Three-Dimensional Reconstruction of the Georgia Basin and Potential for Carbon Dioxide Sequestration in the Lower Mainland, Southwestern British Columbia (Parts of NTS 092G/01–03)

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Introduction

Steady increases in atmospheric carbon dioxide (CO_2) were first recognized by Keeling (1960), and annual peak concentrations have only increased since (Ewald, 2013; Keighley and Maher, 2015). Although CO_2 is produced naturally, recent (1800s until present) increases are predominantly attributed to human activity (Keighley and Maher, 2015) and specifically to the use of carbon-based resources such as coal, oil and natural gas (methane). Higher CO_2 concentrations affect Earth's atmosphere by increasing the natural greenhouse effect, thereby exerting a warming influence on the planet's surface (Bachu, 2003). As Earth's climate warms, extreme weather events such as heat domes, tropical cyclones, elevated precipitation and flooding are expected to occur more frequently and with greater intensity (Flannigan and Wagner, 1991). As these events threaten infrastructure critical to society, concerns regarding the impacts of climate change on society have understandably increased (Bratu et al., 2022). Nevertheless, CO_2 emissions will continue to rise, as the effort to transition to a carbon-neutral global economy is expected to take decades (U.S. Energy Information Administration, 2021).

Finding practical solutions to decrease carbon emissions while simultaneously maintaining our standard of living and expanding the standard of living of developing countries demands economical and novel solutions. To this end, capturing and sequestering CO_2 underground is the most viable approach to reducing CO_2 emissions over the short to medium term (Intergovernmental Panel on Climate Change, 2014). Carbon capture and storage (CCS) removes CO_2 from industrial sources and injects it underground into suitable geological formations (Bachu et al., 1994; Kaszuba et al., 2003; Bachu and Gunter, 2005; Kharaka et al., 2006; Shukla et al., 2010; Underschultz et al., 2011; Stephenson et al., 2019; Pearce et al., 2021). In most cases, CCS is used in regions with significant hydrocarbon production (Lane et al., 2021). In areas with limited oil and gas exploration, CCS is largely ignored, owing to assumptions that underground storage is not viable.

The Lower Mainland of British Columbia (referred to herein as LMBC) has been evaluated previously for hydrocarbon potential and natural gas storage, and represents a readily accessible and potentially economically feasible locale to store CO_2 (Gordy, 1988; Hannigan et al., 2001). However, no significant effort has been expended yet to evaluate the feasibility of CCS in the LMBC. Sedimentary strata below the LMBC are poorly understood, particularly at depth, and the geological context (e.g., interpretation of depositional environments and facies analysis) of these strata has not been examined in detail. To address this knowledge gap, the proposed research aims to place the strata below the LMBC in geological context, assess these strata for their reservoir potential, and build an integrated three-dimensional (3-D) static geological model of the strata. These data will then be used to estimate the storage capacity and long-term fate of injected CO_2. The geological model will be used to define subsurface geohazards (e.g., faults).

Study Area

The strata underlying the LMBC belong to the Georgia Basin, which is a northwest-southeast–oriented structural and topographic depression. The Georgia Basin extends over 18 000 km^2 and encompasses the Strait of Georgia, eastern Vancouver Island, the Fraser River Lowland and the northwestern portion of the State of Washington, United States (Figure 1; Molnar et al., 2010). The fill of the Georgia Basin comprises three major tectonostratigraphic clastic sedimentary packages: the mainly Upper Cretaceous Nanaimo Group, the Paleogene Huntingdon Formation, and the Neogene Boundary Bay Formation (Figure 1; Monger, 1990; Groulx and Mustard, 2004; Molnar et al., 2010).

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[1]*The lead author is a 2022 Geoscience BC Scholarship recipient.*

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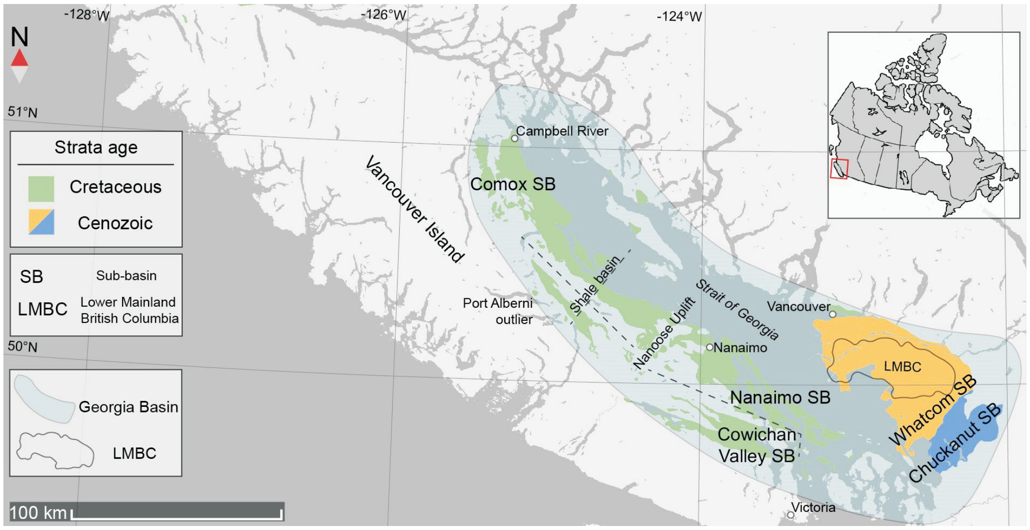

Figure 1. Location map of the Georgia Basin and Lower Mainland of British Columbia, and simplified geological map of southwestern British Columbia, Canada. Outcrop areas in the Georgia Basin include Upper Cretaceous Nanaimo Group strata exposed in the Comox, Nanaimo and Cowichan Valley sub-basins (green); 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 (Huang et al., 2022).

The LMBC encompasses metropolitan Vancouver, the Fraser River Lowland, and the flanks of the surrounding mountainous regions (Figure 1). The region is home to over 60% of British Columbia's (BC) population (>3 000 000) and is Canada's third-largest urban region. The LMBC is bounded by the Coast Mountains to the north, the Cascade Mountains to the east, and the Canada–US international border to the south. Population centres in the LMBC are also major industrial hubs, with several large carbon emitters therein.

