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Current perspectives on natural hydrogen: a synopsis

Betina Bendall

Energy Resources Division, Department of Energy and Mining

Contact: Betina.Bendall@sa.gov.au

Introduction

As the world transitions to a low emissions future, the importance of molecular hydrogen (hereafter 'hydrogen') as a key clean energy resource is increasingly being recognised. Hydrogen provides a fungible, flexible energy solution that can be applied to a broad range of industrial and transportation uses in partnership with broadscale electrification, offering a viable replacement for gas, petroleum and diesel fuels (Körner et al. 2015). Commercial volumes of hydrogen are currently produced via steam reforming of light hydrocarbons or water hydrolysis, but an immediate challenge is to increase production at commercially competitive rates to achieve a critical mass of supply, which will enable rapid growth of the hydrogen market.

Although hydrogen is the most abundant element in the universe, it is highly reactive and has generally been considered to be unavailable in significant volumes as a free gas in nature. It can be produced by a range of natural processes in the subsurface however, and there are historical records of drillholes and natural geological features producing high fluxes of hydrogen. Is it plausible then that additional supply could be found in natural subsurface accumulations of hydrogen?

Many think so. Increasing attention is being given to how natural hydrogen might be generated and stored geologically in accessible volumes, and what exploration techniques could be best applied to locate and exploit such accumulations.

Does natural hydrogen exist?

To date the potential for significant accumulations of natural hydrogen has been considered rare. This belief can be attributed to a number of factors. As the smallest element, hydrogen diffuses rapidly and readily chemically combines with other elements and molecules making it difficult to contain in the gaseous state subsurface (Lemieux et al. 2019; Truche and Barzakina 2019; Gaucher 2020; Boreham et al. 2021a). Historically, samples from drillholes and deep mines have not been routinely sampled and analysed for hydrogen, so its presence is likely to be under-recorded, biasing existing databases (Fig 1) (Zgonnik 2020). This is in part due to inappropriate analytical techniques and equipment (e.g. Coveney et al. 1987) and in part to the self-perpetuating belief that hydrogen is rarely present so why look for it (Gaucher 2020)? Furthermore, if significant natural accumulations of hydrogen do exist, it is possible that they do not necessarily coincide geologically with other targeted commodities (Truche and Bazarkina 2019; Gaucher 2020; Coveney et al. 1987). In other words, a geological environment suitable for ore genesis or the generation, capture and storage of hydrocarbons, is not necessarily prospective for natural hydrogen and may in fact be an overall hydrogen sink since any free hydrogen in these systems is likely to be chemically bound and stored permanently in hydrocarbons or other hydrogen-containing compounds. Perhaps we have been looking in the wrong places.

Mechanisms of subsurface generation

There are a both anecdotal and studied examples of natural hydrogen occurring as diffusive seepages and subsurface accumulations intersected by drillholes. These known accumulations are located in a diverse range of geological environments, suggesting there may be a variety of mechanisms for generating natural hydrogen (Fig 1). Proposed subsurface generation mechanisms include, but are not limited to:

- degassing of magmas and deep-seated hydrogen from the Earth's core and mantle
- cataclasis

