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Evaluating The Natural Hydrogen System in Ampana Basin, Central Sulawesi; An Implication for Natural Hydrogen Exploration in Indonesia

Evaluating The Natural Hydrogen System in Ampana Basin, Central Sulawesi; An Implication for Natural Hydrogen Exploration in Indonesia

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Abstract-Serpentinisasi dikenal sebagai salah satu proses geologi yang dapat menghasilkan hidrogen alami. Oleh karena itu, daerah dengan distribusi batuan ultramafik yang mengalami serpentinisasi, seperti lengan timur Pulau Sulawesi, menjadi target menarik untuk eksplorasi hidrogen alami. Penelitian yang bertujuan untuk untuk menentukan keberadaan sistem hidrogen alami di Cekungan Ampana ini dimulai dengan melakukan review literatur yang dilanjutkan dengan investigasi lapangan pada rembesan gas yang dianggap mengandung hidrogen. Sejumlah sampel baik batuan maupun gas diambil untuk dilakukan Analisa laboratorium yang mencakup petrografi, ICP-MS, komposisi gas, serta isotopnya untuk membuktikan keberadaan hidrogen alami di daerah penelitian. Disamping itu interpretasi data seismik dan gravity juga dilakukan untuk mengetahui konfigurasi bawah permukaan. Hasil studi ini memberikan gambaran awal mengenai pembentukan, migrasi, dan akumulasi hidrogen alami di Cekungan Ampana yang ditunjukkan oleh kehadiran sistem hidrogen alami yang mencakup keberadaan bukti permukaan berupa rembesan gas di Tanjung Api dan di Pulodalagan. Kehadiran batuan ultramafik dari Ofiolit Sulawesi Timur yang kaya unsur besi, adanya sesar utama yaitu Sesar Balantak yang dapat mengakomodasi perkolasi air tanah ke dalam batuan maupun sebagai jalur migrasi hidrogen, serta keberadaan sedimen pengisi cekungan sebagai media untuk akumulasi hidrogen. Pelajaran yang diperoleh dari sistem hidrogen alami di Cekungan Ampana ini kemudian digunakan untuk menentukan daerah eksplorasi lainnya di Indonesia.

Kata Kunci: **Tanjung Api, Hidrogen Alami, Ofiolit Sulawesi Timur, Batuan Ultramafik, Serpentinisasi**.

Abstract *Serpentinization is one of the geological processes capable of producing natural hydrogen. Therefore, areas with a large distribution of ultramafic rocks experiencing serpentinization, such as the East Arm of Sulawesi, emerge as attractive targets for natural hydrogen exploration. Research to determine the presence of natural hydrogen systems in the Ampana Basin begins with a literature review followed by geological investigations of hydrogen-bearing seepage. Samples of rocks and gases are collected for laboratory analysis, including petrography, ICP-MS, gas composition, and carbon isotope, to validate the presence of natural hydrogen in the study area. Additionally, gravity and seismic interpretation are conducted to determine subsurface configurations in the research area. The findings of this study provide insights into the generation, migration, and accumulation of natural hydrogen in the Ampana Basin. It is evidenced by the presence of a natural hydrogen system defined by several key elements, including surface manifestations such as gas seepages at Tanjung Api and Pulodalagan. The occurrence of iron-rich ultramafic rocks from the East Sulawesi Ophiolite, the presence of deep-seated faults such as the Balantak Fault that are capable of facilitating deep groundwater percolation in ultramafic bodies or serving as migration pathways, and finally the existence of sediments in the Ampana Basin for hydrogen accumulation. Lessons learned from the natural hydrogen system in the Ampana Basin are subsequently utilized to determine exploration areas in other parts of Indonesia.*

Keywords: ***Tanjung Api, Natural hydrogen, East Sulawesi Ophiolite, Ultramafic rocks, Serpentinization***

INTRODUCTION

Hydrogen has predominantly been produced through manufacturing processes such as steam reforming and coal gasification, resulting in significant carbon dioxide emissions. Additionally, hydrogen generated through electrolysis, known as green hydrogen, is gaining momentum alongside the fast-paced clean energy development. Apart from these manufacturing processes, hydrogen can also be produced through various geological processes called natural or geologic hydrogen. This phenomenon has been demonstrated and observed globally (Figure 1). Some of these processes, capable of generating significant quantities of natural hydrogen are serpentinization (Etiope *et al*, 2017; Neal and Stanger, 1983; Vacquand *et al*., 2018), water radiolysis (Sherwood Lollar *et al*., 1993; Truche *et al*., 2018), alteration of banded iron formation (Geymond *et al*., 2023), and overmature organic matter (Boreham *et al*., 2023).

Hydrogen's small molecular size and high reactivity define its unique properties. It has the lowest density (0.08999 g/L) among all elements and can rapidly scatter or ascend to the upper atmosphere. Nonetheless, hydrogen inherits the highest combustion energy release of any commonly occurring material, rendering it an ideal fuel (Idriss *et al*., 2015). Therefore, hydrogen has previously been overlooked to accumulate naturally and disregarded in oil and gas exploration. However, the discovery of natural hydrogen accumulation in Bourekebogu, Mali (Prinzhofer *et al*., 2018) suggests that hydrogen gas can accumulate under specific geological conditions. This nearly pure hydrogen gas, with a concentration of 98%, was found alongside 1% nitrogen and 1% methane at a depth of 112 meters in Bogou 1 Well, within a limestone reservoir sealed by dolerite. The carbon isotope analysis of Bougou 1 indicates that gas characteristics differ from typical thermogenic or biogenic origins, suggesting an abiogenic genesis. This discovery has shifted previous paradigms and encouraged a "natural hydrogen rush" in various parts of the world, such as the USA (Zgonnik *et al*., 2015), Brazil (Moretti *et al*., 2021), Australia (Boreham *et al*., 2021; Frery *et al*., 2021; Rezaee, 2021), Europe (Lefeuvre te al., 2022), Oman (Templeton *et al*., 2024), and Namibia (Moretti *et al*., 2022). Circular features on the surface, known as fairy circles, mark some of these locations.

