Key Considerations for Carbon Dioxide Sequestration in the Lower Mainland, Southwestern British Columbia (Parts of NTS 092G/01–03)

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Introduction

The continuous rise in atmospheric carbon dioxide (CO_2) levels, initially observed by Keeling in 1960 (Keeling, 1960), has persisted over time, with annual peak concentrations showing a consistent upward trend (Ewald, 2013; Keighley and Maher, 2015). Although CO_2 is naturally generated, the predominant cause of recent increases, spanning from the 1800s to the present, is largely attributed to human activities, specifically the use of carbon-based resources such as coal, oil and methane-rich natural gas (Keighley and Maher, 2015). Elevated CO_2 concentrations alter the Earth's atmospheric composition by amplifying the natural greenhouse effect, resulting in a warming influence on the planet's surface (Bachu, 2003). As the Earth's climate continues to warm, the frequency and intensity of extreme weather events, including phenomena like heat domes, tropical cyclones, increased precipitation and heightened instances of flooding, are expected to rise (Flannigan and Wagner, 1991). Given the substantial risks these events pose to critical societal infrastructure, concerns regarding the societal impacts of climate change have understandably intensified (Bratu et al., 2022). Nevertheless, it is important to acknowledge that CO_2 emissions are anticipated to continue their upward trajectory, as the global transition toward a carbon-neutral economy is projected to extend over several decades (U.S. Energy Information Administration, 2021).

Discovering practical solutions for reducing carbon emissions while maintaining the current standard of living and improving the quality of life in developing nations necessitates cost-effective and innovative approaches. In this context, the most promising strategy for promptly and moderately reducing CO_2 emissions is CO_2 capture and underground sequestration (Intergovernmental Panel on Climate Change, 2014). Carbon capture and storage (CCS) involves the extraction of CO_2 from industrial sources, followed by its injection into suitable geological formations. Numerous studies (Kaszuba et al., 2003; Bachu and Gunter, 2005; Kharaka et al., 2006; Shukla et al., 2010; Stephenson et al., 2019; Pearce et al., 2021) have explored and validated the feasibility of CCS. Typically, CCS implementation is concentrated in regions with significant hydrocarbon production (Lane et al., 2021). Conversely, areas with limited oil and gas exploration tend to overlook CCS assessment and opportunities, often due to the presumption that underground storage is impractical.

The Lower Mainland of British Columbia (LMBC) has previously undergone assessments related to its hydrocarbon potential and suitability for natural gas storage, suggesting that it could serve as an accessible and potentially economically viable site for CO_2 storage (Gordy, 1988; Hannigan et al., 2001). However, to date, there has been limited effort directed toward evaluating the feasibility of CCS in the LMBC. The sedimentary layers beneath the LMBC remain inadequately understood, particularly at greater depths, and a detailed examination of the geological context, including the interpretation of depositional environments and facies analysis, has not been undertaken. To address this significant knowledge gap, this research provides a concise overview of the essential considerations involved in the assessment of CO_2 sequestration potential within saline aquifers situated in the LMBC. These considerations encompass factors such as geothermal gradient and pressure, reservoir thickness, salinity, mineral composition, porosity and permeability characteristics, seismic activity and fault distribution.

Study Area

The geological strata beneath the LMBC are part of the broader geological feature known as the Georgia Basin, which is characterized by a northwest-southeast orientation and is marked by a structural and topographic depression. The Georgia Basin spans an extensive area of approximately 18 000 km^2 and includes the Strait of Georgia, eastern Vancouver Island, the Fraser River Lowland and the northwestern region of the State of Washington, United States (Figure 1; Molnar et al., 2010).

The sedimentary deposits within the Georgia Basin can be categorized into three primary tectonostratigraphic clastic

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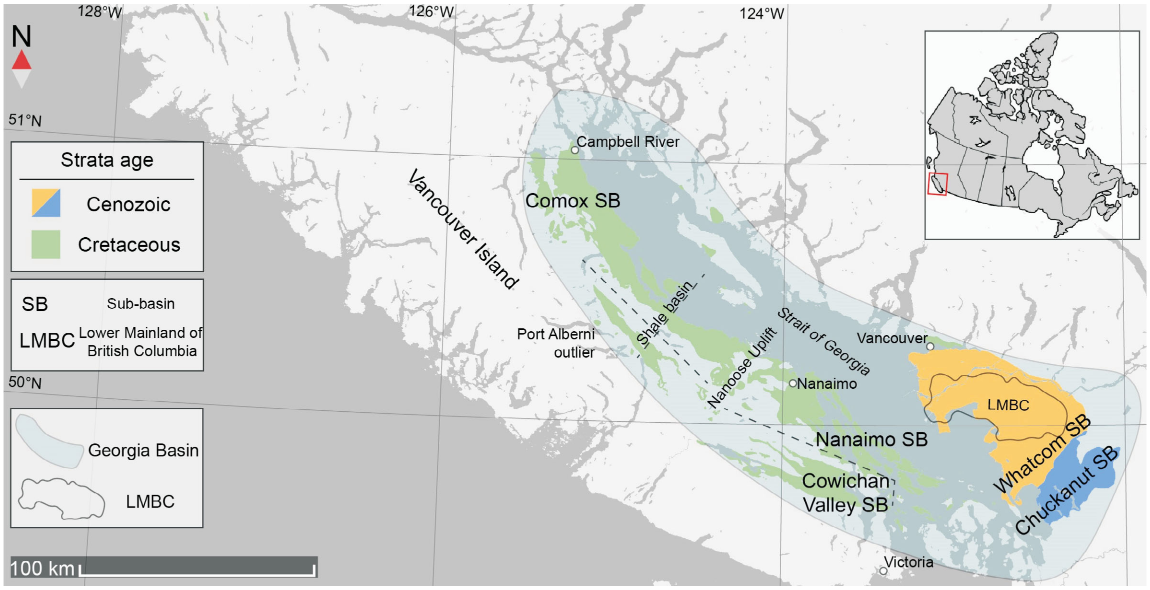