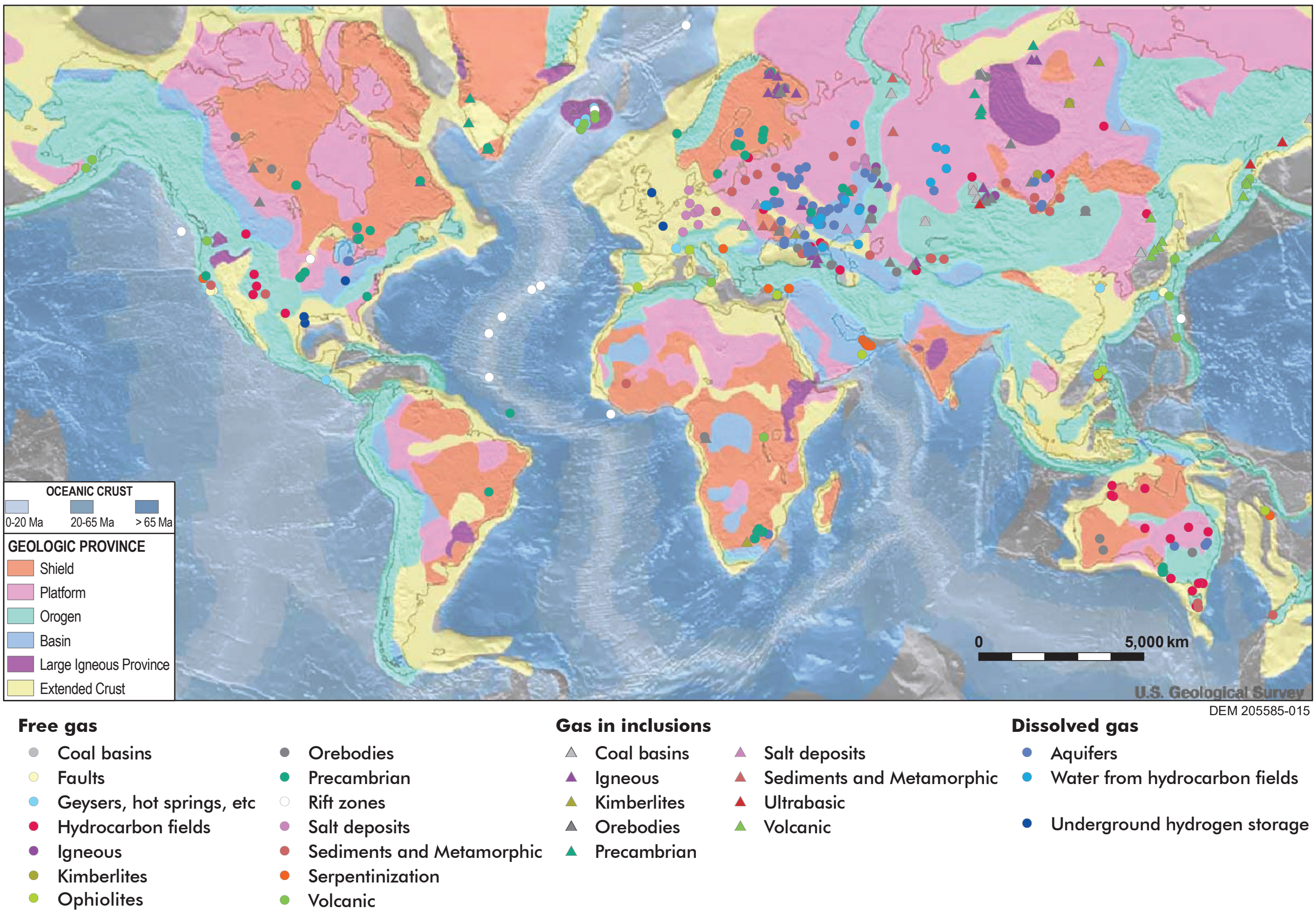

Figure 1 *Locations and geological environments of recorded hydrogen measured at >10% volume around the world. As noted by Zgonnik (2020), the relatively dense distribution of hydrogen discoveries across Europe and Asia reflects biases in data collection rather than an accurate indication of the local prospectivity for molecular hydrogen. (Modified from Zgonnik 2020; Truche et al. 2020, Truche and Barzakina 2019; Boreham et al. 2021a; Sherwood Lollar et al. 2014; Warr et al. 2019; Moretti et al. 2021.)*

- oxidation of divalent iron (Fe^{2+}) rich minerals and lithologies through rock-fluid interaction (e.g. serpentinisation); equivalent redox reactions may also occur using other multivalent elements such as sulfur, nitrogen and manganese
- natural radiolysis of water
- biogenic and abiogenic decomposition of organic matter
- a combination of coincident genetic factors

(Larin et al. 2014; Zgonnik et al. 2015; Zgonnik 2020; Boreham et al. 2021b; Boreham et al. 2021a and references therein).

Magma and mantle degassing

Numerous observations suggest that hydrogen derived from magmatic processes and the degassing of the Earth's upper mantle and, hypothetically, the lower mantle and core (Toulhoat and Zgonnik 2022) is prevalent, and routinely migrates through the crust to the Earth's surface. These observations include:

- high concentrations of hydrogen in air and soil gases, hydrothermal fluids and volcanic gases associated with rift zones, mid-ocean ridges, volcanic and geothermal zones, and ophiolite complexes (Sherwood Lollar et al. 2014; Gaucher 2020; Moretti et al. 2021; Sleep et al. 2004; Truche et al. 2020; Prinzhofer et al. 2018 and references therein)
- the increasing concentration of hydrogen in gases sampled at increasing depth from deep drillholes and deep-seated faults (Kita et al. 1982; Sato et al. 1986; Larin et al. 2014; Zgonnik 2020)
- inclusions from a variety of mantle-derived lithologies and minerals (e.g. kimberlites, olivine, diamonds and perovskite; Zgonnik 2020; Truche et al. 2020; Coveney et al. 1987) and Precambrian basement lithologies (Parnell and Blamey 2017a)
- measurements of isotope ratios (δ^2H) of hydrogen (Zgonnik 2020 and references therein; Boreham et al. 2021a, 2021b).

Theoretical studies indicate that hydrogen can be present in the mantle and core as natural metal hydrides (VH_2) and appropriate pressure–temperature–redox conditions exist in the lower mantle to support the presence of water, and hydrogen-rich and methane-rich fluids (Isaev et al. 2007; Truche et al. 2020; Kenney et al. 2002; Zgonnik 2020 and references therein).

Cataclasis

The presence of natural hydrogen associated with fault zones has also been attributed to the release of occluded hydrogen from silicate minerals during the shearing of rocks, and from the interaction of water with fresh rock surfaces exposed by fault movement. These processes may act as correlative mechanisms to mantle degassing in appropriate tectonic settings or as independent generation processes (Kita et al. 1982; Sato et al. 1986; Guelard et al. 2017; Parnell and Blamey 2017a; Boreham et al. 2021a).