Indonesia presents a fascinating research and exploration opportunity for natural hydrogen as it is one of the three countries with the largest distribution of ophiolite rocks, alongside Oman and Papua New Guinea (Kadarusman *et al*., 2004). However, to date, no specific research has addressed the existence of natural hydrogen systems in Indonesia. The research area is located in Ampana Basin, Tojo Una-Una Regency, Central Sulawesi Province (Figure 1) because of the presence of unusual gas seepages containing hydrogen in the Tanjung Api area has been previously documented by Subroto *et al*(2004) and rewritten in the context of the presence of abiogenic hydrocarbon by vanGorsel and Subroto (2022). This paper aims to clarify the presence of natural hydrogen systems in Indonesia, specifically in the Ampana Basin. This discovery is supported by geological data from the surface and subsurface as well as geochemical analysis of gas seepages in the Tanjung Api and Pulodalagan seepages, which serve as surface indications of natural hydrogen systems. This study's findings are expected to encourage the development of natural hydrogen exploration in Indonesia.

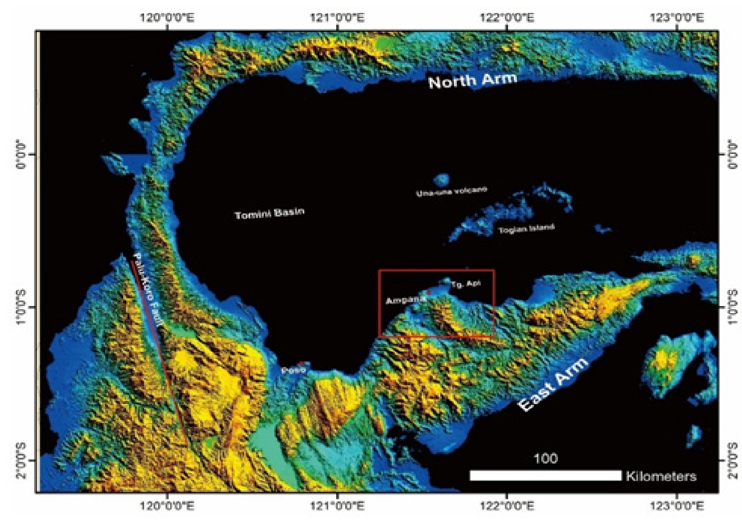

Figure 1. The location of the study area is marked by the red box

METHODS

This study was conducted in a short season of fieldwork by the team of the Center for Geological Survey in July 2023 with various additional references that synthesized natural hydrogen research's state of the art. To identify the suitable locations for gas and rock sampling, satellite image analysis was performed by delineating gas seepage or thermal springs. Laboratory analyses, consisting of gas characterization (e.g., bulk gas composition and stable isotopes) and rock characterization (e.g., petrography and Induced Couple Mass Spectrometry), were executed to gather information on gas generation and water-rock interaction. Additionally, previous seismic data and airborne gravity (@Topex) were analyzed to gain a deeper understanding of structural geology and subsurface architecture. Finally, all these analyses were compiled to explain key elements of the natural hydrogen system within the research area.

BASIC CONCEPT OF NATURAL HYDROGEN

Natural hydrogen system

Natural hydrogen systems share some similarities with conventional petroleum systems, yet fundamental differences exist in their formation and preservation mechanisms (Table 1). Surface indications of this natural hydrogen system are mostly found in areas considered unfavourable for hydrocarbon exploration. Thus, its exploration cannot rely solely on petroleum system knowledge but must also integrate insights from mineral and geothermal exploration.Table 1. Comparison of key elements in natural hydrogen and hydrocarbon systems (Zhao *et al*., 2023).

Table 1. Comparison of key elements in natural hydrogen and hydrocarbon systems (Zhao et al., 2023).

	Hydrogen system	Hydrocarbon system
Source	1. H_2O reduction (e.g. serpentinization)	Pyrolysis of kerogene
	2. Radiolysis	
	3. Pyrolysis of organic matter	
	4. Magma degassing	
	5. Other biotic/abiotic processes	
Migration	Diffusive and advective	Advective
Accumula-tion	1. Structural traps	1. Structural traps
	2. Stratigraphic traps	2. Stratigraphic traps
	3. Absorbed by clay minerals	3. Unconventional
	4. Dynamic	4. Sedimentary rock reservoir and fractured tight rocks
	5. Sedimentary reservoirs and altered igneous rocks	
Preservation	1. Fast seeping rate (104 m^3/day/km^2)	1. Millions of years of preservation
	2. Strong biotic/abiotic consumption	2. Tight seals, including shale, salt, and tight carbonate
	3. Residence time 10-100 years	
	4. Seal rocks include impermeable igneous rocks, salt, tight carbonate and compacted shale	
Location	Sedimentary basins or basement	Sedimentary basins
Burial depth	Near-surface and ultra-deep (core or mantle source)	Above the metamorphic zone

Natural hydrogen generation during the serpentinization

Serpentinization is a low-grade metamorphic when iron-bearing ultramafic rocks (*i.e.*, dunite and peridotite) undergo hydration reactions with water to produce serpentine, magnetite, and hydrogen at temperatures ranging from 200°C to 300°C. It requires iron-rich minerals as reagents to separate the chemical bond of water. It is common for serpentinization to occur at slowly expanding mid-oceanic ridges when mantle rocks ascend and react with seawater. However, various laboratory experiments have demonstrated that serpentinization involves an oxidation reaction of Fe (II) to Fe (III) to reduce water. The process is even observed at lower temperatures below 100°C (Mayhew *et al.*, 2013). Serpentinization also generates hydrogen at temperatures <150°C following the reaction (Oze and Sharma, 2005) as follows:

$$6Fe_2SiO_4 + 7H_2O \rightarrow 3\ Fe_3Si_2O_5\ (OH_2 + Fe_3O_4 + H_2$$

(Fayalite) (water) (Fe-Chrysotile) (Magnetite) (dihydrogen)

Several natural hydrogen seepages in various countries are situated within ophiolite belts, such as New Caledonia, the Philippines, Oman, and Turkey (Figure 2). These seeps are associated with serpentinization in subduction, obduction, and collision tectonic settings (Vacquand *et al.*, 2018). High intensity of tectonic activity leads to intense fracturing of rocks. It increases hydraulic conductivity and accommodates groundwater percolation into the deep ultramafic body, promoting the rock-water interaction. Hydrogen can migrate in the fault zone either as a gas phase or dissolved gas in groundwater from the serpentinization zone to other unsaturated rocks (Figure 3). Manifestations of H_2 are normally associated with abiogenic methane and emerge to the surface as hyper alkaline springs, as observed in Oman (Neal and Stanger, 1983), or as gas seeps, as seen in Los Fuegos Eternos (Abrajano *et al.*, 1988) and Chimaera Flame (Etiope *et al.*, 2011).

