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Natural Deep-Seated Hydrogen Resources Exploration and Development: Structural Features, Governing Factors, and Controls

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Abstract: The interest towards natural, or subsurface, sources of hydrogen is gaining momentum among the scientific and the industrial communities: the former is anxiously looking for the guidelines to de-risk its exploration and development operations, while the latter is trying to match the (mainstream) concepts with this new commodity physical and geochemical properties, which are quite different from the conventional ones (hydrocarbons, etc.). Apparently, it is time for new, alternative concepts capable of resolving the existing discrepancies and offering plausible solutions for removing the obstacles currently existing in the way of this new industry. Currently, the goal is formalized as (i) analyze the vast dataset existing for natural hydrogen shows, and (ii) to provide practical recommendations for natural hydrogen resources' exploration, aiming commercial sources discovery and exploitation. In this lieu, this research attempts to identify and classify the principles of natural hydrogen provenance and distribution within the lithosphere, as well as its manifestations on the surface. While explaining the scientific basics of the subject in commonly acceptable terms, the authors bring the theoretical part of the discussion to the bare minimum, at the same time concentrating on the practical implications and outcomes. This study analyzes the majority of known natural hydrogen cases in Australia and compares them with several examples known around the globe. The main controls, such as structural, stratigraphical, lithological, geochemical, and tectonic elements are reviewed and ranked. Several commonly accepted conceptual points are confirmed, while others are questioned and debated. The most typical patterns are outlined and interpreted; the practical leads resulting from these patterns are discussed. For the main outcome, the paper attempts offering the well-founded and logically verified scientific basis for the players to get their next steps coherent and reasonably justified. In conclusion, the authors provide more clarity for the audience in regards to natural deep-seated hydrogen distribution patterns in the Earth crust, being the cornerstone for this new commodity development business model/s.

Keywords: Natural Hydrogen, White Hydrogen, Gold Hydrogen, Hydrogen Exploration, Native Hydrogen, Zero Carbon Hydrogen

1. Introduction

The recent changes in the energy marketplace as well as in the current environmental situation call for active steps to identify the new source of energy. The global energy marketplace is being moved towards the new commodities, away from traditional hydrocarbons becoming less attractive from several viewpoints with time. Hydrogen is entering the stage as a new player at a fast pace. Its advantages as an energy carrier are indisputable; its potential in replacing hydrocarbons is more than obvious. With this, Australia as a nation possesses a substantial appetite for becoming the leader in the hydrogen global market [1].

Out of existing "*ways*" to supply hydrogen on an industrial scale, only natural, or "White"[3], hydrogen gets all the boxes ticked, presenting the maximal number of clear advantages while managing drawbacks to be next to none.

New business models and operation scenarios call for new concepts. Therefore, scientific justification becomes the most important factor for the entire process at this point. The authors of this paper attempted to establish the main regularities and patterns for "White" hydrogen manifestations in Australia. This attempt is based on the Primordially Hydridic Earth (hereinafter PHE) concept, first formalized by Dr. V. Larin [2] in early-mid 1970s.

Recently, due to technology developments combined with the activity growth in various disciplines, the Earth science community started seeing a substantial influx of newly acquired data and results of experimental research coming from all directions. Quite often, such data somewhat unexpectedly arrives from the sectors of science that initially seemed to have been very distant from the subject in discussion [3, 4]. On the other hand, the growth of environmental concern among the general public keeps pushing for new energy solutions, requesting to address the new aspects like climate changes, energy efficiency and decarbonization. This change of paradigm inevitably results in the demand for new approaches as well as for original scientific and economical models. With all these factors combined, the number of opportunities arise for the concepts that have emerged earlier but got overlooked for a number of reasons.

A good concept possesses one important feature: *predictability*. In other words, it does not only resolve existing dilemmas and paradoxes but also provides explanation(s) for discoveries yet to be made in the future.

2. Background

The authors of the PHE concept have started promoting hydrogen as a new source of environmentally friendly energy as early as in 1990s, long before this subject became popular in mass-media and among the broad public circles. Deep-seated hydrogen de-gassing flow manifestations on the planet surface as well in boreholes and mines have been forecasted by this concept a long time ago, in the early-mid 2000s. It is worthwhile mentioning that the subject of natural hydrogen provenance enjoys a lot of attention from the scientific community members having different opinions on this subject indeed. The list of versions is quite long; besides the deep- seated hydrogen originating from the mantle and core geospheres, it includes both abiogenic e.g. serpentinization [5], ferrolysis [6], radiolysis [7] and biogenic sources. For the purpose of this discussion, the authors of this paper would like to adhere to the subject of deep-seated natural hydrogen only, by no means attempting to disavow the others mentioned herein.

In brief, the entire history of formation and development of the Solar System including the Earth is "rewound" through the PHE concept, being traced back to the supernova explosion. Consequently, the authors described, explained and substantiated with undeniable reason and irresistible logic the chemical elements' distribution mechanisms across the Solar System. No detail was spared and no stone unturned, while no "assumptions" were admitted.

According to the PHE concept, hydrogen accounted for 59% (atom.) or 4.5% (wt.) at the moment of the Earth formation [8]. With time, these percentages have been diminishing, with hydrogen dissipating outwards from the deeper geospheres and further out into the open space. Its de-gassing keeps taking place in the process of the planet development, while its outflow patterns tend to concentrate into the packed jet-streams with time:

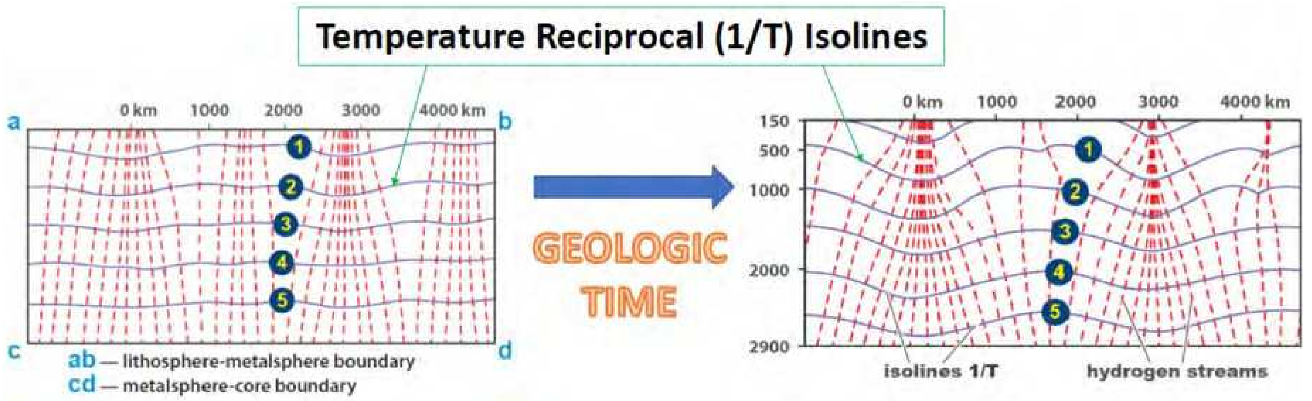

__Figure 1.__ The Hydrogen streams evolution in the metal-sphere (cross-section). Please note that line __a-b__ marks the lithosphere bottom. Modified from [9], translated into English in 2021.

Figure 1 illustrates the hydrogen de-gassing process up to the bottom of the lithosphere. However, from the practical viewpoint, we should be more interested in what happens further up, in the closer proximity to the surface (Figure 2):

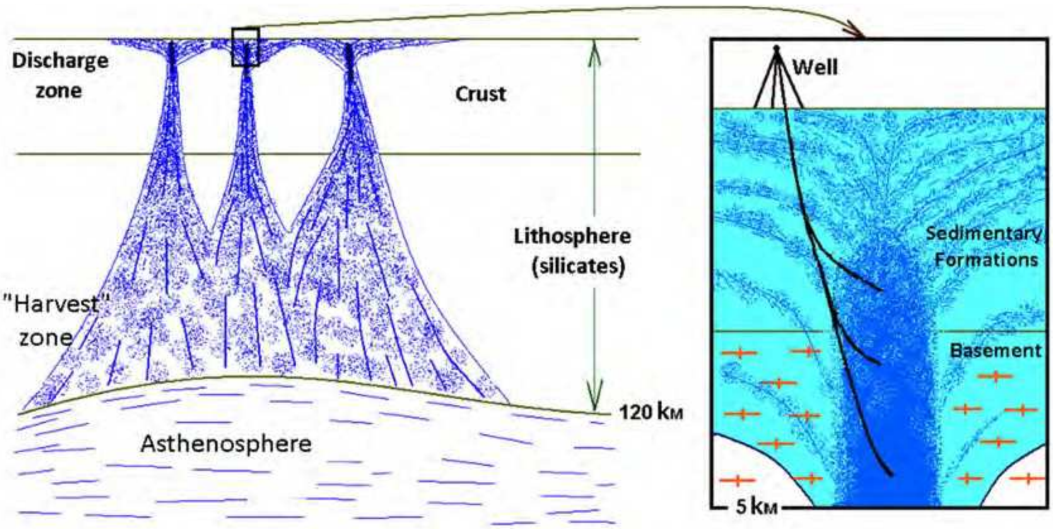

Figure 2. *Hydrogen de-gassing through the lithosphere. Modified from [10].*

Since the top lithosphere layers experience lower (unconfined) lithostatic pressure, they are formed by relatively lighter formations and are typically covered with sedimentary overburden. More often than not, they are also dislocated by tectonic irregularities, crumpled into folds, further altered by metamorphism of various degrees and magnitude, and pierced by intrusions of various structures and compositions. This all complicates the geologic environment, creating numerous obstacles on the hydrogen's way out. If not for its unparalleled volatility and ability to penetrate through any matter in the form of the "*proton gas"* [2], it would be difficult to imagine it making it all the way up to the surface. Combined with the extremely aggressive chemical nature of silanes often preceding or accompanying hydrogen flows, has been registered on a number of occasions [8], this creates a somewhat unique de-gassing system, varying from that of hydrocarbons quite dramatically.

Therefore, it is safe to assume that above the mantle-to-lithosphere boundary (line *a-b* in Figure 1), the "packed" streams of gaseous hydrogen shall experience certain diffusion, scattering across the area for each given horizontal section. The nature of such "discharge zone" dispersion as well as its area close to or on the surface will greatly depend on a number of factors[1]:

1) Depth of contact between the top of the solid basement and the bottom of unconsolidated overburden.
2) Sedimentary overburden and soil substrate petrophysical properties governed by their composition and sedimentology/petrology.
3) Tectonics: faults' depth, direction, displacement and shearing degree, as well as their current and/or past activity.
4) Folding structures type/s, geometry (strike and dip, etc.) and magnitude.
5) Intrusions' nature (concordant/discordant), age, and character (composition, temperature, accompanying fluids, etc.).
6) Metamorphism and local alterations' degree as well as chemical and thermal peculiarities.
7) Fluids' temperature/s and composition, as well as chemical activity and its duration.

Summarizing, in the best case, a hydrogen degassing flow will be found in close proximity to the surface, mostly in concentrated ("packed") shape, discharging at substantial flow day rates, not being dispersed by numerous folds, intrusions and other complications. In the opposite situation, less favorable cases will take place with more erratic hydrogen flow dissipation towards the surface due to the deeper solid basement tops, numerous (micro)tectonic dislocations, complicated lithologies and uncooperating textures.

3. Discussion

The above summary is to be followed by the identification of natural hydrogen gas flow factors, patterns and controls.

3.1. Geomorphology

Circular depressions a.k.a. so-called "*fairy circles*" represent the most apparent case of natural hydrogen flow manifestations. Dr. V. Larin and his colleagues [11] have pointed out these topographic objects back in mid-late'2000s, stressing the fact that these geomorphologic features are clear indications of the natural hydrogen gas emanations from deeper geospheres may become a reliable criterion for this commodity exploration.

[1] It is crucial to bear in mind that in case of hydrogen, we are dealing with extremely volatile and quite elusive substance. Hence, the deposit appraisal and development approaches routinely utilized with hydrocarbons are hardly (if at all) applicable to the natural hydrogen reserves. Consequently, we will not be discussing any "*kitchens*" or other isolated – and therefore inevitably finite - sources of natural hydrogen. Likewise, the "*reservoir*", the "*trap*", the "*caprock*" and other similar terms will only be used to address the temporary nature of deep-seated hydrogen accumulations within the lithosphere. Similarly, there is hardly any reason to discuss a "source rock" same way it's done for kerogen, unless it is done in consideration with very deep Earth bowels like the mantle and the core.