Oxidation of Fe^{2+}-rich minerals and rocks

The oxidation of Fe^{2+} to Fe^{3+} ions by water is another process which is thought to be a significant source of hydrogen production in geological environments. In particular, the metamorphism of ultramafic rocks in oceanic crust, ophiolites and mid-ocean ridges to serpentinite (serpentinisation) and the oxidation of oceanic basalt crust are theoretically capable of producing significant volumes of hydrogen (Sleep et al. 2004; Truche et al. 2020; Boreham et al. 2021a; Murray et al. 2020 and references therein). Similarly, oxidation of Fe-bearing minerals in Fe-rich cratonic areas and ferrous sediments could also be a source of subsurface hydrogen production (Guelard et al. 2017; Sherwood Lollar et al. 2014; Murray et al. 2020; Boreham et al. 2021b; Warr et al. 2019).

Radiolysis

Another proposed mechanism for natural hydrogen generation is the decomposition of water into component H_2 and O_2 molecules via radiolysis, particularly in uranium-rich rocks. In this case, the energy from radioactive decay of K, U and Th in rocks acts to break the chemical bonds in water molecules and produce free hydrogen and oxygen gases (Sherwood Lollar et al. 2014; Parnell and Blamey 2017a; Warr et al. 2019). It is noteworthy, however, that the majority of the energy created through radioactive decay is lost as heat energy to the surrounding rock mass, and the chemical reactions associated with the radiolysis of water are part of a complex combination of redox reactions rather than a single complete and separate reaction sequence. Nonetheless, Parnell and Blamey (2017a) were able to demonstrate that high hydrogen concentrations were present in Precambrian basement rocks and their derived sediments which they attributed to natural radiolysis.

A notable example of radiolytic hydrogen generation is associated with carnallite ($KMgCl_3 \cdot 6(H_2O)$) and sylvite-rich (KCl) potash deposits (evaporites). Gases and aqueous fluids are commonly held within evaporites in fractures and voids, and in intracrystalline (inclusions) and intercrystalline spaces (Warren 2016; Parnell and Blamey 2017b). Accumulations of free hydrogen and other gases have been historically recorded in potash mines and can constitute a hazard to mining and drilling activities (Warren 2016; Truche and Barzakina 2019; Zgonnik 2020 and references therein). It is generally held that these hydrogen accumulations originate from the radiolysis of crystallisation water through the radioactive decay of K and Rb present in carnallite, sylvite and interbedded clays (Smetannikov 2011; Warren 2016; Parnell and Blamey 2017b; Zgonnik 2020 and references therein).

Decomposition of organic matter

Decomposition of organic matter through the processes of anaerobic decay, fermentation and nitrogen-fixing bacteria are also capable of generating natural hydrogen. These processes often take place in complex chemical and biological environments where the hydrogen produced is then taken up by hydrogen-consuming microorganisms or converted by complementary reactions in soil and sediments to produce hydrogen-fixing methane and nitrogenous compounds (Boreham et al. 2021a and references therein). Overall, soils are a major hydrogen sink and it is likely that most hydrogen produced via biologically mediated processes is subsequently fixed in the soil, although Prinzhofer et al. (2019) found soil hydrogen fluxes varied spatiotemporally and hydrogen could also be emitted from soil. An alternative scenario is where high hydrogen concentration is found associated with coal maturation and generation of hydrocarbons, a thermogenic process rather than microbial one (Tissot and Welte 1984; Truche and Bazarkina 2019). Recently, the kinetics of thermogenic hydrogen generation has been determined for lacustrine organic matter where free hydrogen becomes available from generation of overmature organic matter (Horsfield et al. 2022).

The take home message is there is evidence for geologically sourced production of natural hydrogen via a number of mechanisms. The hydrogen cycle is complex and poorly understood as a holistic system however (Zgonnik 2020; Moretti et al. 2021; Murray et al. 2020; Truche and Bazarkina 2019; Truche et al. 2020). The balance between subsurface hydrogen generation and consumption via organic (biologically mediated) and inorganic reaction processes, and hence the extent of hydrogen produced and stored as commercially viable natural accumulations, requires focused study.

Analogues – natural seeps

Arguably, the best place to start developing understanding about natural hydrogen systems is by examining known examples of naturally occurring seeps and producing drillholes. Many naturally occurring hydrogen seeps have been identified on the seafloor and on the continents (Fig 1). Some continental examples, including Mt Chimaera (Turkey), Los Fuegos Eternos (Philippines), the Semail ophiolite (Oman), and other locations in Greece, Portugal, New Caledonia, and Bosnia and Herzegovina, have been linked to production of hydrogen from serpentinisation of ultramafic or ophiolitic complexes (Gaucher 2020; Zgonnik 2020 and references therein). Other diffusive seeps located in intracratonic settings (e.g. Sao Francisco Basin in Brazil, Bourakebougou in Mali, Africa, and Russia) have been attributed to fluid-rock chemical interactions such as the oxidation of Fe^{2+}-rich minerals and lithologies in underlying rocks, or radiolysis of water as outlined above (Prinzhofer et al. 2018; Guelard et al. 2017; Gaucher 2020).

