Natural Hydrogen Play-Type Models from a Development Perspective

Introduction

This paper proposes a broad classification of natural hydrogen occurrences from a viewpoint of not only exploration geology but also technical development-potential and ability to meet current levels of commercial need.

Hydrogen Systems

From a conceptual point of view, working subsurface "hydrogen systems" comprise the same key elements as their "petroleum system" counterparts namely: Source, Reservoir, Trap and Seal. However, petroleum systems occur in sedimentary basin-fills where vertical stacking of source rocks, multiple reservoir levels and sealing lithologies is common and where there is a tendency towards relatively high-relief but gentle structures capable of trapping large amounts of hydrocarbon. In contrasts, such favourable settings are less common in cratonic settings that host much of the suspected hydrogen sources.

Assumed presence of active hydrogen source, effective trapping of hydrogen in the subsurface then critically hinges on presence of 1) a reservoir rock with adequate storage capacity for hydrogen, either as a pore fill or (in the case of coals) adsorbed on a molecular scale; 2) presence of a seal rock with adequate tightness to hold the pressure differential of a trapped hydrogen-gas column; and 3) a trapping configuration of reservoir and seal. Given that hydrogen molecules are small and volatile, exceptional seal-quality will be required. In case of seal-breach, reservoir layers may still contain hydrogen but most of it in aqueous phase rather than in gaseous phase. Unlike trapped hydrogen gas, dissolved hydrogen has no natural drive and its recovery potential will be limited.

Considering the extent of success or failure on elements of the conceptual "hydrogen system" and consequences for technical development-potential, this paper proposes to categorize hydrogen "finds" and prospects into three broad "hydrogen play types":

1. **"Focus Areas of Natural Seepage"**, plays with an active hydrogen source but limited (if any) subsurface trapping of gaseous hydrogen. Elevated hydrogen concentrations in such settings reflect localized migration pathways, mostly of dissolved hydrogen.
2. **"Coal-Bed Hydrogen"** plays where hydrogen is adsorbed on a molecular scale in coals. In such a system, top-seal and trapping configuration are not strictly required.
3. **"Reservoir-Trap-Seal"** configurations with gaseous hydrogen trapped at excess pressure, like in a conventional gas field.

These different play-types are described further below from geology and development-potential perspective, and illustrated with actual field examples.

1. "Focus Areas of Natural Seepage" Plays

This play-type model describes settings where there is active expulsion of hydrogen from one or more subsurface sources (e.g., hydrothermal basement alteration, mantle degassing or radiolysis of formation water) but limited (if any) trapping of hydrogen in gaseous phase due to unfavourable geology. Without trapping, buoyancy forces drive the expulsed hydrogen upward where it will eventually leak out at surface. However, due to subsurface heterogeneity this migration will seldomly be uniform. Instead, structural features like folds and faults will typically funnel the expulsed hydrogen into discrete, major migration pathways such as fault/fracture zones or laterally extensive permeability "thief zones" like karst horizons. Where migration pathways outcrop, notable surface-seeps and corresponding surface expressions (e.g., fairy circles) may result. Where hydrogen migrates through relatively tight formations at slow rates and with long residence times, formation waters in and around migration pathways may be saturated with hydrogen. Consequently, wells intercepting such pathways may see hydrogen "gas shows" especially if the drilling is done at balance or underbalanced. When pressure drawdown is applied (with a downhole sampling tool or during a flowtest), formation-water solubility of hydrogen reduces and some hydrogen will be released in gaseous phase and flow into the well. However, gas flowrates will typically be low and often hampered by water encroachment.

<u>Field Example:</u> Bourakebougou field in Mali features the world's first commercial hydrogen producer well, Bougou-1 which production-tested 1,500m3 a day (0.13 ton/day) of hydrogen from an interval some 60 to 112m below surface. Following the test, Bougou-1 provided fuel for a small power generator with a reported annual-average offtake of around 5 ton. Appraisal wells showed the hydrogen flows from a locally karstified but otherwise rather tight dolomite stringer sandwiched in between dolerite sills (Maiga et al, 2023). The deeper stratigraphy down to granite basement consists of tight sandstones (3-6% porosity; some of it with gas shows but not flow-tested), some shales and additional dolerite sills. The structure is a very gentle anticline that plunges to the north and is open to the south without significant trap closure. Reservoir pressure down to basement appears to follow a hydrostatic trend.

It has been suggested (e.g., Maiga et al., 2024) that a dolerite sill above the karstified dolomite acts as an effective top seal for entrapment of hydrogen gas. However, author's integrated review of all available open-domain data suggests the trapping of hydrogen in gaseous phase at excess pressure in Bougou is extremely unlikely, for the following reasons:

1. The low shut-in pressure observed during the Bougou-1 welltest (61psia, Briere et al, 2017) which, in combination with inferred formation-water pressures, implies that hydrogen cannot exist in gaseous phase in the reservoir;
2. Log signatures in surrounding appraisal wells, notably the complete absence of Neutron-Density cross-over (which should be very strong in case of gaseous hydrogen presence);
3. Lack of structural closure and no obvious relationship between gas shows and structure elevation.

