GS2024-19

Geologic hydrogen in the Williston and Hudson Bay basins, southwestern and northeastern Manitoba (parts of NTS 53, 54, 62, 63)

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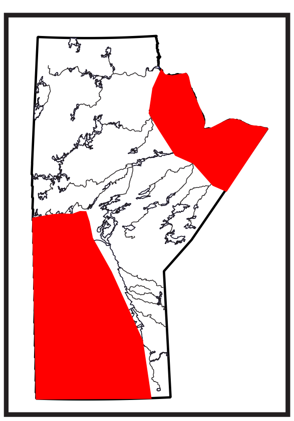
In Brief:

- Manitoba has the right geological conditions to support an active hydrogen system
- Hydrogen generation by radiolysis and rock-water interactions are the dominant sources, with potential in both basins

Citation:
Nicolas, M.P.B. 2024: Geologic hydrogen in the Williston and Hudson Bay basins, southwestern and northeastern Manitoba (parts of NTS 53, 54, 62, 63); *in* Report of Activities 2024, Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, p. 164–171.



Summary

Geologic hydrogen, also referred to as white, gold, natural or free hydrogen, is formed by natural processes and can occur in potentially economic accumulations in the subsurface but has been largely overlooked as a resource. This reconnaissance study focused on hydrogen potential within the sedimentary strata of the Williston and Hudson Bay basins. Geologic hydrogen is formed by several reactions, including radiolysis and rock-water interactions related to serpentinization and iron oxidation of Precambrian rocks—with serpentinization theorized to be the best source of geologic hydrogen. Potential Precambrian hydrogen generation sources were identified by mapping drillholes reported to have basement lithologies with the potential to generate hydrogen from a rock-water interaction. To further define the area of these potential sources, the drillholes were mapped in combination with total field magnetic anomaly data. A compilation of gas analyses results from government petroleum technical well files indicated very low concentrations of hydrogen, with only 10 analyses having hydrogen concentrations of >1 mol. % and two of those with values of ~8 mol. %. The highest values come from wells producing from the Bakken Formation, suggesting the high values may be the product of radiolysis, a result of the radioactive decay of the highly organic shale. These occurrences of low hydrogen concentrations and prejudice in overlooking hydrogen during gas analyses in the past have resulted in potential reporting errors, and may have resulted in bypassing occurrences.

Introduction

Hydrogen, the first element in the periodic table, is an odourless, colourless, highly reactive, mobile and light element that occurs as the molecule H_2 in gas form. Geologic hydrogen, also referred to as white, gold, natural or free hydrogen, is formed by natural processes and can occur in potentially economic accumulations in the subsurface, although its use as a naturally occurring clean fuel resource has been largely overlooked until recently. As a chemical, hydrogen is used in many industrial applications, such as ammonia production and hydrocarbon refining, and is an important clean fuel in space rockets and other propulsion systems (Sukumaran, 2024).

The reactivity and diffusibility of hydrogen has led to the belief that economic accumulations are not possible. In the geological environment, hydrogen is formed as a byproduct of several reactions, including rock-water interactions (e.g., the oxidation of Fe^{2+}-bearing minerals and serpentinization of ultramafic rocks), weathering, decomposition of organic matter and natural water hydrolysis (Lin et al., 2005; Warr et al., 2019). The development of geological models to better understand these hydrogen systems and how the models can be used to predict its viability as a reliable resource and its economic boundaries is still in its infancy. The determination of an economic threshold for hydrogen production from the subsurface is ambiguous, but with an increasing demand for clean hydrogen fuel, these limits are being studied.

In order to understand the geologic hydrogen system in strata of the Williston and Hudson Bay basins in Manitoba, potential bedrock sources of hydrogen were identified and oil and gas wells with reported concentrations of hydrogen were reviewed.

Geological models

As a foundation, lessons can be learned by applying the concepts and methodologies used for petroleum exploration in sedimentary basins to exploring for geologic hydrogen, such as identifying a significant source, migration pathways, porous reservoirs and tight seals. Sedimentary basins, including the Williston Basin, have a long history of oil and gas exploration and production, therefore, there is a good understanding of the migration-reservoir-seal systems in this basin. The challenge is in identifying a significant hydrogen source.

