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Tectonic Geomorphology Analysis in Natural Hydrogen Exploration: A Case Study from Tanjung Api, Sulawesi

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Abstract

Natural hydrogen exploration has been proven to be a challenging endeavor due to many factors. In this paper, we present a new insight into hydrogen exploration by using tectonic geomorphology to identify key target areas based on their tectonic activity in relation to the occurrence of active faults. Tectonic geomorphology analysis is performed using three morphometric indices, such as mountain front sinuosity, basin shape index, and drainage density, to determine the index of relative tectonic activity in this region. Field observation shows that hydrogen seeps occurred in the area with high to very high tectonic activity (Class 1 – 2) that correlates with the presence of active faults in this area. Tectonic geomorphology can be used to narrow down the potential area by identifying active tectonic regions that correlate with active faults in this area.

1. Introduction

Hydrogen (H_2) is a molecular gas with versatile applications and has been used in many ways, such as in petroleum refinery, ammonia production, or as a zero-carbon energy carrier (Bhuiyan & Siddique, 2025). As we move from fossil-based fuel to more sustainable energy sources, hydrogen will play a major role in the energy transition due to its low carbon footprint. The demand for hydrogen is gradually rising, with 94 Mt (million metric tons) in 2021 and projected to double by 2030 (Blay-Roger et al., 2024). Currently, around 95 Mt of hydrogen is produced from various sources, and it is still dominated by the constant use of fossil fuel (International Energy Agency, 2023). Recent technological development and growing concern for clean energy sources have triggered some interest in low-emission hydrogen production. This low-emission hydrogen can be produced from biomass-based, natural hydrogen, and methane decomposition.

Natural hydrogen is produced continuously under the earth through a series of chemical reactions such as serpentinization, organic matter maturation, and outgassing from the Earth's mantle (Zgonnik, 2020). These natural hydrogen manifestations are distributed worldwide and have been encountered by humans since ancient times. Several burning gas seeps along Tanjung Api have been identified by the Dutch since 1869, as shown on the topographic map (van Gorsel and Subroto, 2022). Previous study shows that the Tanjung Api seepages contain 20 to over 35 % H_2 (Sanjaya et al., 2024) and 16,3% H_2 (van Gorsel and Subroto, 2022). Carbon isotope analysis δ13C value of CH_4 shows that the methane found originates from abiogenic processes related to serpentinization (Sanjaya et al., 2024).

Serpentinization is a low-grade metamorphic process in which ultramafic rocks are oxidized by water, transforming into serpentine and hydrogen. Previous study shows that serpentinization occurs intensively around temperatures ranging from 200°C - 310°C (McCollom and Bach, 2009) and that peridotite alteration into serpentinite will decrease its permeability and constrain further contact with water (Zgonnik, 2020). Active faults can play a significant role in hydrogen generation from serpentinization processes. Fault can act as a conduit for water to infiltrate and as a pathway for fluid migration along the numerous and open fractures along the fault plane (Etiope, 2023; Lefeuvre et al., 2022). Studies on the correlation between H_2 and active faults have been performed in the past and show that there is an anomalously high H_2 concentration along active faults before an earthquake occurs (Wakita et al., 1980; Xiang et al., 2020).

Tectonic geomorphology using morphometric indices has been used extensively to identify tectonic activity of a specific region (Chang et al., 2024; Faturrakhman et al., 2024; Keller and Pinter, 1996). Various morphometric indices have been developed and can be used to determine the complex interaction between weathering and uplift force on topography development. This development will be shown in the topography relief and can be quantified to identify the tectonic class of an adjacent region (El Hamdouni et al., 2008). Here, we present our analysis of tectonic geomorphology to support the occurrence of active faults in natural hydrogen exploration in Central Sulawesi.

2. Geologic setting

Our research was conducted in Tanjung Api, Ampana, Central Sulawesi (Figure 1), where the presence of natural gas seeps in this area has been known since the 18th century. The lithologies in the research area consist of Cretaceous ultramafic, Miocene sediments, Quaternary limestone, and surficial deposits (Rusmana et al., 1993). Ultramafic rocks in the research area are part of the East Sulawesi Ophiolite (ESO), one of the three largest ophiolites in the world (Kadarusman et al., 2004). Sulawesi is famous for the presence of ophiolite outcrops and their associated mélange complexes (e.g. Parkinson et al., 1998; Kadarusman et al., 2004; Munasri, 2013). The ESO comprises residual mantle peridotite, mafic – ultramafic cumulate, sheeted dolerites, and basaltic volcanic (Kadarusman et al., 2004). Sedimentary rocks from Salodik and Poh formations overlain the ophiolite and comprise limestone and intercalating sandstone and marlstone. These formations are overlain by molasse sediments from the Bongka Formation, which comprises conglomerate with various fragments. The youngest unit in the research area consists of Quaternary limestone and surficial deposits (Figure 2).

