Sedimentary-rock-hosted Zn-Pb deposits of the Maritimes Basin, Atlantic Canada: Comparison with Irish-type, MVT and SedEx/CD deposit models

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Abstract: The Mississippian (Viséan) Windsor Group of Atlantic Canada consists of a lower carbonate unit overlain by a thick succession of evaporite, clastic, and carbonate rocks. It hosts numerous Zn-Pb deposits, including the Scotia (formerly Gays River deposit), Walton and Jubilee deposits in Nova Scotia, and a number of occurrences on the Port au Port Peninsula, Newfoundland. Geological and geochemical studies show that these deposits share a number of important characteristics, including location on the flanks of sub-basins in carbonate rocks at the base of the Windsor Group, strong structural control on mineralization, and metalliferous fluids sourced from the underlying basement rocks.

Despite these similarities, there is significant inter-deposit heterogeneity, and individual deposits can be classified as typical MVT or SedEx/CD, or deposit types transitional between these end-member types (akin to Irish-type deposits in the Irish Midlands) based on conditions at the site of mineralization. It is best to describe the mineralizing system responsible for the formation of these deposits using a mineral-system approach, focussing on regional-scale characteristics such as triggers for mineralization (e.g., edge-driven convection during transtensional tectonics) and favourable crustal architecture to transport metalliferous fluids to suitable mineralization sites. Ongoing research using state-of-the-art geochronological and geochemical techniques aims to advance the understanding of the timing and nature of mineralizing processes in the sedimentary-rock-hosted Zn-Pb deposits of the Maritimes Basin.

Keywords: Maritimes Basin, timing of mineralization, Nova Scotia, Visean, Walton, Jubilee and Scotia Deposits.

Introduction

The Maritimes Basin of eastern Canada consists of a suite of sub-basins that record a complex history of sedimentation in an active tectonic regime from the Devonian to early Permian (Murphy *et al.,* 2011; Gibling *et al*., 2019). Base-metal (Zn-Pb ± Cu-Ba) occurrences are hosted in the Mississippian Windsor Group, which represents the first sustained open-marine sedimentation in the Maritimes Basin (Gibling *et al.,* 2019). Over 150 separate base-metal occurrences have been described in Nova Scotia, Newfoundland, and New Brunswick (Graves and Hein, 1994), including major deposits at past-producing mines in Nova Scotia (Scotia (formerly Gays River) and Walton mines), as well as significant occurrences at Jubilee (Nova Scotia) and the Port au Port Peninsula (Newfoundland). These occurrences have been the subject of extensive previous research, including detailed geological and geochemical studies (Sangster *et al.,* 1998a and references therein), and have been variably described as MVT, Irish-type, or SEDEX/CD deposits

(Dix & Edwards, 1996; Kontak, 1998; Sangster *et al.,* 1998a; Leach *et al.,* 2005; Sangster, 2020). In the Late Mississippian, Nova Scotia was close to Ireland owing to the configuration of Pangaea, which leads to the idea that sedimentary-rock-hosted Zn-Pb deposits in these two regions may share a similar genetic model (Kontak & Boyce, 1996; Lavoie & Sami, 1998; Leach *et al*., 2001).

This paper summarizes the geological setting and geochemical characteristics of the Scotia, Walton, Jubilee, and Port au Port deposits. These base-metal deposits share a number of important characteristics, and their origin is discussed in terms of the various genetic models that have been applied to them [Mississippi Valley-type (MVT) vs. Irish-type vs. sedimentary exhalative/clastic-dominated (SedEx/CD)]. A number of important research questions need to be addressed in order to constrain the nature and relative timing of Zn-Pb mineralization and improve the classification and understanding of low-temperature, sedimentary-rock-hosted Zn-Pb deposits.
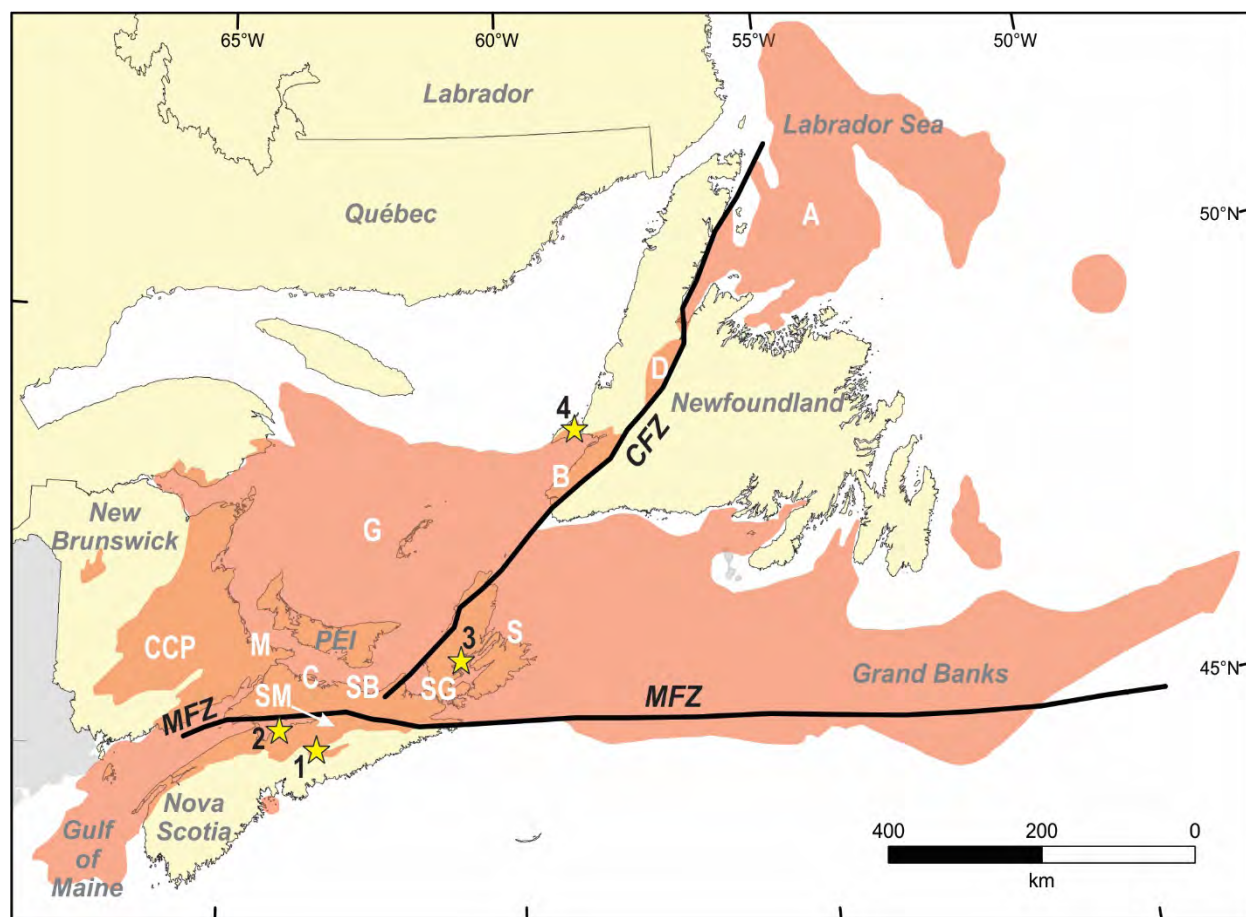
Figure 1: *Maritimes Basin, eastern Canada (orange), showing location of main depocentres and mineral deposits described in text. A, St. Anthony Basin; B, Bay St. George Basin; C, Cumberland Basin; CCP, Central Carboniferous Platform of New Brunswick; CCFZ, CFZ, Cabot Fault Zone; D, Deer Lake basin; G, Gulf of St. Lawrence basin; M, Moncton basin; MFZ, Minas Fault Zone; S, Sydney basin; SB, Stellarton basin; SG, St. George's Bay basin; SM, St. Mary's basin. Also included are the location of mineral deposits discussed in this paper: 1, Scotia deposit (formerly Gays River deposit); 2, Walton deposit; 3, Jubilee deposit; 4, Port au Port occurrences. Modified from Gibling et al. (2019).*

Geological Setting

The Maritimes Basin of eastern Canada consists of a thick (> 12km) succession of Devonian to early Permian strata that were deposited under an active tectonic regime from the Neo-acadian to Alleghanian orogenies (Murphy *et al*., 2011; Waldron *et al.,* 2015; Gibling *et al.,* 2019). Its present-day extent spans a large area from the Gulf of Maine in the southwest to the Grand Banks in the east and the Labrador Sea to the north, and it has been subdivided into a number of discrete sub-basins or depocentres (Fig. 1; Gibling *et al*., 2019). These depocentres record a prolonged, complex tectonic history, with predominantly dextral strike-slip transtensional motion on major faults punctuated by more localized episodes of crustal thickening, extension, and salt tectonics (Murphy *et al*., 2011; Gibling *et al.,* 2019; Snyder & Waldron, 2021). This motion was mainly accommodated on two major trends (Waldron *et al*., 2015), the NE-trending Appalachian trend (including the Cabot Fault Zone; CFZ) and the E-trending Minas Fault Zone (MFZ) (also known as the Cobequid-Chedabucto Fault Zone or CCFZ) which separates the Avalon and Meguma terranes of Nova

Scotia (Williams, 1979; Murphy *et al.,* 2011). Approximately 250km of strike slip motion has been recorded on these faults, which is interpreted to be associated with the final collision of Laurentia and Gondwana and assembly of Pangea between 430 and 320 Ma (Waldron *et al*., 2015; Gibling *et al*., 2019).

Most individual depocentres in the Maritimes Basin have similar stratigraphic elements, reflecting basin-wide events and enabling basin-scale stratigraphic correlations (Waldron *et al.,* 2017; Fig. 2).

These stratigraphic units are described briefly here [for details refer to Gibling *et al*. (2019)]. Late Devonian volcanic rocks are present at the base of several depocentres, and are overlain by late Devonian to early Carboniferous mainly lacustrine clastic rocks of the Horton and Anguille groups.

The Windsor Group (Codroy Group in Newfoundland) reflects a change to sustained open-marine deposition and comprises a succession of limestone, evaporite, and clastic rocks. These are in turn overlain by late Carboniferous to early Permian clastic rocks of the Mabou, Cumberland, and Pictou groups.
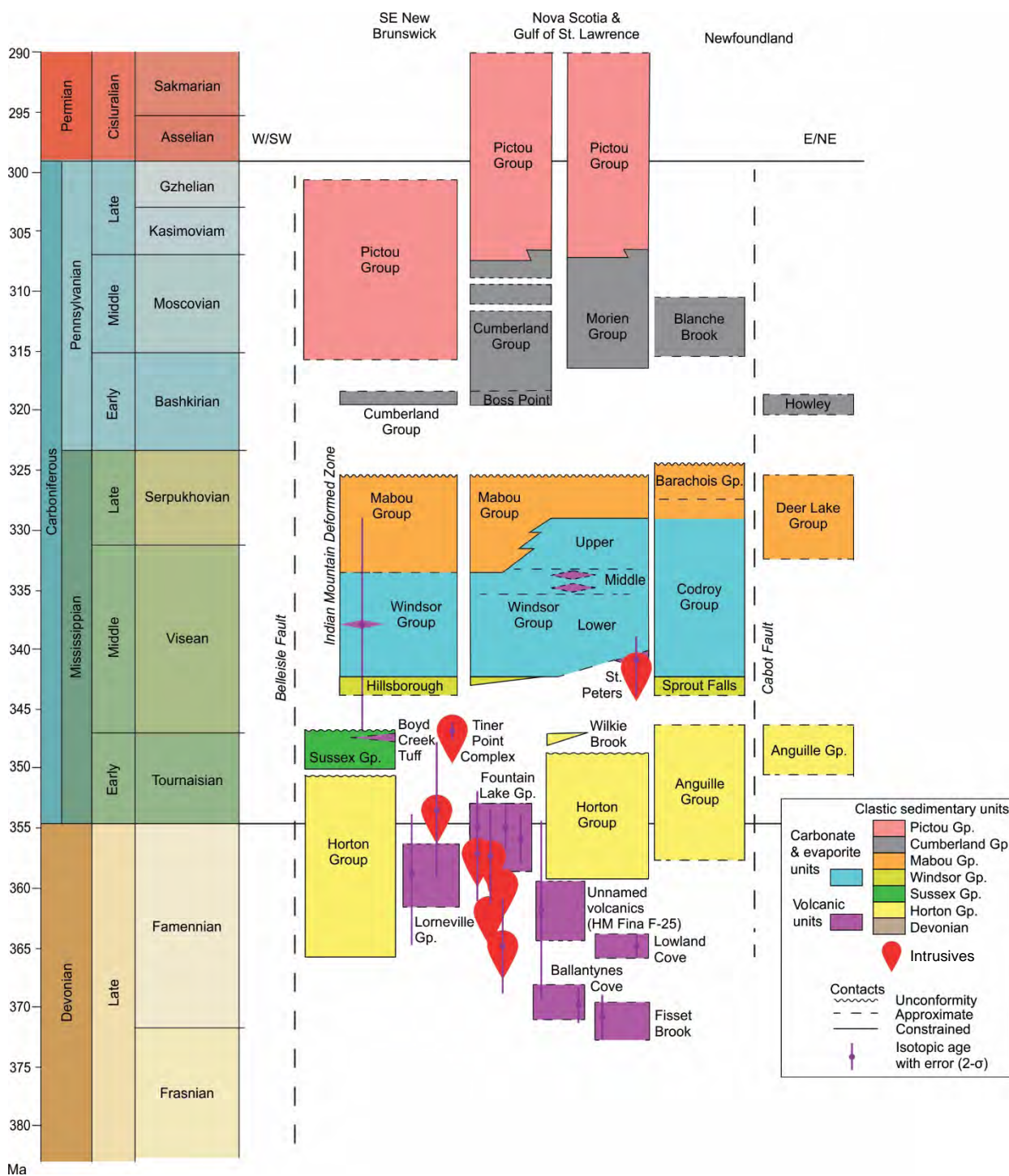
Figure 2: *Simplified group-level stratigraphy of the Maritimes Basin in SW New Brunswick, Nova Scotia and Newfoundland (modified from Waldron et al., 2015 and Gibling et al., 2019). Geological timescale from Walker et al. (2018).*

