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Semi-circular, shallow depressions of enigmatic origin as possible indicators of hydrogen-venting activity: five established examples and a possible discovery in Central America

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ABSTRACT

Previous studies of hydrogen emanations from semi-circular, shallow depressions (SCSDs) of enigmatic origin at many places in the world have shown that these depressions are vents for significant amounts of hydrogen gas emerging from the subsurface. Further, geological investigations of the deep subsurface realm beneath the areas where there are such depressions emitting hydrogen gas indicate that there are one or two possible sources for the gas, either serpentinization of large mafic rock bodies at depth or there exists a tectonic boundary from which mantle-derived hydrogen may be emerging. The present report reviews five previous investigations of hydrogen-gas emanations from SCSDs in disparate parts of the world, and - by comparison with those examples - suggests a new, potential hydrogen-emitting area in southern Belize.

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1. INTRODUCTION

According to a recent report from the United States Geological Survey (USGS) on the "potential for geological hydrogen for next-generation energy," there may be a vast potential for natural hydrogen generation and commercially viable hydrogen extraction in many places in the world, if certain geological conditions are met and appropriate techniques are employed to find and collect this natural hydrogen (USGS, 2023). In this recent synthesis, the USGS authors point to three main hypothetical modes of generation of significant quantities of natural hydrogen. These modes are: (1) *radiolysis*, in which naturally radioactive minerals within basement rocks emit types of nuclear radiation that can split water and thus release hydrogen; (2) *serpentinization*, in which water reacts with iron-rich rocks (especially olivine-bearing rocks) and in so doing hydrogen is released; and (3) *deep-seated generation*, in which streams of hydrogen from Earth's interior (mainly the mantle) rise along tectonic plate boundaries, both active and inactive (USGS, 2023).

On its way to shallower depths, where there may be geological traps, natural hydrogen tends to be lost due to seepage through to the surface, consumption by microbes, or by abiotic reactions (formation of water, methane, or new minerals) (Fig. 1A; USGS, 2023). The USGS (2023) report also notes that natural hydrogen would have to be extracted in large quantities in order to be useful as a source of energy, and the possible extraction scenarios include (1) piercing natural traps akin to natural gas traps, (2) direct extraction by drilling into fractured iron-rich rock that is emitting hydrogen, and (3) enhanced recovery in which water and/or carbon dioxide is forced into fractured hydrogen-emitting rocks in order to stimulate hydrogen emission (USGS, 2023). All the above points just noted are graphically shown in one unifying diagram, which is Fig. 1A in this report.

In order for hydrogen emanations to be discovered, a process of prospecting and in-situ measurement is necessary. One way to do this is to look for surface features consistent with hydrogen emanations and then monitor them with H_2-gas sensors to

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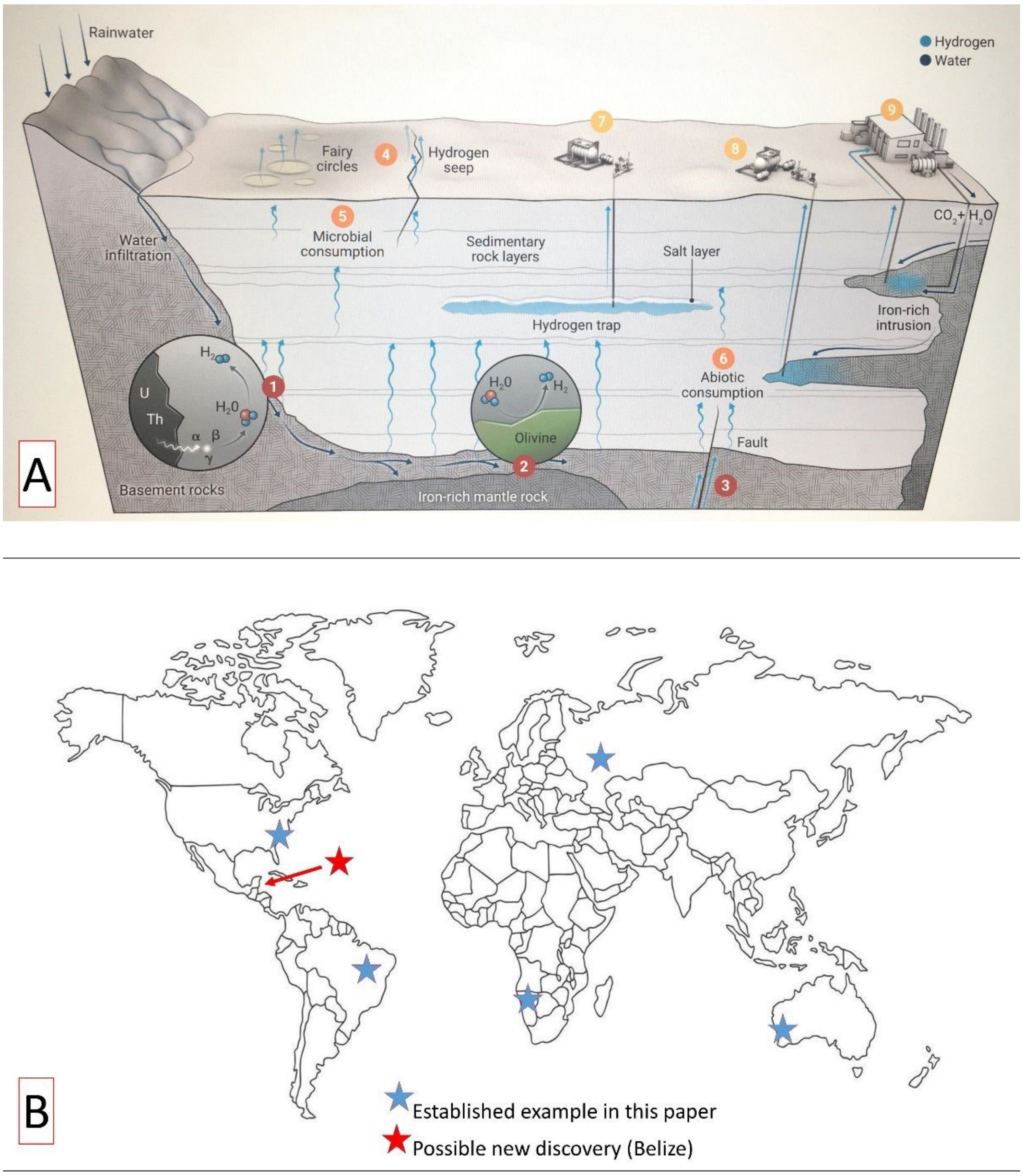


Fig. 1. (A) Global map showing the locations of the established examples of hydrogen-emitting SCSDs and the location of a possible new discovery (Belize). (B) Schematic synthesis diagram showing modes of origin of natural hydrogen: (1) *radiolysis*, in which naturally radioactive minerals in basement rocks emit forms of radiation that can split water and thus release hydrogen; (2) *serpentinization*, in which water reacts with iron-rich rocks (especially olivine-bearing rocks) and in the process hydrogen is released; and (3) *deep-seated generation*, in which streams of hydrogen from Earth's interior (mainly the mantle) rise along tectonic plate boundaries, both active and inactive. On its way to the shallower depths where there may be geological traps, natural hydrogen may be lost due to seepage through to the surface (4), consumption by microbes (5), or by abiotic reactions (6; namely formation of water, methane, or new minerals). Note that "fairy circles" are included as a style of hydrogen seep. Courtesy of *Science* and the U.S. Geological Survey.

determine if hydrogen is presently moving through the soil and if so, how much. The present paper discusses several examples of successful prospecting and hydrogen monitoring of semi-circular shallow depressions with natural hydrogen emitting from them.

In a review of the history of exploration for natural hydrogen emanations by Larin et al. (2015), they note that Russian geologists had been observing and measuring natural hydrogen gas seepage from aquifers and soils at least since the 1980s (Shcherbakov and Kozlova, 1986). As recounted in Larin et al. (2010) and Sukhanova et al. (2013), work by V. N. Larin and N. V. Larin circa 2005 clearly established that natural hydrogen was venting from "sub-circular structures (called 'zapadyny')" in several places on the craton of European Russia. This research in Russia was the impetus for the work by Zgonnik et al. (2015), which established the Carolina bays of several eastern states of the U. S. A. were of hydrogen-emission origin. Since 2005, studies of SCSDs and their associated hydrogen emissions indicated that SCSDs exist on all continents except Antarctica and South America. Many of these studies were reviewed by Zgonnik (2020), who estimated that over the whole Earth, a total of 23 x 10^{12} grams of hydrogen are emitted presently per year.