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Figure 1. Location map of the Georgia Basin and Lower Mainland of British Columbia (LMBC), and simplified geological map of southwestern British Columbia, Canada. Outcrop areas in the Georgia Basin include Upper Cretaceous Nanaimo Group strata exposed in the Comox, Nanaimo and Cowichan Valley sub-basins (green); Paleogene and Neogene strata in the Whatcom sub-basin (orange); and Paleogene and Neogene strata in the Chuckanut sub-basin (blue). The inset figure shows the location of the larger map within the context of the province of British Columbia and the rest of Canada. Figure reprinted from Huang et al. (2022).

sedimentary units: firstly, the predominantly Upper Cretaceous Nanaimo Group; secondly, the Paleogene Huntingdon Formation; and, thirdly, the Neogene Boundary Bay Formation (Figure 1; Monger, 1990; Groulx and Mustard, 2004; Molnar et al., 2010). The LMBC includes Metro Vancouver, the Fraser River Lowland and the adjacent mountainous areas. This region is home to more than 60% of British Columbia's (BC) population, exceeding 3 million residents, making it the third-largest urban area in Canada. The LMBC is geographically defined by the Coast Mountains to the north, the Cascade Mountains to the east and the international border separating Canada and the United States to the south. Furthermore, the LMBC features prominent population centres that also serve as significant industrial hubs, housing numerous large carbon-emitting facilities.

Geological Background

Tectonic Setting and Basin Type

The Canadian Cordillera is geologically categorized into five distinct morphological belts, arranged from west to east: the Insular, Coast, Intermontane, Omineca and Foreland belts (Figure 2; Monger and Price, 2002). Each of these belts is characterized by a unique combination of geological features, including landforms, rock types, metamorphic grade and structural characteristics (Gabrielse and Yorath, 1991). The formation of the southern Canadian Cordillera can be attributed to the amalgamation of two superterranes, which also correspond to two of the morpho-

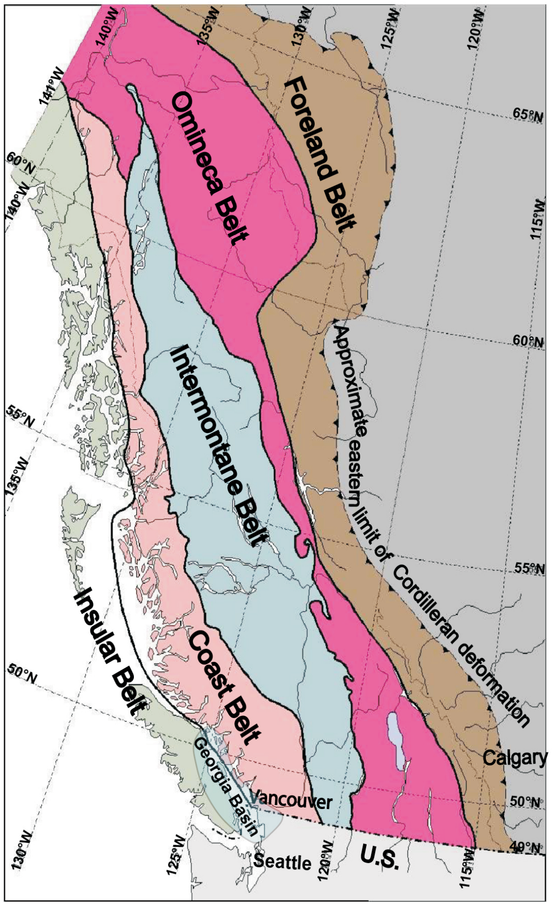

Figure 2. Morphogeological belts of the Canadian Cordillera (from Wheeler et al., 1991).

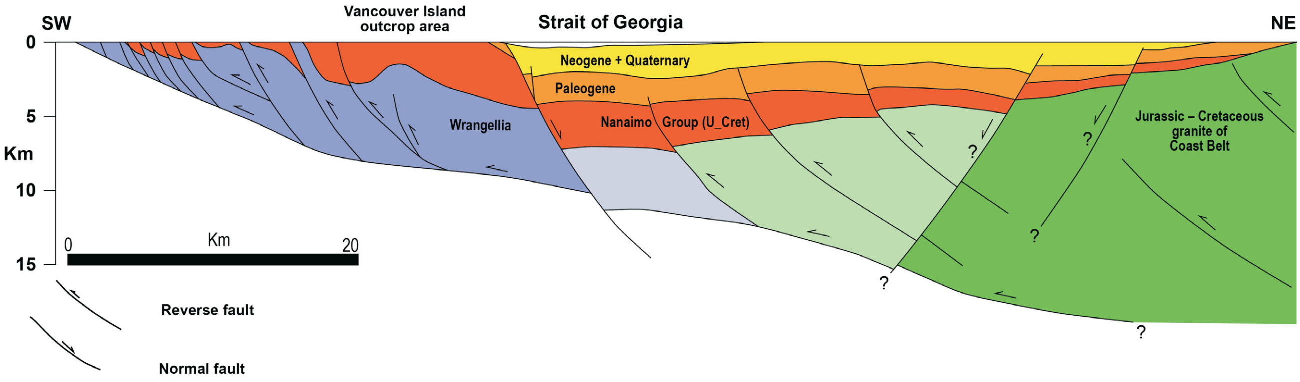

Figure 3. Idealized structural cross-section of the southern Georgia Basin based on LITHOPROBE data, modified after England and Bustin (1998), England and Calon (1991) and Gordy (1988). Question marks along the fault surfaces indicate interpreted locations. Paler shades of purple and green are used on the strata below the Strait of Georgia, but they are still part of the Wrangellia (purple) and Jurassic–Cretaceous (green) sequences. Abbreviations: NE, northeast; SW, southwest; U_Cret, Upper Cretaceous.

logical belts (Figures 2, 3). Specifically, the eastern Intermontane Superterrane was accreted during the Middle Jurassic, whereas the western Insular Superterrane was accreted during the Early Cretaceous (Monger, 1991a, b; Zelt et al., 2001). These two superterranes are separated by the Coast Belt or Coast Plutonic Complex (CPC), which represents a region characterized by high-grade metamorphic rocks and intrusive plutonic formations. It is believed that the Coast Belt or CPC formed during the Early Cretaceous when the Insular Superterrane accreted to the western margin of North America (Monger et al., 1994).

