The AAPG and AAPG Foundation

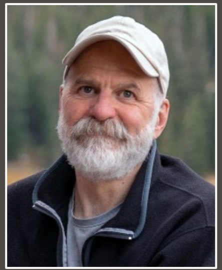
Distinguished Lecture Program 2024 - 2025

Natural Hydrogen: An Overlooked Potential Energy Resource

Geoffrey Ellis

Research Geologist

U.S. Geological Survey

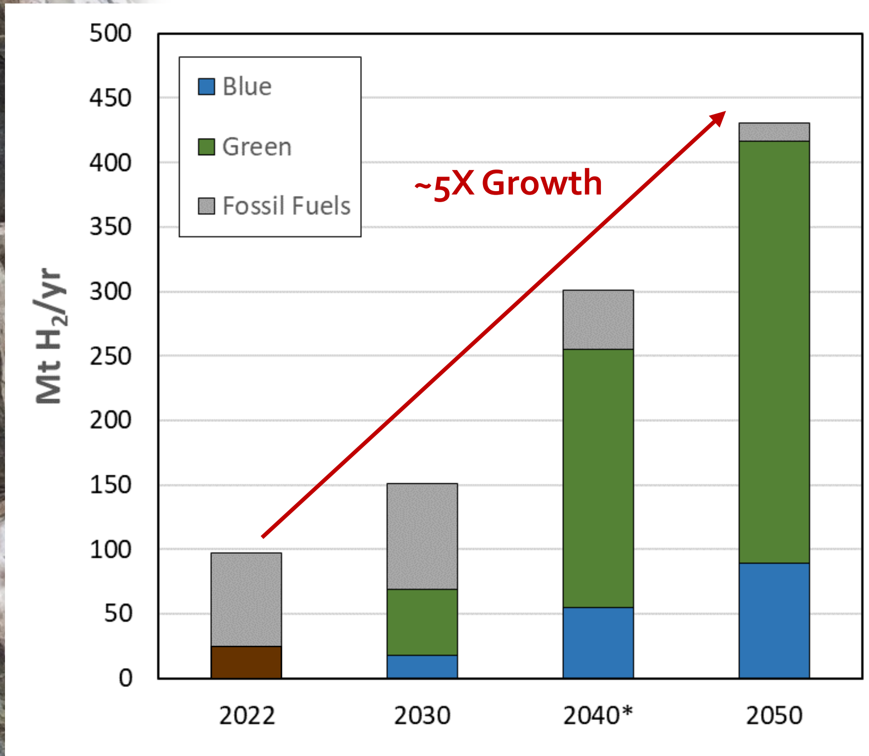


USGS
science for a changing world

Natural Hydrogen Workshop in Japan, February 14, 2025

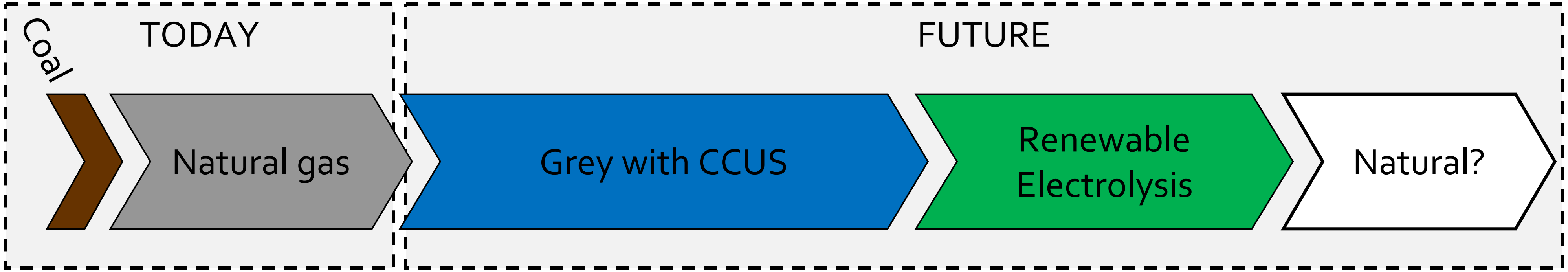
Photo credit: Alexis Templeton

Global hydrogen supply today & tomorrow



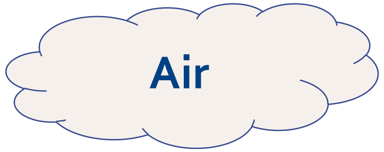
IEA Net Zero Global Roadmap 2023 Update

- *Today* – petroleum upgrading, fertilizer, petrochemicals
- *Future* – energy for hard-to-abate sectors — such aviation, steel manufacturing, industrial heating, mining
- Meeting this demand with blue and green hydrogen is likely to be expensive and mineral intensive
- Hydrogen is viewed exclusively as a medium for energy storage and transport **not a primary energy resource**
- What is the resource potential of natural hydrogen?

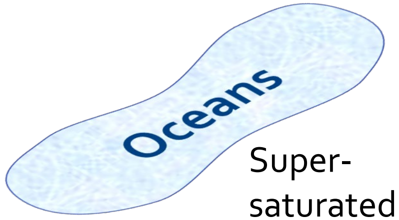


USGS
science for a changing world

Observations of natural hydrogen on Earth



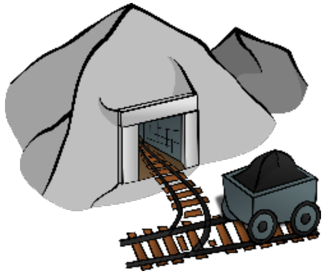
0.5 ppmv



Super-
saturated

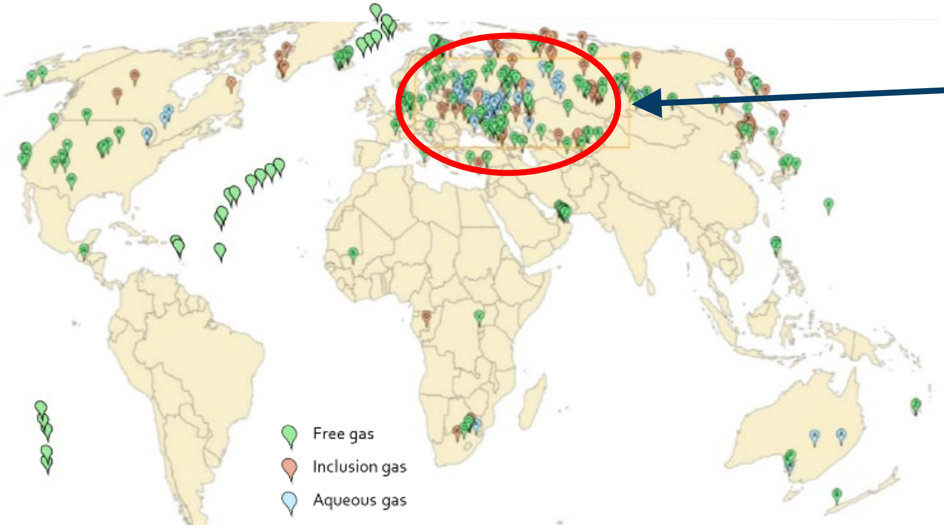
10-1000s
ppmv

Deep mines & boreholes



% Concentrations

Surface observations of hydrogen concentrations >10%



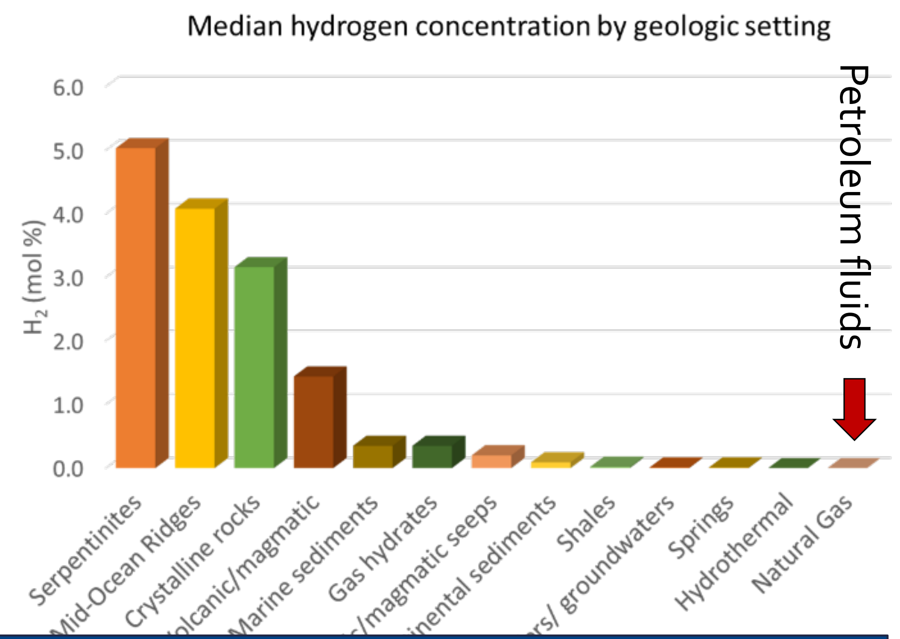
Modified from Zgonnik, 2020 and Prinzhofer & Deville, 2015

Density of observations in eastern Europe and former Soviet Union due to active research efforts in this region

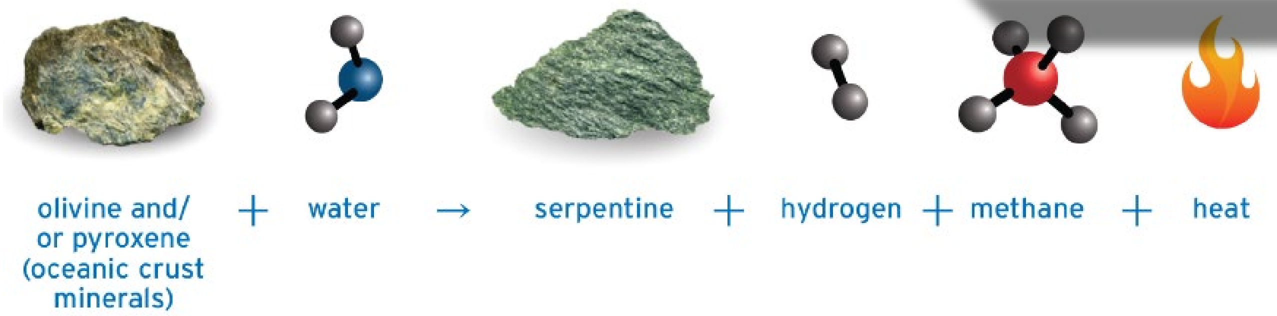
The more we look for hydrogen the more we find it

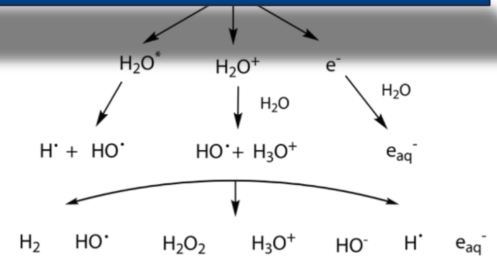
Observations of natural hydrogen on Earth

- More than 30 distinct generation mechanisms
- Reaction of water with ultrabasic rocks (i.e., serpentinization)
- Natural radiolysis of water
- Deep-sources of hydrogen (primordial or generated in the lower crust)
- Other mechanisms
  - Thermal stress of organic matter
  - Mechanoradical reduction of water



High diffusivity and reactivity of hydrogen ***probably*** means that accumulations cannot form





