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The geology and hydrogeology of faults on Cape Breton Island, Nova Scotia, Canada

an overview

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Article abstract

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The geology and hydrogeology of faults on Cape Breton Island, Nova Scotia, Canada: an overview

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ABSTRACT

Cape Breton Island provides a hydrogeological view into the roots of an ancient mountain range, now exhumed, glaciated, and tectonically inactive. It exhibits deep crustal faults and magma chambers associated with formation of the Appalachian mountain belt and the Maritimes Basin during the Paleozoic, as well as Mesozoic rifting relating to the opening of the Atlantic Ocean. Cenozoic exhumation brought these features near surface and into the active groundwater flow field where they were impacted by glaciation and fluctuating sea level. The faults have been important from a societal viewpoint in development of municipal groundwater supplies, controlling inflows to excavations, hydrocarbon exploration, quarry development, and geotechnical investigations. Conceptual models presented here outline fault control on groundwater flow based on seven case studies. Future research should focus on basin-bounding faults in support of managing their role in aquifer development and protection, mountain-front recharge, controlling large-magnitude springs, groundwater–stream interaction, and channel morphology. The hydrogeological importance of these faults has historically been underappreciated.

RÉSUMÉ

L'île du Cap Breton procure un aperçu hydrogéologique des racines d'une ancienne chaîne de montagnes, maintenant exhumée, érodée par la glaciation et tectoniquement inactive. Elle présente des chambres magmatiques et des failles crustales profondes associées à la formation de la ceinture montagneuse des Appalaches et du bassin des Maritimes au cours du Paléozoïque, ainsi qu'au rifting du Mésozoïque lié à l'ouverture de l'océan Atlantique. L'exhumation survenue durant le Cénozoïque a rapproché ces particularités de la surface à l'intérieur du champ d'écoulement des eaux souterraines actif, où elles ont été touchées par la glaciation et les fluctuations du niveau de la mer. Les failles se sont avérées importantes sur le plan sociétal pour l'établissement de réserves municipales d'approvisionnement en eau souterraine, le contrôle des infiltrations d'eau dans les excavations, la prospection des gisements d'hydrocarbures, l'aménagement des carrières et les études géotechniques. Les modèles conceptuels présentés illustrent le contrôle par les failles de l'écoulement des eaux souterraines d'après sept études de cas. Les recherches futures devraient porter sur les failles délimitant des bassins aux fins de la gestion de leur rôle dans le développement et la protection des aquifères, l'alimentation du front des secteurs montagneux, le contrôle des sources de forte magnitude, l'interaction entre les eaux souterraines et les cours d'eau et la morphologie des canaux. L'importance hydrogéologique de ces failles a été sousestimée par le passé.

[Traduit par la redaction]

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INTRODUCTION

Cape Breton Island forms the northeastern part of the Province of Nova Scotia, along the Atlantic seaboard of Canada (Fig. 1). It encompasses an area of approximately 11 700 km^2, surrounded by the Atlantic Ocean on the east and the Gulf of St. Lawrence to the north and west. The island has a temperate, humid, continental climate, with a 30-year climatic normal (1981–2010) annual precipitation of 1517 mm, and mean annual temperature of 5.9 °C. These conditions provide for an estimated annual water surplus and deficit using the Thornthwaite method (Thornthwaite 1948) of 987 and 21 mm, respectively.

Geological mapping has delineated a large number of faults on the island associated with the development of the Appalachian mountain belt, the Maritimes Basin, and the Atlantic Ocean. Cenozoic exhumation brought these fault systems to near-surface crustal levels and into the active groundwater flow field. They were subsequently impacted by glaciation, fluctuating sea levels, microclimates, and development of Acadian, Boreal, and Taiga forest covers. Anthropogenic land use patterns have also had an influence over the last approximately 200 years.

It is important to understand the hydrogeological characteristics of these approximately 1200 to 65 Ma old fault systems to aid in managing Cape Breton Island's fresh water resources. Fault zones have been important on the island in developing municipal groundwater supplies and springs, undertaking regional water resource evaluations, understanding the presence of natural oil and salt in seeps and wells, predicting and controlling inflows to underground excavations, targeting base metal mineralization, and quarry development, as well as geotechnical investigations for transportation corridors and infrastructure. Differential erosion of up to 400 m along some of these faults has created broad landscape vistas and associated ecotourism opportunities.

This paper provides a summary of 90 years of geological studies and mapping over Cape Breton Island pertinent to understanding the hydrogeology of faults. It draws from consulting, government, and university reports (many of which are unpublished and unavailable in the public domain), as well as seven case studies to conceptualize the role of faults in controlling groundwater flow. The discussion expands upon the initial work of Baechler (1986, 2009) and Baechler and Boehner (2014), while integrating previous work using the system of hydrological regions and hydrological districts for Cape Breton Island (Baechler and Baechler 2009). A greyscale, digital terrain image provided by the Nova Scotia Department of Natural Resources is used in several figures to highlight geological structures. A discussion of paleohydrology related to faulting is followed by a description of the present hydrological setting of the island, characteristics of the Structural Hydrostratigraphic Unit (HU), and seven hydrogeological case studies.

PALEOHYDROLOGY

Cape Breton Island's ca. 1 Ga geological history has resulted in a complex lithological and structural terrain through continental collision, mountain building, sedimentary basin formation, opening of the Atlantic Ocean, and prolonged exhumation. Cape Breton Island presently provides a hydrogeological view into the roots of an ancient, exhumed, glaciated, presently tectonically inactive, former mountain range, within a maritime climate surrounded by the sea.

The structural geology of Cape Breton Island is complex (e.g., Keppie 1979) and while much is known a number of concepts are still open for discussion. Ten attributes of fault systems in Cape Breton Island that are relevant to understanding their hydrogeological characteristics are summarized below:

(1) *Multiple orogenic episodes*. The island's fault systems are associated with the interaction among as many as six orogenic cycles spanning a period from approximately 1200 to 65 Ma (e.g., van Staal and Barr 2012). They include the Grenvillian (1240–980 Ma), Taconic (470–450 Ma), Salinic (450–423 Ma), Acadian (423–400 Ma), Neoacadian (375–360 Ma) and Alleghanian (325–260 Ma) orogenies. The Salinic, Acadian, and orogenies dominated these events affecting the entire width of the Appalachian orogen from the most outboard terrane (Meguma) to the Laurentian foreland with the accretion of the Meguma terrane (Fig. 1). These events, and their predecessors, raised the Appalachian mountain belt along the eastern margin of the North American continent.

(2) *Tectonostratigraphic terranes*. The orogenies noted above sutured at least four tectonostratigraphic zones or terranes together (Figs. 1 and 2) during closure of the Iapetus and Rheic oceans, through the sequential "docking" of land masses onto the Laurentian margin of ancestral North America (Barr and Raeside 1989; White *et al.* 2003; Hibbard *et al.* 2006; van Staal and Barr 2012). In Cape Breton Island, Laurentia is represented by the Blair River Inlier at the northern end of the island. Fragments derived from the Gondwanan landmass are represented by the Aspy, Bras d'Or, and Mira terranes, with Aspy and Bras d'Or considered to represent a microcontinent known as Ganderia and Mira representing Avalonia (Hibbard *et al.* 2006; Lin *et al.* 2007; van Staal and Barr 2012 and references therein). The Acadian collision between Avalonia and composite Laurentia trapped between them the Bras d'Or terrane, representing a Neoproterozoic subduction zone along a continental margin (Raeside and Barr 1990; Barr *et al.* 1998) and the Aspy terrane likely representing an island-arc system (Barr and Jamieson 1991). Together, these two terranes are interpreted to represent the Ganderian component of Cape Breton Island.

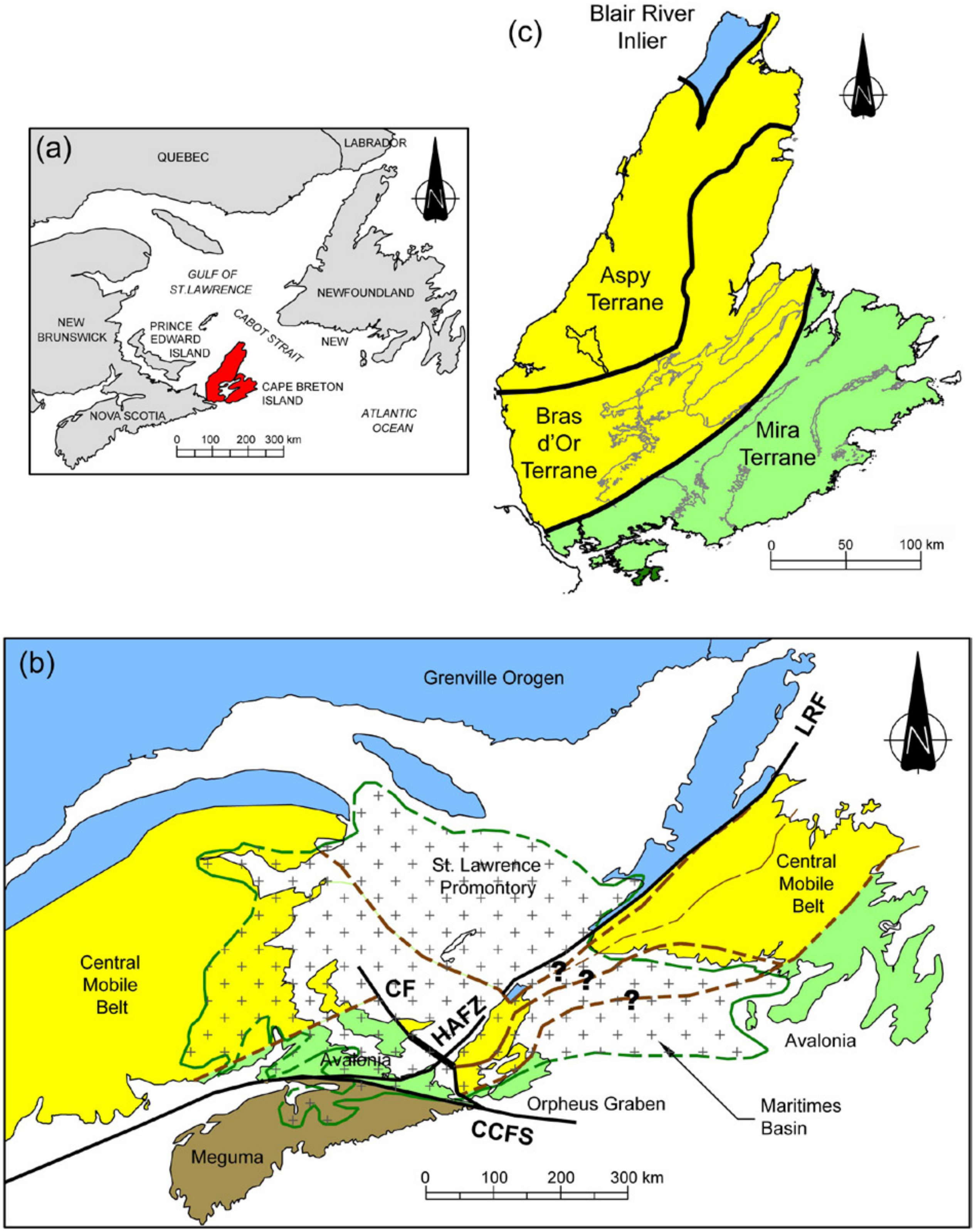

Figure 1. (a) Map of Atlantic Canada showing the location of Cape Breton Island. (b) Geological subdivisons in Atlantic Canada after Hibbard *et al.* (2006), showing the outline of the Maritimes Basin. (c) Geological subdivisions in Cape Breton Island after Barr and Raeside (1989). Abbreviations: CF, Canso fault; CCFS, Cobequid-Chedabucto fault zone; HAFZ, Hollow Fault-Aspy fault zone, LRF, Long Range fault.

