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Prospecting CCS Project in Indonesia: A Case Study in Meratus Mountains, South Borneo

Prospeksi Proyek CCS Di Indonesia: Studi Kasus Di Pegunungan Meratus, Kalimantan Selatan

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Abstract-Long-term extensive carbon dioxide exposure inflicts diseases for humans and endangers the ecosystem. Carbon Capture and Storage (CCS) is a breakthrough to reduce CO_2 in the atmosphere. The purpose of this study is to describe the CCS principles and suitability of this work in Indonesia, especially in the Meratus Mountains. The studied region is the major area of the Meratus Geopark. Selected ultramafic rocks from the Meratus Geopark were analyzed using X-Ray Fluorescence in the University of Tasmania. CCS project should consider the minimum implication for conservation strategy of geopark. Geologically, CCS is adapted through direct sequestration and carbon mineralization. Mafic-ultramafic lithologies are the best option for mineral carbonation. Most of the basaltic rocks in Indonesia are situated near active volcanoes that are heavily risky for CCS works. Ultramafic in the range of Meratus Geopark is clearly suitable for CCS because of its large expanse, far away from active volcanoes, without significant nickel mining activity. The project would promote geohazards and climate change issues of Meratus Geopark. In-situ CSS mineral carbonation should be located avoiding the Sultan Adam Mandiangin Serpentinite Geosite to nourish the geoconservation of Meratus Geopark. A successful CCS adaptation would be good evidence for the Indonesian government implementing the Paris Agreement.

Keywords: Carbon Capture and Storage, In-situ mineral carbonation, ultramafic, Meratus Geopark.

Abstract*-Paparan karbon dioksida dalam jumlah besar dan jangka panjang dapat menimbulkan penyakit bagi manusia dan membahayakan ekosistem. CCS merupakan terobosan untuk mengurangi kadar CO2 di atmosfer. Tujuan dari penelitian ini adalah untuk mendeskripsikan prinsip CCS dan kesesuaian penerapan metode ini di Indonesia, khususnya di Pegunungan Meratus. Wilayah yang diteliti merupakan wilayah utama dalam deleniasi Geopark Meratus. Batuan ultrabasa terpilih dari Geopark Meratus telah dianalisis menggunakan XRF di Universitas Tasmania. Proyek CCS harus mempertimbangkan dampak minimal terhadap strategi konservasi geopark. Secara geologis, CCS dapat diadaptasi melalui penyerapan langsung maupun karbonisasi mineral. Litologi mafik-ultramafik adalah pilihan terbaik untuk karbonasi mineral. Sebagian besar batuan basaltik di Indonesia terletak di dekat gunung berapi aktif yang sangat berisiko bagi proyek CCS. Batuan ultrabasa di kawasan Geopark Meratus dianggap sesuai untuk proyeksi CCS karena hamparannya yang luas, jauh dari gunung berapi aktif, dan tanpa aktivitas penambangan nikel yang signifikan. Proyek ini akan membantu promosikan isu geohazard dan perubahan iklim di Geopark Meratus. CSS jenis karbonasi mineral harus ditempatkan jauh dari Situs Serpentinit Sultan Adam Mandiangin untuk mendukung geokonservasi dari Geopark Meratus. Adaptasi CCS yang berhasil akan menjadi bukti bagus bagi pemerintah Indonesia dalam mengimplementasikan Perjanjian Paris.*

