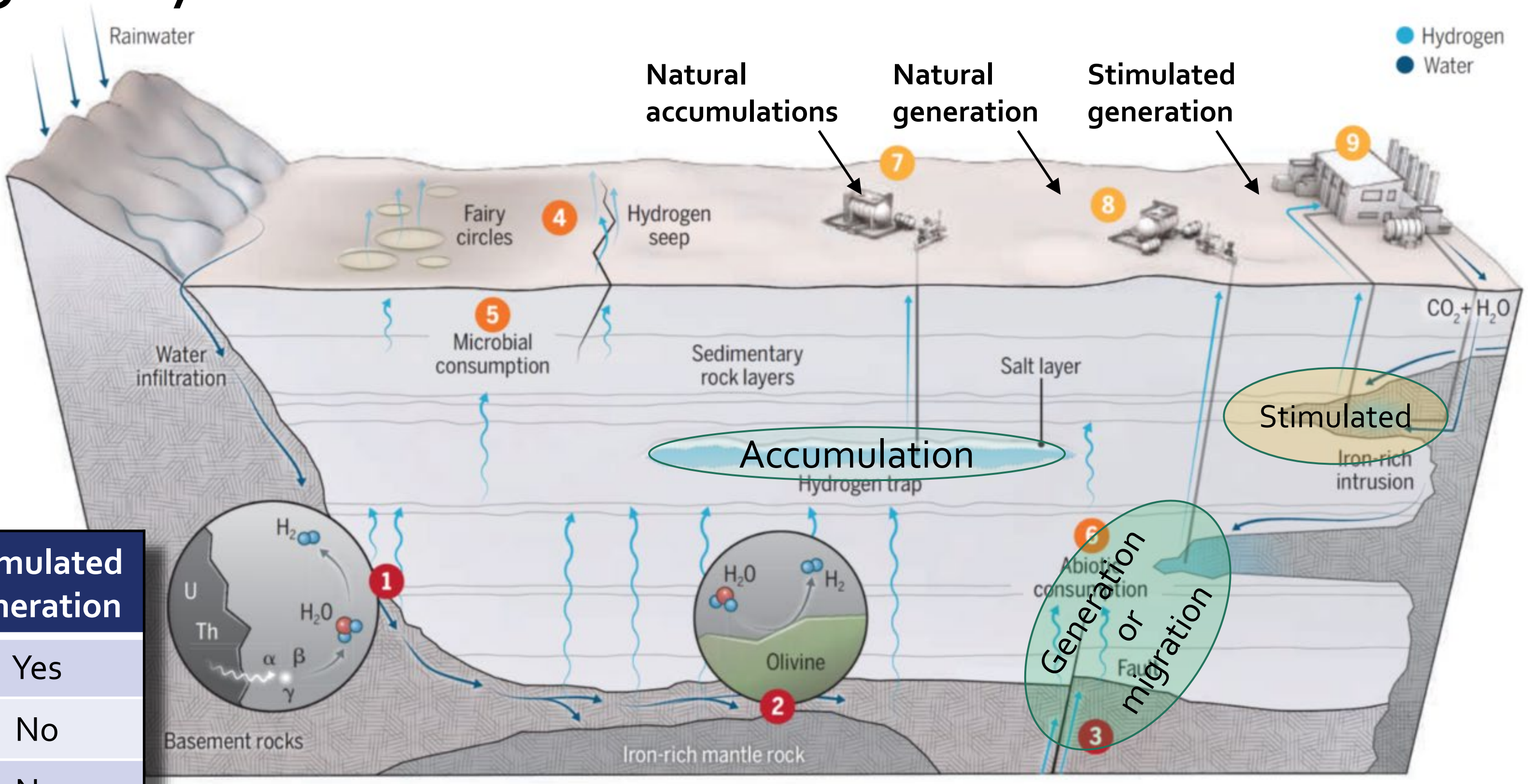


Geologic hydrogen system model

3 conceptual types of exploitable hydrogen resources

Hydrogen system model based on the petroleum system

Component	Natural accumulations	Natural generation	Stimulated generation
Source	Yes	Yes	Yes
Migration pathway	Yes	Maybe	No
Reservoir	Yes	No	No
Trap/seal	Yes	No	No
Preservation	Maybe	No	No
Timing	Maybe	No	No