Ampana and the surrounding area are encompassed by a distinct fault system that formed from active tectonics. These faults are divided into five active fault segments with varied lengths from 11.5 km to 47.24 km (Kamawan et al., 2013). Geophysics analysis shows that some of these faults are subsurface faults in depth ranging from 2000 m to 3000 m, which enable water – rock interaction for serpentinization (Hidayat et al., 2025).

3. Data and methods

This research is carried out by topographical measurement using Geographic Information System (GIS), fieldwork, and laboratory analysis. The spatial data consists of a 5-m IFSAR Digital Surface Model (DSM) and a digital topographic map. Stream network and elevation data are extracted from the DSM to delineate the many adjacent sub-basins in the research area (Siahaan et al., 2023; Tsodoulos et al., 2024). The sub-basins are based on the 3rd order stream to facilitate the morphometric analysis in numerical terms (Singh et al., 2020). Fieldwork is conducted to verify the morphology development, lithological properties, and gas seepage measurement in Tanjung Api for further laboratory analysis. Soil and gas seeps measurement uses a portable gas analyzer GA5000, and gas sampling will be held in tedlar bags to minimize free air contamination.

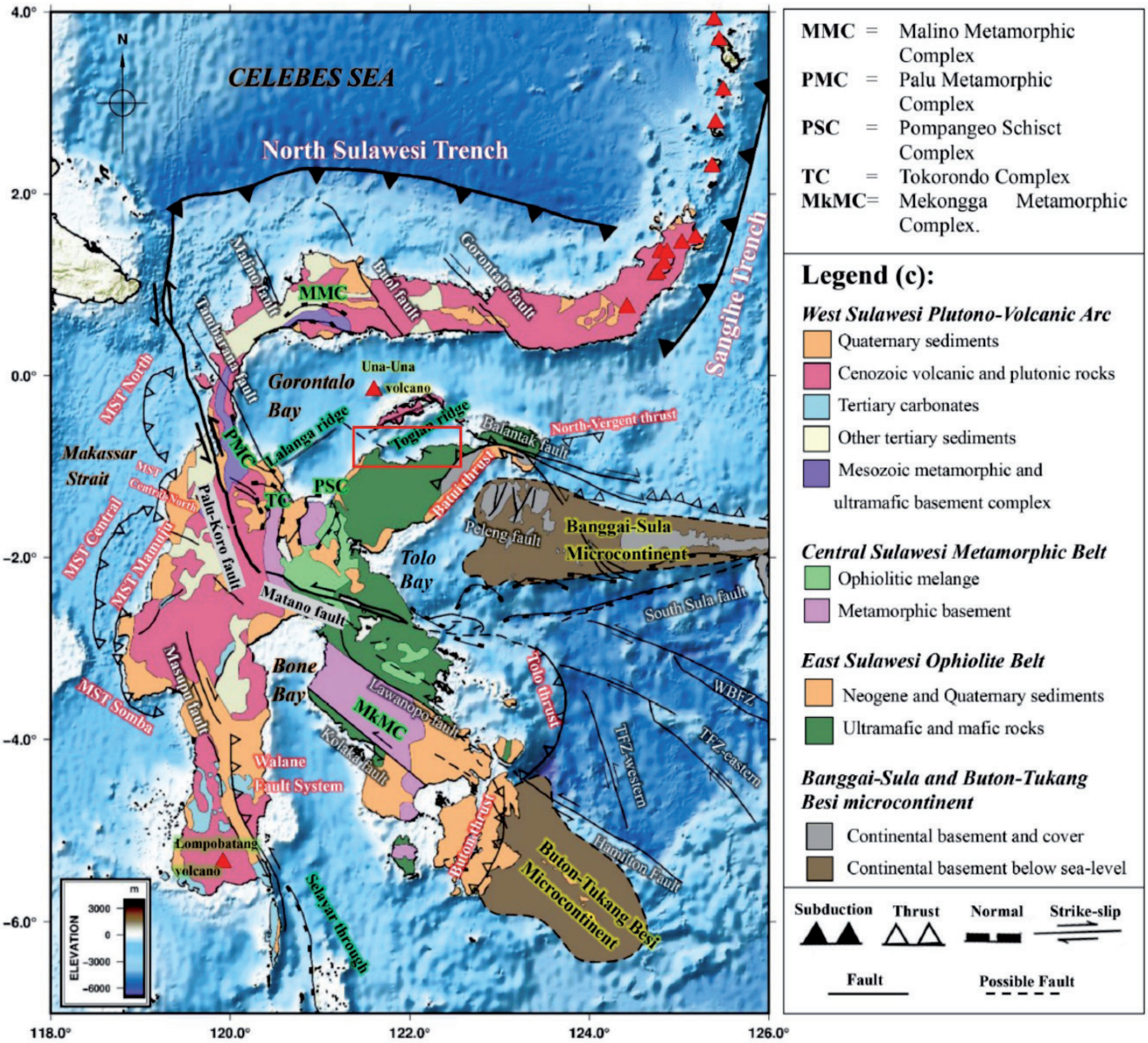

Figure 1. Research location in Tanjung Api, Ampana. Modified after Serhalawan & Chen (2024).

Tectonic events leave an imprint on the mountain fronts and the river basin. The evolution of river basins and topography due to the interplay between uplift and surface dynamics can be quantified using morphometric indices to determine the rate of tectonic activity. Geomorphological analysis of these mountain fronts and river basins provides a valuable insight into the geomorphology frameworks of the research area. We used three morphometric indices, such as mountain front sinuosity (Smf), drainage density (Dd), and basin shape index (Bs) to determine the complex morphology development (Table 1). These morphometric indices are composed of quantitative measurements from different aspects to give a comprehensive review of the tectonic activity in the research area. The result of morphometric measurement was then classified using the Index of Relative Tectonic Activity (IRTA) to determine the relative tectonic activity in the region (El Hamdouni et al., 2008).

Table 1. Morphometric indices used in this research.

Morphometric Indice	Mathematical Formula	Explanation	Reference
Mountain Front Sinuosity (Smf)	Smf =	Smf<1.1 : Class 1 1.1<Smf<1.5 : Class 2 Smf>1.5 : Class 3	Keller & Pinter (1996) El Hamdouni et al (2008)
