



RESEARCH ARTICLE

Identification of Natural Hydrogen Sources from Geochemical Study in Tanjung Api Area, Central Sulawesi, Indonesia: Analysis from Open Dataset and Future Prospects

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Abstract

In the effort to develop environmentally friendly energy, natural H₂ plays a major role due to its large source originating from the Earth's mantle. Therefore, studies on the analysis of the origin of H₂ are crucial. The study in this paper aims to provide additional analysis on the origin of H₂ in gas samples from the Tanjung Api area, Ampapa Basin, Central Sulawesi, Indonesia. This study discusses geochemical analysis and its correlation with the source of H₂. Laboratory tests of gases such as H₂, CH₄ and $\delta^{13}\text{C}_1$ isotopes were used to predict the origin of H₂. The results of these laboratory tests were compared with results from various H₂ source locations from around the world to support and strengthen predictions regarding H₂ sources in this study area. The results of this study show an H₂ concentration value of 35%, $\delta^{13}\text{C}_1$ value of -15.2 ‰ and $\ln(\text{CH}_4/\text{H}_2)$ with a value of -0.0901 correlated with the type of abiogenic gas that is very likely derived from serpentinization reactions in ultramafic rocks in the East Sulawesi Ophiolite (ESO) system. According to the result of this study, future studies are expected to map locations where H₂ gas accumulates in reservoir rocks in the Ampapa Basin. This can be achieved through more comprehensive geophysical (e.g. seismic, magnetic, and/or gravity) and geological studies. Through this study, it is expected that it can contribute to further research and development of natural H₂ energy in Indonesia.

Keywords: Hydrogen, H₂, geochemical, CH₄, Ampapa Basin, Sulawesi

1. Introduction

Nations all over the world are establishing carbon peak and carbon neutrality targets to lower carbon emissions into the atmosphere due to the significance of environmental and energy concerns. One energy source considered environmentally friendly is hydrogen gas (green energy). Natural hydrogen gas (H₂) is considered a clean energy source, whether it is "gold" hydrogen or "white" hydrogen. The discovery of natural hydrogen reserves could be a strategic discovery to meet the global demand for hydrogen energy.

Nowadays, hydrogen has been found in various complex geological setting and environments (Wang et al., 2023; Jackson et al., 2024; Epelle et al., 2022). However, the question of where hydrogen originates remains a mystery and a challenge for geoscientists. Hydrogen sources are usually related to the geochemical properties of naturally occurring hydrogen gas found in each location. Gas geochemistry has been used in a number of investigations to identify natural hydrogen sources, such as organic matter processes, serpentinization, radiolytic decomposition of water (H₂O), and mantle volatiles (Wang et al., 2023; Klein et al., 2020; Liu et al., 2024; Echavez et al., 2025).

Because of their interconnection, the sources of helium (He) and methane (CH₄) can be linked to the source of H₂. In geological formations, methane is typically classified as either biogenic or abiogenic. Heavy carbon isotopes with $\delta^{13}\text{C}_1$ values larger than -20 ‰ are commonly found in abiogenic CH₄ gas. In contrast, biogenic CH₄ gas produced from organic matter usually results in $\delta^{13}\text{C}_1$ values between -55 ‰ and -30 ‰ for

thermogenic gas and less than -55 ‰ for bacterial gas (Babushkina et al., 2018; Holm et al., 2015). Based on this description, the gases CH₄, He, H₂, and the isotope $\delta^{13}\text{C}_1$ can be indicators to predict the source of natural H₂.

Indonesia, as an archipelagic country located in a plate subduction zone and with several ophiolite and ultramafic rock areas, may have natural H₂ sources. One of which has been proven is the H₂ manifestation (gas seeps) in the Tanjung Api Area, Ampapa Basin, Central Sulawesi (Satyana, 2024; Faturrahman et al., 2025). Other study has also reported that there are manifestations of H₂ gas seeps around Tomini Bay, East Sulawesi (van Gorsel and Subroto, 2022). Therefore, this study aims to add information and validation related to the natural H₂ source in the Ampapa Basin using geochemical data (i.e. CH₄, H₂, and the isotope $\delta^{13}\text{C}_1$). Through this study, it is hoped that it can increase understanding of the H₂ source in the Ampapa Basin and can serve as a preliminary result for further studies related to reservoir rocks and cap rocks in this area.