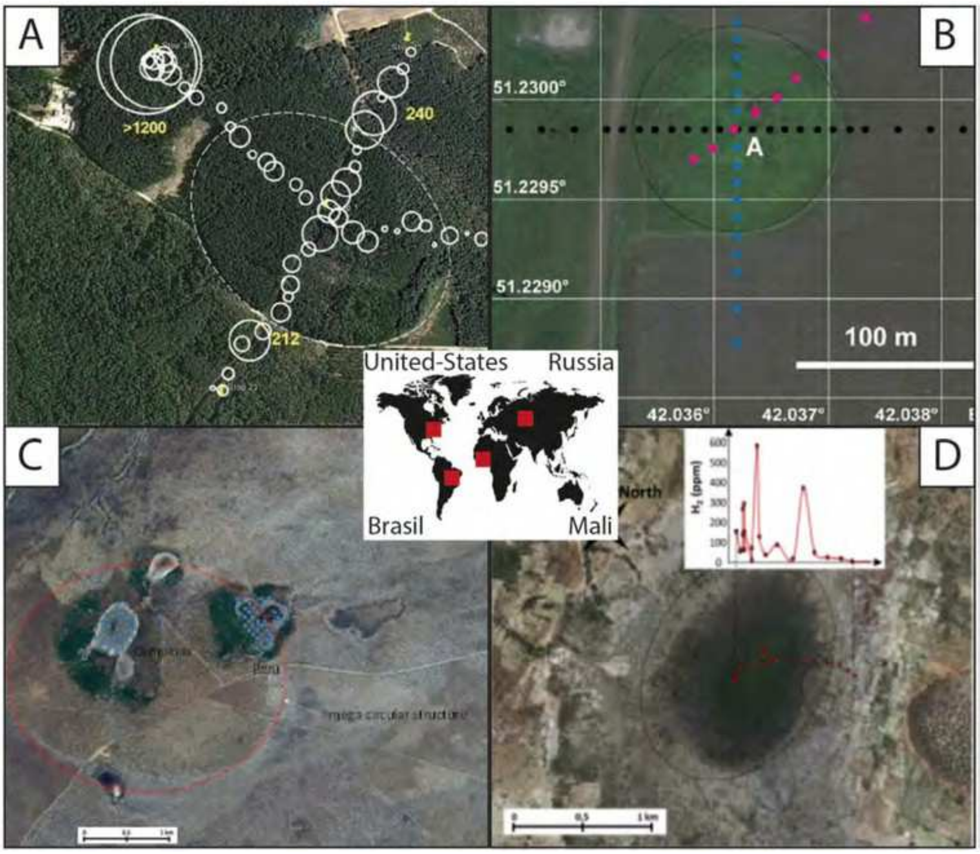

Figure 3. *Circular depressions around the globe, [12].*

Circular depressions (Figure 3) and their relationship with hydrogen de-gassing processes have been discussed in length for the past several years [13, 14]. However, these geomorphological features cannot be recognized as a 100% reliable sign of natural hydrogen emanations, at least in commercial quantities, since their morphology could be attributed to other processes and events, such as karst or inactive/isolated river systems.

On the other hand, the natural hydrogen finds in deep wells are not necessarily marked by any obvious geomorphologic features on the surface: 2,685 m deep Meda-1 well (95% H_2) in the Canning Basin, WA, Australia (Figure 4) and 2,295m deep Mt Kitty 1 well (11% H_2) in the Amadeus Basin, NT, Australia (Figure 5) presenting the perfect examples:

Figure 4. *Meda-1 well location (Western Australia, Australia) on the Google Maps, the exact coordinates taken from [15].*

Figure 5. *Mt Kitty 1 well location (Northern Territories, Australia) on the Google Maps, the exact coordinates taken from [16].*

Noticeably, circular depressions are manifested atop of both relatively young basins with thick sedimentary sequences such as Perth Basin, WA, Australia (Figure 6) and massive ancient cratonic structures such as Yilgarn Craton, WA, Australia with little or no regolith overburden being thin to none (Figure 7).

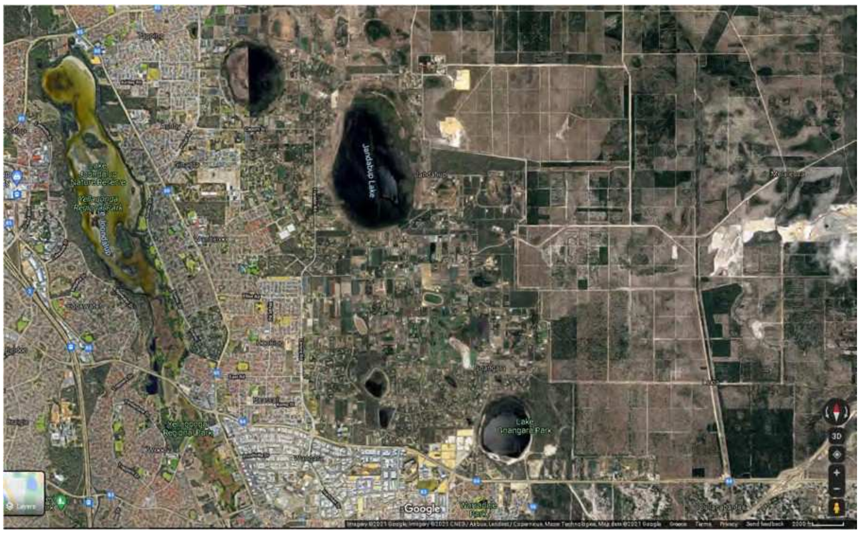

Figure 6. *Jandabup Lake and surroundings on the Google Maps, Perth Basin, Western Australia, Australia.*

Figure 7. *Lake Norring and surroundings on the Google Maps, Yilgarn Craton, Western Australia, Australia.*

While still being the indisputable signs of H_2 seepages through the Earth's crust, at least in the distant past for the taken area, circular depressions may become just one of the (early "reconnaissance") criteria for natural hydrogen industrial resources prospecting and exploration.

3.2. Petrophysics

Stratigraphy and lithology parameters influencing formations'/rocks' petrophysical properties are likely to be the most important controls governing hydrogen emanations, distribution, and dissipation in the lithosphere and on the surface. Although hydrogen possesses extremely high volatility, especially compared to methane or even helium, its rate of infiltration through the different substrates varies in a broad range, up to several orders of magnitude [8]. As a result, hydrogen flows in heterogeneous lithologies and, further above, in soils substrates tend to follow "*paths*" along loosened or weakened "*channels*", while trying to avoid denser zones and low permeable "*knots*" within the particular area.

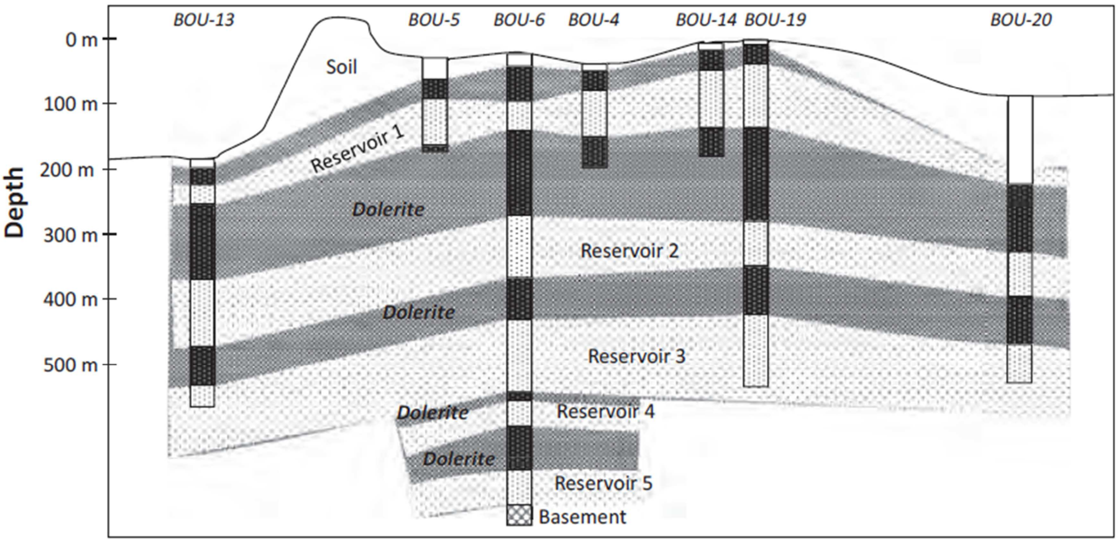

Figure 8. *Schematic cross-section of the Bourakebougou gas field (Mali), with the indication of probable hydrogen "reservoirs". [17]*

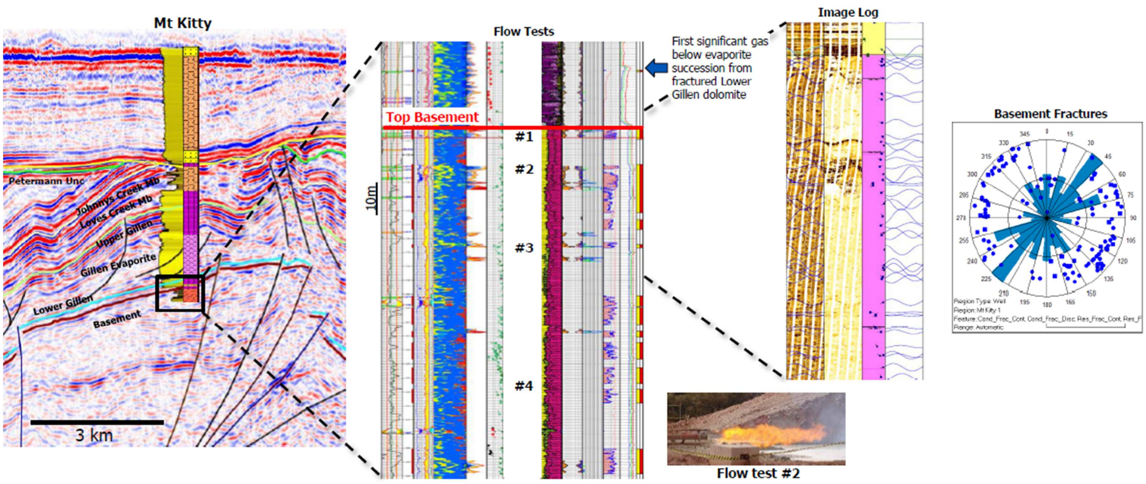

Figure 9. *Gas flows from natural fractures in granite and pre-salt carbonates. Mt. Kitty 1 well (Northern Territories, Australia) stratigraphy and flow test results, from [19].*

It is quite obvious that unconsolidated lithologies like uncemented sandstones, loose marls and highly fractured schists would conduct hydrogen easier than intrusive bodies (especially the concordant ones like sills, etc.). The latter factor sometimes becomes crucial for forming a "*caprock*", thus creating conditions for a temporary "*trap*" where hydrogen gas accumulates, which behavior resembles hydrocarbon gases to some extent. This prompts some researchers [17] to see the abovementioned similarities in behavior of hydrogen and gaseous hydrocarbons (Figure 8)[2]:

[2] 110 m deep Bougou-1 well in Mali was tested to flow 98% H_2 gas after it was drilled in 1987 and keeps producing at the same low rate for the past decade. However, it needs to be shut-in three to four times a day in order to allow for pressure to build. It is safe to assume that it is necessary for the temporary "*reservoir*" recharging by means of delivering hydrogen from deeper zones through the jet-stream channel.

