# Subsurface Energy Storage Program

Nova Scotia Energy Storage Atlas and
Gap Analysis & Road Map to Energy Storage

Report May 2025

net-zero atlantic

# ACKNOWLEDGEMENTS

The Subsurface Energy Storage Program - Nova Scotia Energy Storage Atlas and Gap Analysis & Road Map to Energy Storage is a research project developed and led by Net Zero Atlantic. The research was conducted by RESPEC Consulting Inc. The project is supported by funding from Nova Scotia Department of Energy.

Letter from Net Zero Atlantic

Net Zero Atlantic is pleased to share the findings from the Onshore Nova Scotia Subsurface Energy Storage Assessment and Gap Analysis with our research colleagues and stakeholders.

In 2024, the project was set to explore the potential for onshore subsurface energy storage in Nova Scotia. It aimed to address the lack of detailed information regarding the geological characteristics and locations of potential storage sites for transitional energy sources, such as hydrogen, compressed air, natural gas, and carbon dioxide.

We would like to thank our project funder, Nova Scotia's Department of Energy, Energy Resources Development Branch, Subsurface and Offshore Energy Division. This project aims to support Nova Scotia's energy policy objectives, focusing on climate change, economic growth, and sustainable development.

To conduct the work, we needed an experienced team with in-depth knowledge of our region. We would like to thank the consulting firm RESPEC Inc. for its assistance in undertaking this important work and for providing us with this thorough technical report.

We would also like to acknowledge the participation of the provincial government staff involved in the review process of this study.

Thank you for reading.

Nicolle Jaramillo, Research Manager
Tim Bachiu, Research Director
Net Zero Atlantic

# ONSHORE NOVA SCOTIA SUBSURFACE ENERGY STORAGE ASSESSMENT AND GAP ANALYSIS

## REPORT RSI-3586


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# 1.0 PROJECT DEFINITION

RESPEC Consulting Inc. (RESPEC) conducted this study to investigate the geological characteristics of potential subsurface energy storage sites in Nova Scotia. Potential storage of transitional energy sources such as hydrogen, compressed air, natural gas, and carbon dioxide ($CO_2$) are considered . The study was prepared for Net Zero Atlantic on behalf of Nova Scotia's Department of Energy, Energy Resources Development Branch. This work supports the province's energy policy objectives related to climate change, inclusive economic growth, and sustainable development. A map showing the outline of the study area and age of Nova Scotia bedrock is shown in Figure 1-1. The objectives of the study are as follows:

- **Geological and supporting information gathering to** synthesize geological and supporting data needed to evaluate the feasibility and suitability of subsurface reservoirs in Nova Scotia for energy storage purposes.
- **Comparative analysis with global analogues to** provide critical insights and best practices for subsurface energy storage in Nova Scotia.
- **Gap analysis and strategic recommendations.** Existing knowledge and data gaps are assessed with a comprehensive gap analysis. Recommendations to guide strategic planning and decision-making processes for advancing subsurface energy storage initiatives in Nova Scotia are made.

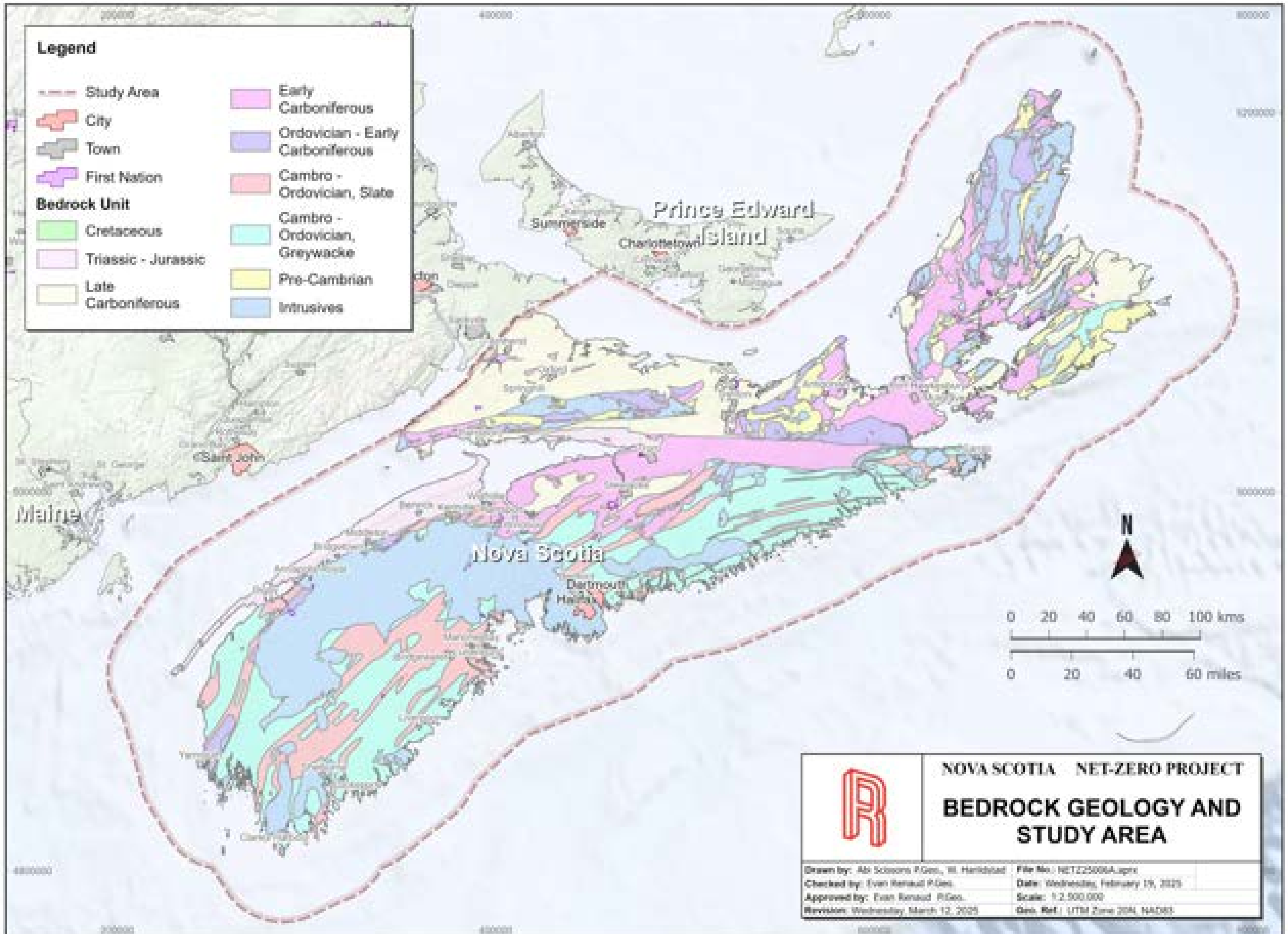


Figure 1-1. Bedrock Geology Of Nova Scotia and Outline of Study Area.

# 2.0 SUBSURFACE ENERGY STORAGE ASSESSMENT

This chapter provides an overview of the data compilation and literature review on the regional geology of Nova Scotia. This chapter focuses on sedimentary rocks in the Maritimes and Fundy Basins; hard rock formations in the Meguma, Avalonia, and Ganderia terranes; and abandoned mine sites. Findings from Section 2.1 support the storage assessment presented in Section 2.2.

## 2.1 DATA COMPILATION AND LITERATURE REVIEW

RESPEC conducted a comprehensive review of data and literature to evaluate the regional geology of Nova Scotia as the foundation for a storage feasibility assessment. Identification and analysis of porous rocks, evaporite formations, hard rock, and abandoned mines within the region are made to explore potential storage opportunities. A combination of published research, industry data, GIS datasets, well data, and documentation provided by the Nova Scotia Department of Energy has been assessed.

For subsurface storage in porous rock, key factors analyzed included lithology, porosity, permeability, depth (pressure), thickness, trapping mechanisms, and the presence of adequate sealing formations. For salt cavern storage feasibility, similar factors were considered, along with the purity of the salt. Porosity and permeability were not assessed for salt formations which can act as wall rocks or seals in cavern storage applications. For storage in hard rock caverns, lithology was the primary factor analyzed.

The complex structural geological history of Nova Scotia results in significant variation in the depth and thickness of geological units across the province. Variations are caused by the interplay of tectonic events, faulting, folding, salt movement, and differential subsidence, which have shaped the regional geology over millions of years. Consequently, units such as the Glass Sand unit of the Horton Group can exhibit considerable depth differences depending on location, influenced by factors like regional tectonic deformation, erosion, and sediment deposition patterns.

RESPEC prioritized understanding the condition of mine abandonment and the available void space within the underground workings when evaluating abandoned mines. RESPEC focused on the largest and most prolific mines to emphasize the scale of underground development and the potential for repurposing void spaces for energy storage applications.

### 2.1.1 SEDIMENTARY ROCK

The Maritimes Basin formed and evolved in the context of Late Paleozoic strike-slip tectonics prior to the final assembly of Pangaea. A tectonic history involving east–west faults (Minas trend), northeast–southwest faults (Appalachian trend), and northwest–southeast faults conjugate to the Minas trend has been inferred [c.f., Waldron et al., 2015]. Basin development likely began in the Late Devonian with dextral movement across Appalachian trend faults. Subsidence within transtensional releasing bends and the creation of several fault-bounded subbasins took place including for the Cumberland, Windsor, Shubenacadie, Musquodoboit, St Mary's, Debert-Kemptown, Stellarton, Antigonish, Central Cape Breton, Western Cape Breton, and Sydney subbasins as shown in Figure 2-1.

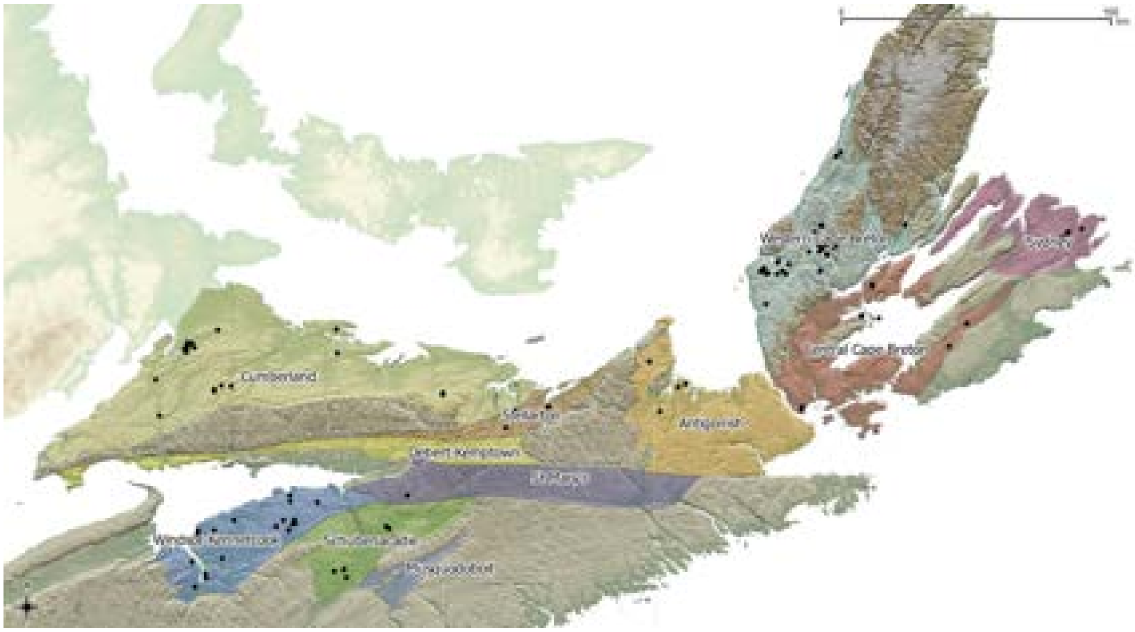


Figure 2-1. Subbasins in Nova Scotia Within the Broader Maritimes Basin [Bianco, 2013].

Strike-slip faulting along the Appalachian trend persisted through the Mississippian, accompanied by significant movement along east–west Minas trend faults. Tectonic activity may have ended around the Mississippian-Pennsylvanian boundary positioning the Meguma and Avalonia terranes of the Appalachians in a configuration similar to their current arrangement. A final episode of mainly sinistral transtension and transpression resulted in the opening of the Atlantic Ocean and the development of accommodation space within the Fundy Basin in the Mesozoic, as shown in Figure 2-2. Maps showing the distribution of Windsor Group salt and the most promising sedimentary units for $CO_2$ storage (the Horton Group and Wolfville Formation) are presented in Section 2.2.5.


Figure 2-2. A Thickness Map of Triassic – Jurassic Stratigraphy in the Fundy Basin of Nova Scotia and New Brunswick [Wade et al., 1996].

### 2.1.1.1 MARITIMES BASIN

The following sections detail the Group-level stratigraphy of the Maritimes Basin, from the oldest rocks to the youngest. Formation naming conventions vary across subbasins. Formation and unit-level geology names vary widely across Atlantic Canada, but can be correlated at the Group level throughout the Maritimes Basin [c.f., Waldron et al., 2017], which is shown in Appendix A. A simplified stratigraphic for the Maritimes Basin stratigraphy is shown in Figure 2-3.

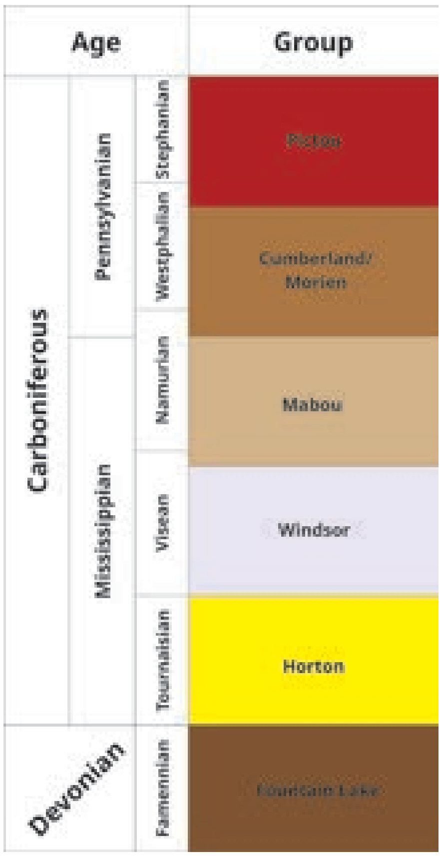


Figure 2-3. Simplified Stratigraphic Column, Maritimes Basin.

**2.1.1.1.1 Fountain Lake Group.** The earliest record of sedimentary deposition in the Maritimes Basin in Nova Scotia is the Late Devonian Fountain Lake Group. The Fountain Lake Group is characterized by bimodal volcanic basalts and rhyolites interbedded with conglomerates, sandstones, and siltstones [Dostal et al., 1983; Waldron et al., 2015]. Clastic units within Fountain Lake Group are relatively thin (approximately 25 meters [m]) and have undergone extensive burial and secondary alterations, including the development of calcite, chlorite, and quartz within fractures and vesicles. Secondary alteration of Fountain Lake Group clastic rocks may have significantly reduced the primary porosities and permeabilities although no direct sampling and measurement was undertaken in this study.

**2.1.1.1.2 Horton Group.** The Horton Group unconformably overlies Precambrian basement and may both overlie and interfinger with Fountain Lake Group rocks. The Horton Group is characterized by conglomerate, sandstone, and shale successions deposited within alluvial fans, deltas, lakes, and estuaries [Martel and Gibling, 1996]. The Horton Group in New Brunswick includes the primary reservoir rocks at the McCully and Stoney Creek hydrocarbon fields [Atkinson et al., 2020].

The Glass Sand is a promising reservoir unit in the upper Horton Group section. The Glass Sand unit is characterized by mature quartz arenites and coarsening upward gamma-ray signatures [Cameron et al., 2018], as shown in Appendix B. The Glass Sand unit varies in porosity between 6 and 12 percent and has uniformly sub millidarcy (mD) permeability in the Windsor subbasin of Nova Scotia [Cameron et al., 2018]. A geomechanical study was conducted on the Horton Bluff Formation in the Windsor subbasin, where significant fracturing was observed. Fractures could be critically pressured through injection methods to enhance reservoir permeability. [Dell'Angelo et al., 2008]. The Glass Sand unit has been interpreted as a top unit in a marine parasequence and may not be continuous across the basin [Cameron et al., 2018].

Lower Horton Bluff Formation sandstones at the base of the Horton Group and Cheverie Formation sandstones at the top of the Horton Group (approximately 600 m) are candidate reservoir intervals in the Windsor Basin as well [Hayes et al., 2017]. Waldron et al. [2013] suggests a potential Horton Group in which good reservoir-quality sandstones could be sealed laterally by Windsor Group salt diapirs. Waldron et al. (2013) infer that Horton Group reservoirs may be preserved poorly in anticline cores conversely. An abundance of faults and folds within Nova Scotia creates numerous potential structural traps.

**2.1.1.1.3 Windsor Group.** The Windsor Group was deposited in a marine environment both conformably and uncomformably overlying the Horton Group. The Windsor Group also unconformably overlies the Meguma Group in places [Lavoie, 1994; Thomas et al., 2002]. The Visean-aged Macumber Formation is the oldest formation in the Windsor Group. The Macumber Formation is a laminated basal limestone throughout Nova Scotia interpreted to have been deposited in a subtidal sabkha environment. Locally, the Gays River Formation may represent an up-dip, reef build-up facies equivalent of the Macumber Formation. The Gays River Formation is characterized by relatively thick (approximately 60 m) reef build-up facies with good porosity and permeability as identified in outcrop [Boehner et al., 1988]. Forent Resources explored for Gays River Formation reservoirs at depth in the Shubenacadie Basin but no wells have penetrated reef build-up facies at depth to date [Hayes et al., 2017]. Some wells (P-136, P-81, and P-82) have identified gas in the Macumber Formation, but the formation typically has poorly developed intergranular and mouldic porosity. Gays River and Macumber formations are vertically sealed by the overlying evaporitic formations (detailed in the following paragraph). Reef build-up facies of the Gays River Formation may create effective stratigraphic traps.