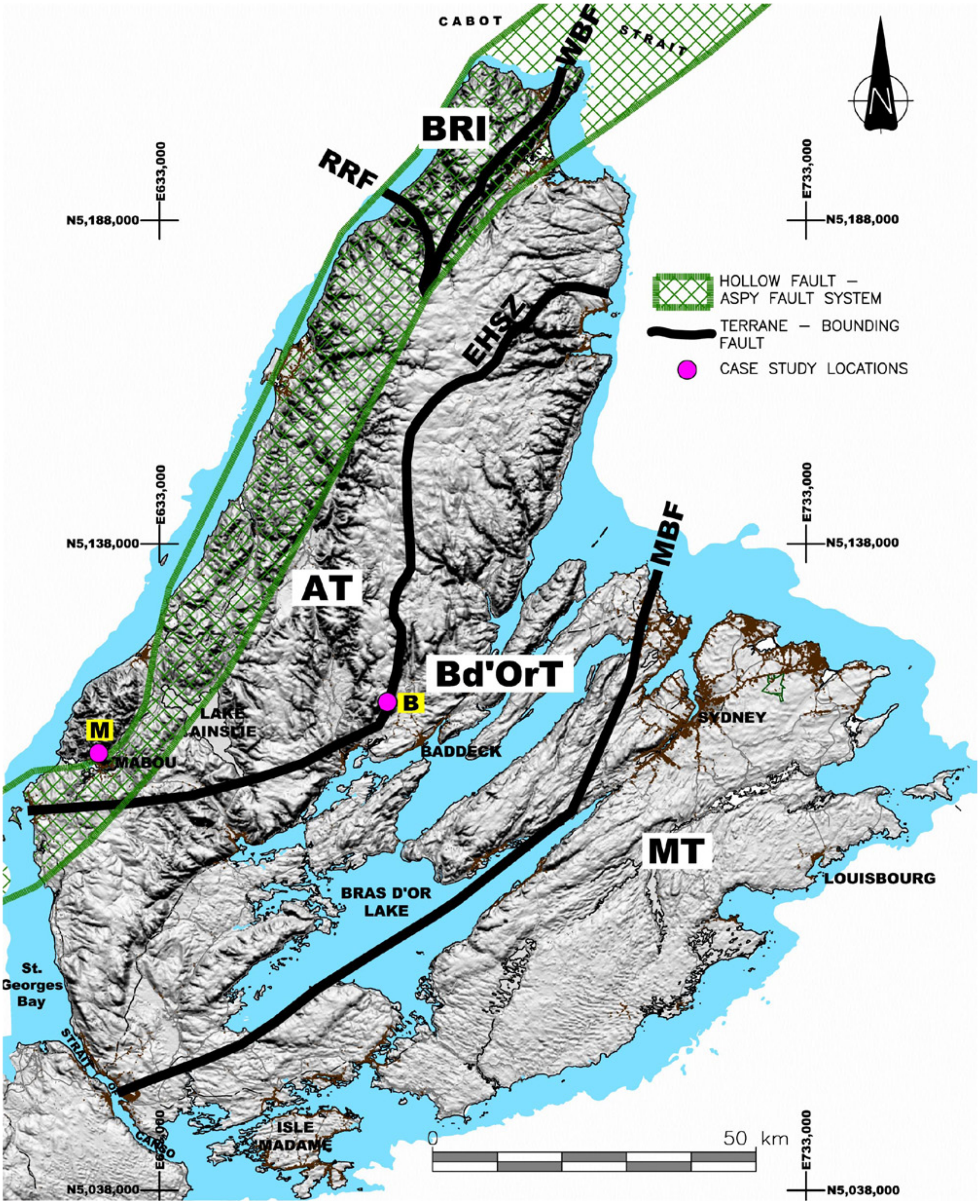

Figure 2. Greyscale digital terrain image of Cape Breton Island provided by the Nova Scotia Department of Natural Resources showing inferred terranes, terrane-bounding faults, and case-study locations (B, Baddeck; M, Mabou). Abbreviations: MT, Mira terrane; Bd'OrT, Bras d'Or terrane; AT, Aspy terrane; BRI, Blair River Inlier; EHSZ, Eastern Highlands Shear Zone; MBF, MacIntash Brook fault; RRF, Red River fault; WB, Wilkie Brook fault.

(3) *Telescoping of terranes*. Cape Breton Island was positioned where the St. Lawrence promontory on the western (Laurentian) margin and the Cabot promontory on the eastern (Gondwanan) margin met obliquely (Stockmal *et al.* 1987; Lin *et al.* 1994). As a result the Gondwanan terranes of Cape Breton Island were telescoped into a width of only tens of kilometres in comparison to around 200 km (Hall *et al.* 1998) elsewhere (Fig. 1). This oblique, compressional collision resulted in significant tectonic burial, crustal thickening, faulting, and mountain building.

(4) *Offset of terranes*. Offset along the northwest-trending Canso Fault (McCutcheon and Robinson 1987; Stockmal *et al.* 1987; Barr and Raeside 1989; Cook *et al.* 2007) on the western edge of Cape Breton Island (Fig. 1) shifted the tectonostratigraphic terranes dextrally by approximately 200 km (White *et al.* 2003). Recent geophysical interpretations (Barr *et al.* 2014) suggest no similar movement along the Cabot Strait to the north of Cape Breton Island.

(5) *Varied fault types*. A variety of crustal faults developed within the crystalline "basement" rocks of Cape Breton Island to accommodate the stresses built up during telescoping of the terranes. Suture zone faults (Fig. 2) originated at the edge of the various terranes and include the Eastern Highland Shear Zone (ESHZ), between the Bras d'Or and Aspy terranes, as well as the north-dipping MacIntosh Brook Fault between the Mira and Bras d'Or terranes (King 2002; Cook *et al.* 2007). Large-scale fault systems (Figs. 1 and 2) related to the docking of the Meguma terrane include the Cobequid-Chedabucto fault zone (CCFZ) or Minas Fault Zone south of Cape Breton Island (Gibling *et al.* 1987; Pe-Piper and Piper 2004; Murphy *et al.* 2011), as well as the Hollow Fault-Aspy Fault zone (HAFZ) which strikes northeast along the western edge of Cape Breton Island (Durling *et al.* 1995b). The Wilkie and Red River faults between the Blair River Inlier and Aspy terrane (Fig. 2) have been inferred to mark a cryptic suture between Laurentia and accreted peri-Gondwanan terranes (Barr *et al.* 1998). The Cabot Nappe has been proposed to extend over part of the southern Cape Breton Highlands, as a result of thrusting of the Bras d'Or terrane over the Aspy terrane (Lynch 1996, 2001), although that model has not been accepted by all workers (e.g., Lin *et al.* 2007). Northeast-trending basin-bounding faults (Fig. 3) along the edges of the Carboniferous basins (Gibling *et al.* 1987) formed initially as strike-slip faults, later re-activated as normal faults. Lefort and Miller (1999) suggested that the strong northwest-oriented, mega-lineaments present over the island could be related to wrench faulting formed during the collision between Gondwana and Laurasia in the late Paleozoic, during the closure of the remaining oceanic tract between the two continents.

(6) *Development of the Maritimes Basin*. The 215 000 km^2, post-Acadian Maritimes Basin (Fig. 1) overlies the crystalline basement. It contains a succession of three pulses of continental and shallow marine strata of Late Devonian to Permian age, deposited in a series of half-graben depocentres, which are bounded by northeast-trending strike-slip fault systems and normal listric faults (Fig. 3), as exemplified by the Marconi, Cranberry, Point Aconi, and St. Anns half-grabens (Gibling *et al.* 1987; Pascucci *et al.* 2000). The second pulse was the primary one relevant to regional fault systems within the basin (Baechler and Boehner 2014), incorporating marine evaporite units which exhibit complexly deformed salt basins, karstification, localized halokinesis with kilometre-scale intrusion of salt diapirs (Aslop *et al.* 2000), and possibly a regional, evaporite-controlled, bedding-parallel gravity slide (Lynch and Giles 1995).

(7) *Continental rifting*. Rifting near the end of the Triassic (ca. 200 Ma) was associated with fragmentation of Pangaea and opening of the Atlantic Ocean (Withjack and Schlische 2005). During the Cretaceous (145 to 66 Ma) a proto-ocean started to form in the Newark Rift Valley system, which extended northeast through the Fundy Rift system of mainland Nova Scotia into the Orpheus Graben adjacent to the southern coast of Cape Breton Island (Fig. 1). This rifting resulted in reactivation of the Cobequid-Chedabucto and Hollow Fault-Aspy Fault systems, as well as reactivation of basin-bounding strike-slip faults as normal faults (Faure *et al.* 2006; Herman 2009). Lefort and Miller (1999) suggested that the northwest- to west-oriented wrench faults created pre-existing basement weaknesses, which were reactivated during Mesozoic rifting.

(8) *Pluton emplacement*. More than 100 named plutons of various ages and compositions are exposed throughout Cape Breton Island (e.g., Raeside and Barr 1990; Barr *et al.* 1992; 1996, 1998; Lin *et al.* 2007), intruded at a range of crustal levels. Igneous activity in the Mira terrane ranges from 339 to 680 Ma, whereas ages of 565 and 495 Ma dominate in the Bras d'Or terrane. Silurian and Devonian plutons are dominant in the Aspy terrane (Barr *et al.* 1998), mainly in the 440 to 370 Ma range, although older plutons are also present.

(9) *Reactivation of faults*. The Appalachian story is one of initial compressional faulting related to Paleozoic shortening, followed by extensional faulting related to Mesozoic rifting (Williams *et al.* 1995; Herman 2009). During the latter event major faulting was primarily through reactivation along old faults. Reactivation varied during different stages in the evolution of each orogeny and therefore created a complicated deformational history within the fault complexes (Murphy *et al.* 1999). The zones of hydrogeologic interest include reactivation along the HAFZ, normal faulting along basin-bounding faults, and cross-cutting northwest- to west-trending faults.