Basin Shape Index (Bs)	Bs =	Bs>4 : Class 1 3<Bs<4 : Class 2 Bs<3 : Class 3	Ramirez-Herrera (1998) El Hamdouni et al (2008)
Drainage Density (Dd)	Dd =	5.5<Dd<8.2:Class 1 4.14<Dd<5.5:Class2 Dd<4.14 : Class 3	Hidayat et al (2021)
Index of Relative Tectonic Activity (IRTA)	IRTA =	1-1.5 : Very High Tectonic Activity (Class 1) 1.5 – 2 : High Tectonic Activity (Class 2) 2 – 2.5 : Moderate Tectonic Activity (Class 3) IRTA > 2.5 : Low tectonic Activity (Class 4)	El Hamdouni et al (2008)

Mountain Front Sinuosity (Smf)

Mountain front sinuosity is a morphometric index used to verify the control of tectonic and weathering on the topographic development of mountain fronts. Mountain front incision from erosion will result in a sinuous pattern and can be distinguished from relatively straight fronts, which result from fault-controlled processes. The formula to calculate this index is as follows:

$$Smf = \frac{Lmf}{Ls}$$

Lmf represents the length of the mountain front measured along the curve junction of the piedmont and the base of the mountain, and Ls is the length of the mountain front measured along a straight line connecting each segment (Keller and Pinter, 1996). Low Smf values will suggest relatively straight mountain fronts indicative of high tectonic activity. As the rate of tectonic or uplifting decreases or halts, erosional forces will begin to shape the mountain fronts into sinuous and irregular forms with high values of Smf.

Drainage Density (Dd)

Drainage density is a morphometric index used to identify tectonic activity from the density of streams in a basin. A basin in an active tectonic region will have concentrated streams from physically erosive lithology (Hidayat et al., 2021; Mawardi et al., 2019). The formula to calculate this index is as follows:

$$Dd = \frac{\sum L}{A}$$

$\sum L$ represents the total length of streams, and A is the total area of a single basin. High Dd values will suggest a relatively dense stream in a single basin, indicative of high tectonic activity.

Basin Shape Index (Bs)

Basin shape index is a morphometric index used to determine the role of tectonics in relation to a drainage basin shape. Younger drainage basins will typically have an elongated shape due to active uplifting, while older drainage basins will have a more circular shape due to horizontal incision from weathering (Ramírez-Herrera, 1998). The formula to calculate this index is as follows:

$$Bs = \frac{Bl}{Bw}$$

Bl is the drainage basin length from the highest point to the basin mouth, and Bw is the basin width measured at its widest point. Higher Bs values will indicate an elongated basin shape due to active tectonic, while lower Bs values will indicate a circular basin shape due to lower tectonic activity.