Instead, this author believes that Bougou field comprises concentrated seeps of hydrogen dissolved in formation water, possibly originating from the red beds near basement. The karsted and laterally extensive dolomite stringer provides an obvious migration flow-path within a succession of otherwise rather tight rocks. Gas production in Bougou-1 may be due to the pressure drawdown applied, reducing hydrogen solubility and releasing some of it in gaseous phase. Considering thickness and properties of the dolomite stringer, 26psi depletion within a 110m radius around the well may release some 135kg hydrogen, enough to explain the flow-test result. Similarly, Bougou-1 annual-average production (5 ton hydrogen) can be explained by depletion within a 670m radius.

Resource Density (hydrogen-per-unit-area in the karsted dolomite and four deeper horizons) at Bougou may be around 3,100 ton hydrogen-in-place-per-km^2, of which tentatively (assuming a modest but possibly achievable depletion) around 180 ton hydrogen-per-km^2 might be recoverable. These estimates are compatible with reported production in Bougou-1 but at least two orders of magnitude less than the demand of a typical large industrial facility (Figure 1).

<u>Technical Potential:</u> Since "focused seep" plays have no excess pressure to provide reservoir "drive", increasing pressure drawdown by lifting out large amounts of formation water is the only avenue to increase rates and recover more of the dissolved gas. However, pumping constraints and factors like formation tightness and aquifer extent will inevitably limit the achievable drawdown and consequently, the question how much hydrogen may be extractable from a "focused seep" setting will typically depend on the density of drilling. Due to inevitably low flowrates, "focused seep" plays are not suitable to meet the demand of large industrial hydrogen customers and instead, hydrogen commercialization would rely on small local offtake. Low-cost wells and proximity to market could be key commercial enablers.

2. <u>"Coal-Bed Hydrogen" Plays</u>

Coals can adsorb significant quantities of gas: they preferentially adsorb methane but they can also adsorb hydrogen. Experimental data (e.g., Iglaurer et al, 2021) shows that the "isotherm curves" which describe adsorption capacity of hydrogen in coals increase with pressure and decrease with temperature (similar to methane and CO2 isotherms). In principle, hydrogen adsorption in coals does not require structural trapping.

Hydrogen is not uncommon as a component of coal-mine gas; according to Zgonnick (2020) the first discovery of natural hydrogen was in fact made in gas from a coal mine in Ukraine. Hydrogen usually occurs in proportions of less than 30% mixed with other gases, notably methane and CO2.

Field Example: Folschviller-1 in Lorraine (France) is a coal-bed-methane test well where hydrogen shows were recently reported (FDE press release, 2023). Gas shows were detected in Carboniferous coal beds of between 4 to 13m net thickness, sandwiched in between tight sandstones and shales (EGL press release 2006; Allouti et al, 2023). Gas is predominantly methane but hydrogen content increases with depth from some 6% H2 at 760m to 20% at 1250m. Measured Gas Content of the coal seams varies between 7 to 10m^3 per ton (EGL press release 2006) which suggest the coals may be undersaturated. Reported permeability is between 0.5 to 4mD.

This author estimates a Resource Density (hydrogen-per-unit-area, total across the 6 coal seams in Forschviller-1 well) of around 11,000 ton hydrogen-in-place-per-km^2, of which tentatively (CBM analogue recovery-factors) around 5,400 ton hydrogen-per-km^2 might be recoverable (Figure 1).

Technical Potential: Given predominance of methane, Forschviller would be a coalbed methane development with hydrogen as a byproduct. Drawing-down pressure to let gas desorb will be key to recovery and given the relatively low Gas Content, large quantities of water may have to be pumped off before gas production peaks. Based on analogue experience with coalbed methane developments worldwide, production from coals deeper than 1,200m would be extremely challenging.

Assuming a typical CBM well-spacing of 4 wells per km^2 and one well per seam (i.e., 24 wells per km^2) it becomes evident that high well-counts will be required to recover material resource quantities. Gas recovery per well may be in the order of 0.7 Bscf only, of which just 0.1 Bscf (230 ton) would be hydrogen. Added to this the complexity and cost of separating the different gases to a sales-specs hydrogen purity, it becomes apparent that commercial developments of “Coal-Bed Hydrogen” would be highly challenging especially if the target is to meet industrial hydrogen demand.

3. “Reservoir-Trap-Seal” Plays

This play-type model describes settings with an active hydrogen source combined with a favourable trapping configuration involving one or more porous and permeable reservoir(s) capped by a seal that can hold the pressure differential of a column of gaseous hydrogen. Existence of such systems, analogous to conventional gas fields, for now remains a speculation that awaits exploration confirmation. Despite numerous reports of hydrogen seeps at surface and traces of hydrogen in the subsurface (Zgonnick, 2020; Stalker et al., 2022), none of these finds convincingly demonstrate the presence of hydrogen trapped in a porous and permeable reservoir, in gaseous phase and at excess pressure.