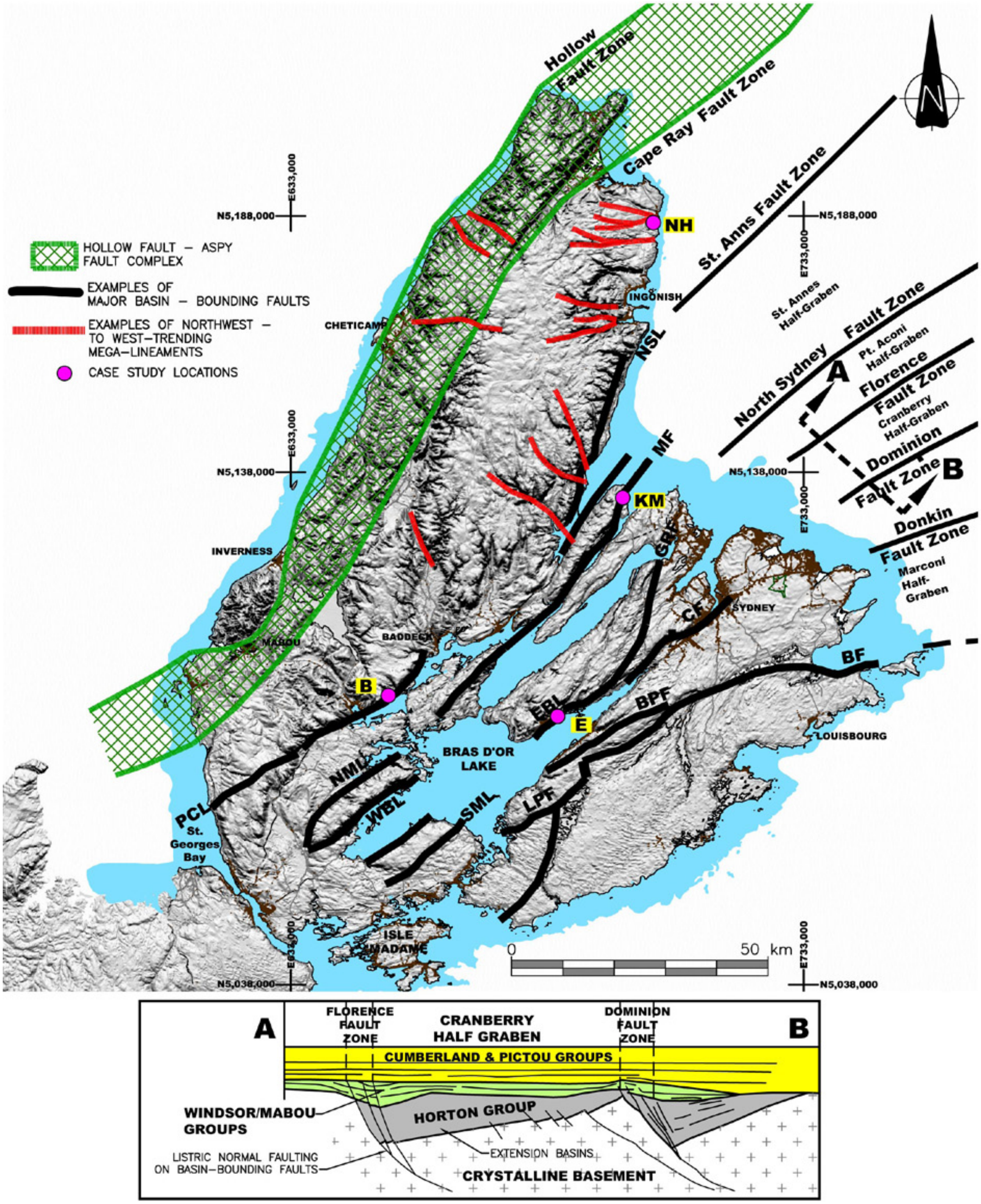

Figure 3. Greyscale digital terrain image of Cape Breton Island provided by the Nova Scotia Department of Natural Resources showing examples of major northeast-oriented basin-bounding faults and northwest- to west-trending faults and case study locations (E, Eskasoni; KM, Kellys Mountain; NH, Neils Harbor; B, Bucklaw). Cross-section A-B is after Pascucci *et al.* (2000). Abbreviations: MF, Mountain fault; LPF, Lennox Passage fault; BPF, Big Pond fault; EBL, East Bay lineament; CF, Coxheath fault; BF, Bateston fault; GRF, Georges River fault; NSL, North Shore lineament; PCL, St. Patricks channel lineament, NML, North Mountain lineament; WBL, West Bay lineament; SML, Sporting Mountain lineament.

(10) *Exhumation*. The Mesozoic exhumation of Pangaea lasted from approximately 270 to 200 Ma, and created a peneplain-like surface on the Appalachian mountain chain with the removal of several kilometres of latest Paleozoic to early Mesozoic strata (Pascucci *et al.* 2000). This was followed by regional uplift around 110–80 Ma, followed by exhumation and erosion from around 65 to 3 Ma. Stea and Pullan (2001) suggested that the present topography is an older, "preserved", structurally controlled landscape, rather than erosional and younger. This erosion and isostatic uplift allowed "daylighting" of plutons, deeper crustal zone fault systems, and lower parts of the sedimentary-basin fill. The crystalline rocks were least erosive and underlie the highlands, while the sedimentary packages form the lowlands. The present-day geomorphological character of Cape Breton Island was established during this time with its strong landscape contrasts, which now drive the present ground and surface water flow systems.

PRESENT-DAY HYDROLOGICAL SETTING

Sharpe *et al.* (2014) divided Canada into hydrogeological regions and positioned Cape Breton Island in both the Appalachian and Maritimes Basin regions. Rivard *et al.* (2014) noted that the geological complexity inherent in Cape Breton Island makes it difficult to develop conceptual models at the local scale. Baechler and Baechler (2009) provided a means for refining these mapping techniques for Cape Breton Island, which delineated hydrological regions and districts. Conceptual models were developed by mapping the occurrence, quantity, quality, pathways, and chemical evolution for ground and surface waters as these are transported through the waterscape. This approach follows the concept of comparative hydrogeology (Davis 1988; LeGrand 1970).

The conceptual models for Cape Breton Island focus on the active groundwater flow system. This paper uses the definition of Mayo *et al.* (2003) in which an active zone has groundwater flow paths that are continuous, responsive to annual recharge and climatic variability, and have groundwater residence times that become progressively older from recharge to discharge areas. The Council of Canadian Academies (2014) identified the upper of three zones as the Fresh Groundwater Zone (FGWZ), which has potable water and somewhat deeper water that can be made potable by minimal water treatment (total dissolved solids up to 4000 mg/L). They noted that no comprehensive study has defined the depth range of the FGWZ in Canada, but suggested a general estimate of 100 and 300 m below land surface, although it may be as deep as 500 to 600 m. Nova Scotian regulators have not defined the depth range of the FGWZ in the province, but note that legislation allows for control over groundwater resources even to depths of 1000s of metres, regardless of physical or chemical characteristics (Delorey 2014).

Research over a variety of similar hydrological settings has provided a range of depth values for the FGWZ. Randall *et al.* (1988) noted that for the Northeastern Appalachian groundwater region, flow is generally most rapid in the uppermost 15 to 35 m below the bedrock surface, with fractures much less abundant below 75 m depth, but with localized productive zones at depths of 100 to 650 m. Diggins (2014) investigated fracturing in granite, schist, and amphibolite in the Appalachian belt in Massachusetts, noting minimal flow below 170 m and the majority of flow constrained to the upper 100 m. Dummer *et al.* (2015) recorded that most of Nova Scotia's 117 000 domestic wells in bedrock aquifers are less than 155 m deep. Baechler and Boehner (2014) suggested that active karst solution of saline evaporite rocks on Cape Breton Island can occur locally at depths exceeding 400 m. Farvolden *et al.* (1988) in an assessment of crystalline rocks in the Canadian Precambrian Shield stated that while a case can be made for a log-linear decrease in hydraulic conductivity with depth in the upper 100 to 400 m, fracture zones associated with steep fault zones have been encountered down to at least 1000 m.

In Cape Breton Island, another factor controlling the depth of the FGWZ is the topographic relief adjacent to faults, which can be in the range of 150 to 400 m. Wyrick and Borchers (1981) noted the stress forces present with such relief can cause compressional and extensional fractures and faults to extend out into the adjacent rock mass. Therefore the FGWZ in most parts of Cape Breton Island is expected to range between 200 and 300 m depth. This depth range represents a gradual, not distinct, transition into an "intermediate" groundwater flow field for which very little hydrogeological information is known. Localized, deeper active flow zones along faults can potentially be present to over 1000 m depth.

Six hydrological regions have been mapped in Cape Breton Island by defining areas with characteristic types, numbers, and orientations of Hydrostratigraphic Units (HUs), coupled with climate, topographic relief, and forest cover. Three of these regions are relevant to the discussion of faults including the Highland, Mountain Flank, and Canyon (Fig. 4). Representative 3-D block conceptual models are presented in Figures 5 and 6. This approach to modelling, as discussed by LeGrand and Rosen (2000), Bredehoeft (2005), Hill (2006) and Savard *et al.* (2014), focuses on using generalizations and inferences with existing geological information to draw conclusions from imprecise and incomplete information. The block models are designed to meet the three goals of simplicity, refutability (constructed such that assumptions can be tested), and transparency (dynamics are understandable). Such conceptual models should not be regarded as immutable, and surprises will be inevitable as new concepts require either refinements or a complete paradigm shift.

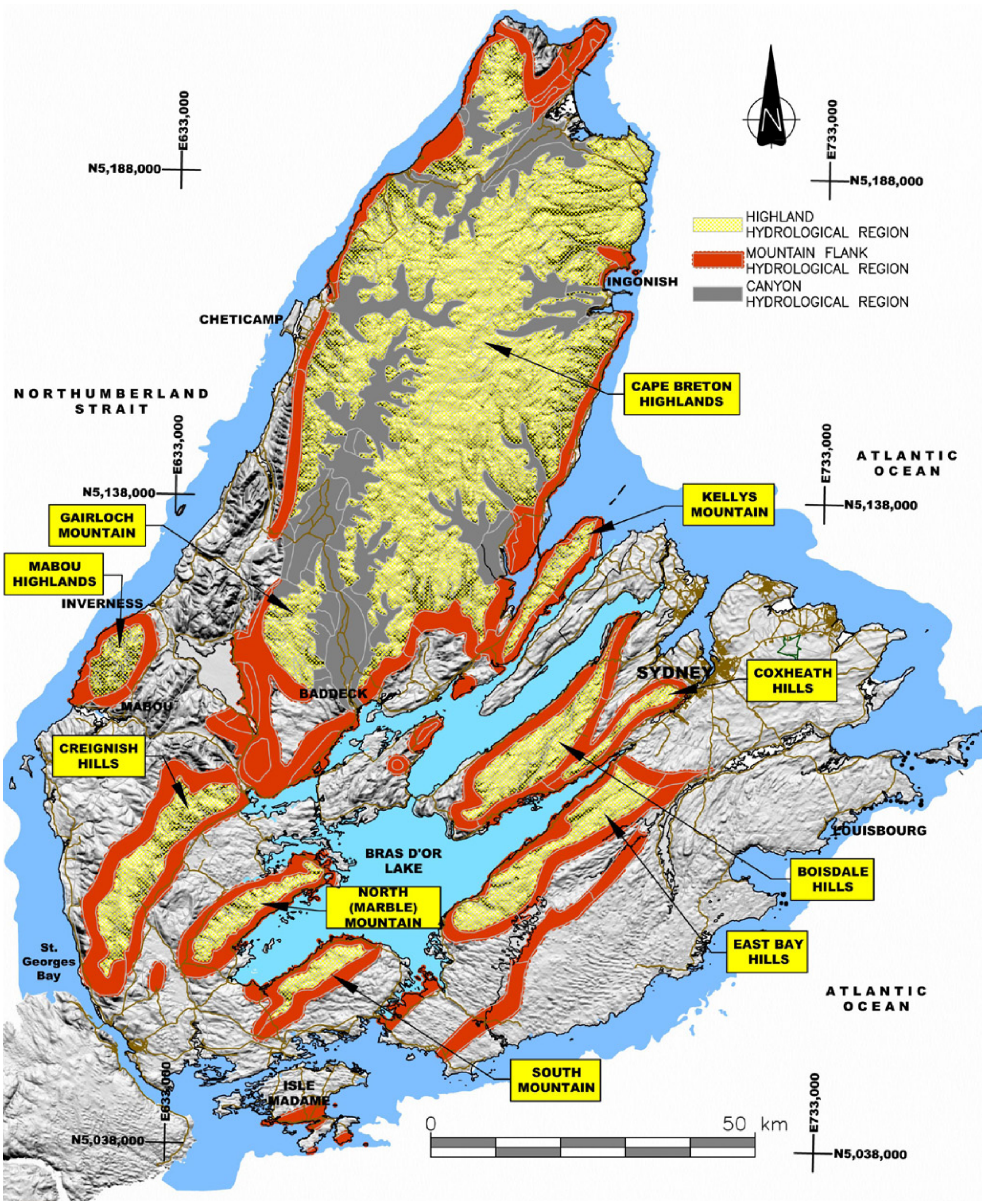

Figure 4. Greyscale digital terrain image of Cape Breton Island provided by the Nova Scotia Department of Natural Resources showing the Highland, Mountain Flank and Canyon Hydrological regions.

The Highland Hydrological Region on Cape Breton Island covers approximately 28% of the Island (Fig. 4). It comprises most of the northern part of the island referred to as the Cape Breton Highlands, as well as nine isolated remnants. This region contains three main hydrological districts, each with distinct fault types. In the Peneplain Hydrological District (Fig. 5a), faults generally do not follow topographic relief, occurring in a peneplain where local relief is bedrock-controlled, with thin to discontinuous glacial till and residuum, high water tables, notable snowbelt, low hydraulic gradients, and a range of Boreal and Taiga forests. In selected areas the region is cross-cut by northwest- to west-oriented faulted mega-lineaments (Fig. 5b – Granite Plain District). Local, or first-order flow systems, as envisaged by Toth (1962), are expected to dominate. The isolated highlands form crests (Fig. 5c - Mountain Crest District) in which faulting is associated with plutons, northeast-trending basin-bounding faults along their margins, and cross-cutting northwest- to west-oriented faulted mega-lineaments.

