Abiogenic gas seepage from serpentinite at Tanjung Api, Tomini Bay, East Sulawesi

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INTRODUCTION AND SUMMARY

Oil and gas seeps are common across the Indonesia region and are usually associated with breached anticlines or faults in Cenozoic or Mesozoic sedimentary basins, where they were generated from biogenic or thermogenic conversion of organic matter in sediments. In contrast, the methane gas at Tanjung Api in East Sulawesi is emerging from an area of ultramafic mantle rocks, which are part of the large East Sulawesi Ophiolite Complex (Figures 1 and 2).

Tanjung Api is a prominent cape along the South side of Tomini Bay (also called the Gorontalo Basin, along the north shore of the East Arm of Sulawesi). The name means 'Fire Cape' and reflects the presence of several burning gas seeps on the beach. This phenomenon must have been active and known for more than 150 years, as the name was already shown on Dutch topographic maps in 1869, and possibly earlier (Figure 3).

In this brief review of the enigmatic Tanjung Api gas seeps, we argue that the gas is not a conventional, organic-derived hydrocarbon gas, but an abiogenic (or abiotic), gas, dominated by isotopically anomalous methane and hydrogen, which formed from the serpentinization of ultramafic rocks.

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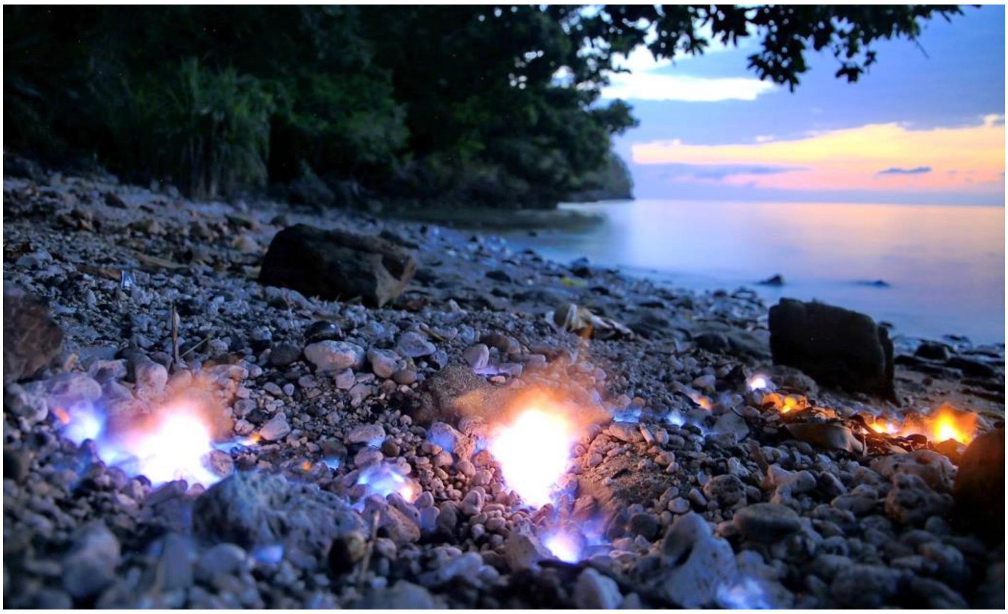

Figure 1. *Burning gas seeps on beach at Tanjung Api, Tomini Bay, East Arm of Sulawesi (Mark Levitin 2019; www.itinari.com/eternal-fire-on-the-beach-tanjung-api-sulawesi-ivid).*

Figure 2. *Smokeless burning gas on the beach at Tanjung Api (Chien Lee 2014, www.naturepl.com, image00541862).*

Most petroleum geologists outside Russia did not accept that abiogenic hydrocarbon gas generation could exist. The overwhelming majority of oil and gas discovered could indeed be proven to have formed by thermogenic or biogenic conversion of organic material in sedimentary rocks. However, the peculiar composition of the Tanjung Api gas and the presence of very similar methane-hydrogen gases in many other ophiolite complexes in the world (Abrajano et al., 2018; Etiope et al., 2011; Etiope, 2017; Vacquand et al., 2018) shows rather convincingly that methane gas can also be generated by inorganic chemical processes, usually associated with serpentinization of ultramafic rocks.