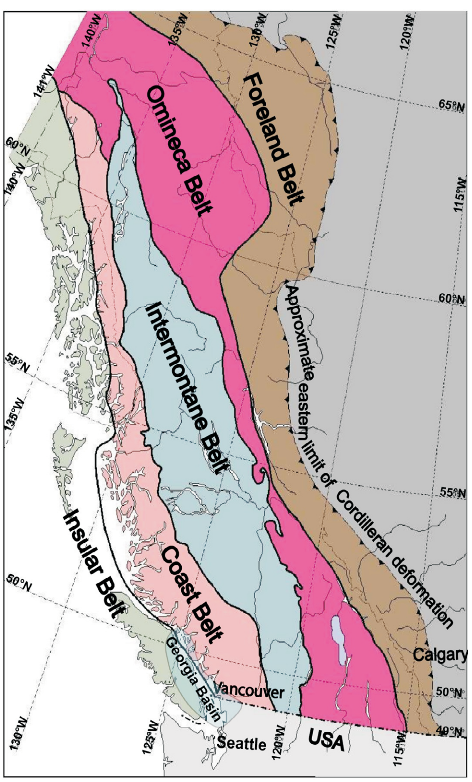

Figure 2. Morphogeological belts of the Canadian Cordillera (from Wheeler et al., 1991).

Geological Background

Tectonic Setting and Basin Type

The Canadian Cordillera is divided into five morphological belts. From west to east, these include the Insular, Coast, Intermontane, Omineca and Foreland belts (Figures 2, 3; Monger and Price, 2002). Each belt is characterized by a distinct combination of landforms, rock types, metamorphic grade and structural style (Gabrielse and Yorath, 1991). The southern Canadian Cordillera was established through the accretion of two superterranes, which also equate to two of the morphological belts (Figures 2, 3). The eastern Intermontane Superterrane accreted in the Middle Jurassic, and the western Insular Superterrane accreted in 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 is a high-grade metamorphic and plutonic belt that probably formed when the Insular Superterrane was accreted to the western margin of North America in the Early Cretaceous (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

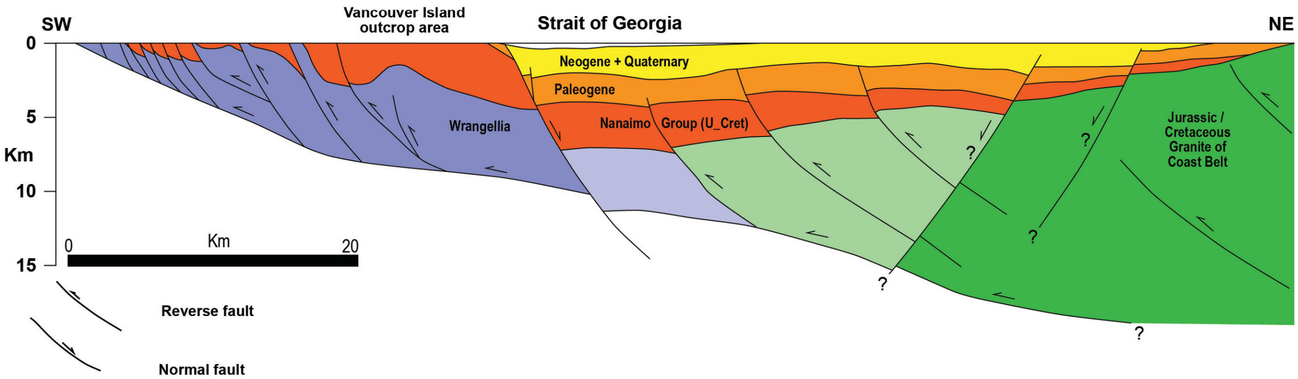

Figure 3. Idealized structural cross-section of the southern Georgia Basin based on LITHOPROBE data, modified after England and Bustin (1998), England and Calon (1991) and Gordy (1988). Question marks along the fault surfaces indicate interpreted locations. Paler shades of purple and green are used on 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.

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 Georgia Basin has been interpreted variably as a fore-arc basin, a strike-slip basin, and a foreland basin (Muller and Jeletzky, 1970; Pacht, 1984; England, 1989; Monger and Journeay, 1994; Mustard and Monger, 1994). Monger (1991a) postulated that the Georgia Basin developed in a foreland setting, with associated west-verging thrust faults, crustal thickening and regional uplift of the CPC. England and Calon (1991) suggested that Nanaimo Group sedimentation occurred in a fore-arc setting, and was associated with Late Cretaceous subduction and convergence in the CPC. Recognition of multiple source areas for Cretaceous sedimentary rocks, including areas west of the Georgia Basin, suggests the fore-arc basin model is most applicable, and that is the model adhered to herein. The Georgia Basin has been identified as an 'anomalous' fore-arc basin, owing to the preservation of thick successions of paralic and shallow-marine strata (Dickinson and Seely, 1979; Miall, 1984; Hamblin, 2012; Kent et al., 2020). Preserving 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 fill of the Georgia Basin attains a thickness locally in excess of 6 km (England and Bustin, 1998). Late (and possibly Early) Cretaceous through to modern sedimentary strata comprises the fill (Figure 3; Hannigan et al., 2001). The Georgia Basin comprises five 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 southeast coast of Vancouver Island, the adjacent Strait of Georgia and the Gulf Islands. The Comox sub-basin is situated farther north, along the east-central coast of Vancouver Island and the adjacent Strait of Georgia. The Cowichan Valley sub-basin was defined as a separate sub-basin on the basis of its strata having an unknown relationship to the rest of the Nanaimo Group. Later studies incorporated the Cowichan Valley sub-basin into the Nanaimo sub-basin, with no reason given for this revision (Clapp, 1913). The Cowichan Valley sub-basin was redefined by Huang et al. (2022) and Girotto (2022) as a separate sub-basin, based on strata near the basal unconformity yielding substantially different detrital zircon age populations and maximum depositional ages than strata in the Comox and Nanaimo sub-basins.

The Chuckanut and Whatcom sub-basins include the Fraser Delta and northwestern Washington, respectively (Figure 1; Hannigan et al., 2001; Kent et al., 2020). Nanaimo Group sedimentary strata exist within the Whatcom sub-basin, and these strata are overlain by Paleogene sediments of the Huntingdon Formation, Neogene sediments of the Boundary Bay Formation, and Quaternary sediments of 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 accommodates more than 1.5 km of southward displacement (Miller, 1963; Johnson, 1985). The fill of the Chuckanut sub-basin comprises the Chuckanut Formation, Boundary Bay Formation, and overlying Quaternary deposits (Figures 1, 4).