Windsor group

The Mississippian (Viséan) Windsor Group (and the equivalent Codroy Group in Newfoundland; Snyder & Waldron, 2021) represents the only significant marine incursion in the Maritimes basin (Gibling *et al.,* 2019). The stratigraphy of the Windsor Group is complicated by the plethora of formation names used in individual depocentres, but broad correlations can be made across the basin (Waldron *et al.,* 2017; Snyder &

Waldron, 2021). In Nova Scotia, the basal unit of the Windsor Group is laminated limestone of the Macumber Formation (Boehner, 1984), which laterally transitions and thickens to biohermal mounds on local palaeotopographic highs (e.g., Meguma Supergroup rocks) where it is referred to as the Gays River Formation (Giles *et al*., 1979; Boehner *et al.,* 1989; Thomas *et al.,* 2002). Basal Windsor Group carbonate strata are generally overlain by a thick succession of interlayered evaporitic, clastic, and carbonate rocks, including the Carrolls

Corner (evaporite), Meaghers Grant (sandstone and sandy shale), and Stewiacke (evaporite) formations (Waldron *et al.*, 2017). In Newfoundland, basal limestone of the Ship Cove Formation and limestone conglomerate and bryozoan-microbial mounds of the Big Cove Formation are equivalent to the Macumber and Gays River formations, respectively, and the overlying clastic and evaporitic units of the Codroy Road and Robinsons River formations are equivalent to similar strata in Nova Scotia (Knight, 1983; Snyder & Waldron, 2021).

Deposit descriptions

Numerous sedimentary-rock hosted Zn-Pb-Ba deposits are present in the basal Windsor Group across the Maritimes Basin, with more than 150 occurrences in Nova Scotia, Newfoundland and New Brunswick (Graves and Hein, 1994). Major deposits include the past-producing Scotia (formerly Gays River) and Walton mines in Nova Scotia, as well the Jubilee deposit on Cape Breton Island, and the Port au Port occurrences in western Newfoundland (Fig. 1). These have been the subject of significant previous work, including detailed geological and geochemical studies (e.g., Chi et al., 1998; Dix & Edwards, 1996; Fallara *et al.*, 1998; Kontak, 1992, 1998; Kontak & Sangster, 1998; Sangster *et al.,* 1998a, 1998b, 1998c; Savard & Kontak, 1998), and are the focus of this paper. The main geological features of mineralization at each deposit are summarized below.
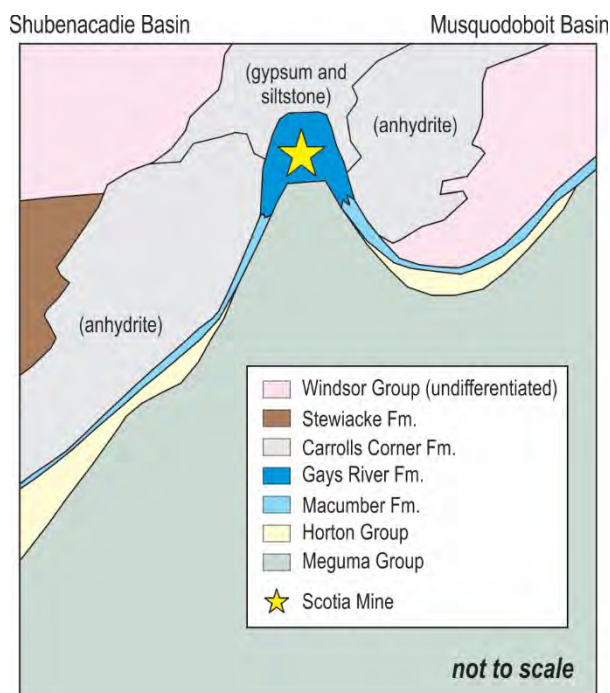

Figure 3: *Simplified local stratigraphy near the Scotia deposit, showing location of the deposit on a basement high between the Shubenacadaie and Musquodoboit basins (modified from Giles and Boehner, 1982).*

Scotia Deposit

The Scotia deposit is on a northeast-trending basement high between the Shubenacadie and Musquodoboit sub-basins of southern Nova Scotia (Fig. 3). The mine was active

intermittently from 1979 to 2007, with current NI 43-101 proven and probable reserves of 13.7 Mt of 2.03% Zn and 1.10% Pb (Hannon, 2021). The basement high consists of greenschist-facies metasandstones (i.e., turbidites) of the Meguma Supergroup, upon which carbonate mounds and inter-mound facies of the Gays River Formation developed (Lavoie & Sami, 1998; Fig. 5A, B). The mounds consist of basal coarse siliciclastics overlain by various boundstone facies (Fig. 5C), with skeletal grainstone occupying framework voids; peloidal and bioclastic wackestone make up the intermound facies (Lavoie & Sami, 1998). A basal breccia unit consists of fragments of Meguma Supergroup metasedimentary rocks cemented by dolomite. The Gays River Formation grades laterally into laminated limestone of the Macumber Formation (Lavoie and Sami, 1998) and is overlain by evaporite rocks (anhydrite, gypsum) of the Carrolls Corner Formation (Kontak, 1998; Figs. 3, 5B). Both the Gays River and Macumber formations around the Scotia deposit record extensive marine dolomitization prior to mineralization (Savard, 1996).

Massive and disseminated mineralization is hosted by carbonates of the Gays River Formation, with some mineralization also extending downwards into the basal breccia unit (Kontak, 1992, 1998). The massive ore (Fig. 5D, E, F) is composed of finely crystalline (≤10-20 μm) beige sphalerite and mm- to cm-sized galena, which is restricted to the proximal carbonate-evaporite contact (Kontak, 1992, 1998). The disseminated ore occupies primary porosity in the dolomitized carbonates and consists of millimetric yellow to orange euhedral sphalerite and millimetric to centimetric euhedral galena (Kontak, 1992, 1998). Mineral paragenesis indicates early dolomitization of the host carbonates, followed by precipitation of euhedral manganiferous dolomite cements, burial diagenetic phases, and sphalerite and galena accompanied by trace Fe sulphides (Savard, 1995; Kontak, 1998). The remaining porosity was then occluded by late calcite (minor fluorite, barite, and quartz), and evidence of late-stage hydrocarbon migration is preserved as liquid petroleum inclusions in post-mineralization calcite and fluorite (Kontak, 1992, 1998). The timing of fluid movement, and thus indirectly mineralisation, has been determined using paleomagnetic evidence (300-330 Ma; Pan *et al.*, 1993) and K-Ar (345-359 Ma; Ravenhurst *et al.*, 1989) and Ar-Ar (≤330 Ma, Ravenhurst *et al.,* 1987; ca. 300 Ma, Kontak *et al.,* 1994) methods. The K-Ar age range indicates some contamination by detrital components (Ravenhurst *et al.,* 1989).

Walton Deposit

The Walton Pb-Zn-Cu-Ag-Ba deposit is in the Kennetcook sub-basin of southern Nova Scotia. Between 1941 and 1978 it produced approximately 4.5 Mt of >90% barite and 412,853 t of sulphide ore with 4.28% Pb, 1.29% Zn, 0.52% Cu and 348 g/t Ag (Cranstone, 1982; Patterson, 1987). Mineralization is hosted primarily by the Macumber Formation, which conformably overlies Horton Group sandstone (Fig. 4; Sangster *et al.*, 1998b). In the Walton area, the Macumber Formation is subdivided into a lower 9-12m thick laminated limestone and an upper carbonate breccia mound forming two bodies up to 21m thick (Sangster *et al.*, 1998b). Lavoie *et al.* (1998) recognized three breccia generations in the Macumber Formation at Walton: early synsedimentary brecciation, later tectonic brecciation, and karstic brecciation that postdates mineralization. The
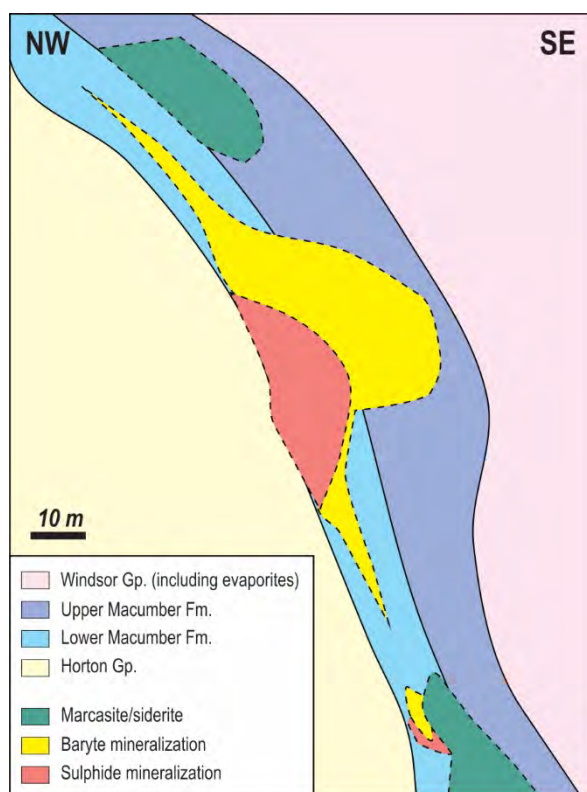
Figure 4: *Diagrammatic representative cross-section through a distal part of the Walton deposit (after Sangster et al., 1998a, 1998b).*

Macumber Formation in and around the Walton deposit was extensively sideritized by marine fluids (Fig. 6A, B; Savard *et al.,* 1998). It is overlain by dense, finely crystalline grey anhydrite of the White Quarry Formation (Sangster *et al.,* 1998b).

Mineralization is expressed as massive replacement of intensely sideritized carbonate rocks in the Macumber Formation (Fig. 6C, D, E), and to a lesser extent in the underlying Horton Group sandstone (Sangster *et al.,* 1998b). The deposit is located in a fault-bounded fold and consists of a sulphide body (Pb-Zn-Cu-Ag; Fig. 6F, G) overlain by a barium sulphate body (Fig. 4; Burtt, 1995; Sangster *et al.,* 1998b). Barite mineralization was relatively early, followed by main-stage sulphide mineralization (pyrite/marcasite-sphalerite-galena-chalcopyrite-rammelsbergite) and a secondary mineralization phase consisting of siderite, barite, tennantite, and chalcopyrite (Burtt, 1995; Sangster *et al.,* 1998b). The sulphide ore is subdivided into two types based on barite and metal contents (Burtt, 1995; Sangster *et al.,* 1998b). Type I ore forms concordant barite-rich ore with Pb- and Cu-rich lenses and is primarily located along the contact between the upper and lower Macumber Formation. Type II ore contains no barite, and forms sulphide-rich pods primarily in the thickest parts of the upper Macumber Formation mounds, but also extending into the underlying Horton Group sandstone (Burtt, 1995; Sangster *et al.,* 1998b). There are many intriguing features of the deposit needing further investigation and explanation in the context of the origin of the deposit, which includes textures in the massive sulphide ore suggestive of zone refining (Fig. 6G), the presence of pyrite framboids

(Fig. 6H), and the presence of liquid petroleum (Fig.6I) through the paragenesis (Kontak & Sangster, 1998).

The timing of mineralization at Walton is poorly constrained but may have predated deformation and karstic brecciation of the Macumber Formation; this would place the age of mineralization between 330 and 307Ma (Lavoie *et al.,* 1998; Sangster *et al.,* 1998a, 1998b).

Jubilee Deposit

The Jubilee Zn-Pb deposit is located in the River Denys sub-basin on Cape Breton Island (Nova Scotia), and the most recent exploration has defined an inferred NI 43-101 mineral resource of 3.1 Mt containing 3.81% Zn and 0.89% Pb (Webster, 2009). The deposit is hosted in Macumber Formation limestone, which overlies Horton Group conglomerate (Hein *et al.,* 1993; Fallara *et al.,* 1998). The Macumber Formation at the Jubilee deposit has been subdivided into three lithofacies (Fallara *et al.,* 1998). A lower micritic limestone (~10m) grades upward into laminated limestone (2-15m thick). An upper mineralized breccia is subdivided into an early, synsedimentary matrix breccia and a later, tectonic breccia with angular fragments of stromatolitic limestone (Fallara *et al.,* 1998). The Macumber Formation is overlain by evaporites (anhydrite and gypsum) of the Carrolls Corner Formation. The Jubilee deposit is bounded by two northwest-trending subvertical faults (Fig. 7) and is below a major unconformity that removed the overlying upper and middle Windsor Group strata (Fallara *et al.,* 1998). This unconformity is associated with a regionally extensive flat-lying structural feature at the top of the Macumber Formation on Cape Breton Island which Lynch & Giles (1996) attributed to extensional tectonics, but which more recent studies suggest may relate to evaporite withdrawal (possible evaporite weld; Waldron *et al.,* 2015). Regardless of the breccia's origin, this unit controls ore distribution (Fallara *et al.,* 1998).