The Windsor Group contains a Visean-aged succession of evaporites ranging from 1 to 3 kilometers in thickness, spanning approximately 14 million years. The Maritimes Basin experienced intermittent connections with the Rheic Ocean and shifted between restricted and non-restricted conditions during this period [MacNeil et al., 2018]. Differential loading of the evaporites, along with transpression, led to the vertical expulsion and movement of salt into thick salt diapirs that coalesce along major anticlines throughout the Cumberland and Antigonish Subbasins in Nova Scotia [Waldron et al., 2013; Thomas and Waldron, 2024], as shown in Figure 2-4. Windsor Group salt movement caused by halokinesis is well documented in studied basins. Analagous salt diapirs, salt welds, and halokinetic structures could potentially exist in other Nova Scotia subbasins. Thickened sections of the Windsor Group along anticlines in the Cumberland Basin can reach up to 3,567 m, as observed in well P-85.

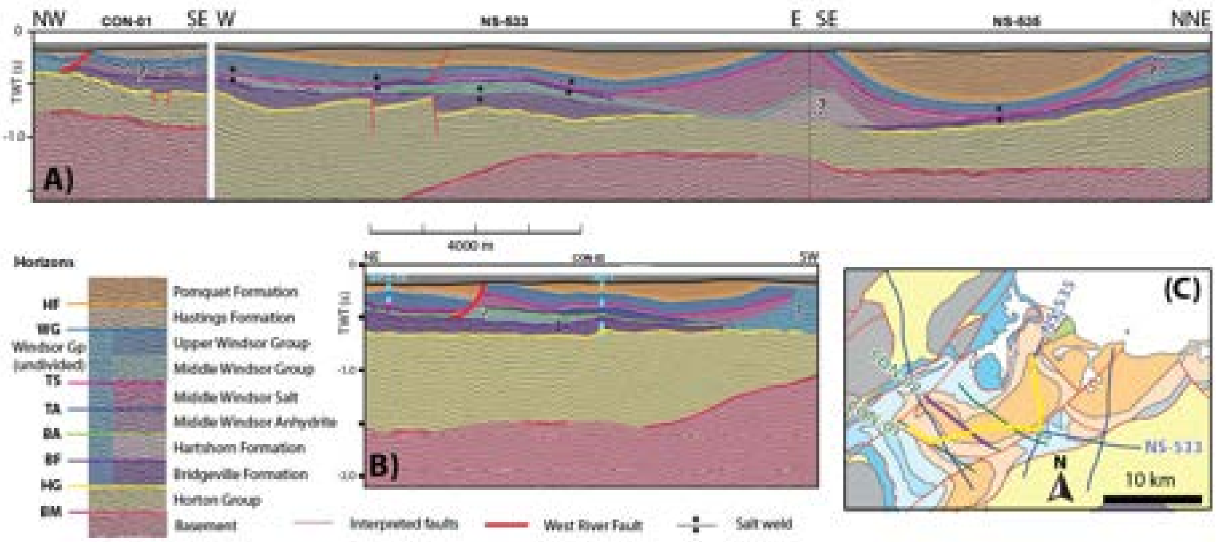


Figure 2-4. Interpreted Seismic Data Showing the Middle Windsor Salt Within Expelled Diapirs Near the Center of the Antigonish Subbasin [Thomas and Waldron, 2024].

Howie [1988] offers a comprehensive review of the evaporite deposits found onshore and nearshore in Nova Scotia, as shown in Figure 2-5. In addition to the Cumberland and Antigonish subbasins, salt deposits have been identified in the Windsor, Shubenacadie, Western Cape Breton, Central Cape Breton, and Sydney subbasins. Historical drilling by Domtar Incorporated in the Kingsville area of the West Cape Breton subbasin revealed salt layers ranging from 381 to 518 m thick, with purity levels reaching up to 95 percent. Further south in the subbasin, Murphy Oil identified 381 m of salt with similar purity near MacIntyre Lake. In the Inhabitants Bay area, DOW Chemical encountered 245 m of salt with a purity of up to 91 percent, but also observed significant lateral heterogeneity, even in wells spaced approximately 100 m apart. Additional historical drill intercepts of thick evaporite sequences have been reported in the Kempt Head and Malagawatch areas. Many salt occurrences are characterized by interbeds of gypsum, anhydrite, clastics or carbonates, as shown in Domtar Incorporated wells in the Kingsville area, illustrated in Figure 2-6.

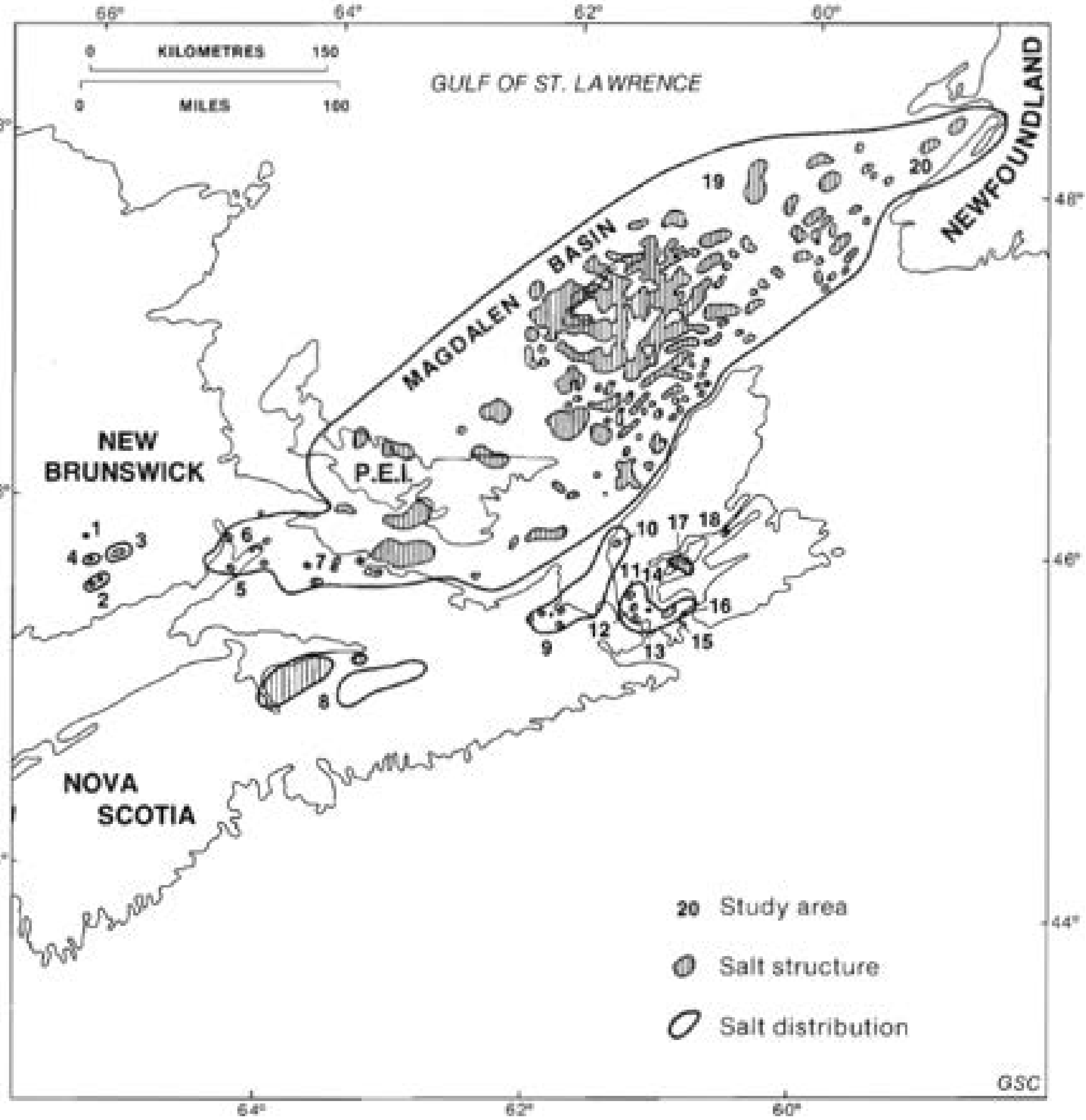


Figure 2-5. Distribution of Windsor Group Salt in Nearshore and Onshore Nova Scotia [Howie, 1988].

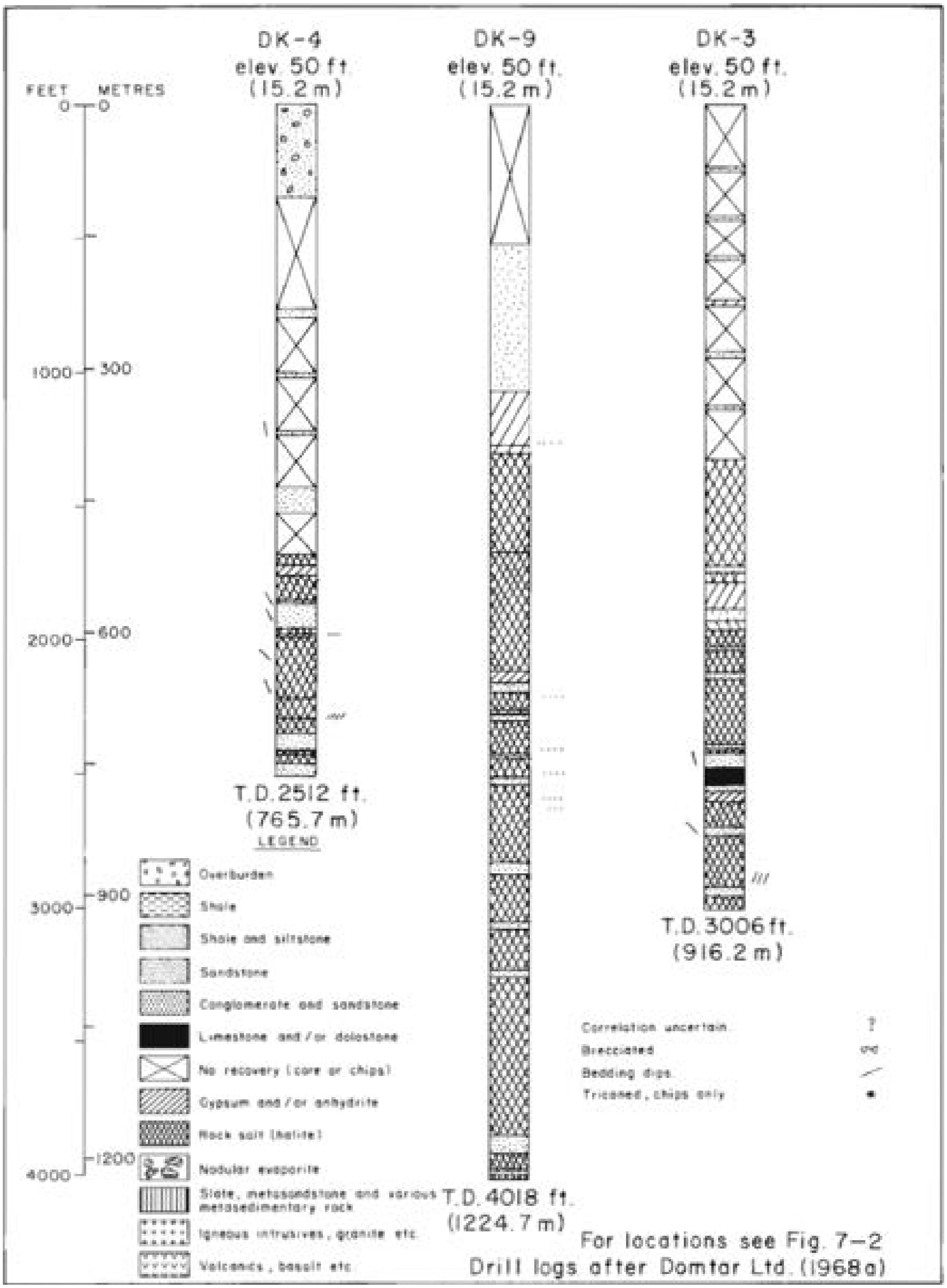


Figure 2-6. Lithologic Logs From Domtar Inc. Wells In Kingsville Showing Anhydrite, Gypsum, Clastic, and Carbonate Interbeds Within Thick Halite Sections [Boehner, 1986].

More recent drilling by Alton Gas in the Shubenacadie subbasin encountered salt ranging from 420 to 476 m thick, with purities exceeding 90 percent. The salt displayed a uniform top elevation, with only a slight dip of about 1 degree, suggesting the potential for a relatively flat, undeformed, and bedded salt deposit. Highly deformed deposits have been observed in other parts of Nova Scotia in contrast [RESPEC, 2007]. The salt deposit in Shubenacadie is estimated to contain approximately 50 billion tonnes of salt, averaging 85 percent NaCl, with localized zones reaching up to 94 percent purity [Boehner, 1986]. The halite of the Stewiacke Formation is relatively undeformed, and its significant lateral extent, favorable depth, and thickness make this area well-suited for salt cavern development. Stewiacke Formation halite is easily identified on well logs, characterized by a low density of ~2000 on the density log (RHOZ), before transitioning stratigraphically below into the higher-density anhydrite of the Carrolls Corner Formation (Appendix B).

**2.1.1.1.4 Mabou Group.** The Mabou Group sediments were deposited conformably to unconformably above the Windsor Group in lacustrine and terrestrial environments. The Mabou Group comprises siltstones, sandstones, grainstones, and stromatolites predominantly [Crawford, 1995]. Sandstone reservoirs within the Mabou Group typically exhibit poor quality and are further constrained by the absence of significant overlying seals [Hayes et al., 2017].

**2.1.1.1.5 Cumberland/Morien Group.** The Cumberland Group unconformably overlies the Mabou Group, the Cobequid Highlands, and Windsor Group strata [Ryan et al., 1991]. The Cumberland Group's primary lithologies include conglomerates, sandstones, mudstones, siltstones, coal, and occasional thin limestone or shale beds. Reservoir quality within the Cumberland Group is generally poor, with porosity below 10 percent and permeability typically less than 1 mD [Bibby and Shimeld, 2000]. Cumberland Group sediments pose a high risk for sealing potential because of their stratigraphic relationship above the Windsor Group evaporites similar to the Mabou Group.

**2.1.1.1.6 Pictou Group.** The Late Pennsylvanian Pictou Group overlies Upper Carboniferous strata or Precambrian basement. Basal contacts of the Pictou Group range from disconformities and paraconformities to unconformities and nonconformities. The Pictou Group is predominantly composed of redbeds with variable proportions of sandstone and mudstone [Ryan et al., 1991]. Porosity in the Pictou Group mainly ranges from 3 to 10 percent at depth; permeability in the Pictou Group is mainly less than 10 mD [Bibby and Shimeld, 2000]. The Pictou Group exhibits relatively better reservoir quality compared to older units. The Pictou Group represents the youngest formation in the Maritimes Basin and lacks an overlying seal.

#### 2.1.1.2 FUNDY BASIN

The following sections focus on the Wolfville and Blomidon Formations of the Fundy Basin. The McCoy Brook Formation is excluded from this analysis because it lies stratigraphically above the primary regional seal, the North Mountain Basalt. A simplified stratigraphic column for the Fundy Basin stratigraphy is shown in Figure 2-7.


Figure 2-7. Simplified Stratigraphic Column, Fundy Basin.

**2.1.1.2.1 Wolfville Formation.** The Wolfville Formation consists of sandstones, conglomerates, and claystones deposited in fluvial, alluvial, aeolian, and playa environments [Kettanah et al., 2008; Leleu and Hartley, 2010]. In the Bay of Fundy region, the Wolfville Formation unconformably overlies the Horton Group or the Meguma Terrane. Outcrop studies indicate porosity values ranging from 2.6 to 16.6 percent. In outcrop, aeolian successions of the Wolfville Formation near Rainy Cove, Nova Scotia, show permeability values as high as 31 darcies, with an average porosity of 20 percent [O'Connor, 2016]. Offshore in New Brunswick, two wells encountered 100 to 280 m of Wolfville Formation sediments with porosity ranging from 3 percent to more than 20 percent [Wade et al., 1996]. This formation is capped by the North Mountain Basalt, a thick and widespread volcanic unit that could be an effective seal.

Deformation within the Wolfville Formation sediments increases toward the northwest along the Bay of Fundy coast and decreases moving southwest. Trapping mechanisms are more prevalent near the northern depositional limit of the formation consequently. Favorable trapping conditions may also be found basinward in the nearshore/offshore environment, away from the outcrop limits along the coast [Carey et al., 2023].

**2.1.1.2.2 Blomidon Formation.** The Blomidon Formation conformably overlies the Wolfville Formation and comprises massive to cross-bedded sandstones, laminated mudstones, and massive mudstones, deposited in fluvial and lacustrine environments [Leleu and Hartley, 2010]. Similar to the Wolfville Formation, the Blomidon Formation is capped by the North Mountain Basalt, which could serve an effective seal, and the same structural trapping mechanisms observed in the Wolfville Formation are applicable here. Unlike the Wolfville Formation, however, reservoir units in the Blomidon Formation are generally more cemented and lack the well-developed sandstone reservoirs observed in the underlying unit [Wade et al., 1996].

### 2.1.2 HARD ROCK

This section provides a functional description of the lithologies across the Meguma, Avalonia, and Ganderia terranes. Meguma, Avalonia, and Ganderia terranes host Precambrian and Paleozoic basement rocks of the geological framework of the Canadian Maritimes region, as shown in Figure 2-8. We assess the lithological characteristics of Meguma, Avalonia, and Ganderia terranes to address suitability of basement rocks for creating stable hard rock caverns.