General Stratigraphy

The basement of the Georgia Basin comprises predominantly Wrangellia. Wrangellia itself comprises the Sicker

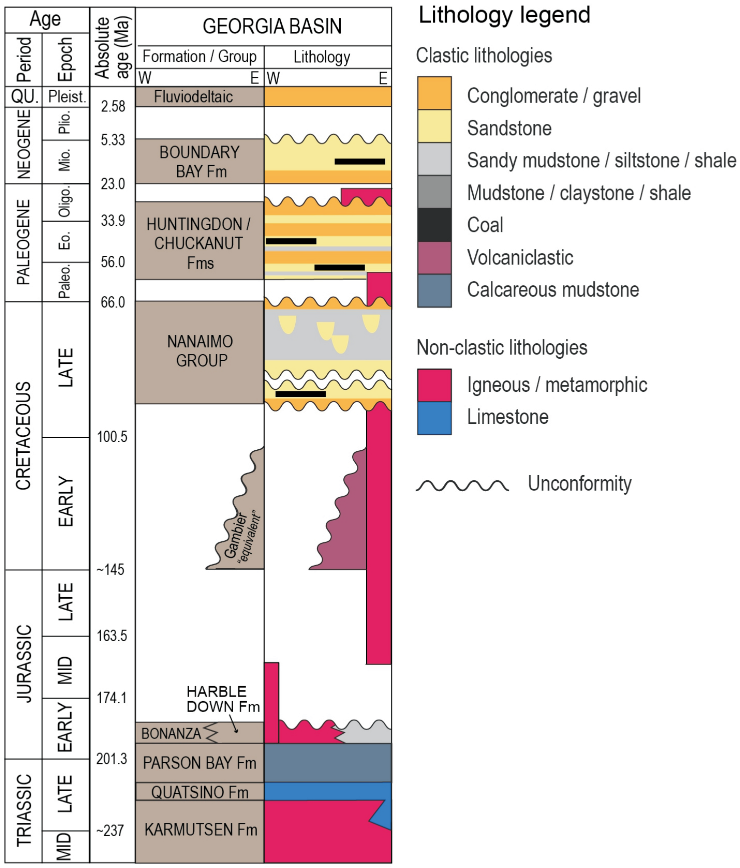

Figure 4. Simplified stratigraphic column for the Georgia Basin (with data from Haggart, 1992, 1993; Hannigan et al., 2001; Bain and Hubbard, 2016; Englert et al., 2018; Huang et al., 2019; Kent et al., 2020). Potential reservoir strata occur in coarse clastic rocks of the Huntingdon and Boundary Bay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

arc, a Silurian to Devonian island arc; the Karmutsen Formation, a Triassic mid-ocean–basalt plateau; the Bonanza arc, a Jurassic bimodal arc; and sedimentary rocks associated with these features (Huang et al., 2022). The eastern Georgia Basin is floored by the CPC, a middle Jurassic to Eocene continental arc (Monger and Journeay, 1994), and the Gambier Group, which is a sequence of Lower Cretaceous volcanogenic sedimentary and volcaniclastic rocks (Figure 4; Lynch, 1991; Lynch, 1992; Monger and Journeay, 1994). The mainly Upper Cretaceous to lowermost Paleocene fill of the Georgia Basin comprises the 4 km thick Nanaimo Group (Figures 3, 4; Mustard, 1991; Mustard et al., 1994; England and Bustin, 1998; Huang et al., 2022). The Nanaimo Group is divided informally into the lower and upper Nanaimo groups, with the lower Nanaimo Group comprising predominantly continental to shallow-marine strata in sedimentologically isolated sub-basins, including the Comox, Nanaimo and Cowichan Valley sub-basins (Figure 1; Girotto, 2022; Huang et al., 2022). The Comox and Nanaimo sub-basins are divided into lithostratigraphic formations, which alternate between dominantly coarse- and fine-grained strata. The lower Nanaimo Group in the Comox sub-basin encompasses the Comox and Trent River formations, whereas in the Nanaimo sub-basin, it comprises the Sidney Island, Barnes Island, Comox, Haslam, Extension, Pender and Protection formations (Figure 5; Girotto, 2022). The transition between the lower and upper Nanaimo Group represents the unification of the isolated sub-basins into a single basin, and the initiation of basin-wide, deep-marine sedimentation (England, 1991; Mustard, 1991; Mustard and Monger, 1994; Kent et al., 2020; Girotto, 2022). The upper Nanaimo Group includes 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). The Nanaimo Group is exposed predominantly in eastern Vancouver Island, but these strata also occur in the subsurface under the Strait of Georgia and below the LMBC (Figures 3, 4). The subsurface distribution and character of Nanaimo Group strata are poorly understood, owing to limited data.

The Huntingdon Formation in BC, and the time-equivalent Chuckanut Formation in Washington, comprise the main Paleogene fill of the Georgia Basin (Figure 4; Vance, 1975; Johnson, 1984; England and Hiscott, 1992; Hannigan et al., 2001). Paleogene strata are dominated by continental deposits both in the Canadian and American extents of the Georgia Basin (Johnson, 1984, 1991; Mustard and Monger, 1994; Hannigan et al., 2001). Paleogene and Cretaceous strata are intruded locally by Oligocene dikes and sills in the Vancouver area (Figure 4; Mustard et al., 1994). In the LMBC, the Huntingdon Formation disconformably overlies the upper Nanaimo Group (Figures 3, 4; Mustard et al., 1994).

In the Whatcom sub-basin, there is a thick succession of mainly Miocene sediments that are distinct from older Cenozoic sediments (Hopkins, 1966, 1968; Rouse et al., 1990; Mustard and Rouse, 1991; Mustard et al., 1994). These strata are referred to as the Boundary Bay Formation (Mustard et al., 1994). The Boundary Bay Formation is exposed mainly in scattered outcrops along the lower Fraser River valley, and east and northeast of Bellingham in Washington (Figure 1; Hannigan et al., 2001).

Exploration History and Regional Studies

The Georgia Basin has been the subject of scientific investigations for over 140 years, initially due to large bituminous coal resources discovered in the basin between 1850 and the early 1900s, and later due to its potential for signifi-