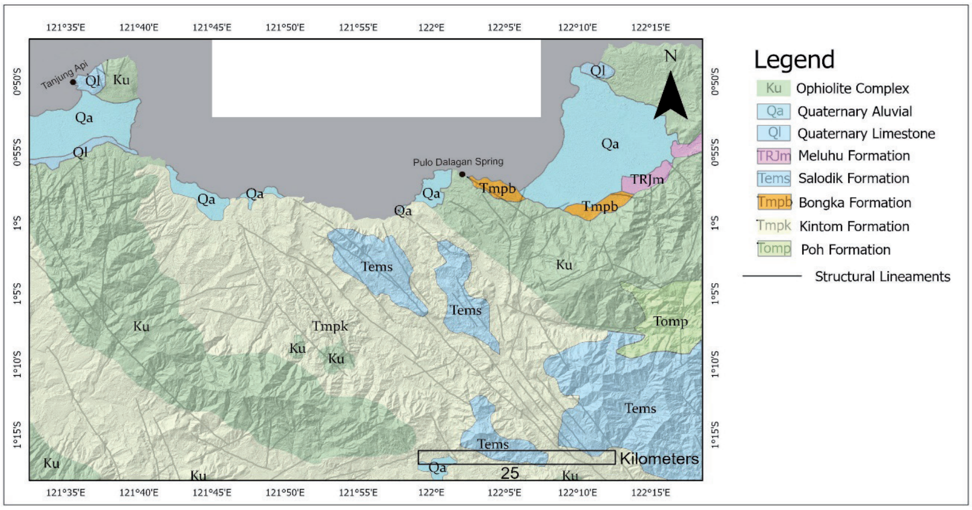

Figure 2. Geological map and hydrogen seeps location. Modified after Rusmana et al (1993) and Sanjaya et al (2024).

Index of Relative Tectonic Activity (IRTA)

Index of Relative Tectonic Activity is a method to quantify various morphometric indices to determine the relative tectonic activity from a specified region (El Hamdouni et al., 2008). Quantitative geomorphological studies have been used extensively by many researchers in different subjects such as active fault mitigation, spatial planning, and resources exploration (Faturrakhman et al., 2024; Faturrakhman et al., 2023; Rendra et al., 2024; Topal et al., 2016). The three morphometric indices described above are then classified into different tectonic classes to determine the level of tectonic activity. The Index of Relative Tectonic Activity (IRTA) is calculated by averaging the sum of all tectonic classes and then classified into four different classes.

4. Results

Mountain Front Sinuosity (Smf)

The measurement of 30 mountain fronts in the research area shows that Smf values range from 1.01 to 1.50. These values can be classified into class 1 (19 mountain fronts), class 2 (10 mountain fronts), and class 3 (1 mountain front) (Figure 3). Relatively straight to moderately straight (class 1 – 2) mountain fronts are distributed evenly across the research area. These mountain fronts are present in the Ophiolite complex and the Bongka Formation.

Drainage Density (Dd)

The measurement of drainage density from 52 sub-basins in the research area shows that Dd values range from 4.36 to 6.04. These values can be classified into class 1 (9 sub-basins) and class 2 (43 sub-basins) (Figure 4). Moderately dense streams network (class 2) is distributed evenly across the research area, while dense streams network (class 1) is scattered in some sub-basins at the east and west parts of the research area.

Basin Shape Index (Bs)

The measurement of basin shape index from 52 sub-basins in the research area shows that Bs values range from 0.4 to 4.6. These values can be classified into class 1 (3 sub-basins), class 2 (4 sub-basins), and class 3 (45 sub-basins) (Figure 5). Basins with circular shape are the predominant shape in the research area and are distributed evenly across the research area. Elongated and moderately elongated basin areas are scattered in some parts of the east and west parts of the research area.

Index of Relative Tectonic Activity (IRTA)

The measurement of an index of relative tectonic activity from 52 sub-basins in the research area shows that IRTA values range from 1.0 to 2.67 (Table 2). These values can be classified into class 1 (4 sub-basins), class 2 (22 sub-basins), class 3 (25 sub-basins), and class 4 (1 sub-basin) (Figure 6). Very high and high tectonic activity is the predominant class in the research area, and is distributed throughout the research area with higher quantities in the eastern parts. Moderate tectonic activity is scattered evenly across the research area, with higher quantities in the western parts.