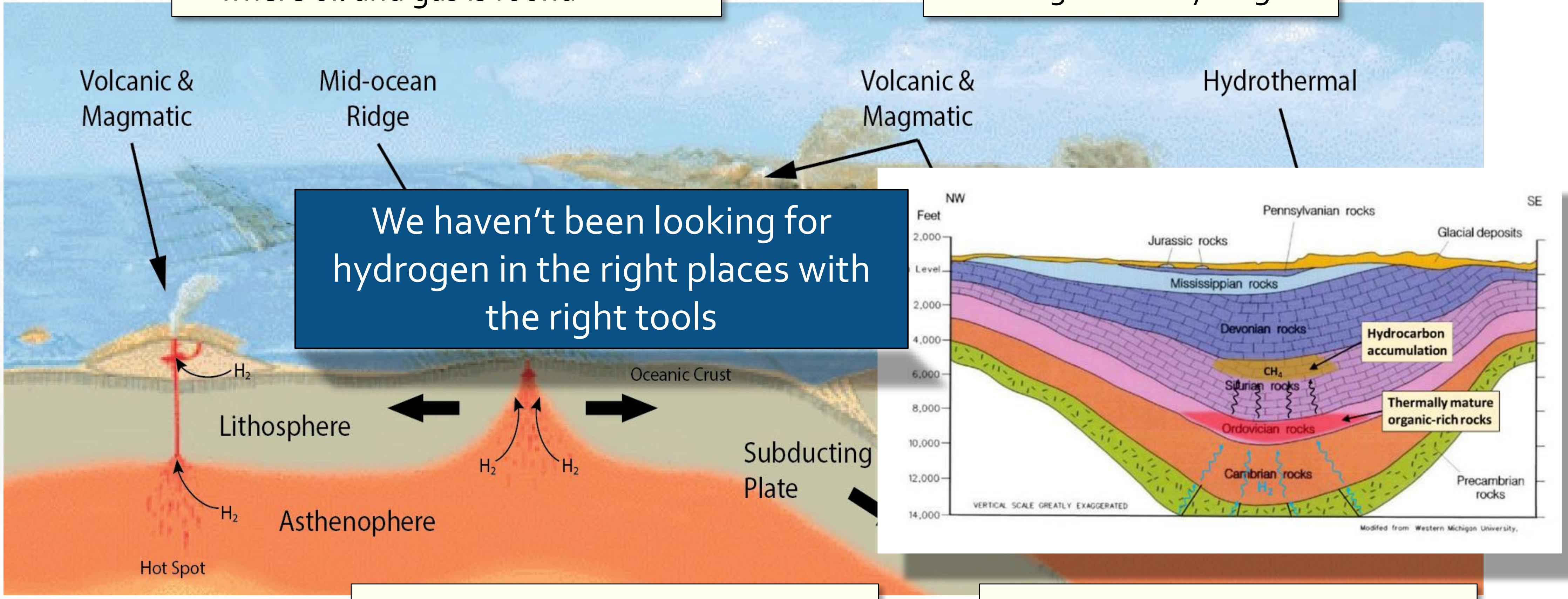
USGS
science for a changing world

Rethinking geologic hydrogen accumulation potential

Hydrogen generation is generally not where oil and gas is found

Petroleum exploration is not targeted at hydrogen

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

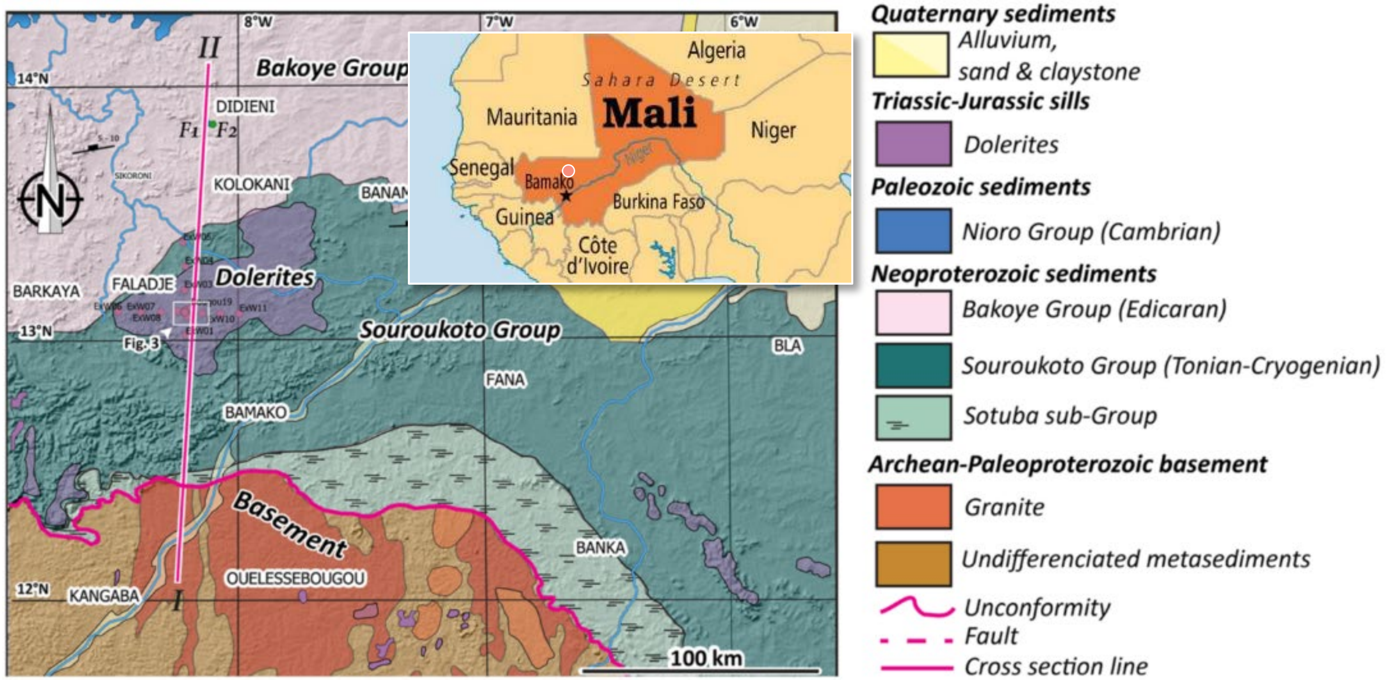


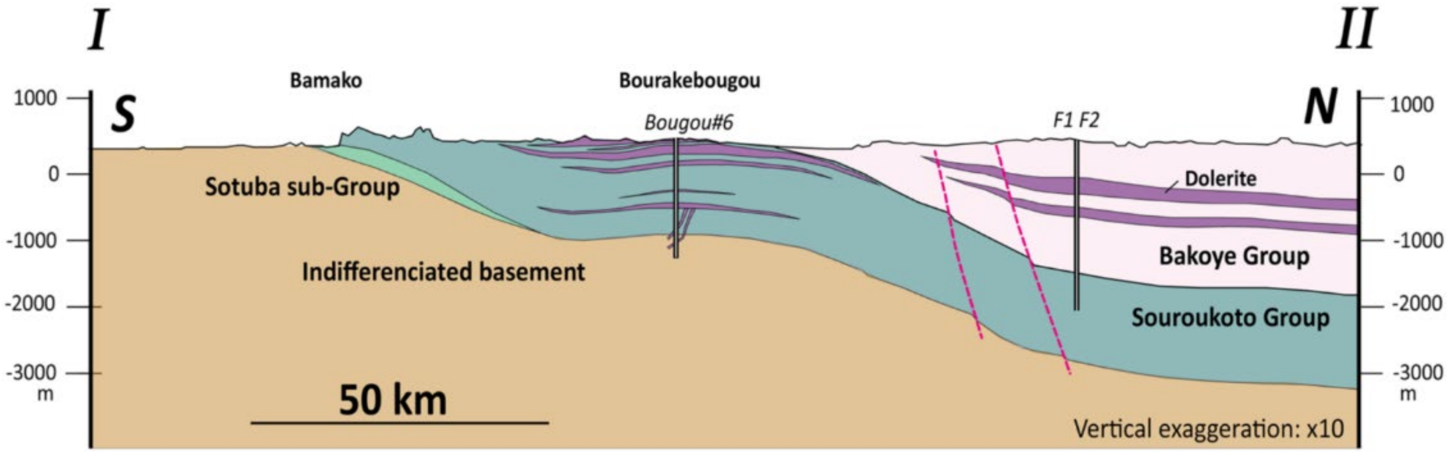
Mineral exploration generally does not look at gas composition

Hydrogen is consumed by hydrocarbon forming reactions

Hydrogen discovery and production in Mali

- Accidental gas explosion during water well drilling in 1987
- Reoccupied as a gas well in 2012 and produced **>97 % H_2**
- Exploration campaign including seismic, gravity, magnetic surveys and coring
- Multiple stacked reservoirs interbedded with doleritic seals
- The **discovery well is still producing**, with the gas generating electricity
- Source of H_2 is not known
- The resource potential is estimated to be **630 Bcm of H_2** (Hydroma, 2021)





(*Maiga et al., 2023*)

USGS
science for a changing world

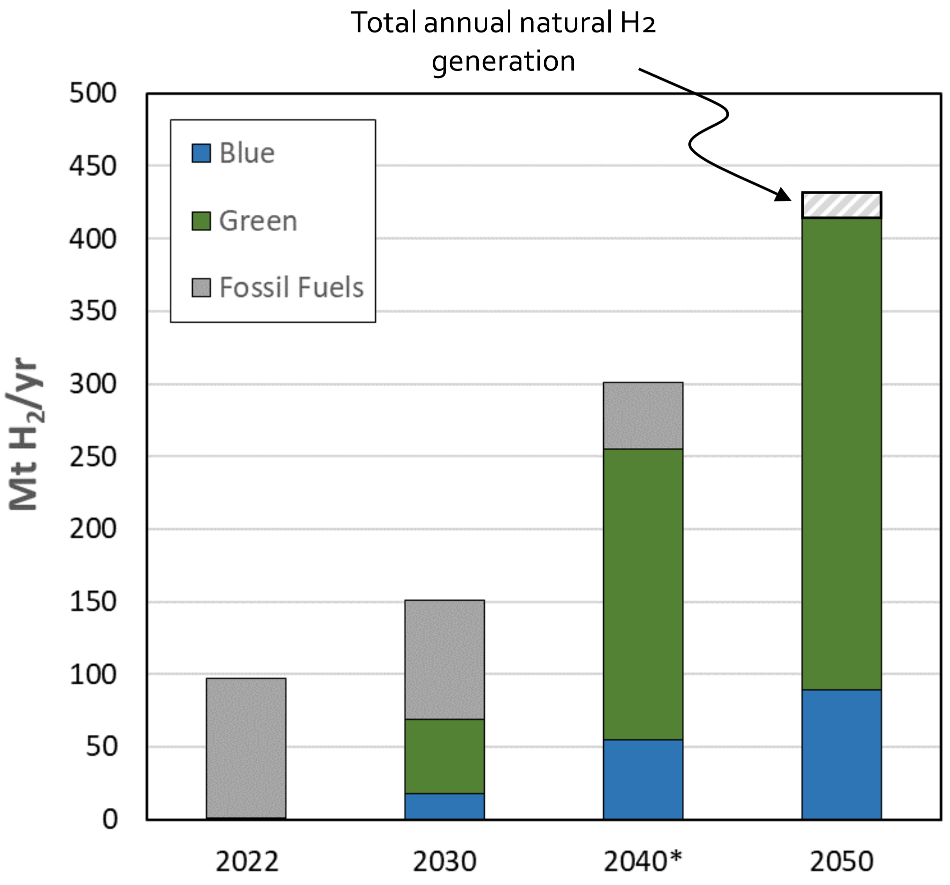
What could the global hydrogen resource potential be?