Jackson et al. (2024) indicated that the most efficient hydrogen generator in the geological environment is serpentinization, but other popular generators being considered are iron-rich rock–water interactions and radiolysis, where water is decomposed by natural radiation. In Manitoba, the best geological setting for these processes to occur are in the Canadian Shield, particularly in greenstone belts, which form the complex fabric of the Precambrian basement of the Williston Basin.

Radiolysis

The natural radioactive decay of uranium, thorium and potassium will breakdown water to form helium and hydrogen, with large accumulations taking hundreds of millions of years to form (Broadhead, 2005). Based on the radiolysis formation model, the areas of helium potential discussed in Nicolas (2018) and Nicolas et al. (2023, 2024) would also be areas of potential for geologic hydrogen. The helium atom is smaller than the hydrogen molecule, making any seal tight enough to trap helium also sufficient to trap hydrogen thus allowing it to accumulate, notwithstanding the reactivity of hydrogen. In Manitoba, granitic basement rocks and highly radioactive shales would be the best geological environments to produce hydrogen by radiolysis.

Rock-water interactions

Serpentinization is seen as the most effective process for hydrogen production but it requires metamorphic conditions of between 200 and 300 °C and higher pressures than those seen in most undeformed sedimentary basins. Therefore, any hydrogen found within these sedimentary basins must have migrated into the strata from deeper sources. Hydrogen generation by serpentinization is geologically instantaneous, occurring over hundreds of thousands to one million years (Rüpke and Hasenclever, 2017). At points in the past, Precambrian greenstone belts within continental crust have been exposed to these conditions and likely contain enough remnant olivine to activate serpentinization at a later date via deep groundwater circulating through old and reactivated faults and fractures (Jackson et al., 2024). Through these processes, hydrogen generation can occur anew, initially migrating in an aqueous phase, followed by the upward migration in a gas phase to be trapped in the porous sedimentary strata above. Exsolution of hydrogen into a gas-rich phase would occur as the pressure and temperature decreases.

Oxidation of iron-rich rocks in the Precambrian basement is another source of hydrogen but with lower yields than that from serpentinization (Jackson et al., 2024). Iron formations are the best target in this case, but other iron-rich sulphide deposits are not to be discounted, including Mississippi Valley–type (MVT) deposits within the sedimentary strata.

Hydrogen sources

Identifying local sources of hydrogen is an important step in evaluating the hydrogen potential of a region. This can be done by identifying where rock types most likely to generate hydrogen would occur. For this study, a digital compilation of all the drillholes that penetrated the Precambrian in Manitoba prior to 2013 (McGregor, 2013) was reviewed. This compilation includes core and drill cuttings descriptions from industry and government reports. These descriptions were filtered for the following keywords: serpentinized (including serpentine), iron (iron formation, iron sulphide, iron-rich), olivine and ultramafic (including dunite, peridotite, komatiite). From this, a subset of drillholes—and potential hydrogen generating sites—emerged (Figures GS2024-19-1, -2).

Williston Basin

The first obvious trend in the Williston Basin (Figure GS2024-19-1) is the overall higher density of drillhole occurrences in the northwestern part of the map area; this is directly related to the mineral exploration drilling where the Phanerozoic cover is relatively thin. In the northwestern area, there are two separate high-density clusters: an east-west cluster along the northern basin edge resulting from exploration programs related to the sub-Phanerozoic extension of the metalliferous Flin Flon domain and its greenstone belts, and a northeast-southwest cluster related to the sub-Phanerozoic extension of the Thompson nickel belt and the Superior boundary zone (SBZ).

Given the abundance of iron-bearing units, sulphides and serpentinized units in the northern region, natural hydrogen is likely to have been generated but dissipated long ago. It is more likely that recent hydrogen generation would come from oxidation of iron formations. The Phanerozoic cover is fairly thin, well jointed and often karsted, suggesting that any natural hydrogen would degas to surface and not accumulate, although it is not unheard of to have gases trapped at shallow depths. Using the helium system as a model, a minimum depth of approximately 500 m (Broadhead, 2005) would be a preferred depth to ensure higher reservoir pressures for better trapping and economic accumulation.