Field Observation

Field observation shows that morphologically the research area consists of faulted hills, linear valleys with fault trace, and an alluvial plain. Faulted hills in the research area are composed of ultramafic rocks and Quaternary limestone with elevations exceeding 100m. The linear valleys are predominantly exposed in the eastern parts of the research area and are composed of ultramafic rocks and conglomerates of the Bongka Formation. The alluvial plain consists of sediment deposits eroded from older rocks, mainly the Bongka Formation. These deposits can form an alluvial fan with a width exceeding 150 m (Figure 7a).

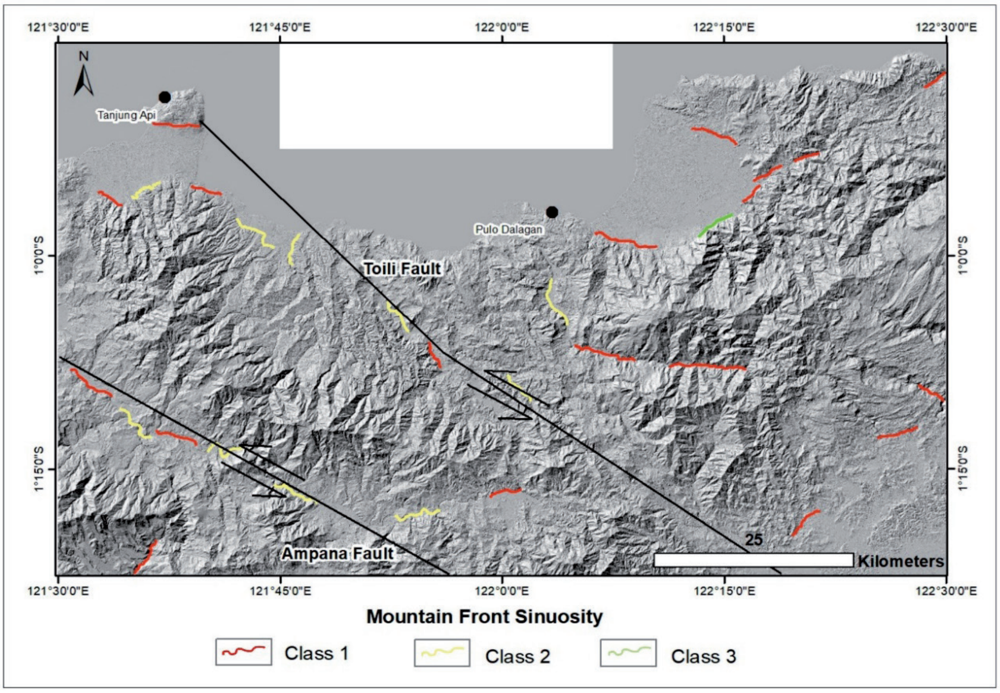

Figure 3. Mountain front sinuosity measurement and its classification.

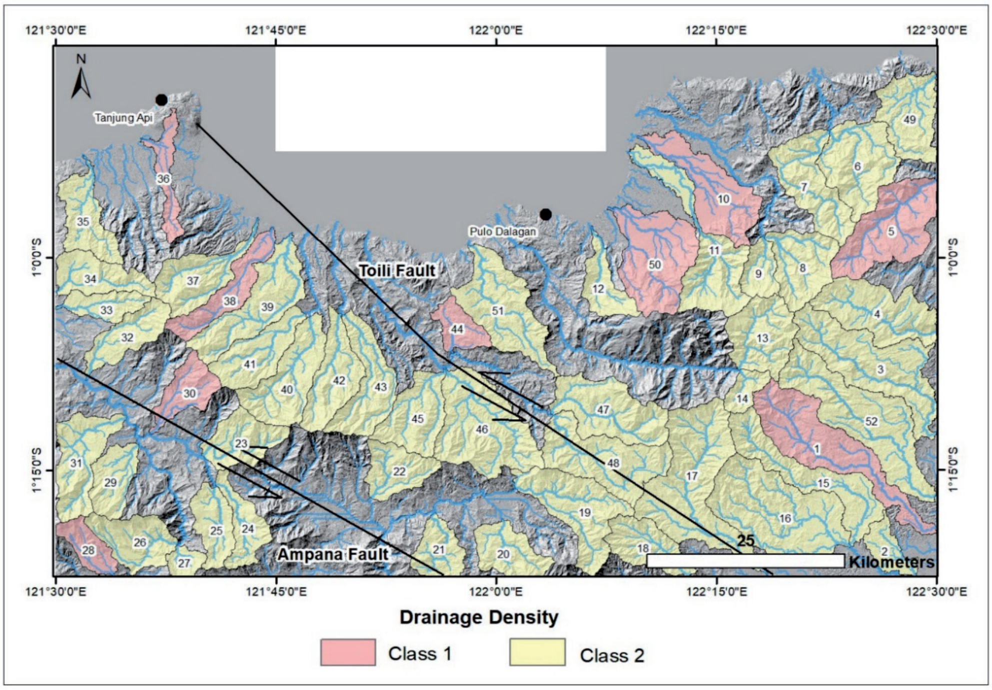

Figure 4. Drainage density measurement and its classification.