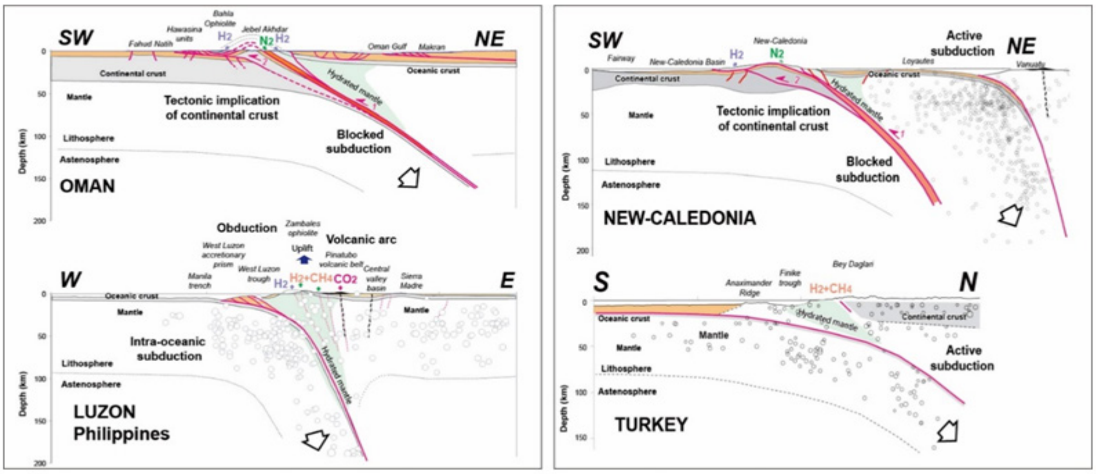

Figure 2. Geological setting of natural hydrogen seeps in Oman, Philippines, New Caledonia, and Turkey (Vacquand *et al.*, 2018).

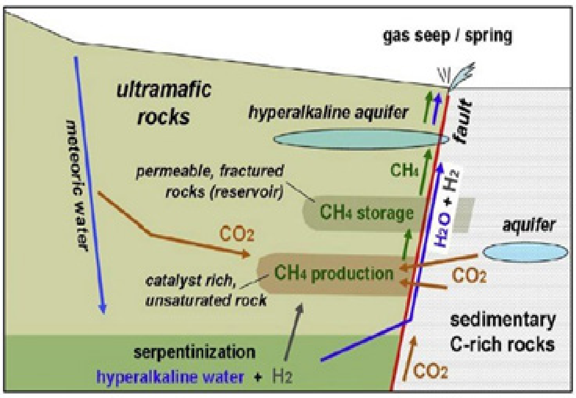

Figure 3. Schematic model of hydrogen and abiotic methane generation by serpentinization (Etiope *et al.*, 2017)

GEOLOGICAL SETTING

Stratigraphy

Stratigraphy of the research area comprises the Cretaceous Ultramafic Complex, the Eocene-Miocene Carbonate Salodik Formation, the Mio-Pliocene Bongka Formation, Quaternary Limestone, and superficial deposits as shown in Figure 4 (Rusmana *et al*., 1993). The ultramafic complex in this region is part of the East Sulawesi Ophiolite (ESO), extending from Central Sulawesi to the East and Southeast arms. ESO represents a tectonically dismembered ophiolite lithology, consisting primarily of residual mantle peridotite with mafic-ultramafic accumulations through layered, isotropic gabbro, sheeted dolerites, and basaltic volcanic rocks of mid-oceanic-ridge composition. Although the ESO displays a complete ophiolite sequence, the main constituents are ultramafic rocks composed of layered harzburgite, lherzolite, and dunite with varying degrees of serpentinization (Kadarusman *et al*.,2004; Parkinson, 1998).

The Eocene to Early Miocene carbonates of the Salodik Group represent the Cenozoic sediments of the Sula micro-continent, comprising three sedimentary facies, namely *Nummulitic* grainstone-rudstone, grainstone intercalated with calcareous sandstone, and rudstone intercalated with reefal limestone deposited in a reefal to the shallow marine environment (Husein *et al*., 2014). The Bongka Formation is part of the Celebes Molasse, consisting of terrestrial, marginal marine, and shallow marine deposits. This formation can be divided into three members: Member A, the lower carbonate unit; Member B, the middle unit, which is a well-consolidated ultramafic-rich siliciclastic unit; and Member C, the uppermost part consisting of ophiolite-rich siliciclastic materials that are not fully consolidated (Nugraha *et al*., 2022). Overlying the Bongka Formation is the Quaternary limestone, consisting of three facies: limestone breccias, limestone conglomerates, and rudstones deposited in a shallow platform environment.

Structural Geology

The Ampana Basin is typically a "fore-arc" basin which is, tectonically part of the collision belt of the Banggai-Sula microcontinent, originating from western Papua (Watkinson *et al*., 2011), and the Cretaceous East Sulawesi Ophiolite, originating from the mid-oceanic ridge and oceanic plateau of the Pacific Plate (Kadarusman *et al*., 2004). The Ampana basin is considered a tertiary basin formed after the collision; hence, the basin was filled by molasse sediments in response to this collision tectonics. Similarly, strike-slip faults emerge ahead of the collision zone (Figure 4) in the East Arm region, including the Balantak, Toili, Ampana, and Wekuli Faults (Simandjuntak, 1993)