The Georgia Basin is a Cretaceous to Cenozoic fore-arc basin that straddles the boundary between the Insular Superterrane and the CPC (Figures 1, 2; England, 1991; England and Bustin, 1998; Monger and Price, 2002). Based on the structural evolution of the Canadian Cordillera, previous workers have posited that the Georgia Basin was developed in the arc-trench gap between Wrangellia and North America and overlies the eastern portion of Wrangellia and the western portion of the CPC (Figure 1; Muller and Jeletzky, 1970; Bustin and England, 1991; England, 1991; England and Calon, 1991).

The preserved thick successions of shallow-marine proximal facies could reflect a more oblique convergent character for the Georgia Basin. However, recent studies of fore-arc basins globally have identified thick basal successions of terrestrial and shallow-marine strata in similar fore-arc settings, suggesting shallow-marine strata are common in these basins and particularly in ridged fore arcs (Takano et al., 2013; Jones, 2016; Takano and Tsuji, 2017; Kent et al., 2020).

The siliciclastic sedimentary fill within the Georgia Basin can locally reach a thickness exceeding 6 km (England and Bustin, 1998). This sedimentary fill consists of Late Cretaceous through to modern strata (Figure 3; Hannigan et al., 2001). The Georgia Basin is subdivided into five distinct sub-basins (Figure 1; Mustard and Monger, 1994; England and Bustin, 1998; Hannigan et al., 2001; Huang et al., 2019, 2022; Kent et al., 2020; Girotto, 2022). The Nanaimo sub-basin encompasses the southeastern coast of Vancouver Island, the adjacent Strait of Georgia and the Gulf Islands. The Comox sub-basin is located farther north, along the east-central coast of Vancouver Island and the adjacent Strait of Georgia. The Cowichan Valley sub-basin was initially designated as a separate sub-basin due to uncertainties regarding its relationship with the rest of the Nanaimo Group. Subsequently, later studies incorporated the Cowichan Valley sub-basin into the Nanaimo sub-basin without providing a specific rationale for this revision (Clapp, 1913). The Cowichan Valley sub-basin was subsequently redefined as a distinct sub-basin by Huang et al. (2022) and Girotto (2022). This redefinition was based on differences in detrital zircon age populations and maximum depositional ages observed in strata near the basal unconformity compared to strata in the Comox and Nanaimo sub-basins.

The Chuckanut and Whatcom sub-basins encompass specific geographic regions, with the Whatcom sub-basin covering the Fraser Delta and the Chuckanut sub-basin encompassing northwestern Washington (Figure 1; Hannigan et al., 2001; Kent et al., 2020). The Whatcom sub-basin hosts sedimentary strata of the Nanaimo Group. These strata underlie sedimentary layers, including Paleogene sedimentary rocks of the Huntingdon Formation, Neogene sedimentary rocks of the Boundary Bay Formation and Quaternary sediments from the Fraser River (Figure 4; Zelt et al., 2001).

The Chuckanut sub-basin is separated from the Whatcom sub-basin by the Lummi Island fault, which has experienced more than 1.5 km of southward displacement (Miller, 1963; Johnson, 1985). The sedimentary fill within the Chuckanut sub-basin comprises the Chuckanut Formation,

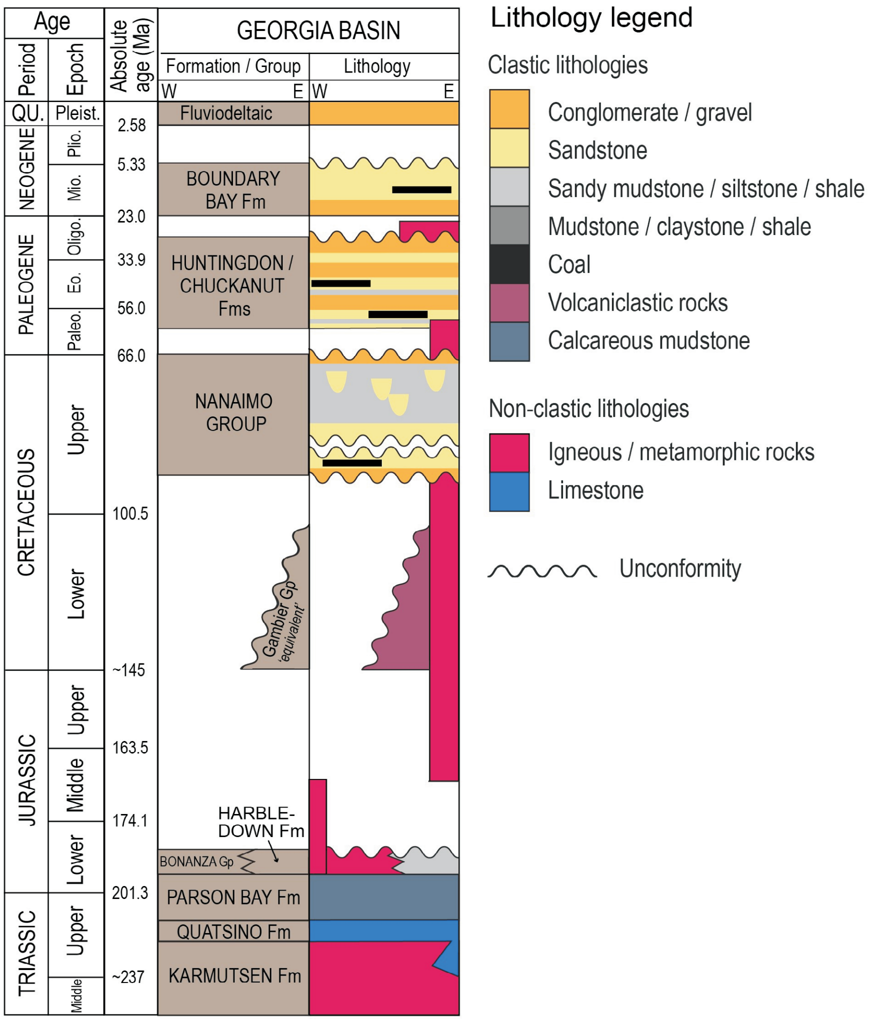

Figure 4. Simplified stratigraphic column for the Georgia Basin (with data from Haggart, 1992, 1993; Hannigan et al., 2001; Bain and Hubbard, 2016; Englert et al., 2018; Huang et al., 2019; Kent et al., 2020). Potential reservoir strata occur in coarse clastic rocks of the Huntingdon and Boundary Bay formations and the Nanaimo Group. Abbreviations: E, east; Eo., Eocene; Fm, Formation; Gp, Group; Mio., Miocene; Oligo., Oligocene; Paleo., Paleocene; Pleist., Pleistocene; Plio., Pliocene; QU., Quaternary; W, west.