Context

- Annual global demand projected to be **~430 Mt/yr** by 2050
- Annual global production of natural hydrogen in the subsurface estimated to be **~23 Mt/yr** (*Zgonnik 2020*)
- 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 Net Zero Global Roadmap 2023 Update

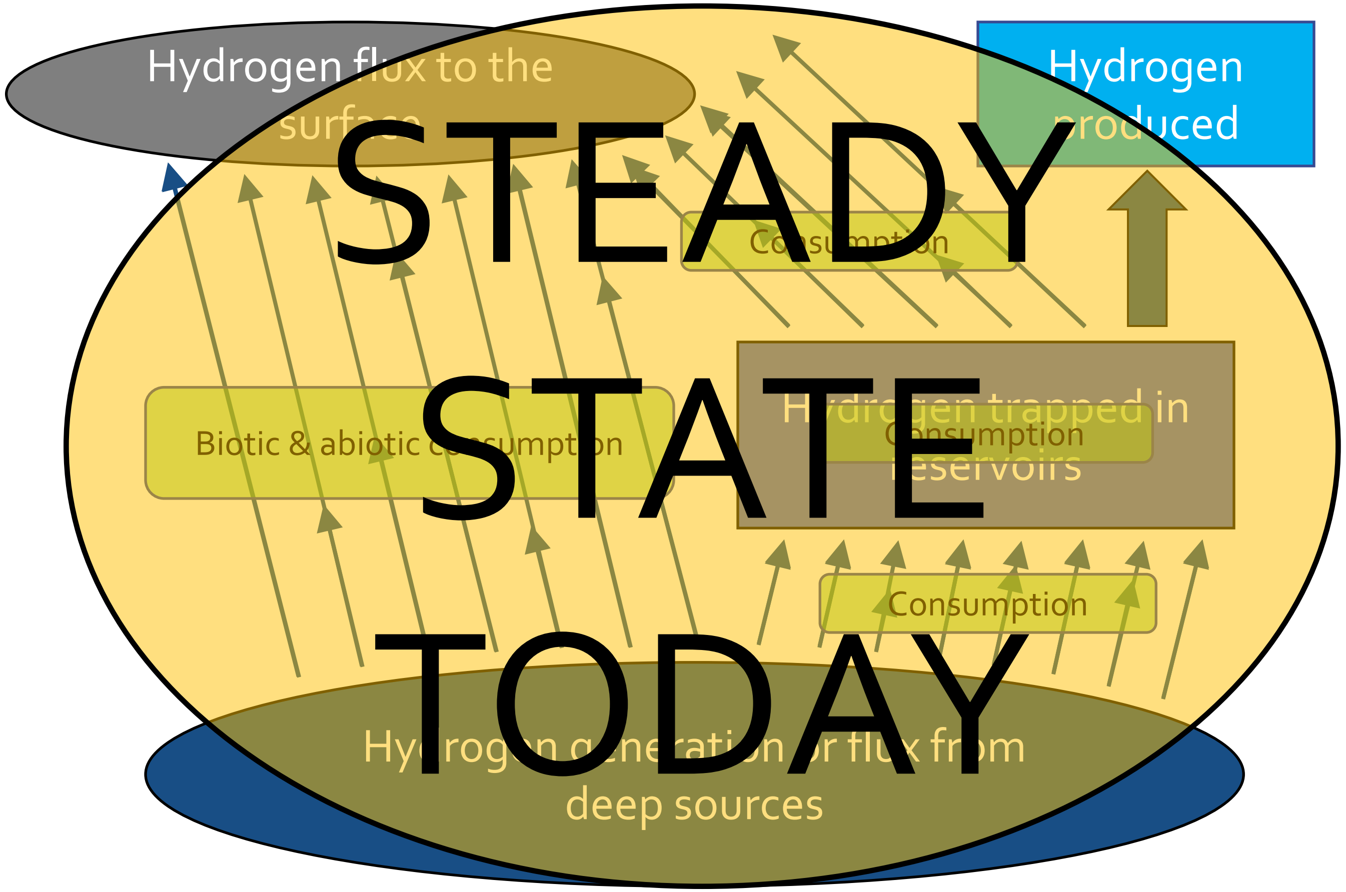
USGS science for a changing world

Geologic hydrogen resource model

Calculated & compared to estimates

Biotic & abiotic consumption estimated based on observations

Varies based on depth & migration distance



Exploration & production efficiency estimated from petroleum systems

Residence time estimated from analogues (He & CO_2)

Trapping efficiency estimated from petroleum systems

Estimated based on observations

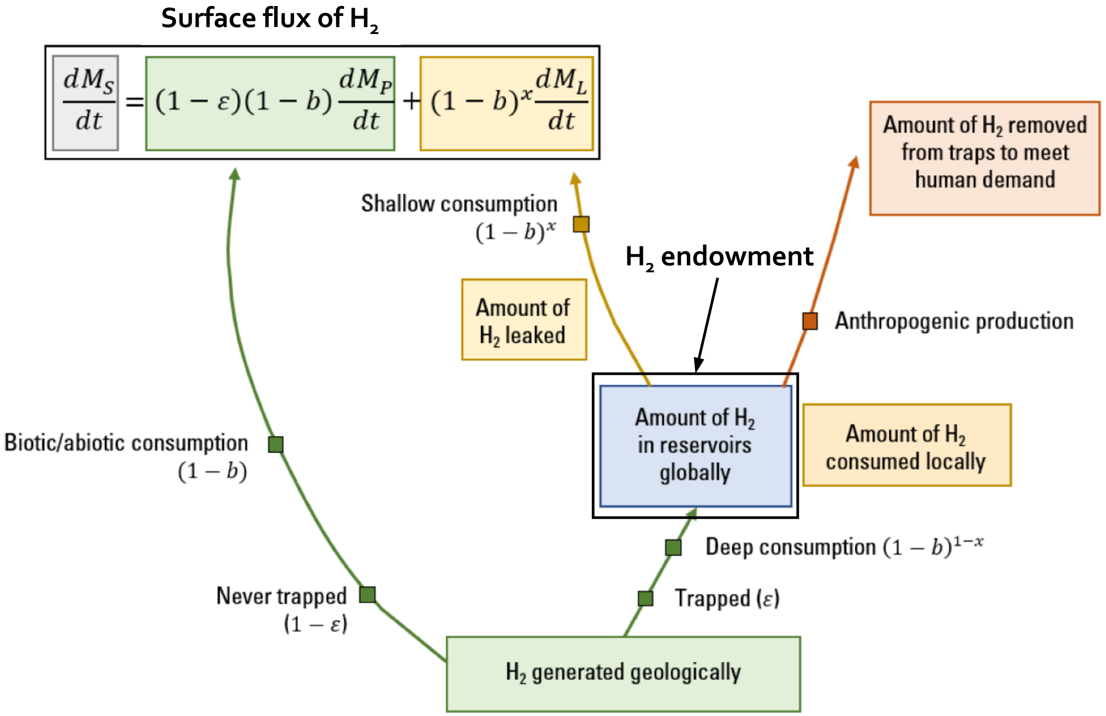
Ellis & Gelman, 2024

USGS science for a changing world

Geologic hydrogen resource model

Amount of H_2 in reservoirs globally	Amount of H_2 produced geologically; trapped and not consumed	Amount of H_2 leaked out of traps	Amount of H_2 consumed in traps	Amount of H_2 removed to meet demand

$$\frac{\partial M_R}{\partial t} = \varepsilon(1-b)^{1-x}\frac{dM_P}{dt} - \frac{M_R}{\tau_L} - \frac{M_R}{\tau_C} - \frac{dM_D}{dt}$$



Ellis & Gelman, 2024

ε = trapping efficiency (fraction trapped)
b = total fraction of generated H_2 consumed
x = dictates the portion of shallow vs. deep consumption of H_2:
- $x = 0$ 0% shallow & 100% deep
- $x = 1$ 100% shallow & 0% deep

Trap-related leakage (L) and consumption (C) are time-dependent decay processes:
- λ is half-life
- τ is residence time

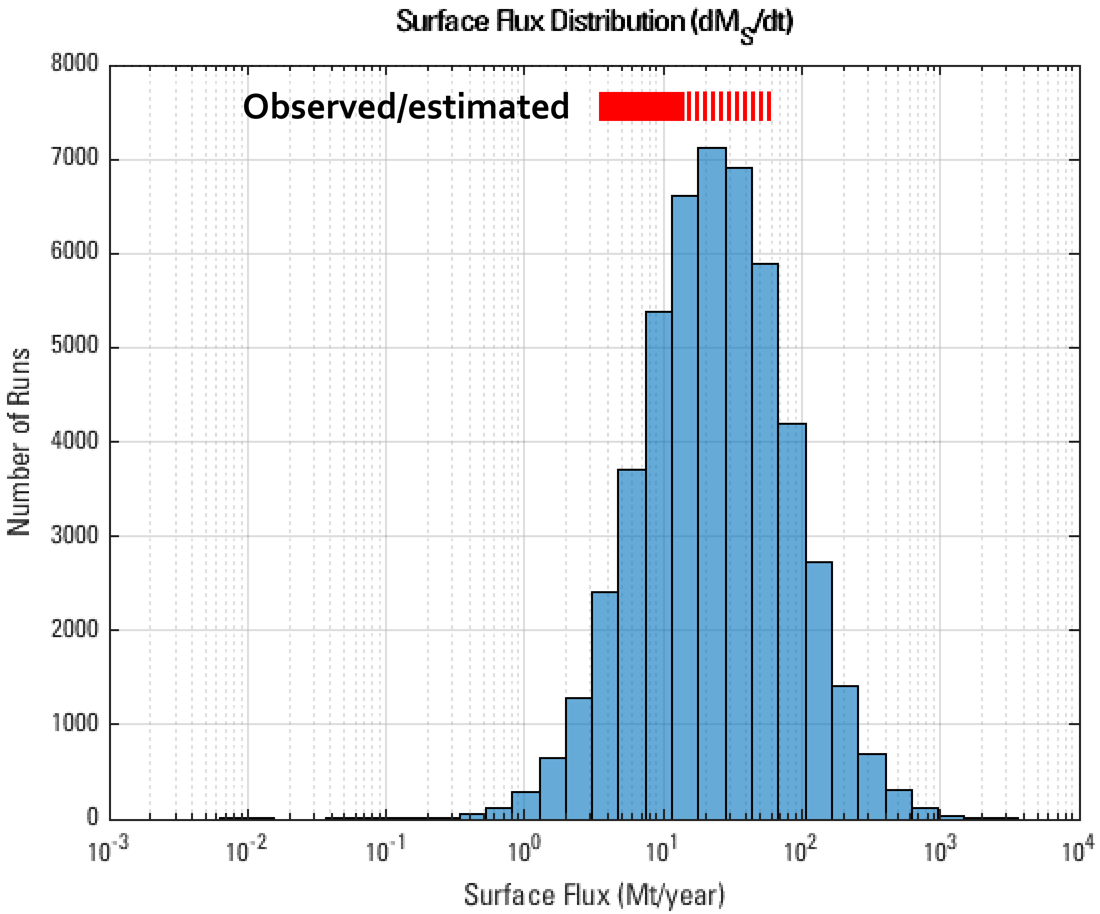
$$M_R(t) = M_R(0)e^{-\lambda t}$$

$$\frac{dM_f}{dt} = \lambda M_R = \frac{M_R}{\tau}$$

Monte Carlo input parameters
- Generation of H_2
- Trapping efficiency
- Residence time
  - Leakage
  - Consumption
- Consumption
  - Shallow proportion
  - Deep proportion

Estimated hydrogen flux to the atmosphere

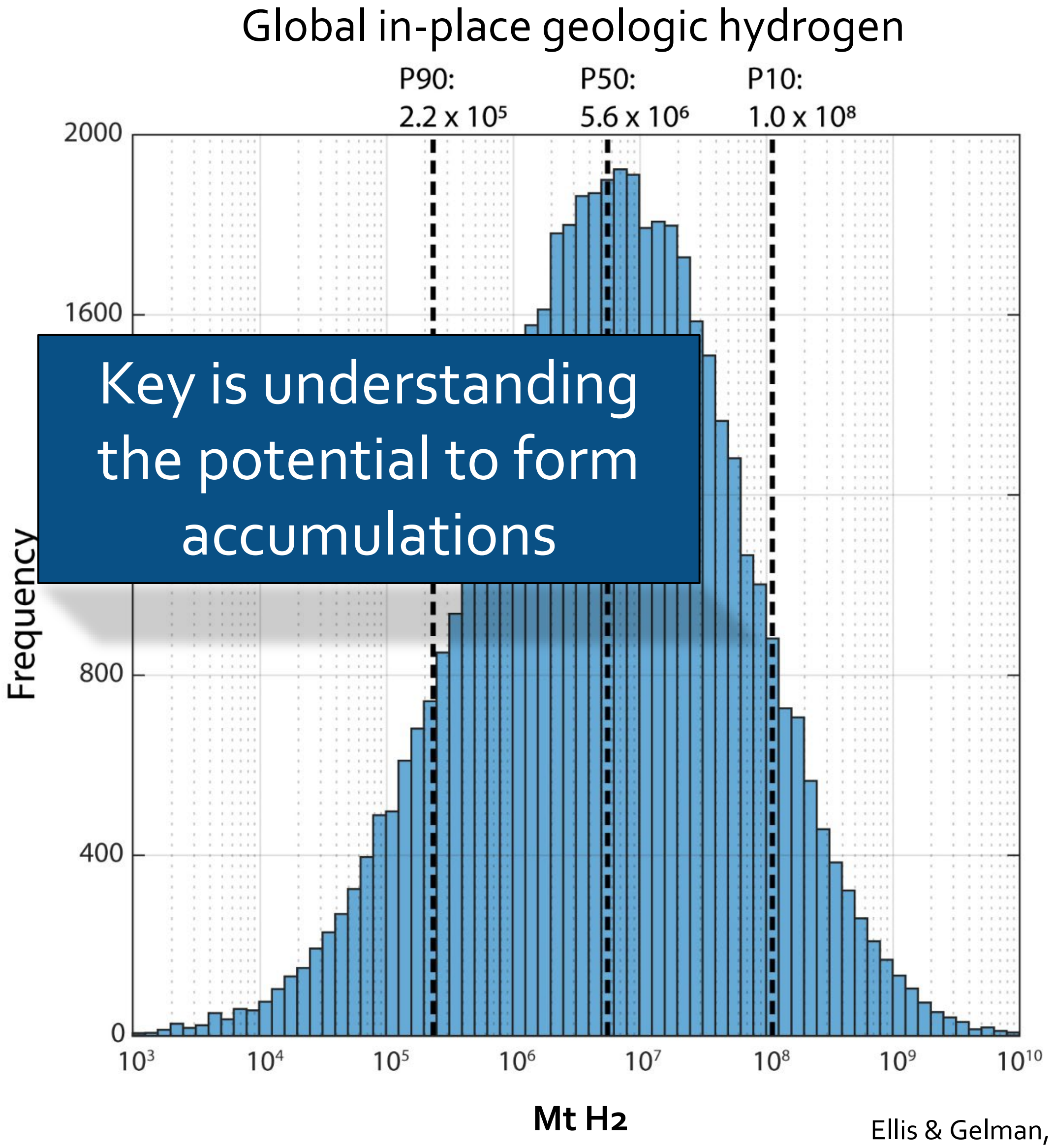
- Model predicts subsurface flux of hydrogen from **<1 to ~1000 Mt/yr**
- Most probable value (p50) is **~20 Mt/yr**
- Estimated flux from volcanoes and hydrothermal settings is **~9.6 ± 7.2 Mt/yr** (*Holand, 2002*)
- Other sources of subsurface flux exist and are not quantified
- Given the orders of magnitude variability of the inputs and outputs, **agreement is quite good**



