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CO_2 Geo-Sequestration Potential in the Onshore Mafic Basalts of Malaysia: Case Study on their Morphology, Geochemical, and Geomechanical Properties

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Abstract

Earth's ecosystems have been greatly affected since the Industrial Revolution, with a significant increase in the atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) from burning fossil fuels and large amounts of emissions produced by the Cement and Steel industries (Chien et al., 2023; Joarder et al., 2023). Recently, interest in developing Carbon Capture, Utilization, and Storage (CCUS) technologies has surged, aimed at eliminating CO_2 emissions associated with fossil fuel consumption (Al-Shafi et al., 2023). CCUS could offer diverse and enhanced solutions for reducing CO_2 greenhouse gas emissions and achieving net-zero emissions. Carbon Capture and Storage (CCS) technology is an effective strategy for mitigating climate change and has emerged as a promising strategy to address global warming (Massarweh et al., 2024). It comprises capturing CO_2 from stationary emission plants, industrial and power plants, transporting it through pipelines or ships, and storing it in underground geological formations such as depleted hydrocarbon reservoirs, deep saline aquifers, coal beds (which can't be mined), and un-conventional shale formations which facilitates its isolation from the atmosphere for a long time (Bachu, 2003; IPCC, 2005; Zhang and DePaolo, 2017; Vishal et al., 2013). In addition to these geological sites, oceanic, biological, and mineral carbonation sites are also considered for CO_2 storage. This storage of CO_2 is mentioned as Geo-sequestration or Geologic storage (Herzog et al., 2004). CO_2 is stored in geologic formations by several dissimilar trapping mechanisms such as Physical trapping (Structural, Residual Traps) and Chemical Trapping (Solubility and Mineral Traps), with the exact mechanism depending on the formation type. Carbon mineralization in igneous rocks such as Basalts and Peridotites is another potential CO_2 storage technique that does not suffer from the limitations of sedimentary formations (Kelemen et al., 2019; Snaebjornsdottir et al., 2020). According to the International Energy Agency (IEA), carbon mineralization can reduce up to 10-15% of the global CO_2 emissions (IEA, 2011). However, given the lack of resources and rapid mineralization, only small to medium emitters (<2.5 Mt. CO_2 per year) are considered for CO_2 mineralization (Sanna et al., 2012). Suitable Rocks for effective carbon mineralization are mafic (basalt) or ultramafic lithologies (peridotites) due to their high content of divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}), favorable mineral compositions (pyroxene and olivine) and high reactivity (Snaebjornsdottir et al., 2020). Currently, there are two known pilot projects for CO_2 injection into basalts in Iceland (CarbFix Project) and in the USA (Wallula Project) which demonstrate new insights for CO_2 geo-sequestration through mineralization and development of pilot projects in the Basalts for future studies (McGrail et al., 2017). Carbon mineralization methods are generally divided into two categories: i.) ex-situ, ii.) in-situ methods. In-situ mineralization involves the idea of capturing CO_2 and injecting it into reactive rocks such as mafic (basalts) and ultramafic (peridotites) where, secondary trapping mechanisms, including solubility trapping by the dissolution of CO_2 in reservoir fluid, capillary trapping by capillary forces, and mineralization by fluid-rock interactions cause CO_2 trapping depending on geological and operational conditions (Raza et al., 2016; Iglauer, 2011; Oelkers et al., 2008; Takaya et al., 2013). The main advantage of this method is the low risk of leakage due to the rapid transformation of CO_2 into stable carbonate minerals (mineral trapping) (Goldberg et al.,

2008). The carbon mineralization rate by these methods depends on the amount of dissolved CO_2, the presence of divalent ions in the host rock, and the alkalinity of the solution (Kelektsoglou, 2018). The acidity of the aqueous solution plays a complicated role, as a low pH (<7) environment promotes mineral dissolution while a high pH (>7) solution enhances carbonate precipitation (Park and Fan, 2004; Pokrovsky and Schott, 2004). The present study targets the onshore mafic basaltic rock sites with potential for CO_2 geo-sequestration around Western and Eastern Malaysia. The existing works of literature and field observations suggest that the few exposures of offshore and onshore Basalts found in Kuantan, Pahang (Peninsular Malaysia); Sematan, and Kuching (Eastern Malaysia) hold the effective potential for CO_2 geo-sequestration due to their mineral composition (plagioclase, pyroxene, olivine), high reactivity and suitability for CO_2 mineralization. The methodology is demonstrated through field-scale observations, geological mapping of the suitable area, collection of rock samples from the outcrop, laboratory experiments, and understanding of the morphology and thickness of the onshore basalts of Malaysia. The case study is conducted based on the Geochemical and Geo-mechanical properties of the onshore basalts upon injection or reactivity with CO_2 through various experiments for sequestration potential. The laboratory experiments based on geochemical properties are conducted to examine the various mineral and oxide compositions of the basalts, their characteristics & morphology, and surface area through (XRD, XRF, FESEM, SAP, MIP, and Raman spectroscopy) analysis; and the experiments based on geo-mechanical properties such as (Uniaxial, Triaxial, Pulse-wave velocity with acoustic sensors) for identifying strength/integrity; and experiments based on petrophysical properties such as (Porosity and Permeability) for enhancing the potential for CO_2 mineralization and Geo-sequestration in the onshore basalts of Malaysia. The Core-flooding experiments using the relative Permeability system are carried out to demonstrate the fluid-rock interactions and fluid flow studies with the (core samples); experiments using Batch reactors (powdered samples) are carried out at various pressures, temperatures, and pH conditions to understand the properties of CO_2, mineralization, and reaction kinetics processes through which it undergoes dissolution of the divalent cations as bicarbonates which precipitate to form solid carbonates such as calcite, magnesite, dolomite. The Preliminary results obtained from the Geochemical, Geomechanical, and petrophysical properties of the Kuantan area and Sematan area Basalts suggest that the mineral compositions, morphology, characteristics, strength/integrity, natural fractures, and porous nature could yield the necessary potential for CO_2 Geo-sequestration study in the onshore basalts of Malaysia for long-term stability and for conducting further pilot-scale studies in the future.

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