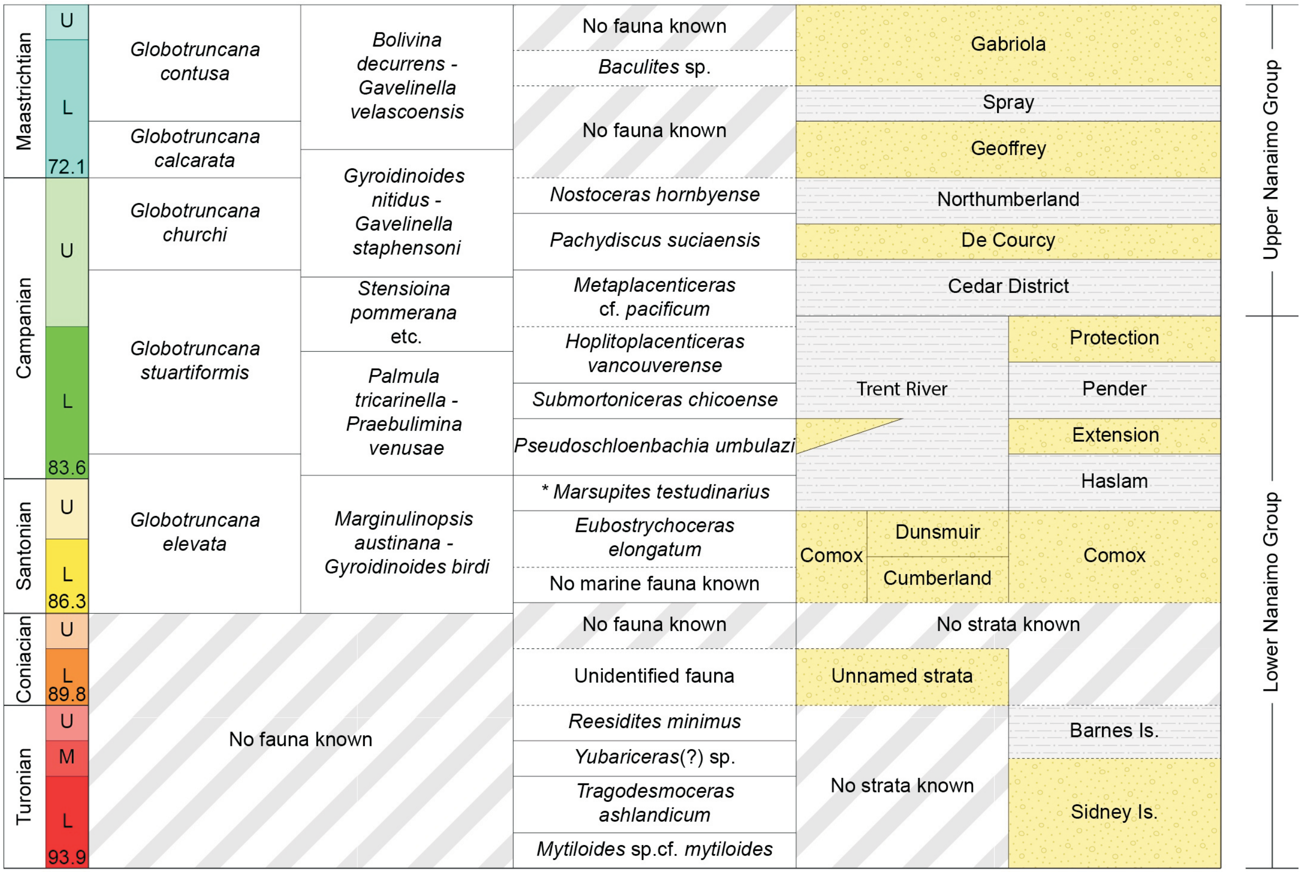

Figure 5. Nanaimo Group lithostratigraphy in the Nanaimo and Comox sub-basins (Mustard et al., 1994; Haggart et al., 2005) including foraminiferal (Sliter, 1973; McGugan, 1979) and molluscan biozones (Muller and Jeletzky, 1970; Haggart et al., 2005; Ward et al., 2012; Haggart and Graham, 2018). In the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

cant hydrocarbon accumulations (Bustin and England, 1991; Bustin, 1995).

Exploration surveys (e.g., geological, seismic, gravimetric, magnetic) and drilling for hydrocarbons has 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). Out of all the wells drilled for oil and gas exploration within the Georgia Basin (particularly in the Canadian part), only 40 wells have known location and drilling information (Figure 6). Twenty-three of the drilled wells within the Canadian part of the Georgia Basin have wireline log data (10 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 acquired 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 on 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 Ltd. acquired a 1150 km long gas-exploder marine seismic survey in the Strait of Georgia. An extensive marine seismic program was performed by Texaco Exploration Canada in the Strait of Georgia from 1968 to 1969 that acquired 300 km of marine seismic data. In 1987, British Petroleum Resources Canada Ltd. acquired 160 km of seismic surveys on eastern Vancouver Island. Following that survey, two wells were drilled into seismically defined

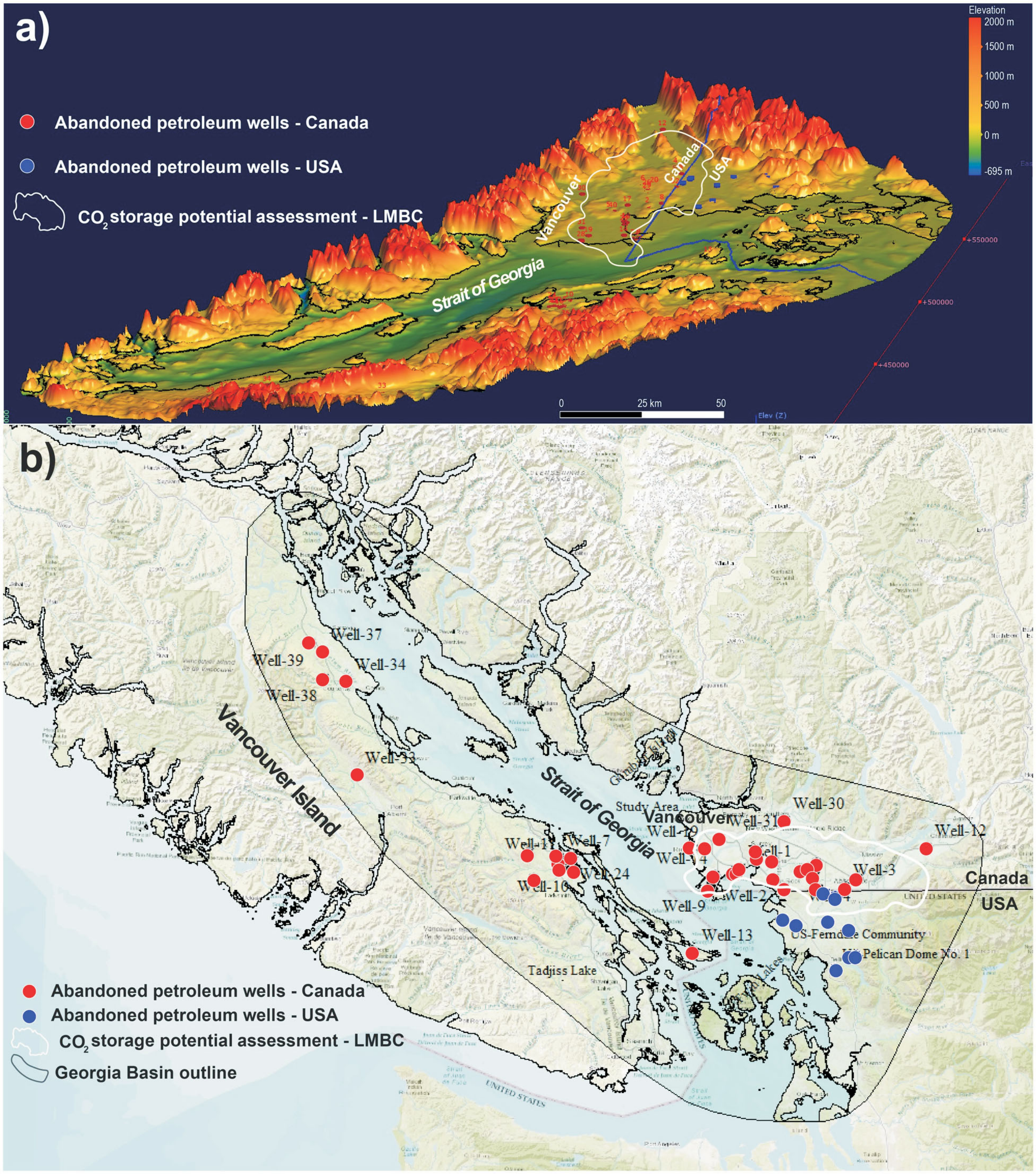

Figure 6. a) Digital elevation model and bathymetry of the Georgia Basin. **b)** Location of drilled wells in the Georgia Basin for which drilling data (e.g., hole location, kelly bushing, depth, etc.) are available. Among the 40 wells in the Georgia Basin with drilling data, only 23 have wireline log data: 10 in the Lower Mainland of British Columbia (LMBC), and 13 on Vancouver Island.

structures. Offshore seismic data acquired in the Strait of Georgia remain difficult to find.