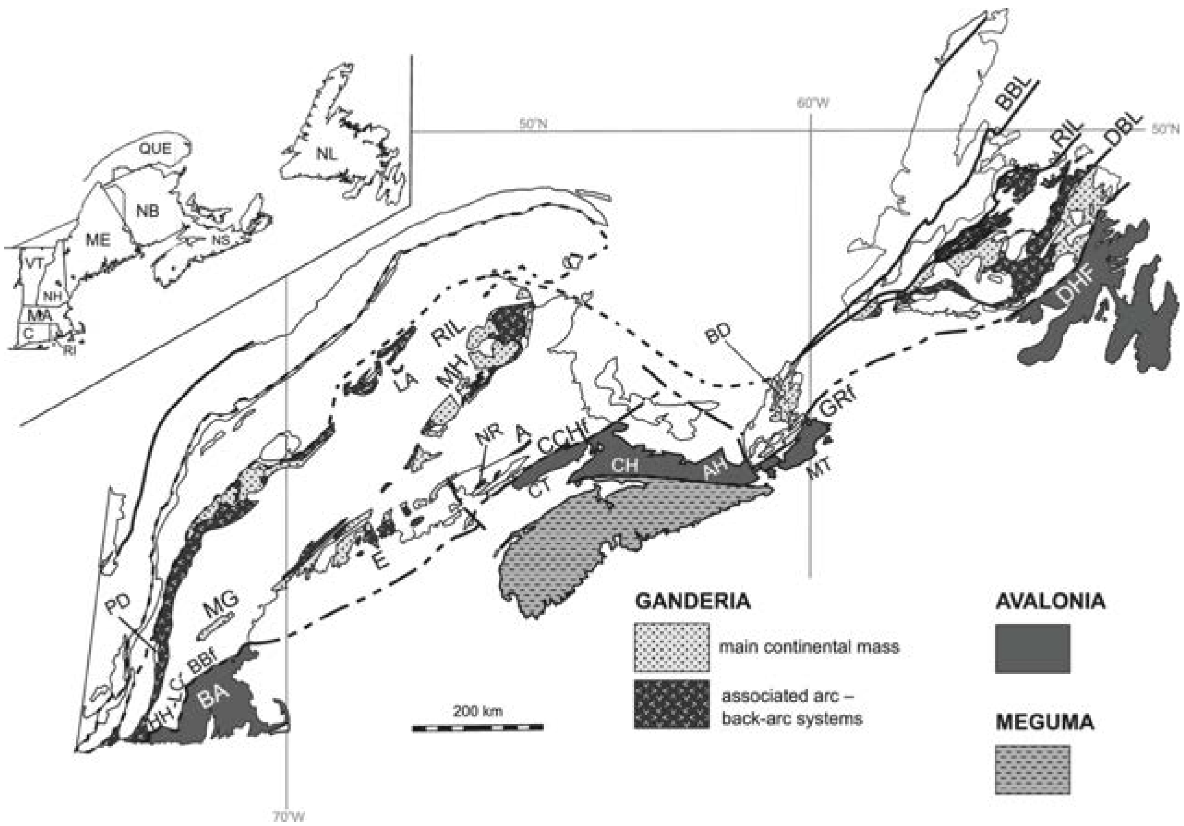


Figure 2-8. Distribution of Meguma, Avalonia, and Ganderia Terranes in the Maritimes Region [Pollock et al., 2011].

#### 2.1.2.1 MEGUMA TERRANE

The Meguma Terrane primarily comprises the Early Cambrian to Early Ordovician Goldenville and Halifax groups, characterized by metasandstone and slate. Overlying these groups along the terrane's northwest margin is the Rockville Notch Group, an Early Silurian to Early Devonian unit composed of slate, quartzite, and metavolcanic rocks [White and Barr, 2012]. The Goldenville and Halifax groups are intruded by Middle to Late Devonian granitic plutons, including the prominent South Mountain Batholith. In the eastern portion of the terrane, the metasandstone-dominated formations of the Goldenville Group reach a thickness of approximately 4,750 m, whereas in the western portion, the group thickens significantly to 8,500 m [Archibald et al., 2024].

#### 2.1.2.2 AVALONIA TERRANE

The Cobequid–Chedabucto Fault separates the Meguma Terrane to the south from the Avalonia Terrane to the north. The Avalonia Terrane consists of Late Neoproterozoic volcanic and plutonic rocks, Cambro-Ordovician sedimentary and volcanic rocks, gneiss, and low-grade sedimentary and volcanic rocks [Murphy et al., 1990]. Sedimentary and volcaniclastic rocks of the Georgeville Group were intruded by plutons as early as 615 million years ago (Ma). Overlying the Georgeville Group are conglomerates, sandstones, and siltstones of the Bears Brook Formation, along with basalt flows of the Arbuckle Brook Formation. These units are succeeded by volcanic and interbedded clastic sequences of the Ordovician Dunn Point and McGillivray Brook formations, which are further overlain by Silurian rocks of the Arisaig Group and the Devonian Knoydart Formation [White et al., 2021].

#### 2.1.2.3 GANDERIA TERRANE

The Ganderia Terrane outcrops in Nova Scotia in northern Cape Breton. The Ganderia Terrane is characterized by a diverse range of geological units, predominantly composed of sedimentary, volcanic, and metamorphic rocks [van Rooyen et al., 2024]. The Ganderia Terrane includes Cambrian to Ordovician sedimentary units such as sandstones, shales, and conglomerates, which were deposited in deep marine environments. These are interspersed with volcanic rocks, primarily basalts and andesites, reflecting past island-arc volcanic activity. In addition, the Ganderia Terrane contains metamorphic rocks, including schists and gneisses, formed by the tectonic processes that led to the closure of the Iapetus Ocean and the collision of terranes during the Appalachian orogeny.

### 2.1.3 ABANDONED MINES

This section explores abandoned mines in Nova Scotia as potential underground storage sites. Compressed gas storage in abandoned mines is a strategy that could help address several transitional energy storage opportunities in Nova Scotia. RESPEC assesses the viability of candidate mine workings to be used as secure and sustainable storage solutions by examining the geological characteristics and stability of select sites. Section 2.2.5 shows a map of abandoned mines with available volume for repurposing into energy storage projects, which are described in the following text.

Nova Scotia's mining history dates to 1685, when French military authorities began extracting coal from seam outcrops in the Sydney Coalfield area of Cape Breton [Shea, 2009]. More than 300 underground coal mines have operated in Nova Scotia since commercial mining commenced in Cape Breton in 1720, producing approximately 400 million tonnes of coal [Nova Scotia Department of Natural Resources, 2024a]. While most underground mining in the Sydney Coalfield ceased in 2001, leaving behind an extensive network of interconnected shafts, tunnels, drifts, boreholes, mining-induced fractures, and de-pillared zones, coal mining remains active in parts of the coalfield. Subsurface structures in the Sydney Coalfield extend northward for at least 25 miles beneath the Atlantic Ocean, reaching depths up to 2,700 feet (823 m) below sea level.

The Sydney Coalfield includes 26 hydrologically connected systems with a combined volume of approximately 190 million cubic meters ($m^3$) [Wolkersdorfer, 2024]. Despite occasional inflows from flooded mine workings into adjacent dry mines, no incident of seawater intrusion has ever been recorded. The lack of seawater intrusion may highlight the possible effectiveness of stratigraphic seal between the mine workings and the overlying Atlantic Ocean [Shea, 2009].

Similar mine networks are present in Pictou County, including the Thorburn, Stellarton, and Westville Mines, as well as in Cumberland County at the Springhill and Joggins Mines. The Springhill Mine alone may contain approximately 4 million $m^3$ of water-filled void space [Jessop et al., 1995].

Nova Scotia also has a history of small-scale subsurface gold mining. Notable underground gold mines include the Goldenville and Lower Seal Harbour Mines. Despite significant exploration activity in the Goldenville area, the average shaft depth is only 28 m, with a few shafts extending to 100 to 200 m [Hill et al., 1997].

Barite mining in the Walton area of Nova Scotia began in the early 1940s. A drilling program initiated by the Nova Scotia Department of Mines in 1956 discovered a lead-zinc-silver-copper orebody beneath the previously mined barite deposit. The mine operated until 1978, when a blast near one of the fault zones caused seawater from the adjacent Minas Basin to flood the workings, leading to its abandonment [Nova Scotia Minerals, 2024]. The Dresser Minerals Walton No. 2 Main Shaft extends to a depth of approximately 515 m, with at least four crosscuts intersecting the orebody [Nova Scotia Department of Natural Resources, 2024b; Boyle, 1972].

The Stirling Mine, located in southeastern Cape Breton, contains a volcanogenic massive sulfide deposit that was mined for zinc, lead, copper, silver, and gold. Initial mining began in 1904 with copper extraction from a small open cut. Stirling Mines Limited extended a shaft to a depth of 240 m in 1926 but discontinued operations in 1931 when low metal prices forced the mine to close. Mining resumed in 1951 when Dome Explorations Limited constructed a second shaft reaching 357 m, but operations ceased again in 1956 [Nova Scotia Department of Natural Resources, 2008].

The Malagash Mine, situated on the north shore of Cumberland County, became Canada's first rock salt mine when operations started in 1918. Mining continued until 1956, after which activity shifted to the now-active Pugwash Mine. At Malagash, extraction occurred at depths ranging from 33 to 381 m, with a travel distance of 853 m to the salt deposit. In 1941, a second stope was sunk west of the initial stope, and by 1948, the mine had interconnected three separate levels [Malagash Museum, 2024; Miller and Norman, 1936].

## 2.2 STORAGE ASSESSMENT

Nova Scotia's potential for subsurface energy storage is examined here for four primary storage types: (1) porous rocks, (2) salt caverns, (3) hard rocks, and (4) abandoned mines, as shown in Figure 2-9. The term "porous rocks," refers to both depleted reservoirs and aquifers in this study. The different storage types each offer distinct advantages and challenges, determined by geological characteristics, engineering requirements, and suitability for specific energy products including natural gas, hydrogen, $CO_2$, and compressed air. RESPEC analyzes the four storage types and discusses potential opportunities, benefits, and economics for their development in Nova Scotia.

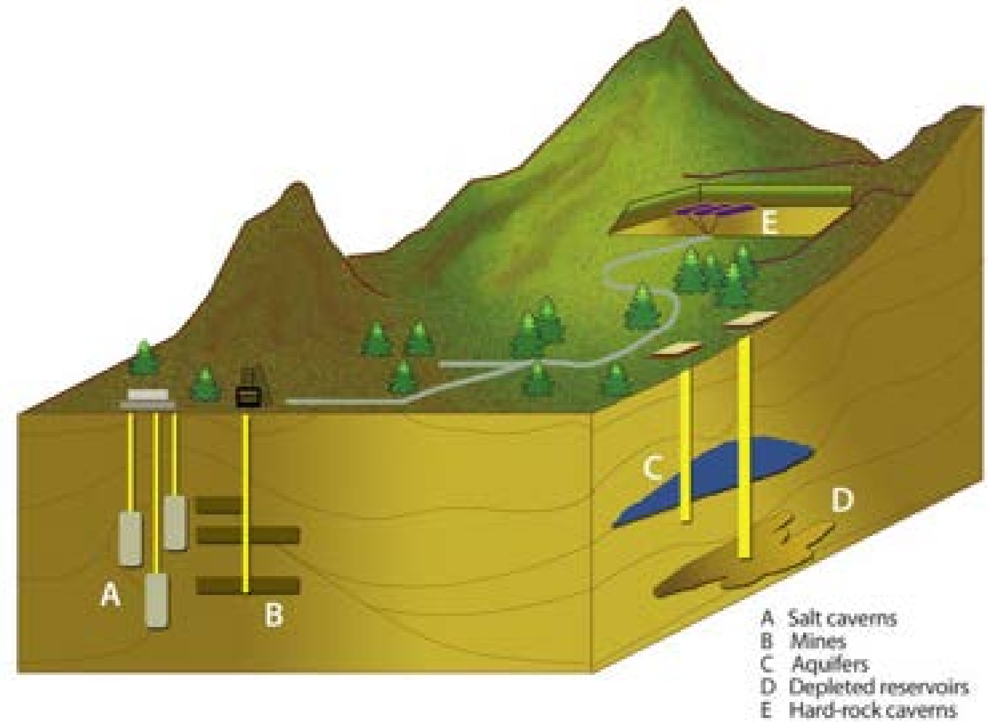


Figure 2-9. Graphical Representation of Underground Storage in Salt Caverns, Porous Rocks, and Mined Rock Caverns [U.S. Energy Information Administration, 2025].

### 2.2.1 STORAGE IN POROUS ROCKS

#### 2.2.1.1 BACKGROUND AND IMPORTANCE OF STORAGE IN POROUS ROCKS

Porous rocks, such as sandstone, limestone, and dolomite, are commonly used for underground storage of gases, including natural gas and $CO_2$. Unlike salt caverns or hard rock excavations, storage in porous rocks takes advantage of the natural pore spaces within these geological formations. These rocks are typically found in sedimentary basins, where they have accumulated over millions of years under layers of sediment.

The most common method of storing gas in porous rocks involves injecting the gas into a subsurface reservoir where it is trapped by an overlying impermeable layer, often referred to as a caprock. This method is similar to how natural gas and oil are trapped in reservoirs over geological timescales. Porous rock storage is widely used in the natural gas industry, particularly in the form of depleted oil and gas fields or aquifers that are repurposed for storage.

The importance of porous rock storage lies in its ability to provide large-scale, long-term storage solutions essential for managing fluctuations in energy supply and demand. Porous reservoirs can be naturally occurring and widespread, making them a practical underground storage choice in many regions worldwide. Governments and energy companies rely on porous rock formations for strategic reserves and seasonal storage.

#### 2.2.1.2 BENEFITS OF STORAGE IN POROUS ROCKS

Storage in porous rocks offers the following key advantages:

- **Large-scale capacity.** Porous rock formations, such as depleted oil and gas fields, often provide substantial storage capacity, making them suitable for storing large volumes of gas over long periods.
- **Widespread availability.** Porous rocks are widely distributed across many regions, particularly in sedimentary basins, making them a readily available resource for underground storage.
- **Cost-effective use of existing infrastructure.** Using depleted oil and gas fields for storage takes advantage of existing wells, pipelines, and other infrastructure, reducing the need for new construction and lowering overall costs.
- **Long-term stability.** The geological characteristics of porous rocks, combined with effective caprock, ensure that stored gases remain securely contained, providing safe and reliable long-term storage.
- **Versatility.** Porous rock formations can be used for a variety of storage applications, including natural gas storage and $CO_2$ storage as part of carbon capture and storage (CCS) initiatives. Additionally, porous rock storage is increasingly explored for storing compressed air and hydrogen, reflecting its adaptability to emerging energy storage needs.

#### 2.2.1.3 POTENTIAL OF STORAGE IN POROUS ROCKS IN NOVA SCOTIA

A southeastern part of the Maritimes Basin outcrops in Nova Scotia. The Maritimes Basin is known for its extensive sedimentary formations, including porous rocks like sandstone, limestone, and dolomite, as reviewed above. Maritimes Basin reservoirs have been linked to oil and gas exploration and production in the region [Atkinson et al., 2020], which may indicate potential suitability for gas storage. Horton Group clastics produce gas in New Brunswick, for example. Equivalent clastic reservoirs in Nova Scotia may have regional potential for CCS development. Good reservoir quality has not been discovered at depth in Gays River Formation. CCS storage potential in Gays River carbonates may be possible if high-quality facies can be located at depth in the future. The Mesozoic Wolfville Formation demonstrates great reservoir potential for CCS, contingent upon the discovery of suitable trapping and sealing elements in the nearshore environment of Nova Scotia. Feasibility of developing a CCS project in the nearshore environment would require a significant volume of $CO_2$ for injection.

Nova Scotia could use depleted oil and gas reservoirs or suitable aquifers within these porous rock formations for underground storage. Porous rocks could be used for natural gas storage, contributing to energy security, particularly during periods of high demand. Additionally, the growing interest in CCS could further drive the development of porous rock storage in the region. Porous formations could be used to safely store $CO_2$ and help meet climate goals. Porous formations could also represent opportunities for storing compressed air and hydrogen to support advancements in renewable energy integration, infrastructure, and the growing hydrogen economy.

#### 2.2.1.4 RELEVANT PARAMETERS

Considering key geological and operational parameters is essential when evaluating the feasibility of porous rock storage in Nova Scotia. The following factors ensure the suitability, safety, and efficiency of the formations for long-term storage applications:

- **Porosity.** Porosity determines the volume of gas that can be stored within the rock. Higher porosity indicates more storage space within the rock formation, making it a critical factor in storage feasibility. For large storage projects, porosity above 7 percent is generally preferred, with values exceeding 15 percent being optimal, depending on the reservoir type.

- **Permeability.** Permeability is essential for gas movement through the pore space of the rock. Higher permeability facilitates efficient gas injection and withdrawal, ensuring operational efficiency. Suitable permeability levels are typically greater than 5 mD for permanent storage and greater than 50 mD for temporary storage scenarios.
- **Caprock integrity and trapping mechanism.** Caprock integrity ensures the stored gas remains securely confined by preventing upward and lateral migration. A robust and impermeable caprock is essential for reliable storage, serving as the natural seal that traps the gas within the reservoir. Additionally, an effective trapping mechanism, such as structural or stratigraphic traps, is crucial to prevent gas leakage and ensure long-term containment.
- **Reservoir pressure.** Reservoir pressure must be carefully managed to maintain storage stability and operational safety. Pressure levels should remain within limits to avoid compromising the site's structural integrity while maximizing storage capacity and injection efficiency.
- **Reservoir continuity and thickness.** The continuity and thickness of porous rock reservoirs influence the overall storage capacity and efficiency. A continuous reservoir with sufficient thickness is preferred to ensure an adequate storage volume and avoid disruptions caused by faults or heterogeneities within the reservoir.
- **Depth.** The depth of the porous rock reservoir affects the pressure and temperature conditions that govern the behavior of the stored gas. Depths greater than 900 m are generally suitable to maintain the optimal phase and pressure conditions for storing gases like $CO_2$ in a supercritical state. Storage reservoirs at depths greater than 3000 meters are rare given the reduction of porosity due to compaction that may become significant at greater depths.
- **Seismic activity.** Seismic stability is crucial to ensure that the storage site is not affected by seismic events that could compromise structural integrity. Areas with low seismic risk are considered more favorable for gas storage operations.

### 2.2.2 STORAGE IN SALT CAVERNS

#### 2.2.2.1 BACKGROUND AND IMPORTANCE OF STORAGE IN SALT CAVERNS

Salt caverns, formed by solution mining within thick salt beds, are increasingly used for underground storage of various energy products, including hydrocarbons, hydrogen, and compressed air. Salt caverns are created by injecting water into the salt formation, dissolving the salt, and extracting the brine, leaving behind a large, sealed underground void. The impermeable nature of salt makes salt caverns an ideal option for storing fluids and gases underground. Salt caverns provide a secure and isolated environment that minimizes leakage and contamination risks.

Salt caverns are crucial to energy infrastructure, offering a secure and reliable method for storing large volumes of energy products that can be accessed rapidly. Governments, particularly in North America, rely on salt caverns for energy security. The U.S. Strategic Petroleum Reserve uses salt caverns to store millions of barrels of crude oil, providing a buffer against supply disruptions and serving as a key element of national security, for example.

Major oil and gas companies also use salt caverns extensively for commercial storage. Salt caverns enable companies to manage supply and demand fluctuations using stored hydrocarbons (such as natural gas and crude oil) as a buffer to help maintain continuous operations or to optimize market opportunities. Salt caverns are increasingly adapted for hydrogen and compressed air storage as the energy industry transitions towards renewable sources, which is vital for integrating renewable energy into the economy.