Ellis & Gelman, 2024

Estimated global in-place hydrogen resource

- Model predicts the amount of in-place hydrogen may range from 10's of **thousands** Mt to **billions Mt**
- Most probable amount (p50) is **~5 x 10^6 Mt** (mean value is ~8 x 10^7 Mt)
- Most H2 is likely inaccessible – too deep, too far offshore, too small accumulations
- **2%** recovery (100,000 Mt) would supply all projected H2 demand (~430 Mt/yr) for >**200** years
- Global proven natural gas reserves ~7257 Tcf (**8.4 x 10^{15} J**); 100,000 Mt of H2 (**1.4 x 10^{16} J**)



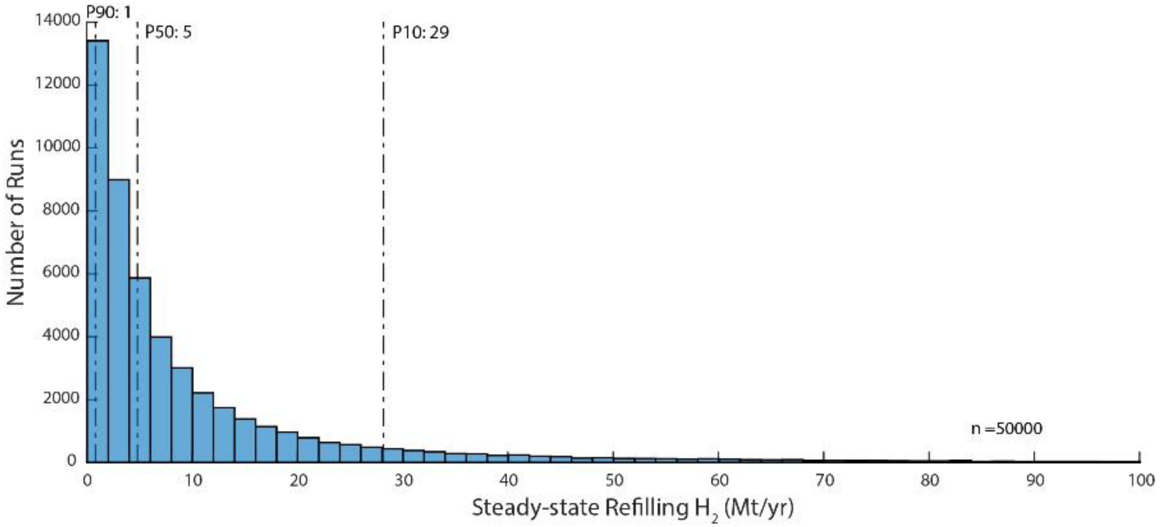
Key is understanding the potential to form accumulations

Ellis & Gelman, 2024

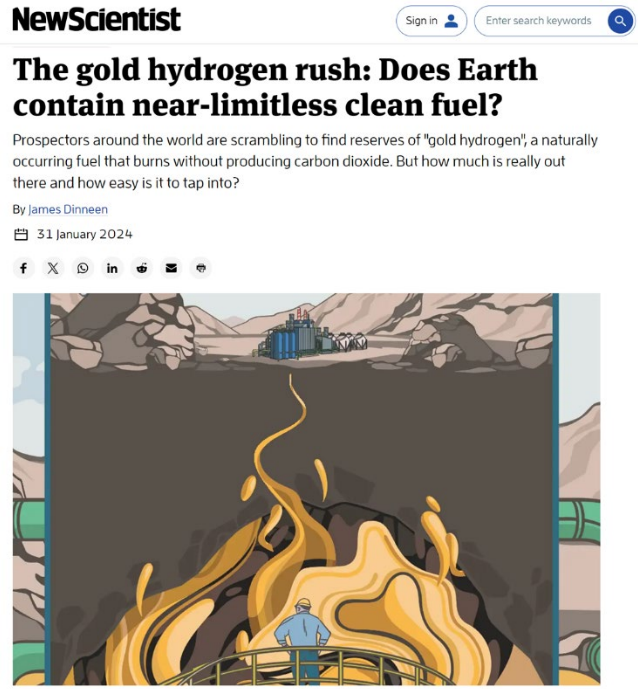
Estimated renewable hydrogen resource

- Geologic hydrogen is frequently referred to as a potentially **renewable resource**
- Most probable (P50) renewable amount **~5 Mt/yr** for entire globe
- There is only a 10% chance (P10) of the renewable potential >29 Mt/yr
- Geologic accumulations of hydrogen are **not likely to be substantially renewable**

Renewable resource potential



Ellis & Gelman, 2024


NewScientist

Sign in

Enter search keywords

The gold hydrogen rush: Does Earth contain near-limitless clean fuel?

Prospectors around the world are scrambling to find reserves of "gold hydrogen", a naturally occurring fuel that burns without producing carbon dioxide. But how much is really out there and how easy is it to tap into?

By James Dinneen

31 January 2024

Hydrogen system analogous to the petroleum system

Petroleum System	Hydrogen System
Critical elements	*Essential components*

Petroleum System

Critical elements

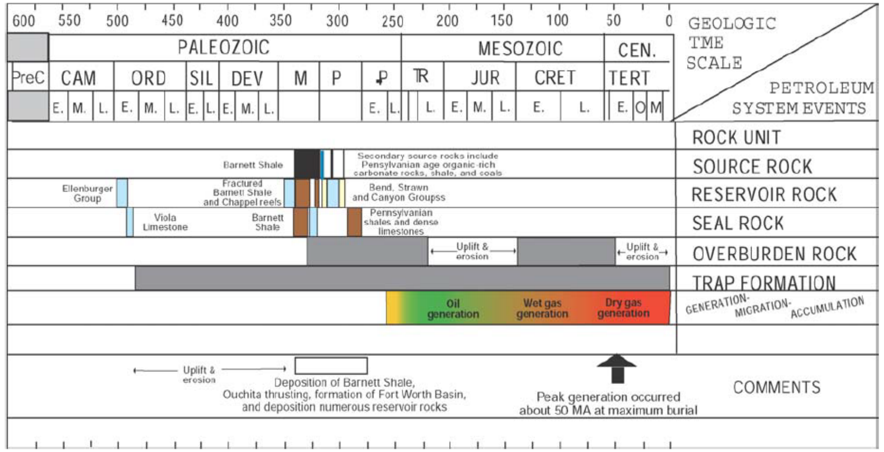
- Source
- Migration pathway
- Reservoir
- Trap/seal
- Preservation
- Timing

Hydrogen System

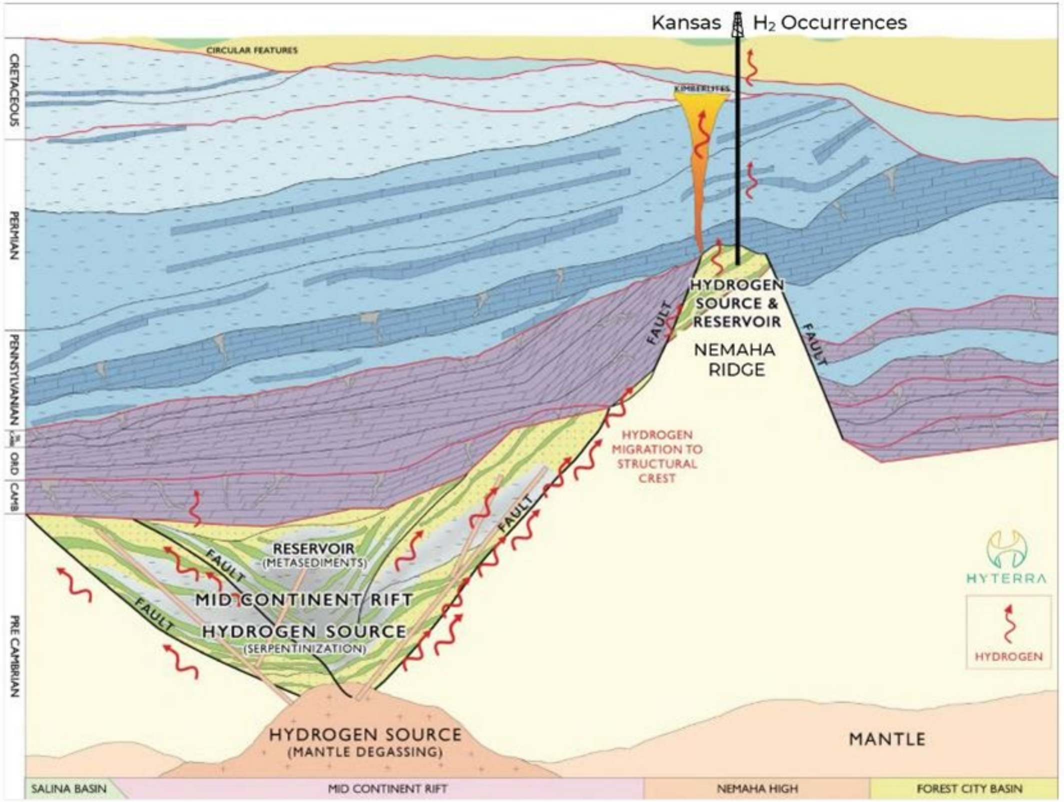
Essential components

- Source
- Migration pathway
- Reservoir
- Trap/seal
- Preservation
- Timing

Petroleum system events chart



(Pollastro et al., 2003)