Keywords: *CCS, karbonasi mineral, ultramafik,Geopark Meratus.*

INTRODUCTION

Carbon dioxide (CO_2) emission happens both naturally and by anthropogenic activities. Outgassing from the ocean, metamorphism of carbonate-bearing sedimentary rocks, decomposing vegetation, venting volcanoes, naturally occurring wildfires, and belches from ruminant animals are the natural source of CO_2 (Azharuddin *et al*., 2022; Arzilli *et al*., 2023). The sharp rise of CO_2 emissions happened since the industrial era at the beginning of the 18th century because of human activities. Fossil fuels combustion, land use conversion, livestock production and fertilizer consumption are the primary anthropogenic CO_2 emission sources (Azdarpour *et al.*, 2014; Elmabrouk *et al.*, 2017; Ilyas *et al*., 2019; Farooq *et al*., 2019; Okoko & Olaka, 2021). The emission increases continually to meet the energy demand generated by population growth. Without serious work, CO_2 concentration was predicted to reach >1,000 ppm at the end of the 21st century (Li and Hitch, 2017). Besides energy production, CO_2 emission leads to various diseases in humans. Obstructive lung, low haemoglobin concentration, iron deficiency, nervous system impairment, and cancer are health impacts due to long-term high carbon exposure (Farooq *et al.*, 2019). Reduce, reuse, and recycle programs are the simple solution which is adaptable for any communities to reduce the environmental problem. In bigger scale, some countries introduced a carbon tax to lower their emissions and ultimately shift from a fossil fuel-based to lower-carbon energy. Nevertheless, the tax policy would degrade the industrial strength in the short run.

The Carbon Capture and Storage (CCS) scheme was proposed as a breakthrough on decreasing anthropogenic CO_2 emissions. The main concept of CCS is capturing carbon before released into the atmosphere, transporting it to a proper location, and storing it for a length of time. CCS implementation should be studied carefully because it requires a large capital investment and a high percentage of fixed assets. CCS is geologically adaptable through direct sequestration and mineral carbonation (Azdarpour *et al.*, 2014; Mohammed *et al.,* 2021). Direct sequestration scheme is worked in oil reservoir, deep saline formation, and unmineable coal seams, whilst mafic-ultramafic rocks are the most suitable lithology for CCS mineral carbonation because of the abundant composition of CO_2-reactive ions (Višković *et al*., 2014; Elmabrouk *et al*., 2017; Zhou *et al*., 2021).

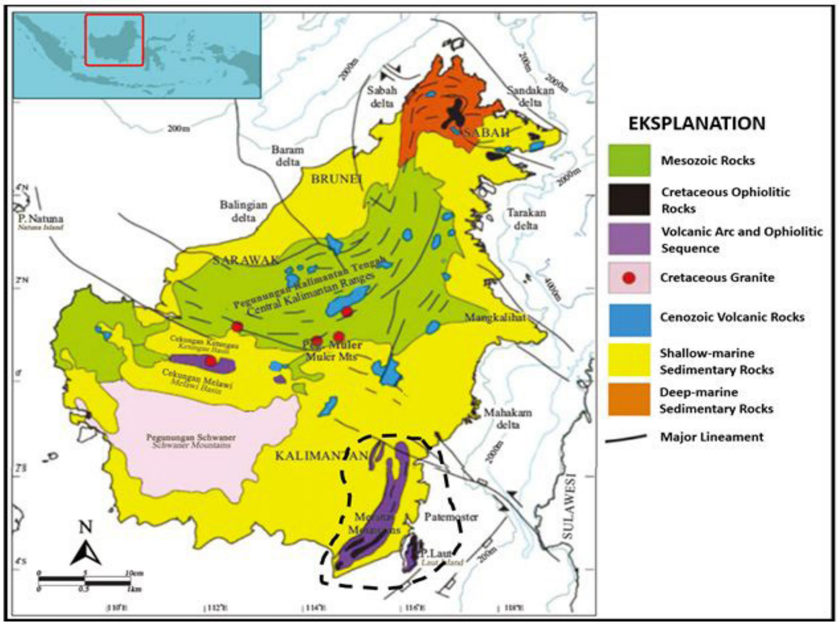
Geopark is a specific area comprised of geological heritage sites of specific significance, rarity or beauty for preservation. The essential purpose of building a geopark is to link conservation, education, and economic developments of a natural history (Dzulkafli et al., 2019; Xu and Wu, 2022). Meratus Geopark is located in the South Borneo Province, Indonesia (Figure 1). The area is principally built of Neogene sedimentary and ophiolite rocks. The expanse of ancient Meso-Tethys ophiolite is the theme of the geopark to amplify the mafic-ultramafic lithology of the geopark. Ecotourism in the Meratus Geopark is supported by a high level of geo-biodiversity and cultural resources that are crucial for the future (Normelani et al., 2021). No active volcanoes are identified in the Meratus region, so farming expansion and forest cover reduction are considered the most significant source of CO_2 emission. Although CCS is useful for constructing a green environment, the implementation may risk the natural conservation (Sanchez and Kammen, 2016; Hansson *et al.*, 2022).