The Mountain Flank Hydrological Region (Fig. 4) encompasses approximately 13% of the island. It incorporates the steep transition slopes of up to 400 m in relief at slopes of 20 to 40%, as well as a zone approximately 1–2 km back from the crest and out from toe-of-slope. It exhibits the most complex hydrological settings, incorporating hydraulically active, strike-slip, dip-slip, and normal faults with northwest- to west-trending cross-cutting faults (Fig. 6c - Fault District). Groundwater flow may be augmented by thrust faulting (Fig. 6b - Evaporite District). In some locations, the large topographic relief is absent and faults may be buried by overlying sedimentary sequences, principally the Horton Group (Fig. 6a - Horton District). In the Fault and Evaporite districts, the topography over the steep slopes is bedrock-controlled, with minimal glacial diamicton and covered by primarily an Acadian hardwood forest. Locally overburden can comprise thick colluvium, in the form of talus, inactive alluvial fans, and kame terraces. The local, intermediate, and regional flow systems of Toth (1962) may be present. Normal faulting associated with Mesozoic rifting deformed adjoining sedimentary basin beds some distance out from the toe-of-slope, thereby expanding the "fault zone".

The presence of perennial streams discharging out of gorges and ravines and transiting a combination of fault zones, adjacent steeply dipping, fractured sedimentary basin rocks, glaciofluvial outwash, and active karst (Fig. 6 - Fault and Evaporite districts) provides a mechanism for mountain front recharge (MFR), as outlined by Manning (2011). This concept allows for vertically directed recharge down-dip into basin-scale flow systems, a wide range of FGWZ - stream interaction, and karstification of adjacent evaporite strata (Baechler and Boehner 2014).

The Canyon Hydrological Region (Fig. 4) is incised into the Highland Region, covering approximately 8% of the Island. It is created by nine separate river systems including Blair River, Grande Anse River, Cheticamp River, Northeast Margaree River, Middle River, North/Barachois Rivers, Indian Brook, Ingonish River and Power Brook. It contains an assemblage of attributes derived from the Highland, Mountain Flank, and Lowland regions.

STRUCTURAL HYDROSTRATIGRAPHIC UNIT

Seaber (1988) noted a lack of formal procedures for defining hydrostratigraphic units (HU). He defined a HU as a body of rock distinguished and characterized by its porosity and permeability. It may occur in one or more lithostratigraphic, allostratigaphic, pedostratigraphic, or lithodemic units and is unified and delimited on the basis of its observable hydrologic characteristics that relate to its interstices. In delineating HUs he advised that discretion must be left to the field hydrogeologist, as they must be practical and utilitarian, following the United States Geological Survey dictum that the selection of formations shall be such that they will best meet the practical and scientific needs of the users of the map. For Cape Breton Island Baechler and Baechler (2009) enhanced the approach by incorporating architecture, the capacity to store and transmit groundwater, and water chemistry. This defined a total of 18 HUs of which one is a Structural HU encompassing a range of regional-scale faults.

Consideration of faults as hydrogeologic entities is essential to the study of faulted flow systems (Bense *et al.* 2003; Marler and Ge 2003; Apaydin 2010; Ball *et al.* 2010). Four issues were addressed in defining the Structural HU on Cape Breton Island:

(1) Known faults on the island have been derived primarily from historical, intermediate to regional scale (1:50 000 to 1:250 000) geological mapping. This process has delineated large faults at a variety of defined, approximate, assumed, and lineament conditions. The presence, extent, and mode of formation of these faults are open to geological debate in the literature, as well as during informal discussions for the purposes of this paper. In response in this paper I have attempted to provide a summary of the geological debate. It should be noted that regional bedrock geological mapping of the province compiled by Keppie (2000) synthesized the individual maps and identified most of the assumed faults and lineaments as approximate faults, but does not take into account the significant amount of work done since the 1990s. It is also recognized that hydrogeological studies are more recent than the map published in 2000 and focus at a more detailed level (1: 500 to 1:10 000-scale) when identifying exploration targets for groundwater supplies, delineating groundwater flow systems, assessing groundwater-stream interaction, calculating inflow to mines, and supporting geotechnical

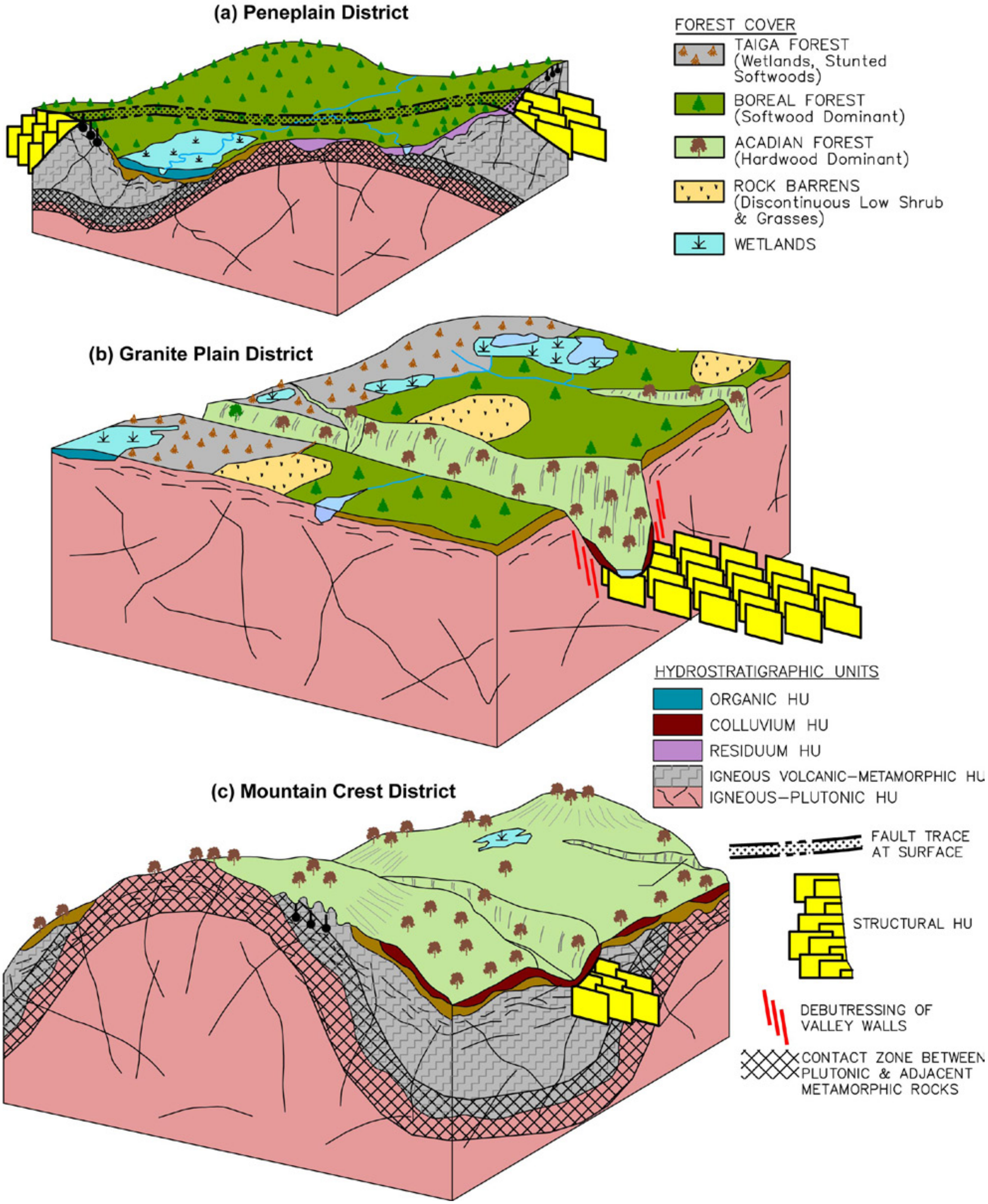

Figure 5. Conceptual 3-D block models for faults and other features in the Highland Hydrological Region in (a) Peneplain District, (b) Granite Plain District, and (c) Mountain Crest District.

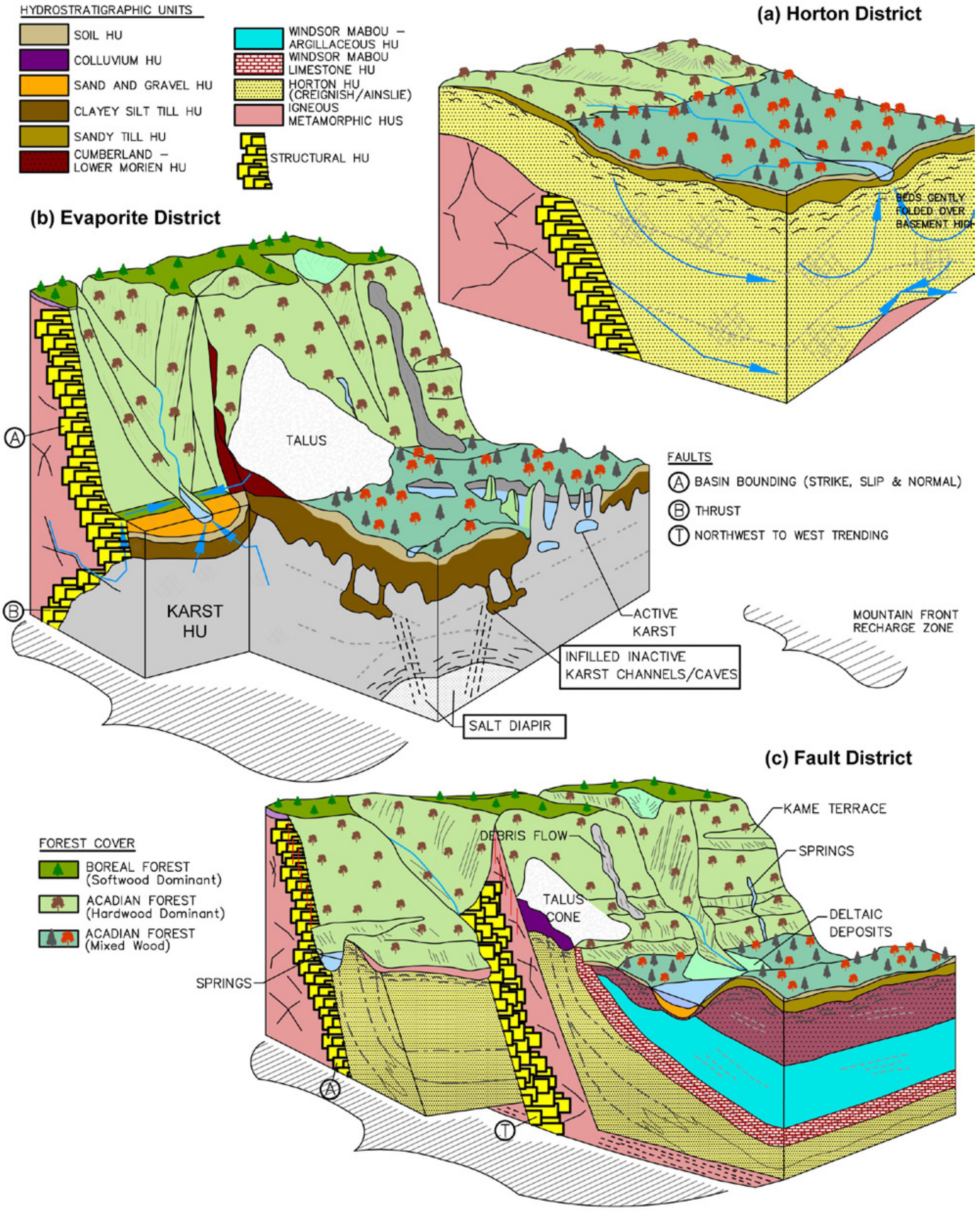

Figure 6. Conceptual 3-D block models for faults and other features in the Mountain Flank Hydrological Region in (a) Horton District, (b) Evaporite District, and (c) Fault District.

investigations. At these scales new faults have been identified and the presence of faults along some lineaments confirmed.