Prospecting for surficial features is the first step in finding natural hydrogen gas resources, and one of the most obvious surficial features that has been shown to be closely related to hydrogen-gas emanation in many places is the "fairy circle" or "fairy ring." These "fairy rings" are shown schematically on Fig. 1A. "Fairy rings," which is a fanciful term for enigmatic semi-circular, shallow depressions that typically have slightly raised rims and peculiar patterns in the distribution of soils textures and/or vegetation types within and upon the rims of the depressions, are in fact hydrogen-venting structures. The term "fairly ring" probably does not properly convey the potential importance of these features as hydrogen venting sites. Instead, this term usually conjures up the thought of a ring of mushrooms on a residential lawn or in a farmer's meadow. However, with regard to hydrogen-gas emanations, "fairy rings" is a term meant for features that are 10s to 100s of meters in diameter, which have an underlying, soil geochemical origin. In this paper, the term *semi-circular, shallow depressions of enigmatic origin*, or SCSDs, is used in most instances to identify these structures. It should be noted that in some places where SCSDs are closely spaced, they can coalesce to form irregular, amoeboid-shaped depressions, which are clearly of multiple, co-joined SCSD origin.

The method of detection of natural hydrogen is relatively simple, and varies only slightly depending on local conditions. A shallow boring is typically made and a tube is inserted in the boring. Then, a commercially available sensor able to detect up to a few 1000 ppm hydrogen, and typically other soil gasses such as CO_2, CH_4, and H_2S, is inserted into the tube and gas measurements are collected at several locations over periods of hours, days, and weeks, depending upon local conditions of emission. Specific techniques used are described in the main hydrogen-exploration papers cited for the five examples discussed below. In a recent paper, Lévy et al. (2023) reviews tools and workflows in natural hydrogen exploration.

There are several well-known examples of SCSDs that are related directly to hydrogen emission in various places in the world, and all are associated with either serpentinization (more specifically, they are located above deep, intra-crustal mafic intrusions as indicated by geophysical study); and/or they are related to deep-seated generation from Earth's interior (or more specifically, they are related to interpreted tectonic boundaries) (Zgonnik, 2020). In this report, some of the occurrences of SCSDs known to be associated with hydrogen-gas emissions of both potential modes of origin (serpentinization and deep-seated generation) will be briefly reviewed. The occurrences to be reviewed here are located in North Carolina (USA), Russia, Western Australia, Namibia, and Brazil (Fig. 1B). In order for an SCSD to be known as a hydrogen-emitting surface feature, in-situ monitoring for hydrogen emissions must have been completed over a reasonable span of time (e.g., several months to a year or more) and there must be evidence of hydrogen gas continually or episodically rising from the SCSD in excess of amounts that might be expected for the soil in that general area. Typically, the hydrogen emissions are most notable near the rim of the SCSD, as suggested by studies cited herein for the example sites discussed in this report.

In addition, in this report, a new area where there are SCSDs of potential hydrogen-emanation origin, specifically near the lower reaches of the Monkey River in the Toledo District of southern Belize, will be discussed. There has been no is-situ monitoring of this area for hydrogen gas emission by these SCSDs, therefore their hydrogen potential is not presently known. However, this instance in Belize serves as an example of the type of initial prospecting that can be done using satellite imagery in advance of field studies and in-situ monitoring of hydrogen-gas emission. The Monkey River SCSDs of Belize look remarkably similar to other SCSDs elsewhere in the world that have been linked to hydrogen emission.

The search for natural hydrogen is presently very important. The scale-up of clean hydrogen production has the potential to play a role in helping the world reach net-zero carbon emissions by 2050, beyond technologies such as renewables, carbon capture and storage (CCS), and nuclear power. Hydrogen can provide energy to many hard-to-decarbonize commercial sectors such as steel, chemicals, and power generation. China, Europe, and North America could soon be the largest hydrogen markets, accounting for over 50% of global demand.

2. FIVE ESTABLISHED EXAMPLES

2.1. North Carolina's "Carolina bays"

Along the eastern (Atlantic) coastal plain of the United States, principally in North Carolina, South Carolina, and Georgia, there are many tens of thousands of elliptical to nearly circular depressions with slightly elevated rims of 1 to 3 m height. The diameter of the long axis of these bays ranges from approximately 100 to 8,000 m (Zgonnik et al., 2015). In some places, they are situated very near to one another so that the rims touch or nearly touch one another. The Carolina bays are typically densely to sparsely vegetated wetlands or actual lakes that have a general oval shape. These ovals tend to have their long axes oriented toward the north-northwest (Zgonnik et al., 2015). Many bays have been cleared for agricultural or other economic purposes, and thus have lost some of their original character. Soil bleaching tends to occur on their slightly elevated rims, which is also the typical site of notable hydrogen-gas emission, based on in-situ measurements. The general stratigraphy of the region where there are Carolina bays consists of a substantially thick section of coastal plain and shallow marine clastics, which lie upon deep, crystalline continental crust.

A widely cited study by Zgonnik et al. (2015) of in-situ hydrogen gas measurements from the rims and interiors of three Carolina bays located in Bladen and Robeson counties, North Carolina, indicated hydrogen gas concentrations in the range of approximately 200 to 3,700 ppm. Flow rates for hydrogen calculated for the bays of their study ranged from a few hundred to 4,400 $m^3/day/km^2$. The authors of this study show photographic evidence of tree withering over a period of only one year as an apparent result of perhaps even higher hydrogen flow rate within a small 60-m diameter circle located in the interior area of one vegetated bay. Other bays in the area show historic evidence of past tree-withering within small circular areas inside of larger Carolina bays.

In the study discussed above, the authors interpreted the origin of the three bays, and thus the general origin of Carolina bays, as 'surficial manifestations of hydrogen-rich fluid migration pathways' (Zgonnik et al., 2015). According to Zgonnik et al. (2015), the bays themselves, owe their specific origin to "local structural collapses associated with the rock alterations induced by H_2-enriched fluid flowing the crust and deeper." They note that similar-appearing features can be seen on all continents, except Antarctica, and that many of these other locales have good evidence from in-situ measurements of significant hydrogen emanations. There are dozens of sites globally (see the inventory given by Zgonnik, 2020), mainly on the continents of North America, Eurasia, Africa, and Australia, where hydrogen gas is emitted and features similar to the Carolina bays are found. This report does not include the Belize example discussed in the present report.

The occurrence of Carolina bays, assuming all or nearly all are of hydrogen gas-emission origin, coincides with the ancient suture-then-rift boundary between the now-parted continents of Laurentia (North America) and Gondwana (Africa and Europe). This boundary lies parallel to the present Appalachian Mountain belt on the seaward side of these mountains. The Carolina bays are, therefore, an example of deep-seated hydrogen generation from major tectonic plate boundaries, a mode of origin suggested in the U.S. Geological Survey synthesis noted above (USGS, 2023).

Google Earth images in Fig. 2A-D show many elliptical Carolina bays near Elizabethtown, North Carolina, an area near to the bays studied by Zgonnik et al. (2015) and discussed above. There are at least 20 bays in the geographic area of Fig. 2A, and many, many others in that same vicinity. Fig. 2A-D shows that the Carolina bays in the vicinity of Elizabethtown, North Carolina (as elsewhere along the eastern U.S. coastal trend of these bays) have an interior that is heavily vegetated and a rim that is not so much so, and can be seen as a rim of white, sandy soil. Fig. 2C-D show close up views of some selected Carolina bays in the area.

2.2. European craton area of Russia's "sub-circular structures"

In the European continental craton area of Russia, a physiographic area extending from near Moscow to the Russian border with Kazakhstan, there are many thousands of sub-circular structures with slightly elevated rims that range in size from a few 100 m to