Hidden Hydrogen - *Science* 2023

Global in-place resource estimate only for natural accumulations

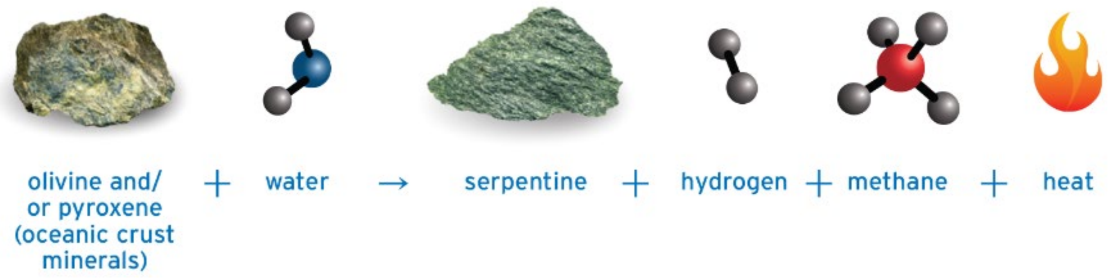
Natural or stimulated generation could provide additional resources

Hydrogen system: Sources

- Identify mechanisms that can generate the largest volumes
- Reaction of water with ultramafic rocks (i.e., serpentinization)
- Deep-sourced hydrogen (may be primordial or generated in the upper mantle)
- Other lesser mechanisms

Sources	x10⁹m³ H_2 /year	Tg/year (=10^6 t/year)	Reference
Geological			
Mid-oceanic rift system	1.3	0.12	(Welhan and Craig, 1979)
	2	0.18	(Charlou et al., 2012)
	3.7	0.33	(Cannat et al., 2010)
	4.3	0.38	(Keir, 2010)
Oceanic crust, by various oxidations	10 ± 7	0.9 ± 0.6	(Bach and Edwards, 2003)
Oceanic crust serpentinization	**1.8–2.9**	**0.16–0.26**	**(Canfield et al., 2006)**
	8.5	**0.76**	**(Sleep and Bird, 2007)**
	22.4	**2**	**(Worman et al., 2016)**
Ophiolite massifs	2–4	0.18–0.36	based on (Zgonnik et al., 2019)
Basaltic layer of the oceanic crust	**84**	**7.5**	**(Sleep and Bird, 2007)**
	139	**12.6**	**(Holloway and O'Day, 2000)**
Precambrian basement	0.45–4.3	0.04–0.38	(Sherwood Lollar et al., 2014)
	0.9–1.2	0.08–0.11	(Warr et el., 2019)
Volcanoes and hydrothermal systems	**108 ± 81**	**9.6 ± 7.2**	**(Holland, 2002)**
Subaerial volcanoes	2–7.7	0.18–0.69	(Canfield et al., 2006)
	2.7	0.24	(Stoiber, 1995)
Mid-ocean ridge volcanoes	0.2–0.6	0.02–0.05	(Canfield et al., 2006)
Coal metamorphism	0.02	0.0014	(Koyama, 1963)
Deep-seated hydrogen	**?**	**?**	
Sub-total for geologic	254 ± 91	**23 ± 8**	