(2) Presence of faults along northwest- and west-trending lineaments in Cape Breton Island. Keppie (1976) noted the presence of a complex network of deeply incised mega-lineaments with these orientations on Cape Breton Island. Examples of larger ones have been identified on Figure 3 as ravines, gorges, and canyons. However, in many places, regional bedrock geological mapping has not identified faults associated with these features. Using geophysical data, Lefort and Miller (1999) mapped northwest- and west-oriented faults and lineaments on both sides of the Atlantic rift throughout western Europe (supported by Dore *et al.* 1997) and eastern Canada. They suggested that the features were initially formed as a result of northwest-oriented wrench zones located close to the initial Gondwana and Laurasia collision front in the late Paleozoic. European features were generally interpreted as fault zones along which there has been dextral movement. In eastern Canada they indicated the presence of similarly oriented features throughout Newfoundland, the Grand Banks, Nova Scotia, and New Brunswick. Thomas (2014) noted a similar trend in transform faults formed during the initial rifting at the Iapetan margin of Laurentia. Both Thomas (2014) and Lefort and Miller (1999) concluded that these faults formed zones of weakness which were subsequently reactivated during rifting in the Mesozoic and Cenozoic with formation of the Atlantic Ocean. The concept was also supported by Thomas (2006) who concluded that these structures were related to transform faults and along with aligned compressional structures show repeated tectonic inheritance through successive Wilson cycles of supercontinent assembly and breakup.

Faure *et al.* (2006) and Williams *et al.* (1995) built upon the concept of reactivation during Atlantic Ocean formation, noting that extensional structural features are well recorded along the east coast of Maritime Canada extending up to 400 km into the interior, as noted in Quebec and New England, in the form of widespread west- and northwest-oriented extensional paleostress trends. These trends were related to one or two successive extensional events creating brittle normal faults during rifting related to the opening of the Atlantic Ocean. Wherever the faults are seen in outcrop, they overprint all other structures, in some cases crossing tectonostratigraphic terrane boundaries, and can be traced into Carboniferous strata. These lineaments were defined as Group 2 transcurrent faults by Williams *et al.* (1995) with both sinistral and dextral movement measurable in tens of kilometres. During recent, detailed structural mapping in the Johnstown area of the Mira terrane, van Rooyen (personal communication, 2015) noted six west-trending faults over a 100 m coastline exposure in metavolcanic rocks of the East Bay Hills Group and along a faulted contact with the Windsor Group. The faults are characterized by subvertical dips, 2 to 4 m-wide fault gouge and breccia, extensive damage zones, linear surface depressions over the fault core, and evidence of strike-slip movement.

(3) Association of lineaments with faults. Mabee *et al.* (1994, 2002) noted how lineament analysis in the New England area of the Appalachians is used extensively in groundwater investigations to locate high-yield water wells in fractured bedrock. Henriksen and Braathen (2006) noted that lineaments observed on aerial photographs are almost everywhere positively correlated with zones of high macroscopic and mesoscopic fracture frequencies. No detailed lineament maps have been made for Nova Scotia, other than the regional work by Keppie (1976) which did link some mega-lineaments with known faults, at least on Cape Breton Island. The general geological consensus appears to be that unless geological mapping can show evidence for faults, even mega-lineaments may not be faults. However, Gabrielson *et al.* (2002) in assessing nearly 8000 regional-scale bedrock lineaments in Norway indicated that almost all of the lineaments identified by remote sensing are faults. Hydrogeological studies by Henriksen and Braathen (2006) noted that areas within 250 to 300 m of a large lineament in crystalline metamorphic rocks are positively correlated with zones of higher fracture frequencies. The work in Johnstown, noted above, exhibits linear depressions in topographic relief of less than 10s of metres associated with the fault gouge zones. Hence, in this paper the position is taken that at least mega-lineaments, either as northwest- or west-oriented, deeply incised ravines, gorges, and canyons within the Highland Hydrological Region, or northeast-oriented, steep transition slopes within the Mountain Flank Hydrological Region exceeding approximately 1 kilometre in length are fault related, although not necessarily identified as such on existing bedrock maps.

(4) Fluid flow in faults is generally not well understood, as they are typically poorly exposed, with only a limited portion of their three-dimensional, heterogeneous, internal structure observable (Ball *et al.* 2010). This issue is addressed with a brief summary from the literature, supported by the case studies described below.

Hatcher *et al.* (1988) grouped Appalachian faults into 13 categories. Based on my experience, six of those categories appear relevant to Cape Breton Island including bedding-plane thrusts (Group 3), strike-slip faults of varying ages (Group 8), normal faults of Mesozoic age (Group 9), compound faults which underwent multiple episodes of movement or reactivation (Group 10), structural lineaments of complex and enigmatic appearance with more than one origin (Group 11), and faults associated with local centres of disturbance such as igneous intrusions (Group 12). Understanding whether these faults are presently hydraulically active and, if so, to what depth, is critical for groundwater management. The presence of springs and higher well yields suggests that some are active in the near surface, perhaps as a result of "progressive exhumation" (Cowan *et al.* 2003). In this process, as deeply buried fault zones are gradually brought to the surface over geological time, the reduction in temperature and confining pressure creates brittle phenomena, such as mesoscale fracturing and microscale cataclasis, which are further altered by fluid movement in the FGWZ. Hydraulically active faults have been documented in the Appalachian orogen by Seaton and Burbey (2005) and White and Burbey (2007). Raven and Gale (1977) documented fault and shear zones as thick as 30 to 60 m to depths of 2000 m within crystalline rocks in the southern Canadian Shield.

Faults are generally highly complex zones, propagating through a rock volume as an irregular and segmented surface resulting in both brittle and ductile shear zones (Ramsay 1980). Groundwater flow in these zones is dominantly controlled by fracture density, length, geometry, connectivity, infill, weathering, and the effects of the present-day in situ stress field. Of these connectivity is possibly the most difficult to determine (Mortimer *et al.* 2011). The centre is the "Fault Core" most highly influenced by stresses associated with displacement. It may undergo mylonitization, cataclasis, brecciation, geochemical alteration, and development of clay-rich fault gouge. All contribute to a decrease in porosity and permeability by one to three orders of magnitude with respect to the protolith (unaltered rock). The "Damage Zone" is the network of subsidiary structures that extends outward between the core and protolith, being composed of secondary structures, primarily fractures, and other small faults, but also including veins, cleavage, and folds. Boundaries between the damage zone and fault core are typically sharp, whereas the damage zone to protolith transition is typically gradational (Caine *et al.* 1996; Jeanne *et al.* 2013; Evans *et al.* 1997). A broad correlation between fault displacement and fault-rock thickness is well established and controlled by fault geometry such as locations and dimensions of steps or bends of the fault surface produced during fault propagation (Childs *et al.* 2009).

The complexity of fault architecture is further enhanced in contact zones surrounding magma chambers. Here the physical stresses producing faults associated with chamber inflation and evacuation are enhanced by magmatic-hydrothermal systems driven by cooling plutons (Hayba and Ingebritsen 1997). The latter result in high geothermal temperatures (Muffler 1979; Delaney 1982), chemical gradients and mineralization (Sibson 1987), and enhanced pore-fluid pressures (Reid 2004), as well as buoyancy and thermal expansion effects associated with hydrothermal vapour and/or water-dominated convection plumes within the adjacent groundwater flow field (Hurwitz *et al.* 2007). Hurwitz *et al.* (2003) noted that groundwater dynamics within a volcanic edifice play a dominant role in geothermal energy and epithermal mineralization. Matter *et al.* (2006) noted that intrusion of the Palisades sill in the Newark Rift Basin of New York caused thermal fracturing and cracking of both the sill and its host rocks, resulting in higher permeability along the contact zone. Which combination of the above processes was prevalent during emplacement of the numerous plutons on Cape Breton Island and what is presently exposed after they were peneplained, exposed, and underwent progressive exhumation has not been investigated to date.

The Structural HU can create a wide variety of alteration in a flow system by acting as a flow fault (hydraulic connection from one side to the other), conduit fault (permeable zone of preferential flow), barrier fault (an impermeable barrier), and obstruction fault (the character of both flow and barrier faults). Different combinations of hydraulic gradients, intrinsic permeability, anisotropy, and structural position lead to complex three-dimensional flow paths (Apaydin 2010), steep gradients (Mayer *et al.* 2007; Yechieli *et al.* 2007), compartmentalization of flow systems (Ball *et al.* 2010), and varying structure and hydraulic properties over time and space (Evans *et al.* 1997).

EFFECT OF QUATERNARY PROCESSES ON FAULTS

Four Quaternary processes are conceptualized as potentially impacting Cape Breton Island fault systems, to as yet an unknown extent:

(1) Seismic activity. Canada's present-day east coast is a passive continental margin, large scale seismic activity is relatively rare (www.earthquakescanada.nrcan.gc.ca), and formation of new faults is not expected. Approximately 600 earthquakes occur in southeastern Canada annually. With the exception of the Grand Banks earthquake of 1929 (M = 7.2), and the Miramichi earthquake in New Brunswick in 1982 (M = 5.7), all instrumentally determined earthquakes in Atlantic Canada have had magnitudes less than 5.2 (Rast *et al.* 1979). The 1929 earthquake was strongly felt in Cape Breton Island, notably at Skye Glen in Inverness County. Residents reported having to find new sources of water after the shaking re-routed springs that had supplied their homes (Doyle 2011).

Brodsky *et al.* (2003) noted that large earthquakes can induce groundwater level fluctuations at remote distances. Because earthquakes cause changes in the hydrogeological properties of faults and such changes in fluid pressure promote seismicity, hydrogeological, and seismological processes are coupled (Mango and Wang 2007). For example, Baechler and Baechler (2011) recorded the impact of the M 9.0 Japan earthquake of 11 March 2011 in an open 180 m deep bedrock well on Bell Island, Newfoundland, some 600 km northeast of Cape Breton Island. Water levels fluctuated over approximately 0.08 m above and below the groundwater recession curve present at the time of impact. Water-level fluctuations were recorded due to the passage of first a P wave and then an S wave some 25 minutes after the event in Japan (C. Woodgold, NRCan, personal communication, 2011), with an elapsed time of recorded fluctuation of 107 minutes.

(2) Glaciation. The last Wisconsinan glacial period (peaking at 21 ka and ending between 12 and 10 ka) is expected to have enhanced progressive exhumation, thereby enhancing the permeability of fault zones. This ice advance incorporated an ice sheet thickness of 2 to 3 km (Person *et al.* 2007), as well as interaction between the main Laurentide Ice Sheet and the Appalachian ice complex. This resulted in the interplay of sea level change, ice sheet stability, pressure-focused sub-glacial recharge mechanisms (Person *et al.* 2007; Lemieux *et al.* 2008), and isostatic rebound within a lithologically and topographically diverse terrain (Stea *et al.* 1998).

(3) Present regional stress field. The World Stress Map (WSM) data base (Heidbach *et al.* 2008) indicates a regional, smoothed, direction of maximum horizontal stress oriented northeast-southwest over eastern Canada. This direction is parallel to the major northeast-trending fault systems, which may enhance permeability along these structures, while limiting permeability along northwest- to west-oriented faults.

(4) Stress relief. The major basin-bounding and cross-cutting fault zones tend to be associated with major changes in relief, ranging from 150 to 400 m. Increased permeability of these fault zones is expected to be enhanced by fracturing and faulting associated with stress relief, valley rebound, and valley flexure concepts, as outlined by Wyrick and Borchers (1981) and Matheson and Thomson (1973). In localized areas this has resulted in actively eroded bedrock promontories, creating talus rock cones covering the fault scarp.