Mineralization is confined to a tectono-hydraulic breccia in the Macumber Formation, with Zn-Pb mineralization concentrated around subvertical normal faults (Fallara *et al.,* 1998; Fig. 7). Hydrocarbon fluid inclusions and abundant bitumen staining indicate that hydrocarbon migration began after this brecciation but predated mineralization (Hein *et al.,* 1993; Fallara *et al.,* 1998; Rogers & Savard, 2002). The main mineralization phase consists of early pyrite-marcasite followed by sphalerite and galena (trace chalcopyrite) (Fallara *et al.,* 1998). This was followed by post-mineralization calcite and sulphates, with hydrocarbon migration continuing through the entire mineralization and post-mineralization processes (Fallara *et al.,* 1998). Although there are no direct age constraints for Jubilee mineralization, it postdates extension related to the Ainslie Detachment during the Westphalian (~330 Ma; Fallara *et al.,* 1998).

Port au Port Peninsula occurrences

The Port au Port Peninsula, western Newfoundland is located on the northern margin of the Bay St. George sub-basin. Stratabound mineralization is present in limestone and limestone breccia of the Mississippian Big Cove Formation (Codroy Group), and vein-hosted mineralization is present in underlying Ordovician carbonate rocks (Saunders *et al.,* 1992). The Big Cove Formation unconformably overlies the Ordovician
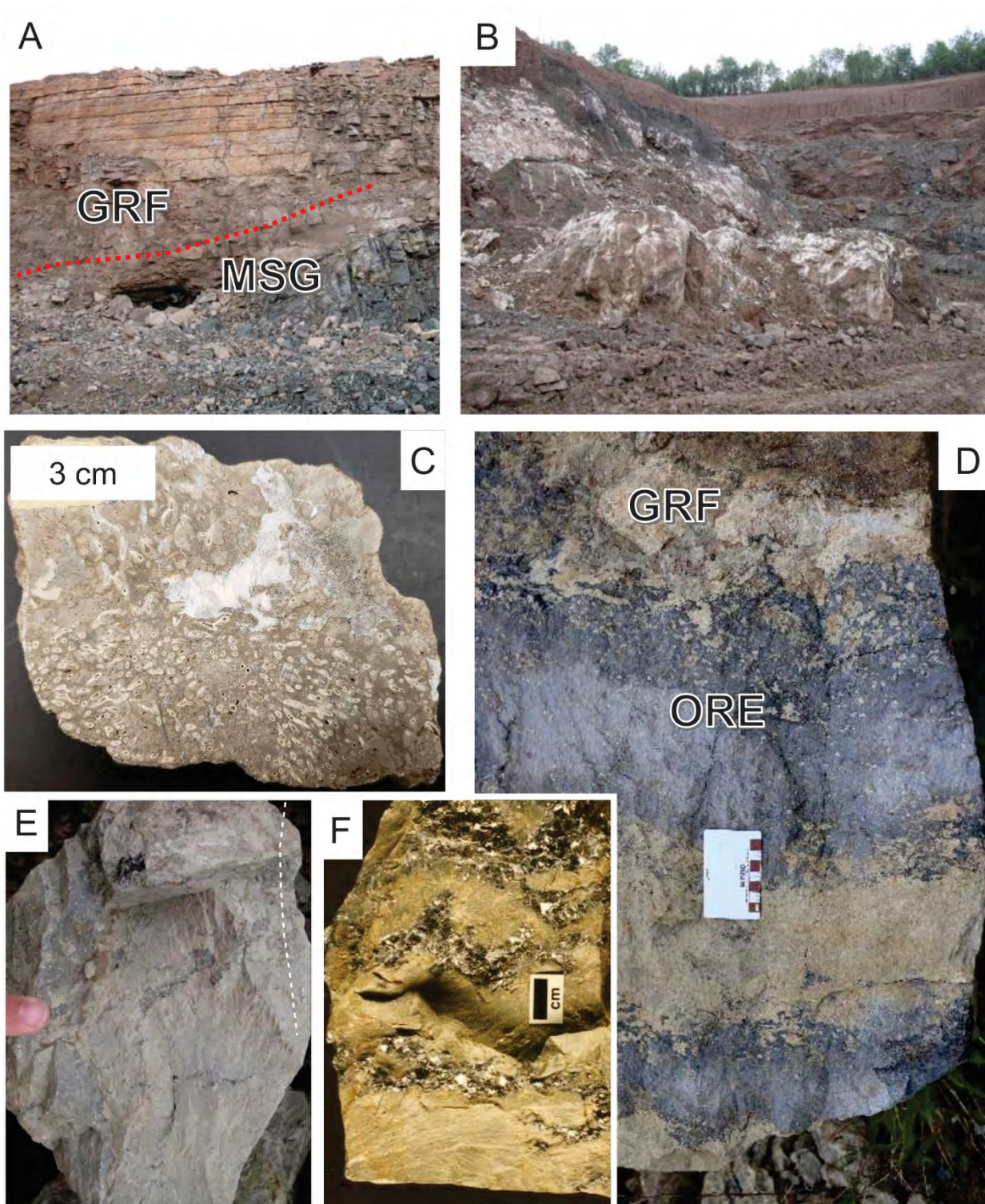
Figure 5: Representative images from the Scotia deposit. A). Open pit exposure showing the Gays River Formation (GRF) on top of a palaeo-topographic high of Meguma Supergroup (MSG) metasandstone basement rocks. B). Open pit exposure showing evaporates (i.e., anhydrite) of the Carrolls Corner Formation, the putative source of S for the sulphide ore. C). The barren host rock to the ore. Note the abundance of calcite (white) lining primary porosity in the now dolomitized boundstone unit. D). Large boulder showing the high-grade ore zone of massive ore consisting of fine-grained beige sphalerite and massive galena (grey) in contact with the GRF. E). Boulder of massive fine-grained beige sphalerite ore. F). Hand sample of the massive high-grade ore showing fine-grained sphalerite cut by coarser galena.
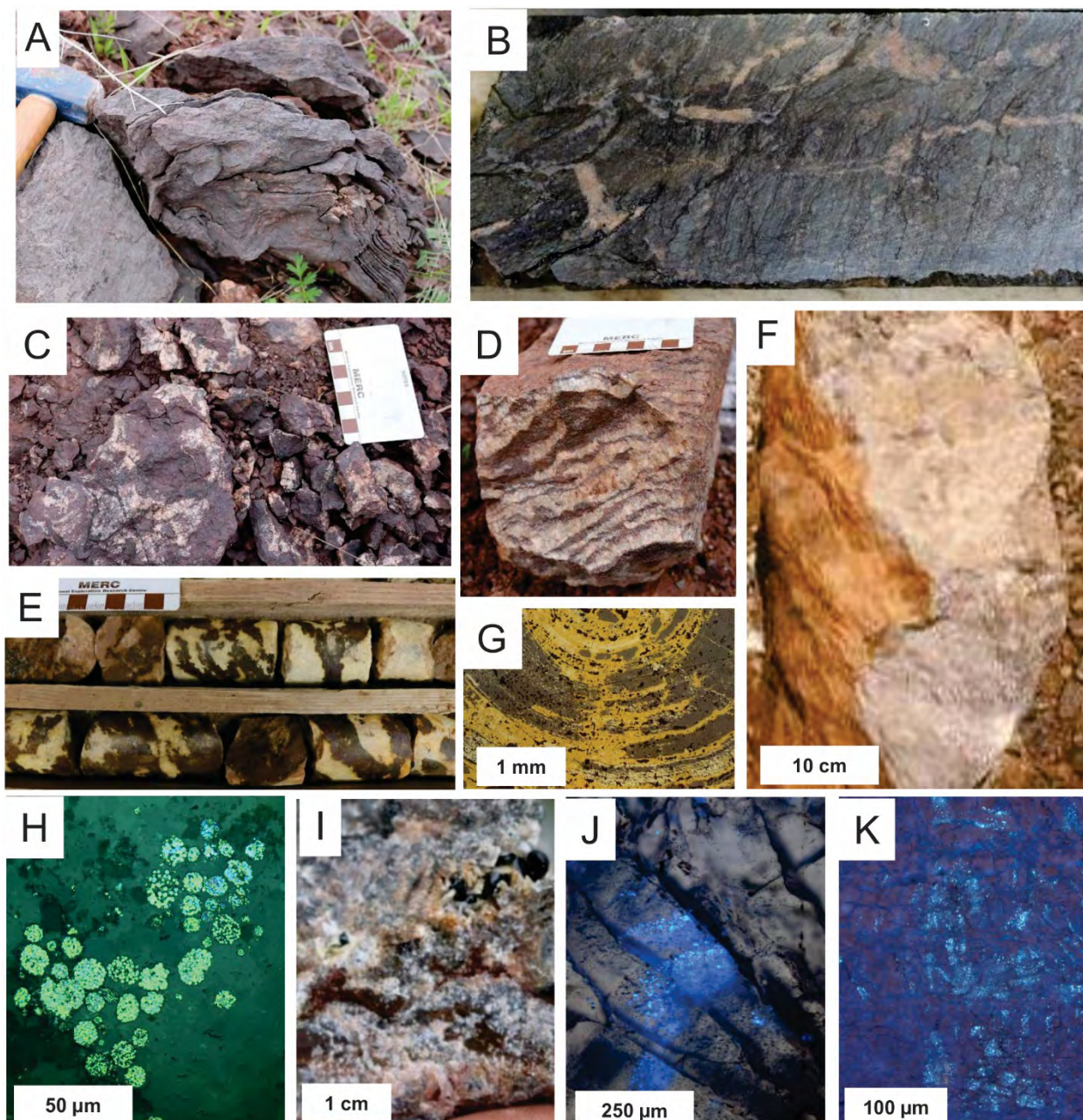
Figure 6: *Representative photos and photomicrographs from the Walton deposits. Note the outcrop photos were observed at the base of the former open pit (i.e., water level) in May of 2022. The scale card in C, D and E is in cm.*

A, B). *Black laminated sideritized Macumber Formation (MF) micritic lime mudstone seen in outcrop (A) in the open pit and in drill core (B); note the latter sample is cut by barite.* ***C).*** *Massive black sideritized MF rock cut by barite.* ***D).*** *Zebra-textured black sideritized MF alternating with barite.* ***E).*** *Barite cutting black sideritized MF rock as seen in drill core.* ***F).*** *Boulder of massive Pb-Zn sulphide ore.* ***G).*** *Reflected light image of massive sulphide ore showing chalcopyrite (yellow) replacing sphalerite (grey).* ***H).*** *Hand sample of sideritized MF rock with cavity lined by euhedral barite that is coated with petroleum (upper right part).* ***I).*** *Pyrite framboids* ***J, K).*** *Inclusions of liquid petroleum hosted in barite showing fluorescence (image taken under UV).*
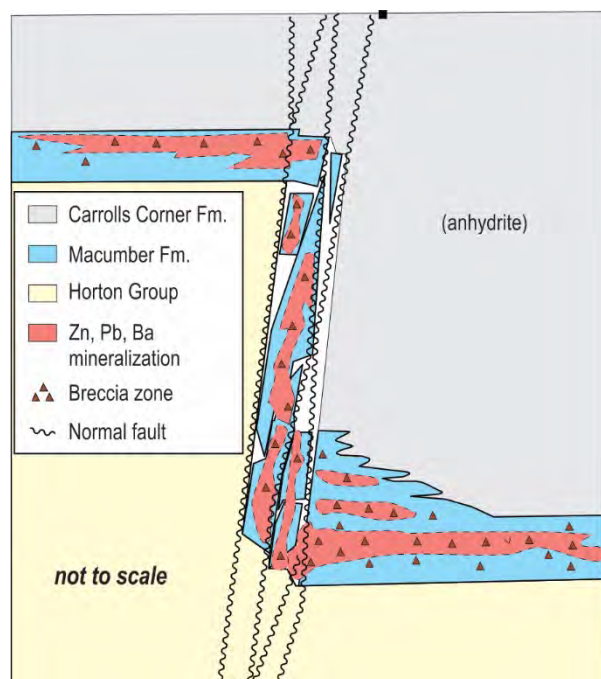
Figure 7: *Cross-section through the Jubilee deposit, showing location of orebody in tectono-hydrothermal breccia around subvertical normal faults (modified from Webster, 2009).*

carbonates of the Table Head and St. George groups and is located in karstic palaeovalleys that formed in the Ordovician carbonates in the late Devonian to early Mississippian (Dix and James, 1989). The Big Cove Formation is composed of carbonate buildups, interbedded siliciclastic rocks, and limestone conglomerate, and grades laterally into laminated limestone of the Ship Cove Formation, which are overlain by massive gypsite of the Codroy Road Formation (Fig. 8A; Dix & James, 1989). The palaeovalleys are bounded on one or both sides by northeast- trending normal faults, which form grabens and are associated with brecciation and fracturing of the host limestone (Fig. 8B; Dix, 1982; Dix & Edwards, 1996).