This paper aims to describe the CCS principles and suitability of the project in Indonesia, especially in the Meratus Mountains. Because the studied region is included in the Meratus Geopark delineation, the CCS project should consider the minimum implication for the conservation strategy of a geopark. This study explains that CCS and geoconservation programs can be compromised by choosing the proper carbon-capturing mode and location. The CCS adaptation is good evidence for the Indonesian government on Paris Agreement implementation.

BASIC CONCEPT OF CCS

Capturing the Carbon Dioxide

CCS is basically a method for capturing CO_2 from large-scale emitters such as power plants, fossil fuel refineries, industrial chimneys, and directly from the air to be stored or converted into other harmless compounds. There are three options to capture carbon dioxide, namely pre-combustion, post-combustion, and oxy-fuel combustion (Bandilla *et al*., 2015; Lockwood, 2017; Tan *et al.,* 2020). In the pre-combustion scheme, CO_2 and H_2 from fossil fuels are separated before burning so that CO_2 is captured for storage, while H_2 is available for directly use in electricity generation (Nanda *et al.*, 2016). Adapting post-combustion, CO_2 in the furnace is separated after combustion. High-purity oxygen is added before combustion takes place so that CO_2 is easier to be trapped by adapting the oxy-fuel combustion method (Lockwood, 2017).



source: modified from Kausarian et al., (2019).

Figure 1. The location of Meratus Geopark in the South Borneo Province

The post-combustion is a well-developed capturing option. This method is better than the pre-combustion because of the availability of CO_2 partial pressures and can be installed to already existing plants. Nevertheless, a high energy load is required for post-combustion capture on trapping significant amounts of carbon, especially in the low CO_2 concentration in power plant flue gas of 4-14 % (Olajire, 2010). Pre-combustion capture is a solution for this condition which resulted in a much higher CO_2 concentration in comparison to the post-combustion. The most recent capture is through oxy-fuel combustion by firing coal in O_2 rather than air. This method produces a flue gas of mostly CO_2 and water, from which CO_2 can be simply separated. Nevertheless, the costs and energy required for this scheme are not notably different from the post-combustion capture (Lookwood, 2017).

Previous study gave a life cycle assessment of post-combustion, pre-combustion, and oxy-fuel captures comparison (Zhou *et al.*, 2014; Višković *et al.*, 2014; Mohammed *et al.*, 2021). The three options indicate system boundaries both in upstream and downstream processes of the power generation. Pre-combustion and oxy-fuel based plants needed less coal to generate equal electrical output compared to a power plant with post-combustion one so they reduced emissions and wastes. On acidification category, pre-combustion method was the safest because most of the SOx and NOx emissions have been trapped in the gas cleaning process after coal gasification. Moreover, this capture is the best for eco-toxicity because it can remove almost heavy metals and benzene in the gas cleaning process. Oxy-fuel scheme showed the least eutrophication potential and air-point source impacts as it produced a small amount of NOx and NH_3 which were further removed through compression and purification units.

Transporting the Captured CO_2

A reliable CO_2 transporting system from where the gas captured to a storage site is the next step in CCS works. The number of investments on transportation infrastructure depend on the scale, safety, and distance between capturing and storage units. Transportation system is determined by the scale of CCS plant. Pipelines, truck and ships are adapted in CO_2 commercial-scale transportation. Liquid CO_2 exhibits much less volume than its gas form, which is why it is often compressed into a liquid state before transport. Trucks are the best option for a plant in which capturing site is nearby the storage location. On the other hand, pipeline and shipping are the most common transportation method for very large CO_2 quantities. The pipelines should be high pressure resistance due to liquid CO_2 transportation and must be dried to prevent corrosion. Shipping is the most common for global scale liquefied gas transportation to connect locations separated by waters.