Although all of these processes have been ongoing to varying extent throughout the Quaternary, Grant (1990, 1994) noted that evidence of Cenozoic crustal movement in Atlantic Canada is limited to rare, small, stepwise displacements of glaciated outcrops. The largest was an abrupt offset with 15 m upthrow along the south side of the Aspy Fault in Cape Breton Island sometime in the last 125 000 years. Fenton (1994) summarized all evidence of postglacial faulting in eastern Canada, noting three additional sites in Cape Breton Island and eight over the remainder of the province.

HYDROGEOLOGICAL CASE STUDIES

Seven Cape Breton Island hydrogeological case studies provide support for the conceptual models discussed above. For the most part this work was privately funded and carried out by consultants for a variety of municipal, industrial, mining, and commercial clients over the past 40 years. The associated reports referenced herein have been submitted to clients and in some instances to Provincial regulatory agencies in support of permit applications. Therefore this "grey" literature has not been published in peer-reviewed journals, and for the most part is not available to the reader. Nevertheless the importance of this type of applied research is becoming recognized in establishing a base for groundwater knowledge management. For example, Holysh and Gerber (2014) noted that data, knowledge, and understanding of hydrogeological conditions that have been gained through such work are in danger of winding up on shelves, lost during company dissolution, or forgotten due to retirement and turnover of hydrogeological staff, unless a concerted effort in knowledge management is undertaken.

Baddeck

The Baddeck hydrogeological case study centres northwest of the Village of Baddeck (Fig. 2, Site B). The fault trace comprising a series of parallel splays is exposed over a length of approximately 7 km and is positioned along the edge of a Carboniferous basin in proximity to the Eastern Highlands Shear Zone (EHSZ) of Barr and Raeside (1989). Raeside and Barr (1990, 1992) positioned the EHSZ along the westernmost fault splay at the western edge of the Kathy Road Dioritic Suite and therefore in-bound of the contact with the Carboniferous basin, suggesting that the fault being exploited is not the EHSZ. The easternmost fault splay, along which the site is located, is positioned at the contact with the Carboniferous basin and therefore may be a basin-bounding fault. At its northern end, the EHSZ represents a poorly understood, deeply rooted, thrust fault, but its character and even its position in the southern highlands are uncertain (e.g., Horne 1995). In the north, Lin (1995) noted the shear zone dips steeply to the southeast and the movement direction pitches steeply to the southwest. In its northern part, movement along the shear zone is dominantly east-over-west dip-slip with minor sinistral strike-slip component. However, detailed structural studies along the southern part of the shear zone have not been done and different authors display different configurations (e.g., Horne 1995).

This complexity is further enhanced as the shear zone may also form part of a larger fault system termed the Cabot Nappe, suggested to represent northwesterly thrusting and folding of an allochthonous sheet of the Bras d'Or terrane over the Aspy terrane (Lynch 2001). It is also possible that it represents thrust faulting of crystalline basement of the Cape Breton Highlands over adjacent Carboniferous sedimentary rocks, as has been suggested in this general area by Currie (1977). This concept is also supported by Tizzard and Raeside (2003) for a site some 25 km to the north, as well as Boehner and Giles (2003) approximately 30 km to the south along the proposed extension of this fault, termed the St. Patricks Channel lineament. Faulting may also be enhanced given the position of the site along a contact zone adjacent to the eastern edge of the Kathy Road Dioritic Suite. Therefore the location, nature, and origin of this fault zone remain speculative.

The hydrogeological characteristics of the fault at site B has been investigated by ADI Ltd. (2008), Earth-Water Concepts Inc. (2011), and Exp Services Inc. (2013). The field program initially consisted of monitoring eight springs and geological mapping. This work was followed by exploratory core drilling and finally drilling of five large diameter test holes, of which two have gone into production as municipal wells.

A cross-section view (Fig. 7a) positions the site within the Mountain Flank Hydrological Region with crystalline rocks of the highlands to the west and evaporite rocks of the Windsor Group in the lowlands to the east. The fault is positioned under the steep (25%) transition slope with a topographic relief of some 250 m, which is bedrock controlled. The minimal overburden and hardwood Acadian forest allows for development of thick snowpack and rapid vertical infiltration into the fault zone during precipitation and snowmelt events. There are no fault-controlled gorges cross-cutting the site, or talus cones or alluvial fans covering the fault. Windsor Group evaporite rocks adjacent to the lowland toe-of-slope exhibit karst and are covered with a mantle of fine-grained glacial till.

Eight springs discharge near the base of the transition slope along approximately 800 m of fault strike length. The discharge points are approximately 5 to 20 m above the contact with the Windsor Group rocks, which may be acting as a subsurface dam. The combined discharge ranges from approximately 1200 Lpm during low summer flows to 8600 Lpm under spring recharge. Maximum individual discharges range from seepage to 3800 Lpm, defining category 8 to 4 springs using the Meinzer (1927) classification. Temperatures ranged from 6° to 8°C throughout the year, similar to the mean annual air temperature of the region, and hence indicating non-thermal water.

Core hole DDH 1 (Fig. 7a) was drilled to a depth of 29 m along the toe-of-slope at the edge of a rock quarry which exposes faulted, crystalline metasedimentary rocks. However the core revealed 10.4 m of fine-grained clayey silt (glacial till) overlying argillaceous mudstone, shale, and gypsum of the Windsor Group, suggesting the presence of a steeply dipping fault zone. Core hole DDH 2 was drilled within the fault zone some 20 m in elevation above DDH 1, adjacent to the largest magnitude spring. It indicated 4 m of colluvium and/or sand diamicton overlying highly broken granodiorite to 52 m depth. The core exhibited low Rock Quality Designation (RQD) (0 to 5%), with intense fracturing and evidence of faulting through shearing, slickensides, and hematite on fracture surfaces, as well as flowing conditions. Three high intensity rubble zones, ranging in thickness from 3 to 10 m, did not indicate the presence of fault gouge.

Five large diameter production wells were drilled over the lower half of the transition slope to depths ranging from 44 to 152 m, with the deepest (PW 4) located at the highest elevation. Well construction was hampered by the intense fracturing, necessitating 100 slot stainless steel screen in PW 4. All 5 wells encountered a variety of highly brecciated, slickensided metasedimentary rocks of presumably the George River Metamorphic Suite, with no evidence of the granitic rocks found in DDH 2. However, test well 1B encountered limestone, gypsum, and clay of the Windsor Group underlying the metasedimentary rocks from 56 to 79 m depth. This observation suggests either a very steep, west-dipping fault zone, or low-angle eastward thrusting of the crystalline basement rock over Windsor Group sedimentary rocks, as discussed above.

The transmissivities and safe yields from hydraulic testing of producing wells 2A, 2B at site 2 and site 4 are summarized in Table 1. Storativity ranges from 9.1 x 10^{-1} to 1.3 x 10^{-3}, indicating a water table aquifer. In comparison, non-faulted granitic and metasedimentary rocks elsewhere on Cape Breton Island exhibit much lower transmissivities and 20-year safe yields averaging 5 m^2/day (range 0.1 to 21.6 m^2/day) and 40 Lpm (2.7 to 110 Lpm), respectively. McBeath *et al.* (1988) summarized 67 pump tests in mainland Nova Scotia from the Nova Scotia Department of Environment pump test data base in these rock types, which provided a similar average low transmissivity of 4.5 m^2/d and safe yield of 77 Lpm.

Twenty-three water samples from the springs, DDH 2, and the production wells all exhibited similar water, characterized as fresh, with total dissolved solids (TDS) ranging from 42 to 107 mg/L, corrosive (negative Langlier Index), mixed sodium, calcium - bicarbonate, chloride type water (Fig. 8), with an alkaline pH (7.6 to 8.3). Farther up-slope at PW4 the water is more dominantly a calcium bicarbonate type. No evidence of mineralization from fault gouge or enhanced nutrients from the hardwood forest cover was observed. The low concentrations of TDS, sulfate (3 to 9 mg/L), chloride (8 to 36 mg/L), and water typing delineated by a Piper diagram suggests a FGWZ. Figure 8 shows a normal 2-D Piper plot, as well as a 3-D plot using TDS along the vertical axis off the central diamond. The latter provides a means of further separating distinct water types. It demonstrates no pronounced impact of any underlying saline water associated with: (1) gypsum-dominated waters, (2) brines as exemplified from Phalen coal mine workings within the sedimentary basin on Cape Breton Island (ADI Ltd. 1993), or (3) crystalline rocks as recorded in the Canadian Shield (Frape and Fritz 1987). This observation is also supported by the non-thermal water temperatures of 6° to 8° C, compared with elevated temperatures in the Phalen coal colliery at 600 m below sea level of approximately 20° C.

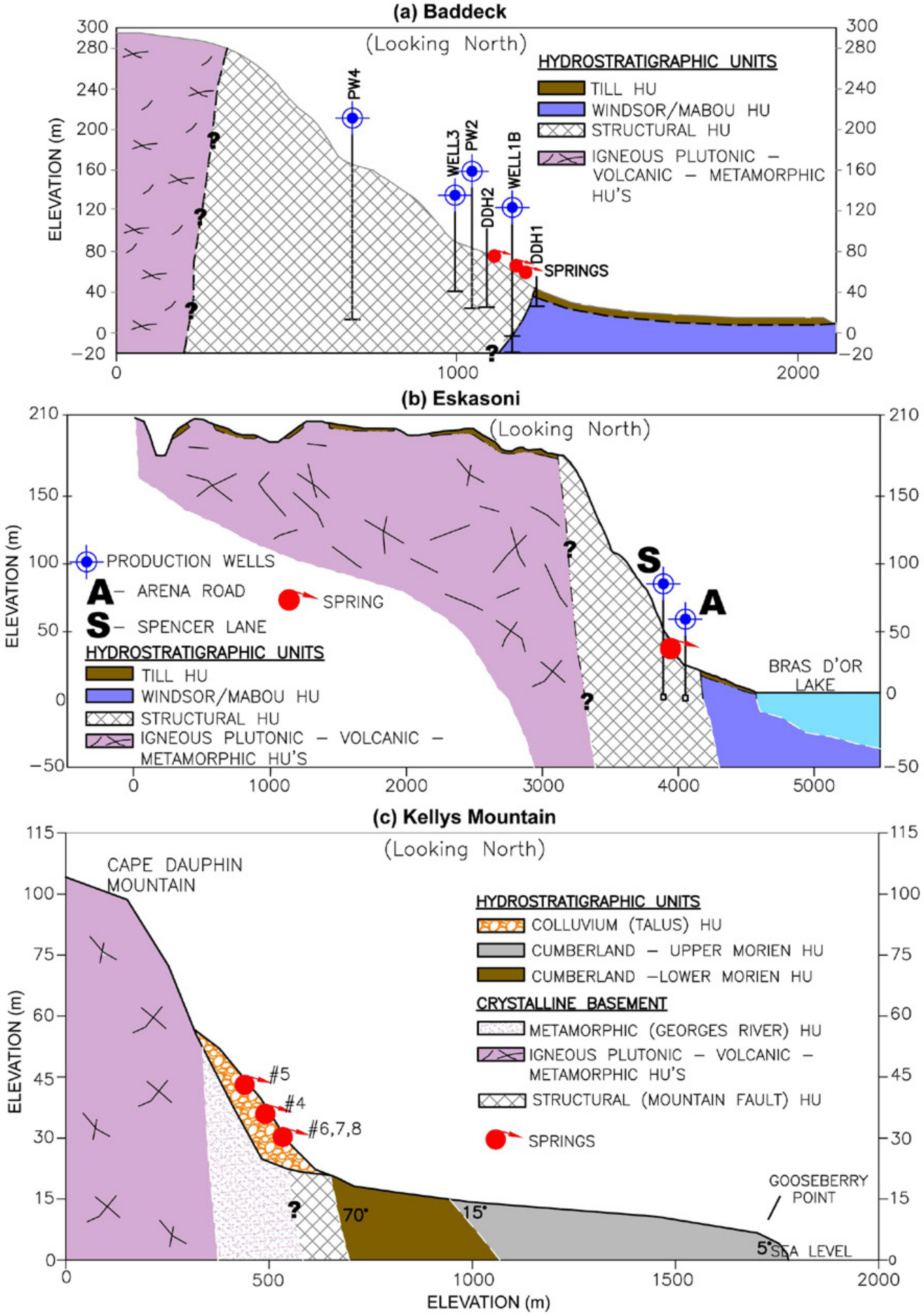

Figure 7. Composite hydrogeological cross sections for (a) Baddeck, (b) Eskasoni and (c) Kellys Mountain case study areas.