Modified from Zgonnik, 2020

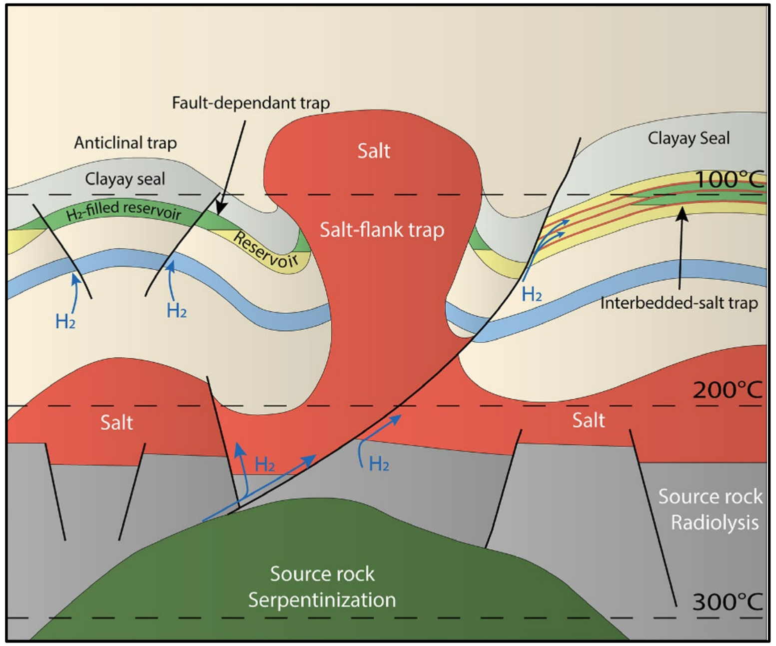


Critical for all hydrogen play types

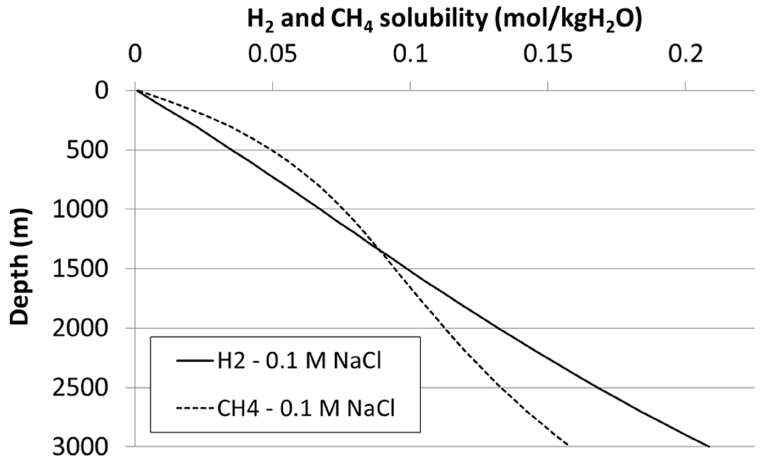
Hydrogen system: Migration

- Broadly similar to hydrocarbon migration
- Hydrogen solubility in water is complex
- Hydrogen migration pathways in crystalline rocks
- Must account for potential migration losses

Only relevant for hydrogen accumulations and some generation play types



Lefeuvre et al., 2022



Lopez-Lazaro et al., 2019

Hydrogen system: Reservoirs

- Porosity and permeability determine reservoir quality
- Conventional sedimentary reservoirs
  - Siliciclastics and carbonates
- Fractured reservoirs in crystalline rocks
- Self-sourced (e.g., porous serpentinites)

Only relevant for hydrogen accumulations and some generation play types

U. Bergen

Fractured granite gas reservoir rock from Qaidam Basin , China (Yang et al., 2020)