Unlike oil and gas, carbon dioxide is much safer to transport because it does not form flammable or explosive mixtures with air. However, a very rapid and in extremely high quantities of CO_2 leakage is catastrophic. Pipeline wrapping and routine gas seal test is applied to prevent such leakage (Xiuzhang, 2014). Serious impact on unadaptable plant species and microorganisms were reported due to CO_2 infiltration along CCS transport line (Rastelli *et al*., 2015; Lake and Lomax, 2019). The best solution for reducing the transportation cost and minimising the hazard risk is to select the nearest storage location from the capturing site.

Types of Geological CCS

Basically, CCS is adaptable through biological, physio-chemical, and geological principles. Carbon dioxide is important for plants to synthesize carbohydrates, proteins, and lipids through photosynthesis so plantations would reduce CO_2 composition in the atmosphere. Previous study applied algae to capture CO_2 on biological CCS principle (Beal *et al*., 2018). Various membranes, solvents, and sorbents are applied for physio-chemical based CCS. There are two options in geological CCS application: direct sequestration and mineral carbonation. The carbon is simply stored for a length of time without changing it into a new mineral in the direct sequestration method. On the other hand, carbon is synthesized into a new environmentally friendly mineral using mineral carbonation scheme.

Depleted oil and gas reservoirs, deep saline reservoirs, and unmineable coal seams are the three types of geological formations for CCS direct sequestration. Carbon dioxide is injected in a dense liquid state underground into a porous rock formation that holds or previously held fluids. Injection proximity, porosity, permeability, and leakage potential are factors to determine a suitable formation (Bandilla *et al*., 2015). Boosts of oil and gas productions are indicated after injecting carbon into the reservoirs (Elmabrook *et al*, 2017). Coal beds are commonly permeable and can trap methane which can be extracted. Injecting carbon into an unmineable coal seams improve the methane recovery (Vishal *et al*., 2013; Višković *et al*., 2014).

Carbon dioxide could be store permanently employing the mineral carbonation process which is adaptable through in-situ and ex-situ options. Moreover, the yield of mineral carbonation are environmentally friendly and leakage-free carbonate minerals. The concept of in-situ mineral carbonation is injecting CO_2 into a subsurface porous rock for a direct reaction of the gas with the rock's components, while the ex-situ mineral carbonation is worked by exposing the rich CO_2-reactive rock to the atmosphere. The second type of mineral carbonation has been adapted to remediate mining tailing and generate construction material. The storage potential of mineral carbonation assumed at 100,000–250,000 $GtCO_2$ (Snæbjörnsdóttir and Gislason, 2016).

Rocks containing large number of CO_2-reactive ions are the most appropriate for mineral carbonation. Ultramafic and basaltic rocks are the ideal target for mineral carbonation because of the high content of common CO_2-reactive minerals such as olivine, serpentine, brucite, wollastonite, and anorthite-rich plagioclase (Hamilton *et al*., 2020; Tan *et al*., 2020). Equation (1) and (2) shows the serpentine and olivine carbonation.

$$\underset{\text{(serpentine)}}{Mg_6Si_4O_{10}(OH)_8} + 3CO_2 \rightarrow \underset{\text{(magnesite)}}{3MgCO_3} + \underset{\text{(quartz)}}{2SiO_2} + \underset{\text{(water)}}{2H_2O} \quad (1)$$

$$\underset{\text{(olivine)}}{Mg_2SiO_4} + 2CO2 \rightarrow \underset{\text{(magnesite)}}{2MgCO_3} + \underset{\text{(quartz)}}{SiO_2} \quad (2)$$

