The emerging Paleozoic gold district of central Newfoundland: New insights on structural controls and tectonic drivers of gold mineralization and preservation

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ABSTRACT

The formation and preservation of orogenic gold deposits are associated with a predictable set of magmatic, structural, and tectonic processes that have recurred throughout Earth's history. In world-class Archean gold districts, such as in the Superior Province of the Canadian Shield and the Yilgarn Craton of the West Australian Shield, the main gold-mineralized fault zones are characterized by early imbrication, lithospheric extension, synorogenic magmatism and sedimentation, thick-skinned re-imbrication, and late-stage strike-slip. Such an evolution results in the occurrence of gold-mineralized, upper crustal sequences of synorogenic magmatic and sedimentary rocks above terranes of granitoid rocks and/or older poly-deformed volcanic rocks. Targeted exploration for orogenic gold mineralization relies on remnant panels of synorogenic rocks (e.g. polymict conglomerate and bimodal magmatic rocks) as first-order field indicators of structurally controlled gold preservation along prospective crustal-scale fault zones.

Paleozoic crustal-scale fault zones in central Newfoundland have been known to host significant gold mineralization and recent major discoveries (e.g. Valentine Lake gold deposit) and associated exploration suggest the emergence of a new district centred on the footwall rocks of the Victoria Lake shear zone. Fieldwork, combined with structural analysis and high-precision U-Pb geochronology throughout central Newfoundland, demonstrates that the structurally controlled Paleozoic gold district is remarkably similar to the much older Archean Abitibi gold district in scale, geological setting, structural architecture, synorogenic magmatism and sedimentation, style of mineralization, tectonic evolution, and process rates. In central Newfoundland, orogenic gold occurs within footwall blocks of an overall northwest-directed fault system that juxtaposed and deformed Neoproterozoic basement granitoid rocks and Late Silurian to Early Devonian synorogenic rocks during the Acadian Orogeny. Preliminary high-precision U-Pb zircon and rutile geochronology demonstrates that the key tectonic interval driving gold mineralization and synorogenic sedimentation and magmatism, including syenogranite and monzonite intrusions, occurred between 424 and 407 Ma, approximately the same relative time interval (15–20 million years) as the Abitibi greenstone belt. The similarities between the gold systems of central Newfoundland and the Abitibi imply that a common predictable set of structural and tectonic processes throughout Earth's history, and thus independent of time, have led to the deposition and preservation of orogenic gold mineralization.

INTRODUCTION

Orogenic gold mineralization is known to occur within, and in proximity to, crustal-scale fault systems across the geological record (e.g. Poulsen et al., 1992, 2000; Groves, 1993; Hodgson, 1993; Groves et al., 1998; Goldfarb et al., 2001; Dubé and Gosselin, 2007; Percival, 2007). Similar geology and structural architecture in Archean gold systems world-wide, such as between the Abitibi greenstone belt of the Superior Province and the Yilgarn craton in West Australia, indicate a common sequence of structural and tectonic processes driving gold mineralization (e.g. Poulsen et al., 1992; Groves, 1993; Hodgson, 1993; Robert, 2001; Bleeker, 2012, 2015). The most productive gold mines in Canada have historically exploited structurally controlled Archean fault-vein systems (Hodgson, 1993),

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where thin panels of upper crustal, synorogenic sequences of sedimentary and magmatic rocks overlie deformed and faulted basement terranes along major fault zones that structurally control mineralization. These remnant synorogenic sequences are crucial to understanding the dynamics and overall evolution of crustal-scale fault corridors and associated gold systems because they record the active phase of tectonics driving orogenic gold mineralization.

In the well studied, world-class Abitibi gold district (e.g. Robert and Brown, 1986a,b; Poulsen et al., 1992; Dubé and Gosselin, 2007), the key phase of gold-producing tectonics is characterized by a dynamic chain of processes (Bleeker, 2015): early thin-skinned fold-thrust belt development and imbrication of older volcanic rocks; uplift and erosion of the imbricated fold-thrust belt and development of synorogenic unconformity on this older basement; initiation of a master fault system during transient lithospheric extension; a flare-up in mantle-derived alkaline magmatism; an associated thermal pulse in lower crust; synorogenic sedimentation and volcanism; reactivation of faults as thick-skinned thrusts; development of gold-bearing vein sets; tectonic burial and preservation of mineralized rocks in footwall blocks; and late-stage degeneration to strike-slip deformation. To evaluate the applicability of process-oriented Archean models to younger orogenic gold districts, we are testing if an Abitibi prototype is valid in the emerging structurally controlled Paleozoic gold district of central Newfoundland, where panels of synorogenic magmatic and sedimentary (Rogerson Lake Conglomerate) rocks are preserved along the crustal-scale faults.