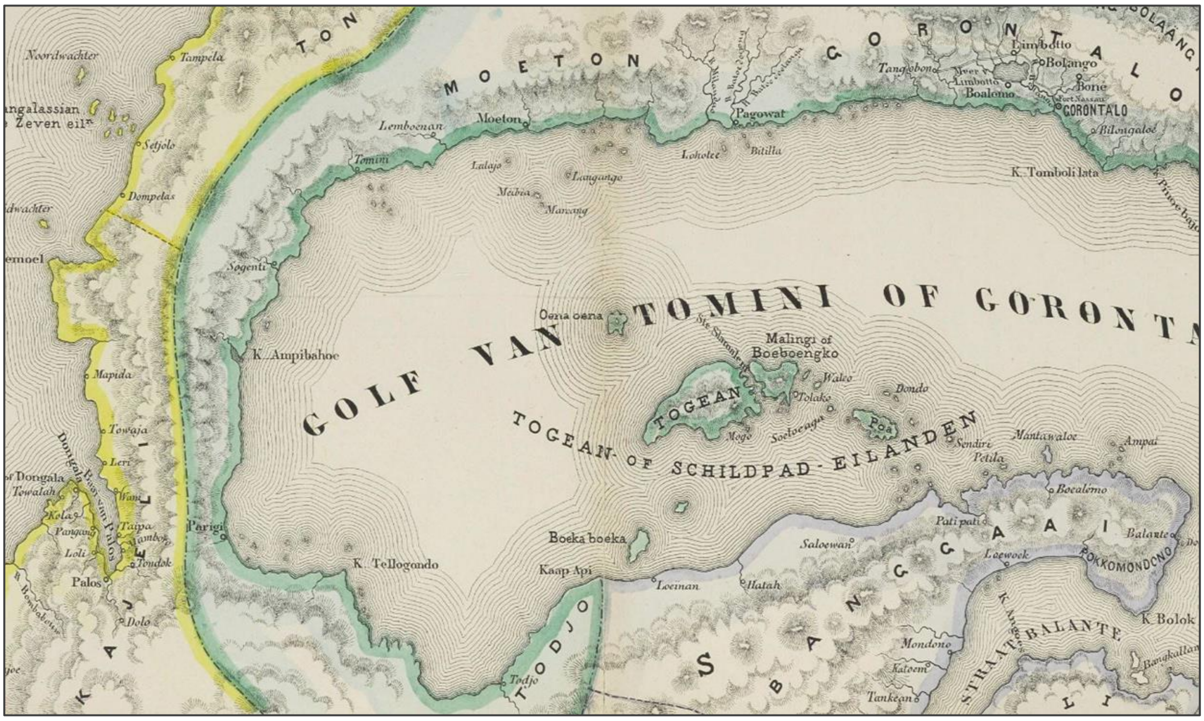

Figure 3. Part of the 'Celebes and de Molukken' topographic map in the 'Atlas van Nederland en zijne overzeesche bezittingen' by I. Dornseiffen (1870). The location of Tanjung Api ('Kaap Api') is shown on the SW side of the Gulf of Tomini, in the Sultanate of Todjo in the Residency of Manado (green outline), near the border with the Banggai District of the Ternate Residency (light blue outline). This map does not accurately portray the protruding cape of Tanjung Api, but the name does show that the burning seeps were already known before 1870.

TANJUNG API GAS SEEPS – SETTING & EARLY DISCOVERY

A prominent, rugged cape in a remote, sparsely populated area along the South side of Tomini Bay has long been known as Tanjung Api (named Kaap Api on some of the oldest Dutch topographic maps of Serne and Versteeg (1869) and Dornseiffen (1870; Figure 3). The name obviously refers to the long-active burning gas seeps here. Other names for Tanjung Api include Cape Api, Tandjong Api, Oedjoeng Api, Ujung Api or Tj. Api. The name in the local Barre language is Ngudju Apu.

The first description in the western literature of the burning gas seeps and rock types at Tanjung Api came from the well-known Dutch Calvinist missionary and ethnographer Albert C. Kruijt, who was the first European to settle in the Poso area of Central Sulawesi in 1891. Kruijt sent the information and rock samples to C.E.A. Wichmann, Professor of Geology at the University of Utrecht, who published the first petrographic descriptions of the rocks from the seep area and identified them as 'serpentinized pyroxene-olivine rocks' (Wichmann, 1896).