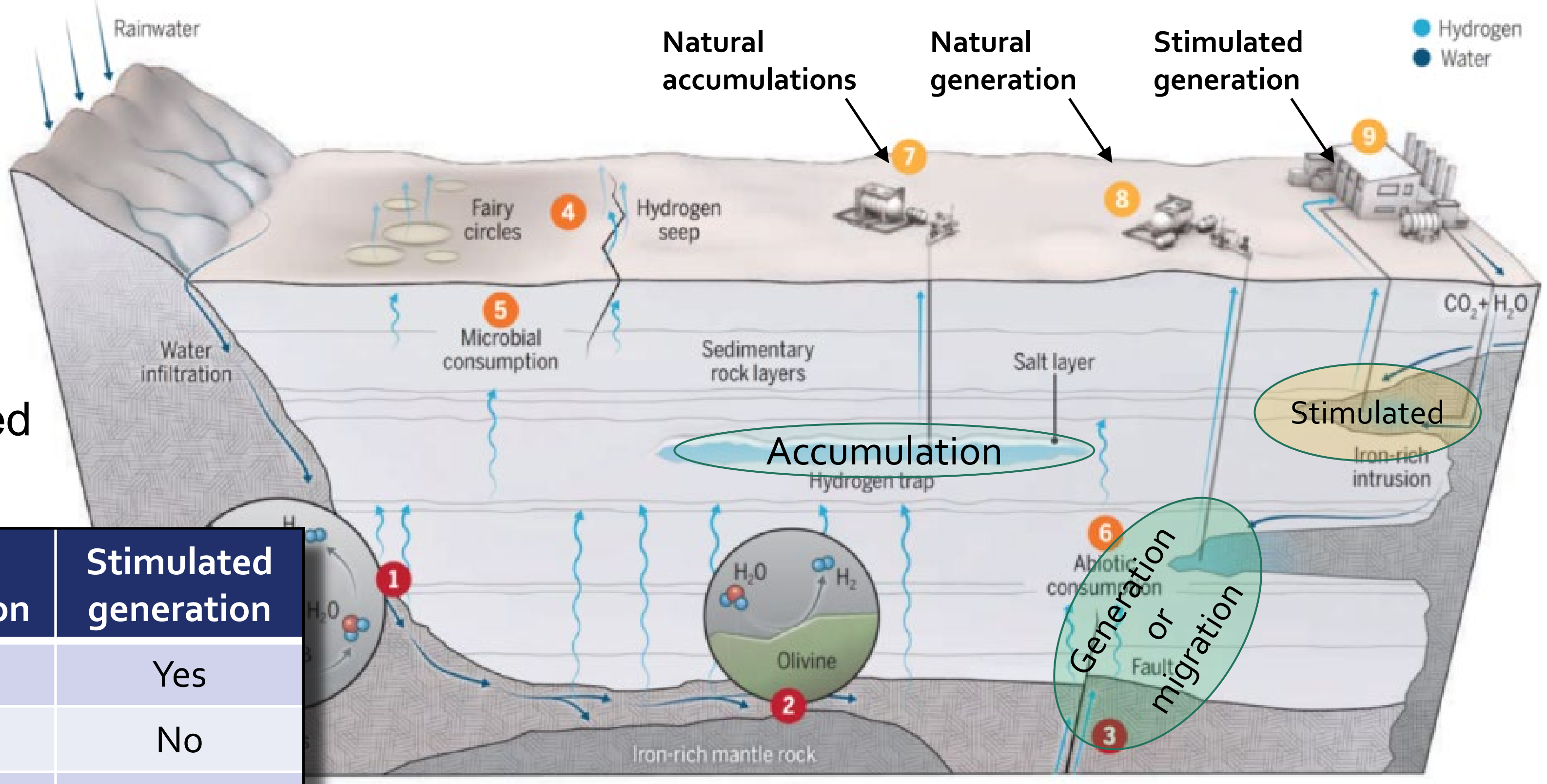


Hydrogen system model – play types

3 conceptual types of exploitable H_2 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	Yes	No	No
Timing	Yes	No	No

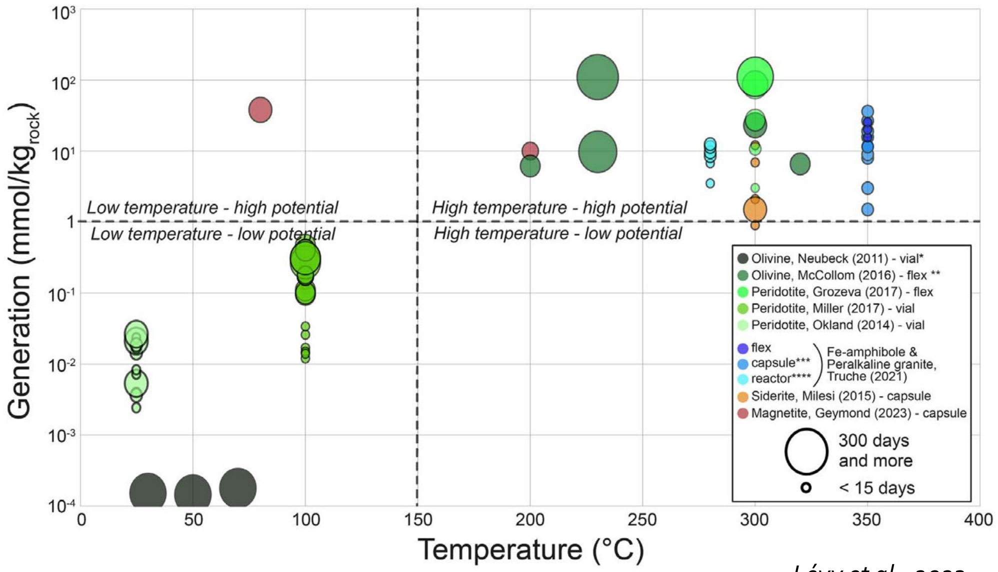


Hidden Hydrogen - *Science* 2023

- Global model only accounts for natural accumulations
- Natural and stimulate generation may be "renewable"
- Viability of natural and stimulated generation is unknown

Hydrogen sources

- Mechanisms that can generate the large volumes of hydrogen
  - Reaction of water with ultramafic rocks (e.g., **serpentinization**)
  - Natural **radiolysis** of water
  - **Deep-sourced** hydrogen (primordial or generated in the lower crust)
- Other potential mechanisms
  - Other iron-containing lithologies (e.g., **banded iron formations**)
  - Thermal maturation of **high maturity organic matter**
  - **Other redox reactions** (e.g., pyritization)



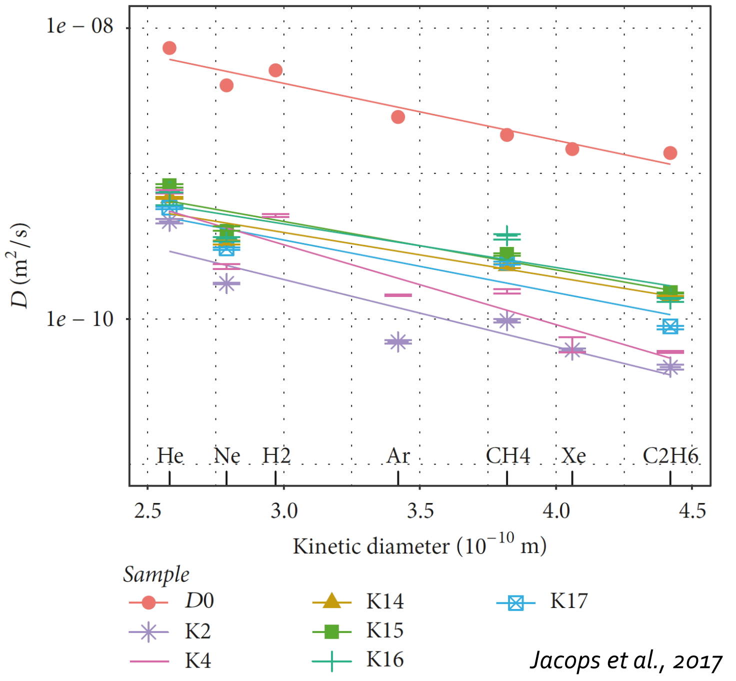
Lévy et al., 2023

What are the generation rates (kinetics)?
What are the controls on rates?
Are reactions catalyzed?
Diagnostic geochemical signatures?

Seals for hydrogen reservoirs

- Seal capacity is likely to be **critical for forming and preserving hydrogen accumulations**
- Kinetic **diameter of hydrogen** is smaller than methane and **close to helium**
- Low-permeability seals (e.g., evaporite minerals) allow helium to be stored for long time periods (**100's of 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**

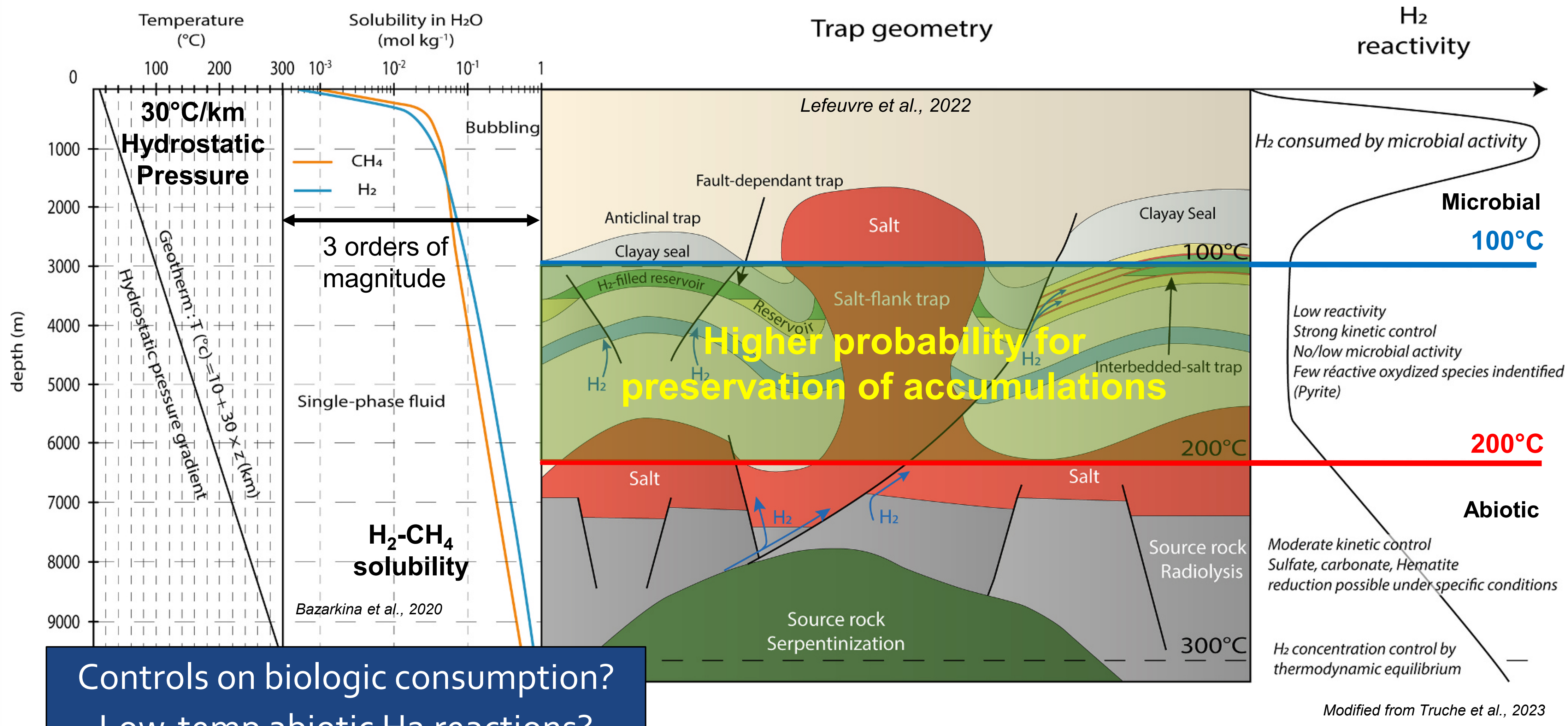
Diffusion coefficients for gases through the Boom clay as a function of kinetic diameter



Jacops et al., 2017

What role does mineralogy play?
How does water effect seal capacity?
What is the capillary entry pressure?