#### 2.2.2.2 BENEFITS OF STORAGE IN SALT CAVERNS

Salt caverns offer the following advantages as a storage solution for energy products:

- **High integrity and safety.** The natural impermeability of salt greatly reduces the risk of leaks. The self-sealing nature of salt under pressure also enhances the long-term reliability of the storage.
- **Flexibility.** Salt caverns can accommodate a wide range of energy products, including natural gas, hydrogen, and compressed air. The flexibility of salt caverns is advantageous for meeting diverse storage needs.
- **High injection and withdrawal rates.** The smooth walls and large void space in salt caverns allow for rapid injection and withdrawal of stored products, making them ideal for responding to short-term fluctuations in energy demand.
- **Superior containment.** Compared to hard rocks and porous rocks, salt caverns provide better containment because of the self-healing properties of salt, which naturally seals any minor fractures and maintains the cavern's structural integrity.
- **Cost-effectiveness**: Salt caverns are economically cheaper to create compared to hard rock mines. Salt caverns are a cost-effective solution for large-scale underground storage.

#### 2.2.2.3 POTENTIAL OF STORAGE IN SALT CAVERNS IN NOVA SCOTIA

Evaporite deposits within the Windsor Group provide a strong foundation for the potential development of salt caverns for energy storage in Nova Scotia. The Windsor Group is the most significant geological formation containing thick, high-purity halite deposits, which are key to creating underground salt caverns. Halite beds in the Windsor Group can exceed 200 m in thickness and are typically found at depths between 500 and 1,500 m, making them potentially suitable for stable gas storage.

Windsor Group halite deposits offer favorable conditions for salt cavern development, with the necessary pressure for secure containment while minimizing risks of leakage or structural failure. The salt beds' substantial thickness (ranging from 200 to 880 m) potentially allows for creating large caverns with significant storage capacity for hydrocarbons, hydrogen, and compressed air.

#### 2.2.2.4 KEY REGIONS WITH SALT DEPOSITS IN NOVA SCOTIA

Salt deposits are distributed across multiple regions, particularly in the following subbasins and formations, which present the potential for salt cavern development, as shown in Figure 2-10:

- **Antigonish Subbasin.** Significant salt deposits are found within the Hartshorn Formation (Lower Windsor Group). Salt deposits have been identified at depths of 279 to 621 m, offering potential for cavern development. Middle Windsor salt units also contribute to the storage potential in this region.

- **Western Cape Breton Subbasin.** This subbasin includes Windsor Group evaporites, with halite deposits reaching thicknesses of up to 880 m, interbedded with shale and gypsum. Locations such as Kingsville and MacIntyre Lake demonstrate the potential for salt cavern development.
- **Cumberland Subbasin.** This subbasin is another important area containing Pugwash Mine Formation evaporites, with thick and pure halite deposits coalescing along anticlines that are potentially suitable for underground storage.
- **Windsor/Shubenacadie Subbasins.** These subbasins have the potential for relatively undeformed Stewiacke Formation evaporites exceeding 100 m in thickness. Data from more recent drilling in 2014 by Alton Gas near Stewiacke could be leveraged to further characterize the evaporites in this area.

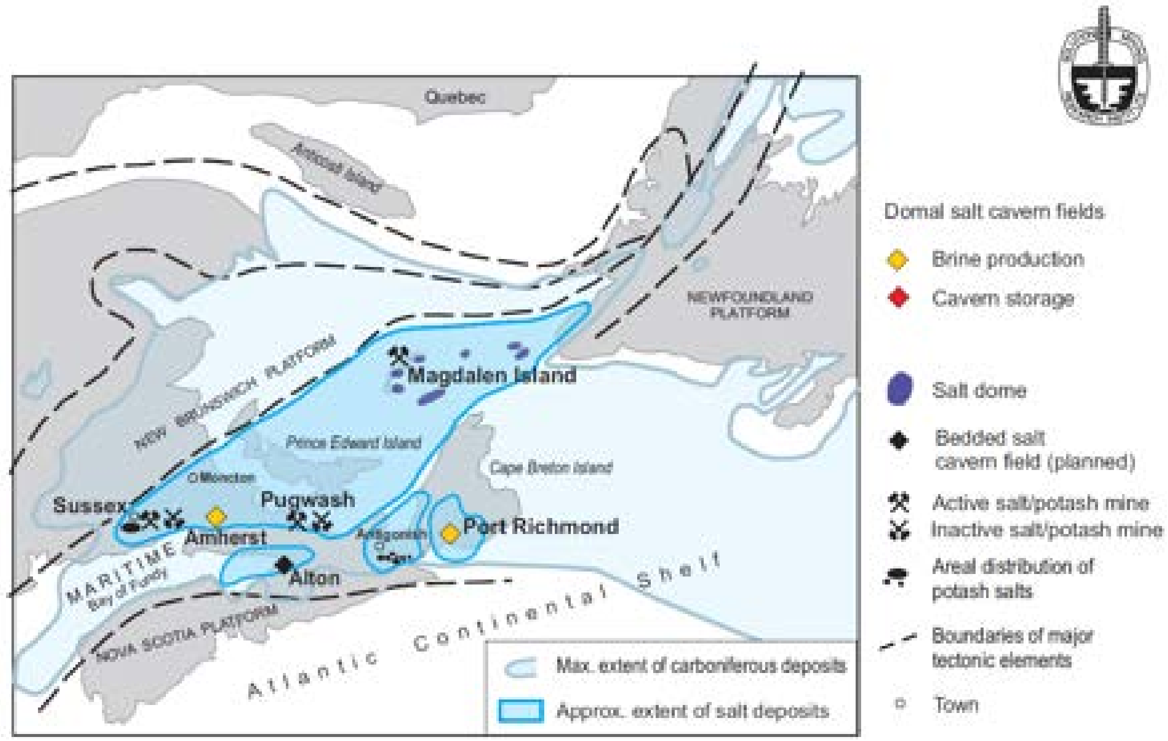


Figure 2-10. Approximate Extent of Salt Deposits in Maritime Provinces [Gillhaus and Horváth, 2008].

### 2.2.2.5 DEPTH AND THICKNESS OF SALT DEPOSITS

The halite deposits in Nova Scotia, particularly within the Windsor Group, are found at depths ranging from 500 to 1,500 m. Salt deposits between 500 and 1500 m depth provide pressure conditions that are potentially favorable for the safe storage of energy products. Salt thicknesses vary from 200 to 880 m which may support the creation of relatively large storage caverns.

### 2.2.2.6 POSSIBILITY OF CREATING SALT CAVERNS

Nova Scotia has the potential to develop salt caverns to store energy products such as hydrocarbons, hydrogen, and compressed air given the bedrock geology. However, further exploration and feasibility studies are required to confirm whether the geological conditions can support salt cavern development. Thick halite deposits, favorable depth, and widespread distribution of salt-bearing formations suggest that economic storage potential exists. Feasibility studies of specific areas can help determine which projects are achievable.

In conclusion, Nova Scotia's geology presents promising potential for salt cavern storage development, particularly in Windsor Group evaporites. An offshore opportunity may also exist in the Mesozoic Argo salt in the nearshore and Scotian basin shelf to the east, but evaluation of the Mesozoic Argo salt was out of scope for this study. For further details regarding the Mesozoic Argo salt, refer to Decalf and Heyn [2023]. High containment integrity and significant thicknesses of salt deposits make salt caverns a potentially advantageous option for underground storage of hydrocarbons, hydrogen, and compressed air generally. The potential safety, durability, and rapid response time of salt caverns make them a preferred option in regions with suitable geology notwithstanding geographic and cost-related limitations.

#### 2.2.2.7 RELEVANT PARAMETERS

The following parameters are relevant for storing gas in salt caverns:

- **Top of salt depth.** The depth of the salt formation is a critical factor because it influences the pressure conditions and the structural stability of the cavern. Depths between 200 to 1,500 m are generally preferred because they provide the required pressure for storage without compromising stability. Depths shallower than ~200 m may pose risks of insufficient pressure. Depths in excess of ~1,500 m can complicate operations and increase costs because of increased cavern closure rate with depth.
- **Thickness.** The thickness of the salt formation affects the size of the storage cavern and its ability to withstand operational stresses. Salt layers with a minimum thickness of 50 m are typically suitable for creating stable caverns with adequate storage capacity. Thinner formations may lead to reduced storage volumes. Thinner formations can also create challenges for maintaining a cavern's structural integrity if the cavern roof is too wide compared to the cavern height.
- **Purity.** The purity of the salt is an important consideration for long-term operational efficiency. Formations with halite content above 90 percent are generally preferred because the higher purity reduces the chance of impurities reacting chemically with the stored gases. Salt deposits with interbedded layers of highly soluble evaporites or other contaminants may require additional assessment before development. For example, sulfate-containing rocks such as anhydrite and gypsum can react with hydrogen, leading to hydrogen loss and the formation of hydrogen sulfide ($H_2S$), a corrosive and pollutant gas.
- **Homogeneity and nonsalt interbeds.** Salt formations with minimal nonsalt interbeds are preferred. Homogeneous salt formations are better suited for stable cavern development because homogeneous rocks ensure uniform structural properties. Salt formations with interbedded nonsalt materials can create weak points that may lead to product leaks or reductions in the structural stability of the cavern. The presence of significant nonsalt interbeds may require a more detailed evaluation to mitigate risks.
- **Access to water for solution mining.** Water availability is a practical consideration for solution mining, the method used to create salt caverns. Sites with reliable access to groundwater or nearby water sources are preferred because continuous water supply ensures efficient cavern development. Locations with limited water availability may face challenges in carrying out solution mining effectively.

- **Brine disposal options.** Brine management is an important consideration for developing and operating salt caverns. Sites with viable disposal options, such as subsurface reservoirs or long-term management plans for treating or selling brine, are preferred.

### 2.2.3 STORAGE IN HARD ROCKS

#### 2.2.3.1 BACKGROUND AND IMPORTANCE OF STORAGE IN HARD ROCKS

Hard rock formations, particularly in excavated mines or purpose-built caverns, are sometimes used for underground storage of energy products, including hydrocarbons, hydrogen, and compressed air. Unlike salt caverns, which are formed through solution mining, hard rock storage often involves either repurposing existing mining infrastructure or excavating new caverns within stable rock formations such as granite, basalt, or other crystalline rocks.

Hard rock storage methods can be especially relevant in regions where other geological formations, like salt beds, are not available. The inherent strength and stability of hard rocks make them capable of withstanding the pressures required for gas storage. However, engineering and construction challenges are generally more significant compared to other storage opportunities. Using hard rock formations for energy storage has been considered in various contexts despite these challenges, particularly in regions with a history of mining or where suitable geological conditions exist.

The importance of hard rock storage lies in its potential to provide additional storage options in areas where salt formations are absent or regions with extensive mining history. Hard rock storage is less common than other types of underground storage, yet it offers a means to diversify energy storage solutions, particularly in countries or regions with significant hard rock resources.

#### 2.2.3.2 BENEFITS OF STORAGE IN HARD ROCKS

Hard rock storage offers the following advantages for storing energy products:

- **Structural stability.** The inherent strength of hard rock formations provides a robust environment that can safely contain high-pressure gases. The relative strength of hard rock formations reduce the risk of structural failure.
- **Large storage volumes.** Excavated mines can offer substantial storage volumes. Excavated mines may be suitable for large-scale storage projects.
- **Geographical flexibility.** More widespread occurrences of hard rock formations provides greater flexibility in choosing storage locations, especially in regions without suitable salt deposits.
- **Reusability of existing mines.** Repurposing existing mines for energy storage is a cost-effective approach to hard rock storage development. Repurposing existing mines leverages existing infrastructure and reduces the need for new excavation.
- **Long-term stability.** Hard rocks typically offer long-term stability for storage caverns. Long-term stability of hard rock caverns ensures that stored gases can remain securely contained over extended periods.

#### 2.2.3.3 POTENTIAL OF STORAGE IN HARD ROCKS IN NOVA SCOTIA

Nova Scotia's geological landscape includes significant hard rock formations and in areas with a history of mining. These formations present opportunities to develop underground hard rock storage solutions. Hard rock storage solutions may be especially useful for storing hydrocarbons and hydrogen. Existing mining infrastructure in Nova Scotia could be repurposed to create large-scale storage caverns and provide a cost-effective and reliable option for energy storage.

Hard rock storage could complement other storage solutions in Nova Scotia, like salt caverns, and can offer additional capacity and flexibility. Nova Scotia's mining heritage and the presence of stable hard rock formations make hard rock storage applications a strong candidate for further exploration and development. New hard rock storage facilities could support Nova Scotia's energy security and renewable energy goals.

In conclusion, hard rock storage offers a viable and potentially valuable option for underground storage in Nova Scotia. Hard rock storage may require more significant investment upfront than salt caverns. The benefits of structural stability, large storage volumes, and the reuse of existing mines could make hard rock storage an attractive solution for Nova Scotia's energy storage needs.

#### 2.2.3.4 RELEVANT PARAMETERS

The following parameters are relevant for storing gas in hard rocks:

- **Rock strength.** The ability of the rock to withstand high-pressure conditions without fracturing is critical for storage in hard rocks. Rock formations with high compressive strength are preferred to ensure structural integrity and long-term containment during storage operations.
- **Depth.** The depth of hard rock formations is crucial in influencing pressure conditions and determining the feasibility of excavation or repurposing. Adequate depth is preferred to ensure effective containment, stability, and pressure management for storage.
- **Fracture density and orientation.** Fracture density and orientation are crucial for ensuring structural integrity and minimizing the risk of gas leakage. Low fracture density and favorable orientations are preferred to reduce weak points in the rock structure and support safe gas containment.
- **Porosity and permeability.** The porosity and permeability of hard rocks is typically lower than in porous rocks but must be considered to assess the potential for gas migration.
- **Seismic stability.** Seismic stability is essential to ensure the long-term safety of the storage site and minimize risks from induced seismicity. Regions with low seismic activity are preferred to prevent disturbances that could compromise gas storage or structural integrity during operations.

These parameters collectively determine the feasibility, safety, and efficiency of gas storage in hard rock formations.

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### 2.2.4 STORAGE IN ABANDONED MINES

#### 2.2.4.1 BACKGROUND AND IMPORTANCE OF STORAGE IN ABANDONED MINES

Abandoned mines can be repurposed to store various energy products, including natural gas, compressed air, hydrogen, and even $CO_2$. Repurposing abandoned mines for underground storage can be considered in stable geological lithologies of igneous or metamorphic, type. Mine workings bounded by stable lithologies offer pre-existing underground cavities that reduce the need for new excavations which can be a cost-effective option for storage development. Coal, salt, or metal mines are the most commonly repurposed for energy storage applications.

Storage in abandoned mines leverages the existing infrastructure, including access roads, shafts, and tunnels, and reduces the capital expenditure required for new construction. Abandoned mine reuse may be an attractive storage solution in regions with a history of extensive mining. The structural integrity of abandoned mines must be carefully evaluated, however. Abandoned mine sites can provide a large storage volume, especially for products like compressed air and natural gas. In some cases, abandoned mines can also be used for pumped hydro storage or as part of CCS initiatives.

#### 2.2.4.2 BENEFITS OF STORAGE IN ABANDONED MINES

Storage in abandoned mines offers the following advantages:

- **Cost-effective utilization of existing infrastructure.** Mines may have established access tunnels, shafts, and ventilation systems, which may reduce the costs associated with building new storage facilities.
- **Large storage volume.** Abandoned mines often have large underground spaces that can accommodate significant volumes of energy products.
- **Geographically flexible.** Abandoned mines may be distributed across many regions which, may make abandoned mines a viable storage option where other formations, like salt caverns, are not available.
- **Environmental benefits.** Repurposing abandoned mines for energy storage may help to mitigate environmental hazards, reduce the need for new excavations, and may prevent subsidence of the rocks above the mine as well.
- **Suitability for multiple products.** Abandoned mines can store a variety of energy products including compressed air, hydrogen, and $CO_2$. Abandoned mines may be versatile for storing different types of gases and liquids.

#### 2.2.4.3 POTENTIAL OF STORAGE IN ABANDONED MINES IN NOVA SCOTIA

With its history of coal and other mineral extraction, Nova Scotia has several abandoned mines that could be repurposed for energy storage. Abandoned coal and mineral mines could potentially be used to store compressed air, $CO_2$, and natural gas. The extensive mining infrastructure in the region, particularly in the Sydney Coalfield, provides strong candidates for developing mine-based storage solutions. With proper structural integrity assessments, repurposing Nova Scotia's abandoned mines could help support the province's energy security and renewable energy initiatives by providing large-scale, low-cost storage options.

Special review should be undertaken addressing the conditions of mine workings when selecting a mine for potential storage uses in Nova Scotia. Mining practices have drastically changed over the centuries in Nova Scotia. For instance, de-pillaring in No. 5 Colliery in the Sydney Coalfield led to widespread collapse of the mine roof and subsidence at the surface [Shea, 2009]. Collapses of mine structures would impact the useful storage volumes of abandoned mines. Priority for mine repurposing should be given to mines that implemented safe and stable mine workings.

In conclusion, storage in abandoned mines offers a cost-effective and geographically flexible option for underground energy storage in Nova Scotia. With careful engineering and safety measures, these mines can be adapted to meet the region's growing need for energy storage, particularly for compressed air and $CO_2$.

#### 2.2.4.4 RELEVANT PARAMETERS

The following parameters are relevant for storing gas in abandoned mines:

- **Mine stability.** The ability of the mine to withstand the pressure of stored gases is critical for ensuring long-term safety and operational reliability. A detailed assessment of the mine's structural integrity, including tunnels, shafts, and surrounding rock formations, is preferred to evaluate its suitability for storage applications.
- **Rock type.** The type of rock surrounding the abandoned mine influences both containment and long-term stability. Hard rock formations or salt deposits are generally more suitable for storage because they provide better containment. Softer or fractured rocks may pose increased risks of leakage and structural instability in contrast.
- **Depth.** The depth of the abandoned mine is crucial in determining the pressure and temperature conditions necessary for safe gas storage. Adequate depth is preferred to ensure optimal containment pressure, reduced risk of surface impacts, and maintenance of long-term stability.
- **Sealing and containment.** Effective sealing and containment are essential to prevent the leakage of gases like hydrogen and $CO_2$. Ensuring proper sealing of all access points, tunnels, and shafts is preferred for maintaining storage integrity and minimizing environmental concerns.

Stability, rock type, depth, and sealing and containment parameters collectively determine the feasibility, safety, and efficiency of gas storage in abandoned mines.