Kruijt's observations on the gas seeps, from a visit in August 1892, were later published in Adriani & Kruijt (1912, p. 71). He described flames of natural gas coming from the ground along the beach. He noted that when the flames were covered by seawater the flames continued to burn above the sea water. Nearby, in 1-2 m water depth, were

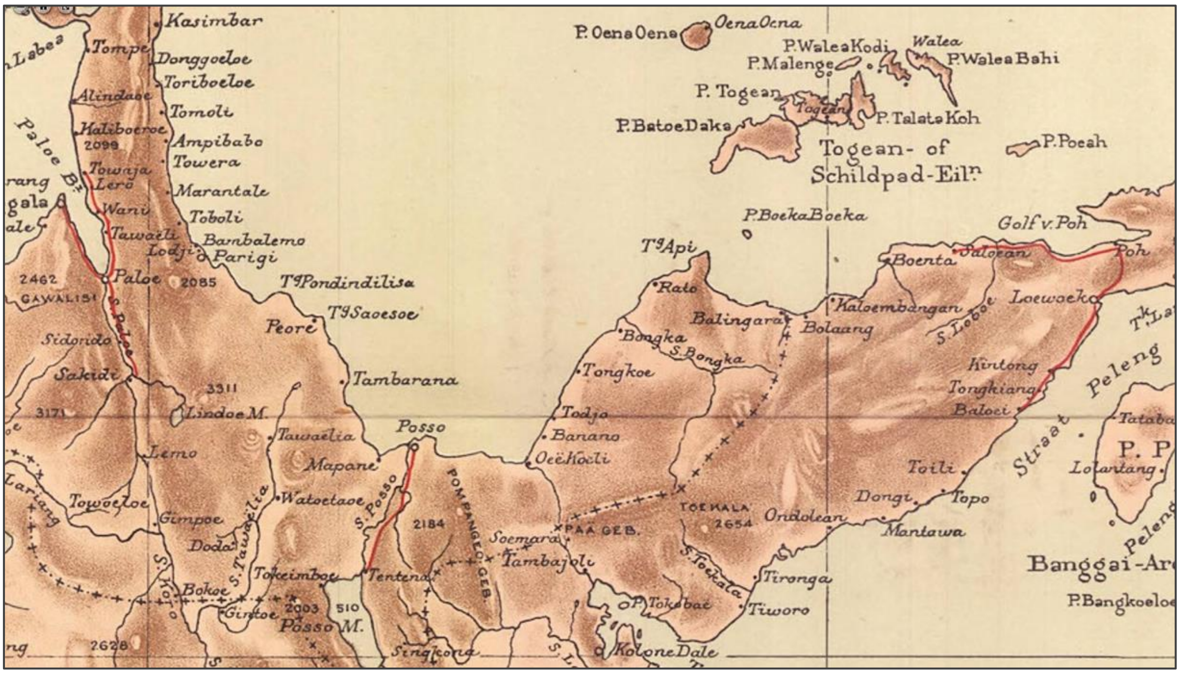

Figure 4. *Part of a more recent and more accurate Dutch topographic map of Celebes (Amsterdam, 1910), with the location of 'Tg. Api' in center of image.*

several spots of bubbling water, which according to the locals were fresh water springs with gas.

Soon afterwards, in 1903, the coastal seeps at Tanjung Api were visited and described in more detail by Dutch mining engineer Marcus Koperberg (preliminary report 1905, final report 1929; Fig. 5). He was the first professional geologist/ mining engineer to visit Tanjung Api during the 'Geological-mining Reconnaissance Project of the Manado Residency' by the Geological Survey (Dienst van het Mijnwezen).

Koperberg (1929, p. 442) noted that the rocks in the gas seeps area were mainly serpentinite and serpentinized peridotites, but he suggested those might be blocks in very coarse conglomerate, which also might contain hornblende schist (not confirmed by later workers). He also noted that the burning gas was odorless, that the flames were hardly visible during daylight hours, and that the seeps could be extinguished with water, but appeared to self-ignite again soon afterwards.

The famous early Sulawesi explorers P.and F. Sarasin (in 1895) and C. Abendanon (in 1909-1910) did not visit Tanjung Api. However, there was more interest in the geology of the East Arm of Sulawesi from the oil company Koninklijke Petroleum (Royal Dutch; BPM-Shell) in the early 1900s, probably driven by reports of oil and gas seeps along the south side of the East Arm, and they possibly also had prior knowledge of the Tanjung Api gas seeps along the North coast.

The first BPM geologist to survey the East Arm of Sulawesi was Johannes Wanner in 1905 (Wanner, 1910, 1913). It is not clear if he visited Tanjung Api, but he did report another oil seep from fractures in ophiolite gabbro in Babason creek near Dolong, which he