MATERIAL AND METHODS

Sample Description

In the Meratus area, ultramafic rocks are part of the ophiolite sequence and are composed of harzburgite, lherzolite, dunit, werlite, websterite and gabbro or ultramafic rocks which are part of the ophiolite sequence. A total of 14 mafic-ultramafic samples were collected from the Meratus Geopark area in Borneo. Most of the rocks were located in Aranio District, while some of them from Sultan Adam Mandiangin Jungle in Karang Intan District and Sebuku Island. Although weathering horizons are identified in some outcrops, fresh ultramafic rocks were carefully selected for laboratory analysis. Megascopically, the rocks are peridotites and are composed of olivine, pyroxene, and amphibole. Serpentines were detected as the alteration results of olivine and pyroxene. One sample is serpentinite because of the high degree of alteration.

Chemical Analysis

Studied samples were send to the laboratory of University of Tasmania for X-Ray Fluorescence (XRF) analysis. After dried out door for one day, the rocks were then crushed with jaw crusher and were grounded using a ball mill to gain particle size of 200 mesh. Before instrument analysis, a hydraulic press was used to make the weighted samples into press pellets. Preparation and analytical procedures of Irzon (2018, 2020) were adapted in this study

RESULT AND DISCUSSION

Prospecting Mineral Carbonation in Indonesia

Mafic-ultramafic rocks are the most suitable lithology for mineral carbonation because of the high magnesium-silicate minerals contents. Basalt qualifies as a mafic igneous rock because of its high amount of MgO that gives basalt its dark color. Basaltic rock is easily adopted for CCS worldwide because of its occurrence both off and onshore on every continent. The mafic rock provides a low-risk option for CCS scheme in areas where traditional hydrocarbon exploration has not existed. Working it near some offshore fields, enabling the use of multiple reservoir storage scenarios. The Carbfix (Island) and Wallula (USA) plants are two active CCS projects on basaltic rocks. Both projects resulted rapid mineralization. About 95% and 60% of the injected CO2 was mineralised within two years in the Carbfix and Wallula, respectively (Snæbjörnsdóttir and Gislason, 2016).

Basaltic rocks in Indonesia outcropped along the Indonesia's volcanic belt which stretches from northern Sumatera - Java - Nusa Tenggara - Maluku to the North Sulawesi. MgO and CaO composition of basaltic rocks of Indonesia range in 1.13-5.93 and 4.54-15.5 (Table 1). Mg and Ca of the rocks are in the range of the basalt of the Wallula CCS Project (Zakharova et al., 2012). However, the significant risk that might eliminate the potential for CO2 storage in most of the listed basaltic rocks is the existence of nearby active volcanoes, except for the Sukadana-Tamiyang and Tanggamus (Figure 2). Tectonic activity enhances fracture formation for mineral carbonation reaction (Abu-Jaber, 2017). However, intensive volcano tectonics could open cracks which enable the injected carbon to release back into the atmosphere.

The higher MgO composition of ultramafic rocks makes them more favourable for the CCS project. MgO content of ultramafics of list range in 23.31-49%, while SiO_2 between 35.94% and 44.41% (Table 1). Unlike Indonesian S-type granites which are associated with tin, the ultramafics are often correlated with nickel (Irzon, 2019; Irzon *et al*., 2021). Studies concluded that North Konawe, North Kolaka, and Barru-Bantimala ultramafics are nickel rich, especially in their lateritic horizons (Maulana *et al.*, 2015; Irzon and Abdullah, 2018). Giant nickel mining industries work in that area. So, the high Ni content clearly eliminate their potential for CCS implementation. Meratus ultramafic spreads from the eastern Borneo and Sebuku Island. Nickel mining in the Meratus ultramafic region is only situated on Sebuku Island (Idrus *et al*., 2022), which means that the outcrop in Borneo and Laut Island is a high potential for CO_2 storage.