Even though the southern half of the map has markedly less data points, some faint patterns do emerge. The Uchi, Bird River and Winnipeg River domains show the highest occurrences of drillholes with lithology keywords, in addition to an interesting occurrence of serpentine/serpentinized occurrences near or along these domain boundaries, as well as the SBZ. These crustal domain junctions are known to cause faulting and fracturing in the strata above and enhance fluid flow. The large crustal suture of the SBZ—the most significant sub-Phanerozoic Precambrian feature in the Williston Basin in Manitoba—is responsible for the development of the oil fields in the south, and has numerous documented faults and fractures and stratal disturbances (McCabe, 1959; Bezys et al., 1996, 1997; Dietrich and Bezys, 1998; Nicolas, 2012). Post-basin–formation hydrothermal systems and large networks of saline water fractures have also been documented; these create the much-needed deep migration pathways required to tap into ancient networks and deep fluids.

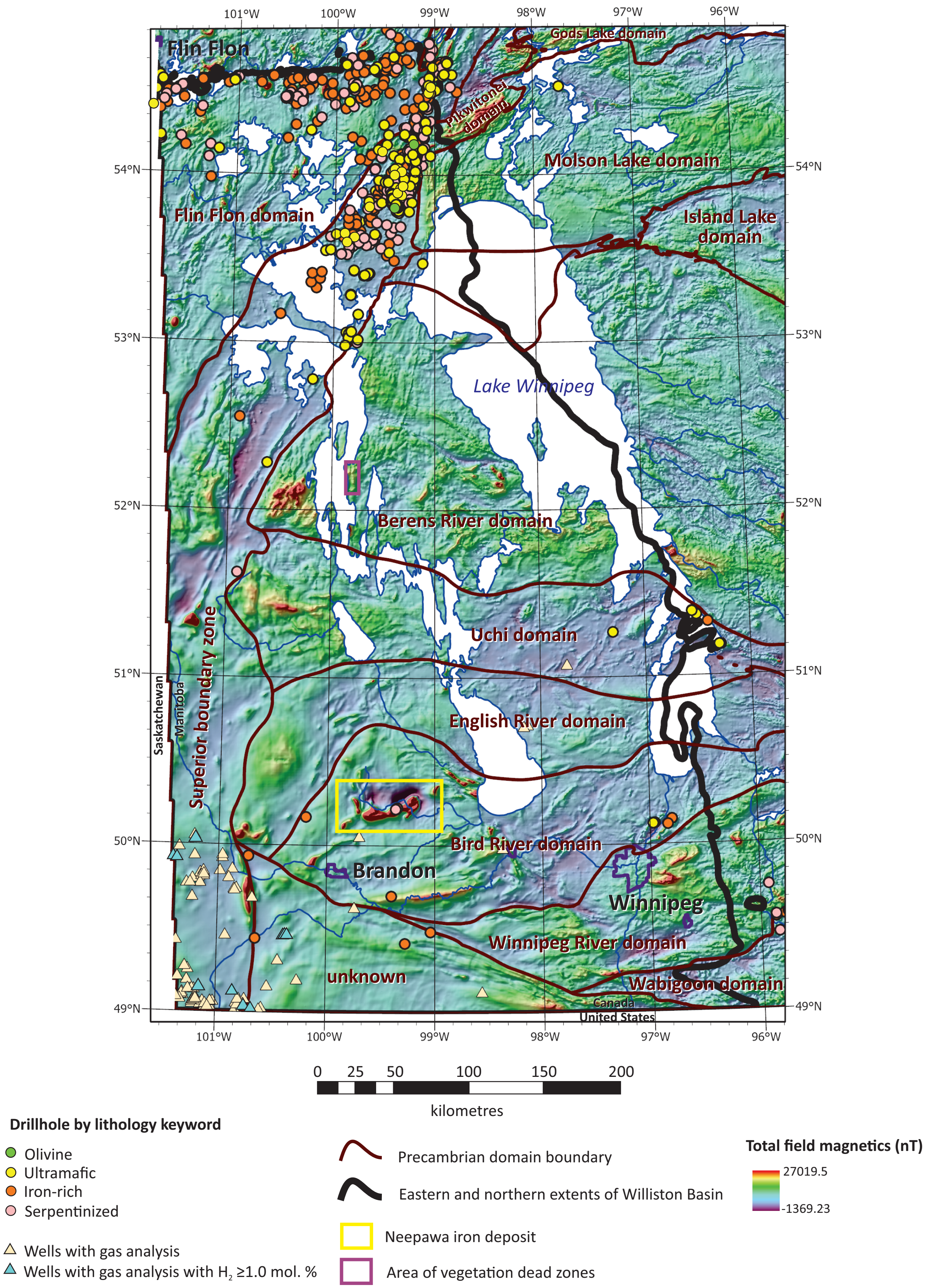


Figure GS2024-19-1: *Shaded total field magnetic anomaly map of the Williston Basin in southwestern Manitoba (Manitoba Economic Development, Investment, Trade and Natural Resources, 2024a) showing the Precambrian domain boundaries as drawn by McGregor (2013), and the distribution of drillholes with records that included the following lithology keywords (from McGregor, 2013): serpentinized (including serpentine), iron (including iron formation, iron sulphide, iron-rich), olivine and ultramafic (including dunite, peridotite, komatiite). Abbreviation: nT, nanotesla.*