Boundary Bay Formation and overlying Quaternary deposits (Figures 1, 4).

General Stratigraphy

The basement underlying the Georgia Basin is primarily composed of Wrangellia terrane, which consists of several geological components. These include the Sicker arc, formed during the Silurian to Devonian as an island arc; a Triassic mid-ocean basalt plateau (the Karmutsen Formation); the Bonanza arc, a Jurassic bimodal arc; and sedimentary rocks associated with these features (Huang et al., 2022). In the eastern part of the Georgia Basin, the basement comprises CPC, a continental arc that spanned from the Middle Jurassic to the Eocene (Monger and Journeay, 1994). Additionally, the Gambier Group, a sequence of Lower Cretaceous volcanogenic sedimentary and volcaniclastic rocks, forms part of the basement in this region (Figure 4; Lynch, 1991, 1992; Monger and Journeay, 1994). The sedimentary fill of the Georgia Basin, which ranges from mainly Upper Cretaceous to the lowermost Paleocene, is primarily composed of the Nanaimo Group, with a thickness of approximately 4 km (Figures 3, 4; Mustard, 1991; Mustard et al., 1994; England and Bustin, 1998; Huang et al., 2022).

The Nanaimo Group is informally subdivided into two main units, known as the lower and upper Nanaimo Group. The lower Nanaimo Group primarily consists of continental to shallow-marine strata and is found in sedimentologically isolated sub-basins, including the Comox, Nanaimo and Cowichan Valley sub-basins (Figure 1; Girotto, 2022; Huang et al., 2022). Within the Comox and Nanaimo sub-basins, the lower Nanaimo Group is further divided into