Petroleum Geology

Reservoir Potential of Mesozoic and Cenozoic Strata in the LMBC

The Nanaimo Group contains the oldest strata inferred to have significant reservoir potential within the Georgia Basin (England, 1991; Hannigan et al., 2001). In general, the Nanaimo Group's lithoformations comprise alternating sequences of coarse-grained (sandstone- and conglomerate-dominated) and fine-grained (mudstone-dominated) units (England and Bustin, 1998; Kent et al., 2020; Huang et al., 2022). This simplified stratigraphy remains reasonably accurate for 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 position of lithoformations is mainly dependent on the architecture of the turbidite system, and hence, is more variable (Bain and Hubbard, 2016; Englert et al., 2018; Huang et al., 2022). Thick sandstone and conglomerate units are potential reservoirs within the Nanaimo Group (England and Bustin, 1998; Hannigan et al., 2001). There are also minor thin sandstone or conglomerate beds within fine-grained units that could potentially act as reservoirs.

A wide array of depositional environments are represented in the Nanaimo Group. Neritic to bathyal marine depositional environments are represented by deep-marine turbidites, submarine fans, and slope facies. Shallow-marine and littoral facies record marginal-marine deposition (Mustard et al., 1994; Katnick and Mustard, 2003; Johnstone et al., 2006; Hamblin, 2012; Girotto, 2022). The lower Nanaimo Group is dominated by coastal, paralic and nonmarine deposition, and the upper Nanaimo Group is dominated by deep-marine and submarine-fan complexes (Girotto, 2022; Huang et al., 2022).

The Paleogene Huntingdon and equivalent Chuckanut formations are fluvial- and alluvial-type clastic deposits (Johnson, 1984; Gilley, 2003). In the subsurface, the Huntingdon Formation is interpreted as a thick fluvial sequence with laterally accreting meandering channels in a sand-dominated floodplain (Mustard et al., 1994; Gilley, 2003). Medium- to coarse-grained sandstone and conglomerate are the principal rock types, with lesser shale, mudstone, siltstone and lignite (Gilley, 2003). Potential reservoir facies include coarse clastic deposits (Hannigan et al., 2001). Feldspars and lithic fragments in Paleogene sandstones are less degraded, contain less silica cement, and show less compaction than Nanaimo Group sandstones (Hannigan et al., 2001; Gilley, 2003). Reservoir-quality rocks are more likely to occur in Cenozoic sedimentary rocks than in the Nanaimo Group (Hannigan et al., 2001).

The Boundary Bay Formation consists of interbedded sandstone, mudstone, and lesser amounts of conglomerate and coal (Figure 4; Gordy, 1988; Mustard et al., 1994; Gilley, 2003). Porous sandstone units are generally thin, with most varying between 0.6 and 5 m in thickness. There are locally 10 m thick reservoir-quality sandstone units that are interpreted as fluvial channel deposits. Gordy (1988) indicated that prospective sandstones in southwestern BC vary in porosity from 8 to 34%, with an average of 15%. In Washington, porous sandstone has an average porosity of 12–15%. There is evidence of secondary fracture porosity due to significant water and gas flows below 2000 m depth and where primary matrix porosity is negligible.

Seal Potential of Mesozoic and Cenozoic Strata

Geological storage of CO_2 must be designed such that the CO_2 cannot escape from the porous rock into which it is injected; therefore, structural trapping of CO_2 plays a crucial role. Injecting into porous and permeable strata should occur below an interval of laterally extensive and thick, low-permeability strata that will act as an impermeable seal and will prevent upward buoyant migration of CO_2. In general, adequate lateral and top seals for Cretaceous reservoirs are provided by numerous interbedded and overlying shale and mudstone units in the Georgia Basin (Hannigan et al., 2001). Structural seals are also present in the Georgia Basin and in the LMBC, and could act as a seal where sandstone and shale units are in fault contact. Seal potential is probably reduced for Paleogene strata due to their overall high sand content (England, 1991).

Objectives

The primary objective of the proposed research is to assess the CO_2 storage potential of sedimentary strata underlying the LMBC. The primary objective will be achieved through four sub-objectives, which are outlined below.

Sub-Objective 1: Facies Characterization and Petrophysical Formation Evaluation of Cenozoic Strata Below the LMBC

Sub-objective 1 focuses on sedimentary facies characterization, petrophysical formation evaluation, integration of wireline logs and sedimentary facies, and paleogeographic mapping of the Huntingdon and Boundary Bay formations in the subsurface below the LMBC. Available drillcore data from relevant intervals across the LMBC will be examined from sedimentologic, ichnologic and stratigraphic perspectives. Identification of sedimentary facies will be done using both qualitative and quantitative parameters, including mineral composition, stratification, sedimentary structures, bioturbation, and grain-size distribution observed in cored intervals. Sedimentary facies will be grouped into facies associations, and facies associations will be used to interpret paleoenvironments (i.e., facies analysis) and to guide genetic stratigraphic correlations across the study area. Stratigraphic correlations and facies associations will be correlated to well-log signatures, and the combined dataset will be used to map the distribution of lithological units in the subsurface.

In addition to the steps outlined above, petrophysical formation evaluation of the Huntingdon and Boundary Bay formations will be completed. Petrophysical data that will be acquired and/or calculated include total porosity (PHIT), effective porosity (PHIE), shale volume (V_{shale}), volume fractions of lithology, horizontal permeability (K_h) and vertical permeability (K_v). Most of these properties will be derived from well logs, with the exception of horizontal and vertical permeability, which will be derived from available core analysis data.

Finally, facies mapping and petrophysical data will be integrated, to identify the sedimentary strata and stratigraphic intervals with the greatest available pore volumes and highest potential for long-term CO_2 storage. The data derived under sub-objective 1 (and 2) will form the backbone of the static reservoir model (sub-objective 3), including predicting the distribution and nature of permeable strata below the LMBC.