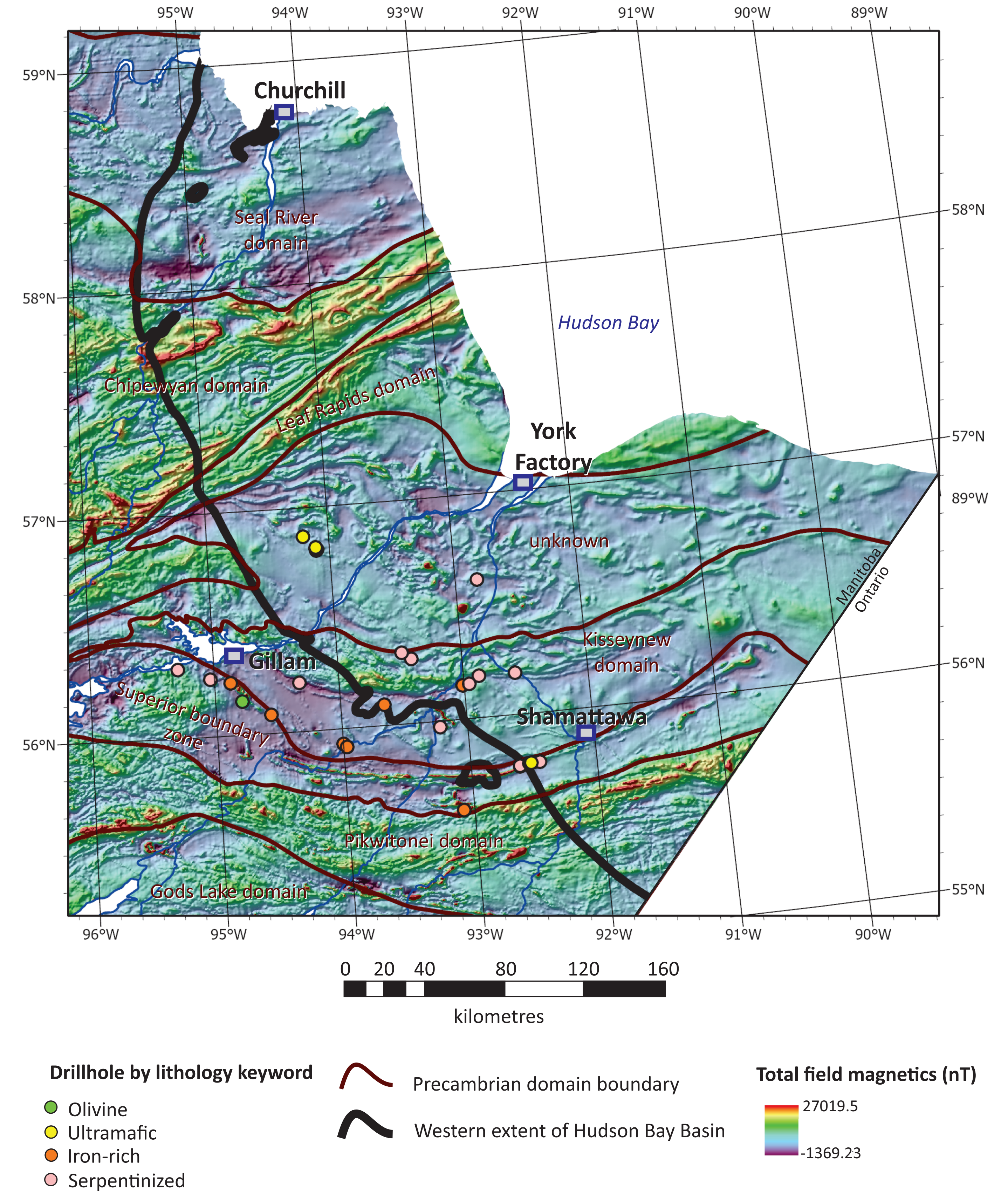


Figure GS2024-19-2: *Shaded total field magnetic anomaly map of the Hudson Bay Basin in northeastern Manitoba (Manitoba Economic Development, Investment, Trade and Natural Resources, 2024a) showing the Precambrian domain boundaries as drawn by McGregor (2013), and the distribution of drillholes with records that included the following lithology keywords (from McGregor, 2013): serpentinized (including serpentine), iron (including iron formation, iron sulphide, iron-rich), olivine and ultramafic (including dunite, peridotite, komatiite). Abbreviation: nT, nanotesla.*

The abundance of documented occurrences of serpentinized rocks points to the possibility of renewed serpentinization within the SBZ at depth, invigorated by hot and warm hydrothermal systems (Bezys et al., 1997; Grasby et al., 2009). Considering these theories, the SBZ and areas around crustal domain boundaries would serve as the best potential natural hydrogen sources and pathways. The migration through a network of pores, fractures and faults into the sedimentary strata above, with its porous reservoirs and multiple sealing units, provide for the rest of the hydrogen system requirements.

Overlying the drillholes with lithology keywords on a total field magnetic anomaly map, single sites (drillholes) become much larger source areas. High magnetic values would align with most of the rock types selected by the lithology search and likely correlate to sub-Phanerozoic greenstone belts, as expected, but would also show broader areas of high magnetic susceptibility, such as iron formations. The best example of this is the iron formation occurrence around the town of Neepawa (Figure GS2024-19-1) in Twp. 14 to 15, Rge. 13 to 16, W 1st Mer., which not only has a documented iron deposit but also has a strong magnetic signature outlining the area. From an iron-oxidation play perspective, this could serve as a large natural hydrogen point source. Despite the theorized low hydrogen yield by oxidation reactions, the size of the iron deposit and the time factor (up to 450 million years) favour its potential for hydrogen production. Drilling records for three wells drilled into this deposit do not mention any gas kicks while drilling but do mention several very porous horizons encountered in the Paleozoic section above the deposit (oil and gas well licence 1, Manitoba Economic Development, Investment, Trade and Natural Resources, Winnipeg).