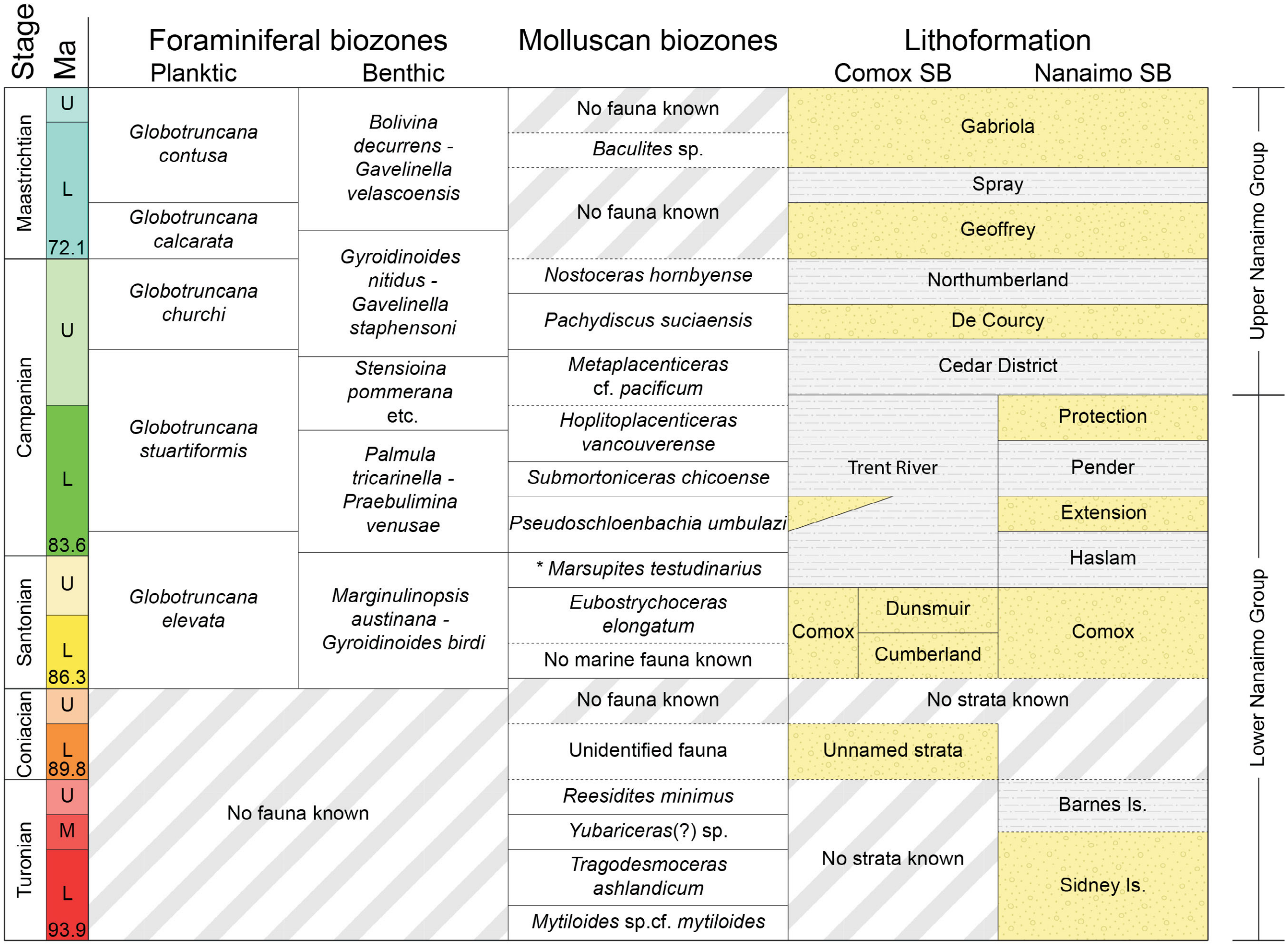

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Figure 5. Nanaimo Group lithostratigraphy in the Nanaimo and Comox sub-basins (Mustard et al., 1994; Haggart et al., 2005) including foraminiferal (Sliter, 1973; McGugan, 1979) and molluscan biozones (Muller and Jeletzky, 1970; Haggart et al., 2005; Ward et al., 2012; Haggart and Graham, 2018). In the formation column, yellow indicates strata that comprise dominantly sandstone and/or conglomeratic intervals, and grey indicates dominantly mudstone and shale. Figure reprinted from Huang et al. (2022). Abbreviations: Is., Island; L, Lower; M, Middle; SB, sub-basin; U, Upper.

lithostratigraphic formations. These formations alternate between predominantly coarse- and fine-grained strata. In the Comox sub-basin, the lower Nanaimo Group comprises the Comox and Trent River formations. The Nanaimo sub-basin includes the Sidney Island, Barnes Island, Comox, Haslam, Extension, Pender and Protection formations (Figure 5; Girotto, 2022).

The transition from the lower to the upper Nanaimo Group marks the consolidation of the previously isolated sub-basins into a unified basin, initiating deep-marine sedimentation across the entire basin (England, 1991; Mustard, 1991; Mustard and Monger, 1994; Kent et al., 2020; Girotto, 2022). The upper Nanaimo Group comprises formations such as the Cedar District, De Courcy, Northumberland, Geoffrey, Spray and Gabriola formations (Figure 5; Mustard and Monger, 1994; Huang et al., 2019, 2022; Kent et al., 2020). Although the Nanaimo Group is predominantly exposed in eastern Vancouver Island, these strata also extend into the subsurface beneath the Strait of Georgia and the LMBC (Figures 3, 4). However, the understanding of the subsurface distribution and characteristics of the Nanaimo Group strata remains limited due to a lack of comprehensive data.

The Huntingdon Formation in British Columbia and the Chuckanut Formation in Washington represent the primary sedimentary fill during the Paleogene within the Georgia Basin (Figure 4; Vance, 1975; Johnson, 1984; England and Hiscott, 1992; Hannigan et al., 2001). In both the Canadian and American portions of the Georgia Basin, Paleogene strata are characterized predominantly by continental deposits (Johnson, 1984, 1991; Mustard and Monger, 1994; Hannigan et al., 2001). Intrusive Oligocene dikes and sills are locally observed in the Vancouver area, penetrating both Paleogene and Cretaceous strata (Figure 4; Mustard et al., 1994). Within the LMBC, the Huntingdon Formation is disconformably situated over the upper Nanaimo Group

(Figures 3, 4; Mustard et al., 1994). Within the Whatcom sub-basin, there exists a substantial and distinctive succession of mainly Miocene sedimentary rocks that differ from the older Cenozoic sedimentary rocks (Hopkins, 1966, 1968; Rouse et al., 1990; Mustard and Rouse, 1991; Mustard et al., 1994). These sedimentary rocks are referred to as the Boundary Bay Formation (Mustard et al., 1994) and are primarily exposed in scattered outcrops along the lower Fraser River valley and to the east and northeast of Bellingham in Washington (Figure 1; Hannigan et al., 2001).

Exploration History and Regional Studies

The scientific exploration of the Georgia Basin has a rich history spanning over 140 years, initially driven by the discovery of substantial bituminous coal reserves in the region between 1850 and the early 1900s. Subsequently, the basin garnered scientific attention due to its potential for significant hydrocarbon deposits (Bustin and England, 1991; Bustin, 1995).

Exploration surveys (e.g., geological, seismic, gravimetric, magnetic) and drilling for hydrocarbons have been conducted intermittently in the basin since the early 1920s, with little tangible success. The first petroleum exploration wells were drilled prior to the acquisition of the first seismic lines, with the first well drilled in Whatcom County, Washington, in 1901, and the first well in the Fraser Valley, Canada, drilled in 1906 (Johnston, 1923; McFarland, 1983). Of all 118 wells drilled for oil and gas exploration within the Georgia Basin (particularly in the Canadian part), only 44 wells have known location and drilling information (Figure 6). Twenty-four of the drilled wells within the Canadian part of the Georgia Basin have wireline log data (11 wells in the LMBC and 13 wells on Vancouver Island; Figure 6).

The first basin-scale exploration survey was a regional aeromagnetic geophysical survey, led by the Geological Survey of Canada in 1955. In 1959, a gravity survey was conducted by Petcal Ltd., which encompassed most of the Fraser Valley and west of Abbotsford. In 1959, the first large-scale seismic reflection survey was conducted by Richfield Oil Corporation. The coverage of the seismic reflection survey extended from Abbotsford to the Strait of Georgia, and between the Fraser River and the United States border. In 1977, a seismic program was conducted by BC Gas (now FortisBC) to assess the potential for underground gas storage in the LMBC; this program involved acquiring 322 km of two-dimensional (2-D) seismic lines. Geophysical surveys outside of the LMBC include surveys in the United States, the Strait of Georgia and Vancouver Island. In the United States, CGG (Companie Général Géophysique) acquired seismic reflection data in 1985 in Whatcom County. In 1962, Canadian Superior Oil Ltd. acquired roughly 245 km of gas-exploder seismic data in the Strait of Georgia. Soon after, the British American Oil Company Limited acquired 1150 km of gas-exploder marine seismic data in the Strait of Georgia. An extensive marine seismic program was performed by Texaco Exploration Canada Ltd. in the Strait of Georgia from 1968 to 1969, which acquired 300 km of marine seismic data. In 1987, British Petroleum Resources Canada Ltd. acquired 160 km of seismic data on eastern Vancouver Island. Following that survey, two wells were drilled into seismically defined structures. Offshore seismic data remain difficult to obtain in the Strait of Georgia.