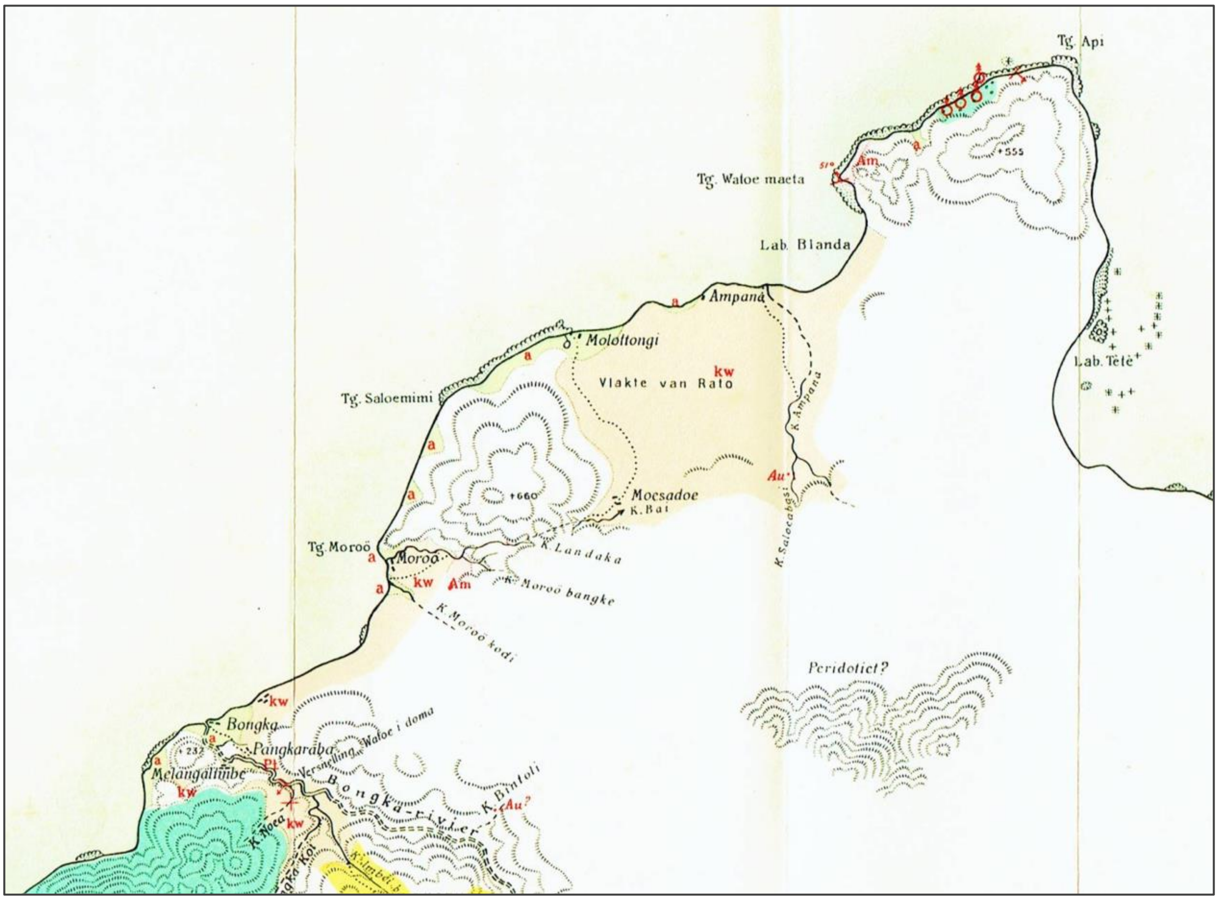

Figure 5. Part of the geological map by government geologist M. Koperberg (1929), based on a 1903 survey. It shows areas of peridotites in green, in the SW (South of the Bongka River), NE (Tanjung Api) and probably also in the mountainous parts of the interior. Along the coast and rivers are Late Neogene- Quaternary deposits. Red symbols along the NW-facing part of the cape 'Tg. Api' are the 3-4 locations of gas seeps.

suggested was sourced from underlying (overthrusted) Tertiary sediments. BPM geologist Hans Hirschi (1913) visited the area in 1909 and probably visited Tanjung Api, but he did not mention the gas seeps in his 1913 publication, perhaps due to BPM confidentiality policies.

Government geologist W.C.B. Koolhoven (1930) mapped the geology of the eastern part of the East Arm of Sulawesi in 1923 for the Dienst van het Mijnwezen (Geological Survey) and was one of the first to interpret the East Sulawesi ophiolite as a broad thrust sheet, derived from the North and covering imbricated Mesozoic-Cenozoic marine sediments. The age of emplacement was believed to be Middle or Late Miocene.

Government geologist J.H.F. Umbgrove briefly visited the gas seeps of Tanjung Api in 1930 and described the serpentinitic rocks around the self-igniting gas seeps as lherzolite (Umbgrove, 1930).