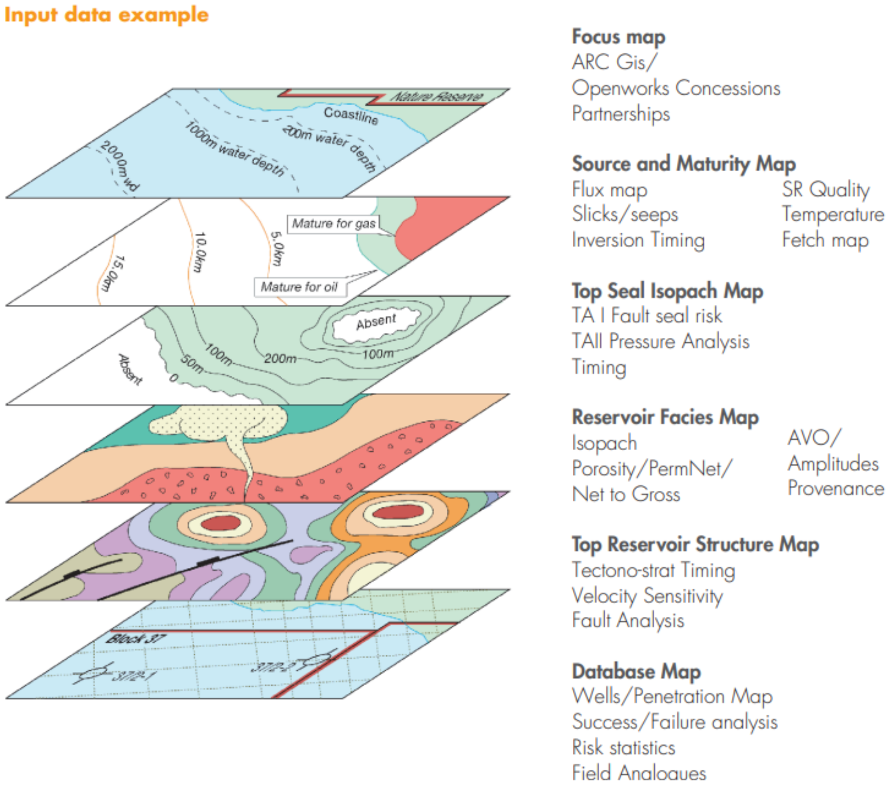
Hydrogen migration and preservation



Controls on biologic consumption?
Low-temp abiotic H2 reactions?
H2 phase behavior?

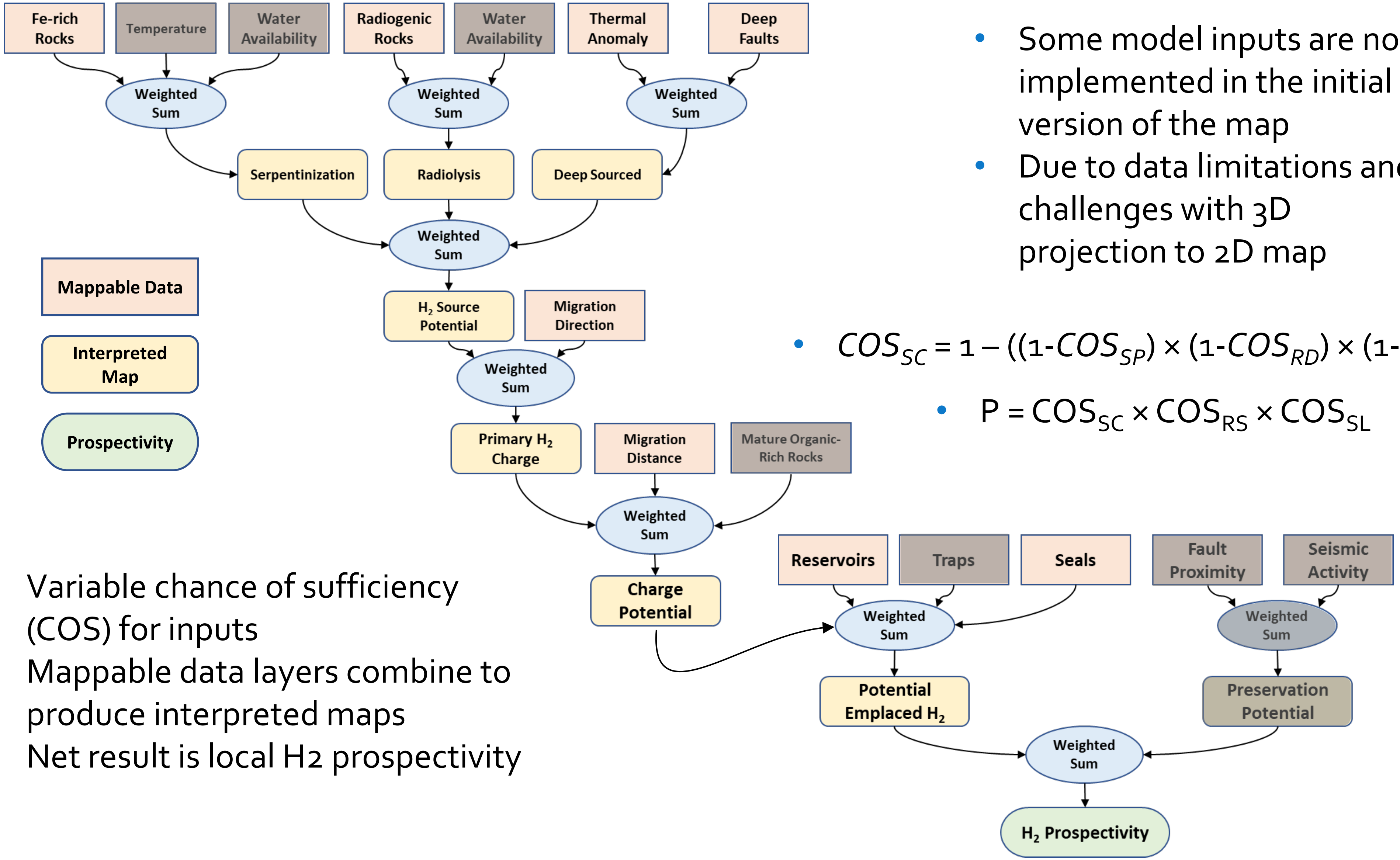
USGS geologic hydrogen prospectivity mapping

- Produce a preliminary map of geologic hydrogen prospectivity for the lower 48 states of the US
- Develop a hydrogen system model for prospectivity mapping
- Identify proxy data sets for each of the essential components of the hydrogen system
- Account for uncertainty in data and the model



Credit: Royal Dutch Shell, AAPG Imperial Barrel Award

Conceptual model for natural hydrogen accumulation



- Some model inputs are not implemented in the initial version of the map
- Due to data limitations and challenges with 3D projection to 2D map

- $COS_{SC} = 1 - ((1\text{-}COS_{SP}) \times (1\text{-}COS_{RD}) \times (1\text{-}COS_{DP}))$
  - $P = COS_{SC} \times COS_{RS} \times COS_{SL}$

- Variable chance of sufficiency (COS) for inputs
- Mappable data layers combine to produce interpreted maps
- Net result is local H2 prospectivity

USGS
science for a changing world

Data Inputs

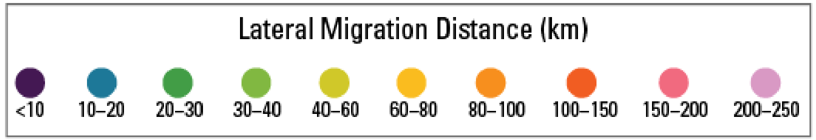
Component		Layer	Chance of Sufficiency			Buffer	Migration
			COS Low	COS Mid	COS High		
Source	Serpentinization	SP1: East Coast Magnetic Anomaly	0.7	0.8	0.9	no	yes
		SP2: Surface Ultramafics	0.6	0.7	0.8	20 km	no
		SP3: Failed Rifts	0.7	0.8	0.9	no	yes
		SP4: Geophysical Anomalies	0.1	0.4	0.7	no	yes
		SP5: All Other Areas	0.0	0.1	0.2	no	no
	Radiolysis	RD1: Uranium Deposits	0.1	0.2	0.3	10 km	yes
		RD2: Uranium Favorable	0.0	0.05	0.1	10 km	yes
		RD3: Precambrian Craton	0.5	0.7	0.9	100 km	no
		RD4: Accreted Terranes	0.1	0.2	0.5	100 km	no
		RD5: Young Granitoids	0.1	0.2	0.3	20 km	no
	Deep Sources	DP1: Surface Faults	0.1	0.2	0.3	10 km	yes
		DP2: Suture Zones	0.2	0.5	0.8	40 km	yes
		DP3: High Heat Flow	0.5	0.7	0.9	±10 mW/m^2	no
		DP4: All Other Areas	0.0	0.1	0.2	no	no
Reservoir		RS1: Sedimentary Rocks	0.8	0.95	1.0	no	no
		RS2: Non-Sedimentary Rocks	0.7	0.8	0.9	no	no
		RS3: Sedimentary Basins	1.0	1.0	1.0	no	no
Seal		SL1: Salt	0.0	0.1	0.2	no	no
		SL2: Sedimentary Rocks	0.6	0.8	1.0	no	no
		SL3: Non-Sedimentary Rocks	0.2	0.5	0.8	no	no
		SL4: Sedimentary Basins	0.1	0.3	0.5	no	no

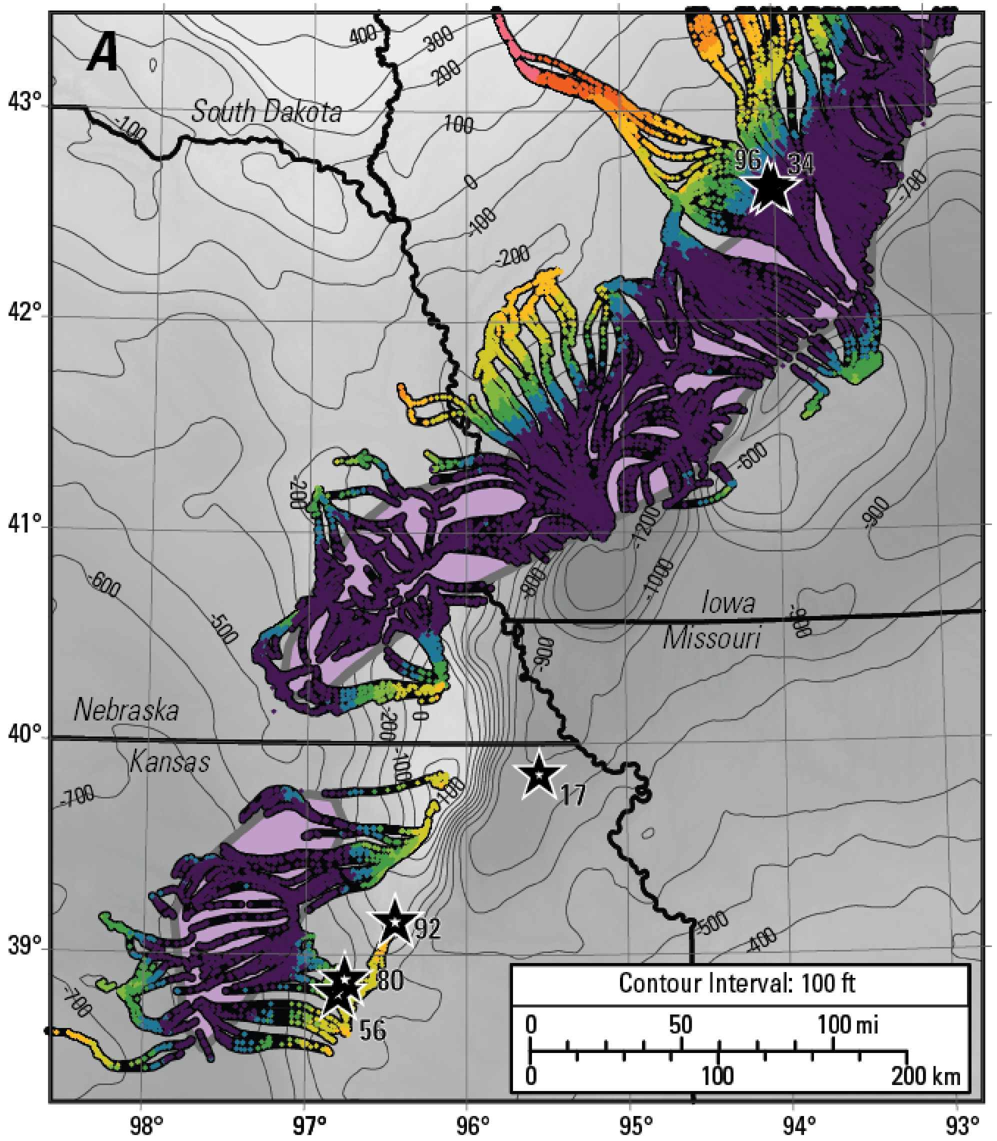
Gelman et al., 2025

Lateral Migration of Subsurface Hydrogen

Limitations:

- Only considering lateral (not vertical) migration
- Only considering lateral migration in sedimentary settings
- Using a regional “Top Basement” surface for flow lines/drainage areas