Stratabound Pb-Zn mineralization is hosted in brecciated Big Cove Formation carbonate strata, with galena, sphalerite, marcasite, pyrite, calcite, and barite forming veins, surrounding limestone fragments, and replacing micritic breccia matrix (Fig. 8C, D; Saunders *et al.*, 1992). Mineralization postdates brecciation and early precipitation of diagenetic calcite-Fe-oxide and has a general paragenetic sequence of marcasite-calcite precipitation with early sulphide (galena-sphalerite) and later sulphate (barite-celestite) mineralization (Saunders *et al.*, 1992; Dix & Edwards, 1996). Vein-hosted mineralization in the underlying Ordovician carbonates consists of zoned calcite-marcasite-galena-sphalerite veins, which are interpreted to record fault-controlled fluid movement during the Mississippian and may be feeders to overlying stratabound mineralization (Dix & Edwards, 1996).

The exact timing of mineralization on the Port au Port Peninsula is unknown, but Dix & Edwards (1996) considered it to have been epigenetic and to have formed under shallow burial

conditions (< 30 m) shortly after deposition of the Big Cove Formation.

Fluid inclusion studies

Scotia Deposit

A number of fluid inclusion studies have been completed on the Scotia deposit, targeting pre-, syn- and post-mineralization minerals (Eaton, 1980; Akande, 1982; Ravenhurst *et al.*, 1987; Ravenhurst *et al.*, 1989; Chi & Savard, 1995; Chi *et al.*, 1998; Kontak, 1998). Fluid inclusions in pre-ore dolomite are characterized by high salinities (~24 wt% eq. NaCl) and homogenization temperatures of 107 to 147°C (Chi & Savard, 1995). Fluid inclusions in ore-stage sphalerite and calcite indicate that mineralization was associated with an influx of higher-temperature (up to 250°C, but most data < 200°C), high-salinity (> 27 wt% eq. NaCl) fluids, which mixed with lower-temperature fluids (i.e., the fluid that dolomitized the carbonates and saturated their pores before mineralization; Chi & Savard, 1995; Kontak, 1998). This was followed by a late, post-mineralization influx of lower-salinity (<20 wt% eq. NaCl eq.) and -temperature (Th <90°C) fluid, which is recorded in post-mineralization calcite, fluorite, and quartz (Chi and Savard, 1995; Kontak, 1998). Bulk crush gas chromatography indicates that inclusion fluids contain up to 1.4 mole % combined CO_2 and CH_4, with the most abundant condensable gases in sphalerite and galena (Kontak, 1998; Chi *et al.*, 1998). Combined with the variability of the NaCl/(NaCl+CaCl$_2$) ratio of the fluids, Kontak (1998) suggested that this represented contamination by dissolution of the host dolostone.

Chi & Savard (1995) and Kontak (1998) documented hydrocarbon fluid inclusions in post-mineralization calcite and fluorite, which may represent migration of liquid hydrocarbons and methane after mineralization (Kontak, 1998; Savard & Kontak, 1998). The pressure of the mineralizing environment is constrained at ~400 bars by the presence of liquid petroleum, aqueous and methane inclusions, and their respective isochoric projections. The relatively high temperature for mineralizing fluids (> 200°C) was interpreted to represent the upward migration of fluids along faults at the margins of a large stable craton in an area that was structurally active during the Mississippian, and within which widespread thermal disturbances are known (Kontak, 1998).

Walton Deposit

Barite, the earliest mineralization phase at Walton, contains three fluid inclusion types (Kontak & Sangster, 1998): aqueous inclusions (liquid- and vapour-rich), hydrocarbon inclusions (liquid petroleum) and rare CO_2-CH_4 inclusions. The presence of three-phase aqueous-petroleum inclusions (Fig. 6J, K), and the close spatial association among inclusion types, indicate contemporaneous trapping of these fluids during the early stages of mineralization (Kontak & Sangster, 1998). Aqueous inclusions are predominantly high salinity (20-28 wt% eq. NaCl), with highly variable NaCl/(NaCl+CaCl$_2$) ratios (0.1 to 1). Both aqueous and liquid petroleum inclusions have a wide range of homogenization temperatures (70 to 320°C). However, variations among individual inclusions in a single fluid inclusion assemblage (FIA) is much less (≤2 to 40°C) and
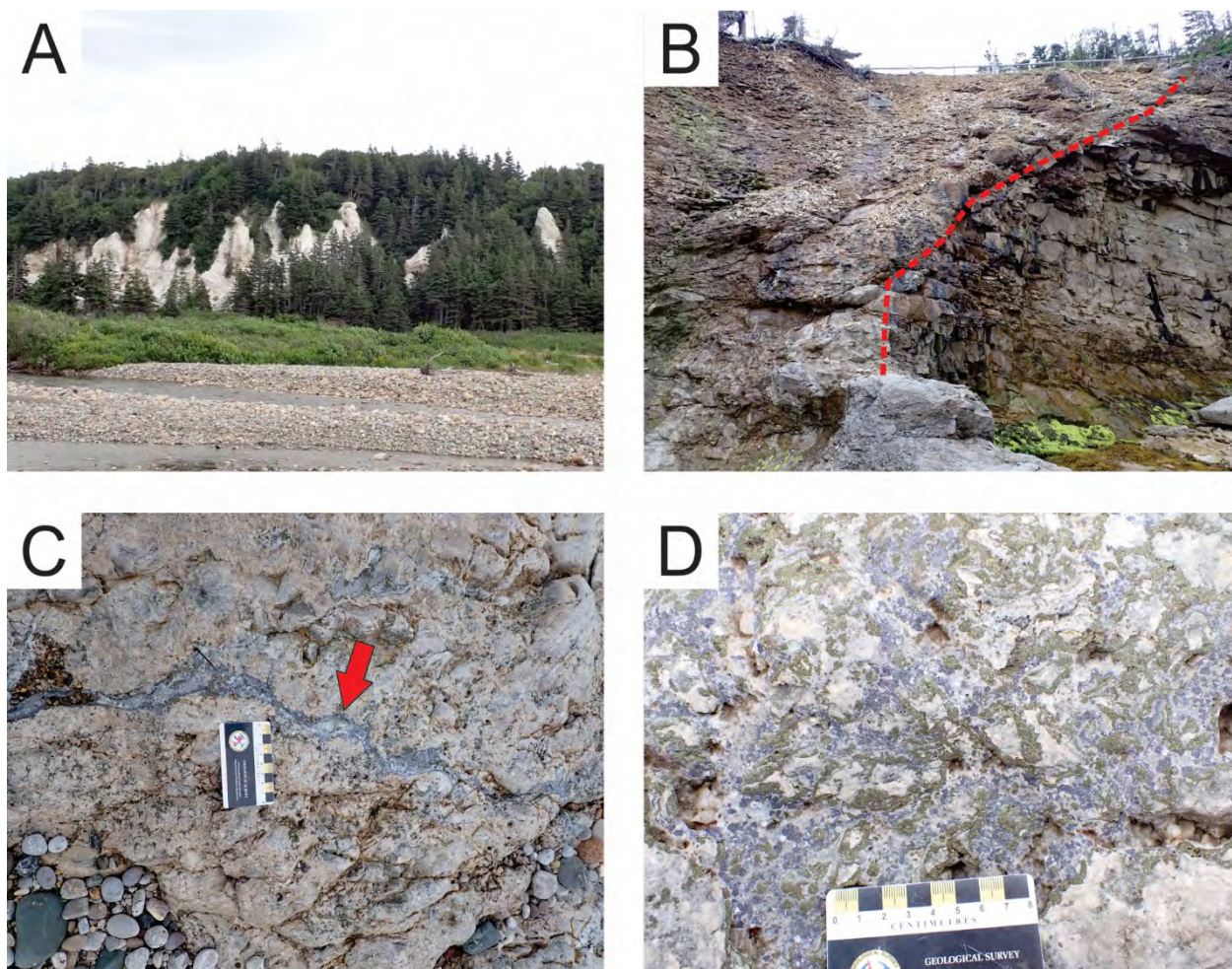
Figure 8: *Representative photos of mineralization on the Port au Port Peninsula (Newfoundland). **A**). Thick succession of gypsite at Romaines Brook, interpreted to overlie mineralization. **B).** Faulted contact between brecciated Viséan limestone of the Big Cove Formation (weakly mineralized; left) and flat-lying Ordovician limestone (right). **C**). Vein of galena and marcasite cross-cutting brecciated Big Cove Formation. **D**). Galena and marcasite mineralization.*

therefore the higher temperatures represent high ambient temperatures rather than post-entrapment effects (e.g., leaking, stretching; Kontak & Sangster, 1998). The high homogenization temperatures and preservation of abundant petroleum inclusions indicates rapid cooling during mineralization, with petroleum generation during interaction of high-temperature metalliferous fluids with organic-rich sediment in the underlying Horton Group (Kontak & Sangster, 1998).

Jubilee Deposit

Chi *et al*. (1995) studied fluid inclusions in pre-mineralization fibrous calcite, ore-stage sphalerite, and syn- to post-mineralization anhedral calcite from the Jubilee Deposit. They identified abundant primary and pseudosecondary aqueous and hydrocarbon fluid inclusions in all minerals. Aqueous fluid inclusions in all minerals have a wide range of homogenization temperatures and salinities. However, overprinting by later secondary FIA makes interpretation of the fluid inclusion data difficult (Chi *et al*., 1995). Fibrous calcite, primary aqueous inclusions have high salinities (21 to 27 wt% eq. $NaCl + CaCl_2$) and low homogenization temperatures (53 to 79°C), and

hydrocarbon fluid inclusions have homogenization temperatures of 34 to 89°C. Chi *et al*. (1995) interpreted this evidence to record pre-mineralization migration of hydrocarbons into a reservoir saturated with brine, causing calcite to precipitate and creating a reservoir of reduced sulphur. Rogers and Savard (2002) showed that the hydrocarbons were probably sourced from lacustrine units of the underlying Horton Group. Aqueous fluid inclusions in ore-stage sphalerite and syn- to post-mineralization anhedral calcite record the influx of moderate- to high-temperature (up to 230°C) and -salinity (~ 24 wt% eq. $NaCl + CaCl_2$) metalliferous brine that mixed with pre-existing aqueous and hydrocarbon fluids and precipitated sulphides at shallow crustal depths (< 1500 m; Chi *et al*., 1995). This was followed by a late influx of low-temperature (70-90°C), moderate-salinity (13-14 wt% eq. $NaCl + CaCl_2$) brine that dominated the post-mineralization hydrothermal system (Chi *et al*., 1995).

Chi *et al.* (1998) reported on the chemical composition of fluid inclusions (cation and gaseous content) from the Jubilee Deposit and compared this with data from the Scotia and Walton deposits. These data show that fluids associated with

mineralization in the Jubilee deposit have distinctive compositions when compared other base metal deposits in Nova Scotia, with lower NaCl/ (NaCl + CaCl$_2$) (<0.6 vs. > 0.4) and CH$_4$/higher hydrocarbon (0.7-1.4 vs. 3.8-9.7) ratios. This is interpreted to represent different fluid sources for the hot metalliferous brines associated with mineralization in individual sub-basins (Chi *et al.*, 1998).

Port au Port Peninsula occurrences

Limited fluid inclusion data from Zn-Pb occurrences on the Port au Port peninsula were reported by von Bitter *et al.* (1990) and Dix & Edwards (1996). Data are reported for calcite-hosted inclusions associated with the pre- and syn-mineralization phases, but detailed petrographic information is not available for these fluid inclusions (e.g., evidence of post-entrapment modification; fluid inclusion paragenesis). Only aqueous fluid inclusions have been recorded, with high salinities (16-25 wt% eq. NaCl) and a wide range of homogenization temperatures (60 to 170°C), with higher temperatures associated with the main mineralization event (Dix & Edwards, 1996). The increase in homogenization temperatures was interpreted to record the fault-controlled influx of relatively hot metalliferous fluid and mixing with lower-temperature connate fluid in the limestone breccia (Dix & Edwards, 1996).

Isotopic data

Carbon and oxygen isotope data from carbonates

Carbon and oxygen isotope data from carbonates from Zn-Pb occurrences in the Maritimes Basin have been used to constrain fluid processes associated with ore formation (Akande & Zentilli, 1984; Ravenhurst *et al.,* 1987; Dix & Edwards, 1996; Fallara *et al.,* 1998; Savard & Kontak, 1998; Savard *et al.,* 1998).

At the Scotia deposit, carbon and oxygen isotope data for host dolostone and carbonates associated with pre-, syn- and post-mineralization stages have been reported (Akande & Zentilli, 1984; Ravenhurst *et al.*, 1987; Savard & Kontak, 1998). These data show that carbonates associated with all stages of mineralization are depleted in ^{13}C compared to the host carbonates (Fig. 9A). Calcite intergrown with sulphides is characterized by lower δ^{18}O values than pre- and post-ore carbonates (Fig. 9A), which is interpreted to reflect the higher temperature of mineralization in this stage as is recorded by fluid inclusion data (Savard & Kontak, 1998). Savard & Kontak (1998) interpreted C-O-Sr isotope data to represent a brine mixing model, consistent with fluid inclusion data (Kontak, 1998).