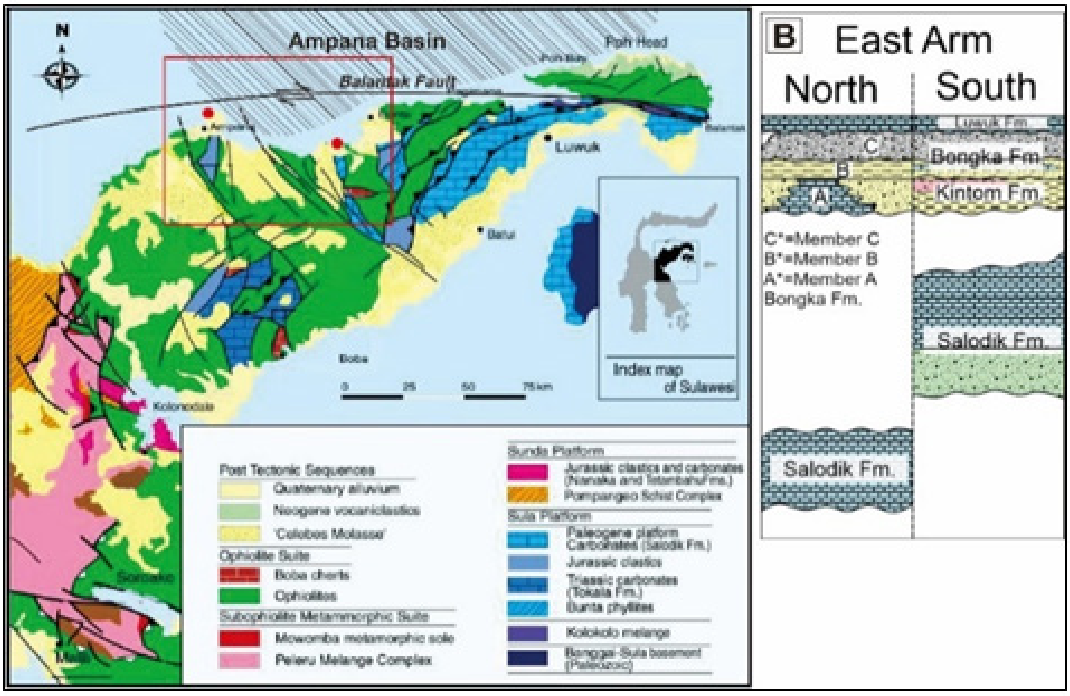

Figure 4. Simplified geological map of East Sulawesi Ophiolite (modified after Kadarusman et al., 2004; Parkinson, 1998), with Balantak Fault (Simandjuntak, 1993), and the Stratigraphy of the east arm of Sulawesi (Nugraha et al., 2022). The red box indicates the study area, and the red circle shows the location of Tanjung Api Eternal Flame and Pulodalagan Spring.

RESULTS AND DISCUSSIONS

Natural Hydrogen System in Tanjung Api

The Ampana Basin is an enigmatic basin with an area of 2,266 square km offshore. This area was previously targeted for hydrocarbon exploration due to the occurrence of sedimentary basins and gas seepages. However, the absence of a complete petroleum system, primarily the scarcity of prominent source rocks, made it an inconclusive result and the basin is less favourable for conventional oil and gas exploration. Adopting the natural hydrogen concept and abiogenic methane formation addresses the issues related to source rocks, as this region has a bulk of ultramafic basement rock. Accordingly serves as a source for natural hydrogen and abiogenic methane.

Building upon the conceptual framework of hydrocarbon exploration, the natural hydrogen system can be bordered by three fundamental processes such as a conventional petroleum system: generation, migration, and accumulation. Herein, we present the key elements of the natural hydrogen system in the Ampana Basin. Our discourse is based on evidence derived from fieldwork, laboratory analyses, and subsurface data interpretation.

1. Surface Indicator

Fieldwork was conducted in the research area, including finding the gas seepage locality and visual observation. We visited Two gas seepages along the southern edge of the Ampana Basin: Tanjung Api and Pulodalagan (Figure 5a). Table 2 gives the bulk gas composition and isotopes from these seepages.

a. Tanjung Api Seeps

Gas seepage is located in the fault contact between peridotite and Quaternary limestone, as confirmed by the presence of fault breccia composed mainly of peridotite and serpentinite fragments. Gas is emitted rapidly 650 meters along the coastline from rock fractures (Fig 5b) and bubbling beneath the sea surface (Fig 5c). The gas burning throughout the year resembles that found in Los Fuegos Eternos (Abrajano *et al*., 1988) and Chimaera Flame (Etiope *et al*., 2011). The presence of gas seepage in the Tanjung Api region, which produces eternal flames, has been documented since the late 18th century, during the Dutch colonial era (van Gorsel and Subroto, 2022). The seepages affected the surrounding soils, showing an unusual temperature of around 50-60^{0}C; surprisingly, the vegetation still exists and is fertile.

b. Pulodalagan spring

Pulodalagan Spring is an alkali thermal spring with a pH of 9 and a temperature of 38^{0}C. It is surrounded by Quarternary limestone, and several gas-bubbling points periodically emerge from the spring indicating a relatively low pressure and flow rate (Fig 5d). The soil temperature is assumed to be unaffected by seepage, and mangroves dominate the natural vegetation. Travertine deposits were observed surrounding the thermal spring.

The gas samples from the Tanjung Api seepage contain a mixture of hydrocarbon and non-hydrocarbon gases, including oxygen, nitrogen, carbon dioxide, hydrogen, and methane. There are noticeable variations in the composition of these gases across the samples. Oxygen content ranges from approximately 3.03% to 7.42%, while nitrogen varies from 3.82% to 29.60%. Carbon dioxide remains constant at very low percentages, typically around 0.03% to 0.04%, in contrast with the significant presence of methane across all samples, ranging from 32.02% to 47.00%. However, the most striking observation is the remarkable variance in hydrogen gas, which varies from approximately 20% to over 35%. This result validates the presence of natural hydrogen in the Tanjung Api seepage. It is relatively similar to the analysis by Subroto *et al*., (2004), which reported a hydrogen content of 16.3%. Conversely, the gas sample from Pulodalagan Spring does not show any hydrogen concentration. A high methane content (46,86%) was also identified, along with nitrogen (46,88%), oxygen (5,64%), and a lower amount of carbon dioxide (0,02%).

The $\delta^{13}C$ values of CH_4 from the Tanjung Api and Pulodalagan gas samples are 15.6‰ and 12.3‰, respectively, while the carbon isotopes of ethane are 18.9‰ and 18.3‰. These isotope values are relatively heavy and differ from those found in biogenic and thermogenic gases, which tend to exhibit lighter values. To explain the origin of methane in both seepages, the results are plotted in the diagram of Milkov and Etiope (2018) , indicating that the methane gases in both seepages are believed to be formed by abiogenic processes (Figure 6). Due to the absence of organic-rich sediment or rocks with high radioactive content in this area, it can be determined that the methane originates from abiogenic processes related to serpentinization. Methane was generated through the Sabatier process, where carbon dioxide (CO_2) reacts with hydrogen (H_2) sourced from serpentinization. This reaction is a key process for methane generation without biological involvement, which usually occurs at low temperatures below 150°C (Etiope *et al*., 2017) by the following reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

(Carbon Dioxide) + (Hydrogen) → (Methane) + (Water)

Table 2. Gas and isotope composition from several sampling locations in Tanjung Api and Pulodalagan seepages.

