UNDERSTANDING THE POTENTIAL FOR GEOLOGIC HYDROGEN RESOURCES

GEOFFREY S. ELLIS
Energy Resources Program
U.S. Geological Survey

Department of Geology and Geological Engineering
Colorado School of Mines
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
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
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.
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 km$^2$ (~⅓) South Australia leased for natural hydrogen exploration
• 1$^{st}$ 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
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
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

The critical unknown for geologic hydrogen resource potential is accumulation processes
Geologic hydrogen system model

3 conceptual types of exploitable hydrogen resources

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

<table>
<thead>
<tr>
<th>Sources</th>
<th>$x10^9\text{m}^3\text{H}_2/\text{year}$</th>
<th>Tg/year ($=10^6\text{t/}\text{year}$)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Geological</td>
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<tr>
<td>Mid-oceanic rift system</td>
<td>1.3</td>
<td>0.12</td>
<td>(Welhan and Craig, 1979)</td>
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<td></td>
<td>2</td>
<td>0.18</td>
<td>(Charlou et al., 2012)</td>
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<td></td>
<td>3.7</td>
<td>0.33</td>
<td>(Cannat et al., 2010)</td>
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<td></td>
<td>4.3</td>
<td>0.38</td>
<td>(Keir, 2010)</td>
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<td>Oceanic crust, by various oxidations</td>
<td>10 ± 7</td>
<td>0.9 ± 0.6</td>
<td>(Bach and Edwards, 2003)</td>
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<td>Oceanic crust serpentinization</td>
<td>1.8–2.9</td>
<td>0.16–0.26</td>
<td>(Canfield et al., 2006)</td>
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<td>8.5</td>
<td>0.76</td>
<td>(Sleep and Bird, 2007)</td>
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<td></td>
<td>22.4</td>
<td>2</td>
<td>(Worman et al., 2016)</td>
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<td>Ophiolite massifs</td>
<td>2–4</td>
<td>0.18–0.36</td>
<td>based on (Zgonnik et al., 2019)</td>
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<td>Basaltic layer of the oceanic crust</td>
<td>84</td>
<td>7.5</td>
<td>(Sleep and Bird, 2007)</td>
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<td>139</td>
<td>12.6</td>
<td>(Holloway and O’Day, 2000)</td>
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<td>Precambrian basement</td>
<td>0.45–4.3</td>
<td>0.04–0.38</td>
<td>(Sherwood Lollar et al., 2014)</td>
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<td>0.9–1.2</td>
<td>0.08–0.11</td>
<td>(Warr et al., 2019)</td>
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<td>Volcanoes and hydrothermal systems</td>
<td>108 ± 81</td>
<td>9.6 ± 7.2</td>
<td>(Holland, 2002)</td>
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<td>Subaerial volcanoes</td>
<td>2–7.7</td>
<td>0.18–0.69</td>
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<td>2.7</td>
<td>0.24</td>
<td>(Stoiber, 1995)</td>
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<td>Mid-ocean ridge volcanoes</td>
<td>0.2–0.6</td>
<td>0.02–0.05</td>
<td>(Canfield et al., 2006)</td>
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<td>Coal metamorphism</td>
<td>0.02</td>
<td>0.0014</td>
<td>(Koyama, 1963)</td>
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<tr>
<td>Deep-seated hydrogen</td>
<td>?</td>
<td>?</td>
<td></td>
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<tr>
<td>Sub-total for geologic</td>
<td>254 ± 91</td>
<td>23 ± 8</td>
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</tbody>
</table>

Critical for all hydrogen play types

Modified from Zgonnik, 2020
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

Lopez-Lazaro et al., 2019
Lefeuvre et al., 2022
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
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
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)?
Engineering challenges of stimulated hydrogen

- Optimized fractures in crystalline rocks
- Maintaining controlled water-rock contact
- Selective gas recovery
- Efficient product recovery – stray H₂ risk
- Flowback water – disposal, reuse, contaminants
- Induced seismicity risks

Gas separation & pressurization

Water tank

Overlying sedimentary rocks

Injection well

Water heating in a conductive process

3000 - 6000 m

Production well

Target zone - Hot Dry Rock

Hydraulic fractures network

500 - 1500 m
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.
Thank you

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