2. Geological and tectonic setting

A complex combination of geological systems consisting of sedimentary basins, metamorphic rocks, ophiolite terranes, volcanic arcs and granitoid belts forming up Sulawesi Island's four arms—which resemble a K and converge in the center—represents a complicated history of subduction, accretion, ophiolite obduction, and collision (Fig. 1) (adapted from Maulana et al., 2015). One area with natural hydrogen potential in Indonesia is Tanjung Api, Ampapa Basin, Central Sulawesi.

Geologically, Ampana Basin is part of the East Sulawesi Ophiolite (ESO), one of the three largest ophiolites on Earth, which covers over 10,000 km² (Zhang et al., 2020). Hydrogen potential in this area is characterized by ultramafic rocks, deep active faults, and manifestations of natural hydrogen seepage (Sanjaya et al., 2024). The lithological description in the research area consists of Cretaceous ultramafic rocks, Miocene sediments, Quaternary limestones, and surface deposits (Sanjaya et al., 2024).

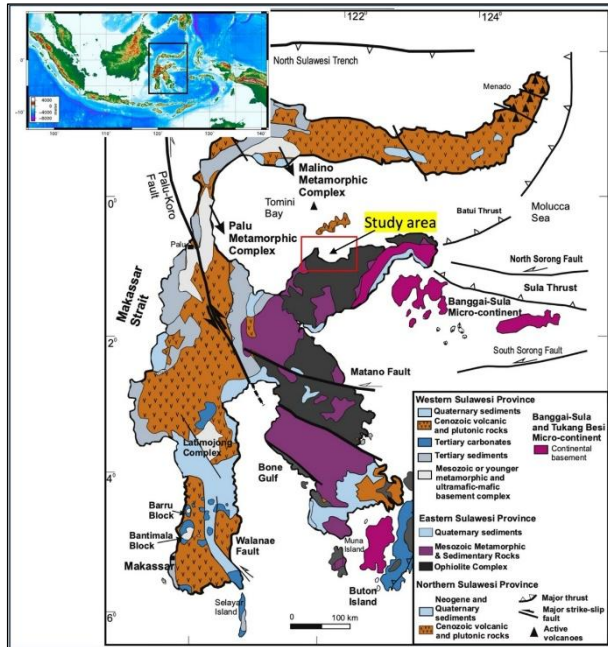


Fig 1. Tectonic framework and geological setting of Sulawesi Island. The study area is in the Tanjung Api area, Ampana Basin, Central Sulawesi (red box) (adapted from Maulana et al., 2015).

The tectonic conditions of Sulawesi Island and its surroundings are part of the collision of active tectonic plates in eastern Indonesia, namely the Pacific Plate, the Indo-Australian Plate, and the Euro-Asian Continental Plate (Maulana et al., 2015; van Leeuwen et al., 2010). These tectonic conditions demonstrate a unique mechanism in Central Sulawesi, indicating that the Indian-Australian Micro-Oceanic Plate (Banggai-Sula block) is subducted from the east beneath the Euro-Asian Continental Plate on the eastern side of Kalimantan Island.

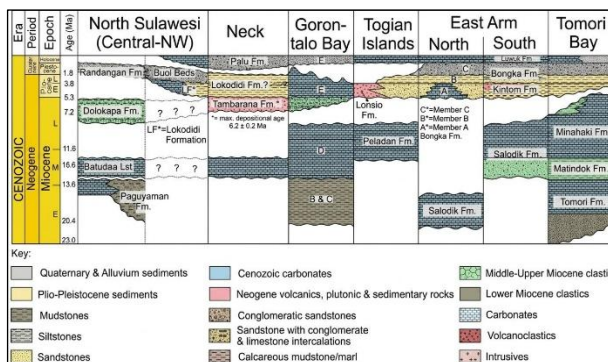


Fig 2. Simplification of the stratigraphic setting in the Tanjung Api Region (adapted from Nugraha et al., 2022.)

In Fig. 2 (adapted from Nugraha et al., 2022), The Cretaceous Ultramafic Complex, the Eocene–Miocene Salodik Formation, the Mio–Pliocene Bongka Formation and Quaternary limestone comprise some of the rock units forming up the Ampana Basin (Advokaat et al., 2015; 2017). After the

Banggai-Sula Microcontinent and the Cretaceous East Sulawesi Ophiolite collided, molasse sediments filled the Ampana basin, which is considered to be a Tertiary basin (Sanjaya et al., 2024; van Leeuwen et al., 2010). Its structural development is further controlled by a series of strike-slip faults, including the Balantak, Toili, Ampana, and Wekuli Faults, which emerged ahead of the collision zone in the East Arm region (Sanjaya et al., 2024).