As the central Newfoundland gold district is still in the relatively early stages of exploration, the crustal-scale structural architecture and magmatic history of the prospective master fault system requires further study. The research herein integrates fieldwork throughout central Newfoundland with regional cross-sections, and new high-precision U-Pb geochronology to define and illustrate the lithological and structural setting of Paleozoic orogenic gold mineralization, the polarity of the master fault system, the magmatic and tectonic evolution, and key similarities with world-class Archean gold districts, such as those of the Abitibi greenstone belt.

GEOLOGICAL SETTING

The Island of Newfoundland in the northeastern Canadian Appalachians represents a Paleozoic accretionary system that formed along the ancient continental margin of Laurentia (Bird and Dewey, 1970; Williams, 1978; van Staal et al., 1998; van Staal and Barr, 2012). The geology of Newfoundland is subdivided into four broad tectonostratigraphic zones based on contrasting fossil assemblages, stratigraphy, structure, and geochemistry in pre-Silurian rocks (Fig. 1; Williams, 1978). The Humber Zone in western Newfoundland comprises rocks of the Laurentian margin, including strongly deformed metasedimentary rocks of the Taconic hinterland (Internal Humber Zone) and allochthonous, low-grade rocks transported towards the foreland (External Humber Zone). The core of the island spans the Dunnage Zone, historically referred to as the Central Mobile Belt (Williams, 1964), which includes peri-Laurentian (Notre Dame Subzone, Dashwoods) and peri-Gondwanan (Exploits Subzone) arc and back-arc complexes that were accreted to the Laurentian margin during Early Paleozoic orogenesis. The boundary between the Notre Dame and Exploits subzones, the Red Indian Line (Williams et al., 1988), is an overall southeast-directed, steep fault system that defines the fundamental suture between peri-Laurentian terranes in the west and peri-Gondwanan terranes in the east. The Red Indian Line suture zone was active in the Middle Ordovician as it buried volcanic and sedimentary cover rocks of Ganderia, along with allochthonous basement granitoid rocks, in its footwall (Zagorevski et al., 2007). Farther east, sedimentary and granitoid rocks of the main Ganderian and Avalonian microcontinents define the Gander and Avalon Zones (Fig. 1), respectively, which were accreted sequentially to composite Laurentia during the Silurian Salinic Orogeny and Devonian Acadian Orogeny.

The pre-Silurian tectonostratigraphy of the Dunnage Zone is conformable with overlying Middle Ordovician black shale and Late Ordovician to Early Silurian turbidite of the Badger Group (Fig. 2a). Unconformably above the Badger Group are Silurian synorogenic magmatic and terrestrial sedimentary rocks of the Topsails Suite (*see* Whalen et al., 2006; van Staal et al., 2014) in the Notre Dame Subzone, and Late Silurian to Early Devonian synorogenic magmatic and sedimentary rocks of the Rogerson Lake Conglomerate sequence and Botwood Group (Fig. 2; Williams, 1962; Colman-Sadd et al., 1990) in the Exploits Subzone. In north-central Newfoundland, the Botwood Group (Williams, 1962) is composed of a lower bimodal volcanic section (Lawrenceton Formation) and an upper section of interbedded green, grey, and red sandstones (Wigwam Formation), whereas farther southwest along strike it is dominated by panels of synorogenic polymict conglomerate (Rogerson Lake Conglomerate; Kean and Jayasinghe, 1980), felsic volcanic rocks, and mafic dykes (Fig. 2). The youngest rocks preserved in Newfoundland are Carboniferous clastic sedimentary rocks that occur along steep zones of late-stage strike-slip that overprint major faults (Colman-Sadd et al., 1990).