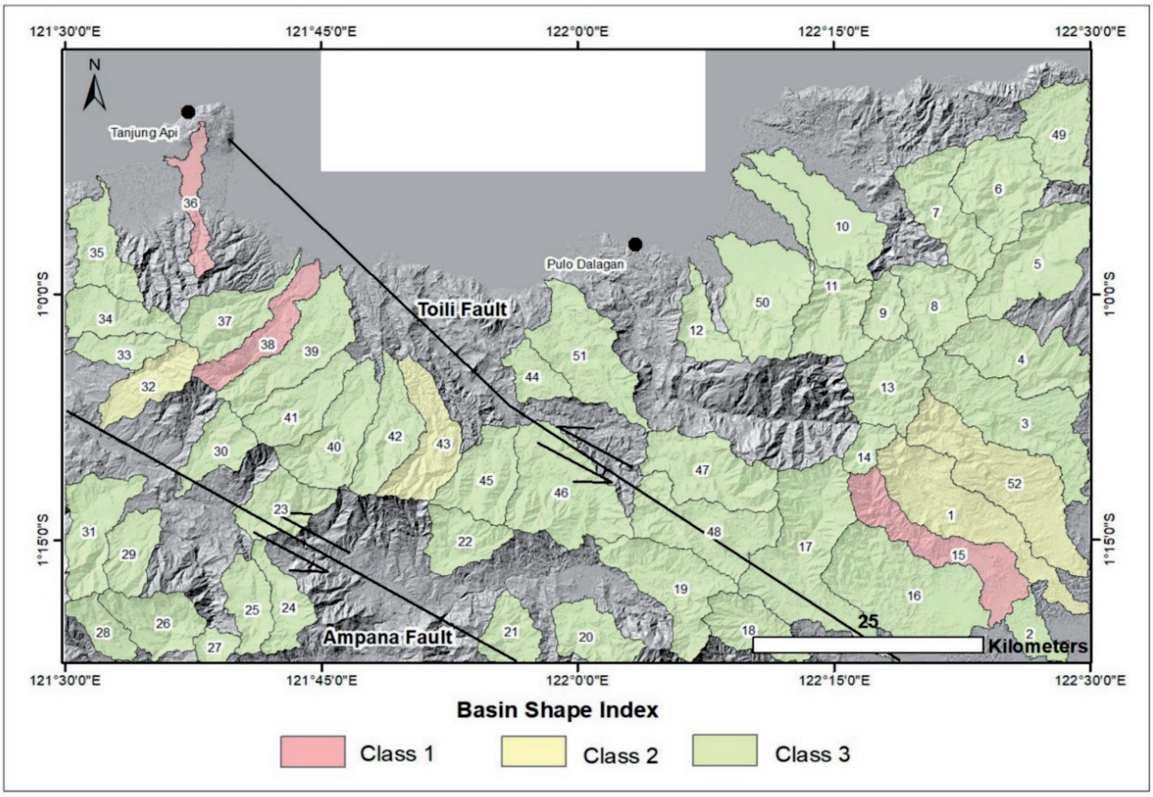

Figure 5. Basin shape index measurement and its classification.

Table 2. Index of relative tectonic activity measurements in the research area.

Sub_Basin	Dd	Bs	Smf	IRTA	Tectonic Class
1	1	2	-	1,50	1
2	2	3	-	2,50	3
3	2	3	1	2,00	2
4	2	3	-	2,50	3
5	1	3	-	2,00	2
6	2	3	-	2,50	3
7	2	3	1	2,00	2
8	2	3	-	2,50	3
9	2	3	-	2,50	3
10	1	3	1	1,67	2
11	2	3	3	2,67	4
12	2	3	1	2,00	2
13	2	3	-	2,50	3
14	2	3	1	2,00	2
15	2	1	-	1,50	1
16	2	3	1	2,00	2
17	2	3	1	2,00	2
18	2	3	-	2,50	3
19	2	3	1	2,00	2
20	2	3	-	2,50	3
21	2	3	2	2,33	3
22	2	3	-	2,50	3
23	2	3	2	2,33	3
24	2	3	2	2,33	3