These intracratonic diffusive seeps sometimes occur within shallow, circular to subcircular surficial depressions on the tens of metres to kilometre scale and are referred to as 'fairy circles' by some researchers (Fig 2). These shallow topographic features are commonly associated with changes in vegetation and bleached soil, often occur in clusters, and can be identified using statistical analysis of their surface geomorphology in conjunction with aerial photography, LiDAR and satellite imagery as

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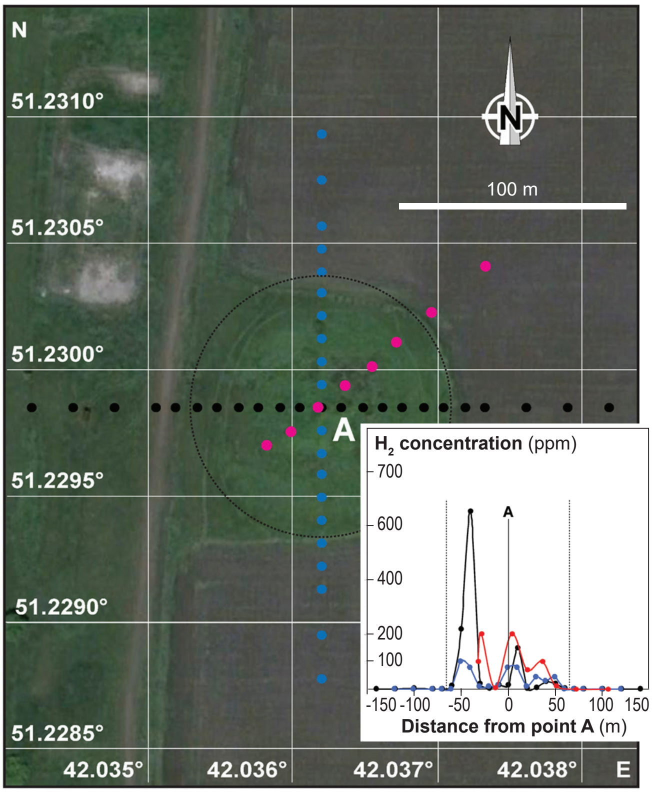

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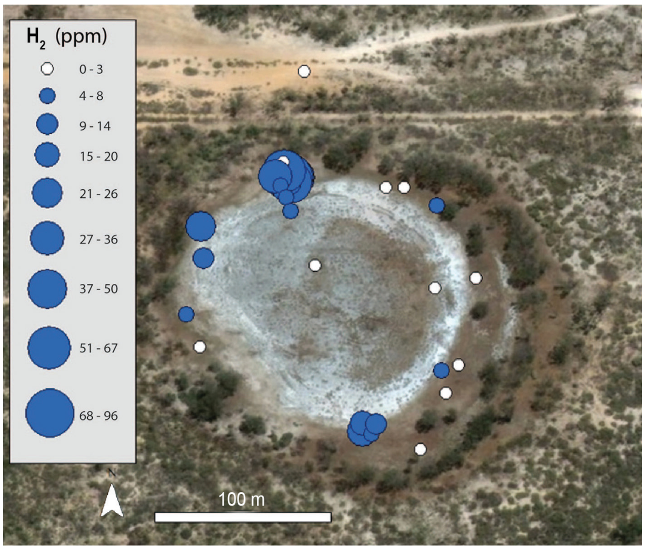