Table 1. Silica, magnesium, dan calcium contents of mafic-ultramafic rocks in Indonesia

Island	Location	Si (%)	Mg (%)	Ca (%)
Sumatra	Mandailing(1)	21.63-22.62	3.54-3.73	4.19-4.54
	Sukadana(2)	23.48-24.60	2.60-3.48	5.33-5.83
	Tanggamus(3)	23-24.51	1.78-3.05	3.25-6.01
Java	Guntur Volc.(4)	24.11-26.41	2.44-2.79	5.68-6.94
	Magelang(5)	24.07-25.01	0.71-1	5.24-5.62
	Kulonprogo(6)	21.32-25.01	1.85-3.59	5.65-11.07
Lembata	Lembata(4)	24.09-24.77	2.56-2.86	7.18-7.21
Halmahera	West Halmahera(7)	Na	Na	Na
Sulawesi	Soputan Volc.(4)	23.08-23.51	2.97-3.53	7.06-7.59
	North Konawe(8)	18-19.20	23.31-27.09	0.64-2.5
	North Kolaka(9)	16.80-19.40	21.03-24.85	0.3-1.19
	Barru-Bantimala(10)	17.11-18.95	28.35-30.87	<0.03
Borneo	Meratus	18.42-20.61	17.87-24.37	0.26-7.56
USA	Wallula(11)	24.99	1.71	5.57

(1) Zulkarnain (2009); (2) Zulkarnain (2011); (3) Irzon (2020); (4) De Hoog et al. (2001); (5) Habib et al. (2021); (6) Irzon (2018); (7) Irzon (2019); (8) Irzon and Abdullah (2018); (9) White et al. (2017); (10) Maulana et al. (2015); (11) Zakharova et al. (2012).

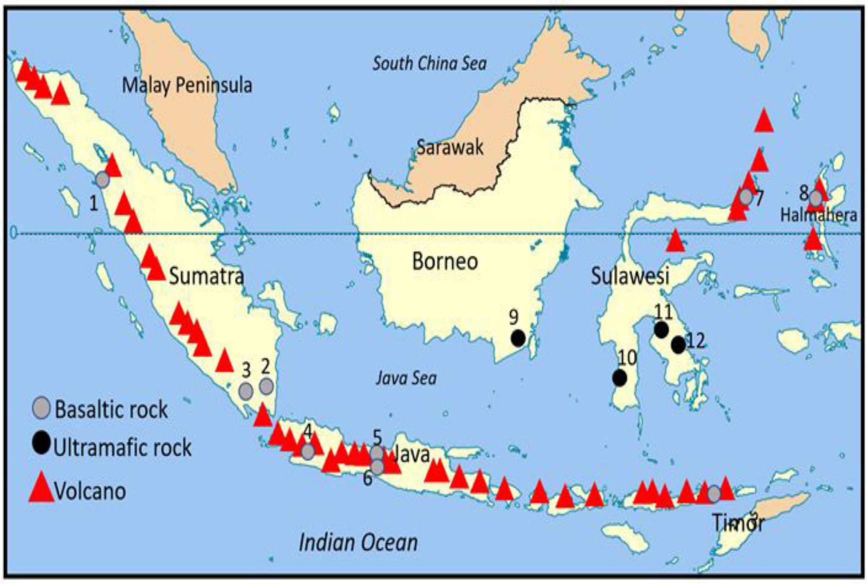


Figure 2. Mafic-ultramafic outcrops in Indonesia. Most basaltic rocks are located near volcanoes, but ultramafic ones are not. 1 = Mandailing, 2 = Sukadana, 3 = Tanggamus, 4 = Guntur, 5 = Magelang, 6 = Kulon Progo, 7 = Soputan, 8 = Halmahera, 9 = Meratus, 10 = Barru-Bantimala, 11 = North Kolaka, 12 = North Konawe.

Possible Risks of CCS Plant

Although CCS recognition has tended to rise since the early 2000s, some potential obstacles should be considered before implementing this program. Political support from national government is crucial. Leaders from Australia, Canada, Europe, the United Kingdom, and the United States of America committed to deploy CCS to fight against climate change (Lipponen *et al.,* 2018). As a member of the G20 forum, Indonesia should issue supportive regulations on the Paris Agreement. Research grants, international collaboration, and constructive permission are helpful to encourage this idea.