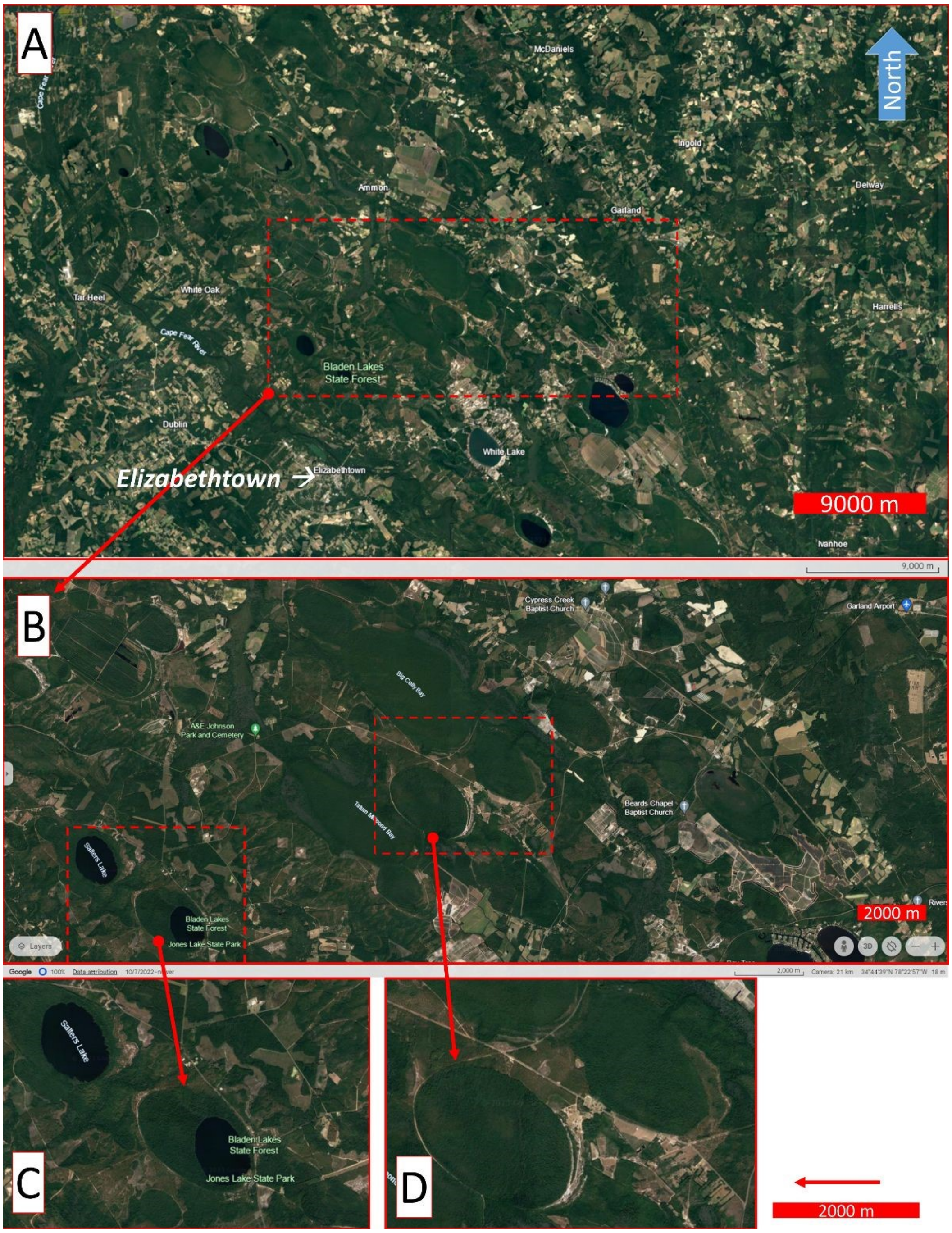


Fig. 2. Google Earth images showing SCSDs (in this instance, elliptical Carolina bays) in the vicinity of Elizabethtown, North Carolina, USA. In this area, Zgonnik et al. (2015) showed that hydrogen gas has been and is presently venting from similar SCSDs. (A) Overview of the Elizabethtown area with numerous elliptical SCSDs, which have long axes that are oriented northwest-southeast. The dashed red box shows the location of enlarged image B. (B) Enlarged image of some SCSDs in the area. (C and D) Enlarged views of some individual SCSDs (elliptical Carolina bays) from the areas shown in red, dashed boxes in image B. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 34 deg, 44 min, 39 sec N; 78 deg, 22 min, 57 sec W.

several kilometers across. These sub-circular structures are densely to sparsely vegetated marshes or lakes, which tend to have a ring of soil bleaching (in particular, humus whitening), which characterizes their slightly elevated rims. The general stratigraphy of the region where there are sub-circular structures upon the European craton region of Russia consists of a thick section of terrestrial clastic sediments (sandstones and shales), including glacial sediments, which lie upon much older, crystalline continental crust.

A study by Larin et al. (2015) of in-situ hydrogen gas measurements from the rims and interiors of six sub-circular structures near the town of Borisoglebsk, Voronezh Oblast, Russia, showed hydrogen gas concentrations in the range of approximately 200 to 8,000 ppm. Flow rates for hydrogen calculated for one of the sub-circular structures of their study ranged from a 26,740 to 34,400 $m^3/day/km^2$. Changes in vegetation over short time periods, e.g., two years, suggested to Larin et al. (2015) that flow rates may occur in pulses, some of which could cause death of trees and other vegetation in small areas of a few 10s of m diameter in a relatively short time.

The occurrence of these sub-circular structures of apparent hydrogen-emission origin are confined to the European cratonic area of eastern Russia, which includes an embedded, ancient continental rift system (Wybraniec et al., 1998). The presence of this rift system suggests that the sub-circular structures there are likely related to the proposed deep-seated tectonic mode of occurrence for hydrogen as discussed above. Like the Carolina bays, the origin of these sub-circular structures is thought to be related to the effects of hydrogen-bearing fluids moving through the soil of the area. Like the Carolina bays, these sub-circular structures may lie above natural traps holding hydrogen gas in the subsurface, but this is not known for certain. The orientations of these sub-circular structures, unlike Carolina bays, are not consistent, and tend to be in coordination with local bedrock structural trends, and thus variable in orientation across the area.

Fig. 3A-C shows at least 20 sub-circular structures of apparent hydrogen-emission origin in an area near the town of Borisoglebsk, Russia, which is the same area as the study by Larin et al. (2015) cited above. The sub-circular structures are mostly small green areas within the rectangular agricultural plots shown in this Google Earth view. Fig. 3A-C also includes enlargement images of part of this area and thus a clearer view of some of the sub-circular structures described by Larin et al. (2015). There are two types of SCSDs in this area, one is a larger, more vague (ghost?) depression and smaller, more vegetated and perhaps younger SCSDs (Fig. 3D-E).

2.3. Western Australia's "salt lakes"

In the North Perth Basin region of the coastal plain of Western Australia, there are many hundreds of small, semi-circular depressions, which are locally called "salt lakes" or swaps. These salt lakes are much like the features noted above in North Carolina and Russia where there are slightly elevated rims surrounding shallow depressions. These salt lakes, which do not necessarily contain any water, tend to have different vegetation patterns on the rims, versus the interior near the rim and the center part of the interior. The most densely vegetated parts tend to be the interior near the rim. There is soil whitening on the rims and evidence of vegetation having died in local, small spots within the interior of the salt lake depression. The general stratigraphy of the area is mafic and ultramafic bedrock at a depth of approximately 10 km, and overlying Mesozoic stratigraphy, mainly clastic sediments (sandstones and shales), which are many kilometers in thickness. Numerous faults, which originate in the basement, persist upward through much of the Mesozoic stratigraphic section of the North Perth Basin and may enhance the venting of hydrogen gas, and/or provide structural traps for accumulation of hydrogen gas.

A study by Frery et al. (2021) addresses the similarities between these Western Australian salt lakes (SCSDs) and other "fairy-ring" features elsewhere in the world. The authors of that study used in-situ measurements of hydrogen emission, which ranged from a few 10s to nearly 100 ppm, to assess the hydrogen-emitting nature of these features. They did not estimate possible flow rates in terms of $m^3/day/km^2$, but based on the reported low ppm values, the flow rates are likely to be much less than the previous examples just noted. Even so, their data suggests that even small amounts of hydrogen gas over time can form the "fairy ring" salt lakes (or swaps), which are comparable to similar SCSD features around the world. Also, it may be that the present flow rates are low, but were higher in the past and may again be high. In the North Perth Basin area of Western Australia, the salt lakes do not seem to have any preferred orientation regarding any elongation of shape, but some of these features aggregate in lines along the surface traces of known, basement-connected fault zones.