### 2.2.5 VOLUMETRIC ESTIMATES AND STORAGE POTENTIAL MAPS

#### 2.2.5.1 POROUS ROCKS

This section provides preliminary volumetric estimates for $CO_2$ injection volumes into Horton Group clastics and the Wolfville Formation using the following volumetric storage equation:

$$M_{CO_2} = A * h * \Phi * S_{CO_2} \times \rho_{CO_2} \qquad (1\text{-}1)$$

where:

$M_{CO_2}$ = mass of $CO_2$ (tonnes)

A = area of reservoir ($m^2$)

h = thickness of reservoir (m)

$\Phi$ = porosity of reservoir (fraction)

$S_{CO_2}$ = $CO_2$ saturation (fraction of pore space that can be filled with $CO_2$)

$\rho_{CO_2}$ = density of $CO_2$ at reservoir conditions

The potential geological storage units were shortlisted based on the identification of relatively superior reservoir quality, as determined through direct sampling, well logs, or outcrop studies. A set of conservative and simplifying assumptions was applied including: (1) a reservoir area of 1 square kilometer ($km^2$), (2) a $CO_2$ saturation limit of 40 percent [Bachu et al., 2007], and (3) $CO_2$ densities of 600 kilograms per cubic meter ($kg/m^3$), 700 $kg/m^3$, and 800 $kg/m^3$ for the minimum, mean, and maximum cases, respectively, as listed in Table 2-1. Note that density of $CO_2$ at the injection point will depend on the formation conditions at the well's completion depth. The values used here represent a realistic range of $CO_2$ density under supercritical conditions for the purpose of storage capacity estimates. The $CO_2$ saturation limit of a storage reservoir is a highly variable parameter that has been observed to reach 80 percent in some reservoirs [Smith et al., 2022]. A $CO_2$ saturation limit of 40 percent is used here for the purpose of estimating underground storage volumes in an initial calculation.

Table 2-1. Minimum, Mean, and Maximum Parameters Used For $CO_2$ Density and Reservoir Area

| | $CO_2$ Density ($kg/m^3$) | Reservoir Area ($km^2$) |
|---|---|---|
| Minimum | 600 | 1 |
| Mean | 700 | 1 |
| Maximum | 800 | 1 |

Porosity and thickness values were sourced from Hayes et al. [2017] for Horton Group clastics. Porosity and thickness values for the Wolfville Formation were obtained from Wade et al. [1996]. These values are shown in Table 2-2.

Table 2-2. Minimum, Mean, and Maximum Porosity and Reservoir Thickness Values Used for $CO_2$ Volumetric Estimates

| | | Horton Group Clastics | Wolfville Formation |
|---|---|---|---|
| Porosity (fraction) | Minimum | 0.05 | 0.1 |
| | Mean | 0.07 | 0.15 |
| | Maximum | 0.1 | 0.2 |
| Reservoir Thickness (m) | Minimum | 3 | 100 |
| | Mean | 117 | 190 |
| | Maximum | 230 | 280 |

Table 2-3 presents the estimated total $CO_2$ storage capacity per km² for each representative unit. The Wolfville Formation exhibits the highest potential, attributed to its relatively thicker reservoir sands and higher porosity. The Horton Group clastics also demonstrate significant potential, provided that thick (approximately 230 m) reservoir-quality sands are present in the subsurface. The location of potential areas for $CO_2$ storage are shown in Figures 2-11 and 2-12, for the Horton Group and Wolfville Formation, respectively.

**Table 2-3.** Minimum, Mean, and Maximum Volumetric Estimates for Storage of $CO_2$

| Potential Geological Storage Units | $M_{CO2}$ (tonnes/km$^2$) | | |
|---|---|---|---|
| | Minimum | Mean | Maximum |
| Horton Group Clastics | 10,800 | 687,960 | 2,208,000 |
| Wolfville Formation | 720,000 | 2,394,000 | 5,376,000 |

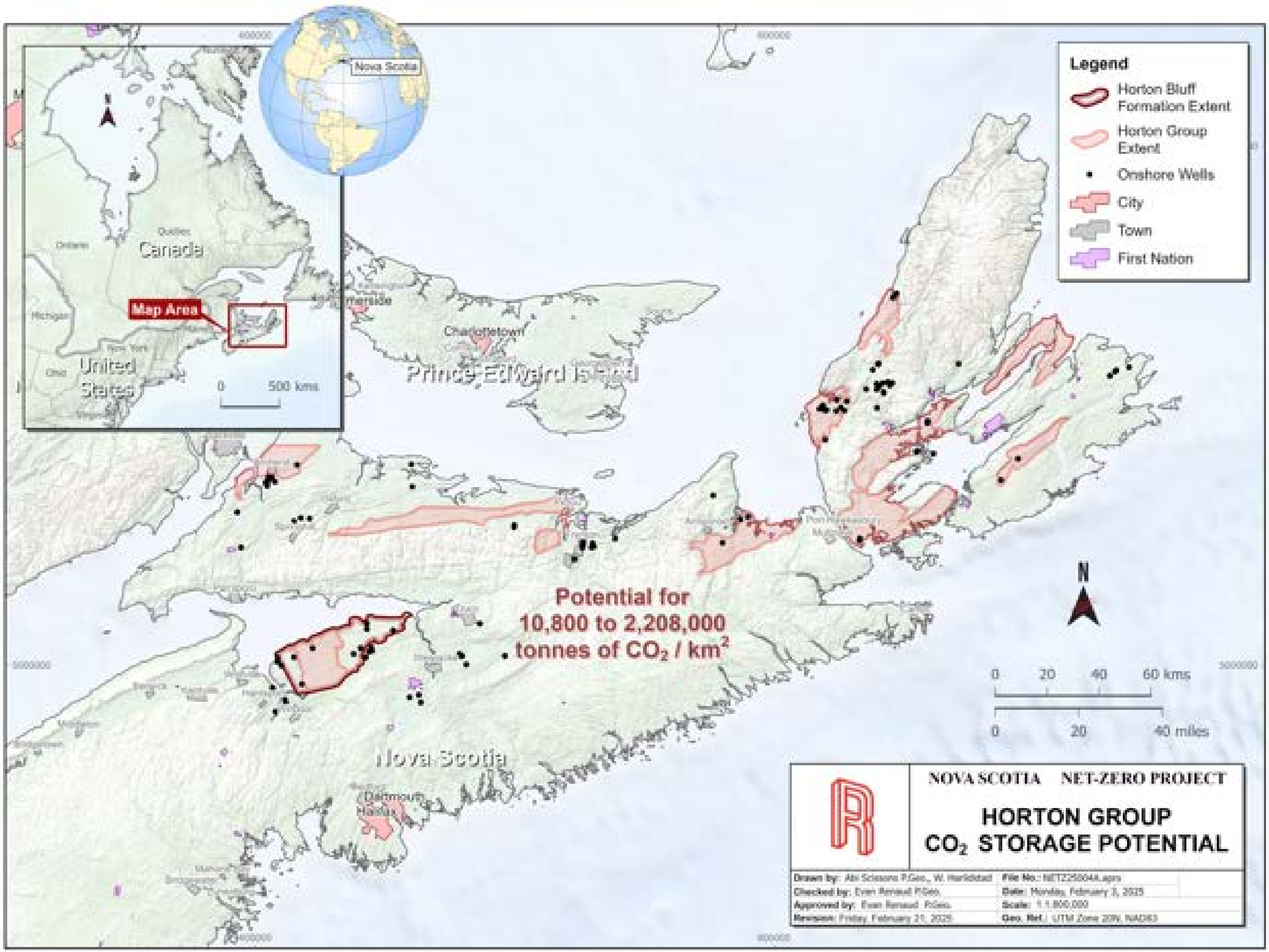


Figure 2-11. Map of Potential Areas for $CO_2$ Storage Development in the Horton Group and Horton Bluff Formation (Windsor Subbasin).

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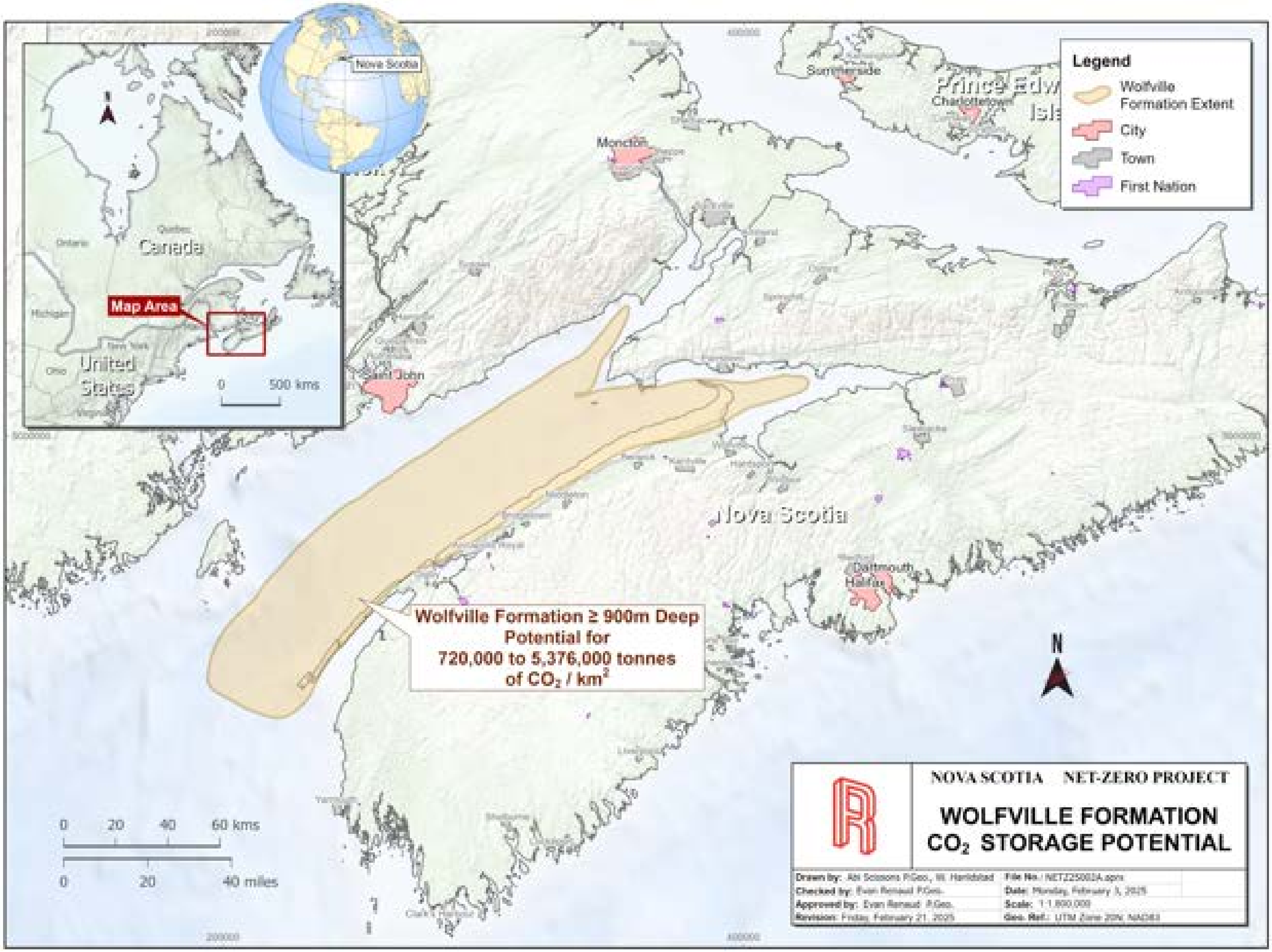


Figure 2-12. Map of Potential Area for $CO_2$ Storage Development in the Wolfville Formation.

#### 2.2.5.2 SALT CAVERNS

For the salt cavern volumetric estimate, RESPEC uses the volume of cylinder equation with a geometric factor of 0.6 applied:

$$Volume_{cyl} = \pi * r^2 * h * 0.6 \quad (1\text{-}2)$$

where:

$Volume_{cyl}$ = volume of salt cavern ($m^3$)

r = radius of salt cavern (m)

h = height of salt cavern (m)

Assumptions for salt cavern heights are based on the observed thicknesses of halite sections within the Windsor Group in Nova Scotia which ranges between 200 and 880 m. Because a certain thickness of salt strata is needed above and below the caverns for integrity and geomechanical stability reasons, the 100 to 550 m range for cavern height provides low- and high-end scenarios for estimates of the total volume available for a single solution-mined cavern. Cavern radii of 30 m for the low-end estimate and 45 m for the high-end estimate are adopted as well. The assumed cavern radii reflect realistic dimensions for potential salt caverns.

Based on the above assumptions, the Windsor Group has the potential to host individual caverns with volumes ranging between 170,000 and 2,100,000 $m^3$. For comparison, a single salt cavern developed at the Advanced Clean Energy Storage (ACES) Project in Utah has a volume of more than 700,000 $m^3$. Cavern dimension assumptions and volume estimates are summarized in Table 2-4. The location of potential areas for salt cavern development in the Windsor Group are shown in Figure 2-13.

**Table 2-4.** Low-End And High-End Cavern Assumptions And Volumetric Estimates

| Cavern Size | Radius (m) | Height (m) | Volume ($m^3$) |
|---|---|---|---|
| Low-end | 30 | 100 | 170,000 |
| High-end | 45 | 550 | 2,100,000 |

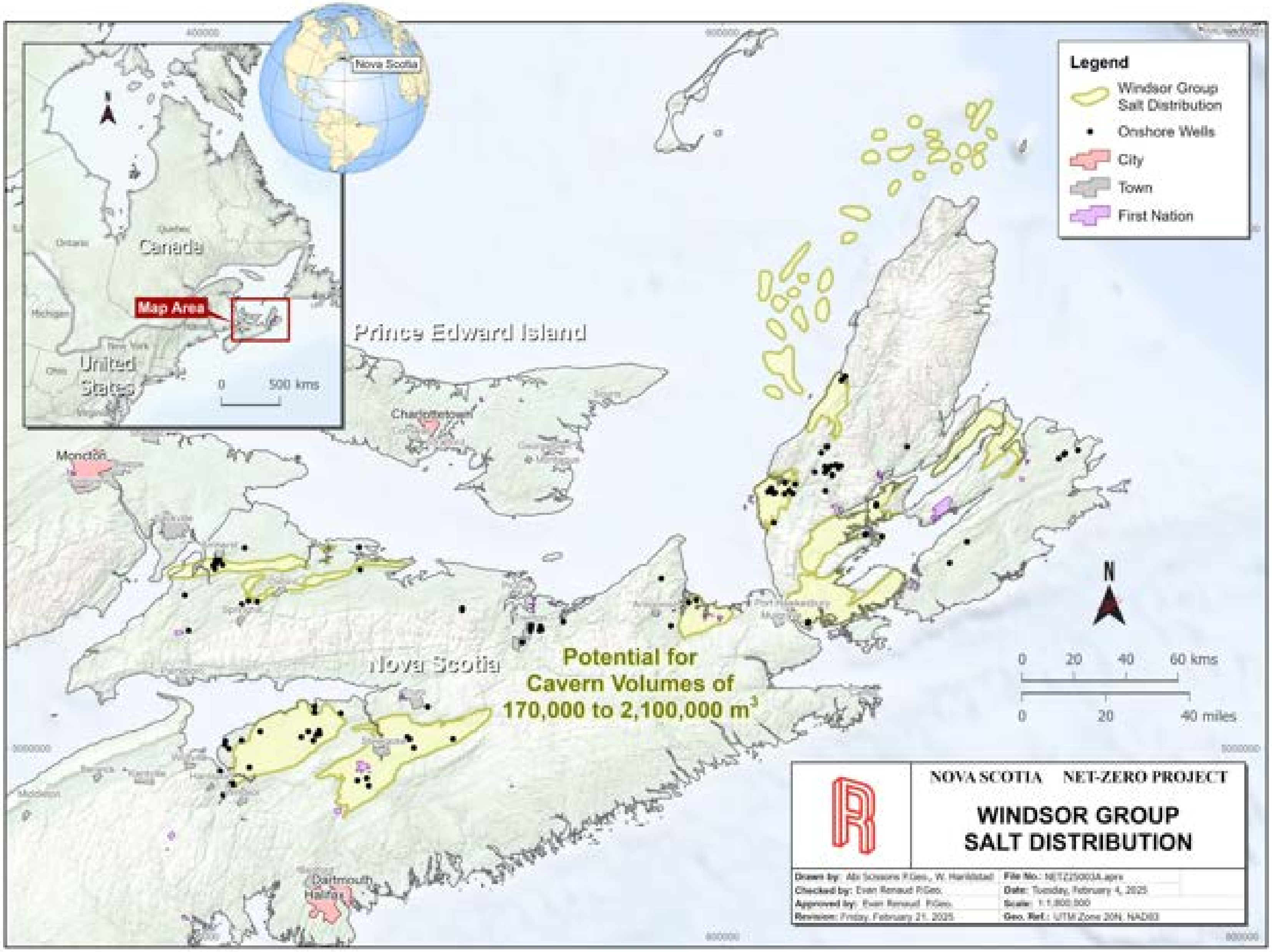


Figure 2-13. Map of Potential Area for Salt Cavern Development in the Windsor Group Evaporites.

#### 2.2.5.3 ABANDONED MINES

Volumetric storage estimates in abandoned mines are reported in the literature and provide approximate measurements for the total void space available in existing abandoned mine workings across Nova Scotia. Coal mines offer the highest potential for large-scale storage because of their extensive subsurface workings compared to other types of mines. Smaller scale storage opportunities may exist in abandoned gold mines, such as Goldenville and Lower Seal Harbour, as well as in other mine types, including Stirling, Malagash, and Walton Mines.

The abandoned Springhill Mine is estimated to contain up to 4 million $m^3$ of water-filled void space [Jessop et al., 1995], for example. In the Sydney Coalfield, 26 distinct hydrological units collectively offer approximately 190 million $m^3$ of void space [Shea, 2009]. Potential for multiple large-scale storage opportunities distributed across the entire Sydney Coalfield may exist. The location of abandoned mines with potential to be repurposed into energy storage sites are shown in Figure 2-14.