A second phase of more systematic geological fieldwork by BPM in the East Arm of Sulawesi was conducted in 1927-1930 by Swiss and Hungarian geologists F. Weber, L. von Loczy and E. Kundig. They also viewed the East and SE arms of Sulawesi as an alpine

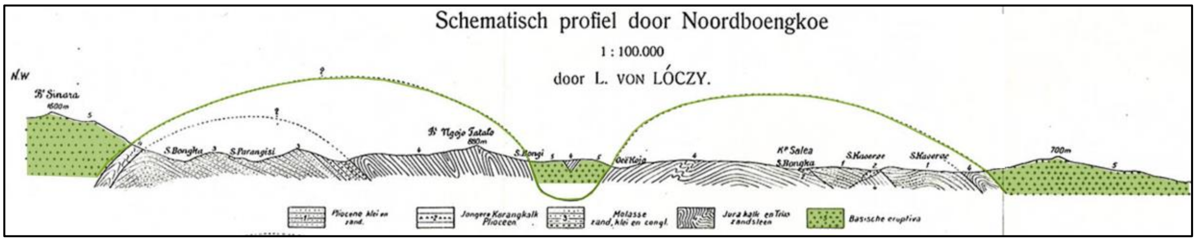

Figure 6. *NW-SE cross section from North Bungku to the Gulf of Tolo, showing folded/imbricated Mesozoic- Early Tertiary sediments in windows below an extensive overthrust sheet of gabbro-type ultrabasic rocks (Von Loczy, 1934).*

thrust belt with SE and E-directed thrusting of a large ophiolite sheet over highly-deformed Triassic- Early Miocene marine sediments (Figures 6 and 7).

It was only in the 1980s that the tectonic framework of the East Arm of Sulawesi was properly understood as the result of the arrival of a microcontinental block (the