The occurrence of these salt lakes of apparent hydrogen-emission origin are related apparently to the nature of the deep bedrock underlying the North Perth Basin, which is mainly mafic and ultramafic rock. The composition of this bedrock would strongly suggest that salt lake SCSDs reported by Frery et al. (2021) are likely related to the proposed serpentiniza-

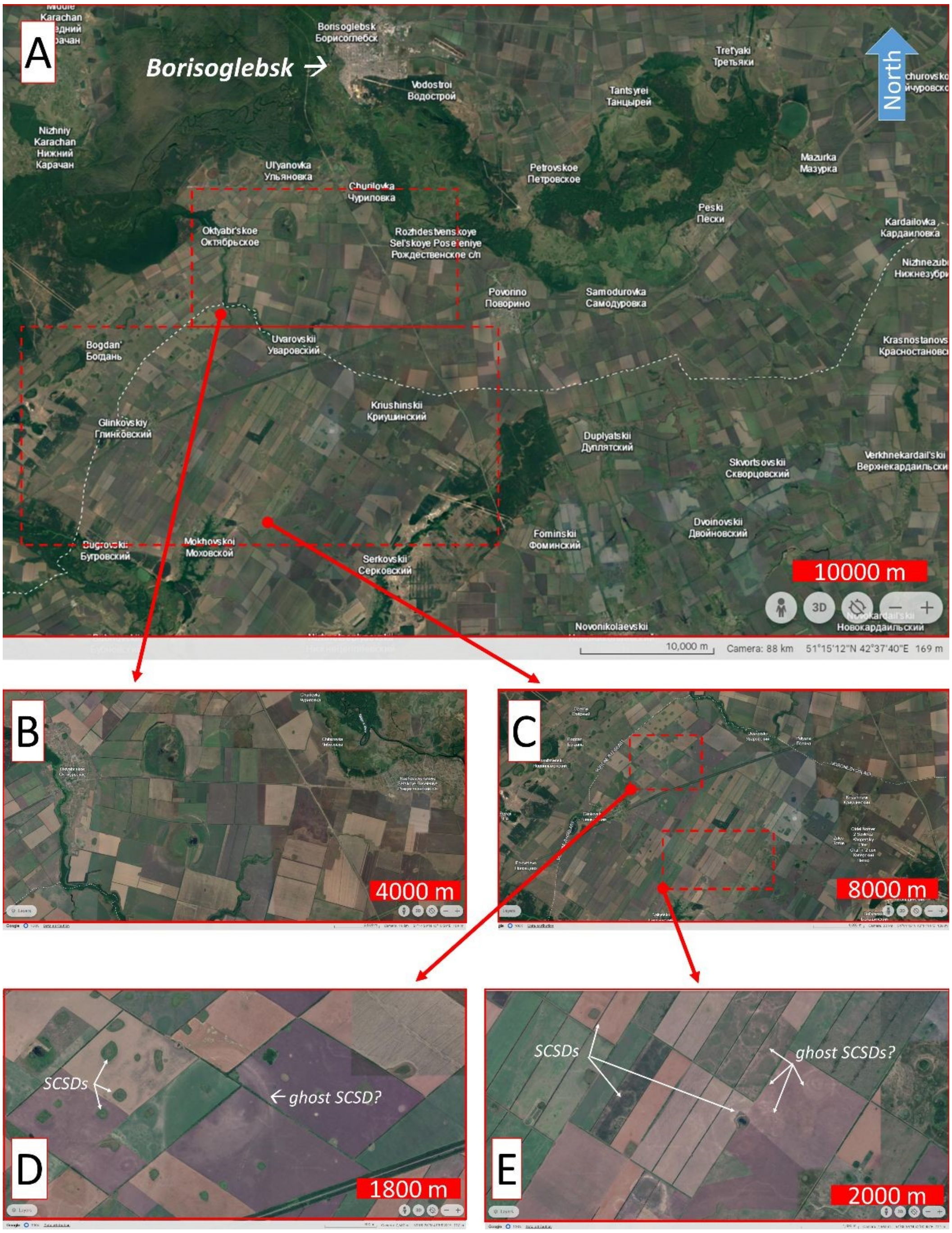


Fig. 3. Google Earth images showing SCSDs (in this instance, sub-circular structures of the European craton) in the vicinity of Borisoglebsk, Voronezh Oblast, Russia. In this area, Larin et al. (2015) showed that hydrogen gas has been and is presently venting from similar SCSDs. (A) Overview of the Borisoglebsk area with numerous SCSDs, which are ovoid to irregular shapes. The dashed red boxes show the location of enlarged images B and C. (B and C) Enlarged images of some SCSDs in the area. (D and E) Enlarged views of some individual SCSDs (sub-circular structures) from the areas shown in red, dashed boxes in image C. Note that newer SCSDs are small and green, whereas there are also larger, more vaguely defined (ghost?) SCSDs in the same area. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 51 deg, 15 min, 12 sec N; 42 deg, 37 min, 40 sec E.

tion mode of occurrence in which mafic minerals like olivine and pyroxene react with water over time and thus release hydrogen in the process. Like similar hydrogen-emitting structures in North Carolina and Russia noted above, the origin of these sub-circular structures is thought to be related to the effects upon soils of hydrogen-bearing fluids moving through the soil of the area. Even though these salt lakes, and likewise some of the sub-circular structures in Russia may superficially appear somewhat similar to karstic sinkholes, there is no carbonate in this area and thus no host rock for karst. Whether there are hydrogen-gas traps in the subsurface of this area in Western Australia remains to be seen.

Fig. 4A-C shows an area of Western Australia, near the town of Moora, where there are at least 20 semi-circular salt lakes that follow a roughly north-south linear trend that is a fault trace. This area near Moora is in the locale studied by Frery et al. (2021), which was discussed briefly above. The salt lakes shown here appear mostly mottled green or grey versus the surrounding plain, which is more nearly brown in tone. Some of the SCSDs are filled with water, e.g., Lake Dalaroo (Fig. 4B); whereas some of the SCSDs are dry and display an outer ring and inner deeper area that is darker in tone (Fig. 4C).

2.4. Namibia's "semi-circular depressions"

In the Damara orogenic belt region of the Congo craton within central Namibia, there are many hundreds of small, semi-circular depressions, which range in size from a few 10s to a few 100s of meters. Some are locally called salt pans, but 'semi-circular depression' is perhaps more appropriate. These small depressions are much like the features noted above in North Carolina, etc., where the depressions typically have slightly elevated rims surrounding a low area only a few meters at most below the rim height. These semi-circular depressions, which do not typically contain any water, tend to have different vegetation patterns upon their rims versus their interiors. Specifically, the most densely vegetated parts tend to be the slightly elevated rim, and the interior tends not have substantial plant life. The soils of the rims of these semi-circular depressions tend to have a more sandy texture than the slightly more clay-rich interiors, but there is no report of soil bleaching as in some other occurrences globally.

A study by Moretti et al. (2022) addresses the similarities between these Namibian semi-circular structures and other "fairy-ring" features in Brazil and elsewhere in the world. The authors of that study used in-situ measurements of hydrogen emission, which ranged from a few 10s to nearly 400 ppm, to assess the hydrogen-emitting nature of these Namibian features. They did not estimate possible flow rates in terms of $m^3/day/km^2$, but based on the reported relatively low ppm values, the flow rates are likely to be also relatively low as compared to the previous examples. The authors note that flow rates appear to vary over time and can vary during the span of one day. Therefore, whereas present flow rates are low, they may have been higher in the past, and may again be high. Some of the semi-circular structures of Namibia are elongated and have a preferred orientation. The trend of the elongation is toward the west and/or northwest, which is consistent with deep-seated, crystalline bedrock structural trends.

The general stratigraphy of the area on interest in Namibia includes granitic bedrock of the Darmara craton and overlying Mesozoic strata, which are mainly clastic sediments (sandstones and shales) that are several 10s to 100s of meters in thickness (Toé et al., 2013). However, there are mafic rocks (amphibolites) and iron-rich sedimentary rocks within the underlying bedrock (Toé et al., 2013), which likely contribute to the generation of hydrogen. Further, this area is an orogenic belt, and thus this area is part of an ancient crustal suture, which may contribute to hydrogen emanation from deeper mantle sources. It is not clear whether the possible source of hydrogen is more likely from serpentinization or a deep-seated tectonic feature of the Darmara craton, or both. If there are potential hydrogen traps within the Mesozoic strata of the area, that is also not known.

Fig. 5A-E shows an area of Namibia, near the town of Okakarara, where there are far more than 20 semi-circular structures (outlined by dark vegetation) that follow roughly west to northwest linear trends, which are consistent with bedrock structure. This area near Okakarara is in the locale studied by Moretti et al. (2022), which was discussed briefly above. Fig. 5B and D show clusters of SCSDs, and Fig. 5C and E show close up views of a few of these semi-circular structures, which have dark vegetation (trees, mainly) on their rims and little vegetation in their interiors.