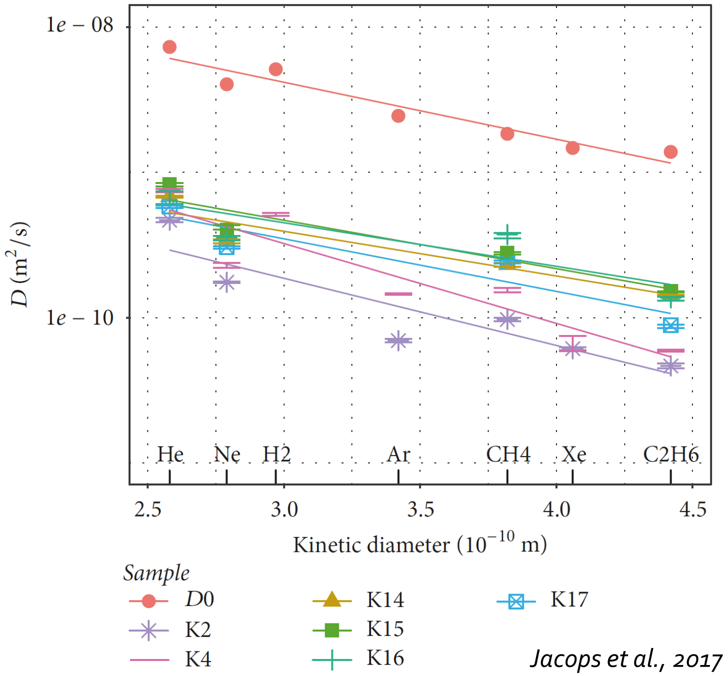
TU Delft

Hydrogen system: Traps and seals

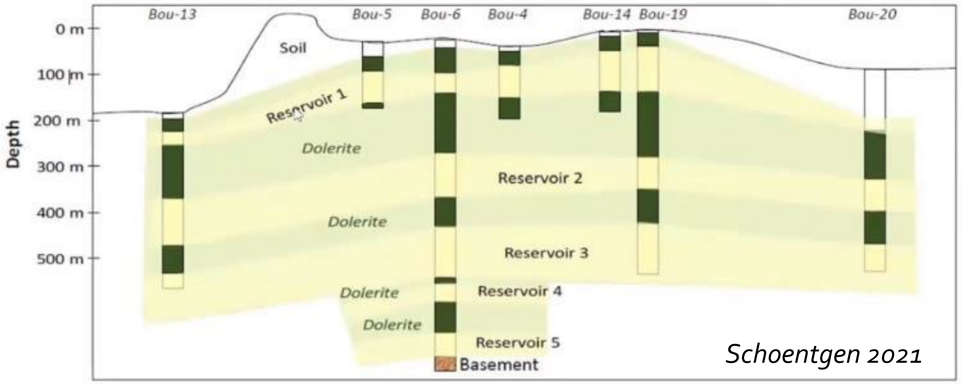
- Seal capacity is critical for forming and preserving hydrogen accumulations
- Kinetic diameter of hydrogen is smaller than methane and close to helium
- Low-permeability seals allow helium to be stored for long time periods (>100 Myr)
- The capillary entry pressure required to force helium gas through seals is similar to CO_2
- Mali accumulation is sealed by dolerite
- Seal capacity of other lithologies is not well understood

Only relevant for hydrogen accumulations

Diffusion coefficients for gases through the Boom clay as a function of kinetic diameter



Jacops et al., 2017

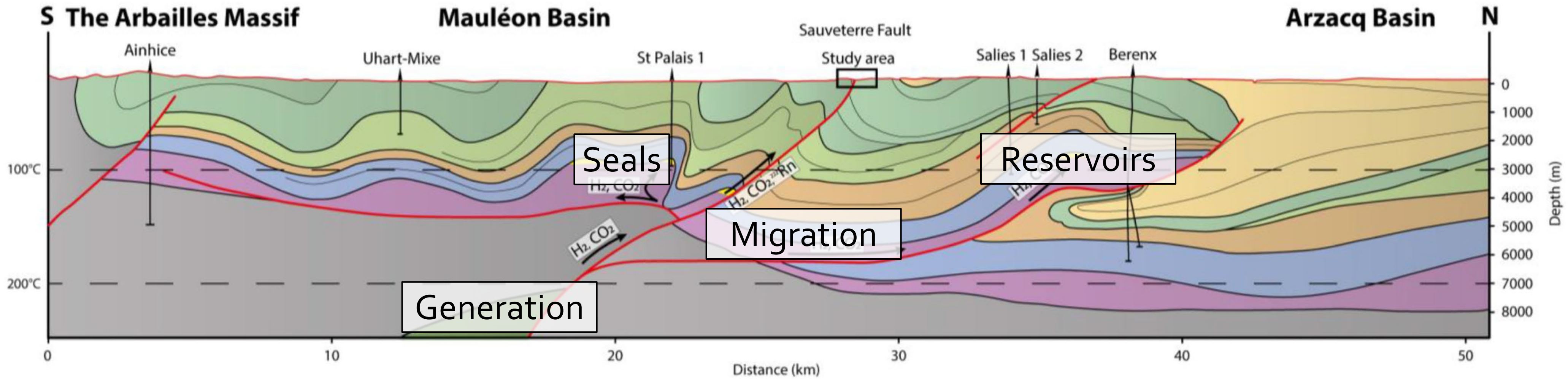


Schoentgen 2021

Refinement of the hydrogen system model

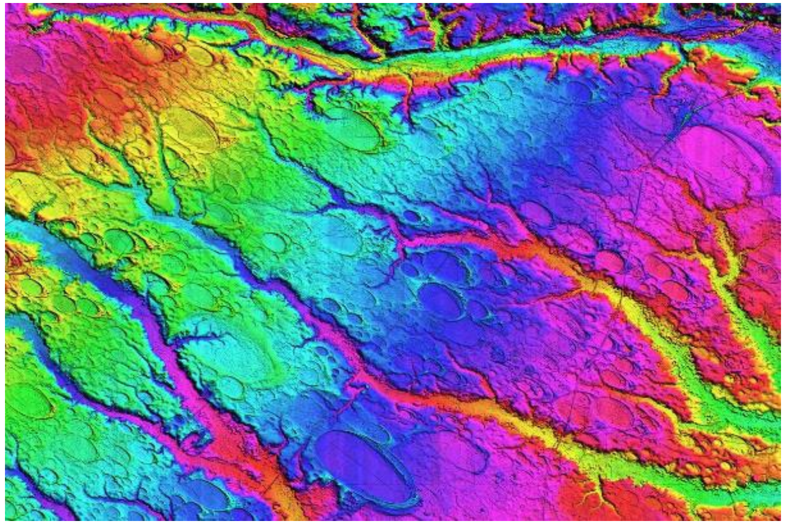
- Experimental, field-based, and modeling studies of:
  - Hydrogen generation mechanisms
  - Hydrogen migration mechanisms
  - Seal properties of cap rocks
  - Reservoir properties/interactions