Sample	Type	% Mol							Wetness	C1	δ13C		
		O2	N2	CO2	H2	C1	C2	C3	(%)	(C2+C3)	C1	C2	C3
23IDS02	Gas Seep	6.57	26.28	0.03	35.04	32.02	0.06	0	0.2	533.67	-15.2	-18.9	-20.9
23IDS02B	Gas Seep	3.03	13.82	0.03	35.56	47	0.5	0	1.1	94			
23IDS03	Gas Seep	5.85	24.21	0.04	30.81	38.74	0.3	0.05	0.9	110.69			
23IDS04	Gas Seep	6.41	26.79	0.03	25.86	40.57	0.3	0.04	0.8	119.32			
23IDS06	Gas Seep	7.42	29.6	0.03	20.01	42.4	0.49	0.05	1.3	78.52			
23ML06	Thermal spring	5.64	46.88	0.02	0	46.86	0.6	0	1.3	78.1	-12.3	-18.3	-22.1

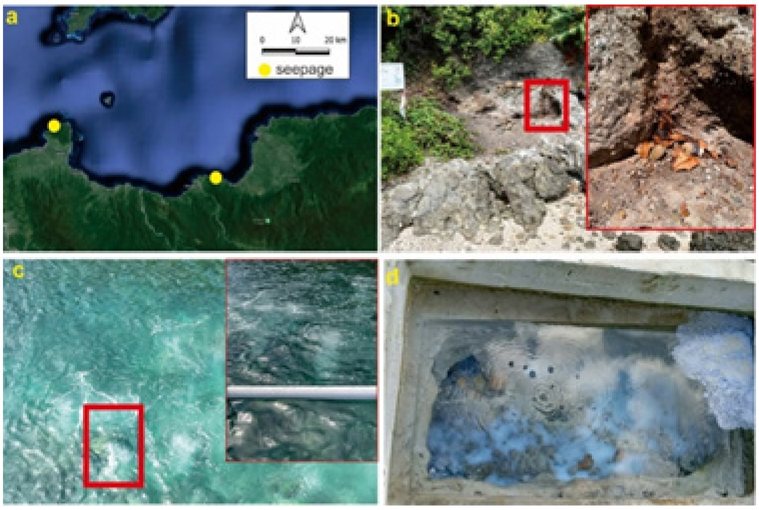

Figure 5. a).Map showing seepages and gas sampling location. Field photograph of seepages in the Ampana area. b) Flammable gas seepage arises from rock fracture in Tanjung Api. b) Submarine gas seepages located around 100 meters from the Tanjung api seepage. c) Gas bubble in Pulodalagan hot spring.

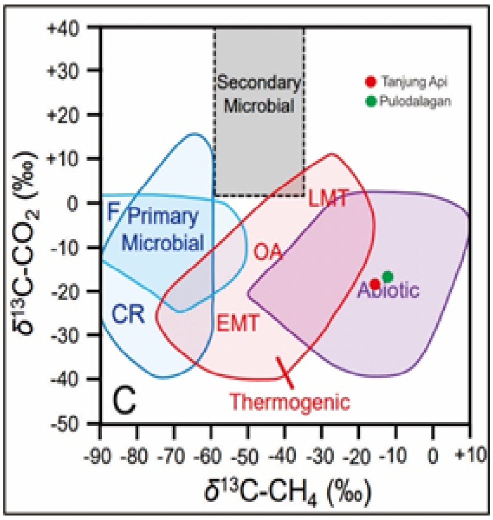

Figure 6. The revised "Bernard plot" after Milkov and Etiope (2018) of $\delta^{13}C$ of methane from Tanjung Api and Pulodalagan seepages to identify natural gas genetic types (F = methyl-type fermentation; SM = secondary microbial; CR=CO 2 reduction; EMT = early mature thermogenic gas; OA = oil-associated thermogenic gas; LMT = late mature thermogenic gas)

Top of Form

2. Iron-rich Basement

It is important to define the processes that generate hydrogen before delineating a target location for hydrogen exploration. In this area, the Serpentinization of ultramafic rocks is deduced as the primary process to generate hydrogen. Therefore, iron-rich rocks such as dunite and peridotite are crucial to the natural hydrogen system. Based on the fieldwork data, the coastline of Ampana Basin is composed mainly of ultramafic rock, which experienced various degrees of serpentinization (Figure 7a). The petrography analysis provides information related to mineral content and paragenesis on samples. Based on petrography analysis, the rock sample collected surrounding the Tanjung Api seepage is high-serpentinized harzburgite (Figure 7b & 7c). Orthopyroxene porphyroblasts occurred as relict grains due to serpentinization. At the same time, olivine in the matrix was strongly serpentinized, forming a mesh texture. Serpentine and magnetite minerals marked previous water-rock interactions to generate hydrogen.

The analysis conducted using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) also supports the hypothesis that the serpentinization of ultramafic rocks in this area has generated natural hydrogen. This is evidenced by low radioactive elements such as Uranium (U) and Thorium (Th) in basement rock. Table 3 shows U and Th content of around 0,035 and 0,10 respectively, whilst this value is too low for triggering water radiolysis compared to the rock from the continental crust, such as granite.

3. Deep-Seated Fault

Field observations prove extensive tectonic activity from the ultramafic basement to the Quaternary sediment. High-angle joints are recorded in Quaternary limestone (Figure 8a). This area has experienced four episodes of uplifting during the Quaternary, as indicated by marine terrace deposits (Figure 8b). Similar to younger rocks, the oldest rocks in this basin have experienced several tectonic episodes, as evidenced by the occurrence of macro and micro-scale jointing and faulting (Figure 8c).