2.5. Brazil's São Francisco basin area "fairy circles"

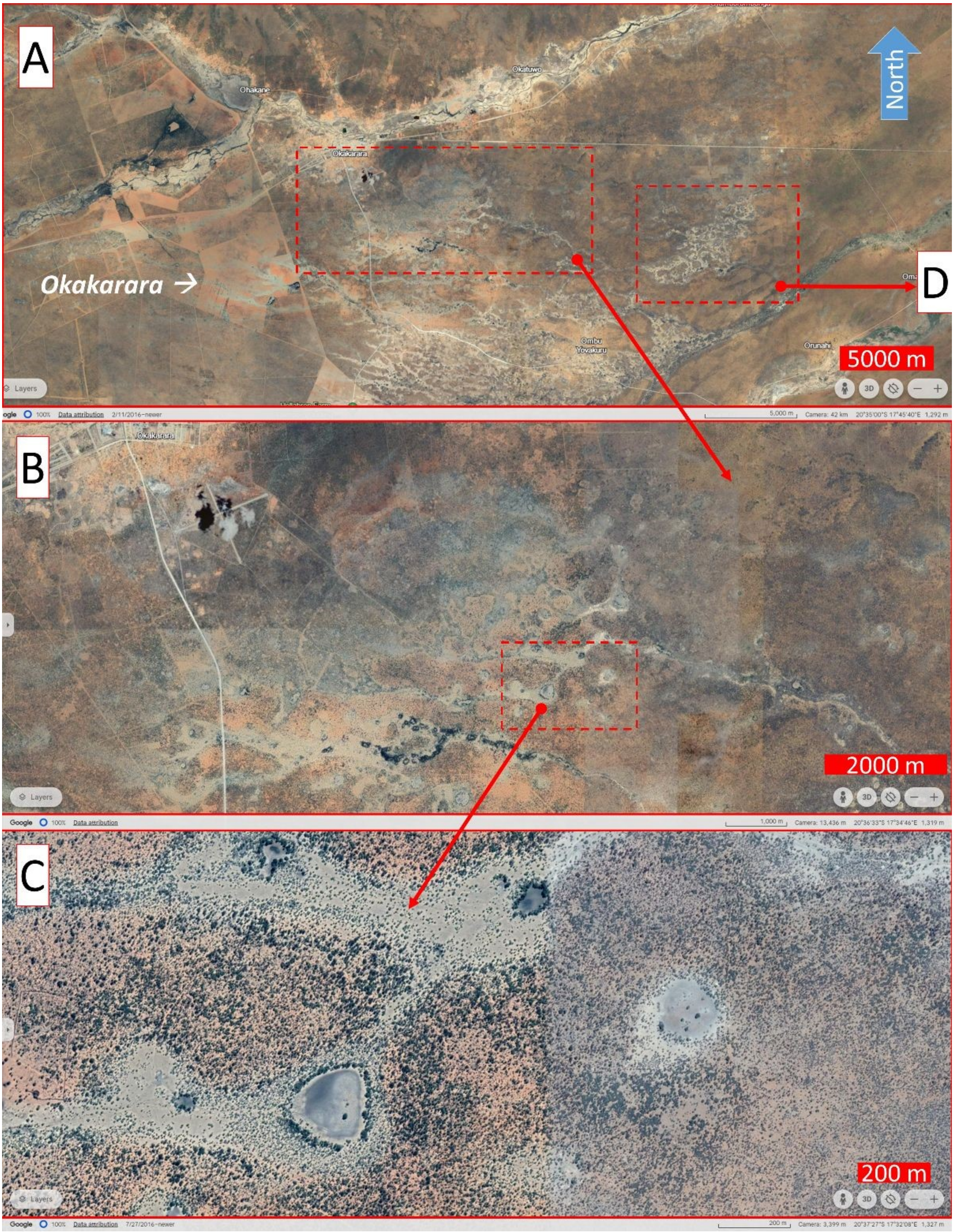
On the surface above some parts of the São Francisco basin, an intracratonic feature that is situated within the São Francisco-Congo craton of western Gondwana (Brazil), there are dozens of small, semi-circular depressions (SCSDs), which range in size from a few 10s to a few 100s of meters. Some are locally called "fairy rings," but in this report the term 'semi-circular depression' will be used. These small depressions are much like the SCSD features noted above in other

Fig. 4. Figure continues on next page.

Fig. 4. Google Earth images showing SCSDs (in this instance, salt lakes or swaps) in the vicinity of Moora, Western Australia, Australia. In this area, Frery et al. (2021) showed that hydrogen gas has been and is presently venting from similar SCSDs. (A) Overview of the Moora area with numerous SCSDs, which are ovoid to circular shapes and some contain water. The dashed red boxes show the location of enlarged images B and C. (B and C) Enlarged images of some SCSDs in the area. (B) The larger, central SCSD (Lake Dalaroo) has a partial ring of what may be small external vents (much smaller SCSDs). (C) The larger, central SCSD is largely dry and consists of an outer ring and inner deeper area; also, there is an apparent, small internal vent (or small SCSD) on the west side. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 30 deg, 35 min, 35 sec S; 116 deg, 02 min, 30 sec E.

locations on other continents, where the depressions typically have slightly elevated rims surrounding a low area only a few meters at most below the rim height. These semi-circular depressions, which do not typically contain any water, tend to have different vegetation patterns upon their rims versus their interiors. Specifically, in this part of Brazil, the most densely vegetated part of the fairy rings (with regard to trees and larger plants) tend to be the slightly elevated rim, and the interior part tends not have nearly as much plant life. The interior area of smaller fairy rings tend to be mostly barren, but the larger and more irregular fairy rings have an inner ring of nearly barren soil and a central area of low vegetation cover (mainly grasses and small shrubs) that forms a green swath in the central area.

A study by Prinzhofer et al. (2019) addresses the similarities between one of these Brazilian semi-



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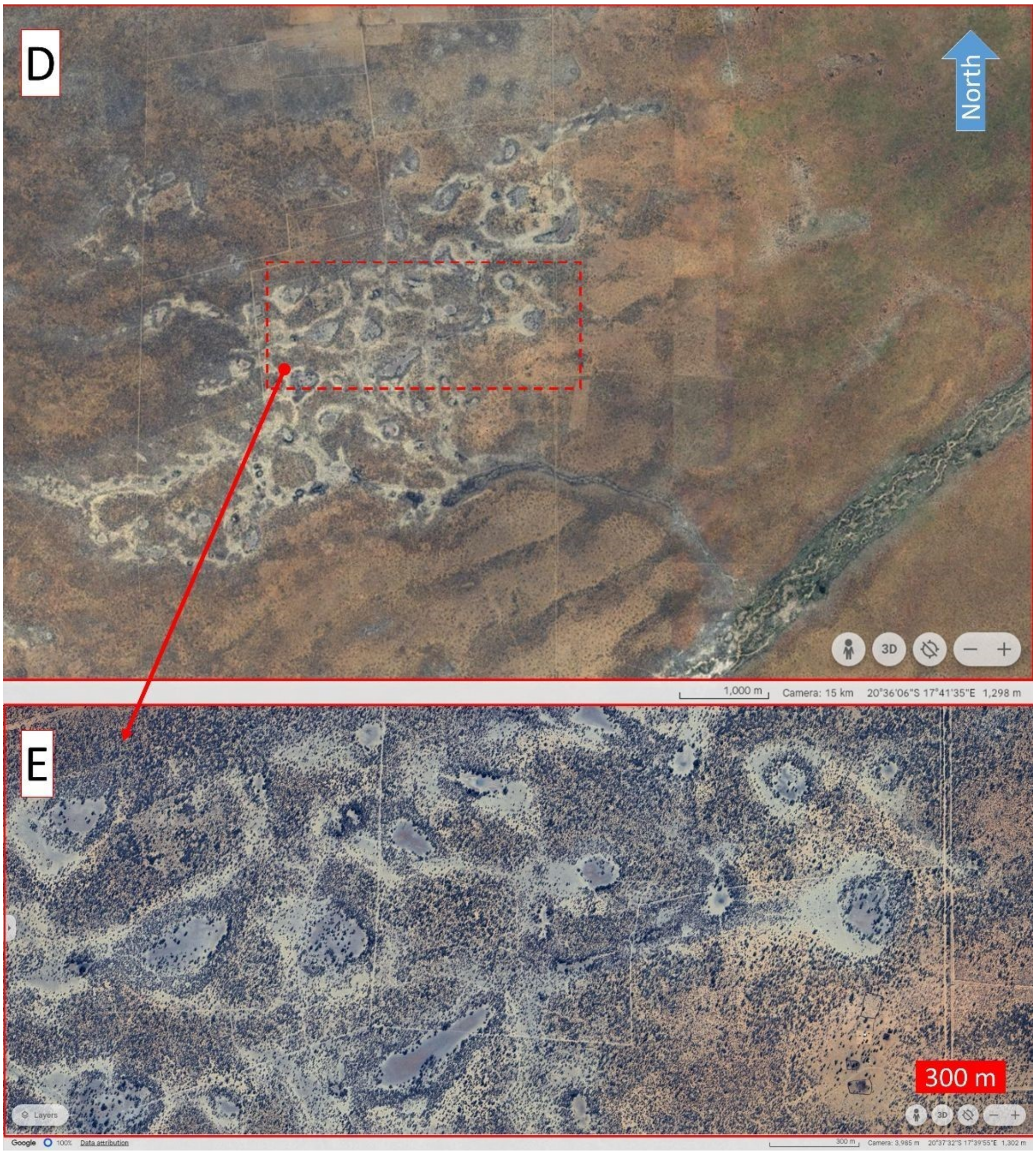