Hudson Bay Basin

The lithological keyword search turned up a few favourable drillholes in a concentrated area of the onshore portion of the Hudson Bay Basin (i.e., the Hudson Bay Lowland; Figure GS2024-19-2). The dominant lithologies identified were iron formations and serpentinized rocks. In the sub-Phanerozoic cover, many of these lithological occurrences are clustered along the edges of the SBZ and the Kisseynew domain, or along major magnetic changes. All lithologies in question were from drillholes that had a Phanerozoic thickness of less than 115 m, meaning that any residual hydrogen released from rock-water interactions would have quickly dissipated to the atmosphere due to a lack of sealing units in the strata above. However, due to the scarcity of exploration drillholes in the Hudson Bay Lowland, including the northeastern extension of the SBZ and Kisseynew domain, more hydrogen-generating lithologies may occur below the Phanerozoic cover, with the thicker sedimentary strata providing more storage space and potential sealing units (Nicolas et al., 2024). Sources for hydrogen in the Hudson Bay Basin in Manitoba could also be from radiolysis of uranium-, thorium- and potassium-bearing bedrock, analogous to the helium system in the Williston Basin, and would be more likely to occur in the northeast where the strata is thicker.

Evidence for hydrogen occurrences

Documented natural hydrogen occurrences are rare and historically did not garner any interest thus finding historical records that mention hydrogen is challenging. This historical disinterest in natural hydrogen caused a prejudice in the way gas samples were collected and analyzed (Zgonnik, 2020). Unless a sample was expected to contain high hydrogen concentrations, the analytical method of gas chromatography commonly used hydrogen as the carrier gas thus hydrogen could not be detected in the sample (Zgonnik, 2020). Hydrogen only becomes more noticeable and noteworthy when concentrations exceed 10% by volume and it becomes flammable (Zgonnik, 2020).