Same way, evaporite concordant (syn-stratigraphic) deposits as well as salt domes tend to assist with forming temporary "*accumulation*" of hydrogen underneath them [18]. Once penetrated by drilling, such "*traps*" quite often do not keep "*producing*" hydrogen for long periods of time [19], since these "*accumulations*" possess temporary nature and therefore cannot be seriously treated as field development targets. This happens because the borehole (for instance Mt Kitty 1, NT, Australia) produces hydrogen gas from the temporary "*reservoir*" (Figure 9), as opposed to the permanent jet-stream flow supplying it to this "*trap*" (Figure 2):

Mt. Kitty 1 well was TD'd at 2,295 m in Amadeus Basin, Northern Territories, Australia in 2014. The well flowed at an initial rate of 0.5 MMscf/d declining to 0.07 MMscf/d after 10 Minutes from 2,144m (Biotite-Chloritized Granodiorite) and at a rate of 0.53 MMscf/d declining to 0.42rMMscf/d after 18 minutes from 2,156m (Biotite-Chloritized Granodiorite). No Drill Stem or StethoScope pressure-while-drilling (FPWD) tests were run in Mt Kitty 1 [19].

In regards to the probable source of hydrogen in this particular case of Mt Kitty 1 well, it may be worthwhile to mention that:

1) No serpentinized or ferric/ferrous formations have been described in the well report [19] - except for siderite [20], the common product of chemically reducing environments, e.g.: $Fe_3O_4 + 3CO_2 + H_2 = 3FeCO_3 + H_2O$
2) The chemistry of biotite chloritization process mentioned in the well report [20] (Core Descriptions, pp. 49, 51) requires strongly reducing environment with sufficient supply of H^+ cations, according to the following equation [21]:
   a) $5Bio + 3An + 3SiO_{2(aq)} + 4H_2O + 6H^+ = 3Chl + 5Kf + 3Ca^{2+}$
   b) $10Bio + Kln + 7H_2O + 10H^+ = 6Chl + 14SiO_{2(aq)} + 10K^+$

Other researches are unanimous in this assertion [22].

The subject of natural hydrogen gas flow rates depletion was addressed in detail for the cases of H_2 recorded in wells drilled in Kansas, USA [23]:

In the 424 m deep Sue Duroche#2 well in Kansas, USA (up to 90% H_2, Figure 10), the Hydrogen gas "*trap*" penetrated by drilling initially demonstrated extremely high concentrations of H_2 in the gas mix; however, these rates have fallen dramatically with time. Apparently, this temporary hydrogen "*deposit*" has been formed beneath the "*caprock*" and was released immediately after being drilled into. Most likely, the feeding hydrogen jet-stream that formed this H_2 temporary "*trap*" has either moved away from it at some later stage or had been quite distant from it in the first place.

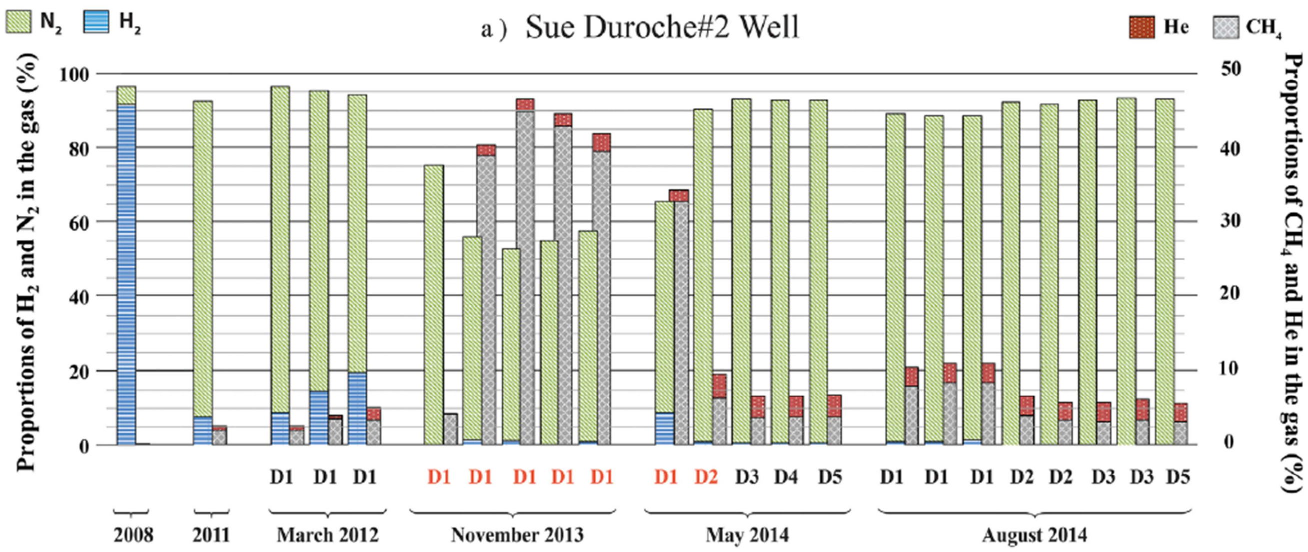

Figure 10. *H_2% concentrations diminishing with time in Sue Duroche#2 well (Kansas, USA), from [23].*

In the 770 m deep Heins well in Kansas, USA (up to 38% H_2, Figure 11b, left), Hydrogen concentration stays more or less stable within the 20% to 38% range for a long period of time, obviously demonstrating this well proximity to the sourcing jet-stream of deep-seated hydrogen gas.

In the 677 m deep Scott well in Kansas, USA (up to 58% H_2, Figure 11c, right), initially, the amount of hydrogen content decreasing with time is similar to that in Sue Duroche#2 well (above), then it grows up again, apparently being replenished from the jet-stream flow nearby.

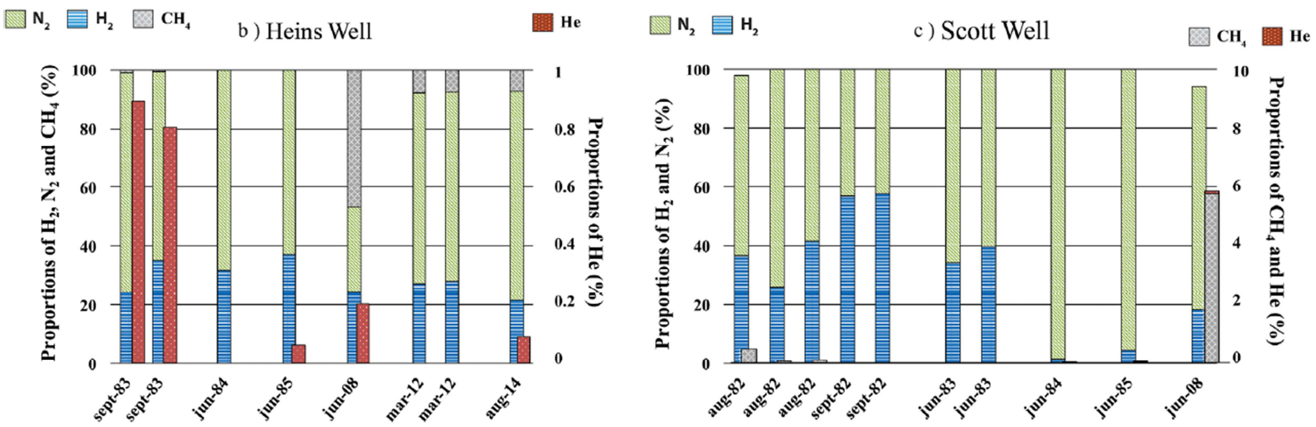

Figure 11. *H_2% concentrations stable in the Heins well (b, left) and depleting then replenishing in the Scott well (c, right), Kansas, USA, from [23].*

Kansas USA wells lithology [24] allows suggesting that hydrogen gas temporary accumulations were formed underneath the layers of interbedded chert in the massive shale deposits (Figure 12). Therefore, the hydrogen migration – or, rather, its release – from these accumulations has been occurring slower than from/through the surrounding and/or formations above/below it, due to their petrophysical parameters, in particular to the higher density of "*tight*" (possibly altered) cherty interbeds and nodules within the less dense sedimentary sequences.

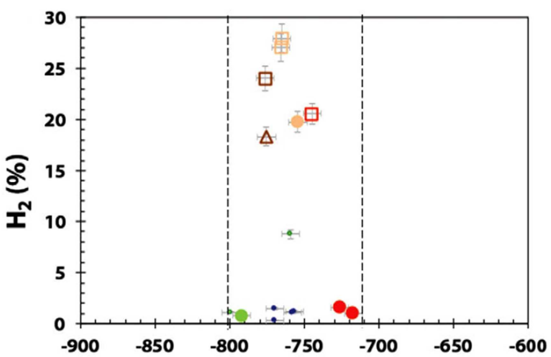

Figure 12. *Gas chromatography results from CFA Oil Company 1 Simpson well, Kansas, USA. From [23].*

Not surprisingly, the results of isotope geochemistry tests of hydrogen samples from the wells in Kansas clearly demonstrate its mantle provenance through extremely low negative δD values (Figure 13):

It is very important to bear in mind that hydrogen gas discoveries in the Kansas USA boreholes as well in other wells have been made accidentally, since these developments have originally been targeting other commodities and/or mineral resources. All the consequent research related to these finds was initiated and conducted on ad-hoc basis, with no such preliminary planning prior to their spud and construction. Therefore, with this research results being extremely valuable, they ought to be analyzed not separately from each other but rather in a system as a whole, based on a sound foundation established by a justified and proven model. So far, the PHE concept presents the only model offering logical explanations for numerous natural hydrogen occurrences on the global basis.

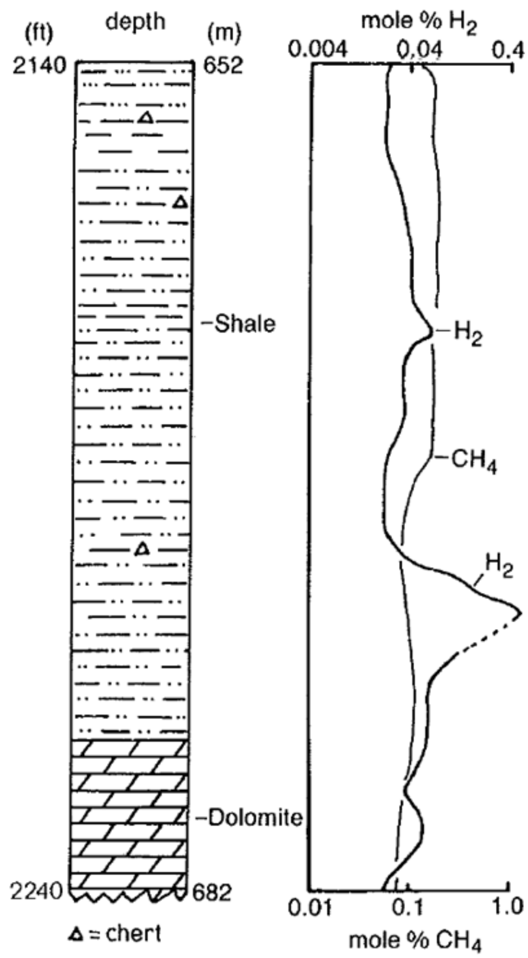

Figure 13. *δD H_2 versus [H_2]. Kansas, USA. From [24].*

3.3. Basement Proximity

Nowadays, the proponents of both deep-seated (mantle and/or core) [2, 8, 9, 25] and crustal-generated hydrogen concepts [5] agree that H_2 gas does not originate in sedimentary overburden but rather emanates from basement rocks. Even the hard-core supporters of the crustal hydrogen genesis viewpoint admit that natural hydrogen is delivered from deeper layers then intersected within the subsurface sedimentary sequences: "A "hydrogen system" is presented with a kitchen of generation in the cratonic basement." [17].