Fig. 5. Google Earth images showing SCSDs (in this instance, semi-circular depression) in the vicinity of Okakarara, Namibia. In this area, Moretti et al. (2022) showed that hydrogen gas has been and is presently venting from similar SCSDs. (A) Overview of the Okakarara area with numerous SCSDs, which are irregular to ovoid shapes. The dashed red boxes show the location of enlarged images B and D. (B) Enlarged image of some clusters of SCSDs in the area south and east of Okakarara (upper left); the dashed, red box shows the location of enlarged image C. (C) Small SCSDs, which are characterized by more dense vegetation on the rims. (D) Enlarged view of a cluster of SCSDs in the area outlined in image A. (E) Enlarged image of area in dashed red box in image D. Small SCSs are similar to the ones in image D, but have more complex internal structure. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 30 deg, 35 min, 35 sec S; 116 deg, 02 min, 30 sec E.

circular structures located in the midst of the São Francisco basin area and other "fairy-ring" features elsewhere in the world. The authors of this Brazilian study used long-term, in-situ measurements of hydrogen emission, which ranged from a few 10s to nearly 2000 ppm, to assess the hydrogen-emitting nature of these features. They did not estimate possible flow rates in terms of m^3/day/km^2, but based on the reported ppm values from sensors and the total flow in m^3/day for the one fairy ring studied, the flow rates are likely to be in the 100s of m^3/day/km^2 at the study site. The authors note that flow rates appear to vary over time and can vary considerably over the span of one day. They suggest that hydrogen flow rates tend to peak at mid-day, in most instances. Therefore, even though presently measured flow rates are modest, they may have ranged considerably over time. As in Western Australia and

Namibia, the semi-circular structures of Brazil do not seem to have any preferred orientation, and can have irregular shapes. In many instances, these SCSDs cluster together in groups of a few to several dozen.

The general stratigraphy of the area discussed here with Brazilian fairy rings consists of Archean granitic and metamorphic bedrock at several kilometers depth, and overlying Meso- and Neoproterozoic strata (Reis et al., 2017). These strata are few 1000s of meters in thickness and area mainly comprised of clastic sediments (sandstones and shales), which include many mafic intrusions (both dikes and sills) (Reis et al., 2017). This area of Brazil is part of an ancient orogenic belt, and contains a Proterozoic crustal suture, which may contribute to hydrogen emanation from deeper mantle sources. It is not clear whether some of the hydrogen emanation may be sourced from serpentinization of the mafic intrusions (dikes and sills) within the Proterozoic sedimentary section or if the ancient suture zone is the main source. Further, the presence of potential hydrogen structural traps within the Proterozoic stratigraphy of the area is not known.

Fig. 6A-D shows an area of Brazil, adjacent to a segment of the São Francisco River, where there are several semi-circular structures (outlined by dark vegetation), which occur in a localized group or cluster (Fig. 6B). This area is near the fairy-ring locality studied by Prinzhofer et al. (2019), which is discussed briefly above. Some of the larger SCSDs consist of an outer ring of very little vegetation and a deeper interior area (typically green; Fig. 6C-D). Some of the SCSDs appear to be due to coalescing of two or more small SCSDs (Fig. 6D).

3. A NEW POSSIBLE DISCOVERY

3.1. Southern Belize's semi-circular, shallow depressions of the Monkey River coastal plain

Close examination of the coastal plain adjacent to the Monkey River on the south of the point where it joins the Caribbean Sea, shows numerous semi-circular shallow depressions of as-yet unknown origin. The area of interest is in a cleared part of the low savannah, and mainly within the Payne's Creek National Park. These depressions of interest closely resemble the SCSDs found elsewhere in the world, some of which are described in the examples given above as being related to hydrogen-gas emanations. The Monkey River SCSDs, a few 10s to about 100 meters in diameter, are characterized by differences in vegetation, mainly grasses, palms, and mangroves (versus the surrounding coastal plain terrain), both within each central, shallow depression and upon the rim of each depression. They are overall roughly circular but are irregular regarding their margins (rims). Specifically, these apparent SCSDs appear to be either more green or more brown than the surrounding coastal plain, which is more of a lighter, greenish brown tone. Fig. 7A-C shows part of this area, which is located just south of the lower part of the Monkey River. A small part of the river, and Monkey River Town at the river delta, can be seen in the upper right corner of this Google-Earth image. Most of the Monkey River SCSDs are more-or-less randomly distributed but some of them, located on the eastern side of the image area in Fig. 7B, appear to form at least one line that is oriented north-northeast. This orientation is consistent with the strike of local, onshore faults as depicted by Purdy et al. (2003).

The Monkey River plain is underlain by a sequence of clastic sediments (mainly sandstones and shales) that are at least 750 m thick (as shown in the well log for nearby borehole Monkey River #1; Purdy et al., 2003). These thick clastic sediments, which are part of the Paleocene-Eocene Toledo Formation, would not be amenable to the development of karstic sinkholes, thus the origin of the Monkey River SCSDs is non-karstic and thus otherwise enigmatic, unless perhaps hydrogen-gas emanations are involved. This area has the requisite underlying geological conditions for natural hydrogen-gas generation, as noted below.

Southern Belize lies closely adjacent to an active crustal plate boundary separating the Caribbean and South American plates, which is a major tectonic boundary that was early on related to compression but now is of lateral fault origin (Rogers and Mann, 2007). On land, this active plate boundary is located approximately parallel to northeastern segment of the Honduras-Guatemala border, and thus is just south of the southern border of Belize with adjoining Honduras. Both the Polochic fault zone and parallel-trending Motagua fault zone, which are prominent structural features of the Belize-Guatemala border region, are a deep crustal structures on land that are closely associated with this plate boundary (Rogers and Mann, 2007). Offshore, in the adjacent Caribbean, this plate boundary continues eastward for many 100s of kilometers along the