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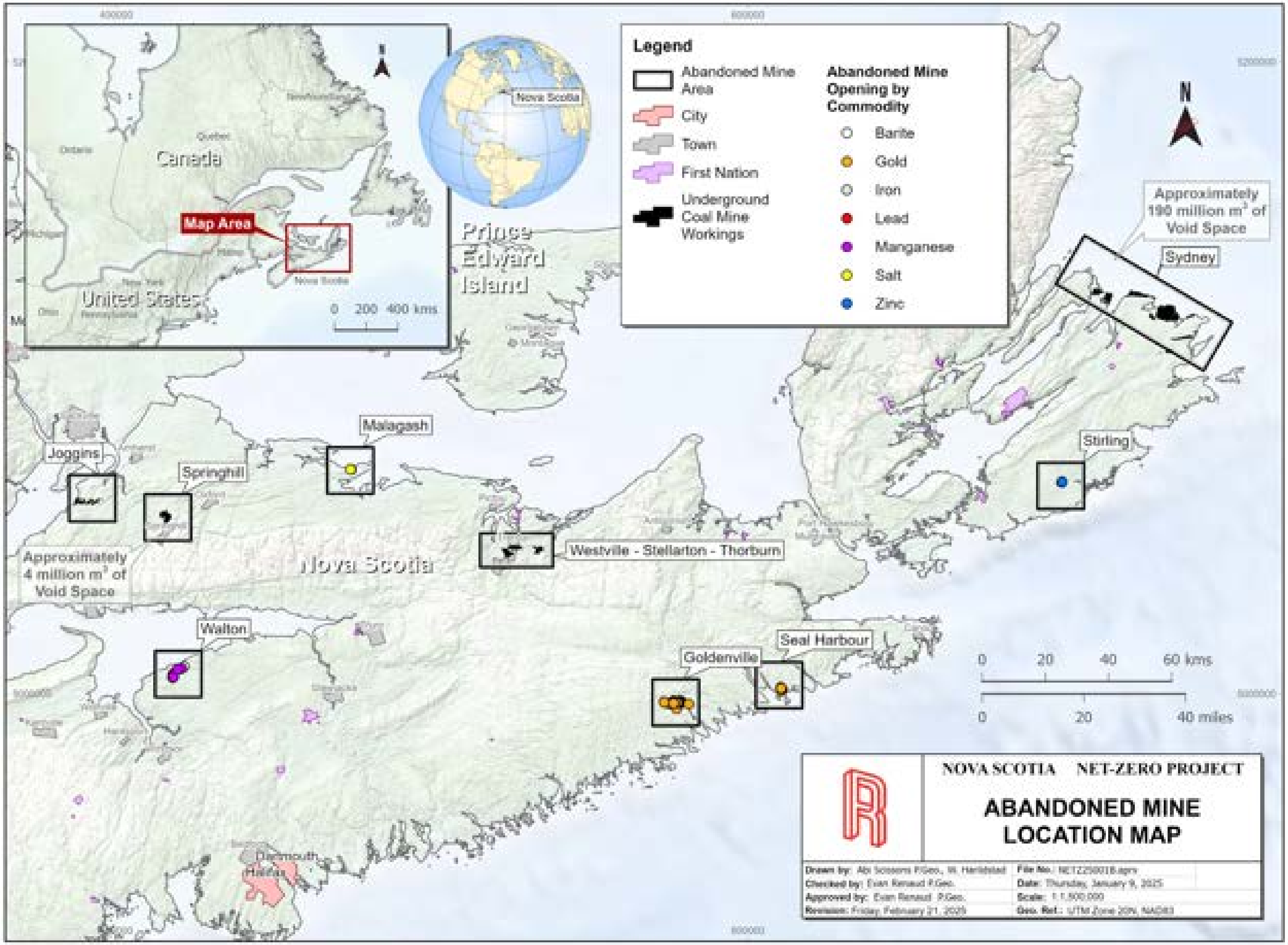


Figure 2-14. Map of Abandoned Mines with Potential to be Repurposed into Energy Storage Sites.

## 2.3 COMPILATION OF SUBSURFACE ENERGY STORAGE ANALOGUES

Section 2.3 presents examples of subsurface energy storage projects relevant to Nova Scotia. Selected analogues provide high-level insights into geological conditions and key features of energy storage projects. Some lessons for an energy storage strategy in Nova Scotia are considered.

- **ACES Project, Utah, USA**
  - **Storage type:** Hydrogen in salt caverns (under development as of December 2024), as shown in Figure 2-15)
  - **Geological conditions:** Uses thick, high-purity salt formations similar to Nova Scotia's Windsor Group salt deposits
  - **Key features:**
    - Comprehensive geological characterization using seismic surveys and core sampling
    - Advanced solution-mining techniques for cavern development
    - Integration into renewable energy grids to support green hydrogen infrastructure
  - **Relevance to Nova Scotia:** Demonstrates best practices in salt cavern storage design, risk management, and alignment with renewable energy strategies

Figure 2-15. Conceptual Image of the Two ACES Hydrogen Storage Caverns [ACES Delta, 2024].

- **Edson Gas Storage Facility, Alberta, Canada**
  - **Storage type:** Natural gas in depleted reservoirs
  - **Geological conditions:** Uses a depleted underground reservoir, originally a natural gas reservoir, repurposed for storage
  - **Key features:**
    - Storage capacity of 50 billion cubic feet of natural gas
    - Provides operational flexibility by storing gas during low-demand periods and withdrawing it during high-demand periods
    - Proven example of reservoir-based hydrocarbon storage with reliable supply management

    - Storage in the Viking Formation exhibiting porosities between 10 and 20 percent and permeabilities between 1 and 100 mD
  - **Relevance to Nova Scotia:** Highlights the potential for Horton Group sandstones, with similar but reduced reservoir characteristics, for hydrocarbon storage and the operational strategies to optimize seasonal demand fluctuations
- Hydrostor's Silver City Energy Storage Centre, New South Wales, Australia
  - **Storage type:** Advanced Compressed Air Energy Storage (A-CAES) in repurposed mining infrastructure (under development as of December 2024)
  - **Geological conditions:** Uses existing mining cavities in hard rock formations, leveraging the structural integrity of the Potosi Mine near Broken Hill
  - **Key features:**
    - A project scale that includes 200 megawatt capacity with 1,600 megawatt-hour storage, providing more than 8 hours of energy delivery
    - Supports Australia's carbon reduction goals with emission-free processes
    - Contributes $1 billion to the local economy and generates more than 750 construction jobs and 70 operational jobs
  - **Relevance to Nova Scotia:** Demonstrates the potential for repurposing existing mining infrastructure (e.g., Sydney Coalfield) for energy storage. The importance of community engagement and regulatory support is highlighted.
- Shell Quest CCS Project, Alberta, Canada
  - **Storage type:** $CO_2$ in deep saline aquifers
  - **Geological conditions:** Uses the Basal Cambrian Sands, known for its regional confinement and storage capacity
  - **Key features:**
    - Captures and stores more than 1 million tonnes of $CO_2$ annually, reducing emissions from Shell's Scotford Upgrader
    - Employs a world-class measurement, monitoring, and verification plan based on risk assessment to minimize storage risks
    - Integrated project development, from $CO_2$ capture to transportation and injection, with significant government funding support
  - **Relevance to Nova Scotia:** Highlights the integration of carbon capture technology with industrial operations, MMV strategies, and effective stakeholder engagement to mitigate risks
- Vortex Energy Hydrogen Storage Project, Newfoundland and Labrador, Canada
  - **Storage type:** Hydrogen in salt caverns (in the exploration stage as of December 2024)
  - **Geological conditions:** Targets Codroy Group salt deposits that may be regionally equivalent to the salt within Nova Scotia's Windsor Group
  - **Key features:**
    - Use of gravity and seismic surveys for detailed geological mapping

    - Phased exploration and development to reduce risks and optimize cavern design
    - Interpretation of complex structural geology that affects the feasibility of salt cavern development
  - **Relevance to Nova Scotia:** Offers a direct comparison for exploring and developing salt caverns for hydrogen storage

## 2.4 COMPARISON TO REGIONAL, NATIONAL, AND GLOBAL OPPORTUNITIES

Section 2.4 compares Nova Scotia's subsurface energy storage opportunities to regional, national, and global analogues. How Nova Scotia can capitalize on its geological and strategic advantages to unlock economic opportunities in underground storage are addressed using insights from the Section 2.3 analogue examples. By examining successful projects worldwide, RESPEC addresses pathways for development and the scale of benefits that can be realized.

### 2.4.1 COMPARISON OF OPPORTUNITIES

1. Regional Opportunities (Atlantic Canada)
   - **Hydrogen storage in salt caverns.** The Vortex Energy Hydrogen Storage Project in Newfoundland and Labrador provides a blueprint for leveraging salt deposits, similar to Nova Scotia's Windsor Group. Nova Scotia can follow the Vortex Energy approach by using phased exploration and development to reduce risks while building a reliable energy storage network.
     - **Economic opportunity.** Collaboration within Atlantic Canada could establish a regional hydrogen supply chain bolstered by Nova Scotia's strategic position near export markets.
   - **Shared resources and knowledge.** Regional collaboration could involve sharing technical expertise to streamline exploration efforts. The Vortex Energy Project used a gravity survey, seismic survey, and drilling techniques to address the Newfoundland opportunity specifically.
2. National Opportunities (Canada)
   - **Natural gas storage in depleted reservoirs.** The Edson Gas Storage Facility in Alberta demonstrates the successful repurposing of depleted reservoirs for natural gas storage. This project highlights the operational flexibility and supply reliability provided by porous reservoirs. Nova Scotia can test and develop porous reservoirs for storage of hydrocarbons or hydrogen moving forward.
     - **Economic opportunity.** By repurposing hydrocarbon or water-charged reservoirs in the Devonian-Carboniferous Maritimes Basin, Nova Scotia could create infrastructure for seasonal gas storage, reducing energy costs and enhancing energy security.
   - **CCS.** The Shell Quest CCS Project in Alberta serves as a prime example of integrating $CO_2$ storage with industrial operations. By capturing and sequestering emissions in saline aquifers, the Shell Quest CCS project demonstrates environmental and economic benefits. Reservoir quality of Horton Group clastics in Nova Scotia is lower than that of the Basal Cambrian Sandstone in Alberta. Potential remains for relatively smaller scale onshore CCS projects within Nova Scotia even so. The Wolfville Formation hosts comparable reservoir

quality to the Basal Cambrian Sandstone and has the potential for larger-scale CCS projects in the nearshore/offshore environment.

  - **Economic opportunity.** Developing CCS infrastructure could attract federal funding and support Canada's net-zero targets, positioning the province as a leader in climate solutions.

3. Global Opportunities

   » **Hydrogen storage (USA).** The ACES Project in Utah highlights the global economic potential of hydrogen storage in salt caverns. Nova Scotia is well-positioned to replicate successes using salt storage caverns, particularly with high-purity Windsor Group salt deposits regionally. Nova Scotia is also well-positioned to serve European and American demand for green hydrogen exports.

   - **Economic opportunity.** Exporting hydrogen to Europe could generate significant revenue and support Canada's Hydrogen Alliance with Germany.

   » **Repurposing mining infrastructure (Australia).** The Hydrostor Silver City Energy Storage Centre demonstrates how abandoned mines can be transformed into valuable storage assets. Nova Scotia's hard rock formations and mining history provide similar opportunities for CAES projects. Use of abandoned mines as underground storage sites could support renewable energy adoption and enhance grid reliability.

### 2.4.2 NATURE AND SCALE OF ECONOMIC OPPORTUNITIES

1. **Hydrogen export revenue.** Projects like ACES (developmental stage) and Vortex Energy (exploration stage) highlight the potential for hydrogen storage to support domestic and international exports. Nova Scotia can capitalize on its proximity to the USA and Europe to establish itself as a major hydrogen supplier.

2. **Job creation.** Subsurface energy storage projects can generate jobs across multiple phases, from exploration and construction to long-term operations and maintenance. Examples like Shell Quest show significant employment opportunities in these sectors.

3. **Energy security and grid stability.** Projects such as the Edson Gas Storage Facility demonstrate how storage solutions can enhance energy resilience. Nova Scotia could adopt similar approaches to support renewable energy integration and reduce reliance on imported energy.

4. **Investment and innovation.** By developing underground energy storage projects, Nova Scotia can attract investments and establish itself as a hub for innovation in subsurface energy storage technologies.

### 2.4.3 SUMMARY

Section 2.4 highlights how Nova Scotia can align its efforts with successful analogues like ACES, Shell Quest, and Vortex Energy. By leveraging known geological resources and a strategic location in northeast North America, Nova Scotia can unlock significant economic opportunities including hydrogen exports, CCS, and CAES advancements. Geology, geography, and economic alignment addresses regional and national energy needs and may help to position Nova Scotia as a global leader in subsurface energy storage.

## 2.5 SUPPORTING OR LIMITING FACTORS

The development of subsurface energy storage projects in Nova Scotia hinges on a variety of factors. This section provides a detailed analysis of supporting and limiting factors categorized into regulatory, geological, infrastructure, and economic domains.

### 2.5.1 REGULATORY FRAMEWORK

A robust regulatory framework is crucial for fostering confidence among stakeholders and streamlining development processes. Nova Scotia's regulatory regime has elements of support but also significant gaps.

- Supportive aspects:
  - The CSA Z341 series for underground hydrocarbon storage provides a strong foundation for regulatory oversight. These standards establish safety, operational, and monitoring protocols, which can be adapted for hydrogen or $CO_2$ storage [CSA Group, 2022].
  - Federal and provincial commitments to achieving net-zero emissions by 2050 align with the objectives of subsurface energy storage. This alignment increases opportunities for funding, policy support, and streamlined project approvals under climate-focused initiatives.
  - Collaboration opportunities with regulators could help establish detailed guidelines for emerging storage technologies like hydrogen and $CO_2$ storage. A proactive approach can ensure regulatory readiness as the industry evolves.
- Limiting aspects:
  - The lack of specific regulations for emerging storage technologies like hydrogen and $CO_2$ storage creates uncertainty for project developers. Uncertainties related to permitting, operational safety, and long-term monitoring requirements could be addressed to facilitate development moving forward.
  - Multi-layered permitting processes require approvals from numerous agencies. Multi-layered permitting processes can result in potential delays and increased administrative burdens for developers.
  - The absence of standardized procedures tailored to energy storage projects adds variability to project timelines and requirements and increases the complexity of compliance.
  - Decommissioning and asset retirement for non-hydrocarbon energy storage projects remains undefined. Decommissioning and asset retirement workflows can be addressed to fill current gaps in lifecycle planning and regulatory clarity.

### 2.5.2 GEOLOGICAL CONSTRAINTS

The geological suitability of subsurface formations is critical to storage success. Nova Scotia offers a range of geological formations, each with unique opportunities and challenges.

- Supportive aspects:
  - The Windsor Group's thick and high-purity salt deposits provide ideal conditions for solution-mined salt caverns, which are well-suited for storing hydrogen or hydrocarbons.

- The Horton Group contains porous sandstones known for their favorable porosity and permeability. Similar porosity and permeability ranges may also be the case for Windsor Group carbonates. Areas of Nova Scotia underlain by Horton and Windsor Group rocks are a promising region for gas storage exploration and development.
- Hard rock formations possess high structural integrity and could be targeted as potential candidates for liquid storage. However, they may be less suitable for gas storage due to the costs associated with installing a liner to prevent gas migration from the excavated space.

/ Limiting aspects:

- Interbedded nonsalt layers within salt formations can complicate solution mining. Interbedded nonsalt layers may reduce storage capacities and increase the risk of structural instability.
- Geological heterogeneity in porous and hard rock formations can result in variable containment and recovery efficiencies which can complicate storage design and operation.
- Significant data gaps exist regarding the depth, lateral extent, and overburden conditions of potential reservoirs, such as the Horton Group clastics and the Gays River Formation. Addressing data gaps would require additional exploratory efforts and will increase initial project costs and timelines.

### 2.5.3 INFRASTRUCTURE CHALLENGES

Infrastructure availability directly impacts the feasibility and cost-effectiveness of energy storage projects.

/ Supportive aspects:

- Nova Scotia's proximity to industrial hubs and planned hydrogen generation facilities along the coastline reduces transportation costs and enhances project viability.
- Existing oil and gas pipelines may be repurposed for energy storage, subject to regulatory and safety evaluations, reducing the need for extensive new infrastructure development.

/ Limiting aspects:

- Limited brine disposal infrastructure is a significant barrier to salt cavern development. Solution-mining operations face logistical and environmental challenges without adequate brine disposal infrastructure.
- Many prospective sites in Nova Scotia lack sufficient access roads and energy transmission networks. Significant infrastructure upgrades or new construction may be required to develop underground storage projects in Nova Scotia which can escalate costs.
- Freshwater resources required for solution mining are scarce in certain regions, which may increase operational expenses and complicate project planning.

### 2.5.4 ECONOMIC AND STAKEHOLDER FACTORS

Economic and social factors are significant drivers of project viability and long-term success.

- Supportive aspects:
  - The global transition toward renewable energy and the rising adoption of hydrogen and CAES both create a strong market demand for subsurface energy storage. Initiatives like the Germany-Canada Hydrogen Alliance further strengthen the market potential for hydrogen storage projects in Nova Scotia.
  - Government funding and clean energy incentives offer financial support for exploratory studies, infrastructure development, and operational costs, reducing risks for early-stage developers. For example, in 2024, the Government of Alberta, through Emissions Reduction Alberta (ERA) and Alberta Innovates, committed $57 million toward 28 projects to advance a hydrogen economy, reduce emissions, and create jobs (add reference). These projects span hydrogen production, storage, transmission, distribution, and end-use applications. Such initiatives highlight the growing government commitment to hydrogen infrastructure, setting a precedent for other provinces, including Nova Scotia, to leverage similar opportunities [ERA, 2024].
- Limiting aspects:
  - High upfront costs are associated with exploration, drilling, and development of underground storage solutions. Requirements for significant capital investment with long payback periods may deter investors. Relative costs among the major subsurface storage types are illustrated in Figure 2-16.