Field Example: the Monzon prospect in Aragon (Spain; Atkinson et al, 2022), is used here to illustrate the potential of a trapped accumulation of gaseous hydrogen, albeit speculative at this stage. The structure consists of a tilted faultblock within which the Triassic Bunter reservoir (at 3600m, average porosity around 10%) is sealed by an 1800m thick interval of evaporites and shales. A 1963 exploration well (Monzon-1) recorded some hydrogen gas-shows in the Bunter but presence of free gas remains ambiguous from available logs and other data.

Based on reported reservoir thickness, properties and temperature and assuming presence of a 60m hydrogen column in the trap, this author estimates a speculative Resource Density of 43,000 ton hydrogen-in-place-per-km^2, of which tentatively around 35,000 ton hydrogen-per-km^2 might be recoverable (Figure 1). If alternatively, Moznon trap is assumed to contain hydrogen in aqueous phase only (dissolved in formation water, not as free gas), Resource Density reduces to 6,000 ton hydrogen-in-place-per-km^2. But more significantly, recovery potential reduces to a few 100 ton hydrogen-per-km^2 only due to the difficulty involved in depleting aquifer pressures.

Technical Potential: The speculative example of Monzon illustrates the critical importance of reservoir energy provided by gas trapped at excess pressure. Assuming free-gas presence in Moznon trap at 5,500 psia initial reservoir-pressure versus 850psia abandonment pressure, recovery efficiency of 80% or more may be achievable. Even with modest reservoir permeability, simple vertical wells may be able to achieve plateau-production of some 6 MMscf/d or 5,500 ton/year of hydrogen each whilst horizontals could potentially do better. Reservoir-Trap-Seal” configurations may be the only types of hydrogen plays that have potential to meet the supply needs of large industrial facilities (Figure 1).

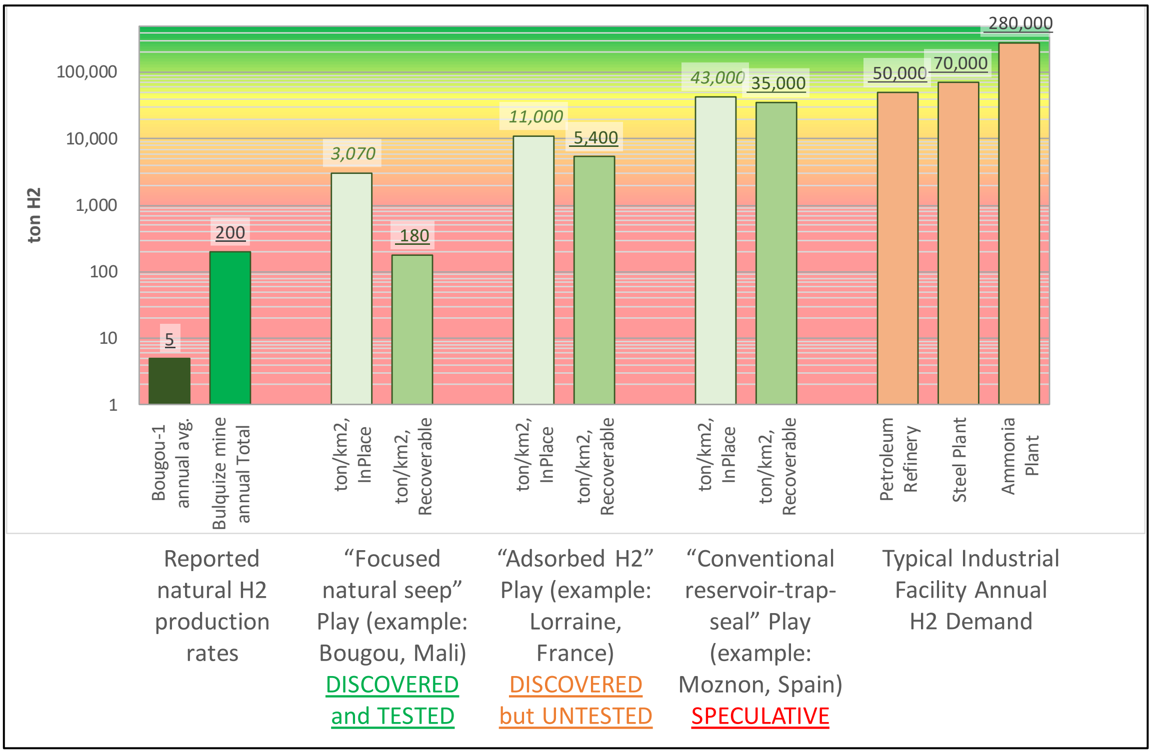

Figure 1: *Hydrogen Resource Density (ton/km2) by Play-Type versus typical Industry Demand*

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