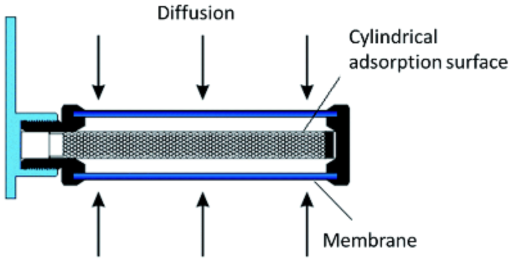
- Reactive losses
- Reservoir charging
- Storage potential
- Exploration tools for crystalline rocks



Development of surface exploration techniques for identification of hydrogen flux

- Remote sensing
  - LiDAR
  - Hyperspectral imaging
- Soils and soil gases
  - Develop new technologies for low-cost sampling for surface geochemistry
  - Application of advanced geochemical techniques (noble gases, bulk and clumped isotopes, etc.)
  - Downhole gas characterization
  - Environmental DNA





Surface observation complications

Temporal and spatial variability

Artificially generated hydrogen

Efficient microbial removal

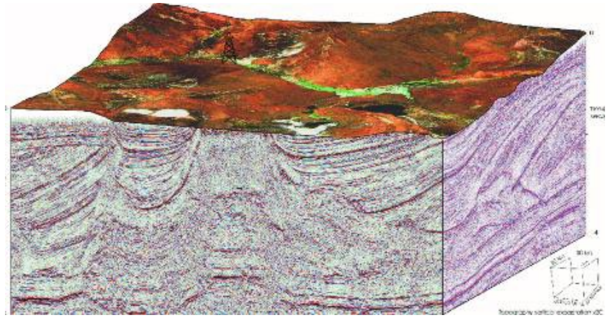
Development of subsurface exploration tools for detection of hydrogen system elements

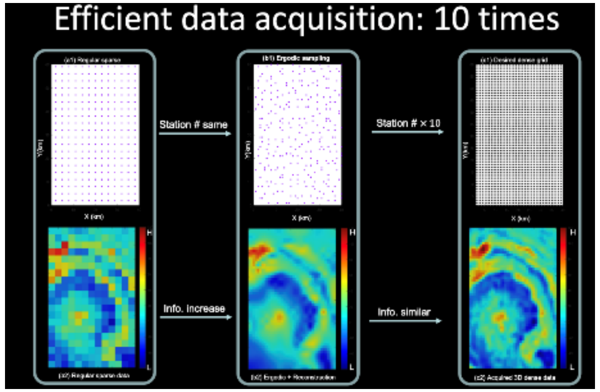
- Numerical modeling for feasibility studies and optimization of geophysical survey designs

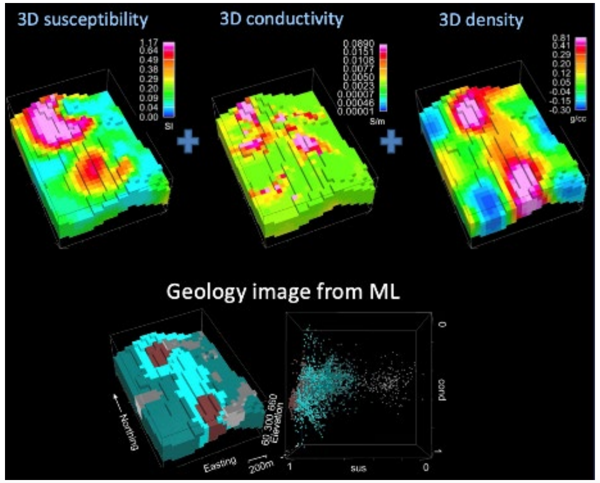
- New technology for seismic imaging of hydrogen system components in low impedance contrast environments (e.g., crystalline rocks)

- Integrated geophysics for imaging H2 geology (e.g., electromagnetics, gravity, magnetics, and seismic)

- AI and machine learning (ML) integration of data on multiple scales and from multiple sources







Stimulated hydrogen unknowns

- What are the details of the reaction mechanisms?
- What natural lithologies are best?
- Can equilibrium conditions be shifted to push reactions forward?
- What are the optimal catalytic conditions?
  - Temperature
  - Pressure
  - Water chemistry
- How long can reactions be sustained (e.g., catalysis poisoning)?