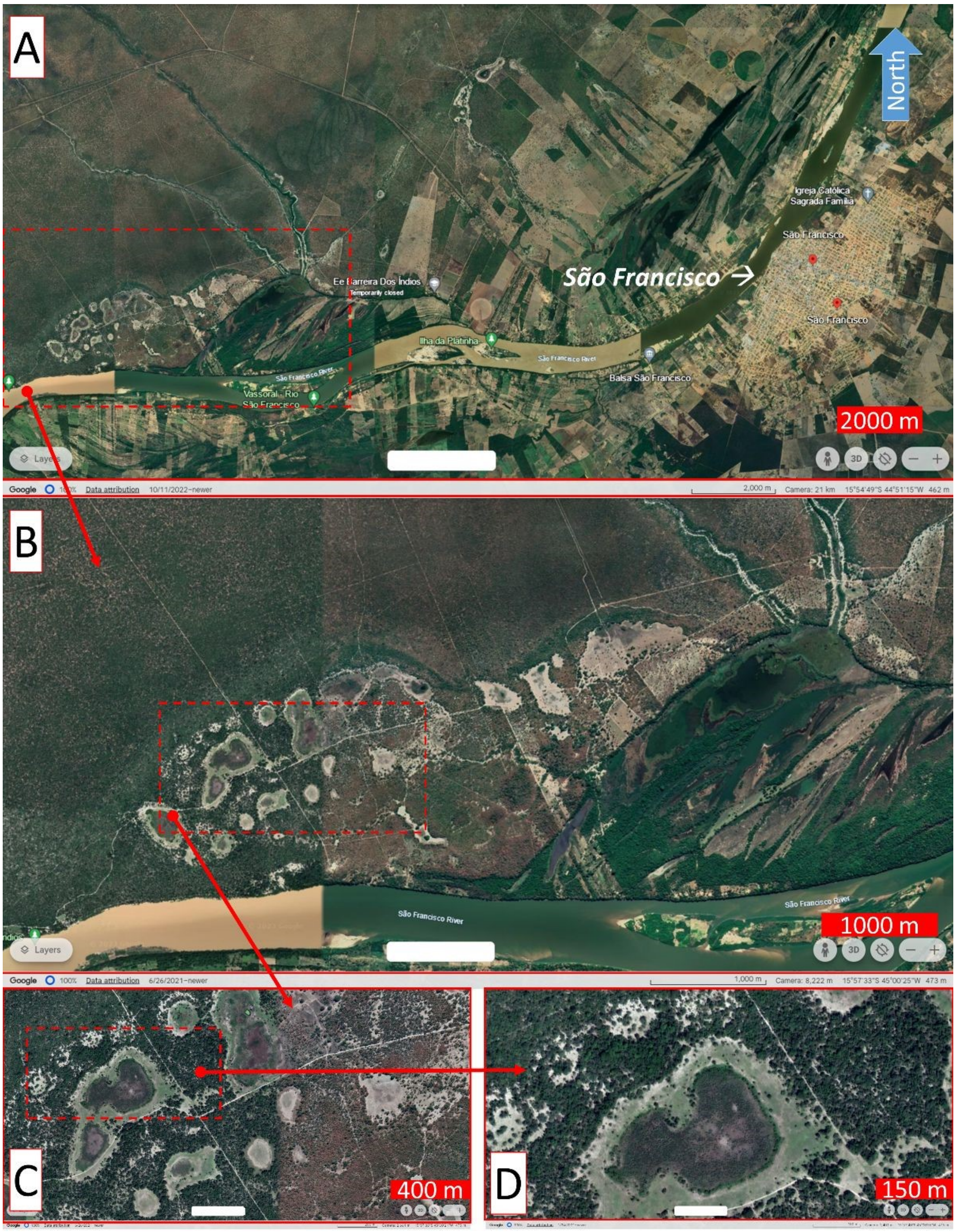

Fig. 6. Google Earth images showing SCSDs (in this instance, "fairy rings") in the vicinity of São Francisco, Brazil. In this area, Prinzhofer et al. (2019) showed that hydrogen gas has been and is presently venting from similar SCSDs. (A) Overview of the São Francisco area with numerous SCSDs, which are ovoid to irregular shapes that are located in a cluster adjacent to the São Francisco River. The dashed red box shows the location of enlarged image B. (B) Enlarged image of the cluster of SCSDs adjacent to the river; dashed red box shows location of image C. (C) An area of numerous, small SCSDs with vegetated rims, and interior dark zones of different vegetation than the rims; dashed red box shows location of image D. (D) One of the larger SCSDs, which consists of an outer low-vegetation ring (greyish green) and inner deeper area (green); also, this SCSD may consist of two separate vents that have coalesced, judging from its irregular shape. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 15 deg, 54 min, 49 sec S; 44 deg, 51 min, 15 sec W.

Swan Islands fault zone (Rogers and Mann, 2007). Fig. 8 schematically shows these faults, the associated plate boundary, and other pertinent information.

On the northern side of the Polochic fault zone, and in the terrain between the Polochic and Motagua fault zones, there are substantial ultramafic rocks

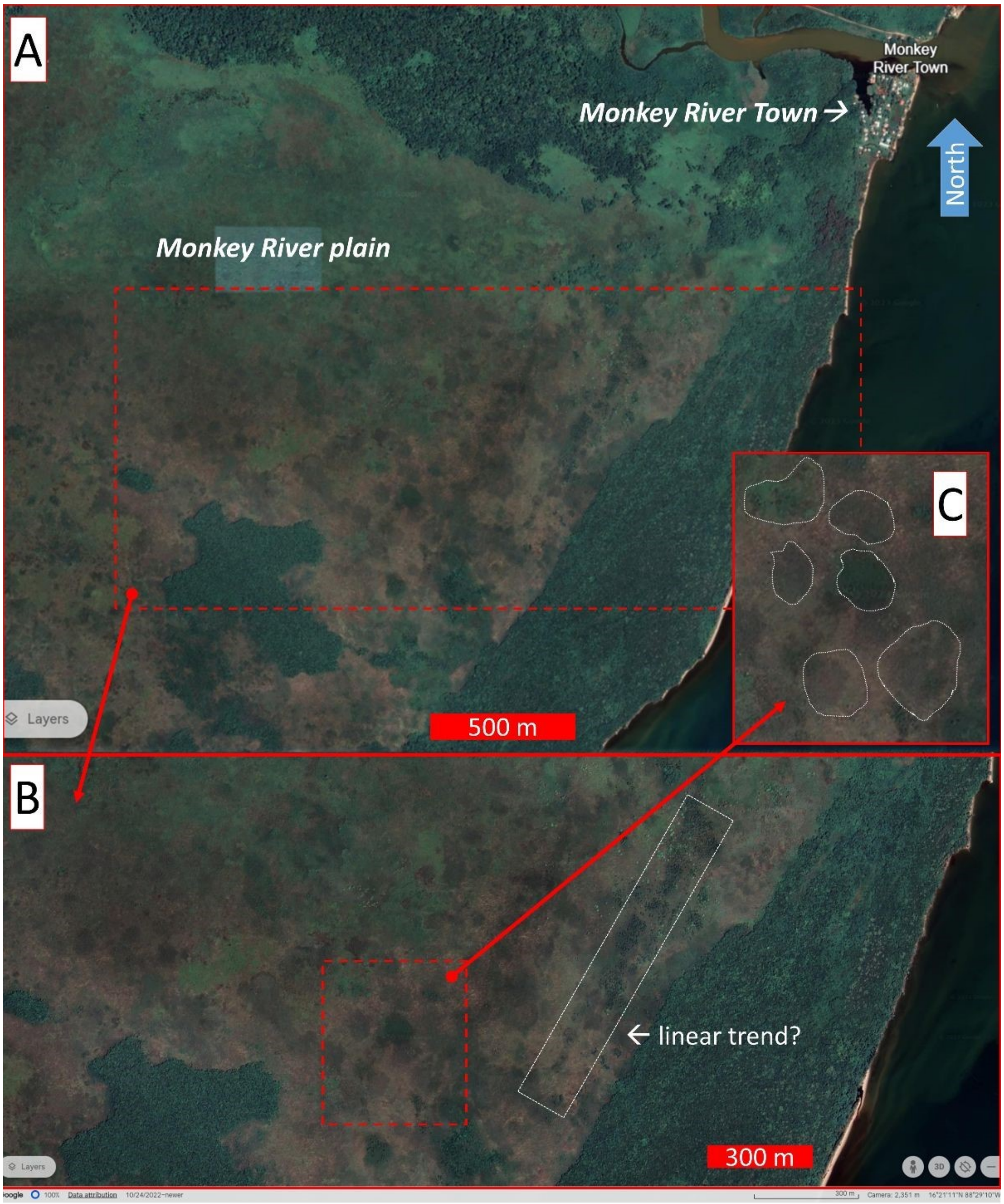

Fig. 7. Google Earth images showing previously undetected, potential SCSDs in the vicinity of Monkey River Town, Toledo District, Belize. Most of this area is within the Payne's Creek National Park. In this area, there have been no studies of hydrogen gas emissions from SCSDs so far. (A) Overview of the Monkey River plain near Monkey River Town, which is a large cleared area of savannah with numerous SCSDs; these SCSDs may be related the hydrogen emission based solely on their similar general appearance and their inferred potential for subsurface hydrogen sources. These SCSDs are ovoid to irregular shapes that are located more-or-less randomly over most of the cleared area of the Monkey River plain, as shown in image A. The color of the interior of most SCSDs is either green or brown, in contrast to the dull tone of the surrounding plain. The dashed red box shows the location of enlarged image B. (B) Enlarged image of the SCSDs in the midst of the cleared area of the Monkey River plain; the white dashed box shows a possible, single linear trend of some SCSDs. The dashed red box within image B shows location of image C. (C) An area of several small SCSDs, six of which have been outlined with fine, white dotted lines. North is up in all instances. Scale bar for each image is red with length noted. Location of the approximate center of image A is 16 deg, 21 min, 11 sec N; 88 deg, 29 min, 10 sec W.

in outcrop as well as in the deep subsurface as indicted by free-air gravity data, which shows evidence of large, deep-seated high-density intrusions of probable mafic and ultramafic origin (Purdy et al., 1975; Rogers and Mann, 2007). Similarly, additional high-density intrusions also underlie parts of southern Belize and the adjacent continental shelf area of Belize as far north as the Monkey River fluvial plain area and to the northeast far beyond that area (Rogers and Mann, 2007). The free-air gravity anomalies (high residual gravity features) in this area indicate additional deep-seated mafic rocks that Rogers and Mann (2007) describe as possible "basement ridges." Fig. 8 shows schematically the distribution of the main features noted here.

Saad (2018) showed the results of aeromagnetic mapping of the Monkey River coastal plain in approximately the same area as Fig. 7A. Saad's (2018) map shows numerous small (< 1 km diameter) magnetic anomalies that are related to localized concentrations of subsurface, iron-rich rocks. Saad (2018) attributes these magnetic anomalies to iron-rich sediments of the folded Toledo Formation at shallow depth, but it seems more likely that these anomalies are related to mafic intrusions, as suggested by Rogers and Mann (2007). Also of note is that Saad's (2018) map shows approximately the same distribution pattern among small aeromagnetic anomalies versus the Monkey River SCSDs shown in Fig. 7A. Specifically, both the small aeromagnetic anomalies and the SCSDs have a seemingly random distribution on the western side of the area, but follow more nearly linear trends on the eastern side. A seismic line near the Monkey River, also presented by Saad (2018), indicates faults in the local strata and underlying bedrock that are parallel to the eastern linear trend of both the SCSDs and the aeromagnetic anomalies.