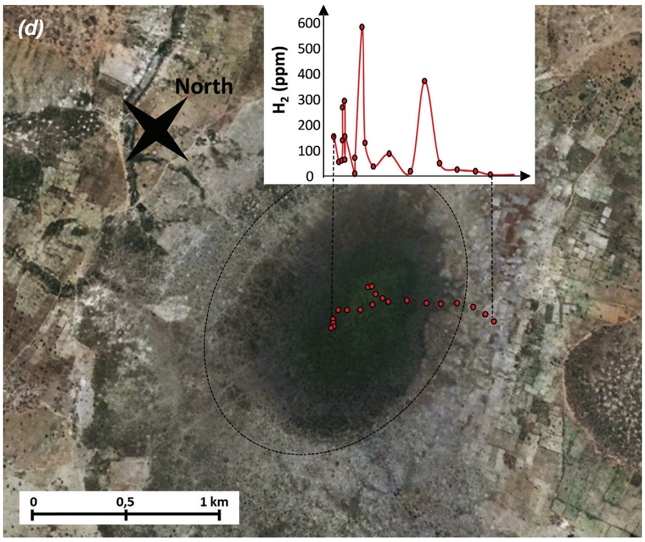

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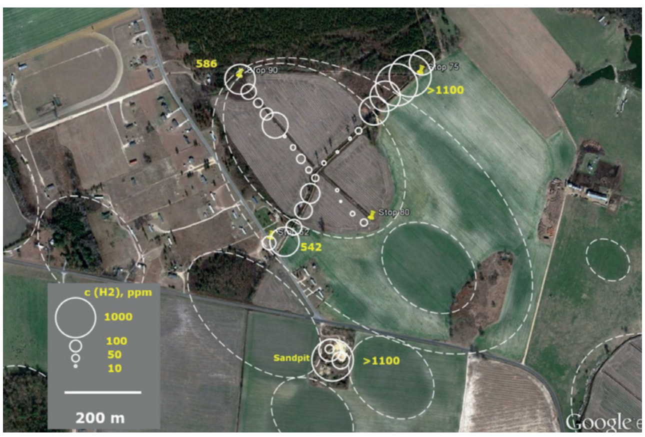

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Figure 2 *Examples of natural hydrogen seeps from shallow, circular to subcircular topographic depressions (aka fairy circles) and associated measured surface H_2 concentration.* ***(a)*** *Podovoye, Russia (after Larin et al. 2014).* ***(b)*** *North Perth Basin, Western Australia (after Frery et al. 2019).* ***(c)*** *Carolina Bays, USA (after Zgonnik et al. 2015).* ***(d)*** *Bourakebougou, Mali, Africa (after Prinzhofer et al. 2018).*

a screening aid for early exploration targets (e.g. Larin et al. 2014; Zgonnik et al. 2015; Moretti et al. 2021). Using satellite imagery, geomorphological features of similar appearance have been identified in the Borisoglebsk area of Russia, on Kangaroo Island and Yorke Peninsula, South Australia, and the Yilgarn Craton, Western Australia (Larin et al. 2014; Rezaee 2020; Moretti et al. 2021; Frery et al. 2021).

The formation of these subcircular depressions has been postulated as a diagenetic effect of hydrogen increasing rock porosity via chemical dissolution as it migrates toward the surface (Larin et al. 2014; Zgonnik et al. 2015; Zgonnik 2020). If so, it is possible that this process can enable the migration of hydrogen away from deep-seated conduits such as fault zones. Hence seeps may be directly connected to an actively producing hydrogen source or to a leaking reservoir. It is also noteworthy, however, that these shallow, subcircular surface features are not ubiquitously present in areas where hydrogen accumulations have been identified, and there are alternative biological and geomorphological processes, such as the mechanical weathering of soil by heavy rain, extreme heat and evaporation, which could also form these features in some locations (e.g. Meyer et al. 2020; Getzin et al. 2016).

Diffusive seeps have generally been confirmed and characterised through the deployment of soil gas chemistry monitoring sensors, which indicate that hydrogen fluxes tend to vary spatiotemporally (Fig 2). In the case of the circular to subcircular topographic depressions, hydrogen is present within the depressions, but absent in the areas outside of and surrounding the depressions (Larin et al. 2014; Zgonnik et al. 2015; Prinzhofer et al. 2018; Moretti et al. 2021). At this stage there are no direct soil gas data indicating an active hydrogen flux at the circular structures documented in South Australia; however, gas analyses from drillholes drilled in the 1920s–30s on Kangaroo Island (American Beach Bore 1) and Yorke Peninsula (Ramsay Oil Bore 1), provide alternative evidence that a hydrogen resource may be present in these locations (Ward 1932a, 1932b, 1941). A recent study by Frery et al. (2021) demonstrated that a series of similar circular structures, spatially related to the Darling Fault in the North Perth Basin, Western Australia, are natural hydrogen seepages. In this location, the Darling Fault juxtaposes Precambrian ultramafic and mafic rocks and Proterozoic Fe-rich granite of the Yilgarn Craton against layered Permo-Mesozoic sedimentary rocks which include multiple aquifers and aquitards. This suggests that the natural hydrogen emitted from the circular structures at surface could be sourced from the oxidation of Yilgarn basement rocks by anoxic fluids, mobilised along zones of transmissivity associated with the Darling Fault system (Frery et al. 2021).

Analogues – high hydrogen fluxes in drillholes and mines

There are also numerous examples of groundwater, oil and gas drillholes, and mines intersecting significant hydrogen fluxes or accumulations in a range of cratonic settings including: Russia (Larin et al. 2014); Brazil (Prinzhofer et al. 2019); Bourakebougou, Mali (Prinzhofer et al. 2018); northeastern Kansas, USA (Coveney et al. 1987; Guelard et al. 2017); the Witwatersrand, South Africa; Canada; Finland (Sherwood Lollar et al. 2014 and references therein); the Otway Basin (Robe 1), Yorke Peninsula, Kangaroo Island and the western flank of the Cooper Basin (Ralgnal 1), South Australia (Ward 1917; 1932a; 1932b; 1941); the Amadeus and McArthur basins, Northern Territory; and many other Australian basins (Boreham et al. 2021a, 2021b) (Fig 1). However, only a few have been comprehensively studied with a view to understanding the hydrogen system. A number of authors (Zgonnik 2020; Gaucher 2020; Moretti et al. 2021; Prinzhofer et al. 2019; Boreham et al. 2021a) have noted the similarity between the development of the hydrocarbons industry and the current state of knowledge about natural hydrogen. A possible analogue and reasonable starting point to developing an exploration strategy then might be the petroleum systems (source – migration pathway – reservoir–seal–preservation) approach that underpins hydrocarbon exploration (Magoon and Dow 1994).