Therefore, the proximity of the basement is a very important factor for natural hydrogen exploration activities. This point can be illustrated by the Santos/Central Petroleum's Mt Kitty 1 well in NT, Australia (see *Petrophysics* section above, Figure 9). The thickness of sedimentary sequences above the Tonian Gillen Evaporites formation which apparently served as a "*caprock*" and assisted with the formation of a temporary hydrogen "*trap*" is less than 500 m, as compared to 2,300+ m to the NW from this well, just across the major fault striking in NE-SW direction (Figures 14, 21):

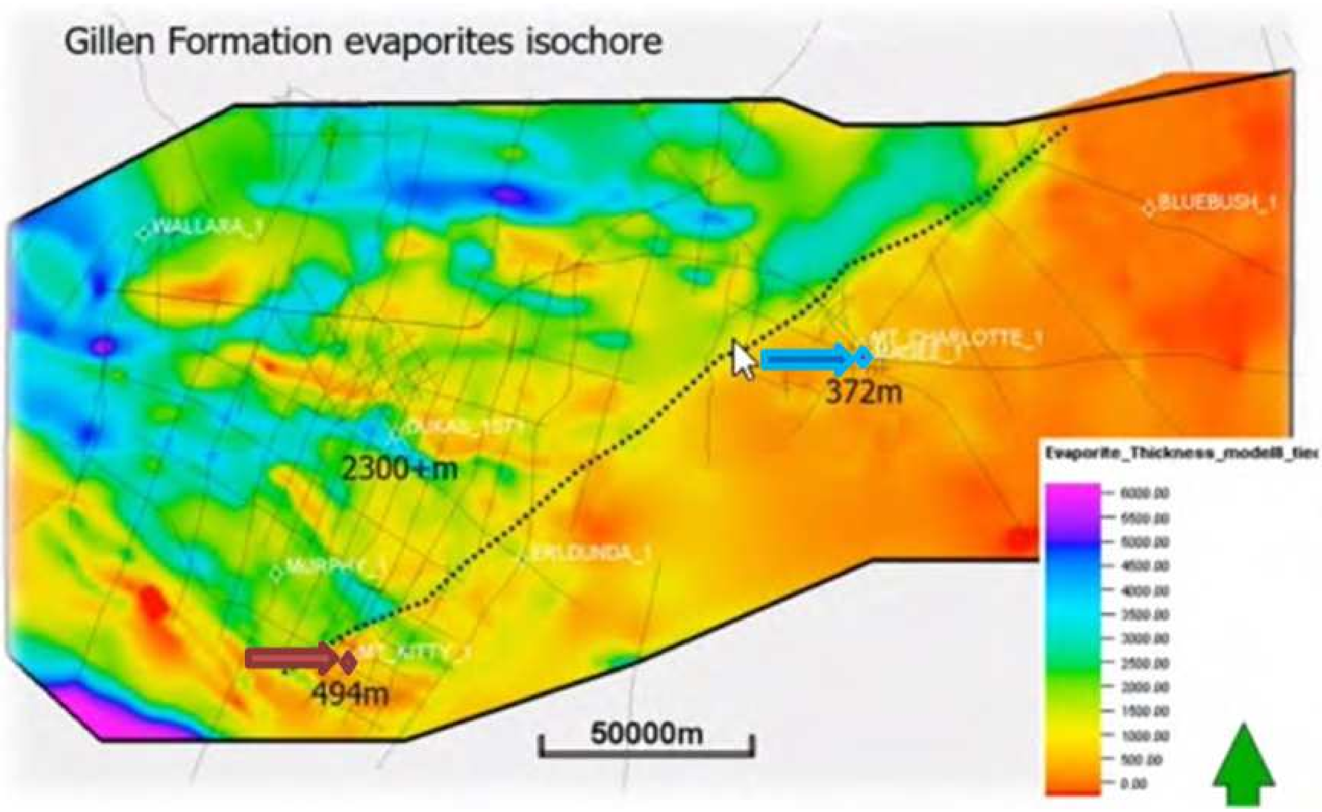

Figure 14. *Mt. Kitty 1 (red diamond) and Magee 1 (blue diamond) well positions on the map (Northern Territories, Australia) related to the sedimentary sequences above the Tonian Gillen Evaporites formation. The major fault is marked with the black dotted line. Modified from [25].*

In particular, Mt. Kitty 1 well (NT, Australia) is a great example of the combination of factors favorable for the natural hydrogen manifestation:

1) Proximity of the crystal basement.
2) Evaporites layer having had created the "*seal*" for the hydrogen temporary "*trap*".
3) Proximity of the deep major fault, most likely accompanied with the active shear zone.

Notably, 2,395.8 m deep Magee #1 well in NT, Australia located on the same acreage farther away from the major fault demonstrated gas signs as well; however, hydrogen concentration was quite low (0.03%) while helium exceeded 6%, well above the commercial deposit threshold.

This could possibly be interpreted as the result of Magee #1 borehole (NT, Australia) drilled farther away from the major fault channeling hydrogen from below ([25], Figure 14). As a result, hydrogen had a chance to disperse away from the channeling source, therefore depleting the "reserve".

1,751 m deep Shittim #1 well (up to 8.5% H_2, 4.8% He) on Bruny Island, Storm Bay, Tasmania, Australia [25] may serve as a perfect example of the crystal basement formations' role in conducting hydrogen gas jet-streams towards the surface. This stratigraphic well was TD'd ("suspended") at 1,751m and penetrated relatively deep into the Proterozoic phyllites/slates and quartzites (Figure 15). We don't think it was coincidental that the bulk of gas shows (Figure 16) were picked up from the basement, despite the presence of the more porous and permeable Bundella formation sandstones up above the column: "Porosities range from 7.5% to 12% and permeabilities from 0.1 to 9.8 md above it", [26].

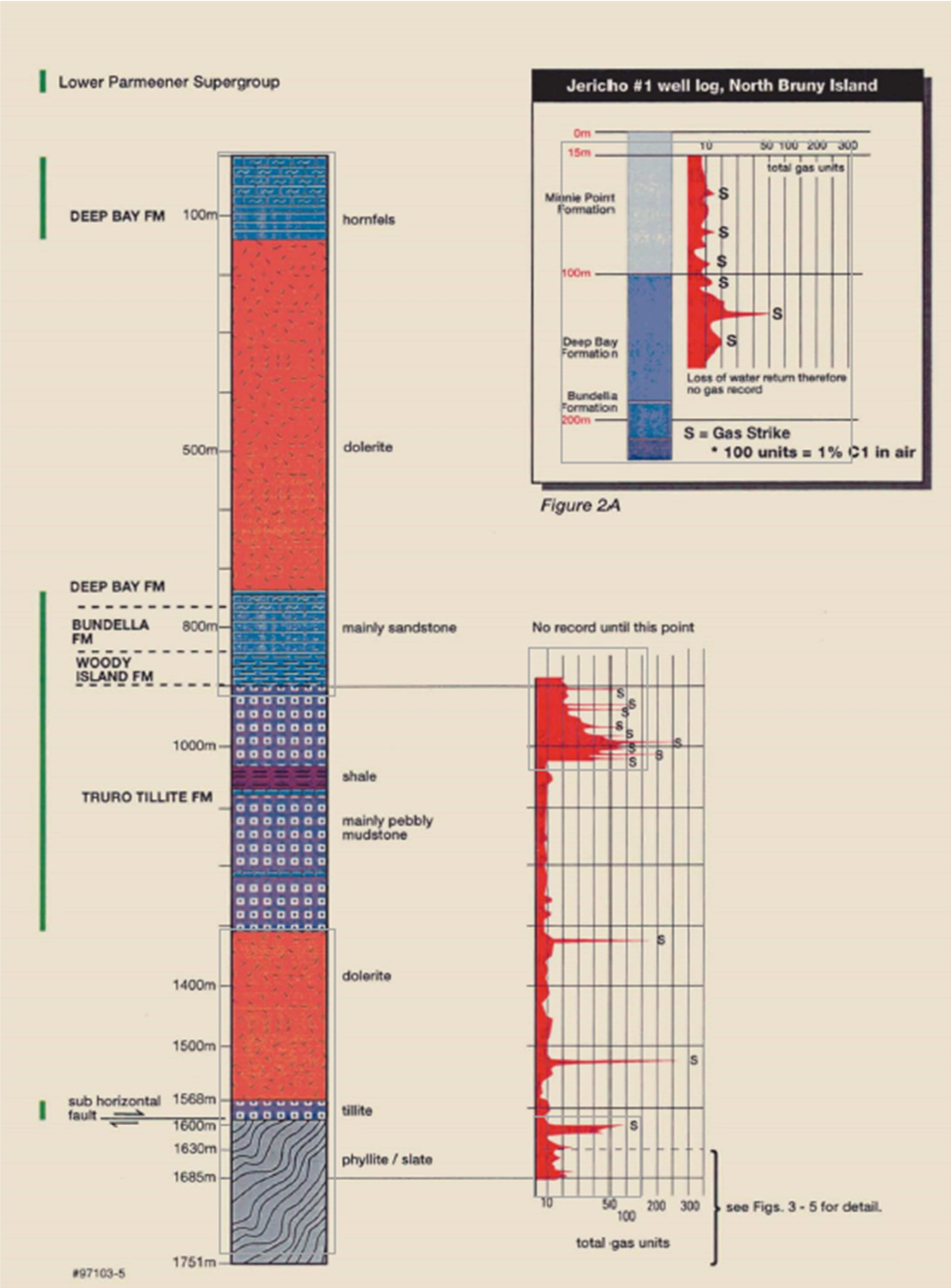

Figure 15. *Shittim #1 well log, North Bruny Island, Tasmania, Australia. Modified from [26].*

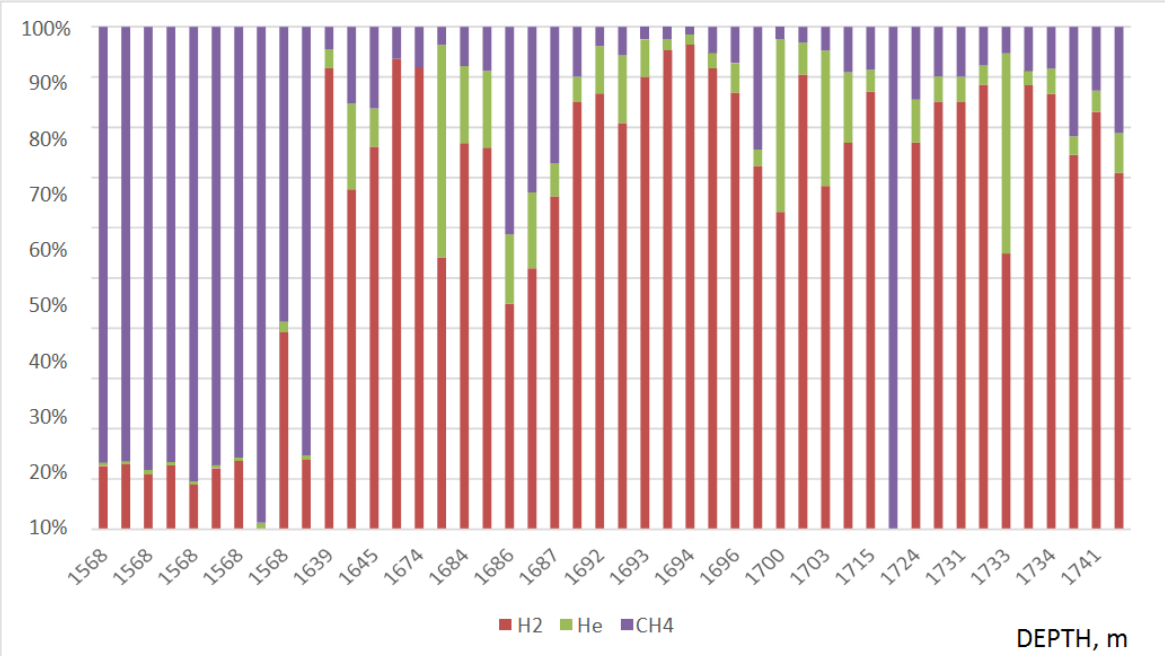

Figure 16. *Gas Analysis for Shittim #1C and #1D, North Bruny Island, Tasmania, Australia. Cuttings gas analysis (air, nitrogen and CO_2 corrected by the paper authors). From [27].*

3.4. Formation Textures and Structural Features

The mining industry has supplied its share of data on the hydrogen gas emanations - in particular, Glencore's Cobar CSA mineral deposits in New South Wales, the cradle of the Australian mining industry. Natural hydrogen seepages near the surface were detected over several occasions, with concentrations of H_2 exceeding 80% in the mine shafts [28]. H_2 concentrations in the surface soil samples (loamy sands) exceed 12% [28], which is extremely high for such volatile chemical element. This particular case is very interesting because the formations hoisting the CSA deposits (Great Cobar Slate and CSA Siltstone) are of sedimentary origin (deep-water siliciclastic sediments), having had been metamorphized at some stage through its history. No major intrusive bodies were detected immediately nearby this group of deposits. The environment is described as "a shallow to deep marine, extensional, intracratonic basin <…> dominated by siliciclastic turbidites, with local, margin-derived felsic volcaniclastic mass flow deposits in the SW of the basin and proximal submarine volcanism in the south" [29]. Mineralization processes are in general attributed to hydrothermal (porphyry, vein, volcanic, and replacement types – [30]) and to some extent to metamorphic processes, with the deposits being controlled structurally.