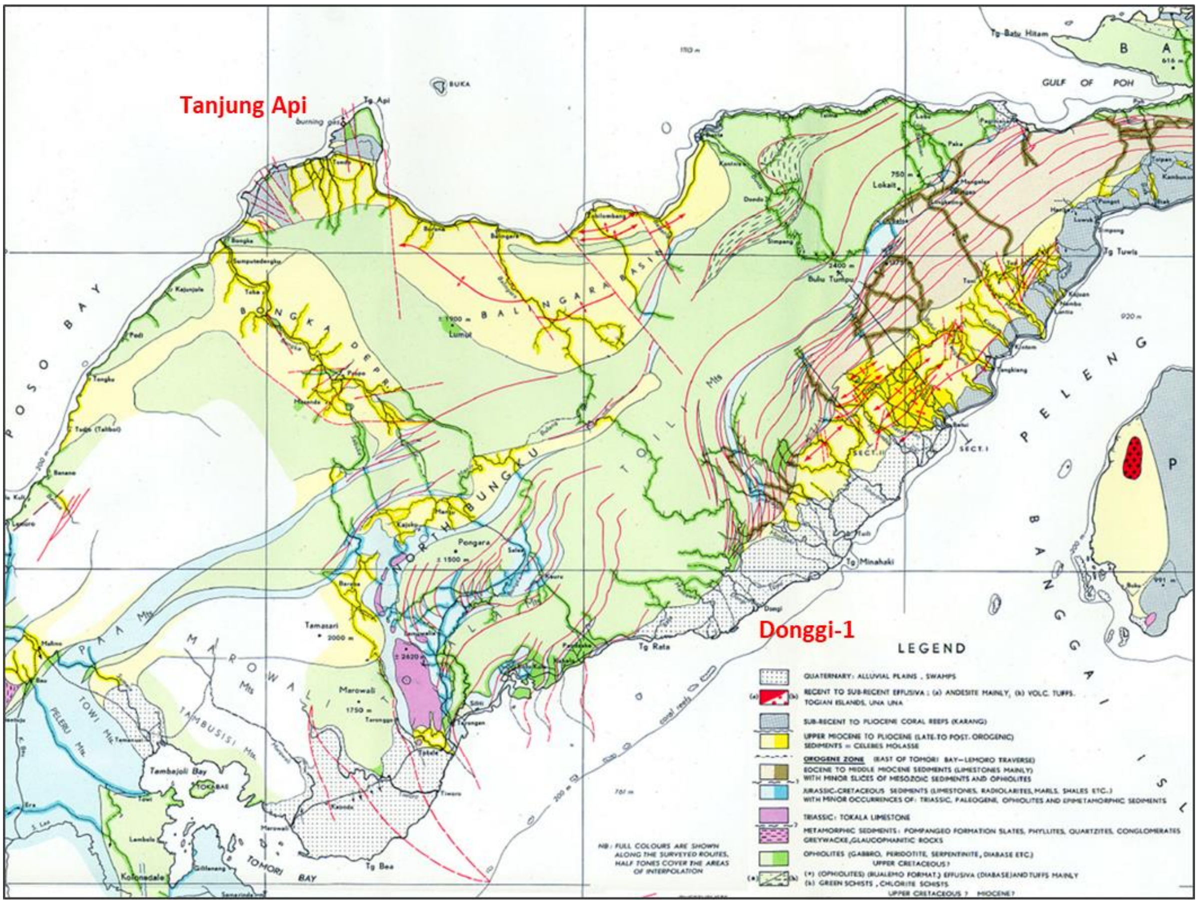

Figure 7. *Geologic map of the East Arm of Sulawesi from Kundig (1956; part), compiled from the Kundig, Von Loczy and Weber BPM fieldwork in 1929-1930, as well as earlier published work. In green is the large East Sulawesi Ophiolite sheet, with windows into underlying imbricated Late Triassic limestones (violet), Jurassic-Cretaceous pelagic limestones (light blue) and Eocene-Middle Miocene limestones (tan). In yellow Late Miocene-Pliocene post-orogenic 'Celebes Molasse'.*

Gondwana-derived Banggai-Sula block) at a subduction zone/volcanic arc. The buoyance of the subducted parts of the continental block eventually choked the subduction process and resulted in slab break-off and uplift, resulting in the apparent 'obduction' of the East Sulawesi Ophiolite (upper plate oceanic mantle and crust) over the scraped-off Mesozoic-Tertiary sediment cover of the partly subducted Banggai-Sula block (Simandjuntak, 1986). The timing of the main deformation phase was placed in Middle Miocene by Kundig (1956), mainly based on the presence of Late Miocene *Lepidocyclina* at the base of the post-orogenic 'Celebes Molasse'.

TANJUNG API GAS COMPOSITION & ANALOG OPHIOLITE OCCURRENCES

The first (and only?) chemical analysis of the gas from Tanjung Api revealed its rather unusual composition, different from 'normal' organics-derived hydrocarbon gases, like the gases produced from wells in the Tomori Gulf in the South of the East Arm of Sulawesi (Subroto et al., 2004). The gas is dominated by methane (CH_4; 52%), nitrogen (N_2; 23%), hydrogen (H_2; 16%) and oxygen (O_2; 7.3%), as well as small amounts of higher hydrocarbons (ethane C_2H_6, propane C_3H_8; 1.5%).

N_2 and O_2 are not generally parts of ophiolite-generated gases. The nitrogen-oxygen ratio in the Tanjung Api gas sample is similar to that of atmospheric gas, so these components in the sample are likely to represent about 30% atmospheric contamination during sampling, as also suggested by Subroto et al. (2004). Eliminating the N_2 and O_2 presence in Tanjung Api gas leaves us a likely actual composition of 75% methane, 1% ethane and 23% H_2.

Another typical feature of the Tanjung Api gas is the unusually heavy carbon isotope values. In nature, carbon is represented by two stable isotopes, ^{12}C and ^{13}C. Plants and marine organisms with calcareous shells preferentially assimilate the lighter ^{12}C carbon isotope into their tissues. The ratio $^{13}C/^{12}C$ (generally expressed in the formula $\delta^{13}C$ [PCB]) is therefore lower than normal in organic carbon.

The $\delta^{13}C$ values of Tanjung Api methane and ethane are -19$^{o}/_{oo}$ and -22$^{o}/_{oo}$, much 'heavier' than the usual values of biogenic hydrocarbon gas (typically near -60$^{o}/_{oo}$ for biogenic methane and -40$^{o}/_{oo}$ for thermogenic methane; e.g. Fig. 8). This clearly suggests that the carbon in the Tanjung Api gas is inorganic. Subroto et al. (2004) already recognized the unusual Tanjung Api gas as probably abiogenic, but other options were left open as well. This was the first record of possible abiogenic methane in Indonesia. Satyana (2005) explored the theory of abiogenic petroleum genesis by serpentinization in basal peridotites of overriding ophiolite complexes in Indonesian collision zones, via 'Fischer-Tropsch-type' reactions, but did not include the example of Tanjung Api (or any other ophiolite-associated gas in SE Asia).