Hydrogen occurrences in the subsurface can only be identified through a gas analysis test, but as mentioned above, the gas chromatography methods used are usually biased against hydrogen. Gas analysis conducted on samples from subsurface fluids is done through drillstem tests, or sampling at the wellhead or battery site. There are 101 gas analyses reported in Manitoba's petroleum technical well files for the Williston Basin, many of which have hydrogen measured (Manitoba Economic Development, Investment, Trade and Natural Resources, 2024b; Nicolas, 2024[1]); there are no gas analyses available for wells in the Hudson Bay Basin. Most gas analyses reported trace to very low hydrogen concentrations. These low concentrations were affected by sample flushing and by the hydrogen reacting readily with hydrocarbons (Hand, 2023) as these analyses were generally run on hydrocarbon-rich samples. Only 10 wells reported hydrogen values of >1 mol. %, with three of those having higher than average values (L.S. 13, Sec. 26, Twp. 12, Rge. 28, W 1st Mer. [abbreviated 13-26-12-28W1], 5-20-11-29W1 and 6-20-11-29W1, with values of 8.49, 3.28 and 7.99 mol. %, respectively); all of these wells were producing from the Middle Member of the Mississippian Bakken Formation. The Bakken Formation has been identified as a potential helium source due to its radioactive highly organic shale beds (Nicolas, 2018; Nicolas et al., 2023, 2024), therefore, it may be possible that the hydrogen measured here is a product of radiolysis. Whether these higher concentrations are a function of residual hydrogen from the flushing process in the gas chamber, or they are representative of naturally occurring hydrogen, it is uncertain, since other gas analyses of samples from the Bakken Formation do not show such high concentrations. All three of these gas analyses come from wells located around Twp. 11 to 12, Rge. 28 to 29W1, coinciding with the Kirkella Field, an area

[1] MGS Data Repository Item DRI2024012, containing the data or other information sources used to compile this map/report, is available online to download free of charge at https://manitoba.ca/iem/info/library/downloads/index.html, or on request from minesinfo@gov.mb.ca, or by contacting the Resource Centre, Manitoba Economic Development, Investment, Trade and Natural Resources, 360-1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

known for structural disturbances and high helium occurrences (Nicolas, 2018; Nicolas et al., 2023, 2024). The other seven analyses with >1 mol. % hydrogen occur in the Mississippian Mission Canyon Formation and Virden Member of the Lodgepole Formation in the Pierson, Waskada and Souris Hartney oil fields. The Waskada and Souris Hartney oil fields, like the Kirkella Field, are also known for their complex structural disturbances, including multistage salt collapse caused by fluid movement through deep fracture systems. In particular, the Waskada Field falls along the eastern boundary of the SBZ suggesting the deep fractures that penetrate to the Precambrian basement are the result of lithospheric flexure along this large crustal suture. These deep fractures provide the ideal scenario for hydrogen generated in the Precambrian to move upward into the sedimentary strata.

Hydrogen dead zones

Surface seeps of hydrogen have been documented worldwide, many of them referred to as eternal fires (Zgonnik, 2020; Sukumaran, 2024). When hydrogen occurs below ignition concentrations (below 10% by volume), vegetation dead zones—also known as fairy circles—can occur around surficial hydrogen seeps. Searching for hydrogen from the 'top-down' requires looking for the presence of fairy circles, then investigating the subsurface for the source—a common hydrogen exploration method.