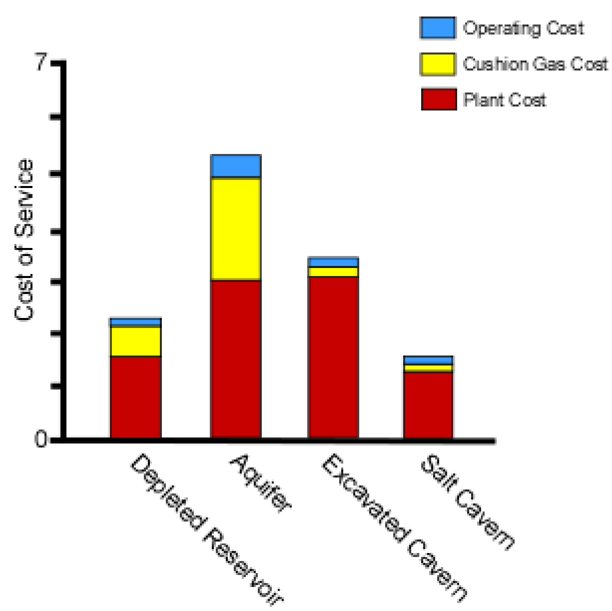


**Figure 2-16.** Relative Costs of Underground Storage Types [Lord, 2009].

  - Public concerns about environmental risks include groundwater contamination or ecosystem disruption. Public concerns about environmental risks can lead to project delays and increased mitigation costs.
  - Market uncertainty surrounding the long-term pricing and demand stability for hydrogen or $CO_2$ storage adds financial risk and may limit investment and scaling efforts as well.

## 2.6 STANDARDS OF PRACTICE

### 2.6.1 OVERVIEW

Standards of practice in exploration, development, and public engagement are essential to mitigating risks and ensuring the successful implementation of subsurface energy storage projects. These standards draw from global best practices and are tailored to Nova Scotia's geological and regulatory context.

#### 2.6.1.1 EXPLORATION STANDARDS

The primary goal of exploration is to identify and characterize subsurface formations that are geologically, environmentally, and economically suitable for energy storage while minimizing risks. A systematic approach reduces uncertainties, supports compliance with regulatory requirements, and facilitates the development of detailed geological models. Detailed geological models are critical for designing storage systems and mitigating risks like gas migration, caprock failure, or induced seismicity.

- **Geophysical surveys.** Geophysical surveys provide a cost-effective and non-invasive means of gathering critical subsurface data over large areas and is the first step in exploration. Geophysical methods identify promising formations for detailed investigation, reducing the number of exploratory wells required and optimizing time, cost, and environmental impact.
  - **Seismic surveys.** 2D and 3D seismic imaging can provide high-precision mapping of subsurface formations, as well as, faults, fractures, and caprock continuity. Advanced processing of seismic data can enhance site selection by detecting subtle variations in rock properties.
  - **Gravity surveys.** Gravity data detect density contrasts in subsurface bedrock. Density contrasts in bedrock are particularly useful for identifying salt domes and their geometry. Gravity surveys can complement seismic surveys in regions with challenging imaging conditions.
  - **Magnetic and electromagnetic surveys.** Magnetic and electromagnetic survey techniques delineate hard rock formations and basement structures based on electromagnetic properties of bedrock. Magnetic and electromagnetic data provide valuable insights into mineralized zones and their impact on storage feasibility.
  - **Integration with data modeling.** Results from geophysical surveys are combined with geological datasets to refine subsurface models. Models well-calibrated with different geological and geophysical data enhance the accuracy of subsequent drilling and characterization efforts.
- **Exploratory drilling.** Exploratory drilling validates geophysical data and provides direct access to subsurface formations for precise characterization. Exploratory drilling reduces uncertainty in site selection and helps to ensure safe and efficient storage operations.
  - **Core retrieval and testing.** Continuous core samples reveal critical properties such as porosity, permeability, and mineral composition. In salt formations, these analyses confirm halite purity and detect nonsalt interbeds that may complicate solution mining.

- Well logging and formation testing. Advanced well logging, including gamma-ray and resistivity logs, characterizes formation layers and identifies anomalies like fractures. Formation integrity and pressure tests assess caprock strength and containment capacity.
- **Real-time monitoring.** Tools like mud logging and measurement while drilling helps to monitor subsurface conditions. Real-time adjustments in drilling parameters can help to mitigate risks, including intersections with high-pressure intervals or weak zones.
- **Challenges and mitigation.** Risks, such as nonsalt interbeds and faults, are addressed by integrating geophysical data into well design and employing advanced drilling techniques.
- **Integration with exploration data.** Drilling results are incorporated into 3D models and help to ensure accurate representations of subsurface conditions are maintained and appropriate storage system solutions are designed.

/ **Core sampling and testing.** Core sampling and testing offer essential insights into the physical and chemical properties of subsurface formations. Storage designs and risk management can depend on accurate assessments of subsurface formation properties.

- **Key tests.** Laboratory tests evaluate porosity, permeability, and rock strength. In salt formations, halite purity is assessed to confirm the absence of contaminants or interbedded materials that could disrupt solution mining or storage.
- **Relevance to design.** Results from core testing influence design parameters, including cavern size, injection rates, and operational pressure limits. Core test results also help to reduce risks like dissolution irregularities or structural instability.
- **Integration with data.** Core results are combined with geophysical and logging data to improve the accuracy of geological models and reduce uncertainties in site selection.

/ **Reservoir characterization.** Reservoir characterization synthesizes data from geophysical surveys, core sampling, and well logs to determine storage suitability and identify risks.

- **3D geological modeling.** Integrated models map formation thickness, lateral extent, and caprock continuity and provide a comprehensive subsurface view for storage system design.
- **Caprock integrity.** Geomechanical and petrophysical models assess caprock strength, test for potential leakage pathways, and help to ensure long-term containment.
- **Risk mitigation.** Challenges like nonsalt interbeds or soluble layers are addressed in design to optimize safety and efficiency.
- **Integration with development plans.** Characterization results guide critical decisions in well placement, casing design, and operational parameters for enhanced reliability.

#### 2.6.1.2 DEVELOPMENT PRACTICES

Development practices focus on designing and constructing safe, efficient, and durable storage systems tailored to geological requirements.

/ **Well design and drilling.** Multi-layered casing systems ensure containment and protect aquifers from operational zones. Directional drilling optimizes well placement relative to storage formations. Directional drilling helps to maintain structural integrity and operational efficiency.

- **Storage system construction.** Salt cavern construction requires carefully controlled solution mining to create uniform shapes and prevent instability. Porous reservoir systems must account for pressure fluctuations to avoid risks like induced seismicity. Hard rock formations demand precise engineering to ensure structural integrity.
- **Safety protocols.** Regular pressure monitoring and integrity testing detect potential issues early, and robust emergency response plans address risks such as leaks or equipment failures. These measures ensure the safety of both facilities and nearby communities.

#### 2.6.1.3 PUBLIC ENGAGEMENT

Transparent communication and active stakeholder involvement build trust and foster community support for energy storage projects.

- **Stakeholder outreach.** Public forums and informational sessions allow project teams to address community concerns about safety and environmental impacts. Collaboration with local governments aligns projects with regional development priorities.
- **Transparent communication.** Clear updates on project milestones and risk management strategies helps to build credibility. Visual aids like GIS maps illustrate benefits and dispel misconceptions effectively.
- **Educating the public on subsurface energy storage.** Educational initiatives such as workshops and informational campaigns explain the technology, benefits, and safety measures of energy storage projects, reducing skepticism and fostering support.
- **Community benefits.** Highlighting economic opportunities, such as job creation and sustainability initiatives, demonstrates the project's value to the community and enhances long-term engagement.

### 2.6.2 SUMMARY

By implementing exploration, development, and public engagement standards, Nova Scotia can ensure the safe, efficient, and socially accepted deployment of subsurface energy storage projects. Exploration, development, and public engagement practices work together to mitigate risks, align with regulations, and support regional energy goals.

# 3.0 SYNTHESIS, GAP ANALYSIS, AND ROADMAP RECOMMENDATIONS

Section 3 integrates findings from Sections 1 and 2 to evaluate Nova Scotia's readiness for subsurface energy storage development. It focuses on identifying gaps in the regulatory framework, geological knowledge, and infrastructure. A roadmap is provided to address regulatory framework, geological knowledge, and infrastructure issues systematically.

## 3.1 READINESS AND GAP ASSESSMENT

Nova Scotia's readiness for subsurface energy storage is examined in three key domains: regulatory framework, geological knowledge, and infrastructure. Gaps are identified along with actionable recommendations for improvement..

### 3.1.1 REGULATORY FRAMEWORK

A well-defined regulatory framework ensures clarity, reduces risks, and attracts investment in energy storage projects. Nova Scotia's current framework has foundational elements but requires significant advancements to address emerging storage technologies.

- **Strengths:**
  - The CSA Z341 series for subsurface hydrocarbon storage provides a solid regulatory base that can be adapted for hydrogen, $CO_2$, and compressed air storage. CSA Z341 series standards already cover critical aspects such as safety, monitoring, and operational protocols and offer a strong starting point for regulatory expansion [CSA Group, 2022].
  - Established regulations for exploration, drilling, and environmental assessments ensure baseline processes that facilitate project initiation. Existing resource development frameworks can be leveraged to fast-track energy storage projects while ensuring environmental and safety compliance.
  - Alignment with Canada's net-zero targets opens access to federal funding programs and policy supports which may facilitate the adoption of energy storage technologies [Environment and Climate Change Canada, 2022].
  - Nova Scotia's existing regulatory institutions, including the Canada-Nova Scotia Offshore Energy Regulator (CNSOER), provide structured oversight mechanisms that may support regulatory expansion as well.
- **Gaps:**
  - The lack of specific guidelines for hydrogen, compressed air, and $CO_2$ storage creates ambiguity for developers. Developers face uncertainty without clear regulations for long-term monitoring, containment strategies, and operational safety. Development uncertainties can deter investment and extend project timelines.
  - Complex permitting processes with multi-agency approvals create administrative burdens. The lack of a centralized permitting authority results in delays. The lack of a centralized

permitting authority also escalates project costs and may discourage developers from pursuing energy storage initiatives in Nova Scotia.

- Limited public consultation requirements hinder transparency and trust. The absence of formalized stakeholder engagement processes can lead to community resistance. Community resistance can in turn delay projects or result in cancellations from unresolved concerns about environmental and safety risks.
- No decommissioning protocols for energy storage projects pose long-term risks. The lack of guidelines for asset retirement and site restoration leaves gaps in lifecycle accountability. Gaps in lifecycle accountability increases the potential for environmental liabilities and public opposition.

/ **Recommendations:**

- Develop comprehensive regulations tailored to hydrogen, compressed air, and $CO_2$ storage to address unique challenges such as containment monitoring, safety requirements, and lifecycle accountability. Nova Scotia should leverage lessons from global analogues to establish clear, enforceable standards to reduce uncertainties for developers.
- Establish a centralized permitting authority to streamline approval processes. A centralized permitting authority would consolidate permits across regulatory agencies and ensure efficiency, consistency, and reduced administrative burdens for developers.
- Integrate community engagement requirements into the regulatory framework to mandate public forums, stakeholder consultations, and educational campaigns. Integrated community engagement processes will build trust, enhance transparency, and align projects with community priorities.
- Create standardized decommissioning protocols to ensure lifecycle accountability by defining clear responsibilities for site restoration, financial assurances, and environmental risk management. Decommissioning protocols will safeguard public and environmental interests while ensuring developer accountability.

### 3.1.2 GEOLOGICAL KNOWLEDGE

Nova Scotia's diverse geological formations present opportunities for subsurface energy storage. Incomplete data and limited exploration hinders the full realization of this potential at present.

/ **Strengths:**

- The Windsor Group salt deposits feature thick, high-purity formations ideal for solution-mined caverns.
- The Devonian-Carboniferous Maritimes Basin and Triassic Fundy Basin contains sandstone and carbonate formations with favorable porosity and permeability for gas storage.
- Hard rock units, including igneous and metamorphic rocks in the Avalonia, Meguma and Ganderia terranes, exhibit high structural integrity and may be suitable for CAES.

- **Gaps:**
  - Data gaps in formation characteristics restrict storage assessments. Limited information on the thickness, lateral extent, and structural integrity of key formations hinders the ability to accurately evaluate suitability for storage applications.
  - Uncertainty in chemical compatibility poses operational risks. Insufficient studies on the interactions between stored products (e.g., hydrogen or $CO_2$) and host formations could lead to unforeseen chemical reactions that compromise storage integrity.
  - The lack of comprehensive geological models reduces feasibility study accuracy. Without integrated 3D models, understanding subsurface conditions remains fragmented, which increases risks during development.
- **Recommendations:**
  - Conduct gravity and seismic surveys and exploratory drilling programs to gather detailed data on high-potential formations, reduce uncertainties, and improve storage assessments.
  - Develop 3D geological models to visualize and analyze subsurface conditions comprehensively. 3D geological models will integrate existing data with new findings to provide a robust framework for feasibility studies.
  - Conduct chemical compatibility studies to evaluate potential reactions between stored materials and host formations. Chemical compatibility assessments will mitigate risks related to chemical degradation or adverse reactions.

### 3.1.3 INFRASTRUCTURE AVAILABILITY

Infrastructure is a critical enabler for energy storage development. Nova Scotia faces significant infrastructure gaps that must be addressed to enhance project feasibility and reduce costs.

- **Strengths:**
  - Proximity to industrial hubs, planned wind plants, and planned hydrogen generation facilities reduces logistical challenges. Geographic advantages for Nova Scotia simplify transportation and enable cost-effective integration with local industries and energy networks.
  - Existing pipeline infrastructure offers potential for repurposing. Pipelines can be adapted to transport the stored product and reduce the need for entirely new infrastructure.
- **Gaps:**
  - Inadequate transport and energy networks limit access to potential storage sites. The lack of roads, transmission lines, and other infrastructure increases development costs and delays timelines for high-potential projects.
  - Freshwater scarcity complicates solution-mining operations. Limited access to freshwater resources raises operational costs and introduces logistical challenges for salt cavern development.
  - Brine disposal limitations remain a significant challenge. Nova Scotia lacks adequate brine disposal options. Lack of adequate brine disposal options creates environmental and logistical hurdles for salt cavern storage projects.

/ **Recommendations:**

- Upgrade and expand transportation and transmission networks to connect potential storage sites with industrial hubs. Ensure accessibility and feasibility for large-scale projects.
- Investigate alternative water sources for solution mining to address freshwater scarcity. Consider using treated wastewater or seawater for operations.
- Develop a brine disposal strategy to support salt cavern development. Consider subsurface disposal or alternative treatment methods to mitigate environmental risks.

## 3.2 ROADMAP FOR ADVANCING SUBSURFACE ENERGY STORAGE IN NOVA SCOTIA

This roadmap provides a phased approach to address identified gaps and to position Nova Scotia as a leader in energy storage technologies.

A. **Immediate Priorities (0–3 Years).** The immediate priorities focus on establishing foundational regulatory and geological knowledge, initiating pilot projects, and fostering public trust.

- **Regulatory framework:**
  - Draft and implement regulations tailored to hydrocarbons, hydrogen, compressed air, and $CO_2$ storage. Provide clear guidance for site selection, containment, monitoring, and safety requirements. Offer a predictable environment for developers.
  - Establish a centralized permitting process to simplify multi-agency approvals. Create a unified permitting authority that coordinates across regulatory bodies, expedites approvals, and minimizes administrative delays.
  - Study international regulatory frameworks to incorporate best practices. Analyze lessons learned from successful energy storage programs with a focus on permitting, safety protocols, and public engagement. Take advantage of lessons learned from other projects to avoid common pitfalls.
- **Geoscience and exploration:**
  - Identify high-priority geological targets suitable for energy storage. Leverage existing data to locate salt deposits, porous sandstones or carbonates, or hard rock structures. Prioritize areas with favorable depth and thickness, overburden integrity, and infrastructure proximity.
  - Conduct gravity and seismic surveys to evaluate geological targets and generate high-resolution subsurface maps. Identify key features like rock types, faults, fractures, and target structure geometries to reduce exploration risks.
  - Develop integrated 3D geological models for key formations to provide a comprehensive understanding of subsurface conditions. Improve the accuracy of feasibility studies and guiding exploration programs.
- **Infrastructure development:**
  - Conduct a study to map existing infrastructure and assess suitability for energy storage projects. Identify pipelines, transportation networks, and facilities that can be repurposed or upgraded.

- Identify infrastructure gaps. Propose actionable solutions to address deficiencies in transportation, brine disposal, and energy transmission networks. Enable smoother project execution.
- Conduct feasibility studies for brine disposal for salt cavern storage. Explore subsurface disposal options or alternative treatment solutions to address environmental concerns.
- Identify locations for potential pilot projects to test storage systems based on geological suitability, infrastructure availability, and alignment with provincial energy goals.

» **Community engagement:**

- Launch public education campaigns to build trust and awareness by communicating the benefits, safety measures, and environmental impact of energy storage technologies through targeted outreach.
- Organize stakeholder forums to gather input and address community concerns by creating platforms for transparent dialogue and collaboration to align projects with local priorities.

» **Attract investors and build pilot projects:**

- Invite companies to launch demonstration projects for hydrogen, compressed air, and $CO_2$ storage to validate technical feasibility, refine operational strategies, and generate investor interest through early successes.
- Outline financial and policy incentives to stimulate industry-driven geoscience exploration by offering targeted grants, tax credits, and cost-sharing mechanisms for exploratory drilling, core sample analysis, and subsurface modeling. Implement regulatory streamlining to fast-track permitting and create public-private partnerships that support collaborative research and data-sharing. Introduce performance-based incentives that reward companies for achieving key exploration milestones, such as confirming suitable geological formations or demonstrating containment integrity.

B. **Medium-Term Goals (3–6 Years).** Medium-term goals emphasize regulatory refinement, geoscience advancements, and infrastructure expansion to support scalable energy storage projects.

» **Regulatory advancements:**

- Finalize and implement hydrogen, compressed air, and $CO_2$-specific storage regulations. Address long-term monitoring, containment, and lifecycle accountability to ensure comprehensive guidance for developers.
- Develop standardized decommissioning and lifecycle planning protocols. Establish requirements for site restoration, financial assurances, and long-term environmental risk management.
- Harmonize regional and federal policies to facilitate collaboration. Align Nova Scotia's regulations with federal frameworks to enable seamless integration of cross-border infrastructure and partnerships.

- Evaluate and update regulatory effectiveness based on industry feedback. Conduct periodic reviews to address emerging challenges and incorporate advancements in technology and best practices.

» **Geoscience enhancements:**

- Initiate exploratory drilling for high-priority targets. Confirm the presence of suitable formations, retrieve core samples, and collect real-time data on subsurface properties like pressure and porosity.
- Perform core analysis and chemical compatibility studies. Evaluate the physical, chemical, and mechanical properties of host formations and assess potential interactions with stored products.
- Refine 3D geological models with exploratory drilling results. Improve the accuracy of 3D models and resource assessments to support informed decision-making for developments.
- Develop a province-wide geological atlas accessible to stakeholders to centralize data and attract investors, developers, and researchers. Showcase Nova Scotia's energy storage potential.