Sub_Basin	Dd	Bs	Smf	IRTA	Tectonic Class
25	2	3	-	2,50	3
26	2	3	1	2,00	2
27	2	3	-	2,50	3
28	1	3	-	2,00	2
29	2	3	2	2,33	3
30	1	3	1	1,67	2
31	2	3	2	2,33	3
32	2	2	1	1,67	2
33	2	3	-	2,50	3
34	2	3	-	2,50	3
35	2	3	1	2,00	2
36	1	1	1	1,00	1
37	2	3	-	2,50	3
38	1	1	2	1,33	1
39	2	3	2	2,33	3
40	2	3	-	2,50	3
41	2	3	-	2,50	3
42	2	3	-	2,50	3
43	2	2	2	2,00	2
44	1	3	-	2,00	2
45	2	3	1	2,00	2
46	2	3	1	2,00	2
47	2	3	1	2,00	2
48	2	3	-	2,50	3
49	2	3	1	2,00	2
50	1	3	1	1,67	2
51	2	3	2	2,33	3
52	2	2	1	1,67	2

Ultramafic rocks in the research area comprise serpentinized peridotite, serpentinite, and amphibolite that are exposed locally in the northern parts of the Tanjung Api coast (Figure 7b). The conglomerates of the Bongka Formation cropped out in the middle – western area and are composed of polymict conglomerate with fragments from different origins, like ultramafic, metamorphic, and igneous rocks, medium to poorly sorted with cross bedding. Quaternary limestones are composed of coral reef limestone and clastic rudstone intercalation, and some are jointed. These Quaternary limestones are overlain by terrace deposits with fragments of different origin, like ultramafic, metamorphic, and igneous rocks, that are bound by carbonate cement and matrix.

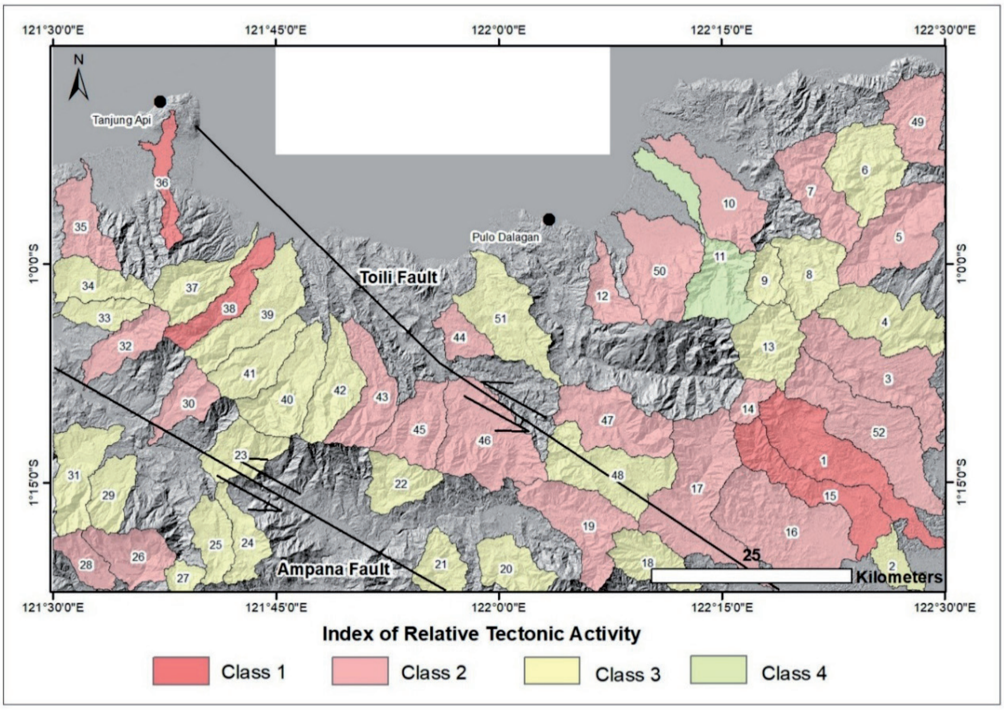

Figure 6. Classification of relative tectonic activity in Tanjung Api.