In Manitoba, there are recorded circular vegetation dead zones that occur on the east side of Lake Winnipegosis, across the lake from Duck Bay (Figure GS2024-19-1). D. Berk (pers. comm., 2008) showed the author photos of these dead zones, which occurred on his mineral exploration mining claim; the assessment file for this claim includes mention of "vegetation dead or kill zones" (Assessment File 74929, Manitoba Economic Development, Investment, Trade and Natural Resources, Winnipeg). The assessment file for this claim also mentions faulting and bedrock movement and includes results from a soil gas hydrocarbon geochemistry survey. There was no mention of hydrogen in the results or discussion, but the presence at depth of a volcanogenic massive-sulphide (VMS) deposit was suggested; a theory that is also supported by the results of a magnetic geophysical survey. Unfortunately, there was no deep drill program executed on this claim to verify the presence of VMS deposits at depth, or MVT deposits or kimberlites–which were also a consideration. On the mining claim site, significant bedrock disturbances were observed, including brecciated carbonate units with a blue-grey clay matrix and zebra-textured dolomite (similar to hydrothermal dolomite) in vertical fractures (D. Berk, pers. comm., 2008). This all suggests that there were fluids moving through the system in the past. The fact that there are vegetation dead zones in modern day, suggests ongoing processes. Although it is uncertain if hydrogen degassing is the cause, it should not be too quickly discounted as a possibility without thorough investigation. If buried iron-rich deposits are not the source, then perhaps investigating kimberlite intrusions as the source is worthwhile, as these intrusions, which can have the correct metamorphic conditions for serpentinization, can release high volumes of hydrogen (Zgonnik, 2020).

Hydrogen production of the future

Zgonnik (2020) lists several locations worldwide that have hydrogen production directly from Precambrian wells. This brings to question the opportunity for hydrogen production in Manitoba directly from Precambrian wells, either collared directly on the Precambrian shield rocks or through the Phanerozoic sequence of the Williston and Hudson Bay basins. The benefit of the sedimentary basin is the extra space to migrate and store hydrogen long term in porous sedimentary reservoirs. Storage of hydrogen, over the long term, can include a porous reservoir with a good seal, but recent work by Truche et al. (2018) suggests hydrogen may be adsorbed onto water-saturated clays and trapped below the surface, a theory Yurkowski et al. (2024) is investigating in Saskatchewan. These clay alteration haloes over hydrogen-producing deposits may be an important play type to consider in the future (Truche et al., 2018).

Future recommendations

Currently industry is not exploring for geologic hydrogen in Manitoba; however, it is clear that exploration opportunities do exist. Future gas analyses conducted on fluids from oil and gas wells (through drillstem tests or sampling at the wellhead or battery site) should consider testing for hydrogen to ensure accurate results going forward. Current exploration for helium in deeper horizons than those accessed for oil and gas production may yield insights into the potential for deeper hydrogen resources in the short term. Known deep-sourced fluids in the Phanerozoic cover could be potential conduits for hydrogen generated by serpentinization or iron oxidation, with migration and entrapment opportunities nearby.

Outside of the sedimentary basins, exploration into the Precambrian shield is also a possibility, with some successes reported globally (Zgonnik, 2020). Artificial intelligence and optical character recognition methods applied to mineral exploration assessment files may assist in this venture, as there may be records of hydrogen gas pockets encountered during drilling programs or hydrogen seeps observed in mine workings.

Economic considerations

Hydrogen is a clean-burning fuel and is seen as an important energy source for the future. As hydrogen has been overlooked throughout history, geologic hydrogen systems are poorly characterized and the understanding of the mechanisms of formation is still mostly theoretical—much work is still needed. Once the economic potential of geologic hydrogen is fully understood, it will revolutionize the energy sector. However, until such time, purposeful and mindful observations of hydrogen occurrences is important, no matter how low or high the concentrations.

Occurrences of hydrogen in gas analyses from oil and gas wells in Manitoba are very low, but this may be a result of analytical blindless to hydrogen and is not indicative of any hydrogen anomalies. Gas analyses of samples from nonhydrocarbon-bearing strata are required to verify for hydrogen; such tests are more likely to come from future green helium test wells, or perhaps hydrogen test wells.

Even though there are no clear indications of accumulated hydrogen in Manitoba records, the Precambrian basement rocks underlying the Williston Basin strata do have the right lithologies to form hydrogen under the right conditions. The Hudson Bay Basin hydrogen potential is not well constrained due to lack of data, but should not be discounted. Overall, Manitoba has good potential to support a hydrogen system, as it has good potential sources, migration pathways, reservoirs and seals required for accumulations.

Acknowledgments

The author would like to thank S. Bergen from the University of Manitoba for her assistance in compiling the gas compositions, M.M. Nicolas from the University of Manitoba for her library support, and M. Yurkowski from the Saskatchewan Geological Survey for her good discussions and innovative research. C. Couëslan and E. Enaworu are acknowledged for their critical review of this report.

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