A large budget is another barrier to CCS deployment. The Australian Integrated Gasification Combined Cycle (IGCC) project was postponed due to huge cost of AUD 6.9 billion (about Rp. 68 trillion). Estimating the actual budget for CCS and explaining it to the public is challenging because of the lack of empirical data. Technology selection, domestic productivity factors, access to suitable storage, infrastructures, and gas transportation are some factors associated with the project cost (Budinis *et al.*, 2018; Lipponen *et al*., 2018). The capture technology is definitely the most expensive factor of the CCS chain. The transport budget depends on location and the type of pipeline, while storage site category and possible reuse of existing facilities highly influence the storage cost (Budinis *et al.*, 2018).

Leakage is a possible drawback to a large-scale CCS plant. Leaked fluids up to a formation above the storage reservoir might result in several ways, namely remaining isolated from other subsurface activity, being involved in any subsurface activity, contaminating the groundwater, or arriving at the surface and released into the atmosphere (Deng *et al*., 2017). This phenomenon amplifies the significance of both surface and subsurface seepage studies before starting a CCS plant. Several adoptable researches are available on counting the possibility and the cost of any direct and undirect leakages (i.e., Bielicki *et al.* 2016; Deng *et al*., 2017).

Suitable Location for CCS in Meratus Geopark

Meratus is a mountain range that stretches for ± 600 km² in the southeast of Kalimantan Island and splits South Kalimantan Province into two. The region is unique in its biology, cultural, and geology diversities. Anwar *et al.* (2018) argued that the mountain range has high biodiversity with some dominant vegetation such as meranti (*Shorea spp.*), kedondong (*Canarium spp.*) durian (*Durio sp*), kempas (*Koompassia sp*), and maggots (*Quercus sp*). Meratus is the home to the indigenous tribe called the Meratus Dayak. Meratus is largely composed of Paleogene ophiolite and is situated far away from the edges of plate convergence. This ultramafic is the oldest rock in the South Kalimantan region and is also one of the oldest rocks exposed in Indonesia.

The Meratus Geopark was established as an Indonesian national geopark in 2018. Geological, cultural, and biological heritages are delineated into the geopark area for sustainable development (Dzulkafli *et al*., 2019; Mokhtar *et al.*, 2019). Meratus Geopark is projected for aspiring UNESCO global geopark that its activities should concentrate on the "Top 10 Focus Areas", namely the natural resources; geohazards and climate change; education of inhabitants and visitors; academic research; local cultural heritage; women empowerment and equality; indigenous people knowledge; geotourism; local product promotion; and geoconservation (Fassoulas *et al*., 2022). CCS project is suitable for promoting the geopark through geohazards and climate change issues.

Twenty-five heritages are situated in the Meratus Geopark, consisting of 11 geological sites, 5 biological sites, and 9 cultural sites. Sultan Adam Mandiangin Serpentinite is a geological site comprising Middle Jurassic ultramafic rock and occupies a hill with an altitude of between 400-600 m above sea level (Sikumbang and Heryanto, 1994). The best spot of the site situated in the Grand Forest Park of Mandiangin Village. The serpentinite is quite firmly fractured. In some places it forms boudinage which is bounded by paired cracks, each trending east-northeast and west-southwest.

Previous studies described that a large ultramafic complex comprised of harzburgite, wehrlite, websterlite, pyroxenite and serpentinite is found in the Meratus Geopark (Anwar et al., 2018; Wang et al., 2022). Tectonically, the rock is in contact (faults) with metamorphic rocks, volcanic rocks, and sedimentary rocks. The ultramafic complex spread in a large area along the Bobaris Mountains, Manjam Mountains and Kusan Mountains. The extensive ultramafic dissemination enables a CCS plant in the Meratus region without interfering with the conservation issue of a geopark. Moreover, CCS supports the climate change issue of the geopark. The only concern is that the CCS injection project should be built avoiding the Sultan Adam Mandiangin Serpentinite Geosite.