Sub-Objective 2: Facies Characterization and Petrophysical Formation Evaluation of the Upper Cretaceous Strata Below the LMBC

Sub-objective 2 involves sedimentary facies characterization, petrophysical formation evaluation, integration of wireline logs and sedimentary facies, and paleogeographic mapping of the Nanaimo Group in the subsurface below the LMBC. The data to be collected under sub-objective 2, and the methodology employed, is similar to that of sub-objective 1. However, paleogeographic mapping of the Nanaimo Group differs in that sedimentary facies must be linked to the paleogeographic maps constructed previously for both the lower and upper Nanaimo groups (Bain and Hubbard, 2016; Englert et al., 2018; Kent et al., 2020; Girotto, 2022). This will result in a more complete paleogeographic picture of the Nanaimo Group throughout the Georgia Basin.

Sub-Objective 3: 3-D Static Geological Modelling of the Georgia Basin Below the LMBC

The aim of sub-objective 3 is to produce a 3-D static geological model for the Georgia Basin below the LMBC, and these data will be used to depict the 3-D distribution of reservoirs and seals. The model will combine all subsurface geological data, and will build extensively on the results and outputs from sub-objectives 1 and 2. In addition to these data, available 2-D seismic data, seismic maps, drill-stem test data and water chemistry information will be incorporated in Schlumberger Limited's (Schlumberger) Petrel software.

Construction of the regional static geological model involves three phases: 1) structural modelling, 2) facies modelling, and 3) property modelling (co-dependent on facies modelling).

The structural framework includes all the interpreted faults below the LMBC, as well as structure on interpreted stratigraphic horizons and reservoir layers. The structural model will be constructed in the depth domain using data from drilled wells with geological markers, seismic maps of stratigraphic horizons, and maps of faults derived from seismic data and wells. The extent of structural mapping within and beyond the study area will be determined based on available and resolvable geophysical data and the maximum depth of wells drilled in the region.

Facies modelling will form the interface between geological phenomena and reservoir characterization, and will occur before modelling porosity and permeability. Lateral and vertical facies changes directly control reservoir quality; hence, it is necessary to resolve facies trends and build them into the geological model. For this, facies defined in sub-objectives 1 and 2 will be spatially modelled across the LMBC.

Finally, property modelling involves modelling the parameters calculated from petrophysical formation evaluation and drillcore logs (mainly PHIE and permeability). These parameters will be modelled using results from sub-objectives 1 and 2.

The regional static model generated under sub-objective 3 will enable a reconciliation of differences and an estimation of uncertainty in both the static model and in future dynamic (fluid flow) modelling. The 3-D model is essential for accurately predicting fluid (CO_2) flow behaviour through reservoir simulations.

Sub-Objective 4: Fault Mapping and Identification of Geohazards Below the LMBC

Sub-objective 4 focuses on mapping the distribution and patterns of faults that are only expressed in the subsurface below the LMBC, and assessing their potential as geohazards. The LMBC is situated over an active tectonic zone, and yet the positions of faults within the region are not mapped in detail, especially where they have no surface expression. Each of these surfaces represents a potential slipface that could reactivate during an earthquake, so mapping the position of faults with no visible fault trace will give a better sense of the geohazard risks for the residents of BC's Lower Mainland.

Methods

The datasets that will be used in this research include drillcore data, geophysical well logs, drillstem test results, water chemistry analysis, 2-D seismic lines and seismic maps. These data will be analyzed using one of four methods: 1) core and facies analysis, 2) petrophysical formation evaluation, 3) 3-D static geological modelling, and 4) seismic interpretation.

Core and Facies Analysis

Core logging will be done on the five wells in the LMBC for which drillcore is available. Approximately 190 m of core exist between the five wells (Figure 7). Core descriptions will be used to conduct facies analysis, define sedimentary environments, construct paleogeographic maps, and make genetic stratigraphic correlations through the sedimentary strata below the LMBC. Sedimentary facies will be classified according to their textural, sedimentological and ichnological characteristics. Textural observations include lithology, grain size, grain sorting and roundness. Sedimentological data includes bedding, physical sedimentary structures, cementation and lithological accessories (e.g., macerated plant material). Ichnological information includes ichnogenera, trace-fossil sizes and diversity, bioturbation intensity using the BI-scale of Taylor and Goldring (1993), and the distribution of burrowing between beds. These data will be used to generate paleoenvironmental interpretations. Porosity and permeability values derived from cored intervals will be correlated to facies. Core logs and porosity-permeability data will form the main datasets for sub-objectives 1 and 2.

Figure 7. Photos of core from a well drilled in the Lower Mainland of British Columbia (core 5, with unique well identifier [UWI] of A-017-B/092-G02; BC Oil and Gas Commission, 2022): **a)** cored interval from 1386.9 to 1390.8 m, showing the finely layered sandstone typical of this area; **b)** close-up of core 5 from depth of 1387.30 to 1387.55 m, illustrating the relatively coarse-grained nature of the rock.

Petrophysical Formation Evaluation

Wireline log data (Figure 8) from 10 wells in the LMBC will be used to derive petrophysical parameters, and these data will be incorporated into sub-objectives 1, 2 and 3. Wireline logs will be calibrated to remove artefacts from wireline data acquisition to obtain the best possible petrophysical calculations. In this regard, several quality-assurance steps will be applied to the logs, including depth calibration through depth shifts, log normalization, and the removal of outliers. Core-to-well log-depth shifts will be reviewed and adjusted if necessary. Outliers include intervals with null or missing values (i.e., missing core); intervals with obvious postdepositional overprints (fractures observed in core); and intervals characterized by caliper-indicated washouts or bad wellbore conditions.

Finally, petrophysical data, including PHIT, PHIE, V_{shale}, volume fraction of lithology and predicted permeability, will be calculated via petrophysical formation evaluation using Schlumberger's Techlog software.

Seismic Interpretation

Seismic data are essential for sub-objectives 3 and 4, and available seismic data include 2-D seismic data and interpreted seismic maps of stratal surfaces and faults beneath the LMBC (Figure 9). A basin-wide structural interpretation of the strata underlying the LMBC is limited because of the absence of 3-D seismic data, and poor quality or sparse availability of 2-D seismic data. There are approximately 22 km of 2-D seismic lines available that will be reprocessed and interpreted. In addition, two maps that were constructed using an array of 2-D seismic lines have been digitized. The surfaces on these maps were digitized using Neuralog's NeuraMap software and incorporated into the geological model. The maps are in two-way-travel-time, and will be converted to depth using synthetic wavelet models built from sonic well logs using wells that intersect seismic lines. Stratigraphic horizons and faults below the study area will be picked and interpreted through Schlumberger's Petrel software.