» **Infrastructure expansion:**

- Upgrade infrastructure near high-priority energy storage targets. Improve access roads, transmission lines, and facilities to enable large-scale projects.
- Designate areas for brine disposal, landfills, and storage facilities. Address logistical and environmental needs for salt cavern storage and other subsurface projects in designated areas.

C. **Long-Term Vision (7+ Years).** Long-term goals focus on developing integrated storage hubs, establishing global leadership, and leveraging advanced geoscience capabilities.

» **Integrated storage hubs:**

- Develop centralized storage hubs near industrial zones. Integrate hydrocarbon, hydrogen, $CO_2$, and compressed air storage facilities to support both domestic industries and export markets.

» **Global leadership:**

- Position Nova Scotia as a leader in subsurface energy storage technologies. Capitalize on international partnerships and exporting expertise to secure a foothold in global energy markets.

» **Geoscience database:**

- Implement a state-of-the-art geoscience database accessible to stakeholders to consolidate geological, operational, and environmental data. Foster innovation with a long-term commitment to develop, maintain, and facilitate access to integrated geological, exploration, and development results.

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# APPENDIX A

## CORRELATION CHART FOR LATE DEVONIAN TO PERMIAN STRATIFIED ROCKS OF THE MARITIMES BASIN, ATLANTIC CANADA

# Correlation chart for Late Devonian to Permian stratified rocks of the Maritimes Basin, Atlantic Canada.

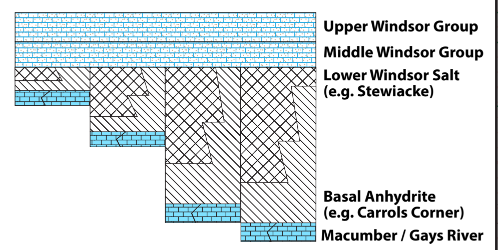
by John W.F. Waldron, Peter S. Giles, and Alison K. Thomas

2017

Nova Scotia Department of Energy Open File Report 2017-02



## Possible age of lower Windsor Group




1. Early Asbian base Windsor favoured by Mamet 1970 and St. Peter & Johnston 2009
2. Holkerian base favoured by isotopic data, and adopted here
3. Arundian base favoured by Utting & Giles 2004
4. Late Chadian base favoured by von Bitter et al. 2006

## LEGEND

Mainly Red / Mainly Grey

- Mainly conglomerate
- Conglomerate & sandstone
- Mainly sandstone
- Mudstone with subordinate sandstone
- Mainly mudstone (Shale and siltstone, minor sandstone)
- Claystone and siltstone
- Dolostone
- Limestone
- Halite, potash
- Sulphate evaporites
- Limestone/evaporite interlayered
- Limestone/clastic/evaporite interlayered
- Limestone/clastic interlayered
- Sandstone/evaporite interlayered
- Mafic volcanic and clastic sedimentary rocks
- Felsic volcanic and clastic sedimentary rocks
- PLUTON

AGE CONSTRAINT (generalized)

- Shelly fossils / Foraminifera
- Palynomorphs
- Isotopic, with 2σ error

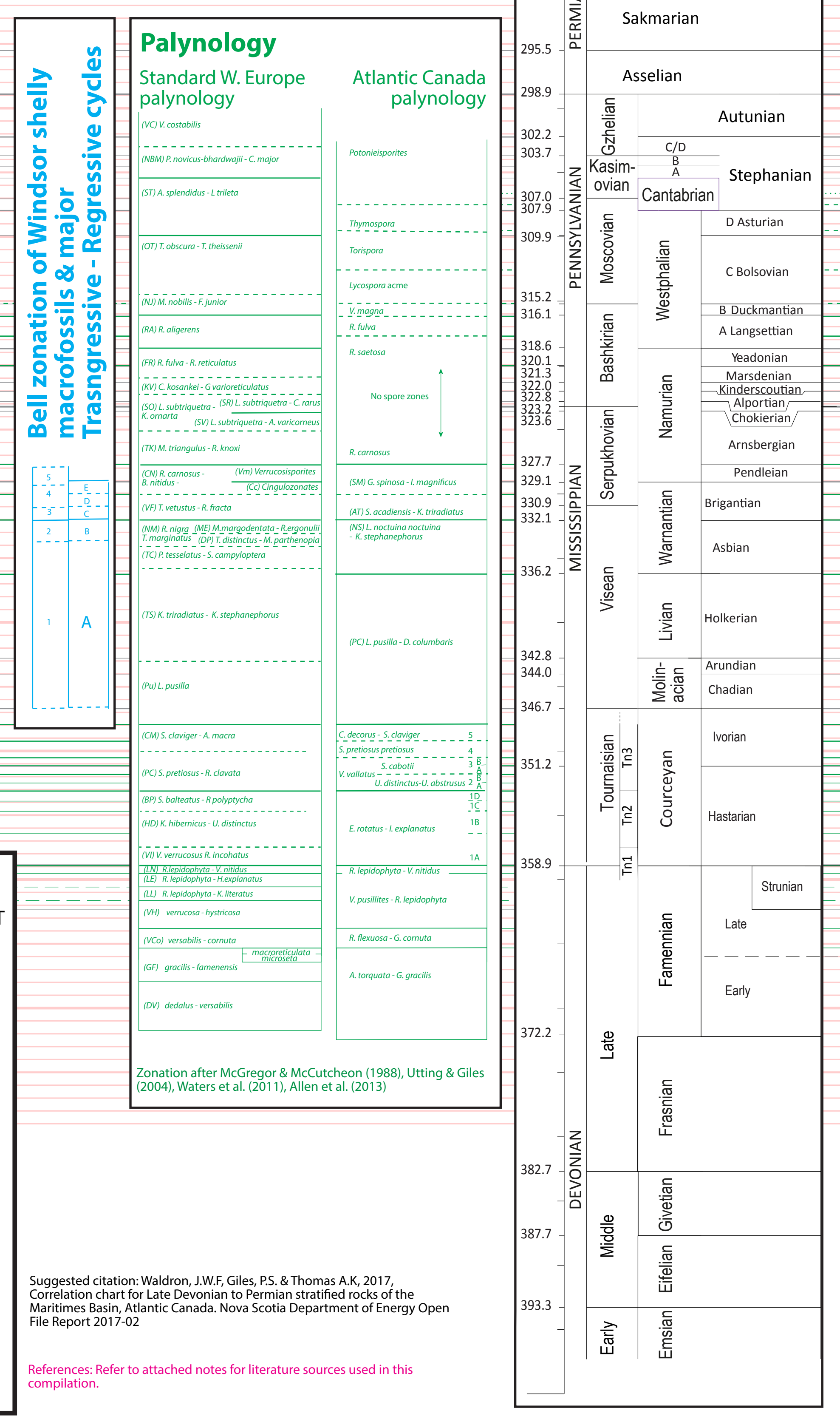
LITHOSTRATIGRAPHIC STATUS indicated by typeface.

**GROUP NAME**

**Formation Name**

*Member Name*

## TIME SCALE REFERENCE





| New Brunswick Platform | Cocagne Sub-basin | SE Indian Mountain Deformed Zone | Westmorland Uplift | Moncton Sub-basin | Sackville Sub-basin | Cumberland Sub-basin | Cobequid Highlands N | Cobequid Highlands S., Debert-Kemp-town | Stellarton Sub-basin | Antigonish Sub-basin |
|---|---|---|---|---|---|---|---|---|---|---|
| Bevier 1988, Richardson and McGregor, 1986; McGregor and McCutcheon, 1988; Tucker et al., 1998; St. Peter & Johnson 2009a, b | St. Peter & Johnson 2009a, b | St. Peter & Johnson 2009a, b | St. Peter & Johnson 2009a, b | St. Peter & Johnson 2009a, b | St. Peter & Johnson 2009a, b; Craggs et al. 2015; M. Stimson & A. MacRae personal communication, 2017. | Ryan et al. 1991; Ryan & Boehner 1994; St. Peter & Johnson 2009a, b; Utting et al. 2010; Waldron et al. 2013; Opdyke et al. 2014) | Ryan et al. 1991; Ryan & Boehner 1994; Dunning et al. 2002; Utting et al. 2010; Waldron et al. 2013., Chandler et al. 1995. | PePiper & Piper 2002; Naylor & Kennedy 1997; Naylor et al 2006. | Yeo & Gao 1987; Chandler et al. 1995; Waldron et al. 1999; Waldron 2004. | Neves & Belt 1970; Mamet 1970; McGregor 1970; Boehner & Giles 1993. |

| Western Cape Breton Island | Guysborough, Southern Cape Breton Island | Prince Edward Island | Cap Rouge | Sydney Sub-basin | Lomond-Glengarry Sub-basin | Windsor-Kennet-cook Sub-basin | Shubenacadie Sub-basin | Musquodoboit Sub-basin | Bay St. George Sub-basin | Deer Lake Sub-basin |
|---|---|---|---|---|---|---|---|---|---|---|
| Utting 1987; Allen et al. 2013; Hamblin 1989. | Hamblin 1989; Barr et al 1994; Teniere et al. 2005; Giles et al. 2010. | van de Poll 1989; Giles & Utting 1999; Giles 2004; Allen et al. 2011. | Giles & Utting 2004 | Boehner & Giles 2008 | Boehner & Prime 1993 | Moore et al. 2000 Martel et al. 1993 | Utting 1980; Giles & Boehner 1979, 1982; Boehner 1986. | Giles & Boehner 1979, 1982; Boehner 1986 | Knight 1982; Utting & Giles 2004, 2008. | Belt 1969; Hyde 1979; Hyde 1984; Hyde et al. 1988; Utting & Giles 2004, 2008. |

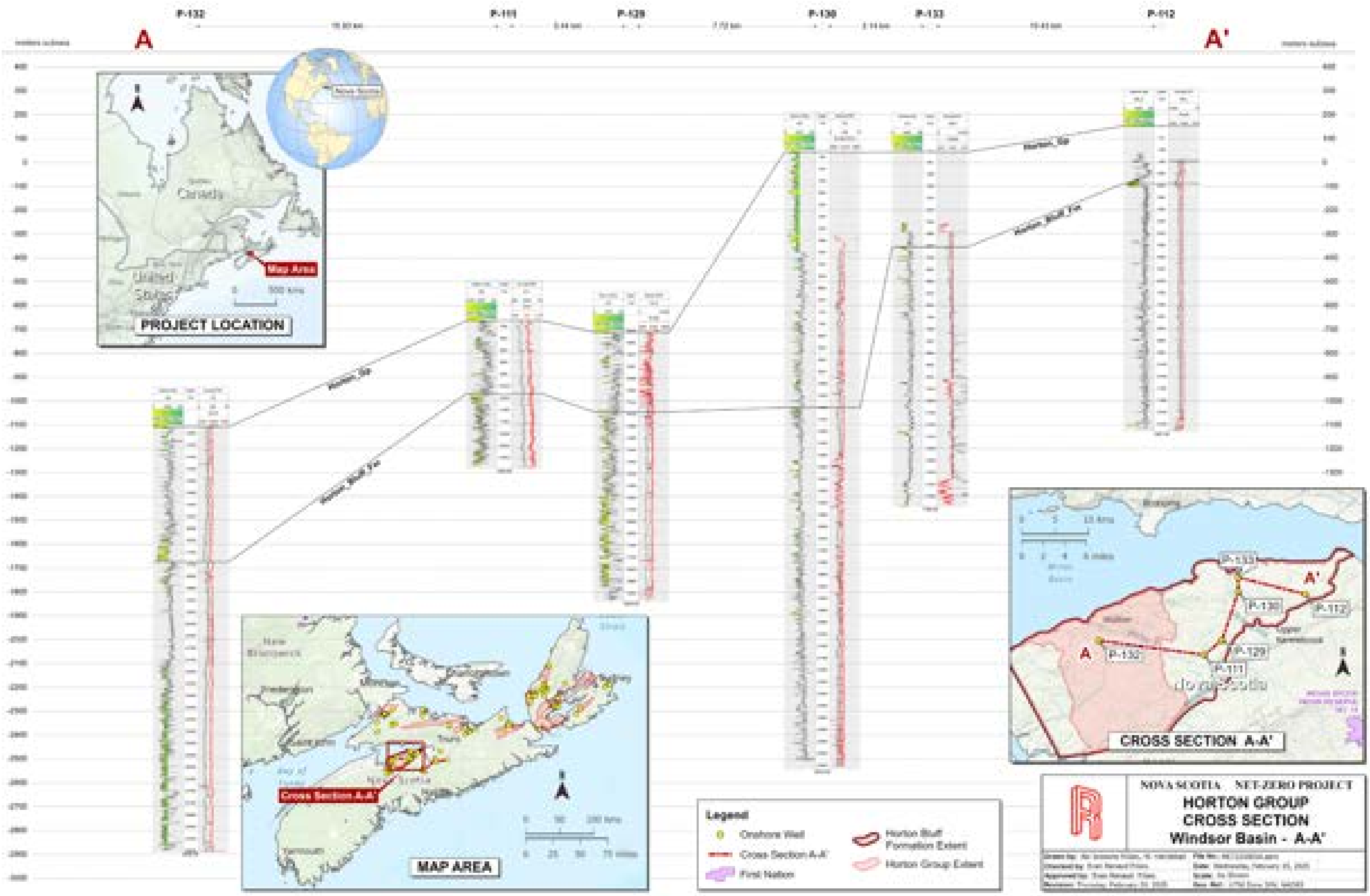
Suggested citation: Waldron, J.W.F, Giles, P.S. & Thomas A.K, 2017, Correlation chart for Late Devonian to Permian stratified rocks of the Maritimes Basin, Atlantic Canada. Nova Scotia Department of Energy Open File Report 2017-02

References: Refer to attached notes for literature sources used in this compilation.

# APPENDIX B

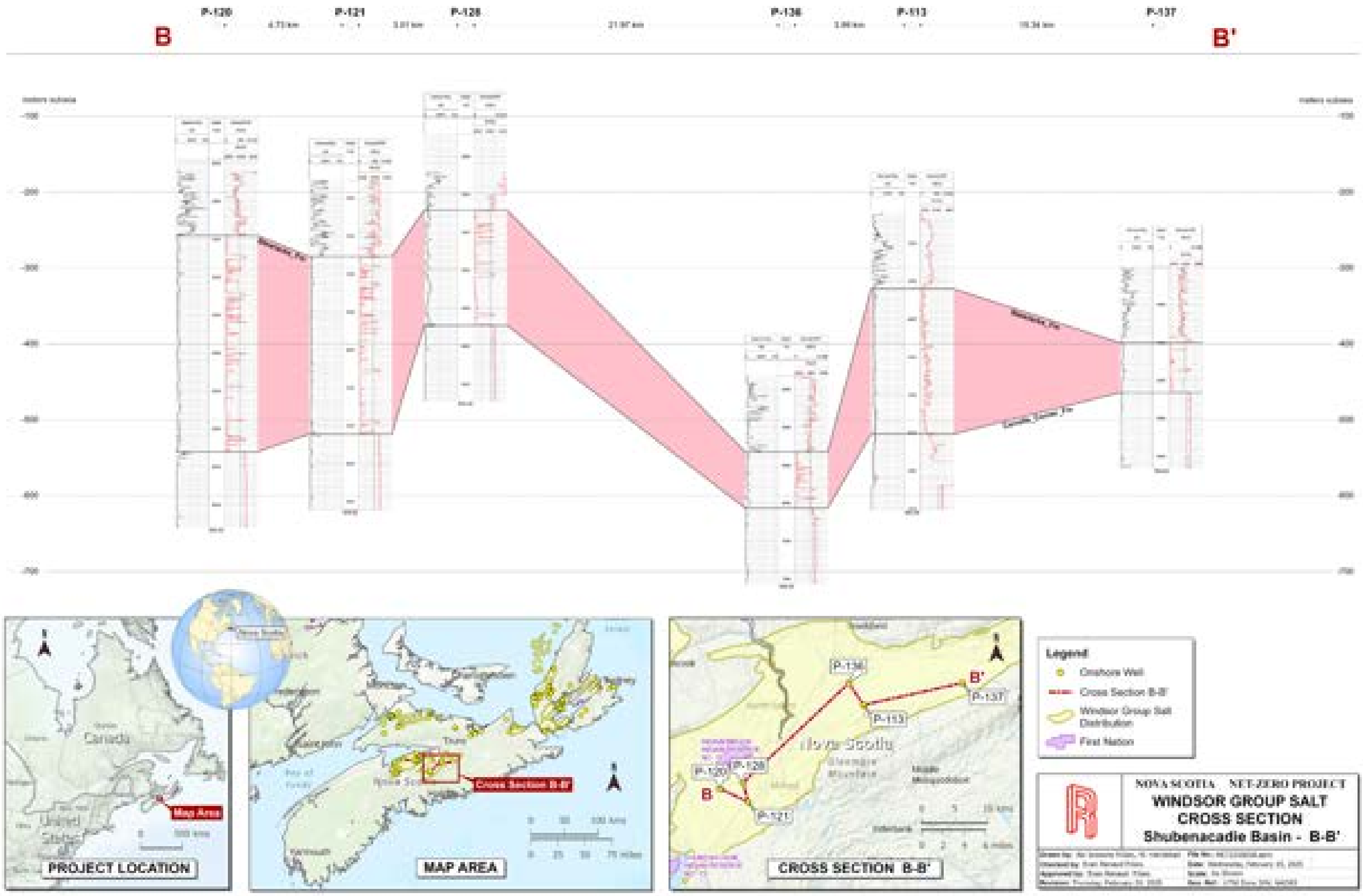
## CROSS SECTIONS

RESPEC



P-132
P-111
P-129
P-130
P-133
P-112
A
A'
Horton_Gp
Horton_Bluff_Fm
PROJECT LOCATION
Canada
United States
Map Area
MAP AREA
Cross Section A-A'
Nova Scotia
CROSS SECTION A-A'
Legend
Onshore Well
Cross Section A-A'
First Nation
Horton Bluff Formation Extent
Horton Group Extent
NOVA SCOTIA NET-ZERO PROJECT
HORTON GROUP
CROSS SECTION
Windsor Basin - A-A'

RESPEC


B
B'
P-120
P-121
P-128
P-136
P-113
P-137
Map Area
PROJECT LOCATION
Cross Section B-B'
MAP AREA
CROSS SECTION B-B'
Nova Scotia
Legend
Onshore Well
Cross Section B-B'
Windsor Group Salt Distribution
First Nation
NOVA SCOTIA NET-ZERO PROJECT
WINDSOR GROUP SALT CROSS SECTION
Shubenacadie Basin - B-B'