Our interest was attracted by the fact that the environment seems to be almost exclusively sedimentary, with very few chances of radiolysis mechanism of hydrogen generation whatsoever. No ferrolysis too could possibly be suggested for this environment, since there is no significant accumulation of ferric and/or ferrous deposits nearby. The Serpentinization process would not be sufficient in terms of volume to feed a steady hydrogen flow for a substantial period of time – the source minerals' formation would be long exhausted, since the veins' combined volume is not that huge. Therefore, hydrogen was not formed in these subsurface conditions but rather should have come from below. How, exactly, and where from was this hydrogen gas delivered to the surface layers?

The subject of hydrogen provenance in CSA[3] deposits is still debated. We suggest it is of a deep- seated nature, being channeled from the mantle (?) sources through the "Silurian or Early Devonian (~410 or possibly as early as ~420 Ma) until the late Early Devonian (~400 Ma)" rifting structure [29]. The cross-section in Figure 18 [30] schematically illustrates this point. Some of the researchers [29] suggest that this hydrogen gas is of metamorphic. However, this researcher suggests that some contamination has taken place later, therefore distinguishing between the various types of inclusions. On the other hand, it Is obvious that the test results of the samples of fluid inclusions (that is, encapsulated and therefore potentially the least contaminated) indicate possibility of their magmatic origin (Figure 19). It is quite possible that water from other samples had been mixed (possibly contaminated) with hydrogen from metamorphic sources at some point.

Noticeably, the CSA deposit is located within the intersection of the two deep faults – Cobar "reverse" Fault and Plug Tank Fault (Figures 24, 25) – apparently controlling

[3] The very question of Cobar deposits provenance is very interesting. One of the PHE concept inferences stipulates that sometimes hydrothermal-type mineral deposits may be formed as a result of upper mantle silicides transformation into lithosphere silicates [9]. The isomorphic capacity of the latter is way lower than that of the former, and "excessive" chemical elements a.k.a. *phases* "fall out" of geochemical balance, being deposited in the mineral deposit form. However, the scope of this work does not allow us to elaborate longer on this subject.

hydrogen flows to the surface. However, this type of controls is reviewed later on (Figure 17).

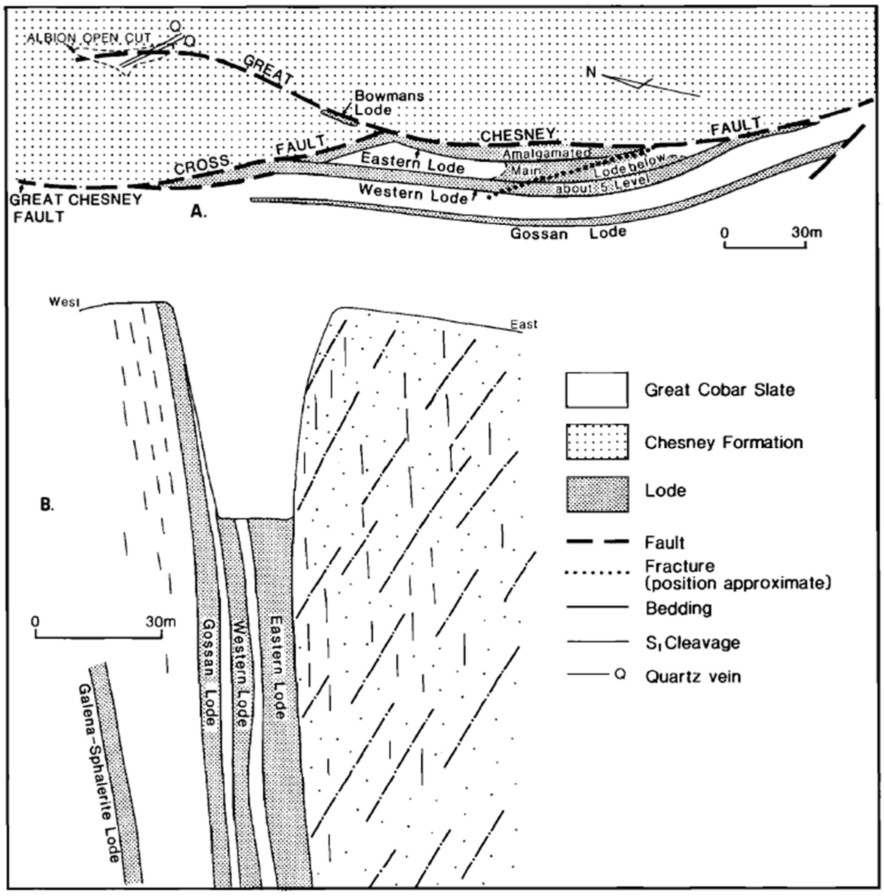

Figure 17. *The cross-section through lodes, New Occidental Deposit, Cobar area, New South Wales, Australia. From [31].*

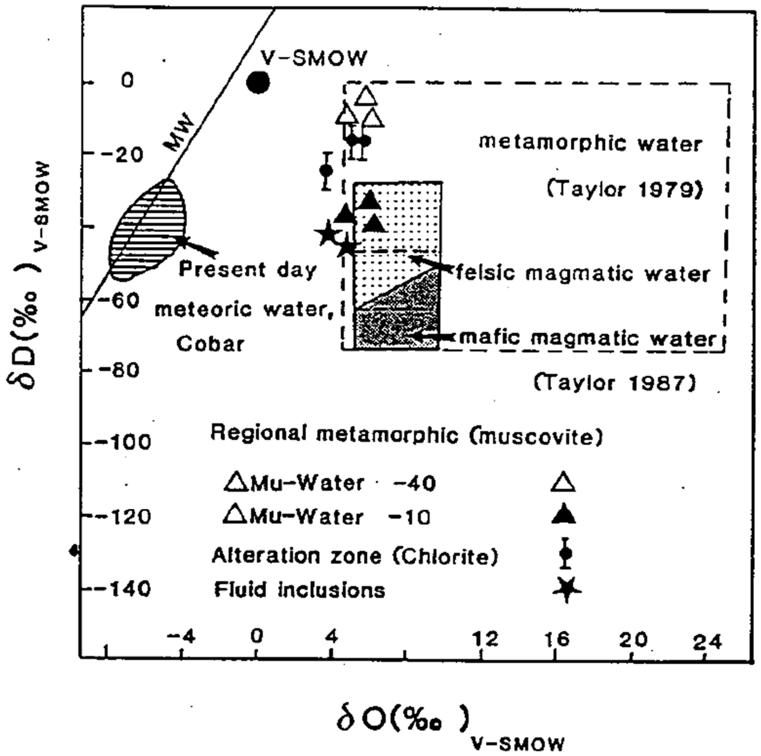

Figure 18. *CSA DEPOSIT HYDROGEN ISOTOPE DATA. Cobar area, New South Wales, Australia. From [30].*

Apart from the tectonic features that apparently participated in the process of channelizing hydrogen from lower geospheres (Figures 25, 26), this process in our opinion was substantially influenced by the hosting formations texture as well as their structural features, namely: lamination planes, lineation vectors and cleavage foliations. From Figure 20, it is quite apparent that ore bodies have been deposited along subvertical planes, supposedly within the weakened channels where hydrothermal fluids could penetrate through with less resistance. Additionally, Figure 21 illustrates bedding and cleavage planes/vectors streamlined sub-vertically, although their exact orientations are not identical.

Although (deep) faults would become the primary hydrogen conduction macro-channels to the sub- surface layers, formation textures are likely to create the "*paths*" for hydrogen de-gassing on the sub-micro-level. (In an opposite situation, if these lamination planes and cleavage foliations were oriented (sub)-horizontally, then the hydrogen de-gassing process would be quite hindered within this particular zone.).

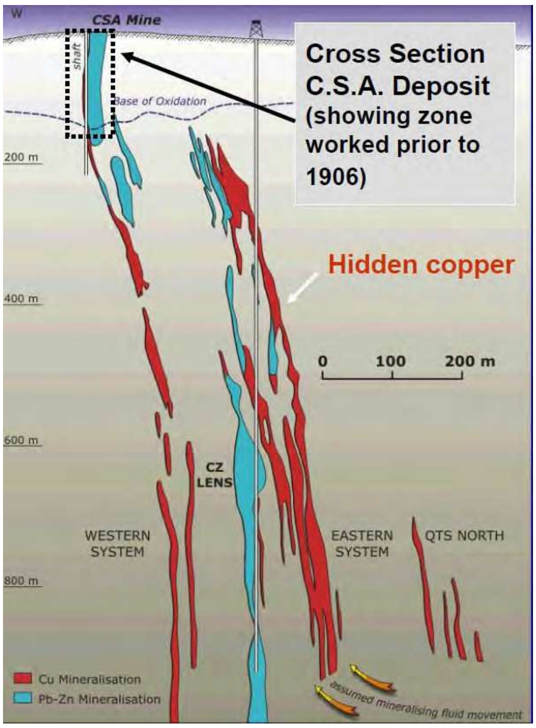

Figure 19. *Cobar CSA deposit cross-section. Cobar area, New South Wales, Australia. From [32].*

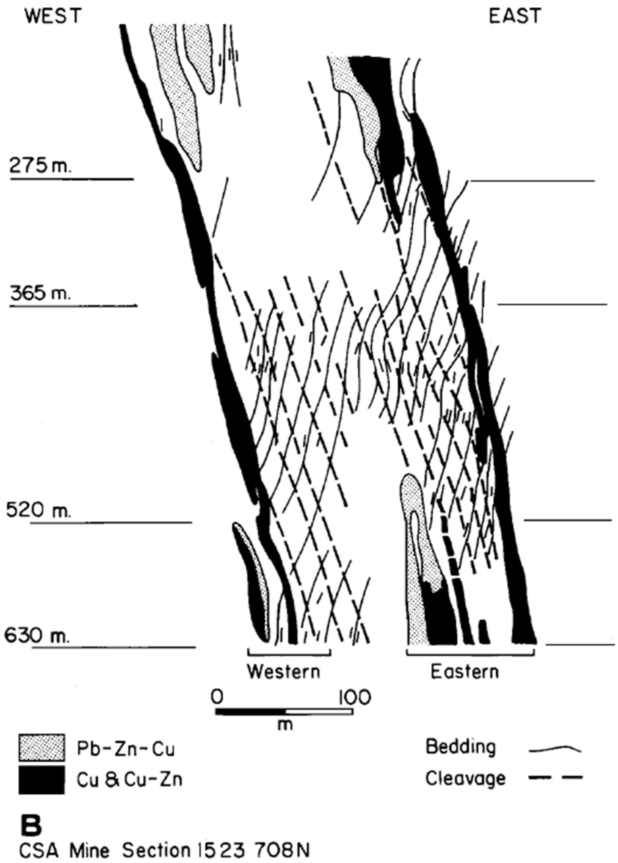

Figure 20. *Bedding and cleavage elations at the C.S.A. mine. Cobar area, New South Wales, Australia. From [31].*

3.5. Tectonics

The role of tectonic structures such as strike-slips, thrusts, shear zones and other fault types is very important and possess dual nature:

A. Deep regional and structural faults: Channeling hydrogen jet-streams from deeper geospheres to the surface. Santos/Central Petroleum's Mt. Kitty 1 well, NT, Australia (Figure 21) drilled in close proximity to the deep fault, and 293 m deep American Beach Oil #1 well [33] drilled on the Eastern Cove shore of Kangaroo Island, South Australia very close if not straight through the thrust located between the two active shear zones (Figure 22) serve as perfect examples:

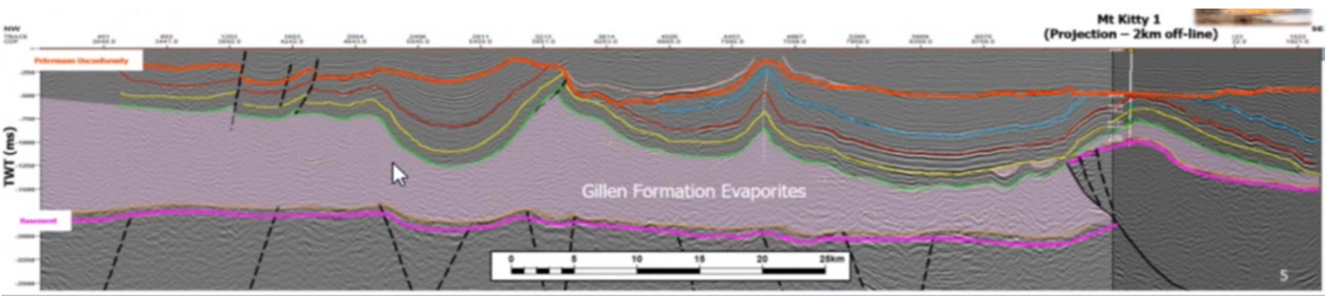

Figure 21. *Cross-section through Exploration Permit (EP) 125, with Mt. Kitty 1 well (Northern Territories, Australia) projected on the traverse line. Modified from [25].*

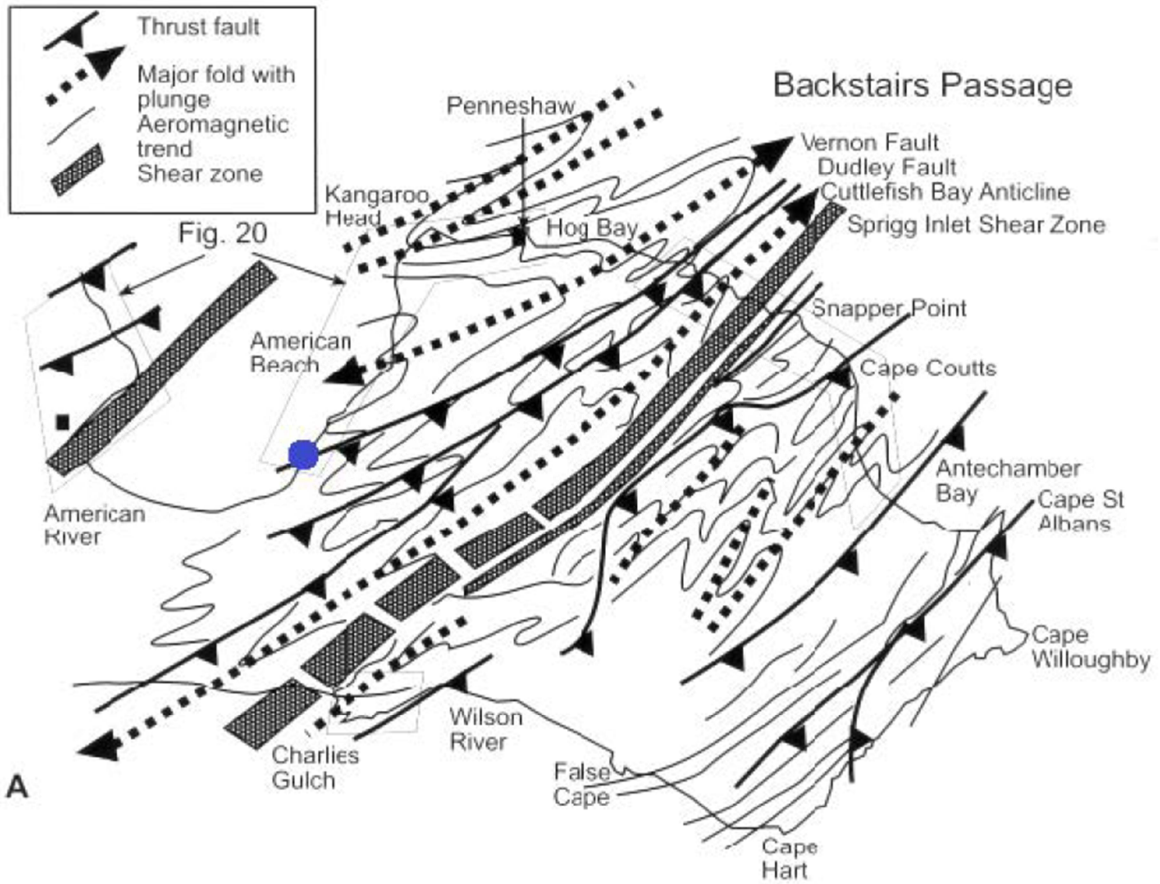

Figure 22. *American Beach Oil #1 well position (blue circle) superimposed on the local tectonics map. South Australia, Australia. Modified from [33].*

B. Shallow surficial faults: Dispersing (dissipating) hydrogen flows within the sub-surficial discharge zone in the upper lithosphere. Bourakebougou structure in Mali [34] is a typical example of this phenomenon (Figure 23).

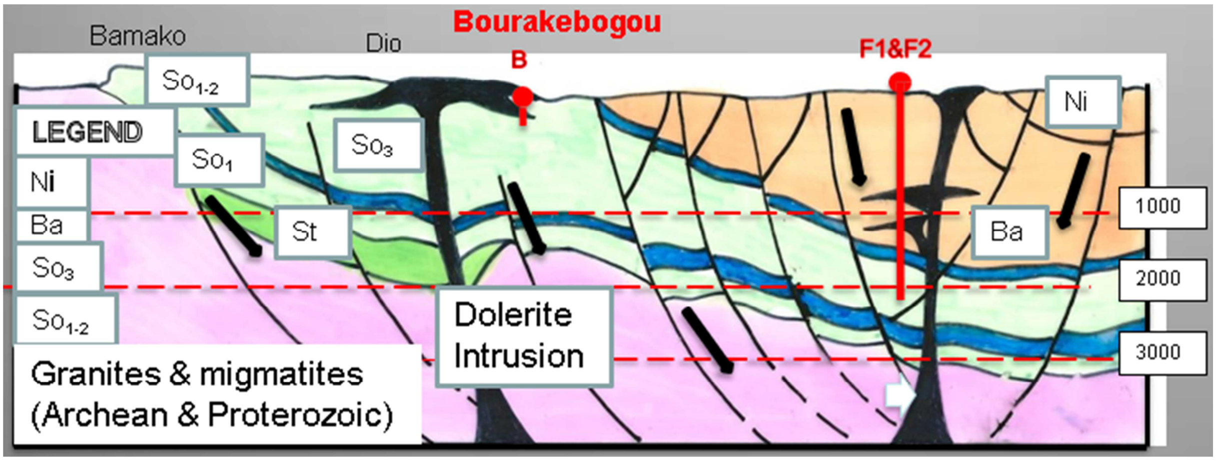

Figure 23. *Bourakebougou hydrogen bearing structure in Mali. [34]*

Another case of hydrogen de-gassing near the surface presented by the mining industry comes from the Boomer deposit, Frog's Leg Gold Camp, Eastern Goldfields Superterrane, WA, Australia [35]. This mine yielded up to 61.7% H_2 from Bent Tree and Victorious basalt (Figure 24). The authors suggest that the hydrogen flow is conducted from a deeper zone through the steep shear "advection", and we could not agree more with this viewpoint. The only suggestion we would like to humbly offer is that the abovementioned Bent Tree and Victorious basalts up-dip quite steeply, and the said sheer zone is perfectly concordant with them. Frog's Leg Gold Camp deposit intersects both the shear zone and the Victorious Basalt contact with White Flag formation.

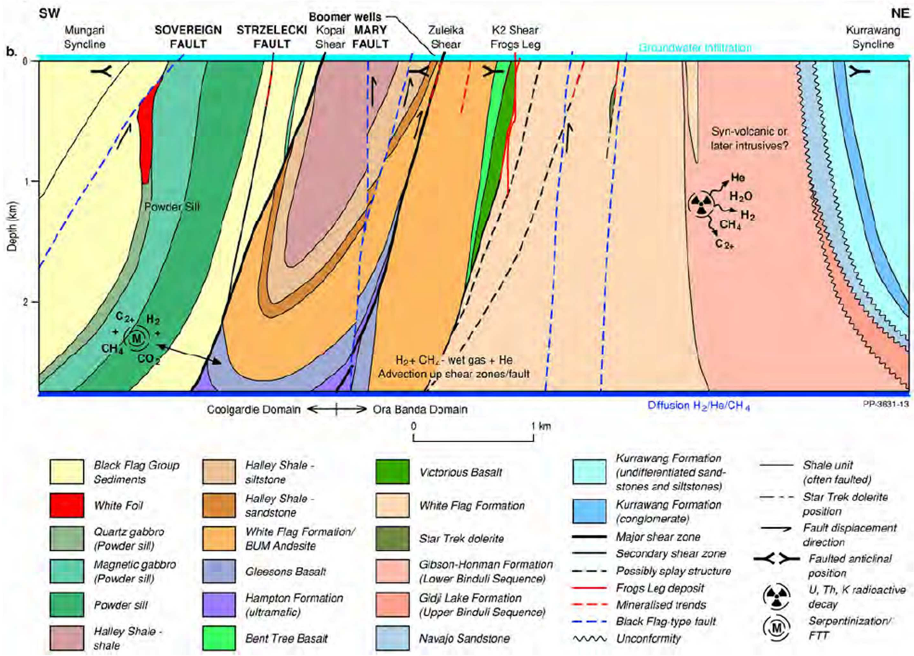

Figure 24. *The cross-section representing the local stratigraphy surrounding the Frog's Leg Gold Camp, Western Australia, Australia. From [35].*

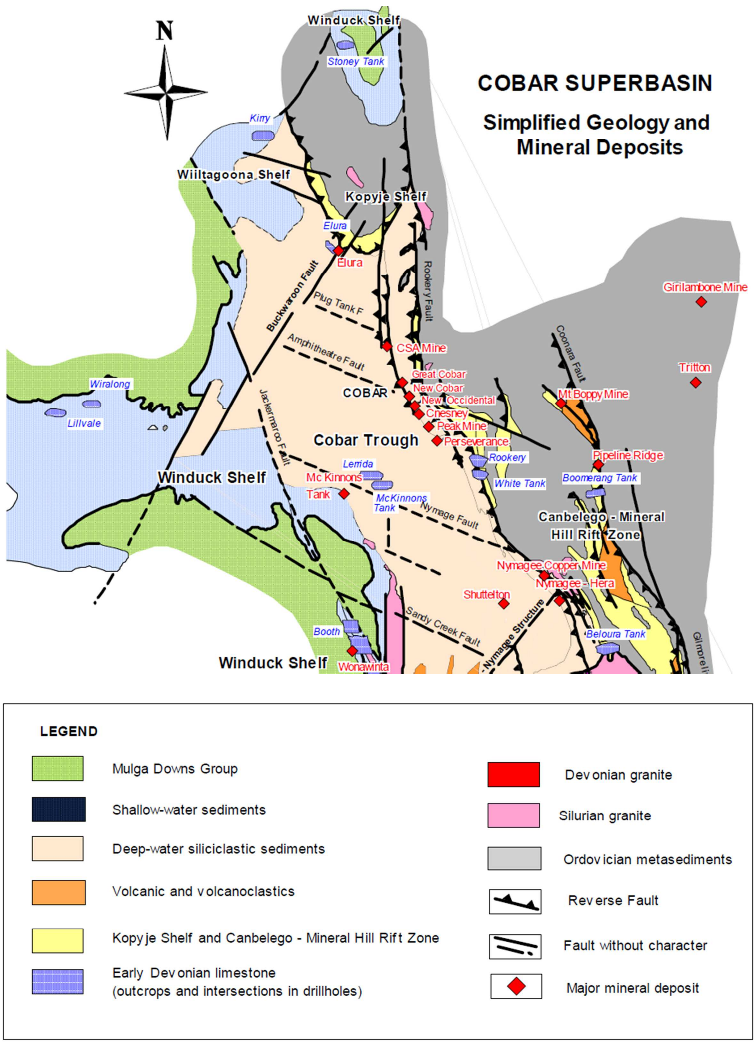

Figure 25. *Simplified geology map of the Cobar Superbasin System, New South Wales, Australia. Modified from [36].*

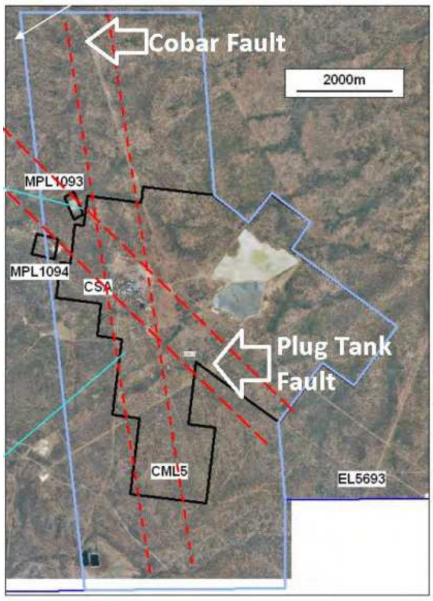

***Figure 26.** Cobar and Plug Tank Faults, CSA mine, New South Wales, Australia. From [32].*

Cobar CSA in New South Wales, Australia (Figures 25, 26) presents a good example of the faults' controlling role over the hydrogen flows formation and conducting to the surface.