Serpentinized Harzburgite in Thin Section from the Samail Ophiolite, Sultanate of Oman

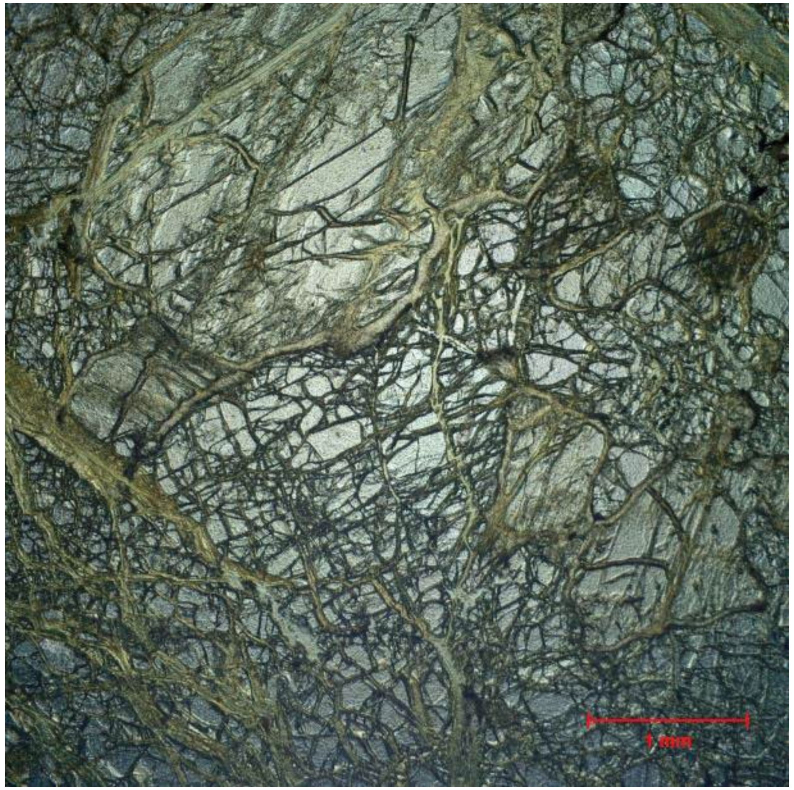
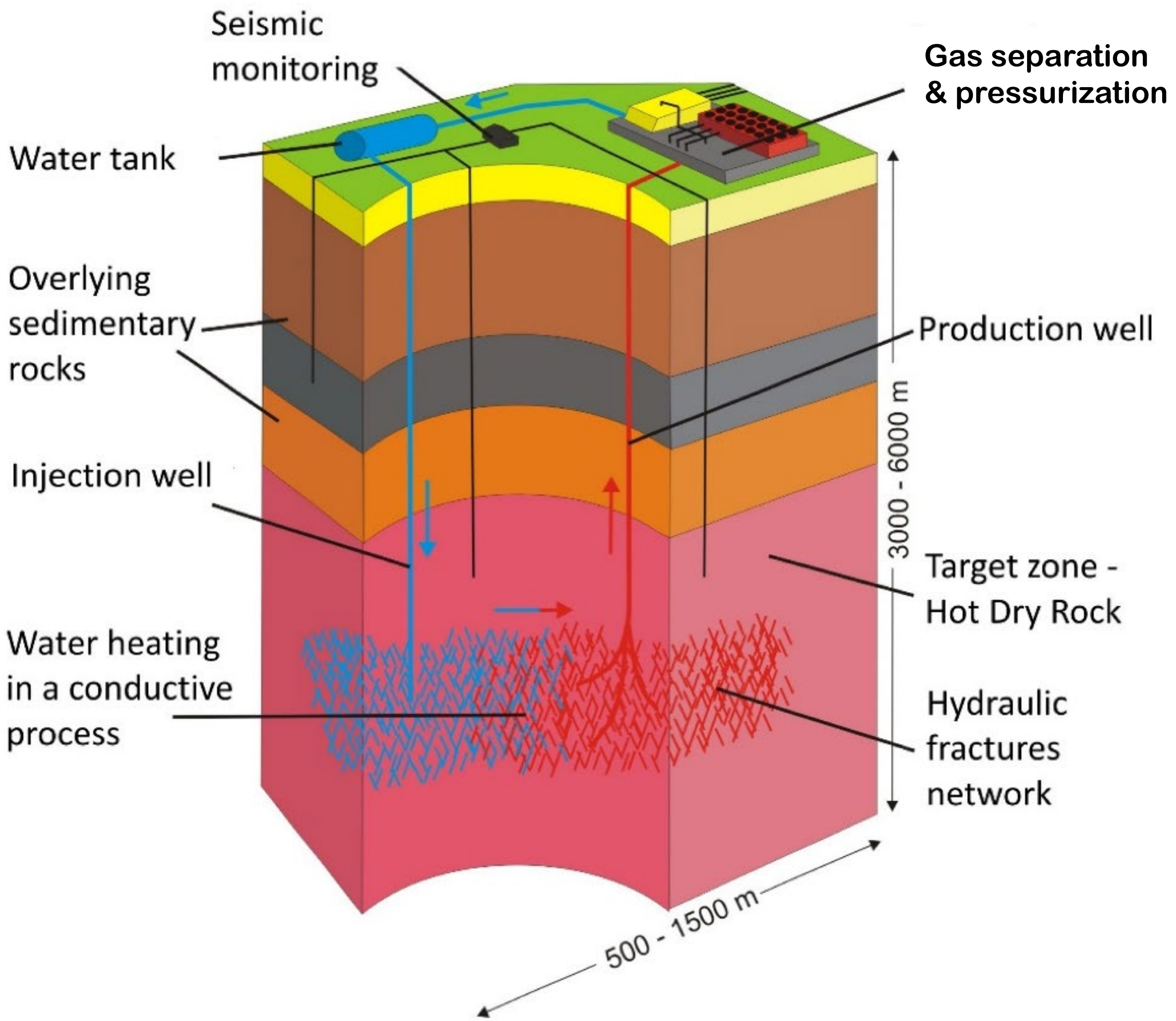