The only carbon and oxygen isotope data available for the Walton Deposit were presented by Savard *et al.* (1998), who reported δ^{18}O and δ^{13}C data from siderite, calcite, and dolomite from the host Macumber Formation. Extensive sideritization of host rocks surrounding the mineralized body at Walton was interpreted by Savard et al. (1998) to have occurred during burial diagenesis and was probably not related to sulphate or sulphide mineralization. The lack of data for the main sulphide ore event relates to the absence of such material during this part of the paragenesis.

Carbon and oxygen isotope data from the Jubilee deposit were

reported by Fallara *et al.* (1998) (Fig. 9B). Carbon isotope data show a significant decrease in δ^{13}C values in the pre-mineralization fibrous calcite (average -25‰) and syn- to post-mineralization anhedral calcite (average -15‰) compared to the least-altered host carbonates, with hydrothermal breccia samples showing a wide range of δ^{13}C values (Fig. 9B). The very low δ^{13}C values were interpreted to reflect oxidation of hydrocarbons during the pre-mineralization phase, which is consistent with low δ^{13}C values reported from carbon isotope anal-
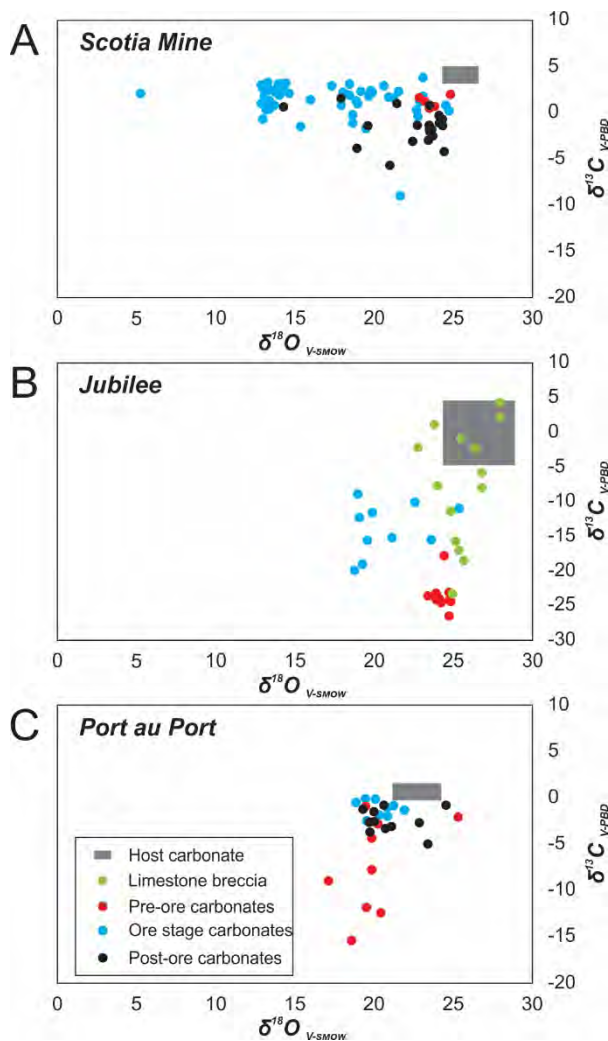

Figure 9: Carbon and oxygen isotope composition of carbonates from Scotia, Jubilee, and Port au Port Zn-Pb mineralization. Shaded field represents data from unaltered host-rock carbonates in vicinity of the mineral occurrence. Data from Akande and Zentilli (1984); Dix and Edwards (1996); Fallara et al. (1998); and Savard and Kontak (1998).

ysis of hydrocarbon fluid inclusions at Jubilee (-30.1 to -30.8‰; Rogers and Savard, 2002). The subsequent increase in ^{13}C during the mineralization phase was due to buffering of carbon isotopes by the host carbonates (Fallara *et al.,* 1998; Rogers & Savard, 2002). The decrease in δ^{18}O values associated with the main mineralization phase was probably associated with an influx of higher-temperature metalliferous fluid (Fallara *et al.,* 1998), but not to the same extent as at Scotia.

Dix & Edwards (1996) reported carbon and oxygen isotope data from Zn-Pb occurrences on the Port au Port peninsula (Fig. 9C). Early diagenetic carbonates are characterized by a relatively narrow range of $\delta^{13}C$ and $\delta^{18}O$ values of 21.3 to 24.2‰ and -6.5 to -9.2‰ respectively. Early hydrothermal calcite cement, which predates the main phase of sulphide mineralization, displays a shift to more negative $\delta^{13}C$ values (-0.9 to -15.4‰; Fig. 9C). This reflects the contribution of another carbon source, probably due to oxidation of organic matter. Calcite associated with sulphide precipitation has higher $\delta^{13}C$ values than pre-mineralization calcite (-0.1 to -2.5‰), consistent with buffering of mineralizing fluids by the host carbonates. The $\delta^{18}O$ values of pre- and syn-mineralization calcite are very similar (17.1 to 25.3‰ and 18.9 to 21.9‰ respectively), and slightly more negative than those of early diagenetic calcite (Fig. 9C), which probably reflects the higher temperature of precipitation of these carbonates.

Sulphur isotopes

Genetic models for the formation of sedimentary-rock-hosted Zn-Pb deposits show that they most commonly derive their sulphide through either bacteriogenic sulphate reduction (BSR) or thermochemical sulphate reduction (TSR) of sulphate or sulphate-bearing brines (e.g., Wilkinson, 2014). BSR typically occurs during diagenesis at low temperatures (<80°C). Microbial activity ceases at temperatures higher than this (Machel, 2001), although some suggest BSR may be active at higher temperatures (see recent discussion in Mathieu *et al*., 2022). In contrast, TSR occurs at temperatures above 100°C through a kinetically controlled process in which temperature and availability of reduced sulphur are critical in determining reaction rates (Goldhaber & Orr, 1995; Machel, 2001; Meshoulam *et al.,* 2016). Because both BSR and TSR have similar by-products (Machel, 2001), sulphur isotope data, combined with independent geothermometers (e.g., fluid inclusion data) is commonly used as a criterion to distinguish between these two processes. BSR is characterized by substantial fractionation of ^{34}S between sulphate and sulphide (up to 75‰; Sim et al., 2011), resulting in sulphides that generally have strongly negative $\delta^{34}S$ values. In contrast, TSR is associated with much less significant fractionation between sulphate and sulphide (< 12.4‰), and there may be no S isotope fractionation between the generated sulphide and source sulphate if the reaction rate is sufficiently rapid (Meshoulam *et al.,* 2016). Given the positive $\delta^{34}S$ of seawater sulphate during the Phanerozoic (~10-40‰; Present *et al.,* 2020), sulphides derived by TSR in sedimentary-rock-hosted Zn-Pb deposits should have positive $\delta^{34}S$ values.

Sulphur isotope data from primary sulphate minerals in evaporites of the Windsor Group show a relatively narrow range of $\delta^{34}S$ values (Fig. 10), with anhydrite $\delta^{34}S$ values of 14.4 to 15.6‰ and gypsum values between 14.6 and 17.4‰ (Boyle *et al*., 1976; Akande & Zentilli, 1984; Gibling *et al.,* 1989; Dix & Edwards, 1996). These values are typical of Viséan (~346.7 to 330.9 Ma) seawater sulphate (17.1 ± 3‰; Present *et al.*, 2020), consistent with the precipitation of these evaporites from seawater in an open-marine setting.

Sulphide minerals from the pre- and syn-mineralization stages at the Scotia deposit show very similar $\delta^{34}S$ values (Fig. 10):

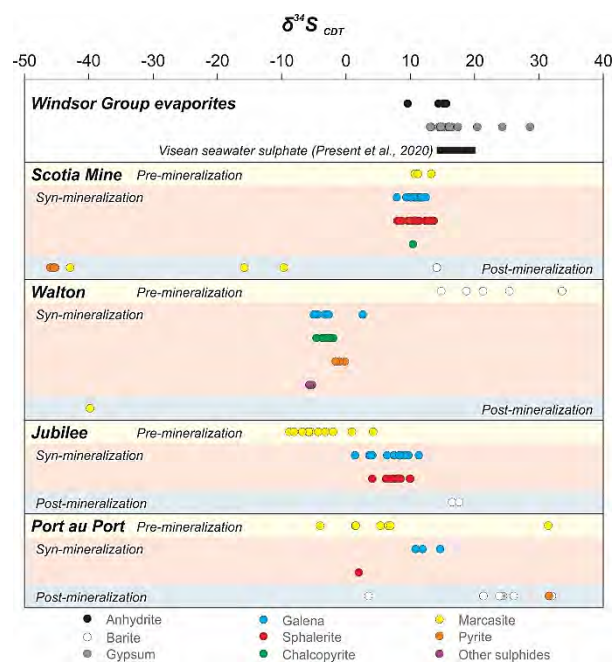***Figure 10:*** *Sulphur isotope data from sulphate and sulphide minerals in base-metal occurrences in the Maritimes Basin (from Boyle et al., 1976; Akande and Zentilli, 1984; Kontak, 1992; Dix and Edwards, 1996; Fallara, 1996). Regional data from sulphates in the Maritimes Basin (top) from Gibling et al. (1989), and average composition of Visean seawater sulphate from Present et al. (2020).*

pre-mineralization marcasite $\delta^{34}S$ values are 10.7 to 13.3‰, and ore-stage galena, sphalerite, and chalcopyrite $\delta^{34}S$ values are 7.9 to 13.7‰ (Akande & Zentilli, 1984; Kontak, 1992). Using average sphalerite and galena data (Kontak, 1992), the $\Delta_{sphalerite-galena}$ value yields a temperature of about 200°C. This agrees with the high temperatures of mineralization inferred from fluid inclusion data (generally >150°C) and is above the temperature feasible for BSR, and therefore TSR is the most likely process of sulphate reduction. These values also overlap with the range of values from sedimentary sulphates in the Winsor Group (Fig. 10). The lack of strong fractionation between sulphate and sulphide during TSR may be due to excess dissolved sulphate in the mineralizing system and rapid precipitation of sulphides (Meshoulam *et al*., 2016). Therefore, mineralization at Scotia probably occurred when a high-temperature, metalliferous brine encountered a large reservoir of reduced sulphate sourced from overlying evaporite units at the site of mineralization, and mineralization occurred rapidly via TSR. The strongly negative $\delta^{34}S$ values (between -9.2 and -46‰) in post-mineralization pyrite and marcasite are consistent with a later fluid event at a lower temperature (< 90°C based on fluid inclusion data), with BSR the dominant sulphate reduction process during this event (Akande & Zentilli, 1984; Sangster *et al.,* 1998a, 1998b) and are also consistent with the more negative $\delta^{13}C$ data (Fig. 10).

Boyle *et al*. (1976) reported sulphur isotope data for early barite mineralization and later sulphide mineralization at the Walton deposit. Barite is enriched in ^{34}S, with $\delta^{34}S$ values of 14.8
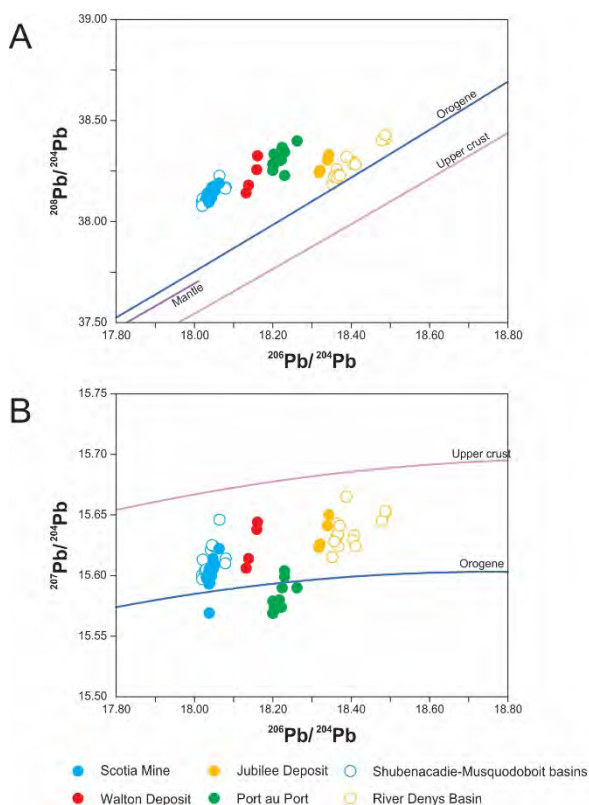
Figure 11: *Lead-isotope data showing values from galena in the Maritimes Basin. Closed circles represent data from mineral occurrences discussed in the text; open circles represent data from other minor occurrences (data from Akande, 1982; Akande and Zentilli, 1984; Swinden et al., 1988; Ravenhurst et al., 1989; Sangster and Vaillancourt, 1990; Dix and Edwards, 1996; and Sangster et al., 1998). Zartman and Doe (1981) model growth curves shown for reference.*

to 33.6‰, whereas sulphides are characterized by negative $\delta^{34}S$ values, mainly between -0.2 and -5.7‰ (Fig. 10). The light sulphur isotope content of sulphides and wide range of ^{34}S values between sulphates and sulphides cannot be accounted for via complete TSR of sulphate from the overlying evaporites. Although negative ^{34}S values might be explained by BSR, mineralization occurred at a temperature too high to support microbial activity (>> 100°C based on fluid inclusion data). An alternative source of isotopically light sulphur, as first suggested in Kontak & Sangster (1998), is that a pre-existing reservoir of sediment-derived, bacteriogenic reduced sulphur in the underlying Horton Group (i.e., Horton Bluff Formation; see Martell & Gibling, 1996) was released along with hydrocarbons during interaction of high-temperature, metalliferous fluids with organic-rich sediment (i.e., pyrolysis).