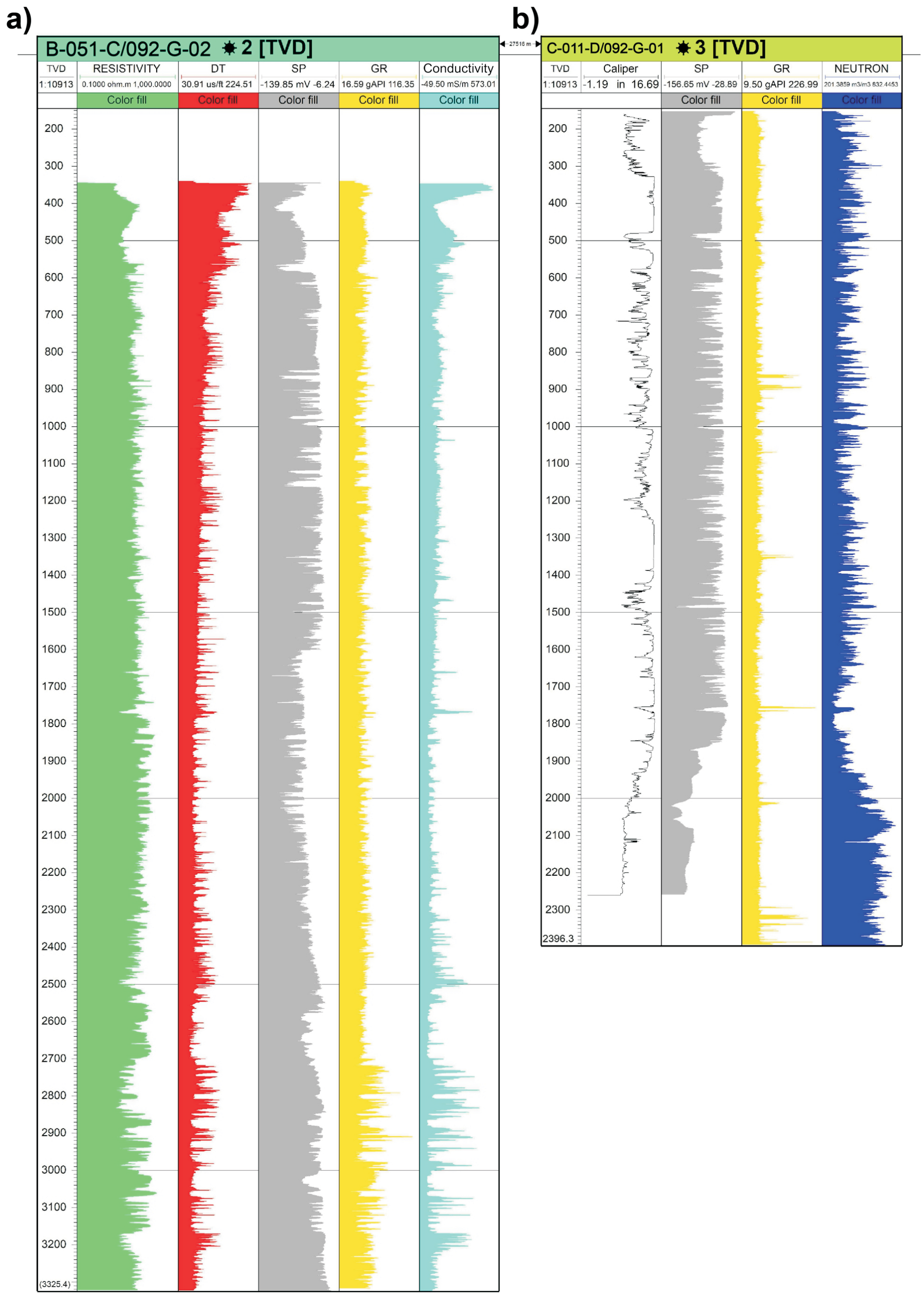

Figure 8. Two of the available wireline logs for wells drilled in the Lower Mainland of British Columbia: **a)** wireline log from unique well identifier B-051-C/092-G-02, and **b)** wireline log from unique well identifier C-011-D/092-G-01 (BC Oil and Gas Commission, 2022). Both logs are corrected for true vertical depth (TVD), given in metres. Abbreviations: DT, sonic log; gAPI, API gamma-ray unit; GR, gamma ray; mS/m, millisiemens per metre; mV, millivolt; SP, spontaneous potential.

Seismic interpretation and the resultant maps are key data needed to identify both CO_2 injection and storage locations and areas with high geohazard risks. Among the most important seismic outputs are the distribution, thickness and depth of potential reservoirs and seals; the fault architecture below the LMBC; and identification of potential reservoir connectivity across faults. Regional seismic interpretation is necessary for the development of an accurate 3-D geological model.

3-D Static Geological Modelling

The 3-D static geological model integrates various data, including core data; geophysical logs and petrophysical data;

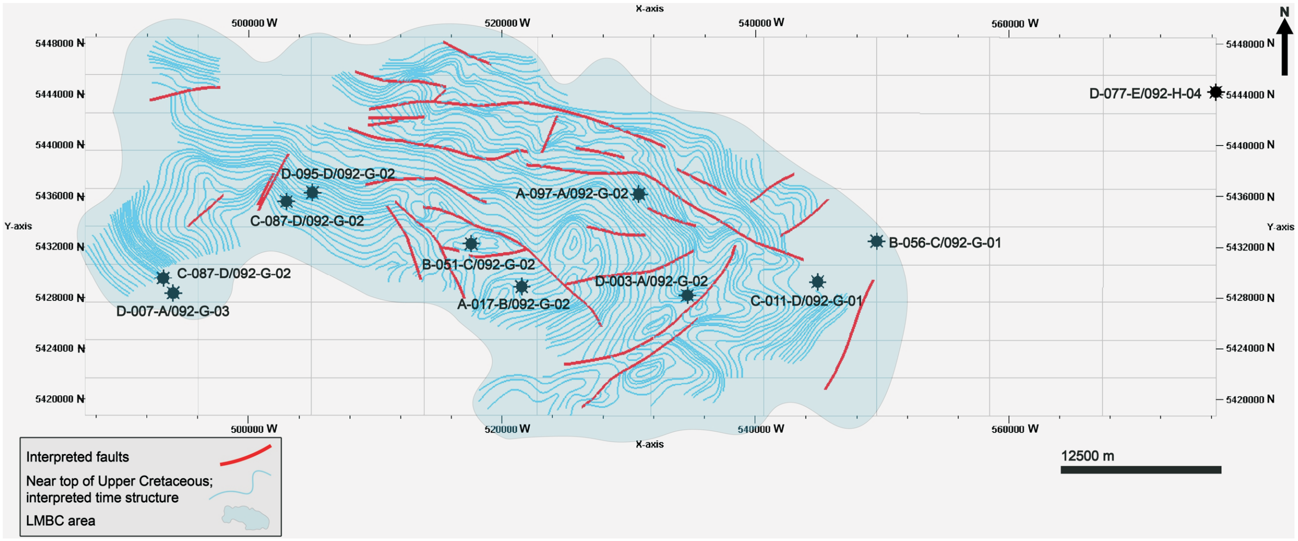

Figure 9. Seismic time structure map of the Upper Cretaceous and the interpreted faults in the Lower Mainland, British Columbia (LMBC). Also shown are the locations of wells (unique well identifiers; BC Oil and Gas Commission, 2022) from which data were obtained. The digitized version of the interpretation of the Upper Cretaceous horizon and faults in the LMBC area was prepared using Schlumberger Limited's Petrel software.