Photo credit: Evelyn Mervine

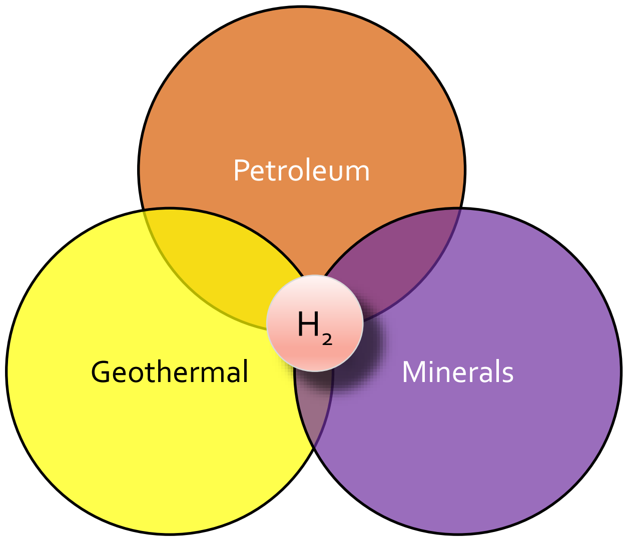
Engineering challenges of stimulated hydrogen

- Optimized fractures in crystalline rocks
- Maintaining controlled water-rock contact
- Selective gas recovery
- Efficient product recovery – stray H_2 risk
- Flowback water – disposal, reuse, contaminants
- Induced seismicity risks



Summary

- Large quantities of hydrogen gas likely exist in the subsurface
- The potential for economic accumulations of hydrogen gas is unknown
- Research is needed to better understand hydrogen accumulation processes and develop exploration techniques
- Beyond naturally existing hydrogen supplies stimulated hydrogen generation in subsurface could greatly augment this resource
- Research is needed in four thrust areas:
  - Improved understanding of the hydrogen system
  - Surface exploration techniques
  - Subsurface exploration tools
  - Stimulated hydrogen production



https://www.science.org/content/article/hidden-hydrogen-earth-may-hold-vast-stores-renewable-carbon-free-fuel

Thank you

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