Since the Subroto et al. (2004) paper was published, many similar abiotic CH_4-H_2 rich gas occurrences have been reported from exposed ophiolite bodies worldwide, all with'heavy' $\delta^{13}C$ values (Figure 9; Etiope, 2017; and other references), and also in many oceanic

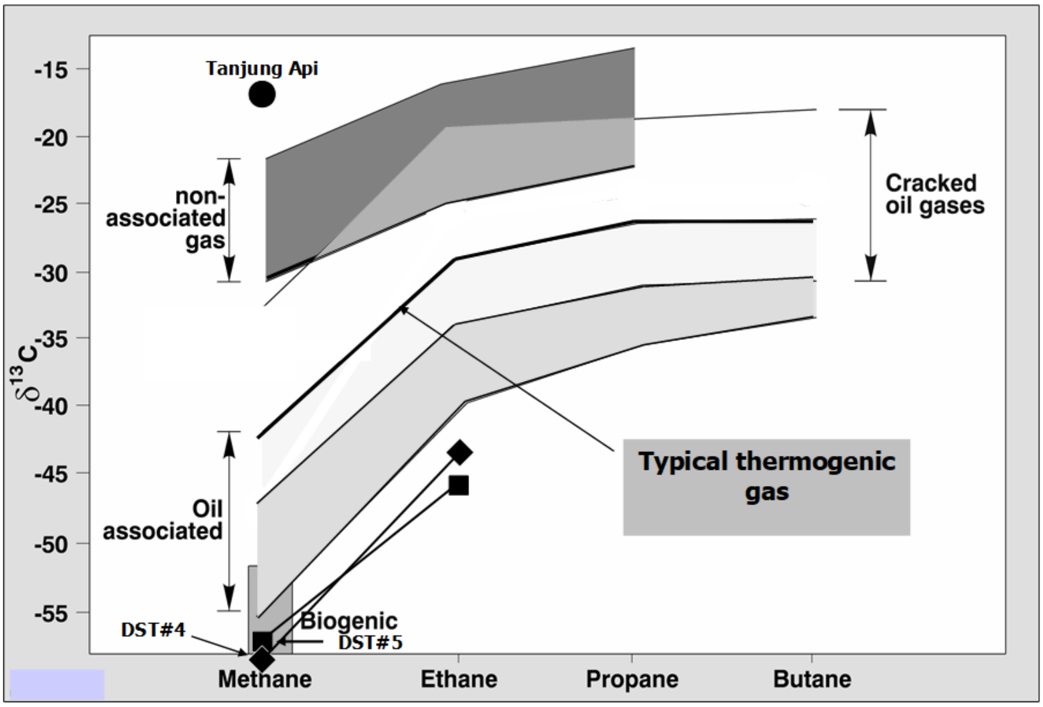

Figure 8. *Graph showing differences in ^{13}C carbon isotope values in methane gas samples from East Sulawesi: abiogenic ophiolite gas from Tanjung Api and biogenic methane and ethane from DST 4 and 5 in the Donggi-1 well in the Tomori area (Subroto et al., 2004).*

settings. In today's oceans such gas has been also been demonstrated from multiple hydrothermal vents along mid-oceanic ridges and transform fracture zones, typically where serpentinite is exposed at of near the ocean floor (Welhan and Craig, 1979; Deville et al., 2018). It is also documented from fluid inclusions in mafic rocks exposed on the seafloor (Klein et al., 2019; etc.).

Dr. Giuseppe Etiope, a leading Italian authority on abiogenic gas from ophiolites, confirmed that the Tanjung Api gas composition and its isotope data as reported by Subroto et al. (2004) are indeed "very, very similar to that of Chimaera (ophiolite), in Turkey, definitively mostly abiotic" (personal comm., January 27, 2022).

The generation of H_2 and CH_4 in ophiolite complexes is now well understood as the result of inorganic chemical processes during serpentinization. Serpentinization occurs where ultramafic rocks react with water, which transforms the common ferromagnesian minerals (olivine, pyroxenes) into hydrous minerals of the serpentine-group and secondary minerals like iron oxydes. This reaction also generates H_2, heat and reducing conditions. The H_2 gas thus created is then capable of reducing CO_2, if present, into methane/CH_4.

Above subduction zones, dewatering of subducted sediments is a significant source of water. CO_2 may be sourced from breakdown of subducted carbonate sediments or perhaps also from other surface sources. In the case of Tanjung Api, a carbonate source is quite likely to be present below the East Sulawesi ophiolite, which was