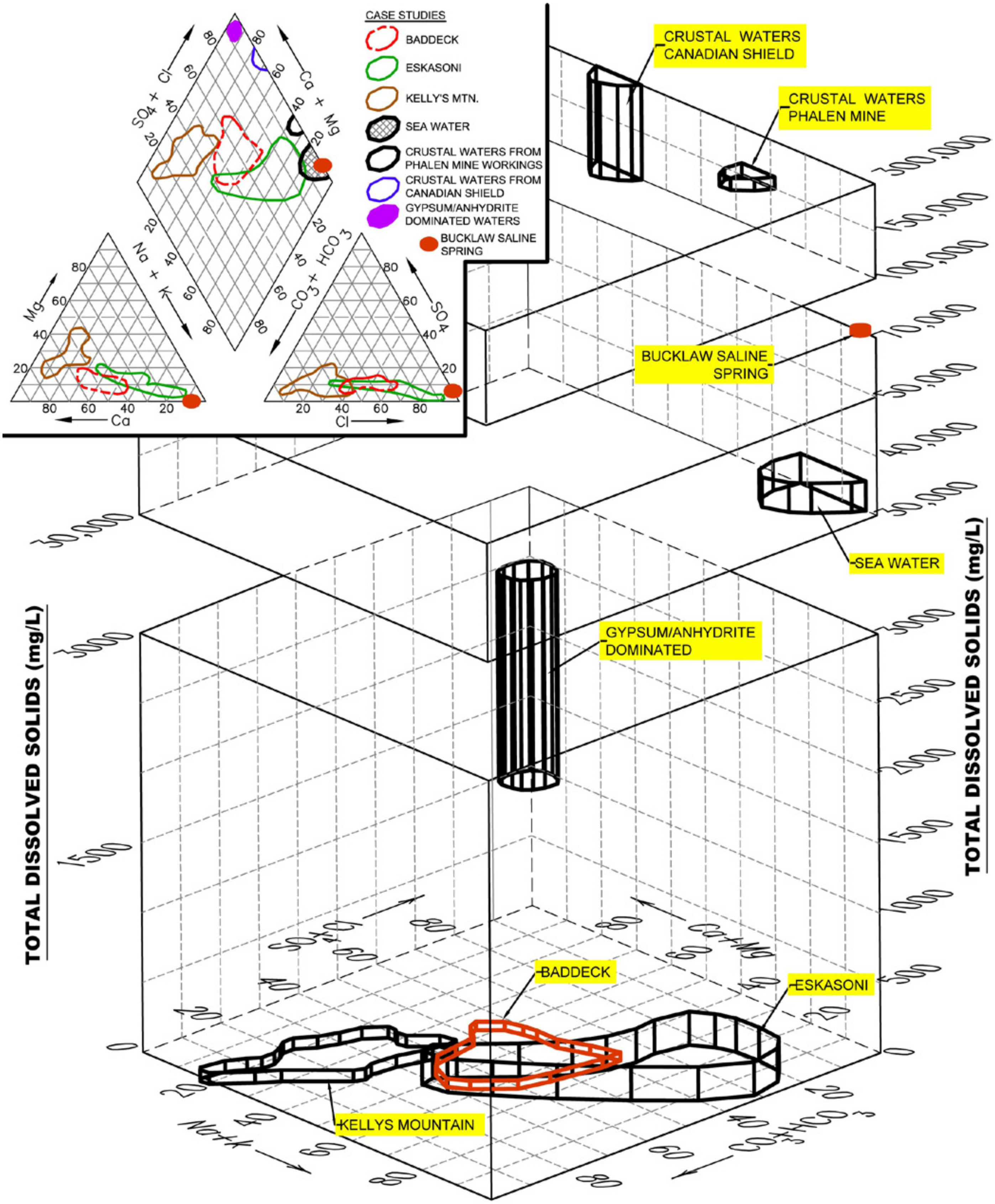

Figure 8. Select major ion chemistries from the case studies presented in 2-D and 3-D trilinear diagrams.

The enhanced yields and chemistry show that hydraulically active faults such as those in the Baddeck area can create suitable water supply aquifers.

Mabou

The development of a groundwater supply for the Village of Mabou provides the second case study (Fig. 2, Site M). The village, as well as nearby homes, previously obtained their water supply from a group of springs discharging from the southwest side of Mabou Mountain (ADI Ltd. 2002a). Drought conditions experienced over the summers of 2000 and 2001 stressed the village's supply, which was augmented by the drilling of production wells by ADI Ltd. (2002b) and C.J. MacLellan and Assoc. Inc. (2007, 2009) in proximity to the spring.

The site is positioned within the Hollow Fault - Aspy Fault zone. These faults are mapped as two, separate, large-scale faults, although Cook *et al.* (2007) suggested that the Hollow fault connects with the Aspy fault system through the Aspy terrane. For the purpose of this hydrogeological assessment their proximity, orientation, architecture, and associated lineaments suggest that multiple faults are potentially present, but not necessarily pervasive. The fault zone trends northeast through the western edge of the island (Figs. 1, 2, 3).

The geology of the Hollow fault - Aspy fault zone has been investigated by, for example, Gibling *et al.* (1987), Hall *et al.* (1998), Braid and Murphy (2006), and Rehill (1996). It is an approximately 20 km wide zone of complex structure (Fig. 2). Northeast of Cape Breton Island it connects with the Cabot Fault System and extends through Newfoundland as the Long Range and Cape Ray faults (Fig. 1). To the southwest it extends onto the mainland, joining up with the Cobequid-Chedabucto fault complex (Fig. 1), after which it continues south into the New England states, as part of a massive San Andreas-style fault system (e.g., Murphy *et al.* 2011). Within the Antigonish-Mabou Subbasin, Durling *et al.* (1995a, b) characterized the fault as a northeast-striking, predominately dextral, strike-slip fault zone, dipping in places to either the northwest or southeast with a vertical displacement of approximately 1600 m down to the south. Just offshore southwest of Cape Breton Island under St. Georges Bay, it is mapped as a 1500 to 2500 m wide deformation zone. It comes ashore in the Mabou area as low angle thrusts and high angle strike-slip faults, with strata folded into northeast-trending open synclines, faulted salt-cored anticlines, and elevated basement blocks. Some faults have large throws up to 3200 m and large uplifted basement blocks.

Mabou Mountain reaches an elevation of approximately 236 m above sea level. The springs discharge at an approximate elevation of 80 m along the strike of a fault line. The mountain is underlain by relatively higher permeability sandstone units of the Cumberland Group, which overlie low permeability argillaceous siltstone and shale of the Pomquet Formation. The sandstone slab capping the hilltop dips to the west directing groundwater flow to the springs.

Four wells were drilled to depths ranging from 32 to 75 m in proximity to fault traces, encountering sandstone as well as mudstone, siltstone and limestone at depth. The elevated transmissivity and safe yield from the production wells are summarized in Table 1. The storativity of 1.0 x 10^{-3} indicates a water table aquifer.

Five water chemistry samples from the springs and drilled well during a pumping test indicated a similar water, best classified as fresh (TDS 55 to 71 mg/L), corrosive, calcium - bicarbonate type with a pH range of 7.6 to 7.9. There was no change in spring chemistry from 1978 to at least 2001.

Eskasoni, Kellys Mountain, Sydney Coalfield, and Bucklaw

These four case studies are combined as they focus on the hydrogeology of basin-bounding faults. The first hydrogeological case study relates to development of a groundwater supply for the community of Eskasoni (Fig. 3, Site E). The second study focuses on springs issuing from the eastern flank of Kellys Mountain (Fig. 3, Site KM). A discussion of hypersaline brines in the coal mine workings in the Sydney coalfield and salt springs at Bucklaw (Fig. 3, Site B) form the last two studies.

During the closing of the Iapetus and Rheic oceans, oblique slip between adjacent continental land masses resulted in intense deformation and megashear along what are now various northeast-trending Carboniferous basin margins. A series of major northeast-trending faults are

Table 1. Hydrogeological characteristics of the structural hydrostratigraphic unit derived from pumping tests.

Location	Number of Production Wells	Well Transmissivity Range (average) m^2/day	Aquifer Transmissivity Range (average) m^2/day	20 year safe yield Lpm
Baddeck	3	80 to 206 (155)	91 to 643 (300)	785 to 1140
Mabou	3	21 to 90 (57)	54 to 111	255 to 348
Eskasoni	2	216+ to 320		680+ to 1020
Neils Harbour	1	6.5		113

present on Cape Breton Island with postulated strike-slip motion, predominantly dextral (e.g., Gibling *et al.* 1987). These are exemplified (Fig. 3) by major faults identified on bedrock geological maps (as defined, approximate, assumed, and/or lineaments); then subsequently mostly defined as approximate faults (Keppie 2000). A number of these faults extend northeast at depth under the Carboniferous cover along the western edge of horst/graben features (Fig. 3) past the present shoreline (Pascucci *et al.* 2000), but were subaerially exposed during post-glacial times when sea level was 50 m lower than present (Shaw *et al.* 2006).

These systems are complex (Figs. 6 b and c – Evaporite and Fault districts), potentially exhibiting multiple movement episodes including initial strike-slip, later reactivated as dip-slip normal faults and cross-cut by northwest- to west-trending faults (Faure *et al.* 2006). Normal faulting allowed for the damage zone to extend some distance out into the adjacent basin sediments, as steeply dipping, highly fractured beds. Fracturing and slip along the faults may have been augmented by stress-relief forces. This type of fault system is best exemplified along the western and southern margins of the Sydney coalfield (Boehner and Giles 2008) by the Mountain, Bateston, Georges River, and Coxheath faults (Fig. 3). The first two are inferred to have substantial, predominately dextral strike-slip motion in the order of 10s of kilometres and dip-slip offset in the order of more than 1000 m, with some component of dip-slip faulting with down-throw to the southeast. The Georges River and Coxheath faults offset strata showing apparent dextral movement, possibly as much as 18 km (Gibling *et al.* 1987). The northeast-trending Big Pond fault system records dextral strike-slip motion along high-angle faults of unknown displacement (Bradley and Bradley 1986). The Mountain Fault at Cape Dauphin exhibits steepening of dips within adjacent sedimentary strata ranging from five degrees some 0.5 km from the fault to nearly vertical adjacent to the fault (Boehner and Giles 2008).

The Mountain Flank hydrological setting in which many of these fault systems are present enhances the importance of mountain front recharge (MFR). Magruder *et al.* (2009) and Manning (2011) noted MFR as a significant recharge component for intermontane basins around the world. However they remain poorly understood, primarily due to the complexity of the systems, heterogeneity of mountain meteorology, range in forest cover types, and presence of faults acting as conduit and/or barrier systems, coupled with minimal instrumentation. MFR is composed of two components including Mountain Block Recharge (MBR) related to subsurface inflow of FGWZ to a deeper basin-fill aquifer from an adjacent mountain block. The second component encompasses interaction between surface waters and the FGWZ along the mountain front.