Source

As is the case in hydrocarbon exploration, the most difficult element of a hydrogen system to constrain may be the source, as this will likely be beyond drillable depths. Geochemistry will be a critical tool to assess the hydrogen source; however, the reactivity of hydrogen can result in perturbed chemical signatures of gas samples, directly affecting stable hydrogen isotope ratios and hydrogen-based geothermometers for example, and thus complicating differentiation of the hydrogen source or sources from contamination (Boreham et al. 2021a, 2021b; Coveney et al. 1987; Guelard et al. 2017; Zgonnik 2020). Conversely, these reactions may also result in characteristic changes to the geochemical signatures of observed associated elements and gases such as nitrogen, helium, ammonia, argon, methane and the noble gases, enabling the identification of the environment of generation by proxy (Guelard et al. 2017; Prinzhofer et al. 2018; Truche et al. 2020; Boreham et al. 2021b; Warr et al. 2019). Comprehensive systematic studies of the geochemical relationships between these elements and hydrogen in various geological settings are needed to develop reliable baseline models and exploration strategies for the future (Coveney et al. 1987; Zgonnik 2020; Prinzhofer et al. 2018; Boreham et al. 2021b; Warr et al. 2019).

As an example, in northeastern Kansas a number of drillholes produce hydrogen-rich gas from Mississippian sedimentary rocks and aquifers. While the origin of the gas is considered likely to be a mixture of deep crustal and surficial processes, a definitive source has not been identified due to the complexity of overprinting signatures from competing hydrogen-producing processes. The most likely hydrogen sources are from oxidation of Fe^{2+}-rich rocks in the underlying Precambrian basement and biologically mediated hydrogen production from headwater in the drillholes (Coveney et al. 1987; Guelard et al. 2017), but mantle degassing and, in particular, serpentinisation of kimberlites, known to be present nearby, have not been discounted due to compositional similarities with gases from the Semail ophiolite, Oman.

Reservoir and seal

As observed by Gaucher (2020), the Bourakebougou field in Mali could serve as the first example of a full natural hydrogen system, occurring within a series of five stacked Neoproterozoic marls and carbonate reservoirs, sealed by interlayered doleritic sills and aquifers, and extending over an estimated area of about 8 km in radius (Prinzhofer er al 2018). Interestingly, hydrogen and methane in this field are not trapped concurrently at the same reservoir depths or by the same seals, suggesting that hydrogen acts differently to hydrocarbons and may require seals or retardants with different physicochemical properties to those effective for hydrocarbon storage (Prinzhofer et al. 2018). In Kansas, hydrogen is present in several zones within late Mississippian sandstone, siltstone and limestone units, and an artesian aquifer directly overlying the Precambrian basement. Gas pressures and chemistry in the various Kansas drillholes appear to vary temporally and can be influenced by restricting exchange between the aquifer and the basement (Coveney et al. 1987; Guelard et al. 2017), suggesting recharge from an active hydrogen flux which may be migrating up adjacent fault structures from a deeper source (Coveney et al. 1987; Guelard et al. 2017).