Seismic data by Fugro Data Service 2006 were interpreted to obtain subsurface architecture in the Ampana Basin. The Balantak Fault's existence has been validated through seismic analysis. The north-south seismic profile reveals that the fault system is penetrated through the basement (Figure 9). Conspicuously, this fault is considered active, evidenced by its trace within the youngest sediment layers, specifically the Quaternary sediment. This result is relevant to the regional model in the North Perth Basin by Frery *et al*. (2021), which states that hydrogen can migrate vertically in the gas phase through the main faults in the basin, namely the Darling Fault, which extends down to the basement. It is possible that the fault zones serve as conduits and may also result from diagenetic changes in porosity and permeability induced by highly chemically reactive gases such as hydrogen (Zgonnik, 2020). On the other hand, deep-seated faults also increase secondary porosity and permeability in ultramafic rocks, which have inherently low initial porosity and permeability. Therefore, the presence of these major and deep structures promotes the water-rock interaction, resulting in hydrogen generation through serpentinization processes.

Table 3. Geochemical results of ICP-MS of ultramafic rock from the Tanjung Api area

No	Elements	Concentration (ppm)		No	Elements	Concentration (ppm)
1	Li	1.35		16	Nd	0.23
2	Sc	7.73		17	Sm	0.057
3	V	146.18		18	Eu	0.012
4	Ga	0.81		19	Gd	0.046
5	Rb	1.40		20	Tb	0.0076
6	Sr	12.06		21	Dy	0.048
7	Y	0.37		22	Ho	0.012
8	Nb	0.42		23	Er	0.037
9	Mo	1.44		24	Tm	0.007
10	In	0.25		25	Yb	0.048
11	Cs	0.30		26	Lu	0.0086
12	Ba	16.06		27	Ta	0.66
13	La	0.29		28	Pb	1
14	Ce	0.61		29	Th	0.1
15	Pr	0.072		30	U	0.034

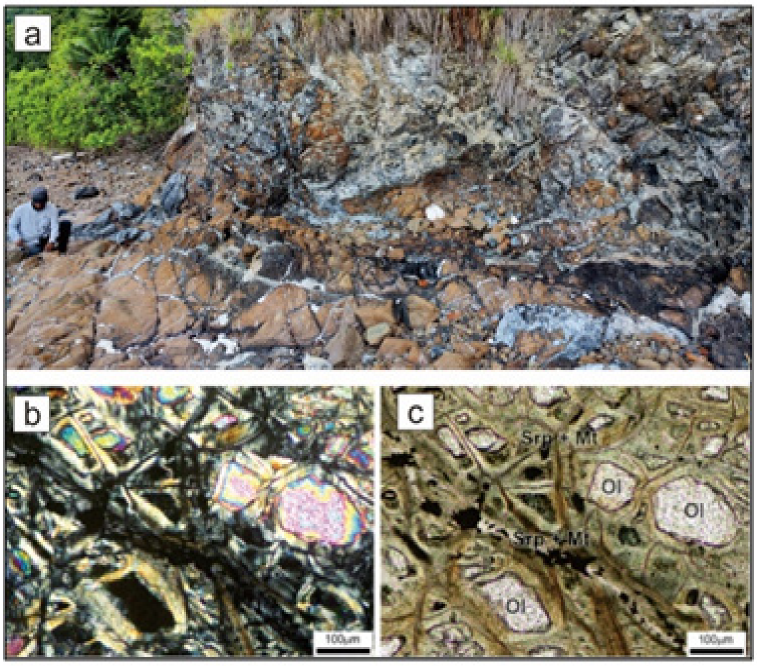

Figure 7. Field photograph and photomicrograph of highly serpentinized harzburgite from Tanjung Api. Olivin shows mesh texture, serpentine, and magnetite, indicating the serpentinization process. a) The outcrop of peridotite in the Tanjung Api coastline; b) cross-polarization; c) parallel polarization.

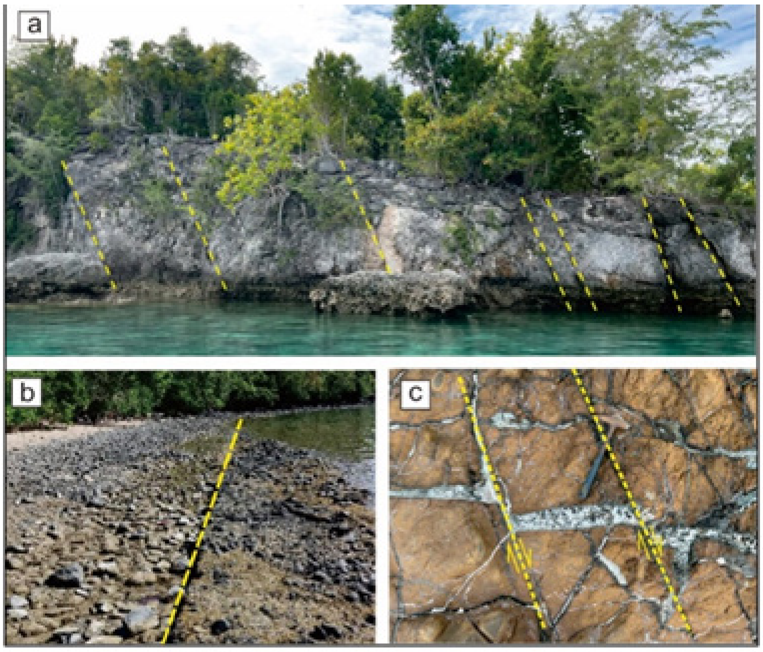

Figure 8. Field photographs of outcrops along the Ampana Coastline show a deformation history in this area. a) High-angle joints in Quaternary Limestone. b) Fracture in Holocene marine terrace deposits. c) Minor displacement of micro-fault in peridotite.