The sulphur isotope composition of pre-mineralization pyrite-marcasite, ore-stage galena and sphalerite, and post-mineralization barite at the Jubilee deposit was reported by Fallara (1996). Early pyrite and marcasite have a wide range of $\delta^{34}S$ values between -8.8 and 4.2‰, whereas galena and sphalerite range from 1.4 to 11.3‰ and 4.1 to 10‰, respectively (Fig.

10). The post-mineralization barite has the most positive $\delta^{34}S$ values, ranging from 16.5 to 17.6‰. A similar pattern is present in Zn-Pb occurrences on the Port au Port peninsula (Dix & Edwards, 1996), with a general increase in $\delta^{34}S$ values from pre-mineralization marcasite (-4 to +6.9‰) to ore-stage galena (10.8 to 14.6‰), and with post-mineralization barite strongly enriched in ^{34}S ($\delta^{34}S$ of 21.4 to 31.6‰). The negative $\delta^{34}S$ values in pre-mineralization sulphides are consistent with relatively early BSR (during hydrocarbon generation at the Jubilee Deposit), followed by TSR as the dominant process during the main phase of mineralization (Sangster *et al.*, 1998a).

Lead isotopes

Lead isotope data from galena is available for a number of Zn-Pb occurrences in Nova Scotia (Akande & Zentilli, 1984; Ravenhurst *et al.,* 1989; Sangster & Vaillancourt, 1990; Sangster *et al.,* 1998c) and Newfoundland (Swinden *et al.,* 1988; Dix & Edwards, 1996), including data from the Scotia, Walton, Jubilee, and Port au Port occurrences. When plotted on standard $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ diagrams, data from individual deposits define discrete, tightly spaced groupings (Fig. 11). The lead isotope signature of samples from the Scotia and Jubilee deposits also overlap with the data from other occurrences in the Shubenacadie-Musquodobait and River Denys sub-basins, respectively (Fig. 11). This indicates that the most likely source of lead was deeply circulating brines leaching metals from underlying basement rocks that include both metasandstone (e.g., Meguma Supergroup) and clastic rocks (e.g., Horton Group) in Nova Scotia and their equivalents in Newfoundland (e.g., Anguille Group and Ordovician carbonate rocks), with the homogeneous Pb isotope signature of galena reflecting a local lead source specific to each sub-basin (Swinden *et al*. 1988; Dix & Edwards, 1996; Sangster *et al.,* 1998c). Variability in the sedimentary provenance of the source rocks would have led to variable lead isotopic signatures in each sub-basin, with the more radiogenic signature of galena in the River Denys sub-basin related to exhumation and erosion of Devonian to Neoproterozoic igneous rocks of the adjacent Mira terrane (Sangster *et al.*, 1998c; Force & Barr, 2012).

Discussion

The general characteristics of the sedimentary-rock-hosted Zn-Pb deposits of the Maritimes Basin (Table 1) shows that they share a number of salient features. All are hosted by the lowermost formation of the Windsor Group (or lateral equivalents in Newfoundland), which were deposited during the Viséan (~346.7 to 330.9Ma) and, significantly, represent the only large-scale marine incursion in the Maritimes Basin (Gibling *et al.,* 2019). The carbonate rocks of the Macumber, Gays River, and Big Cove formations are in turn overlain by thick successions of evaporitic rocks (gypsum, anhydrite and halite). The restriction of base-metal occurrences to this relatively thin (< 5 to 60m; Gibling *et al.,* 2019) stratigraphic unit below a thick succession of evaporites, and thus near an accessible source of sulphur, indicates that this configuration has a first-order genetic control on the formation of Zn-Pb mineralization. There is also a strong structural control on the distribution of the studied deposits, which are all located on the margins of (extensional) sub-basins in the Maritimes Basin. They are also

	Scotia	*Walton*	*Jubilee*	*Port au Port*
Stratigraphy	Hosted in Gays River Formation carbonates (base of Windsor Group), overlain by anhydrite, gypsum	Hosted in Macumber Formation carbonates (base of Windsor Group), overlain by baryte orebody and anhydrite, gypsum	Hosted in Macumber Formation carbonates (base of Windsor Group), overlain by anhydrite, gypsum	Hosted in Big Cove Formation carbonates (base of Codroy Group), overlain by gypsum
Age of host rocks	Visean (~ 346.7-330.9 Ma)	Visean (~ 346.7-330.9 Ma)	Visean (~ 346.7-330.9 Ma)	Visean (~ 346.7-330.9 Ma)
Mineralization age	Epigenetic (~330-300 Ma)	Syngenetic or early epigenetic?	Epigenetic (< 330 Ma)	Epigenetic?
Metal association	Zn-Pb	Cu-Pb-Zn-Ag	Zn-Pb	Pb ± Zn, Cu
Structural setting	Carbonate bioherm on fault-controlled basement high	Located in hanging and footwall faults at nose of S-shaped fold	Horst bounded by NE-SW trending normal faults	Normal fault bounded graben structures
Ground preparation	Early dolomitization and brecciation	Early siderization and brecciation	Post burial tectono-hydraulic brecciation	Early brecciation
Mineralizing fluids	High-temperature (> 250°C) metal-bearing aqueous fluid mixing with lower-temperature pre-mineralization fluid	High temperature (> 300°C) metal-bearing aqueous fluids and contemporaneous hydrocarbon fluid	Moderate temperature (100-230°C) aqueous fluids mixing with low temperature aqueous and hydrocarbon fluids	Influx of moderate temperature (< 170°C) fluids and mixing with lower temperature connate fluids
Hydrocarbons	Late hydrocarbon migration, post-dating mineralization	Hydrocarbon fluids transported along with metalliferous aqueous fluid	Hydrocarbons generated prior to mineralization	n/a
Sulphur precipitation	TSR of Viséan seawater sulphate	TSR of isotopically light sulphur reservoir (negative δ^{34}S values)	TSR of Viséan seawater sulphate	TSR of Viséan seawater sulphate
Metal source	Clastic rocks of Horton Group (Shubenacadie-Musquodobait sub-basin)	Clastic rocks of Horton Group (Kennetcook sub-basin)	Clastic rocks of Horton Group (River Denys sub-basin)	Underlying Cambro-Ordovician basement rocks

Table 1: Summary of main geological characteristics of major sedimentary-rock-hosted Zn-Pb occurrences in the Maritimes Basin

associated with prominent normal or strike-slip faults (Akande & Zentilli, 1984; Dix & Edwards, 1996; Fallara *et al.,* 1998; Sangster *et al.,* 1998b), which would have provided a conduit for deeply circulating brines of basinal or other origin.

There is an important phase of pre-mineralization alteration and ground preparation in all of the deposits, which created or preserved significant porosity in the host rocks, producing a suitable environment for mineral precipitation (Sangster *et al.,* 1998a). Mineralization at the Scotia deposit and Port au Port Peninsula is hosted in large bioherms that have an estimated primary porosity of ~25% (Dix, 1981; Sangster e*t al.,* 1998a). Although the host dolostone at the Scotia deposit was pervasively dolomitized prior to mineralization, the primary porosity remained largely unchanged (Savard, 1996). This is unlike what is documented at other sedimentary-rock-hosted Zn-Pb deposits globally where the host rocks typically experienced an increase in porosity after dolomitization (e.g., Hitzman *et al.,* 1998; Shelton *et al.,* 2009). The Scotia deposit and Port au Port occurrences were also extensively brecciated prior to

mineralization, which would have further enhanced permeability and facilitated the migration of mineralizing fluids.

The Walton and Jubilee deposits are hosted in the Macumber Formation, which is characterized by a much lower primary porosity than laterally equivalent host facies at the Scotia deposit (Sangster *et al.,* 1998a). At Walton the Macumber Formation limestone contained an estimated 5% primary porosity with very localized secondary porosity (up to 5%; Savard *et al.,* 1998). Syn-sedimentary brecciation of the upper Macumber Formation enhanced permeability and probably played a key role in localizing mineral deposition in these relatively tight carbonates (Lavoie *et al.,* 1998). At Jubilee, generation of porosity and permeability, related to a structural event, postdated burial of the low-porosity Macumber Formation. During extension and the development of the overlying Ainslie Detachment (a regional flat-lying extensional fault between the Macumber Formation and overlying evaporites) the high rheological contrast between limestone of the Macumber Member and overlying evaporitic units generated tectono-hydraulic

brecciation of the less ductile limestone, creating enhanced porosity and permeability (Hein *et al.,* 1993; Fallara *et al*., 1998).

The relative timing of mineralization is poorly constrained, as is commonly the case for carbonate-hosted deposits globally (e.g., Leach *et al.,* 2001, 2005), but geological relationships and isotopic age constraints from the Scotia deposit indicate that mineralization is epigenetic, postdating burial by at least 10-40Ma. (Ravenhurst *et al*., 1987; Pan *et al.,* 1993; Kontak *et al*., 1994; Sangster *et al.,* 1998a). Similarly, geological relationships at the Jubilee deposit and Port au Port occurrences show that mineralization is epigenetic and postdated burial and tectonic deformation (Dix & Edwards, 1996; Fallara *et al.,* 1998). For Jubilee, the ore must post-date breccia formation, which Lynch & Giles (996) bracketed to near the Namurian-Westphalian interval (i.e., ca. 315-300Ma).

There are no available age constraints for the Walton deposit, although Sangster *et al*. (1998b) suggested that barite mineralization predated folding and faulting of the host rocks (estimated at 330-307Ma; Sangster *et al.,* 1998b). Importantly, Kontak *et al.* (2000) constrained such deformation to >315Ma based on Ar-Ar dating of a mafic dyke rock at the Cheverie base-metal showing, located west of the Walton deposit, which cross-cuts ductile fabrics in Horton Group rocks at this locality (see Waldron *et al.* (2010) for discussion). Therefore, mineralization at Walton may be syngenetic or epigenetic, which has important implications for the genetic model applied to this deposit (see below).

Fluid inclusion data, which are available from all deposits, indicate that the mineralizing fluid(s) was a moderate- (i.e., 100°C) to high- (i.e. 200°C or more) temperature, Ca-Na bearing saline (>20 wt% eq. NaCl), metalliferous brine that infiltrated the host rocks from the underlying basement along faults (Dix & Edwards, 1996; Fallara *et al*., 1998; Kontak, 1998; Kontak & Sangster 1998). At the Scotia and Jubilee deposits and the Port au Port occurrences, there is some suggestion (based on sparse data) that a metalliferous fluid mixed with lower-temperature connate fluids at the site of deposition, but such evidence for fluid mixing is lacking at the Walton Deposit. The temperature of this metal-bearing fluid is highly variable, with maximum homogenization temperatures at Scotia (> 250°C) and Walton (>300°C) indicating that the fluid was significantly hotter than ambient rock temperatures (Kontak, 1998; Kontak & Sangster, 1998).

Data from the Jubilee deposit show that the majority of homogenization temperatures from fluid inclusions in the syn- to post-mineralizing sphalerite and anhedral calcite overlap with or are slightly higher than those recorded in the pre-ore fibrous calcite (70-100°C; Chi & Savard, 1995). Some rare fluid inclusions have higher homogenization temperatures (150-230°C), but without proper documentation of variations in homogenization temperatures within individual FIAs or examination for evidence of possible post-entrapment modification of these inclusions (e.g., stretching, leaking, necking) it is difficult to determine if these data represent a true influx of higher-temperature fluids. Similarly, fluid inclusion data from the Port au Port Peninsula are sparse and poorly documented, and further work is required to determine the true characteristics of the mineralizing fluids.

The presence of hydrocarbons has been recorded in the Scotia, Walton, and Jubilee deposits, but the relative timing of hydrocarbon generation and its relationship to mineralization varies among these settings. At the Scotia deposit, hydrocarbon migration was relatively late and post-dated mineralization (Kontak, 1998). In contrast, at the Walton deposit it has been suggested, in part based on the sulphur isotope data noted above, that hydrocarbon migration was contemporaneous with the influx of high-temperature metal-bearing brine responsible for mineralization (Kontak & Sangster, 1998). It has been proposed that these hydrocarbons were generated from organic matter in the underlying Horton Group (i.e., Horton Bluff Formation; Kontak & Sangster, 1998), and may have been important in providing a source of reduced sulphur that facilitated mineralization. At the Jubilee deposit, the hydrocarbons were generated prior to mineralization and mixed with connate water in the brecciated limestone to create a reservoir of reduced sulphate, which was important during later mineralization (Chi *et al.,* 1995).