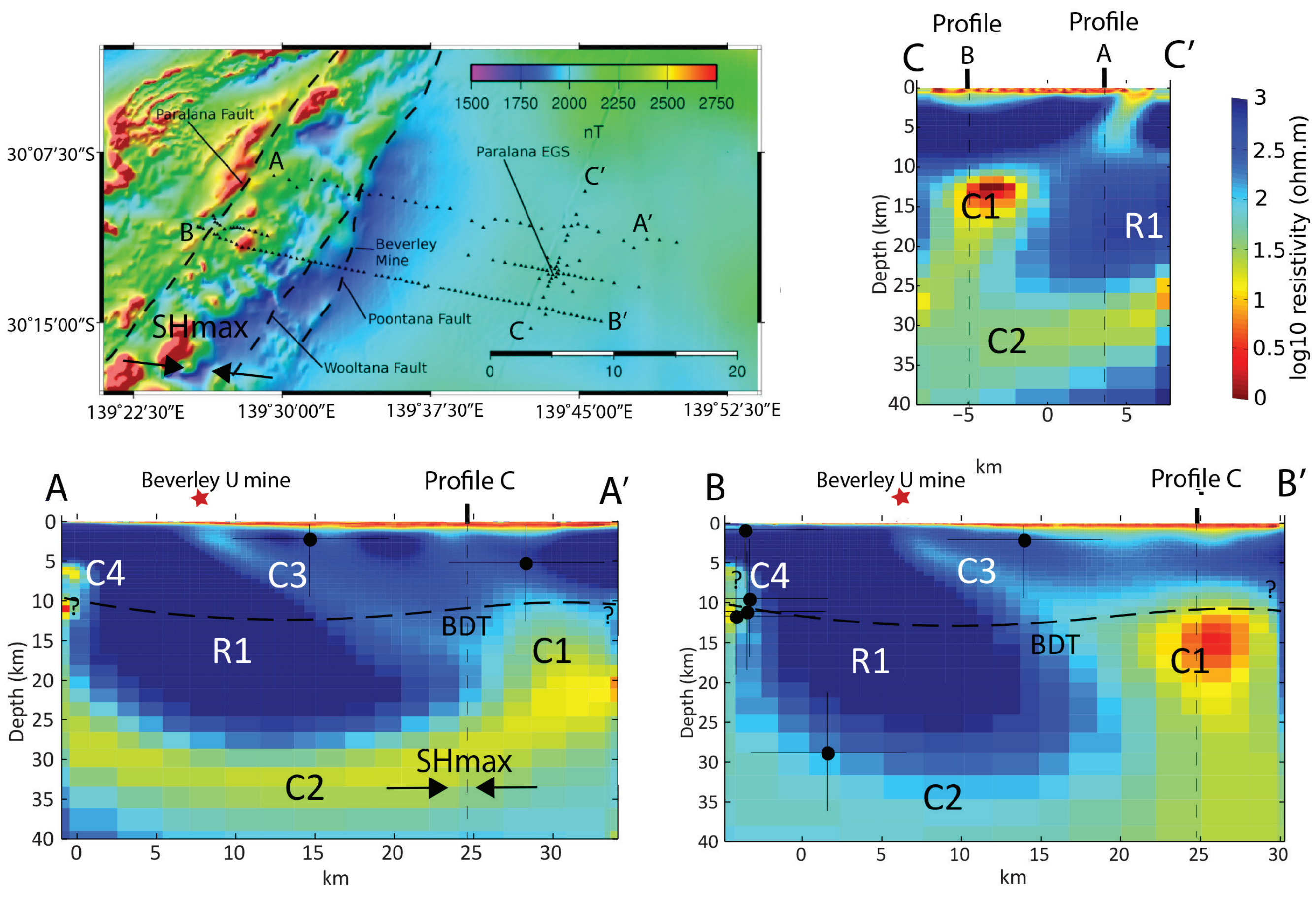
It is possible then that some natural hydrogen accumulations are long-lived dynamic systems resulting from continuous, diffuse generation of hydrogen approaching a steady state in the crust, similar to conductive geothermal systems, rather than static accumulations more akin to oil and gas fields. The permeability of individual rock layers and the presence of aquifers, together with subsurface hydrogen-fixing reactions, may mediate the balance between rates of migration from active generation sites and rates of continuous surface seepage.

Dedicated studies are required to better understand the specific nature of hydrogen solubility in water and its retention in clays and other rock types (Boreham et al. 2021a; Truche and Bazarkina 2019), and work is already underway on understanding the potential suitability of saline aquifers and depleted oil and gas reservoirs for commercial storage of hydrogen (e.g. the HyUnder project) (HyUnder 2014; Ennis-King et al. 2021). Natural gas is frequently stored in depleted reservoirs and salt caverns and there are a few examples of hydrogen being successfully stored over decades in salt caverns in the UK and USA (Caglayan et al. 2020; Lemieux et al. 2019; Körner et al. 2015). Evaporites, in particular, are considered an important geological storage option for both natural and manufactured hydrogen storage due to their rheology, low permeability to gases, and chemically and biologically inert nature (Körner et al. 2015; Caglayan et al. 2020; Lemieux et al. 2019; Ennis-King et al. 2021), and are unique in their potential to form the source, reservoir and seal for a natural hydrogen system.

Exploration tools

Geochemistry is likely to be an important tool to assess an exploration target prior to drilling. As discussed by Zgonnik (2020), a significant impediment to the discovery of natural hydrogen resources is the global paucity of soil monitoring data and monitoring for hydrogen in drillholes and mines generally. Moreover, existing studies have shown that natural hydrogen fluxes can be variable and cyclic (Prinzhofer et al. 2019; Guelard et al. 2017; Larin et al. 2014; Zgonnik et al. 2015; Sato et al. 1986), hence continuous monitoring strategies are likely to be more useful than single grab sampling. The reactivity of hydrogen can result in perturbed chemical signatures of hydrogen gas samples through interaction with casing, storage vessels, fluid-rock interactions during migration (including with clays and soils) or atmospheric contamination during sampling and storage (Coveney et al. 1987; Truche et al. 2020; Warr et al. 2019; Boreham et al. 2021a). Any such interaction can affect measurement quality. Moreover, the natural hydrogen cycle is complex and poorly understood as a holistic process which makes interpretation of data difficult. While high hydrogen soil gas fluxes are an obvious indicator, they may not be directly measurable due to hydrogen fixing chemical reactions in the zone above any given subsurface accumulation. Hence proxy 'indicator' gases may also be an important screening tool. For example, the consumption of hydrogen to produce natural abiotic methane can occur via multiple reaction pathways, meaning that detection of abiotic methane may be a useful indicator for the presence of natural hydrogen systems (Truche et al. 2020; Warr et al. 2019). This is borne out by the presence of elevated abiotic methane in association with hydrogen in gas analyses from natural seeps and drillholes (Guelard et al. 2017; Prinzhofer et al. 2018; Boreham et al. 2021b; Warr et al. 2019), and at rift zones and mid-ocean ridges (Truche et al. 2020 and references therein).