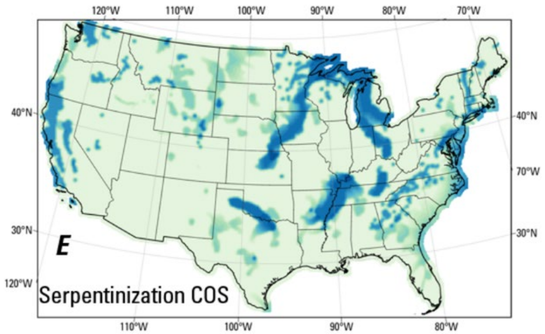


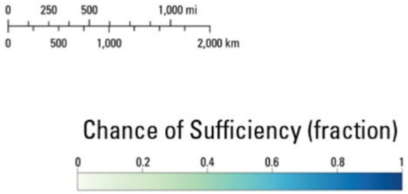
Gelman et al., 2025

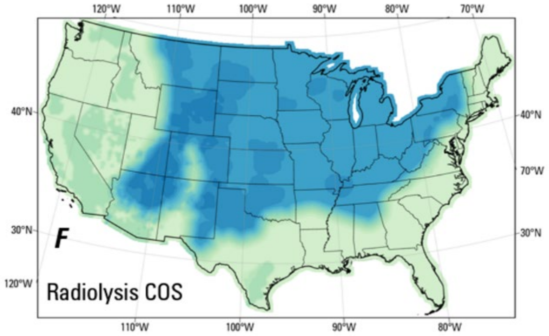
Hydrogen system components

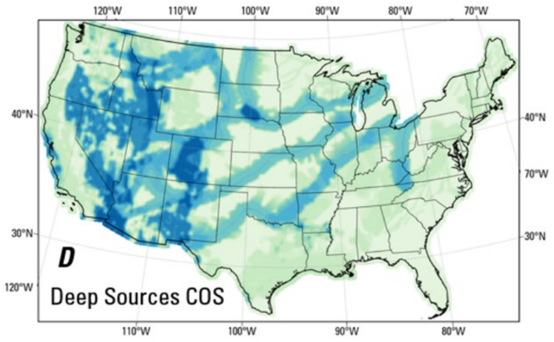
Source

- Serpentinization-type Reactions
  (SP1, SP2, SP3, SP4, …)
- Radiolysis of H_2O
  (RD1, RD2, RD3, RD4, …)
- Cryptic "deep sources"
  (DP1, DP2, DP3, DP4…)





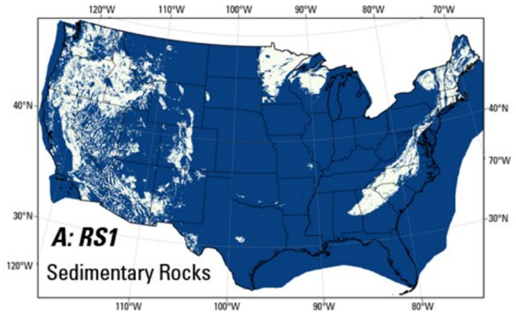


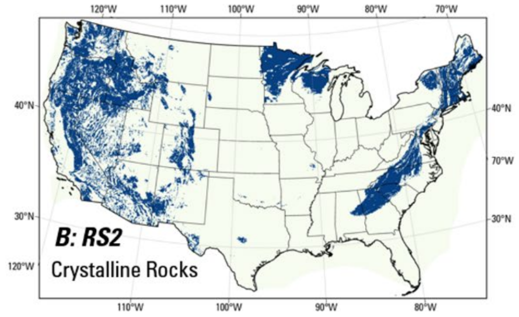


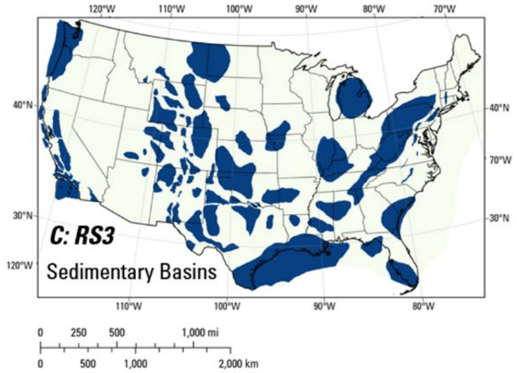
Reservoir Seal Preservation

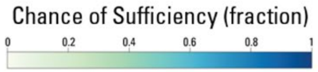
- Sedimentary
- Non-sedimentary

(RS1, RS2, RS3,…)
(SL1, SL2, SL3, …)





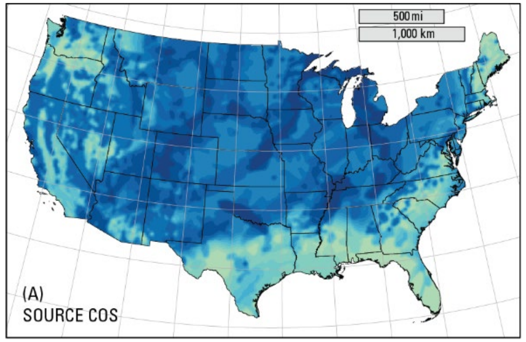




Gelman et al., 2025

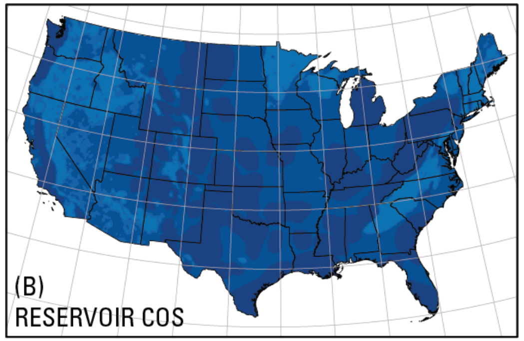
Geologic hydrogen prospectivity

Source COS



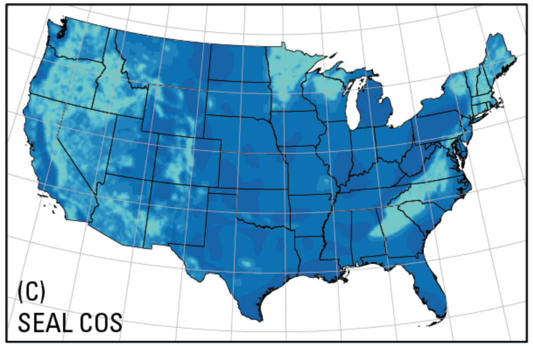
x

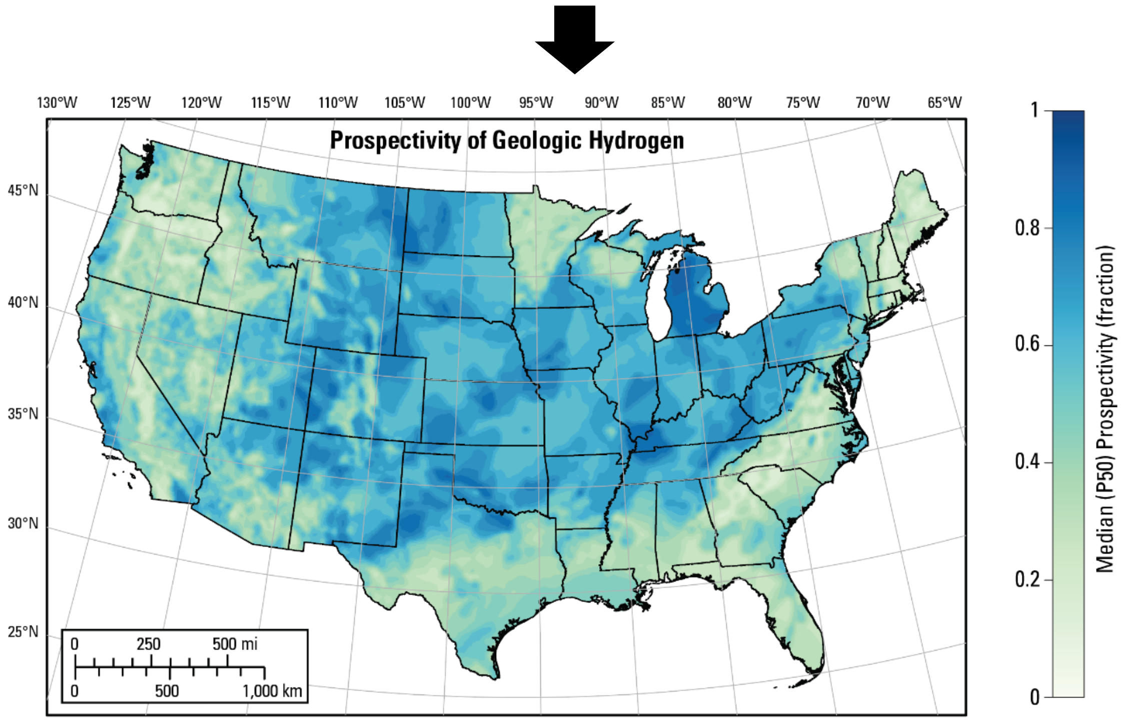
Reservoir COS



x

Seal COS





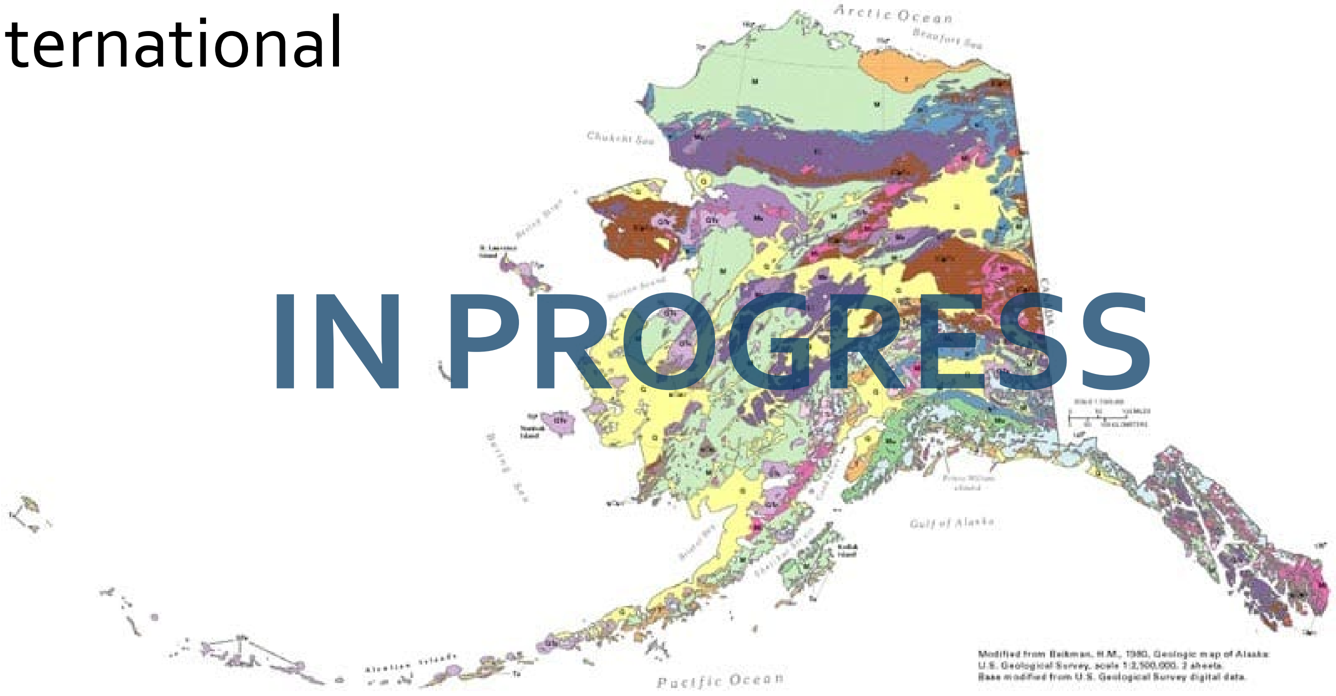
Gelman et al., 2025

https://www.usgs.gov/publications/prospectivity-mapping-geologic-hydrogen

Geologic hydrogen prospectivity mapping status

- Prospectivity mapping of Alaska
- In discussions with international collaborators
  - Canada
  - Australia
  - Brazil
  - Colombia
  - Finland
  - Others …