Gas seeps are observed in 2 places, the Tanjung Api coast and the Pulodalagan hot springs. Tanjung Api gas seeps are scattered along the coast with multiple gas bubbles emerging from underwater seeps (Figure 7c). These gas seeps also emerge from the soil, particularly along the jointed section of the terrace deposits. Flow rate monitoring in Tanjung Api gas seeps shows a flow rate of approximately 1000 – 1400 m3/day with hydrogen contents exceeding 1000 ppm. Gas seeps in Pulodalagan rise from the thermal spring periodically. These bubbles emerged from a crack in the travertine deposits with hydrogen contents ranging from 144 – 197ppm (Figure 7d). Both gas seeps emerge in close proximity to areas with high – very high tectonic activity (Class 1 – 2) and are located among some of the active faults in the research area, the Toili and Ampana faults.

5. Discussion

Tectonic geomorphology, using morphometric indices, has been able to determine the relative tectonic activity in the research area. Based on this morphometric analysis, tectonic and weathering play a major role in shaping the landscape in the research area. Smf analysis from 30 mountain fronts shows that active tectonic and uplift are prominent factors in generating a relatively straight mountain front. Field observation shows that these mountain fronts are composed of linear valleys adjacent to triangular facets with fault traces along their borders (Figure 7e). The presence of these morphological features is commonly correlated with high tectonic activity in another region outside of the research area (Faturrakhman et al., 2024; Rendra et al., 2024; Tsodoulos et al., 2024). Intense uplift evidence also presents in the form of terrace deposits and Quaternary limestone with intense joints along the Tanjung Api coast (Figure 7f). These field evidence and morphometric analysis are in line with geophysical modelling of an active fault with depth up to 3 km along the Tanjung Api coast (Hidayat et al, 2025).

Drainage density analysis from 52 sub-basins shows that the research area is composed of moderate to high-density stream networks. These condensed stream networks are the result of intense tectonic activity that physically erodes into the lithology and will produce a higher stream density compared to a relatively stable area. Field observation shows that many of the stream networks in the research area are dry even amidst the rainy monsoon season, which was due to the input of water from the head of sub-basins not being able to cope with the intense stream networks in the research area.

Figure 7. Photographs of field observation. (a) Alluvial fan composed of sediment deposits from Bongka Fm. (b) Ultramafic rocks along Tanjung Api Coast. (c) Flow rate measurement and gas sampling from H_2 seeps in Tanjung Api. (d) Gas measurement at Pulodalagan hot spring. (e) Triangular facets and linear valleys in Bukit Batu Hitam. (f) Quaternary jointed limestones along the Tanjung Api coast.

Basin shape analysis from 52 sub-basins shows that the research area is composed mainly of basins with circular shape. These circular basins are the result of lateral incision and intense weathering. The research area is composed mainly of Bongka Formation conglomerates and ultramafic rocks that are susceptible to intense weathering due to their young age and mineralogical properties. The Bongka Formation is of early – late Pliocene age (Nugraha et al, 2022). This Formation mainly comprises poorly sorted and cemented ophiolite-rich conglomerate. The ophiolite and ultramafic rocks in this area are rich in olivine and pyroxene, which contribute to their susceptibility to the weathering process.

The analysis of each morphometric index is then compiled to determine the relative tectonic activity in the research area. Index of relative tectonic activity shows that the research area is mainly composed of moderate to high tectonic activity. These high tectonic activities are indicative of the presence of active faults. The hydrogen seepages along sub-basins with high to very high tectonic activity (Class 1 – 2) show that active faults play a significant role in hydrogen production, mainly as a conduit for water infiltration and secondary fracturing, in line with research from Etiope (2023) and Lefeuvre et al (2022). The manifestation of the Ampana and Toili faults can be observed from the presence of faulted hills with triangular facets, uplifted terrace deposits, jointed Quaternary limestones, and condensed stream networks in the research area. Active fault is a significant factor in the occurrence of hydrogen seepage in Tanjung Api and can be identified by using tectonic geomorphology. The occurrence of natural hydrogen in active faults has also been identified along the North Pyrenean Frontal Thrust with concentration values ranging up to 882 ppmv along the fault zone at 1 m depth (Lefeuvre et al, 2022).

6. Conclusions

Tectonic geomorphology using morphometric indices has been proven to be beneficial in determining the potential area for hydrogen exploration. Morphometric analysis shows that the research area is shaped by weathering and active tectonics. The hydrogen seeps occurred within the area with high to very high tectonic activity (Class 1 – 2) and located along the Ampana and Toili faults. These active faults appear to play a significant role in hydrogen generation. Tectonic geomorphology can be used to narrow down the potential area in hydrogen exploration based on its ability to determine the key target area for further analysis.

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