Petroleum Geology

Reservoir Potential of Mesozoic and Cenozoic Strata in the LMBC

The Nanaimo Group contains the oldest strata in the Georgia Basin that are inferred to have significant reservoir potential (England, 1991; Hannigan et al., 2001). Generally, the lithoformations within the Nanaimo Group consist of alternating sequences of coarse-grained units dominated by sandstone and conglomerate and fine-grained units dominated by mudstone (Figure 5; England and Bustin, 1998; Kent et al., 2020; Huang et al., 2022). This simplified stratigraphy remains reasonably accurate when considering the lower Nanaimo Group in recently developed genetic stratigraphic frameworks (Kent et al., 2020; Girotto, 2022; Huang et al., 2022). However, in the upper Nanaimo Group, the positioning of lithoformations depends more on the architecture of the interpreted turbidite system, leading to greater variability (Bain and Hubbard, 2016; Englert et al., 2018; Huang et al., 2022).

The Nanaimo Group encompasses a diverse range of depositional environments. It includes neritic to bathyal marine settings represented by deep-marine turbidites, submarine fans and slope facies. Additionally, there are shallow marine and littoral facies that document marginal marine deposition (Mustard et al., 1994; Katnick and Mustard, 2003; Johnstone et al., 2006; Hamblin, 2012; Girotto, 2022). Specifically, the lower Nanaimo Group is characterized by coastal, paralic and nonmarine deposition, whereas the upper Nanaimo Group is dominated by deep-marine and submarine-fan complexes due to the tectonic deepening of the basin at the end of the deposition of the lower Nanaimo Group (Girotto, 2022; Huang et al., 2022).

The Paleogene Huntingdon Formation and its Chuckanut Formation equivalent are composed of clastic deposits of fluvial and alluvial origins (Johnson, 1984; Gilley, 2003). In the subsurface, the Huntingdon Formation is interpreted as a substantial fluvial sequence featuring laterally accreting meandering channels within a floodplain dominated by sand (Mustard et al., 1994; Gilley, 2003). The primary rock types found within these formations are medium- to coarse-grained sandstone and conglomerate, with lesser

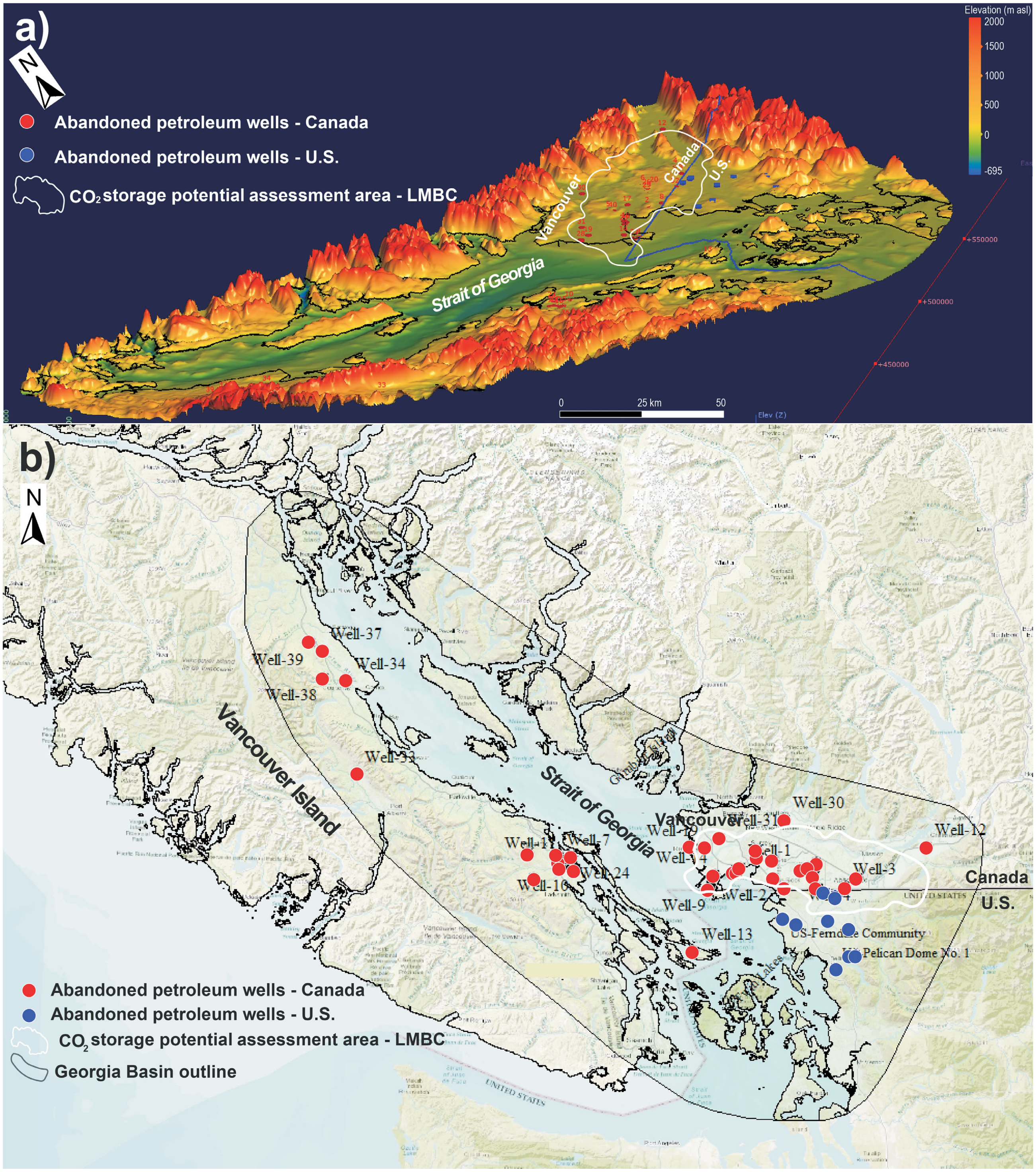

Figure 6. a) Digital elevation model and bathymetry of the Georgia Basin (Natural Resources Canada, 2021). **b)** Location of drilled wells in the Georgia Basin for which drilling data (e.g., hole location, kelly bushing, depth, etc.) are available. Among the 44 wells in the Georgia Basin with drilling data, only 24 have wireline log data: 11 in the Lower Mainland of British Columbia (LMBC) and 13 on Vancouver Island.

occurrences of shale, mudstone, siltstone and lignite (Gilley, 2003).