Why SCSDs would appear at the Monkey River site and not elsewhere above the deep-seated mafic intrusions of southern Belize cannot be fully explained. That said, it is important to note that in other areas of the world where there are hydrogen-related SCSDs, their distribution is not necessarily over the whole area where there is a buried source. In the southern Belize, there is a dense forest canopy in many areas, which may mask some depressions that are actually present. But, it should be noted that much of the area in southern Belize underlain by the high-density intrusions is also covered by shallow water (i.e., the southern Belize continental shelf). Therefore, hydrogen bubbling up from the sea floor would be expected there. There are no published studies of gas bubble occurrences on the southern Belize shelf, but such a study might be very revealing. Also, it may be worthy of note that local fault structures, shown by Purdy et al. (2003), intersect at right angles in the vicinity of the mouth of the Monkey River. This structural confluence may provide a more efficient avenue for hydrogen movement to the surface versus adjacent areas, thus focusing hydrogen emissions on the Monkey River plain area shown in Figs. 7 and 8.

In summary, there are two potential natural hydrogen sources in the southern Belize area, (1) serpentinization of the deeply buried, high-density (mafic and ultramafic) intrusions, and (2) deep-crustal structures associated with the tectonic boundary adjacent to that area. Both of these were noted as being substantial potential natural hydrogen-gas sources in the USGS report discussed at the outset of this paper, and thus may be at play in southern Belize.

In-situ hydrogen-gas monitoring is needed to determine clearly if the Monkey River SCSDs are in fact hydrogen-venting surface features. If they are, study of any subsurface structural traps, perhaps within the 750-m thick Toledo Formation of that area, may reveal subsurface exploration targets (i.e., hydrogen-gas traps) where hydrogen gas may be situated in substantial quantity under this area. For example, the Monkey River seismic line interpreted by Saad (2018) shows structures that could be potential gas traps owing to both fault and fold origin, which occur both within the Toledo Formation and within the underlying bedrock.

4. DISCUSSION AND CONCLUSION

Hydrogen-gas emanations from the deep subsurface have been hypothesized for some time, but only recently has the nature of the hydrogen-venting process been investigated and a surficial topographic feature identified that may signal the location of a vent (Zgonnik, 2020; Moretti et al., 2021). These surficial features are known as "fairy rings," but the more generic term semi-circular, shallow depression (or SCSD) is used in the present paper to identify these features. In the examples reviewed in this paper, from North Carolina (USA), Russia, Western Australia, Namibia, and Brazil, the common denominators in all instances are that the subject depressions are numerous, small features situated within clusters or in lines. All of these depressions have slightly raised rims and are typically 10s to 100s of meters in diameter. They may be elongated or slightly irregularly shaped (even in overlapping groups that form amoeboid shapes), and all are situated more-or-less directly above a deep-seated source of hydrogen gas. In the five examples cited here, the hydrogen-

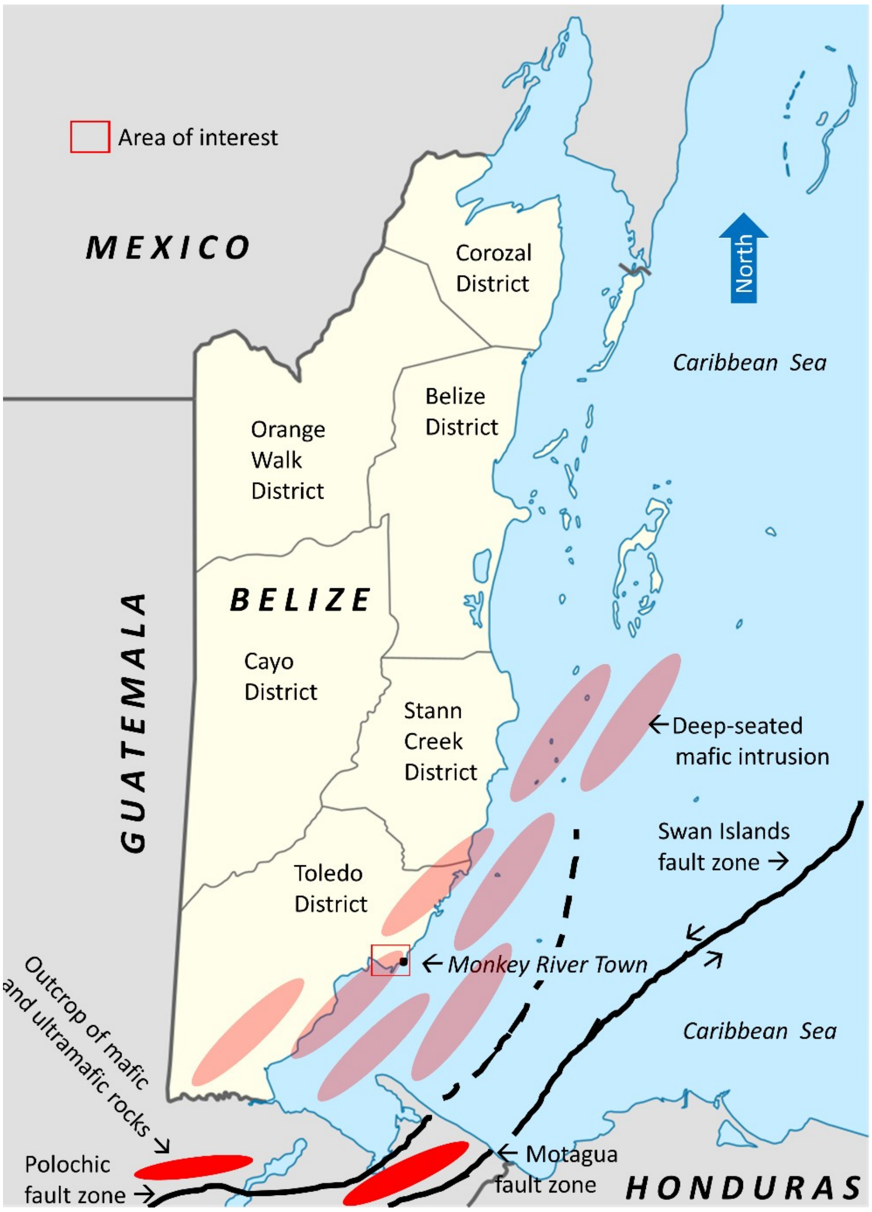

Fig. 8. Generalized map of Belize showing the districts of Belize, and adjoining countries. Also shown are the two fault zones, Polochic and Motagua, both of which occur near the southern border of Belize, and their eastward extension in the Caribbean, the Swan Islands fault zone. Dark red ovals schematically show the general position of mafic and ultramafic intrusive rocks that crop out in the area of the surficial faults zones (Purdy et al., 1975). Pale red ovals schematically show the general position of deep-seated mafic intrusive rock bodies, as inferred by local high gravity values (inferred from Rogers and Mann, 2007). The location of Monkey River Town (shown on Fig. 8) is marked as well. The area of interest (Fig. 8) is in the small red box. North is up.

gas sources may be either from (1) serpentinization of deeply buried mafic or ultramafic rocks bodies, or (2) tectonic boundaries that may provide a pathway for mantle-derived hydrogen to move upward and through the crust. Or, the gas can come from both sources in some instances. None of the examples discussed in this paper illustrates clearly a proposed third means of naturally generating hydrogen gas, namely radiogenic decay processes. In all instances cited, hydrogen gas tends to emerge more at the rims of the SCSDs than in the centers, and the emergence of hydrogen gas varies in quantity and flow rate over time (both short time scales and over long term).

Just because hydrogen gas has been detected flowing from SCSDs does not mean that the area where the SCSDs exist will be productive for hydrogen gas in commercial quantities. For that to be so, hydrogen gas needs to have accumulated over time within subsurface traps, much like methane, for example. Therefore, the existence of potential traps must be established in the area of interest by employing seismic data, whether these are new investigations conducted solely for this purpose or investigations employing the mining of old seismic data from previous non-hydrogen investigations (e.g., hydrocarbon exploration).

The following sequence of events seems most likely for any feasible economic investigation for potential hydrogen production in a given area. First, potential sources for deep-seated hydrogen generation should be identified using new or existing data and there also should be SCSDs in the area directly above these potential sources. Second, potential subsurface traps should be identified using seismic data, and then an exploratory drilling program initiated. From the exploratory drilling, flow rates and quantities of hydrogen can be established, and thus the economic potential of hydrogen gas in the target area can be better understood.

If present in commercially viable quantities, natural hydrogen gas could be a very important non-carbon generating fuel that can be transformative for the energy producing and consuming process within our global society. It is clearly important that natural hydrogen gas is explored and better understood for its future energy potential.

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