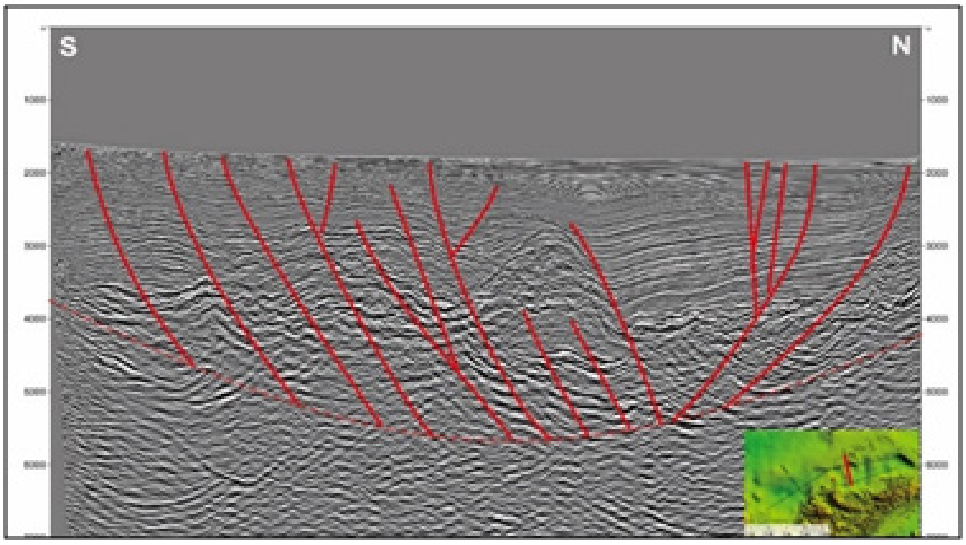

Figure 9. The structural configuration of Ampana Basin is based on seismic interpretation. Tanjung Api seepage is located 20 km west of the seismic line.

4. Sedimentary Basin

Hydrogen is expected to migrate and accumulate in sedimentary rocks in the same way as hydrocarbon gases. However, due to hydrogen mobility, an important role of the basin is that the sediments may act as a medium to slow down and accumulate hydrogen migration from the source to the atmosphere. Gravity data analyses utilizing airborne gravity (@ Topex) are conducted to determine potential basins in this region. It has been confirmed that the Ampana Basin is indeed a sedimentary basin filled with thick sediment sequences, and several major faults were also identified on the gravity map (Figure 10).

Based on seismic interpretation (Figure 11), the Ampana Basin shows sediment accumulation of considerable thickness, approximately 2000 – 2500 m/s TWT. Due to the absence of drilling data in this area, This analysis attempted to employ analogies from fieldwork results. The Ampana Basin is estimated to be filled with three sedimentary units: Unit A, Unit B, and Unit C. Unit A consists of sedimentary rocks equivalent to Salodik limestone, specifically divided into sub-units of carbonate buildup and limestone. Unit B comprises sedimentary rocks equivalent to the lower and middle parts of the Bongka Formation, while Unit C is considered equivalent to the upper part of the Bongka Formation. Unfortunately, these studies have not yet progressed to analyzing potential reservoir and seal rocks. Undoubtedly, further profound investigation into the basin dynamics and the specific characteristics of each rock unit must be conducted shortly.

Future Target for Natural Hydrogen Exploration

Hydrogen emissions from sedimentary basins have been detected in various regions worldwide. Surface manifestations known as "fairy circles" have been identified as hydrogen leakage from the subsurface (Frery *et al*., 2021; Moretti *et al*., 2021, 2022; Prinzhofer *et al*., 2018). However, what has been found in the Ampana Basin area differs from other areas. Surface indications of natural hydrogen do not resemble fairy circles but appear as igniting gas seepages. To localize surface hydrogen seepages in another area in Indonesia, it would be attempted to apply different parameters, including gas seepages and hyper alkaline springs located in ultramafic rocks or adjacent to the major faults. Searching prospect locations using these parameters yielded satisfactory results, as another hydrogen gas seepage was discovered in the One Pute Jaya area of Morowali Regency. This gas seepage is associated with hyper alkaline springs with a pH of 12.5 and a temperature of 39^{0}C. Additionally, we suspect a strong relationship between active faults and the occurrences of hydrogen-bearing seepages, as the Tanjung Api and One Pute Jaya are located within the Balantak and Matano fault zones, respectively. These faults are active, indicated by high seismic activity compared to those adjacent to the East Sulawesi Ophiolite, *i.e*., Kolaka Fault, Lawanopo Fault, and Matarombeo Fault. It might be assumed that the fault movement ruptures in the ultramafic rocks along the fault zone, creating new fresh surfaces for water-rock interactions.

Drawing for our research outcome in the Ampana Basin, we proposed further study in several locations in Indonesia with similar geological conditions for natural hydrogen exploration. These locations possess key parameters for natural hydrogen systems generated by the serpentinization of ultramafic rocks, including iron-rich basements, major faults, and sedimentary basins. Identifying surface manifestations of natural hydrogen to determine the prospect area's suitability for further exploration is important. Determining these surface manifestations is not limited to detecting the hydrogen gas seeps; it can also be achieved through a surface gas emission survey (Dugamin *et al*., 2019; Lévy *et al*., 2023; Rigollet *et al*., 2023).

The following are the recommended prospect locations defined by drawing comparisons to hydrogen systems discovered in the Ampana Basin. Almost all target locations are in the Eastern Indonesia Collision Zone which is associated with the Sorong Fault Zone (Figure 12). These potential areas offer opportunities for advancing the near future exploration of natural hydrogen in Indonesia.

1. East Sulawesi Ophiolite
2. Meratus Ophiolite
3. East Halmahera Ophiolite
4. Gag Ophiolite
5. Central Papua Ophiolite

The occurrence of hydrogen-bearing gas seepage in these regions remains unreported. Consequently, the utilization of remote sensing techniques and comprehensive literature reviews may be occupied as an initial approach to asses the prospect areas.

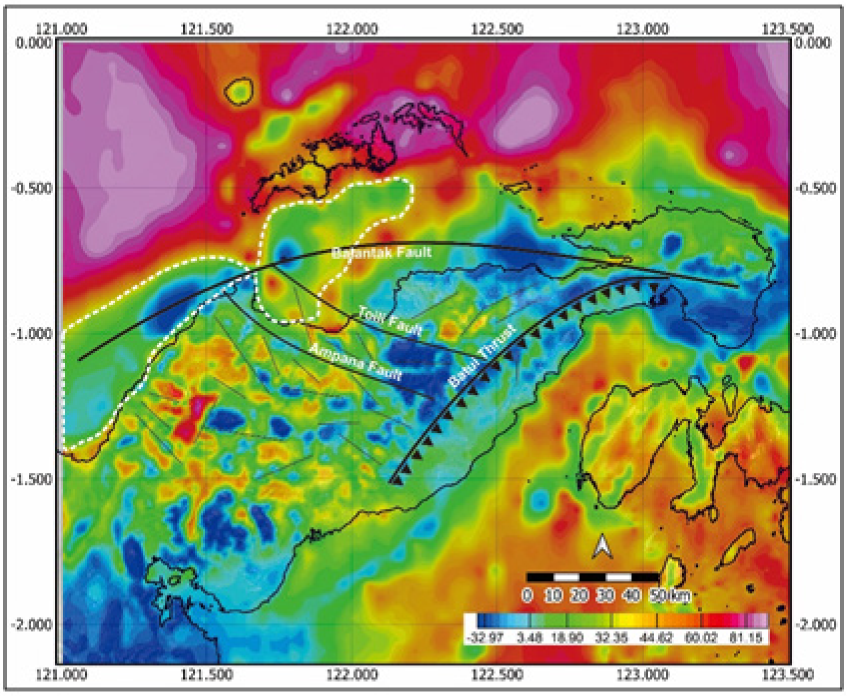

Figure 10. The complex bouger anomaly map from airborne gravity data (@ Topex) indicates the sedimentary basin in this area.