Sometimes, the A and B roles get combined: in some cases, shallow strike-slips and thrusts conduct hydrogen gas from deeper zones, while dissipating it by means of their randomized and haphazardly oriented network closer to the surface.

In some occasions, the concealed faults' role in channeling hydrogen flows to the surface is not apparent and could be detected through the deeper geospheres research. In Shittim #1 well case [27] on Bruny Island, Storm Bay, Tasmania, Australia, deep faults are interpreted to be in the proximity to the borehole trajectory and well TD; however, these faults' extensions intersect the surface at some distance from the well mouth (Figure 27), making this relation not so apparent:

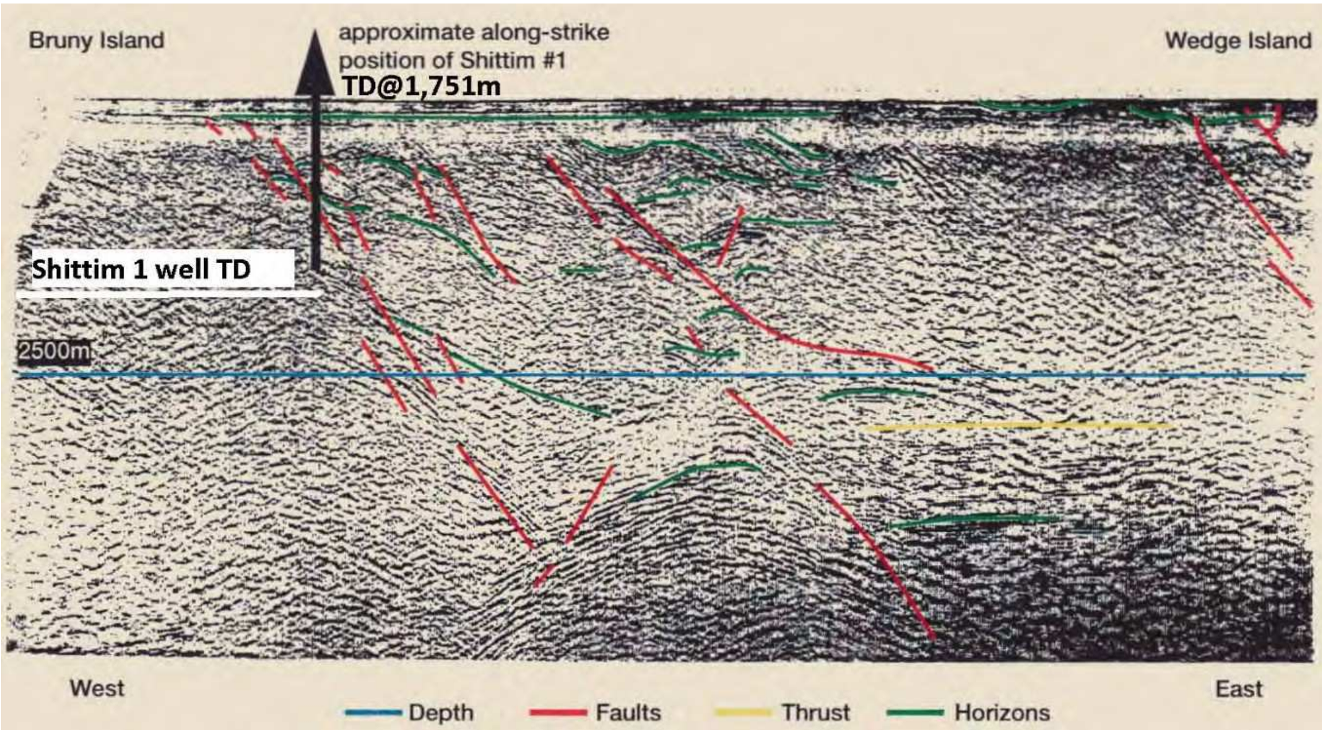

***Figure 27.** Seismic Section across Storm Bay, Southern Tasmania, Australia. A Preliminary Interpretation. Modified from [26].*

3.6. Intrusions

Along with the tectonic features, intrusions play a significant role in channelizing and temporarily "*trapping*" hydrogen gas. Similar to the tectonic features, they become a primary control for the hydrogen distribution in the lithosphere:

A. Concordant intrusions (sills) provide "*caprock*" *sealing* the temporary hydrogen "*deposits*". Apart from the "textbook" Bougou-1 well in Mali (Figures 8 and 23), such occurrence was observed in 557 m deep Lonnavale 1 well in Tasmania, Australia (up to 85% H_2): "A primary seal to these beds is the overlying Jurassic dolerite that covers nearly 3/4 of the basin" [37]. Please note that the hydrogen flow discovered in this well is likely to be also controlled by the faults network, see Figure 28.

B. Discordant intrusions (dikes) *channelizing* hydrogen gas jet streams along the contact zones between the dike body and the hosting formation/s. Apart from serving as "solid phase anisotropy contacts", these zones are often weakened due to being altered both chemically and thermally (chloritized, etc.). Besides, these contact zones quite often serve as channels for migration of both liquid and gaseous phases (fluids) additionally intensifying hydrogen mobility (Lonnavale #1 well in Tasmania, Australia, Figure 29).

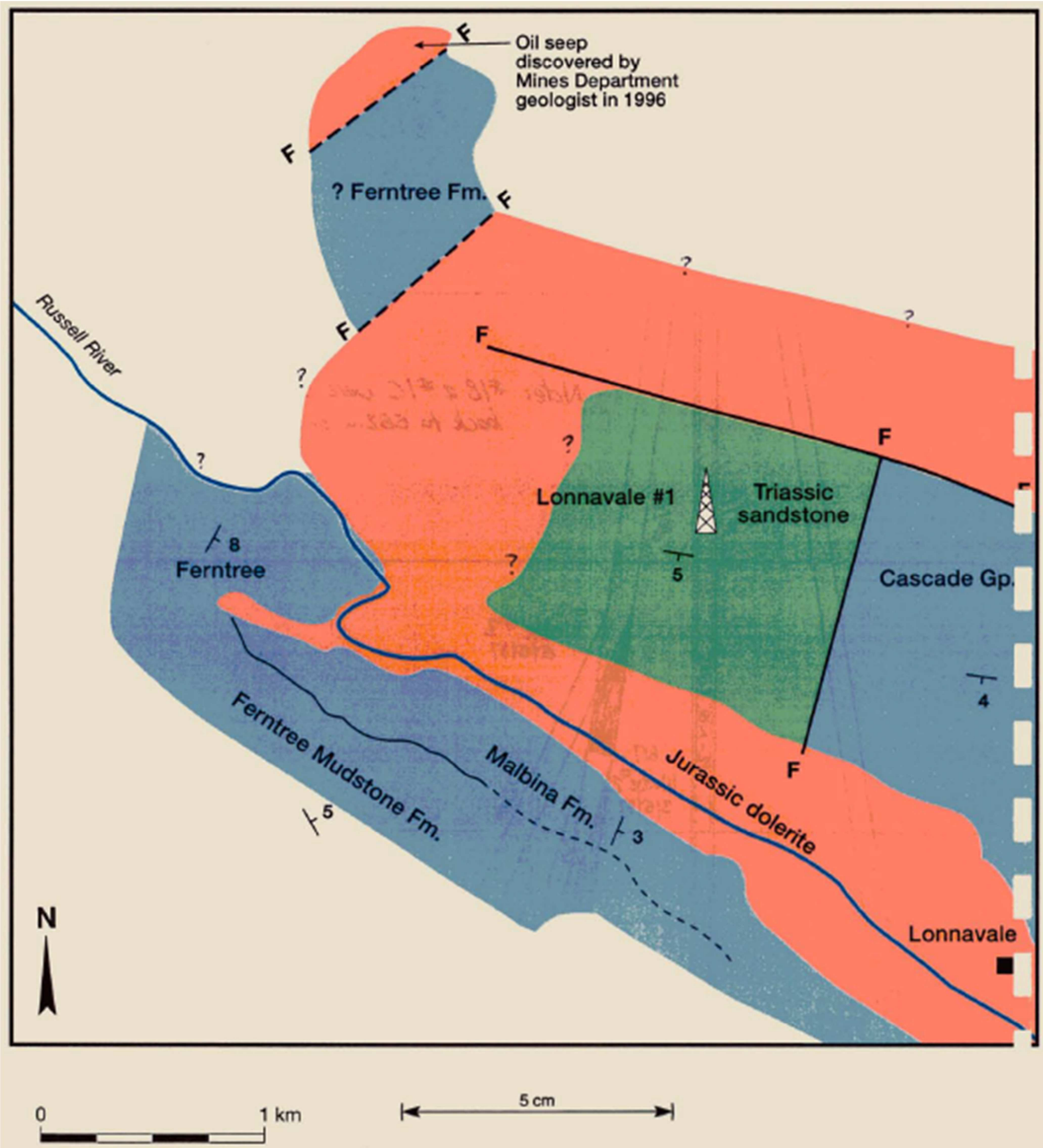

Figure 28. *Lonnavale 1 well geology map, Tasmania, Australia, from [27]. Please note the proximity to both the faults and the Jurassic dolerites.*