The oldest unit at this site is thought to be the Cretaceous Ultramafic Complex, part of the East Sulawesi Ophiolite (ESO), which represents a tectonically fractured ophiolite sequence. The primary components of this unit are ultramafic rocks composed of layered harzburgite, lherzolite, and dunite with different levels of serpentinization (Advokaat et al., 2015; 2017; van Leeuwen et al., 2010). The Salodik Formation, which is formed up of carbonates from the Eocene to the Early Miocene that represent Cenozoic deposits from the Sula Microcontinent, occurs on top of this basement layer. Three sedimentary facies make up this formation: rudstone interbedded with reef limestone, grainstone interbedded with calcareous sandstone, and nummulitic grainstone-rudstone. These sedimentary facies were all deposited in shallow marine habitats, such as coral reefs (Husein et al., 2014, in Sanjaya et al., 2024). The Bongka Formation, which is composed of terrestrial, marginal marine, and shallow marine deposits, is a stratigraphic component of the Celebes Molasse. Member A is the bottom carbonate unit; Member B is the intermediate, well-consolidated, ultramafic-rich siliciclastic unit; and Member C is the top, partially consolidated siliciclastic materials rich in ophiolite (Nugraha et al., 2022, in Sanjaya et al., 2024). The youngest surficial unit, Quaternary Limestone, records an ongoing deformation history expressed as high-angle joints and fractures in Holocene marine terrace deposits along the Ampana coastline (Sanjaya et al., 2024).

In terms of age, the Ultramafic Complex is of Cretaceous age, forming the pre-Tertiary basement of the basin (Sanjaya et al., 2024). The Salodik Formation ranges from Eocene to Early Miocene, with its age more specifically constrained in the Poh–Pagimana area from Early Eocene to Middle Miocene based on planktonic foraminiferal assemblages including *Morozovella aragonensis*, *Morozovella lehneri*, *Paragloborotalia peripheroacuta*, and *Paragloborotalia peripheroronda* (Fakhrudin and Kurniadi, 2019). The Bongka Formation, based on recent revision by Nugraha et al. (2022), ranges from Late Pliocene to Pleistocene, unconformably overlying the Early Pliocene Kintom Formation. Overall, the tectonic development of the basin spanning from the Middle Miocene to Holocene is recorded across the Lonsio, Bongka, and limestone units, with the principal regional stress oriented in a predominantly west–east direction (Saragih et al., 2018).

3. Data and Method

The data used in this study comes from previous research (Sanjaya et al., 2024). The study involved gas (i.e. bulk gas composition and stable isotopes) and rock parameters (petrography and Induced Couple Mass Spectrometry) sampling around the Tanjung Api area, Ampana Basin, Central Sulawesi. Previous petrographic study (Sanjaya et al., 2024) of ultramafic rocks in the Tanjung Api area indicate that the basement is dominated by intensely serpentinized harzburgite, characterized by relict orthopyroxene porphyroblasts, extensively serpentinized olivine, and abundant serpentine and magnetite minerals formed during water-rock interaction. These petrographic characteristics indicate an advanced stage of serpentinization, confirming that the iron-rich ultramafic rocks have undergone hydration reactions capable of generating molecular hydrogen. The presence of serpentine and magnetite as alteration products provides mineralogical evidence of

hydrogen generation via serpentinization and supports the interpretation that the ultramafic basement acts as the primary source of hydrogen in the Ampapa Basin. Laboratory analysis was then conducted to determine the chemical compounds of the collected gas samples for geochemical analysis. In this paper, we used two data i.e. H_2 gas concentration is 35% and $\delta^{13}C_1$ with a value of -15.2 ‰ (data from Sanjaya et al., 2024).