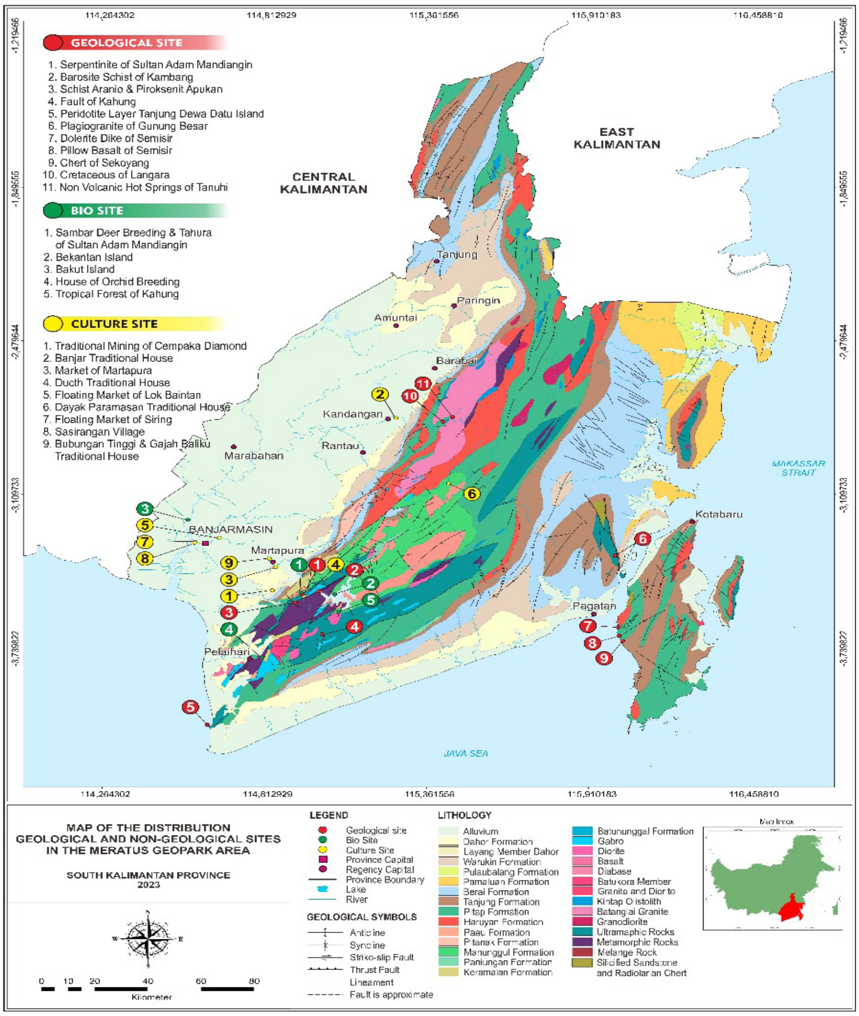


Figure 3. Lithology and twenty-five heritages in the Meratus Geopark.

CONCLUSION

Carbon capture and storage is an option for reducing CO_2 composition in the atmosphere. Based on geological principles, CCS might be adapted through direct sequestration and carbon mineralization. Mafic-ultramafic rocks, including basalts, are the most suitable lithologies for mineral carbonation. Adapting CCS in basaltic rocks of Indonesia is high risk as most of the mafic lithology is situated near active volcanoes. Ultramafic in the range of Meratus Geopark is potential for CCS because of its large expanse, far away from active volcanoes, without significant nickel mining activity. Moreover, the project would help promoting geohazards and climate change issues of Meratus Geopark. In-situ CSS mineral carbonation should be work evading the Sultan Adam Mandiangin Serpentinite Geosite to maintain the geoconservation of Meratus Geopark.

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