Notably, potential reservoir facies are associated with the coarse clastic deposits present in these formations (Hannigan et al., 2001). In comparison to sandstones in the Nanaimo Group, the Paleogene sandstones display less degradation, contain less silica cement and exhibit lower compaction levels (Hannigan et al., 2001; Gilley, 2003). As a result, rocks with reservoir-quality properties are more likely to be found in Cenozoic sedimentary rocks than in the Nanaimo Group (Hannigan et al., 2001).

Gordy (1988) noted that potential sandstone reservoirs in southwestern British Columbia exhibit porosities varying from 8 to 34%, with an average of 15%, and in Washington, porous sandstone displays an average porosity range of 12 to 15%. Additionally, there is evidence of secondary fracture porosity, likely resulting from substantial water and gas flows at depths exceeding 2000 m, especially in cases where primary matrix porosity is minimal.

Seal Potential of Mesozoic and Cenozoic Strata

The geological storage of CO_2 demands meticulous design to ensure the containment of CO_2 within porous rock formations, thus preventing unintended leakage. In this context, the concept of structural trapping assumes paramount significance. To achieve secure storage, the injection of CO_2 into porous and permeable geological strata should be executed beneath a stratigraphic layer characterized by extensive lateral distribution, substantial thickness and low permeability properties, which serve as an effective impermeable seal. This stratigraphic sealing layer plays a pivotal role in halting the buoyant upward movement of CO_2. Generally, Cretaceous reservoirs benefit from adequate lateral and upper sealing provided by the presence of multiple interbedded shale and mudstone units within the Georgia Basin, as detailed by Hannigan et al. (2001). Furthermore, structural sealing mechanisms are observed in the LMBC, potentially serving as seals in situations where sandstone and shale units intersect along fault lines. However, it is important to note that the sealing potential may be diminished for Paleogene strata, primarily due to their high sand content (England, 1991).

Suitable Characteristics for CO_2 Sequestration in Saline Aquifers in LMBC

The most suitable basins for the storage of gaseous or supercritical CO_2 possess specific characteristics (Keighley and Maher, 2015). Ideally, these basins comprise sedimentary strata (referred to as reservoirs) that are water-saturated and permeable, overlain by laterally extensive layers of low-permeability rocks. Furthermore, these basins tend to exhibit structural simplicity, characterized by a scarcity of continuous faults, both laterally and vertically. Such basins are typically found in mid-continent locations, exemplified by the Western Canada Sedimentary Basin.

The following sections will detail the essential characteristics of sedimentary basins and sedimentary strata that are crucial for the successful implementation of CO_2 storage in regions marked by tectonic activity. These key characteristics encompass the geothermal gradient and pressure, reservoir thickness, porosity and permeability, salinity, mineralogy, seismicity and faults.

Geothermal Gradient and Pressure

The behaviour of CO_2 with respect to its phase is significantly influenced by the geothermal gradient and pressure conditions in geological formations (Bachu, 2003; Bachu and Adams, 2003). This interplay is a determining factor for the effective storage and dissolution of CO_2 (Keighley and Maher, 2015). In a scenario with a typical geothermal gradient of 25 °C/km, and under normal hydrostatic pressure conditions, CO_2 transitions into a supercritical state at an approximate depth of 800 m (Holloway and Savage, 1993). However, it's important to note that the depth at which CO_2 achieves supercritical conditions can vary based on factors such as local surface temperature, the specific geothermal gradient of the region and the local hydrostatic and lithostatic pressures (Bachu, 2003). In most sedimentary basins, the pressure conditions conform closely to hydrostatic conditions. However, in cases of lithostatic conditions where pressure is solely attributed to the weight of the overlying rock, the density of water-saturated overburden is employed instead of water density (Bachu and Adams, 2003).

Surface temperatures within sedimentary basins display significant global variations, with arctic and sub-arctic basins experiencing average annual temperatures around 0 °C, whereas low-altitude tropical basins may exhibit average annual temperatures of approximately 30 °C (Bachu, 2003). Under standard pressure gradient conditions in sedimentary basins, the maximum attainable CO_2 density is approximately 850 kg/m³ (Bachu, 2003). Consequently, it becomes evident that in warmer basins (higher temperate gradient), higher pressures (or depths) are required to attain elevated CO_2 density when compared to colder basins (lower temperature gradient).

Reservoir Thickness

The required minimum thickness of a saline aquifer for effective CO_2 storage is typically around 30 m (Intergovernmental Panel on Climate Change, 2005). However, it's important to note that the actual reservoir thickness needed can vary significantly depending on factors such as heterogeneity, reservoir geometry, porosity, permeability and fluid properties. Therefore, conducting site-specific geological assessments and engineering evaluations is crucial to determining the precise minimum reservoir thickness for CO_2 storage in any given location. This approach ensures that the storage site meets the necessary criteria for effective and efficient carbon storage.

Porosity and Permeability

The volume of CO_2 that can be effectively stored in a reservoir and the efficiency of storage depends on several key factors, including effective porosity, reservoir area, thickness, lithology and injectivity, which is primarily controlled by permeability. When supercritical CO_2 or CO_2-rich brine is injected into a reservoir, it displaces much of the existing pore fluid. Storage efficiency, a critical parameter, represents the ratio of the volume of CO_2 stored to the maximum pore volume available for CO_2 storage.

Permeability, the ability of a rock to transmit fluids, plays a fundamental role in the injection and dispersion of supercritical or gaseous CO_2 or CO_2-rich brine mixtures within the reservoir. High-permeability reservoirs facilitate more efficient injection processes. In contrast, insufficient permeability or the presence of flow barriers like faults or fine-grained layers can result in increased fluid pressure near the injection point, limiting injection rates and the overall amount of CO_2 that can be stored (Bentham and Kirby, 2005).