Furthermore, the method used in this study was to cross-plot geochemical data to predict the natural hydrogen source at the study site. First, we plotted the H_2 concentration (%) and $\delta^{13}C_1$ isotope (‰) parameters. Cross-plotting these two parameters can be used to determine whether the hydrogen source comes from bacterial gas or abiogenic gas (Liu et al., 2019). Furthermore, to increase the certainty of the hydrogen source prediction at Tanjung Api, we cross-plotted the $\delta^{13}C_1$ (‰) and $\ln(CH_4/H_2)$ parameters. These two parameters can also be used to predict the gas origin at Tanjung Api (Liu et al., 2019). Finally, we also used various data from locations around the world that are hydrogen producers to be plotted together with data from the Tanjung Api area (Liu et al., 2019; Liu et al., 2024).

4. Results

The data used in this study were obtained from a previously published open dataset (Sanjaya et al., 2024). The published data comprise gas and isotope composition from a number sampling locations in Tanjung Api and Pulodalagan seepages. In this study, we used H_2 , $\delta^{13}C_1$, and CH_4 composition data to provide additional analysis related to the source of H_2 gas in nature.

The results of the geochemical analysis in this study are used to add more information to predict the source of H_2 gas in the Tanjung Api area, Ampapa Basin, Central Sulawesi (Fig. 3). Crossplots of H_2 vs. $\delta^{13}C_1$ and $\delta^{13}C_1$ vs. $\ln(CH_4/H_2)$ can help us predict the source of H_2 gas that we have. In Figure 3a, the H_2 gas concentration is 35% and $\delta^{13}C_1$ is around -15.2 ‰ (marked by an orange rhombus symbol). Then, Figure 3b shows that the plotting of $\delta^{13}C_1$ with a value of -15.2 ‰ and $\ln(CH_4/H_2)$ with a value of -0.0901 is in a specific area.

5. Discussion

5.1 Prediction of the origin of H_2

This paper seeks to provide an analysis that strengthens the results of previous studies discussing the origin of H_2 gas in the Tanjung Api area and its formation system. Investigations into the presence of gas seeps in Sulawesi have been conducted since the 1890s (Satyana, 2024; van Gorsel and Subroto, 2022). Subsequent research has continued to develop and has made significant contributions to the study of natural H_2 gas potential in Indonesia (Satyana, 2024; Faturrahman et al., 2025; van Gorsel and Subroto, 2022).

In this paper, our investigation results provide additional information regarding the origin of H_2 gas in the Tanjung Api area. In Fig. 3a, the geochemical analysis of H_2 gas from the Tanjung Api area correlates with abiogenic gas, supported by its values ($H_2=35\%$ and $\delta^{13}C_1=-15.2$ ‰) which are similar to several places in the world (Oman Peridotite Complex, Chimaera Ophiolite in Turkey, and Zambales Ophiolite in the Philippines). Similar results are also shown in Figure 3b, which confirms that the H_2 gas in Tanjung Api is abiogenic gas. The value of $\ln(CH_4/H_2)$ is around -0.0901 and $\delta^{13}C_1$ at -15.2 ‰, very close to the weak positive values observed in crossplots of $\ln(CH_4/H_2)$ and $\delta^{13}C_1$ values from gases from the Oman Peridotite Complex, Chimaera Ophiolite in Turkey, Zambales Ophiolite in the Philippines, TC Hot Springs in China, and New Caledonia Ophiolite in Australia (summarized by Liu et al., 2024). These two results provide additional information that H_2

gas in the Tanjung Api area is related to the serpentinization process in the East Sulawesi Ophiolite (OSE) rock system. This analysis is consistent with previous studies showing that the East Sulawesi Ophiolite controls natural gas formation around the Tanjung Api area, Central Sulawesi (Satyana, 2024; Faturrahman et al., 2025; van Gorsel and Subroto, 2022).

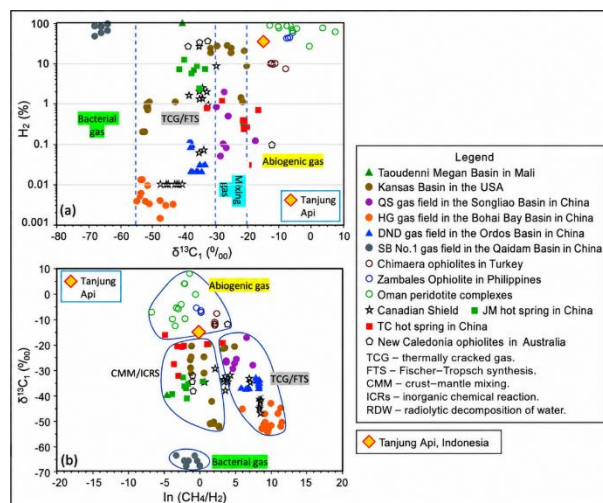


Fig 3. Geochemical data plot results from seeps gas samples around the Tanjung Api area. a) Crossplot between H_2 and $\delta^{13}C_1$. b) Crossplot between $\delta^{13}C_1$ and $\ln(CH_4/H_2)$. There are also plots of geochemical analysis data on gas samples originating from various locations around the world (summarized from Liu et al., 2024).