The association of high hydrogen fluxes from drillholes and seeps located close to active fault systems, ultramafic complexes and Precambrian basement terranes (Coveney et al. 1987; Warr et al. 2019; Boreham et al. 2021b) suggests that traditional geophysical techniques (e.g. magnetics, gravity, airborne electromagnetics, magnetotellurics and deep seismic) may also have a useful role to play in exploration for natural hydrogen resources (e.g. Guelard et al. 2017; Truche and Barzakina 2019; Boreham et al. 2021a). These techniques have been routinely used by the mining sector to map and identify subsurface structures and lithologies obscured by cover. Of particular interest is the ability of magnetotellurics to identify deep-seated conductive zones present through the crust down to Moho depths (Fig 3), which have been associated with significant ore bodies (e.g. Olympic Dam and Beverley in South Australia), graphitic zones, geothermal systems and serpentinised mafic and ultramafic complexes (Heinson et al. 2006; Thiel et al. 2016; Robertson et al. 2015). These conductive zones have generally been considered conduits for crustal-scale hydrothermal systems, but could plausibly also represent migration pathways for other fluids including lower crustal and mantle derived hydrogen fluxes (e.g. Glassley 1982; Boreham et al. 2021a, Dargent et al. 2015 and references therein).



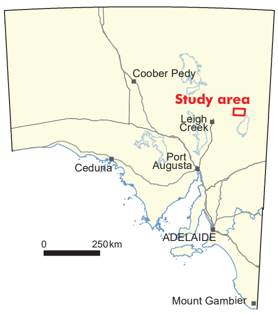


Figure 3 *Two-dimensional resistivity modal of magnetotelluric transects performed across the Poontana Basin in the vicinity of the Beverley uranium mine and Paralana engineered geothermal systems (EGS) project adjacent to the Mount Painter Inlier, South Australia (after Thiel et al. 2016). High conductivity regions in the lower crust (C2) are linked to near-vertical, localised high conductivity zones (C1, C3, C4) which reach into the brittle–ductile transition and toward the surface, potentially focused by fault systems. These vertical zones (C1, C3) are spatially associated with the Beverley mine and Paralana EGS project areas. The reader is referred to Thiel et al. (2016) for detailed discussion of the modelling methodology and results.*

Conclusion

There is clear evidence to indicate that hydrogen exists in a free gas state in the subsurface. The diversity of environments in which it is observed, the variety of proposed mechanisms for generation and apparent inconsistencies in determining correlating causal factors, however, demonstrates that our understanding of its genesis, extent and abundance has been hampered by a lack of focus on exploring specifically for hydrogen. Much of the available evidence has been circumstantial, resulting from studies investigating other commodities or particular geological processes and environments more generally. This has been exacerbated by inappropriate methods for detection, analysis and routine sampling which perturb, or fail to capture, accurate hydrogen measurements. As attention turns toward the increasing use of hydrogen as a sustainable low emission fuel for the future, targeted studies are needed to elucidate the critical criteria for developing specialised exploration approaches for natural hydrogen. Some broad comments can be made however to guide exploration activities targeting continental accumulations of natural hydrogen.

- Target basement areas which contain Fe^{2+}-rich and/or uranium-rich rocks as these have potential for generating hydrogen via oxidation and radiolytic processes, respectively (e.g. Archean greenstone and Precambrian basement terranes).
- If these potential source areas are fractured and seismically active, then deep-seated faults can act to both channel migrating hydrogen from deeper sources to surface and introduce water downward for further chemical reaction with exposed Fe^{2+}-rich rocks.
- A sedimentary overburden may enable entrapment of migrating hydrogen, particularly if aquifer systems and/or evaporites are present in the sedimentary sequence. Evaporites may also constitute a hydrogen source.
- Targets may be associated with surficial hydrogen seeps. Seeps can be blind or coincident with visible subcircular topographic depressions on the metre to kilometre scale, often associated with perturbed vegetation cover. Soil gas monitoring over extended periods can identify an active hydrogen flux.
- Routine monitoring for hydrogen in mines, and groundwater, oil and gas drillholes is a worthwhile practice which should be encouraged to bolster our understanding and existing records of natural hydrogen occurrences.

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