In Cape Breton Island the complexity of MFR is expected to be further enhanced (Fig. 6b Evaporite District and 6c Fault District) by: (1) adjacent, highly fractured, steeply dipping, sedimentary sequences; (2) elevated spring streamflow derived from highland snow packs; (3) enhanced direct recharge into the Structural HU due to minimal overburden and dominant hardwood forest cover with thick snowpacks; (4) springs discharging along the fault trace; (5) cross-cutting gorges with perennial streams which dissect the fault aquifers; (6) glaciofluvial outwash and alluvial fan deposits at the mouths of gorges and ravines, coupled with coarse talus cones; and (7) hydraulically active karst systems adjacent to the mountain front. These attributes create a mixture of seasonally influenced influent and effluent groundwater stream interaction. The complexity and value of these MFR zones on Cape Breton Island has historically been underappreciated.

The Eskasoni case study (Fig. 3, Site E) focuses on the East Bay Lineament positioned along the eastern boundary of the Boisdale Hills adjacent to the north shore of East Bay. Here the fault trace is exposed over an approximately 8 km length within the community, underlying the steep transition zone of the Mountain Flank Region. This area was investigated by Nolan Davis and Assoc. Ltd. (1984, 1989, 1990) and Exp Services Inc. (2012a). The field program initially focused on spring monitoring and geological mapping of faults in quarry exposures and outcrop, followed by drilling of eight large diameter test holes, of which three have served as the municipal water supply for over 20 years. The cross-sectional view (Fig. 7b) positions the site within the Mountain Flank Hydrological Region. The fault is within a steep (20 to 40%) transition slope, exhibiting a relief of 140 m, which is covered by a hardwood Acadian forest. The slope is bedrock-controlled with minimal overburden and no alluvial fans or talus cones, allowing for rapid direct recharge into the fault zone. The fault zone is bounded to the west by crystalline rocks of the Boisdale Hills, and evaporite rocks of the Windsor Group underlie the lowlands to the east, which are mantled by fine-grained glacial till and localized glaciofluvial outwash. The highland is incised by two dominant northwest-trending, "V"-shaped, steep-sloped, high-gradient, bedrock-lined, perennial stream gorges identified as Christmas and Denys brooks, which are assumed to be fault controlled.

The initial water supply was from a Meinzer Category 5 spring discharging at 200 to 300 Lpm, from a heavily fractured, granular, hornblende granodiorite exhibiting slickensides. The test drilling program incorporated wells ranging in depth from 35 to 62 m at three different locations along the fault trace where it intersected cross-cutting faults. The Arena Road well-site, positioned at the intersection of the fault trace with Christmas Brook, is a production well drilled to 26 m in fractured granite, necessitating 1.5 m of #60 slot screen. Test drilling at the Spencer Lane site included two wells to depths of 40 to 50 m where the fault trace was cut by Denys Brook, encountering broken granite and major fracture zones with flowing artesian conditions. Two additional wells drilled to depths of 62 to

68 m at the location of the springs, where there is no notable cross-cutting northwest-trending fault, encountered both competent non-fractured as well as highly fractured zones. The elevated transmissivites and safe yields encountered at the Arena Road and Spencer Lane sites are summarized in Table 1. One pump test at the spring site provided a lower transmissivity of 7 m^2/day and safe yield of 114 Lpm.

The wells and springs have similar water chemistry, characterized as a fresh (TDS 75 to 265 mg/L), corrosive, predominately sodium/calcium/bicarbonate/chloride type water (Fig. 8), with a pH range of 7.4 to 8.5. One well showed a trend toward higher sodium chloride with depth, but did not exhibit mixing with sea water, gypsum formation water, or deep crustal waters (Fig. 8). All three production wells have been pumping for 20+ years with no noticeable degradation in water quality.

The Kellys Mountain case study focuses on springs issuing from the east flank of Kellys Mountain, positioned along the trace of the Mountain Fault (Fig. 3, Site KM). These springs were investigated by Nolan Davis and Assoc. Ltd. (1987). A cross-sectional view (Fig. 7c) positions the site within the Mountain Flank Hydrological Region. The zone is bounded by crystalline rocks forming Kellys Mountain to the west and incised locally by a number of northwest-oriented "V"-shaped steep-sloped ravines. Tilted sedimentary rocks of the Horton, Windsor, and Cumberland groups underlie the Lowland Region immediately to the east, which is mantled by fine-grained glacial till and localized glaciofluvial outwash. Faulting is positioned under the steep transition slope, over a topographic relief of ~250 m which is covered by a hardwood Acadian forest and minimal glacial overburden. The slope ranges from near vertical at the rock outcrop crest, to 15° over the talus slopes covering the fault trace and toe-of-slope.

A total of 10 springs were identified over an approximate 2 km length of the fault trace. The largest is associated with the intersection of a west-trending, possibly fault-controlled ravine. Flows were monitored up to 10 times between March and July 1987, indicating Meinzer category 6 to 4 springs. During peak flows in April the total flow from nine springs was 7 500 Lpm; with Spring 5 being the largest producer at 3 000 Lpm. The lowest flows were recorded in July after a three-week drought with a total of 510 Lpm.

The springs recorded a generally similar type of chemistry, characterized as a fresh (TDS 24 to 108 mg/L), corrosive, mixed calcium/magnesium/sodium bicarbonate-type water (Fig. 8), with an alkaline pH range from 7.0 to 8.1. Water temperatures were constant at 5° to 6° C. The low TDS, water typing, and non-thermal temperatures indicate the absence of any upwelling deep crustal groundwater.

The third case study documents one of the earliest hydrogeological implications of this faulting during deep Permian-Triassic burial. Martel *et al.* (1999, 2001) suggested that crustal-scale hypersaline brines from the Windsor Group moved along faults and were intruded into the overlying Sydney Mines Formation coal seam successions of the Cumberland Group in the Sydney Coalfield. Their saline chemical signatures were also investigated by ADI Ltd. (1993) in the Phalen coal mine workings 2.5 km offshore at 600 m below sea level. Groundwater was characterized as a hypersaline brine (TDS 162,600 to 169,000 mg/L), extremely hard (50 000 to 60 000 mg/L as $CaCO_3$), sodium chloride type water (Fig. 8), with a pH of 5.0 to 7.6.

The fourth case study focuses on the presence of localized salt springs along the St. Patricks Channel lineament at Bucklaw (Fig. 3, site B). These springs have been described by Martel *et al.* (1999), Cross and Goyete (2000), and Boehner and Giles (2003). Here the topographic relief is approximately 260 m with the springs discharging near the toe-of-slope. The most saline chemistry indicated a saline to hypersaline (TDS 77 200 mg/L), sodium chloride type water (Fig. 8), with a pH of 7.7. This chemistry suggests that saline water is being transported upwards from a deep evaporite reservoir (possibly the Orangedale salt diaper) into the FGWZ through collapse/foundering karst breccia and/or hydraulically active faults (Baechler and Boehner 2014).

Neils Harbour

This case study relates to exploration for a groundwater supply for the community of Neils Harbour (Fig. 3 Site NH) within a large northwest- to west-trending mega-lineament. As noted previously, whether these northwest- to west-trending mega-lineaments are faults, and if so their origin, architecture, and nomenclature, is one of the more enigmatic structural issues on the island. In this paper they are postulated to represent faults with possible strike-slip motion.

A groundwater resource evaluation to assess the potential for groundwater to replace the existing surface water supply for Neils Harbour was carried out by ADI Ltd. (2010) and Exp Services Inc. (2012b). This study focused on a large northwest- to west-oriented mega-lineament followed by Halfway Brook. Although no faults have been identified on regional geological maps (e.g., Barr *et al.* 1992) the orientation, linear trend, and depth of incision of this lineament into an igneous pluton suggests that it represents a northwest-trending fault.

The hydrogeological program initially focused on aerial overflights and lineament analysis from aerial photographs and digital terrain image analysis. Regional analysis indicated two major lineament orientations, trending northwest (110° to 130°) and west (70° to 80°). Both orientations have been carved out by major drainages, with the most strongly incised lineaments developed along the northwest orientation by Halfway Brook, Rachel Brook, Neil Brook, and Trout Brook. Halfway Brook was selected for exploration as it is the largest of these features in proximity to the community.

It is a distinct west-trending lineament for some 13 km created by a narrow (300 to 500 m width), “V”-shaped, 50 to 80 m deep valley incised into a peneplain underlain by the Black Brook Suite (granite and granodiorite) (Fig. 5b – Granite Plain District). A test hole was drilled to a depth of 91 m within granite at the base of the valley floor. Six fractured zones were encountered, none exhibiting fault gouge, providing a drillers blow test yield of 160 Lpm. The hydraulic testing (Table 1) indicated a transmissivity of 6.5 m^2/day and safe yield of 113 Lpm, which was notably elevated above background well yields from 37 domestic wells drilled into the same granitic suite, some 1 to 4 km northeast of the lineament. Here well depths of 10.6 to 121.8 m provided an average driller blow test yield of 32.9 Lpm and median of 13.6 Lpm. Four test holes drilled in the community to depths ranging from 76 to 93 m by Washburn Gillis and Associates Ltd. (1995) provided no flow from blow tests at two wells, with one exhibiting 40 Lpm. The fourth hole was pump tested providing a transmissivity of 1.1 m^2/day and a 20 year safe yield of 36 Lpm. Overall these results suggest the presence of enhanced yields in the base of the lineament.

MANAGEMENT ISSUES

This paper has provided evidence for the hydrogeologically active nature of selected faults on Cape Breton Island, their potential ubiquitous presence, as well as their importance to society. However, it has also highlighted the complexity of these systems, and the limited knowledge concerning their geology as well as their physical and chemical hydrogeological characteristics. Therefore, it is suggested that future research should focus on developing a sound scientific understanding of the geology and hydrogeology of fault systems on Cape Breton Island. The focus should be directed primarily to basin-bounding faults, with a secondary interest on large northwest- to west-trending mega-lineaments suspected of being fault-controlled. Research should be targeted to provide a sound technical base to allow regulatory agencies to develop management strategies related to the role of the faults such as: (1) potable aquifers; (2) release pathways for gases and dissolved constituents from natural as well as hydraulic fracturing and CO_2 sequestration activities; (3) Mountain Front Recharge mechanisms governing stream ecology and morphology, groundwater-stream interaction, and recharging of basin groundwater systems; (4) sources of large magnitude springs and the role they play in providing stream baseflow, potentially groundwater dependent ecosystems and influencing salmonid habitat; (5) a component of geotechnical investigations for a variety of infrastructure; and (6) a factor for consideration in development of standards for rural ribbon development, transportation corridors, and forestry practices ringing the edge of the Bras d’Or Lake United Nations Biosphere Reserve. Field programs for investigating faults as potential groundwater supplies should commence with lineament analysis, geological mapping, and spring delineation, as well as possibly surface geophysics. These activities should be followed by core drilling and finally larger diameter water-well drilling and well construction with screens, accompanied by hydraulic testing.

CONCLUSIONS

Cape Breton Island provides a hydrogeological view into a tectonically ancient, exhumed, glaciated, now tectonically inactive, deep crustal terrain, with a range of fault types formed during Paleozoic development of the Appalachian orogen and the Maritimes Basin, as well as Mesozoic Atlantic Ocean opening, and Cenozoic exhumation. These faults have been important in developing municipal groundwater supplies, controlling inflows to underground excavations, hydrocarbon exploration, base metal mineralization, and quarry development, as well as geotechnical designs for infrastructure.

Seven case studies on Cape Breton Island document the hydraulically active nature of these systems and provide the basis for development of conceptual models for fault control on groundwater flow systems. Two of these studies support the ability to extract potable water, one for as long as 25^+ years, with well construction requiring screens. Two studies note upward flow of saline waters from deep evaporite sources. Three note the presence of numerous large magnitude springs influencing baseflow in nearby streams.

It is recommended that future research focus on developing a sound scientific understanding of the geology and hydrogeology of fault systems, both at surface and depth, including their location, architecture, and hydrogeological characteristics. Such work would provide a sound technical basis for targeting them for water supplies and allow regulatory agencies to develop management strategies.

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