There are also significant variations in carbon and oxygen isotopic signatures among the deposits. Carbon isotope data from the Scotia and Jubilee deposits and Port au Port occurrences show a shift towards negative $\delta^{13}C$ values in the pre-, syn- and post mineralization phases as compared to the host carbonates (Fig. 9). However, data for the Jubilee deposit show that there is a much more pronounced negative shift in carbon isotope values (up to -25‰; Fig. 9), which probably reflects the influx of hydrocarbons prior to mineralization (Rogers & Savard, 2002). Oxygen isotope data from these occurrences also show a decrease in $\delta^{18}O$ values during the pre-, syn- and post-mineralization phases (Fig. 9). Carbonates intergrown with sulphides in the main mineralization phase at the Scotia deposit show the most pronounced depletion in $\delta^{18}O$ values (up to 15‰) compared with the host dolostone. This likely reflects temperature-dependent fractionation of oxygen isotopes during mineralization, with the strong depletion associated with the relatively high temperature of the mineralizing fluids (consistent with fluid inclusion data and relatively high $^{87}Sr/^{86}Sr$ signature of ore-stage carbonates; Savard & Kontak, 1998). In contrast, mineralizing fluids at the Jubilee deposit and Port au Port occurrences were lower temperature, which is also reflected in the much more subtle decrease in $\delta^{18}O$ values (< 10‰; Fig. 9).

The heterogeneity among the mineralized settings is also evident in the sulphur and metal sources, as determined by sulphur and lead isotope data. TSR was the dominant sulphur reduction process at relatively high temperatures, as recorded by fluid inclusion data (> 100 to 300°C), and in most cases the sulphur isotope data indicate reduction of locally sourced sulphur from the overlying evaporite units via TSR. However, the negative sulphur isotope data from ore-stage sulphides at the Walton deposit are lower than would be expected for TSR of similar sulphate derived from overlying evaporite units, and instead requires an external source of isotopically light sulphur, which, as noted, is the underlying, locally organic-rich Horton Bluff Formation. Lead isotope data show intra-deposit homogeneity for each setting but inter-deposit variation and thus implies different metal sources, which probably means that metal sources were local and specific to each sub-basin (Swinden *et al.* 1988; Dix & Edwards, 1996; Sangster *et al*., 1998c).
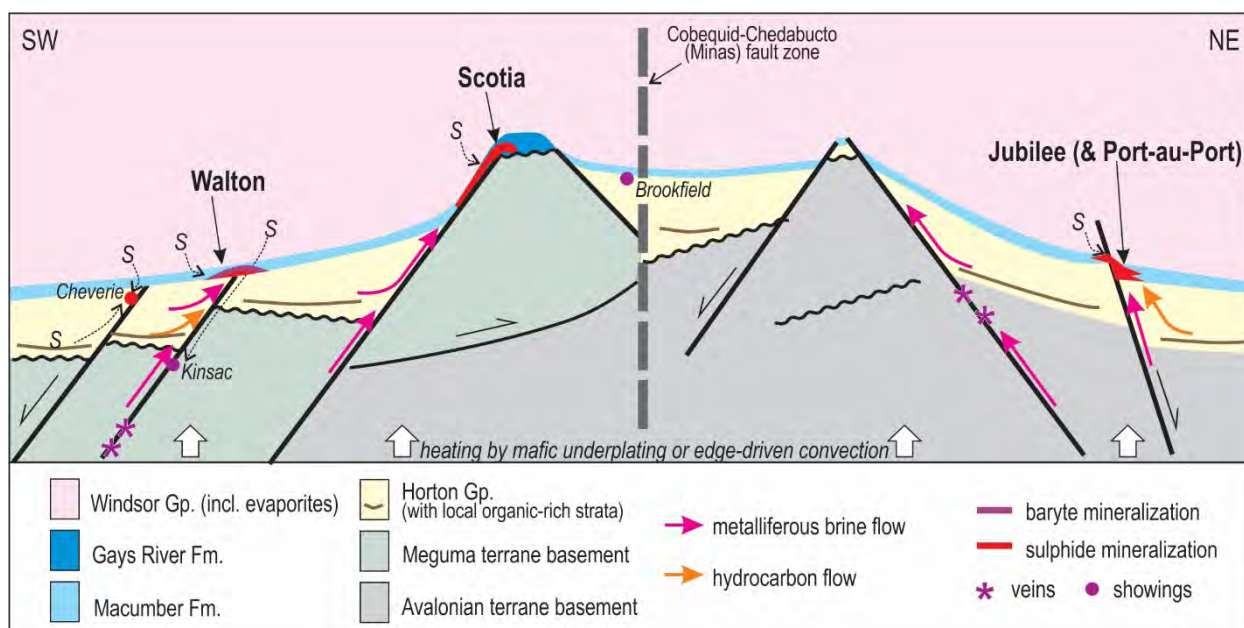
Figure 12: *Schematic cross-section through part of the Maritimes Basin, showing geological controls on the distribution of sulphide and barite ore deposits and showings. Syndepositional normal faulting during Horton Group. deposition established structures later used as fluid conduits during mineralization. Sulphur source (where known) for each deposit or showing indicated by 'S'. Geographic variations in basement composition probably controlled metal sources and budgets, as implied by Pb isotopic data. Some deposits are known to have been influenced by hydrocarbon migration. Not to scale.*

Genetic model for Zn-Pb mineralization in Maritimes Basin

The geological and geochemical features outlined above show that sedimentary-rock-hosted Zn-Pb deposits in the Maritimes Basin are characterized by heterogeneity on a deposit-scale (e.g., nature of alteration, metal ratios, temperature of mineralizing fluid), but commonality in terms of stratigraphic localization and association with sub-basin-bounding faults. Both the deposit-scale heterogeneity and the regional consistency in tectonostratigraphic elements need to be considered when developing a generalized genetic model for the district.

Despite these limitations, a general genetic model, in part modified from Sangster *et al.* (1998a), is proposed for the sedimentary-rock-hosted Zn-Pb mineralization in the Maritimes Basin (Fig. 12):

1. An incursion of global marine water into the Maritimes Basin resulted in the deposition of a regional carbonate unit at the base of the Windsor Group. This was then overlain by a thick evaporite succession (anhydrite, gypsum, halite) representing a proximal source of sulphur for later mineralizing systems.

2. The carbonate units typically have low porosity and permeability, but local conditions at the time of deposition (e.g., formation of bioherms) or during later alteration and tectono-hydraulic fracturing created significant porosity and/or permeability. These reservoir rocks were filled with connate water, or in the case of the Jubilee deposit also by the addition of hydrocarbons, prior to mineralization.

3. Deep circulation of basinal brines along extensional and strike-slip structures took place during the tectonic evolution of the Maritimes Basin. These brines were heated to temperatures far in excess of the ambient rock temperature, which facilitated leaching of metals from clastic strata of the Horton Group or basement rocks (Meguma Supergroup). Importantly, the latter is reflected by Pb isotopes of ore minerals that retain the local signature of the individual sub-basins.

4. The hydrothermal metalliferous brines became overpressured and were expelled during sudden release of pressure due to tectonic events (Chi & Savard, 1998). They ascended along faults until they encountered a suitably porous stratigraphic unit and source of reduced sulphur, which in this case was the base of the Windsor Group, conveniently located immediately beneath impermeable evaporitic units. Local variations in the geological and geochemical characteristics at the individual mineralized settings reflect the local specific conditions that accompanied ore formation, such as relative timing and depth of mineralization (epigenetic vs. syngenetic), fluid temperature (proxy for distance travelled?), sulphur source, and sulphate reduction process.

The presence of more than 150 documented base-metal occurrences in the basal carbonate units of the Windsor Group in the Maritimes Basin indicate that the generation of metalliferous brine and its migration through the stratigraphy was a basin-wide phenomenon, and that the development of significant accumulations of base metals reflects the development of a suitable local mineralizing environment.

Other mineral deposit types in or adjacent to the Maritimes Basin developed over the same time span (~340-300Ma), possibly reflecting the same hydrothermal system. These include structurally controlled vein barite mineralization in the Horton Group (e.g., the Brookfield deposit in Fig. 12; Kontak *et al.*, 2006) and basement granite settings (e.g., Kinsac occurrence in Fig. 12; Kontak *et al.*, 1999) and possible IOCG-IOA mineralization along the Minas Fault Zone [also called Cobequid-Chedabucto fault zone (CCFZ), see Fig. 12] in central Nova Scotia (Kontak, 2006; Kontak *et al.*, 2008; MacHattie & O'Reilly, 2009). Kontak *et al.* (2006) showed that the vein barite in the Horton Group at Brookfield was related to the release of heated (to 250°C), overpressured brine in an active fault zone, which is thought to have occurred relatively late compared to Zn-Pb mineralization in the Windsor Group (~ 315-330Ma; Pe-Piper & Piper, 2021).

Mineralization along the CCFZ includes a number of structurally controlled polymetallic deposits of possible IOCG affinity, including the Bass River magnetite prospect, the past-producing Londonderry iron deposits, the Mount Thom Cu-Co-Au prospect, and the Copper Lake Cu-Au deposit (Kontak 2006; MacHattie & O'Reilly, 2009). These occurrences, presumably driven by an elevated geotherm related to basic magmatism (Kontak, 2006; Kontak *et al.* 2008; MacHattie & O'Reilly, 2009; Kontak, 2022), are associated with intense sodic-calcic alteration of the host rocks and locally abundant magnetite and/or hematite with variable Cu-Au and REE mineralization, and are interpreted to be related to hydrothermal fluid flow along the CCFZ between 340 and 300 Ma (Kontak *et al.*, 2008; MacHattie & O'Reilly, 2009; Kontak, 2022). This time-frame overlaps with the interpreted age of sedimentary-rock-hosted Zn-Pb deposits at the base of the Windsor Group, and therefore IOCG mineralization along the CCFZ may be related to the same basin-wide hydrothermal event. Additionally, it is likely relevant that the $\delta^{34}S$ signature for the aforementioned IOCG-type mineralization indicates that sulphur was sourced from Windsor Group evaporites (Kontak, 2006).

The source of heat required to generate the anomalously high fluid temperatures recorded in some of the deposits (e.g., > 300°C at the Walton Deposit) remain unknown. Sangster *et al.* (1998a) suggested that they may be related to basaltic underplating of the Maritimes Basin or the presence of high-heat-producing (HHP) granites in the basement. An alternative source of heat to the lower crust may be edge-driven convection and asthenospheric upwelling in the Maritimes Basin during transtensional basin development in the Mississippian, as has recently been suggested in the Deer Lake sub-basin of the Maritimes Basin (Hinchey *et al.*, 2022). Edge-driven convection refers to convection and upwelling of asthenospheric material at zones of significant lithospheric thickness gradients, such as boundaries between thick and thin cratonic components (Matton & Jébrak, 2009; Kaislaniemi & van Hunen, 2014; Hoggard *et al.*, 2020; Hinchey *et al.*, 2022). The Maritimes Basin is located where there is a significant thickness gradient between the ancient continental margin of Laurentia and thinner peri-Gondwanan plates such as Ganderia, Avalonia, and Meguma (van Staal, 2007). During the Mississippian, the Maritimes Basin was undergoing significant dextral strike-slip transtensional motion on major faults (Murphy *et al.*, 2011; Gibling *et al.*, 2019; Snyder & Waldron, 2021), which would

have facilitated the upwelling of asthenospheric material and created a significant heat anomaly in the lower crust. This asthenospheric upwelling would have also been responsible for the widespread but generally low-volume alkali mafic lavas in the Maritimes Basin during the Mississippian, which are interpreted to have resulted from low-degree partial melting of an enriched mantle source (e.g., Pe-Piper & Piper, 1998; Jutras *et al.*, 2018; Hinchey *et al.*, 2022).

Comparison to other sedimentary-rock-hosted Zn-Pb deposits globally

Sedimentary-rock-hosted Zn-Pb deposits are commonly classified as MVT, SedEx/CD, or Irish-type deposits, based on their specific geological and geochemical conditions (Leach *et al.*, 2005; Wilkinson, 2014). MVT deposits are epigenetic Zn-Pb sulphide deposits formed in dolostone and limestone in platformal carbonate bodies on flanks of basins or foreland thrust belts, are not directly associated with igneous activity, and typically have temperatures of ore deposition from 90°C to 150°C (Leach *et al.*, 2005, Wilkinson, 2014). SedEx/CD deposits typically form as syngenetic or early diagenetic orebodies in intra- and/or epicratonic rift environments, spatially and/or genetically associated igneous rocks are absent or volumetrically minor, and the mineralizing fluids have a wide range of temperatures from 70 to 300°C (Leach *et al.*, 2005; Wilkinson, 2014). Irish-type deposits were described by Hitzman & Large (1986), Wilkinson (2003) and Wilkinson (2014), but this classification remains somewhat controversial (Leach *et al.*, 2005). Although they share a number of characteristics with MVT and SedEx/CD deposits, they may represent a transitional or hybrid deposit type between these two end members (Wilkinson, 2014). Irish-type deposits typically form during diagenesis, are hosted in carbonate rocks in basins undergoing active extensional faulting and subsidence, there may be an indirect link to igneous activity, and temperatures of ore deposition range from 70 to 280°C but are typically higher than those of MVT deposits (Wilkinson, 2014).