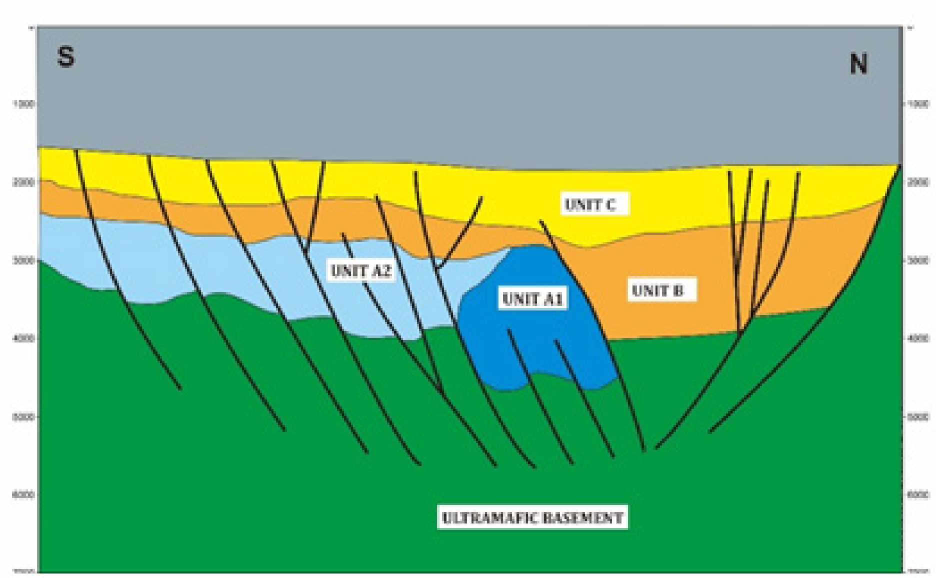

Figure 11. The North-South cross-section of the Ampana Basin is showing a very preliminary natural hydrogen play based on seismic data. The sedimentary units are assumed to be equivalent to rocks around the Ampana Basin.

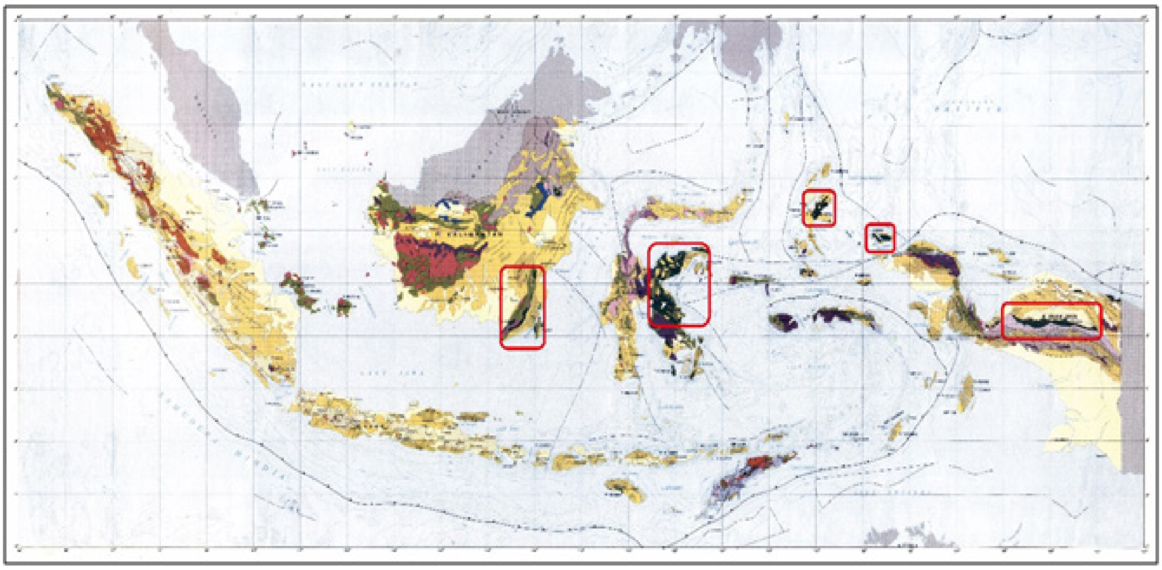

Figure 12. Natural hydrogen prospect location in Indonesia, modified after Sukamto *et al* (2011). The red boxes mark the distribution of natural hydrogen prospect areas.

CONCLUSION

This research proves the natural hydrogen systems present in the Ampana Basin of Indonesia. Through comprehensive fieldwork, laboratory analyses, and data interpretation, the key components of the natural hydrogen system in the Ampana Basin have preliminarily been published. Surface indicators, such as gas seepages in the Tanjung Api and Pulodalagan, confirm the presence of hydrogen alongside abiogenic methane and other gases. The petrographic analysis highlights serpentinization processes in the iron-rich basement, solidifying its role as a hydrogen-generation rock. Seismic interpretation reveals the presence of deep-seated and active faults corresponding to the Balantak Fault, facilitating hydrogen migration and generation through water-rock interaction. Moreover, the Ampana Basin is a sedimentary basin filled with considerable sediment thickness, providing a medium for the natural hydrogen system. Based on these conclusions, potential target areas for future natural hydrogen exploration in Indonesia are proposed, focusing on regions with similar geological characteristics as TheAmpana Basin, *i.e*., East Sulawesi Ophiolite, Meratus Ophiolite, East Halmahera Ophiolite, Gag Ophiolite, and Central Papua Ophiolite.

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