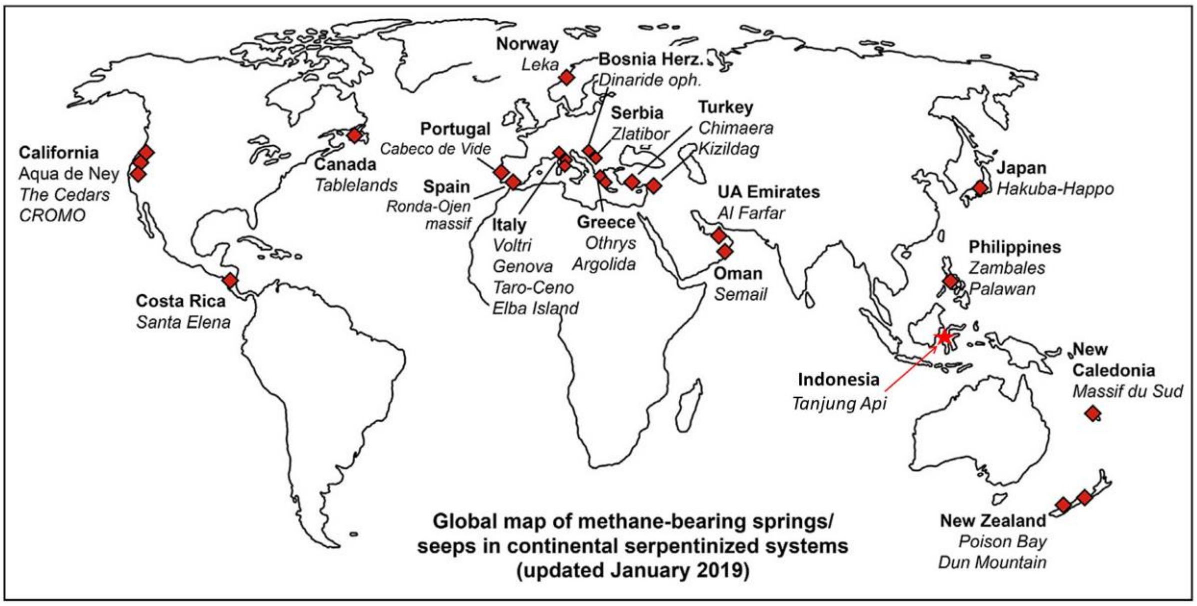

Figure 9. *Global distribution of well-documented abiotic methane occurrences from onland serpentized ophiolite complexes (after Etiope and Whiticar, 2019; with Tanjung Api shown as red star).*

'obducted' over the carbonate-rich Mesozoic-Cenozoic sediments that covered the subducted parts of the Banggai-Sula microplate.

OTHER ABIOGENIC GAS OCCURRENCES IN INDONESIA?

Until now, the abiogenic gas seeps at Tanjung Api in East Sulawesi seem to be a unique feature in Indonesia. However, similar conditions may exist in any of the other Indonesian ophiolite bodies, like in other parts of the East Sulawesi Ophiolite in the East and SE Arms of Sulawesi, or in the ophiolite complexes of Papua and nearby islands, the Meratus Range in SE Kalimantan, Halmahera, Timor and other Banda outer arc islands, as well as in Malaysian North Borneo. These all might yield similar, as yet unreported, abiogenic methane seeps.

ABIOGENIC GAS SEEPS-IMPLICATIONS FOR HYDROCARBON EXPLORATION

1. Tanjung Api and similar abiogenic gas occurences worldwide demonstrate that not all hydrocarbon gas is derived from organic sources, but it can also be generated by inorganic chemical reactions in certain geological settings without organic carbon. So far, this process has been proven only in serpentinized ultramafic rocks in obducted ophiolite complexes and in mid-oceanic ridges and fracture zones with ultramafic rocks close to the seafloor;

2. Abiotic gas may be more common than previously thought. Scrutiny of gas analyses of existing 'conventional' gas fields may reveal hitherto unrecognized contributions of abiogenic gas, a possibility not usually entertained by the petroleum industry;

3. An important implication is that methane gas shows in wells, seeps, hydrates, seismic bright spots or as fluid inclusions in rocks, are no longer proof of a working hydrocarbon system sourced from organic-rich sediments, unless carbon isotope analyses can exclude an abiogenic origin. This is especially relevant in basins with potential subcropping ultramafic rocks. For example, unpublished reports of hydrocarbon inclusions in the basal basaltic-andesitic volcanics in the Rangkong 1 well in North Makassar Straits were interpreted as proof a working hydrocarbon system and nearby source rocks by Bacheller et al. (2011; see also Satyana, 2015), although the well penetrated typical 'Celebes Sea-type' Middle Eocene-Recent deep water oceanic stratigraphy. Carbon isotope analyses should now be required before concluding that such hydrocarbon inclusions are evidence of biogenic gas generation from nearby source rocks, especially when the gas also contains H_2.

4. Today, abiogenic gas is not a target of hydrocarbon exploration. Although its existence is a fact, there are no good estimates of volumes and rates of gas that could possibly be generated from serpentinized ultramafic rocks. Although it may be a slow process, it is tempting to speculate that improved understanding of abiogenic gas generation in ophiolite complexes may someday identify 'sweet spots', from where unconventional abiogenic methane and hydrogen gas can be produced commercially.

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