Sedimentary-rock-hosted Zn-Pb occurrences in the Maritimes Basin have previously been included in discussions of MVT, Irish Type or SedEx/CD genetic models, based on a variety of geological and geochemical characteristics (e.g., Leach *et al.*, 2005, Goodfellow & Lydon, 2007; Paradis *et al.*, 2007; Wilkinson, 2014). Although they are hosted by carbonate rocks and formed in an intra-continental extensional basin, like Irish-type deposits of the Irish Midlands, there has been no comprehensive discussion of how the Maritimes Basin deposits fit into a mineral deposit classification scheme. The local inter-deposit variations outlined above mean that these deposits may have features of a number of deposit types.

Fluid inclusion evidence from the Scotia deposit indicates that the temperature of mineralization was higher than in typical MVT deposits (> 200°C), and instead more typical of Irish-type deposits. In conjunction with the similar tectonic setting between the Maritimes Basin and the Irish Midlands, and the spatial and temporal association with volcanic activity in both locations, this led previous authors to suggest that the Scotia deposit represents an Irish-type deposit (Kontak & Boyce, 1996; Sangster *et al.*, 1998a). However, the Scotia deposit is an epigenetic Zn-Pb deposit, and sulphur isotope data indicate

that TSR was the dominant sulphur reduction process, which contrasts with the Irish-type genetic model of Wilkinson (2014) and is more typical of MVT deposits (Leach *et al.*, 2005; Wilkinson, 2014). An alternative explanation for the high mineralization temperatures is that the Scotia deposit represents a super-deep, high-temperature MVT end-member, as recently described from the Lower Saxony Basin, Germany (Sośnicka & Lüders, 2019).

The Jubilee deposit has many of the features of a typical MVT deposit according to the criteria of Leach *et al.* (2005) and Wilkinson (2014). It is an epigenetic Zn-Pb deposit hosted in brecciated carbonate rocks, TSR was the dominant sulphur reduction process, and fluid inclusion evidence suggests that mineralization was relatively low-temperature (majority of data indicating < 120°C). Zn-Pb occurrences on the Port au Port Peninsula have generally similar geological and geochemical characteristics to the Jubilee deposit. von Bitter *et al.* (1990) argued for a syngenetic origin related to the development of hydrothermal vent communities, but Dix & Edwards (1996) presented persuasive evidence that mineralization was epigenetic and formed in a shallow burial environment. Although the relative timing of this mineralization is unknown, the predominance of TSR suggests that a MVT genetic model may also apply to the Port au Port occurrences.

The Walton deposit is distinct from other Zn-Pb occurrences in the Maritimes Basin and has been variably classified as a SedEx/CD-type (Goodfellow & Lydon, 2007) or MVT deposit (Paradis *et al.*, 2007). The timing of mineralization at Walton is poorly constrained, but it postdates siderization during burial diagenesis (Savard *et al.*, 1998), and therefore is relatively late compared to typical syngenetic SedEx/CD mineralization. However, the Walton deposit has many characteristics more typical of SedEx/CD deposits (Leach *et al.*, 2005), including the presence of significant barite mineralization that predates the sulphide mineralization event, high mineralization temperature (> 300°C) and enrichment in Cu compared to other deposits in the Maritimes Basin. The Walton deposit may perhaps be considered an intermediate deposit type between the SedEx/CD and MVT end-members, akin to Irish-type deposits such as Silvermines (Reed & Wallace, 2004) and carbonate-hosted SedEx deposits such as the Anarraaq Zn-Pb-Ag and barite deposit in Alaska (Kelley *et al*., 2004).

As outlined above, the differences among the genetic models applied to Zn-Pb deposits are expressed only in the local conditions during mineralization. Similar deposit-to-deposit heterogeneity has also been recorded in the deposits of the Irish Midlands, with deposits ranging from probably syngenetic ore bodies such as the Silvermines deposit (Boyce *et al.*, 2003; Reed & Wallace, 2004) to smaller deposits with geological and geochemical characteristics typical of MVT deposits such as Harberton Bridge (see discussions in Leach *et al.,* 2005 and Wilkinson, 2014). Given that this local-scale heterogeneity may overprint a regional-scale consistency of the entire mineralizing system, it may be useful to describe sedimentary-rock-hosted Zn-Pb deposits using a broader mineral systems approach (Wyborn *et al.,* 1994), which appeals to the fundamental geological criteria needed to create an economic mineral deposit, including tectonic trigger events, suitable sources for metals, fluids, and heat, favourable crustal architecture, and

presence of suitable physical or chemical traps to host the ore bodies (McCuaig *et al.*, 2010; Hagemann *et al.*, 2016). On a global scale, Huston *et al.* (2022) showed that many large Zn-Pb districts are located on craton boundaries, similar to the Maritimes Basin and the Irish Midlands (i.e., between the Laurentian craton and peri-Gondwanan plates such as Ganderia, Avalonia, and Meguma). Hoggard *et al.* (2020) demonstrated that this spatial association was associated with the transition between thick and thin lithosphere, and that during later rifting or transtensional tectonic activity, asthenospheric upwelling and edge-driven convection may have triggered hydrothermal systems associated with sedimentary-rock-hosted Zn-Pb mineralizing systems. Fluids generated in the basement due to such a heat anomaly would have leached metals and been transported along favourable crustal structures (extensional or transtensional fault systems) until they encountered suitable traps (porous unit in carbonate rocks with a nearby source of reduced sulphur).

Outstanding research questions

Most of the published research on sedimentary-rock-hosted Zn-Pb deposits in the Maritimes Basin is now more than 25 years old, and as has been shown above, there are many outstanding research questions that need to be addressed. Such work is currently in progress for the Scotia and Walton deposits, as part of an ongoing PhD project. Some of the major research questions follow:

Geochronological studies

Constraining the age of ore formation is paramount to understanding any ore deposit setting. For low-temperature carbonate-replacement deposits, this has traditionally been challenging due to the dearth of materials suitable for dating and their relative paragenesis (e.g., post- versus syn-ore material). However, a wide variety of methods has been applied, including Rb-Sr on sphalerite, TIMS U-Pb, Th-Pb and Nd-Sm on gangue phases (carbonate, fluorite), Re-Os on sulphides and bitumen, fission track of detrital phases (e.g., apatite, zircon), and paleo-magnetism, as summarized by Leach *et al*. (2001). These authors noted that whereas reliable ages are inferred for some districts, mixed or unreliable ages are associated with other areas; the Maritimes Basin falls into the latter category.

To resolve the outstanding problem of constraining the absolute time of ore-fluid migration, current work is applying a variety of methods to the settings described in this paper: 1) in situ U-Pb calcite dating, which has proven successful in a variety of settings in documenting burial history, formation of structurally-controlled veins, and development of hydrothermal ore deposits; 2) Re-Os dating has been particularly successful in a variety of analogous settings [e.g., Nanisivik (Arctic Canada), Irish-type deposits]; and 3) in situ Rb-Sr dating of sphalerite follows on the earlier success of this method using a bulk-leach approach.

Use of modern fluid inclusion protocol

The fluid inclusion studies summarized herein (i.e., Scotia, Walton, Jubilee) were carried out about 30 years ago and thus predate the modern protocol now widely used in such work (see Fall & Bodnar, 2018). Several aspects of this change in

protocol are critical to obtaining meaningful results: 1) adherence to the FIA approach; 2) integration of fluid inclusion classification with thermometric data; and 3) awareness of what constitutes a realistic ranges of homogenization results for individual FIAs in carbonate-replacement base-metal settings. With regard to (3), a realistic Th range for an FIA is +/-4°C (Fall & Bodnar, 2018), which is a much tighter range than has been reported for these deposits. From this discrepancy it can be concluded that outlier data (i.e. anomalously hot or cold homogenization temperatures) for singular data points or for inclusions that do not define an FIA (i.e., two or more paragenetically contemporaneous inclusions in a spatial relationship) have to be interpreted cautiously, and higher temperatures for isolated inclusions omitted from interpretations. Thus, the anomalous data for Jubilee (>120-140°C for isolated singular inclusions) are not considered to record primary conditions, which means that the deposit should be reinterpreted as having developed in a much lower-temperature setting than previously interpreted by Chi et al. (1995). For the same reason, the mixing trends suggested for the Gays River region (Chi & Savard, 1995) are also considered suspect; better-constrained, FIA-based data are needed in order to re-evaluate ore-fluid temperature. As regards the apparently high temperatures for the deposits, the inclusion data reported for the Scotia deposit (Fig. 13 of Kontak, 1998) and Walton (Table 1 of Kontak & Sangster, 1998) define T$_h$ populations with meaningful differences (e.g., sphalerite at Scotia deposit) and ranges (i.e., <20-30°C) and thus the high temperatures inferred for these deposits remain valid. However, this understanding is being re-evaluated to confirm this important conclusion (see below).

In situ isotope analysis and clumped isotopes

Traditional stable isotopic studies (i.e., C, O, S) have provided great insight into fluid sources and ore-forming processes (e.g., TSR versus BSR) in these deposit settings (Leach et al., 2005). However, recently developed in situ methods such as Secondary Ion Mass Spectrometry ("SIMS") provide better resolution (10s microns) with which to track fluid evolution during diagenesis and subsequent hydrothermal base-metal ore formation (e.g., Hahn et al., 2018; Kontak et al., 2022; Mathieu et al., 2022). For example, the latter studies document the source of fluids implicated in cement formation, their redox state, and the processes that generated the H$_2$S necessary for base-metal sulphide formation. Furthermore, where fluid inclusion data cannot be obtained, in situ δ^{18}O data on carbonate can be used as a proxy to estimate temperature using reasonable assumptions (e.g., Mathieu et al., 2022; Kontak et al. 2022). Such work is in progress for the Maritimes Basin to address fluid origin, whether fluid mixing took place, the existence of single or multiple source(s) of sulphur and processes relevant to ore formation. The development of clumped isotope analysis provides a means to assess the temperature of ore-related carbonate independently, (e.g., Pinet et al., 2023), and also to compare with results from fluid inclusion microthermometry and assess the thermal evolution of these systems. The latter is of particular importance where anomalously high temperatures have been suggested.

Application of in situ LA-ICP-MS analysis of fluid inclusions and cements to ore formation

Outstanding issues relevant to the Maritimes Basin, but also globally, include fluid signature which relates to source and aquifers, redox state and ability to transport metals, and metal contents. In situ LA ICP-MS analysis provides the means to address these questions. For example, the results of such analysis in different settings in the classic MVT district in the USA mid-continent region suggest mixing of different fluids (metal-rich versus barren) that record various sources and fluid-flow conditions (Stoffel et al. 2008; Appold & Wenz, 2011; Pelch et al., 2015). In the deposits of the Maritime Basin, appropriate fluid inclusions are present in different parts of the mineral paragenesis at both Scotia and Walton and will provide a basis for quantifying their respective fluid chemistries. The ability to analyse trace elements, such as the rare earths (REE), and redox-sensitive elements (e.g., Ce, Eu, Fe, Mn) at a high spatial resolution in cements in barren and mineralized (i.e., pre-, syn- and post-ore) settings provides the means to track processes such as fluid redox and fluid mixing (e.g., Mathieu et al., 2015, 2022; Hahn et al., 2018).

Conclusions

Sedimentary-rock-hosted Zn-Pb occurrences are common in the Maritimes Basin (eastern Canada), and include past-producing mines at the Scotia and Walton deposits, as well as the Jubilee deposit and significant occurrences on the Port au Port Peninsula (Newfoundland). The geological settings of these deposits share important attributes, such as localization of mineralization in carbonate rocks of the lowermost Windsor Group (Macumber, Gays River and Big Cove formations) overlain by thick evaporite successions, with larger deposits located along the margins of sub-basins with a strong structural control. All of the deposits formed due to the migration of metalliferous fluid generated in underlying basement rocks, which encountered a suitable source of reduced sulphur in a geological setting characterized by anomalous porosity and permeability.

Despite these broad similarities, there are significant differences among the deposits, particularly in terms of metal (and sulphate) ratios and temperature of the mineralizing fluid. Previous studies have attempted to classify deposits in the Maritimes Basin using genetic models for other sedimentary-rock-hosted Zn-Pb deposits globally (MVT, Irish-type and SedEx/CD deposits), but these assignments may be incorrect, and deposits may be transitional between deposit types. A similar picture of inter-deposit heterogeneity is evident in the Irish Midlands, which includes syngenetic Zn-Pb deposits with characteristics similar to SedEx/CD deposits (e.g., Silvermines), classic Irish-type deposits (e.g., Navan, Lisheen), and minor occurrences with MVT-like characteristics.

Because the main genetic models for sedimentary-rock-hosted Zn-Pb deposits mainly depict local conditions and controls rather than the attributes of the larger-scale mineralizing system, it would be appropriate to evaluate sedimentary-rock-hosted Zn-Pb districts such as the Maritimes Basin using a mineral systems approach, which incorporates the large-scale driving factors and triggers for mineralization (e.g., edge-driven convection at cratonic margins during extension and/or

transtension), suitable sources for metals (leaching from underlying basement rocks by hydrothermal fluids), favourable crustal architecture (abundant transtensional or extensional faults facilitating fluid movement to higher crustal levels), and presence of suitable physical or chemical traps that host the ore bodies (porous carbonate rocks with a source of reduced sulphur).

Acknowledgements

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