drillstem test results and water chemistry data, well tops, and 2-D seismic data; structural surfaces from seismic surveys and wells; and paleogeographic reconstruction maps of depositional environment systems. These data will be built into a probabilistic distribution of facies and rock properties. Construction of the 3-D static geological model comprises three phases, including structural modelling, facies modelling, and property modelling (Figure 10). The sequential workflow applied to build the 3-D regional static model is as follows:

1) Stratigraphic surfaces and major fault structures mapped from seismic data will be the input for structural modelling, and the resulting structural framework should enable identification of potential structural traps. The potential factors in defining the grid increment and orientation are the well locations and distribution, the geometry of structures, fault elongation and geometry, boundary/edge of the grid, variography analysis of seismic inversion data, and the behaviour of the reservoir. Structural modelling involves several steps, including defining the fault framework (seismic-interpreted faults, fault naming, matching well markers and interpreted faults, and fault-model quality control); defining the structural framework boundary; stratigraphic and reservoir layer modelling; and constructing the geological grid.
2) A 3-D facies model will be constructed from facies defined in cored intervals (sub-objectives 1 and 2) and then mapped regionally using wireline log signatures. Facies models will be guided by the trends recognized in paleogeographic reconstructions developed in sub-objectives 1 and 2, to guide interpretations of facies trends in the subsurface where no core, wireline or seismic data exist. Facies modelling comprises three main tasks: i) well log up-scaling to grid cells (facies data of wells will be scaled-up in the 3-D grid by averaging the facies log values in the grid cells);

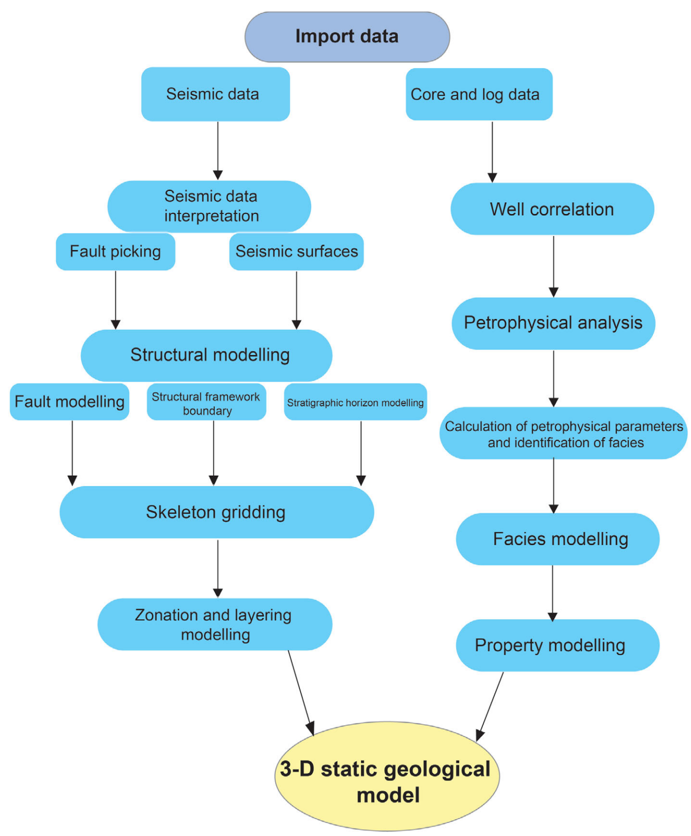

Figure 10. Flow chart of the three-dimensional (3-D) static geological modelling process.

ii) data analysis; and iii) the facies modelling process. Facies data are usually modelled geostatistically using Sequential Indicator Simulation (SIS) algorithms.

3) Property modelling includes modelling effective porosity and permeability distribution in 3-D. Effective porosity will be based on facies-based PHIE values, which are derived from the petrophysical formation evaluation analysis in sub-objectives 1 and 2. Permeability values will also be facies-based, and will be derived from core analysis and permeability prediction via formation evaluation analysis. Property modelling includes three main tasks: i) well log up-scaling to grid cells (PHIE and permeability data of wells will be scaled-up in the 3-D grid by averaging their log values in the grid cells); ii) data analysis; and iii) the property modelling process.

Petrophysical data are usually modelled geostatistically by two methods in Petrel, including Sequential Gaussian Simulation (SGS) and Gaussian Random Function Simulation (GRFS). In the property modelling step, the GRFS method will be used to propagate the porosity and permeability values at facies level into the 3-D model. The property model will be populated using the GRFS method, using variograms, correlation coefficients and trends, to constrain the vertical and lateral distribution of properties. The GRFS method has advantages over the SGS method, as it is faster to run and it provides more accurate results compared to SGS.

Conclusion

In conclusion, carbon dioxide (CO_2) concentration is increasing, and it tremendously influences Earth's atmosphere by intensifying the natural greenhouse effect, exerting a warming influence on the planet's surface. As Earth's climate warms, extreme weather events (e.g., heat domes, tropical cyclones, elevated precipitation, and flooding) occur with greater intensity, raising individuals' concerns about their safety and the safety of their property. Finding practical solutions to decrease carbon emissions while simultaneously maintaining our standard of living and expanding the standard of living of developing countries demands economical and novel solutions. Accordingly, capturing, and sequestering CO_2 underground is the most viable approach to reducing CO_2 emissions over the short to medium term.

British Columbia's Lower Mainland has been assessed previously for hydrocarbon potential and natural gas storage, and these results demonstrated that the area is a readily accessible and potentially economically feasible locale to store CO_2. Nevertheless, not much effort has been made to evaluate the feasibility of carbon capture and storage in the Lower Mainland. Sedimentary strata below the Lower Mainland (at depth) are poorly understood, and the geological context (e.g., depositional environment and facies analysis) of these strata has not been examined in detail. Therefore, this research aims to evaluate the feasibility of carbon capture and storage through several related steps, including facies characterization and petrophysical formation evaluation of Cenozoic and Upper Cretaceous strata below the Lower Mainland, three-dimensional static geological modelling of the Georgia Basin below the Lower Mainland, and fault mapping and identification of geohazards in the same area. Applying these steps will lead to placing the strata below the Lower Mainland in a geological context, assessing these strata for their reservoir potential, and building an integrated three-dimensional static geological model of the strata. These data will then be used to estimate the storage capacity and long-term fate of injected carbon dioxide. The geological model will also be used to define subsurface geohazards (e.g., faults).

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