5.2 Future study

After identifying the source of H_2 gas in Tanjung Api, which originates from the serpentinization process, the next step is to study how this natural H_2 gas migrates from the source to the reservoir rock, possibly through fault planes (Fig. 4), adapted from <https://geoexpro.com/the-genesis-of-natural-hydrogen-exploration/>. As in the petroleum system, understanding the presence of reservoir and overburden rocks is crucial for assessing the feasibility of exploiting natural H_2 gas at this location. Geometry information about this system can be obtained by integrating various data, such as well-log data and geophysical data (Zhang and Li, 2024; Li and Zhang, 2025).

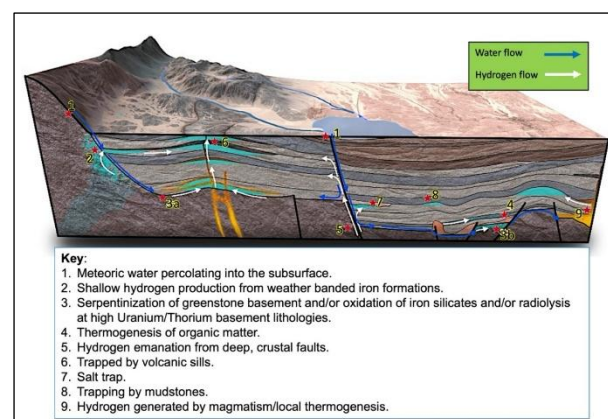


Fig 4. Illustration of comparison of petroleum and natural hydrogen systems (adapted from <https://geoexpro.com/the-genesis-of-natural-hydrogen-exploration/>).

Further research is expected to be conducted using geophysical measurements and well-logging around the Ampapa Basin, dominated by limestone and clastic sediments in Salodik Formation, Minahaki Formation and/or Matindok Formation (Fig. 2), which is highly likely to be a prospective

basin for developing a hydrogen system in this area. From geophysical data (e.g., seismic, magnetic, and/or gravity), we can obtain information about the geometry of the natural hydrogen components at this location. Seismic interpretation, seismic inversion, and attribute analysis can provide comprehensive information about the physical properties of the reservoir of natural hydrogen potential (Su et al., 2025; Chakraborty and Mallick, 2026; Handoyo, 2025). Furthermore, geophysical methods (e.g. seismic 2D and 3D) allow us to estimate the area/volumetric area of the reservoir zone, which can have implications for its prospectivity for exploitation or production (Lucky et al., 2025; Lin et al., 2026). Finally, through the integration of geochemical, geophysical, and well data, it is hoped that the understanding of the natural hydrogen generation, migration, and accumulation system around the Ampana Basin can be more comprehensive.

6. Conclusions

A comprehensive study aimed at identifying the source of H₂ gas in the Tanjung Api area, Ampana Basin, Central Sulawesi was conducted based on previous studies and geochemical analyses. Geochemical analyses were conducted by cross-plotting H₂, CH₄, and $\delta^{13}\text{C}_1$ isotope concentrations and comparing them with previous studies from various locations worldwide to validate and compare the result analysis from this study.

According to this study, the crossplots of H₂ vs. $\delta^{13}\text{C}_1$ and $\delta^{13}\text{C}_1$ vs. $\ln(\text{CH}_4/\text{H}_2)$ suggest that the H₂ in this area originates from abiogenic sources. These results are supported by comparisons showing that the concentration values of H₂, CH₄ $\delta^{13}\text{C}_1$ isotope in the Ampana Basin are similar to those previously reported at other locations worldwide, indicating that the H₂ gas originates from reactions near the Earth's mantle. Therefore, the results of this study support previous studies that suggest that H₂ gas around the Tanjung Api area originates from the serpentinization process of ultramafic rocks in the East Sulawesi Ophiolite.

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