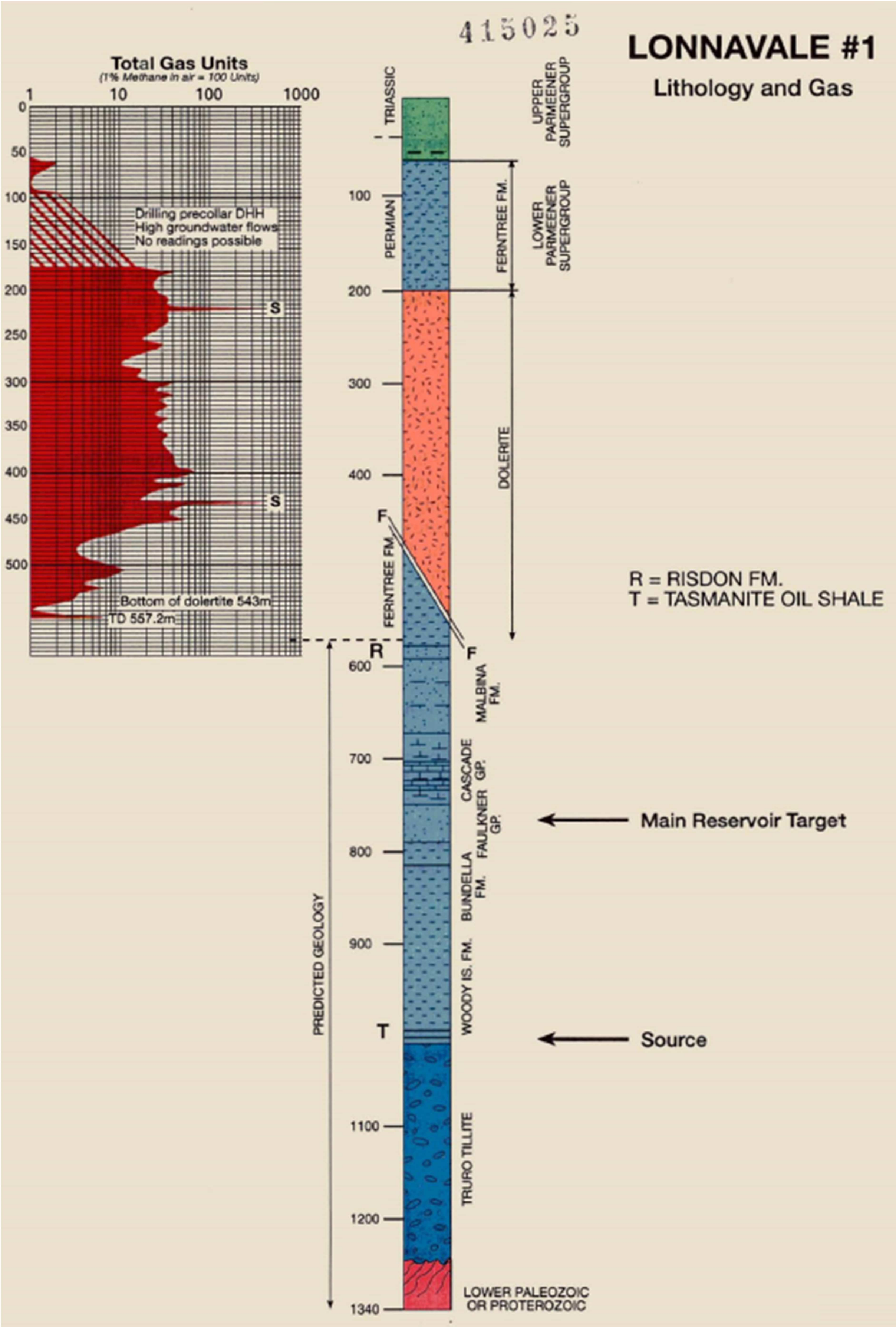

__Figure 29.__ Lonnavale 1 well lithology and gas shows, Tasmania, Australia. Modified from [27].

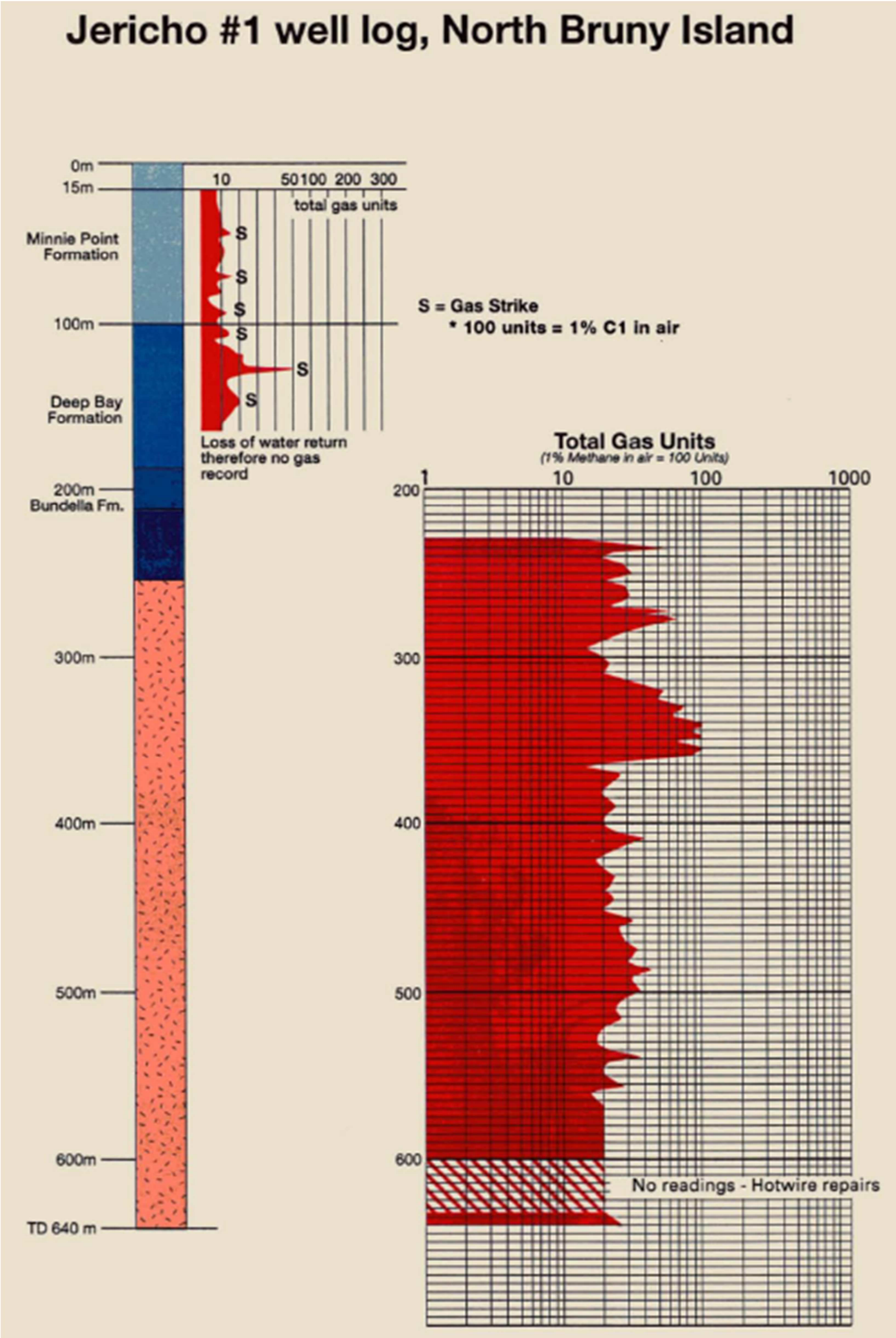

Figure 30. Jericho #1 well log, North Bruny Island, Tasmania, Australia. From [27].

Similar to the tectonic controls (see the *Tectonics* section above), the intrusions' roles A and B in hydrogen de-gassing are quite often combined. Tasmanian well cases clearly demonstrate this, due to the fact that "The dolerite appears is a sill dipping at about 8 degrees to 220 degrees" [26]. This combination is obvious for Jericho #1 well (640 m deep, up to 22% H_2) on the North Bruny Island, Storm Bay, Tasmania, Australia (Figure 30, stratigraphy and lithology): "Significant levels of gas were recorded from cuttings and fractures within the dolerite <…> Hydrogen results ranged up to 23% air-corrected." [27] – see gas flow test results in Figure 31.

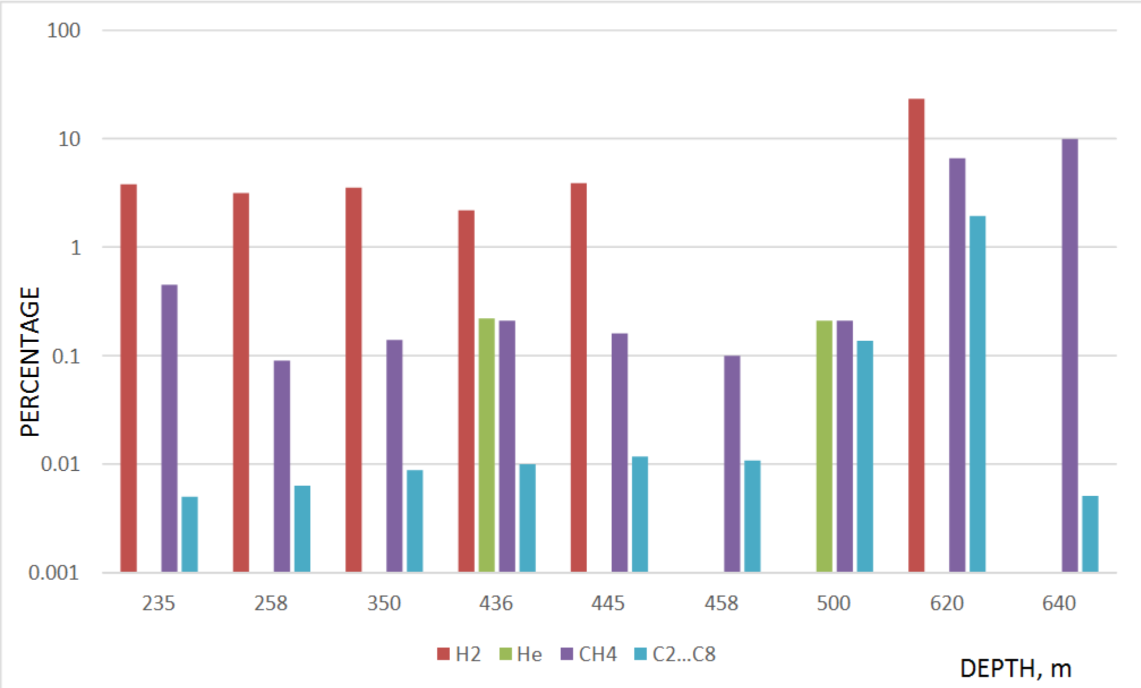

Figure 31. *Gas analysis for Jericho #1, Tasmania, Australia – Hydrogen, Helium, Methane and Wet Gas (Air corrected). From [27].*

Overall, hydrogen migration patterns subject remains to be on the top of the agenda for numerous researchers [39]. Nonetheless, the majority of these researches unanimously arrive to the same conclusion: "However, the recent discoveries of intra-cratonic H_2 seepages and accumulations with no obvious link to an ultramafic formation challenge our current understanding of H_2 production and fate in the crust <…> To date, there is no in-depth understanding of the hydrogen system from source to seep in these latter geological settings." [39].

The real-life situation in the field may become somewhat complicated due to the combination of various aspects of intrusions influence on hydrogen flows' distribution in the lithosphere, therefore calling for attentive and thorough multi-disciplinary research of local geomorphology, lithology, tectonics, petrophysics combined with deep crust and upper mantle data acquisition and interpretation.

4. Conclusions

As of today, the subject of natural hydrogen resources exploration, appraisal and development remain in its cradle stage. Quite random discoveries of natural hydrogen presence in wells and deep mines have taken place rather accidentally, and those records' systematics remains much to wish desired. Natural hydrogen provenance studies are based on the commonly accepted concepts and models, which in turn are being burdened by heaps of unresolved paradoxes and dilemmas, while being challenged by ever growing influx of newly acquired experimental and field data from various domains of science.

The existing amount of data allows us to confidently formalize a list of principles on which natural hydrogen exploration and production shall be based upon. The PHE concept is as suitable as any other– or even better than any other – for serving as a theoretical basis for this process since it explains the subject of deep-seated hydrogen with no obvious contradictions or discrepancies; at least, to this point none of its postulates have been refuted by its opponents using scientifically justified argumentation.

The authors attempted to tie the natural hydrogen paths of distribution in the lithosphere with this element's unique physical/chemical properties. Since the subject is calling for multi-disciplinary approach, various aspects and controls of this process were reviewed. As a result, several patterns influencing this process were identified – both promoting and hindering it.

Indeed, the authors do not claim to be exhaustive, covering all aspects of natural hydrogen exploration and appraisal. This subject is too vast to be covered in full in a single paper. Besides, very few efforts and little funding have been invested directly into this subject, therefore we have to deal with whatever data we can get access to. More often than not, this data is scattered across several domains if not industries, and becomes available from other projects and topics aiming at completely different goals. For instance, such basic yet critically important parameter as hydrogen flow rates are nowhere to be found from the open sources; H_2 concentration in the flow mix is the common property routinely referred to.

The authors of this paper remain quite optimistic and extremely enthusiastic in regards to multiplying efforts while continuing our research for the benefit of this new industry gaining momentum as we speak. This will inevitably give a further push to the development of exploration and appraisal techniques necessary to bring the natural hydrogen production industry to a new level. The set of exploratory techniques looks surprisingly familiar; however, the peers shall be warned against falling to the temptation of using traditional analytical instruments for its interpretation. Above, we tried to demonstrate that this approach may be somewhat misleading.

Conflicts of Interest

The authors declare no conflict of interest.

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The authors of this paper do not necessarily support the “color scheme” terms used to address hydrogen production techniques range; however, in order to simplify such techniques identification for the readers, these terms are referred to in this paper.

Acknowledgements

Dedicated to the memory of Dr. V. N. Larin - the Teacher, the Mentor, and one of the most adorable personalities in the world.

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