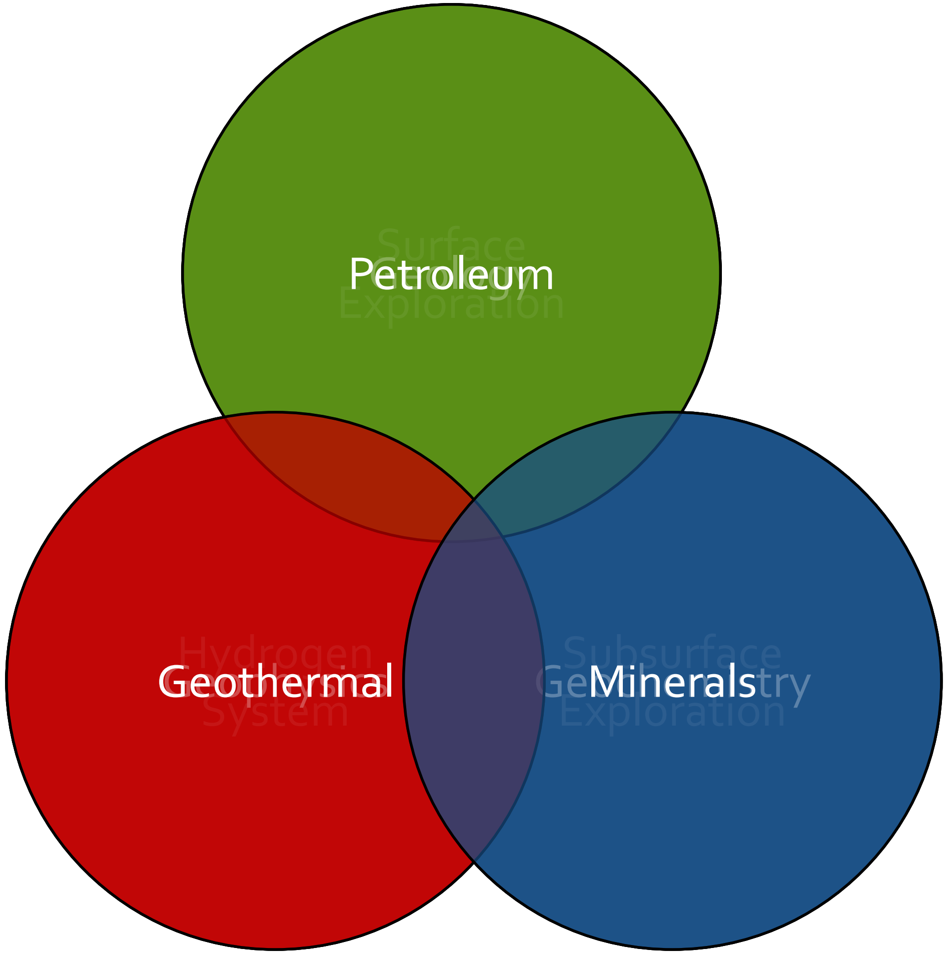
IN PROGRESS



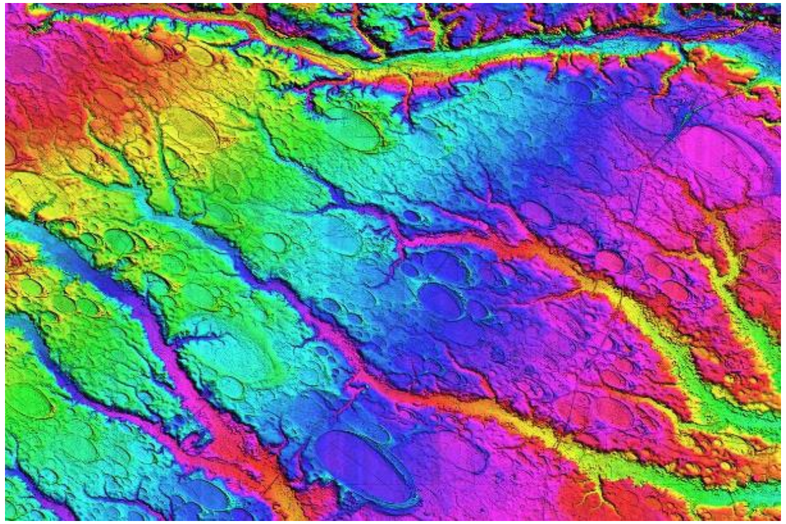
USGS
science for a changing world

Research needs

- **Refinement of the hydrogen system** model
- Development of **surface** and **subsurface exploration** techniques for identification of hydrogen flux
- Development of **modeling** tools for hypothesis testing and evaluating hydrogen system concepts
- **Engineering** approaches for efficient production of hydrogen from the subsurface
- **Integration of Geology, Geochemistry, and Geophysics**
- Much of the needed **expertise and technology exists** in petroleum, geothermal, and mineral resource fields



Development of surface exploration techniques for identification of hydrogen flux



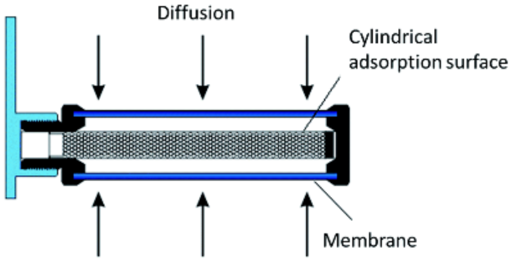
- **Remote sensing**
  - LiDAR
  - Hyperspectral imaging
- **Soils and soil gases**
  - Develop new technologies for low-cost sampling for surface geochemistry
  - Application of advanced geochemical techniques (noble gases, bulk and clumped isotopes, etc.)
  - Downhole gas characterization
  - Environmental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

Surface observation complications

Temporal and spatial variability

Artificially generated hydrogen

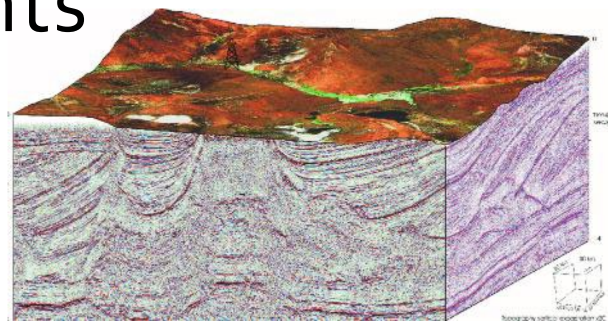
Efficient microbial removal

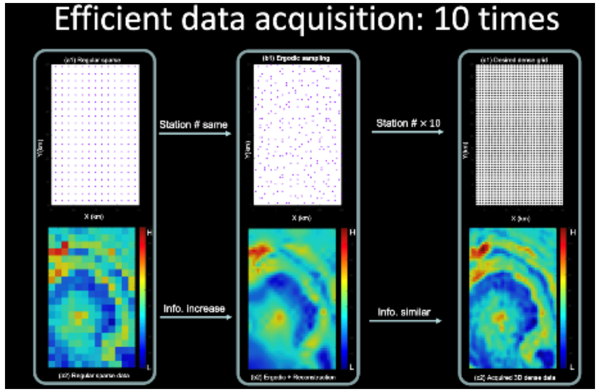


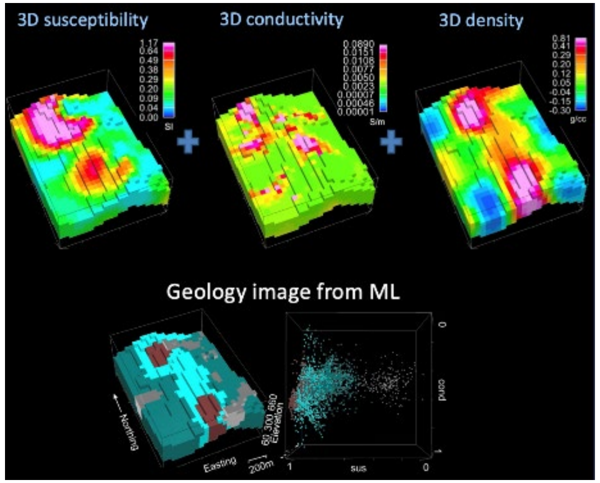
USGS
science for a changing world

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







USGS
science for a changing world

Reactive transport modeling

H_2 Concentration

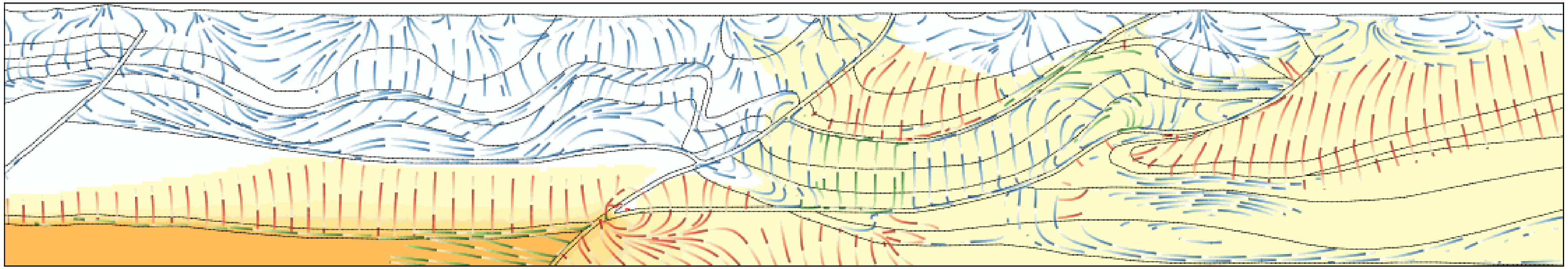
Low High

— Advective Flux (H2O) > 1e-14 m2/s

— Advective Flux (H2) > 1e-14m2/s

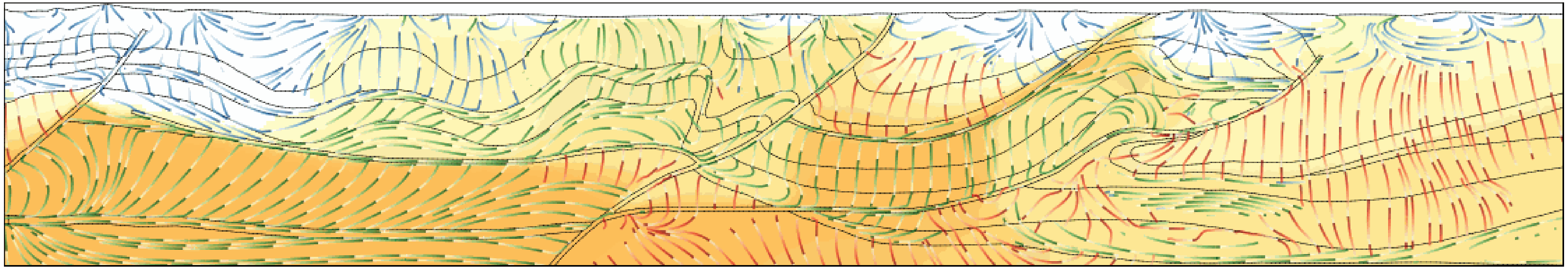
— Diffusive Flux (H2) > 1e-17m2/sec

Without hydraulic head scenario



With hydraulic head scenario

10Mpa



Summary

- Large quantities of natural hydrogen exist in the subsurface
- The potential for economic accumulations of hydrogen gas is unknown
- USGS has mapped the prospectivity of geologic hydrogen resources across the lower 48 states of the US
- Ongoing work to map prospectivity of Alaska
- Research is needed:
  - To better understand the processes that lead to the accumulation of hydrogen in the subsurface
  - To identify effective exploration techniques and strategies
  - To develop efficient engineering approaches for hydrogen production

Natural Hydrogen, LLC

USGS
science for a changing world

USGS-CSM Energy & Mineral Research Facility (coming 2027)

Thank you

USGS-Colorado School of Mines
Joint Industry Research Consortium
Potential for Geologic Hydrogen Resources

USGS science for a changing world

www.geophysics.mines.edu/geoh2

COLORADO SCHOOL OF MINES @150 | 1874-2024

USGS science for a changing world

Geoffrey S. Ellis, PhD
Research Geologist
Energy Resources Program

gsellis@usgs.gov
htpps://energy.usgs.gov

U.S. Department of the Interior
U.S. Geological Survey

Box 25046, MS939
Denver CO 80225-0046