Porosity and permeability parameters collectively determine the suitability of a reservoir for CO_2 storage, as they influence storage capacity and injectivity. Successful CCS projects require careful assessment of these geological and reservoir characteristics to ensure effective and efficient storage of CO_2.

Salinity

Salinity, often expressed as the concentration of total dissolved solids (TDS in ppm), encompasses a wide array of dissolved substances, including minerals, salts, metals and organic compounds in subsurface fluids.

The impact of salinity on CO_2 storage within saline aquifers is noteworthy. Saline water can dissolve more CO_2 compared to freshwater, thereby increasing the potential for CO_2 storage (Bachu, 2008). Nevertheless, elevated salinity levels can also trigger the formation of carbonates when CO_2 reacts with minerals in the water, particularly in proximity to injection wells. This mineralization process can reduce permeability and, consequently, CO_2 storage capacity (Bachu and Adams, 2003).

In the context of supercritical or gaseous CO_2 sequestration, formation water with higher salinity can cause separate-phase CO_2 to migrate upwards within the aquifer, potentially escaping through weaknesses in overlying rock layers. The salinity range conducive to CO_2 dissolution in saline aquifers is typically considered to be between 30 000 and 100 000 ppm. Salinity levels below 30 000 ppm tend to diminish the CO_2 carrying capacity of formation water, whereas salinity exceeding 100 000 ppm may contain high concentrations of minerals that react with CO_2, leading to mineralization and a subsequent reduction in permeability. Careful consideration of salinity levels is crucial for optimizing CO_2 storage and minimizing potential migration risks.

Mineralogy

The interaction of CO_2 with brine in aquifers can have multiple effects, including alterations in the mineral composition of the reservoir, changes in pH levels, modifications in the isotopic composition and adjustments in the ion concentration of the brine (Pearce et al., 2021). Saline reservoirs composed of siliciclastic materials are typically sandstone with varying proportions of clay and silicate minerals. The reactivity of these minerals with CO_2 is variable, with quartz and clay demonstrating lower reactivity, whereas carbonate, plagioclase feldspar and mafic minerals tending to be more reactive (Gunter et al., 1993, 1997; Knauss et al., 2005; Rosenbauer and Thomas, 2010).

The injection of CO_2-rich brine mixtures into saline aquifers can induce the dissolution of feldspar and unstable minerals, subsequently leading to the precipitation of quartz and/or calcite cement within pore spaces. These cementitious materials can diminish injectivity, affecting the efficiency of injection processes (Ang et al., 2022). However, CO_2 injection into siliciclastic formations containing carbonate minerals (e.g., calcium and magnesium) and mafic minerals (e.g., basalt-rich strata) can result in significant sequestration through mineral trapping over extended periods, ranging from hundreds to thousands of years (Amin et al., 2014). These complex interactions underscore the importance of understanding reservoir fluid chemistry and mineralogical changes in aquifers during CO_2 storage operations.

Seismicity

The injection of supercritical/gaseous CO_2 or CO_2-rich brine mixtures into deep saline aquifers carries the potential risk of inducing seismic activity if the injected fluids lead to overpressurization (McGarr et al., 2002; Zoback and Gorelick, 2012). Elevated injection pressures can enhance injectivity but also result in increased mechanical stress and deformation, potentially triggering microseismic events, reactivating faults, creating new fractures, causing ground surface uplift and even generating earthquakes (Rutqvist et al., 2007; Ferronato et al., 2010; Cappa and Rutqvist, 2011). It is important to note that even relatively minor earthquakes, such as those with a magnitude of 3 or less, can pose a significant threat to the integrity of CO_2 storage projects (Zoback and Gorelick, 2012).

Therefore, it is imperative to identify pre-existing faults and take measures to prevent the injection of supercritical/gaseous CO_2 or CO_2-rich brine mixtures in close proximity to these structural features.

Faults

Faults that are either sealed or partially sealed can intersect potential CO_2 storage aquifers leading to complications in

CO_2 storage. These faults may compartmentalize the target reservoir, adding complexity and cost to the storage project (Keighley and Maher, 2015). Alternatively, if some of these faults remain unsealed, they significantly elevate the risk of fluid leakage. Basins that have undergone multiple tectonic or deformation events tend to be more heavily faulted and, as a result, are less suitable for CO_2 storage, especially for supercritical/gaseous CO_2 storage (Celia et al., 2015). Therefore, conducting a structural analysis is imperative for assessing the potential for fluid leakage throughout the life cycle of a storage project (Keighley and Maher, 2015).

Conclusions

The increasing concentration of CO_2 in the Earth's atmosphere is significantly impacting the planet by intensifying the natural greenhouse effect, leading to a warming influence on the Earth's surface. This warming trend is associated with more frequent and intense extreme weather events, such as heatwaves, tropical cyclones, heavy precipitation and flooding, raising concerns among individuals and communities. Addressing the challenge of reducing carbon emissions while sustaining and improving living standards, especially in developing countries, necessitates cost-effective and innovative solutions. Consequently, the capture and underground sequestration of CO_2 emerges as one of the most practical and feasible approaches for reducing CO_2 emissions in the short to medium term.

The Lower Mainland of British Columbia (LMBC) has previously undergone assessments for its hydrocarbon potential and natural gas storage capacity, revealing it as a promising and potentially viable site for CO_2 storage. However, despite these initial assessments, there has been a lack of substantial effort to thoroughly evaluate the feasibility of carbon capture and storage in the LMBC. The sedimentary strata located beneath the LMBC, particularly at greater depths, remain poorly understood, with limited insights into their geological context, such as interpretations of depositional environments and facies analysis. Considering these gaps in knowledge, the objective of this research is to assess the feasibility of carbon capture and storage in the LMBC, by investigating several interconnected reservoir characteristics, including geothermal gradient and pressure, reservoir thickness, porosity and permeability characteristics, salinity, mineral composition, seismic activity and fault distribution. A comprehensive evaluation of these factors is imperative to ensure the safe and effective implementation of CO_2 sequestration projects in such regions.

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