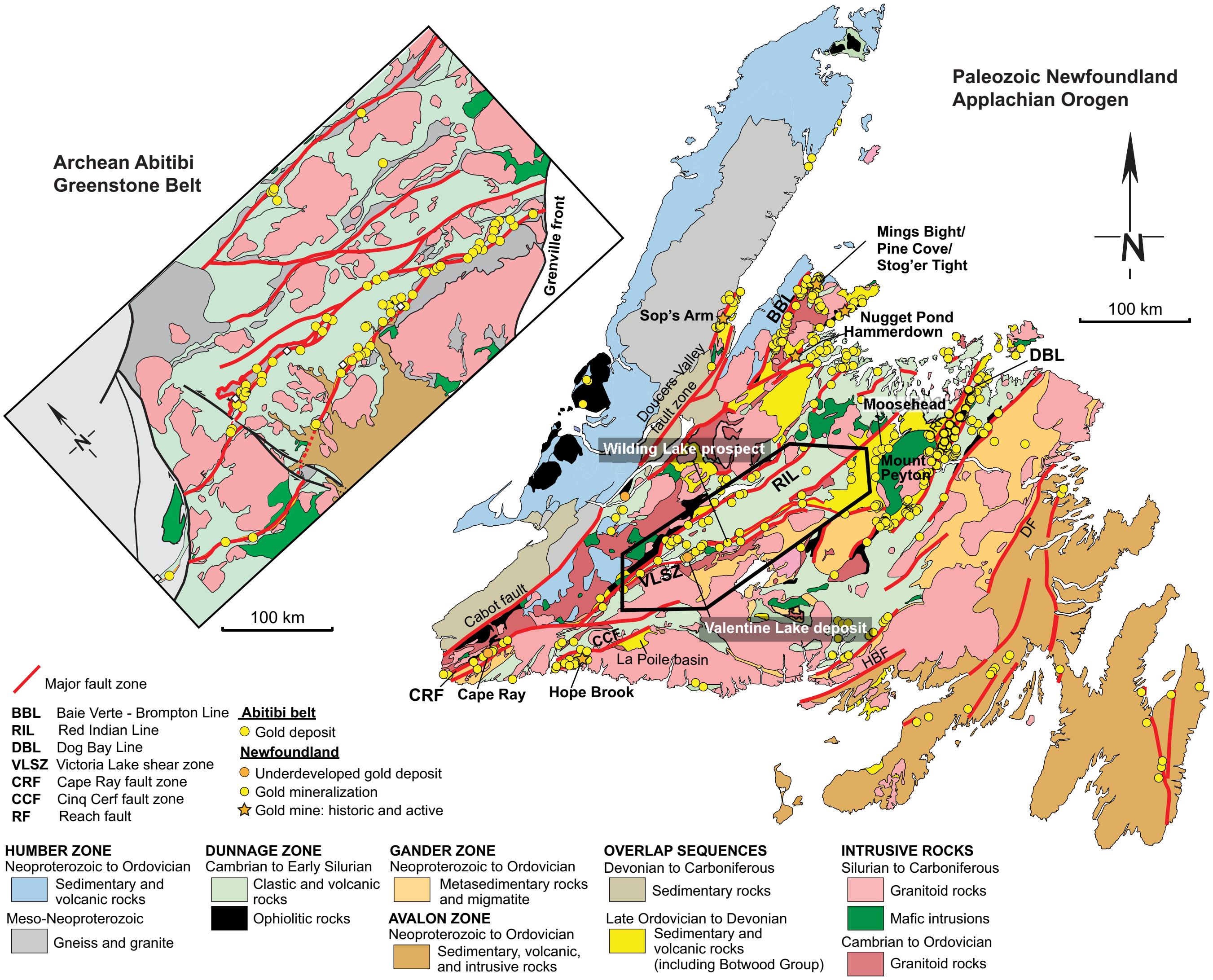

Figure 1. Comparison of the geology and gold-mineralized fault systems of the Archean Abitibi greenstone belt (left) and Paleozoic Newfoundland Appalachians (right), at the same scale. Map of the Abitibi *modified from* Poulsen et al. (2000), Dubé and Gosselin (2007), and Bleeker (2015). Newfoundland map was *adapted from* Colman-Sadd et al. (1990), with gold occurrences *compiled from* Evans (1996), O'Driscoll and Wilton (2005), Wardle (2005), and Sandeman et al. (2017).

GOLD-MINERALIZED FAULT ZONES, CENTRAL NEWFOUNDLAND

Late Silurian to Early Devonian panels of synorogenic, upper-crustal sequences overlying the Dunnage Zone and easternmost Humber Zone in central Newfoundland outline gold-mineralized, crustal-scale fault systems that are comparable in scale to the well endowed fault systems of the Archean Abitibi greenstone belt (Fig. 1; Honsberger and Bleeker, 2018). From west to east across central Newfoundland, the major northeast-trending, Paleozoic fault zones associated with orogenic gold mineralization include Doucers Valley fault zone (Smyth and Schillereff, 1982), Baie Verte – Brompton Line (Williams, 1978), Cape Ray fault zone (Dubé et al., 1996), and the Victoria Lake shear zone (Valverde-Vaquero and van Staal, 2001; Valverde-Vaquero et al., 2006). Table 1 summarizes the key attributes of these gold-mineralized fault zones, including notable gold showings/deposits, tonnages, and timing of synorogenic magmatism and gold mineralization. Although the Hope Brook gold mine is a Neoproterozoic high-sulphidation epithermal gold deposit (Dubé et al., 1995), it is included in Table 1 because it is was the first and most productive gold mine in Newfoundland and is associated with a crustal-scale fault system (Cinq Cerf fault zone) that preserves Silurian synorogenic sedimentary and volcanic rocks (Fig. 1; O'Brien et al., 1993; Dubé et al., 1995).

The focus of this study is the northeast-trending, gold-mineralized fault corridor that extends for more than 200 km between Cape Ray in southwestern Newfoundland and Mount Peyton in north-central Newfoundland, and includes the Cape Ray fault zone

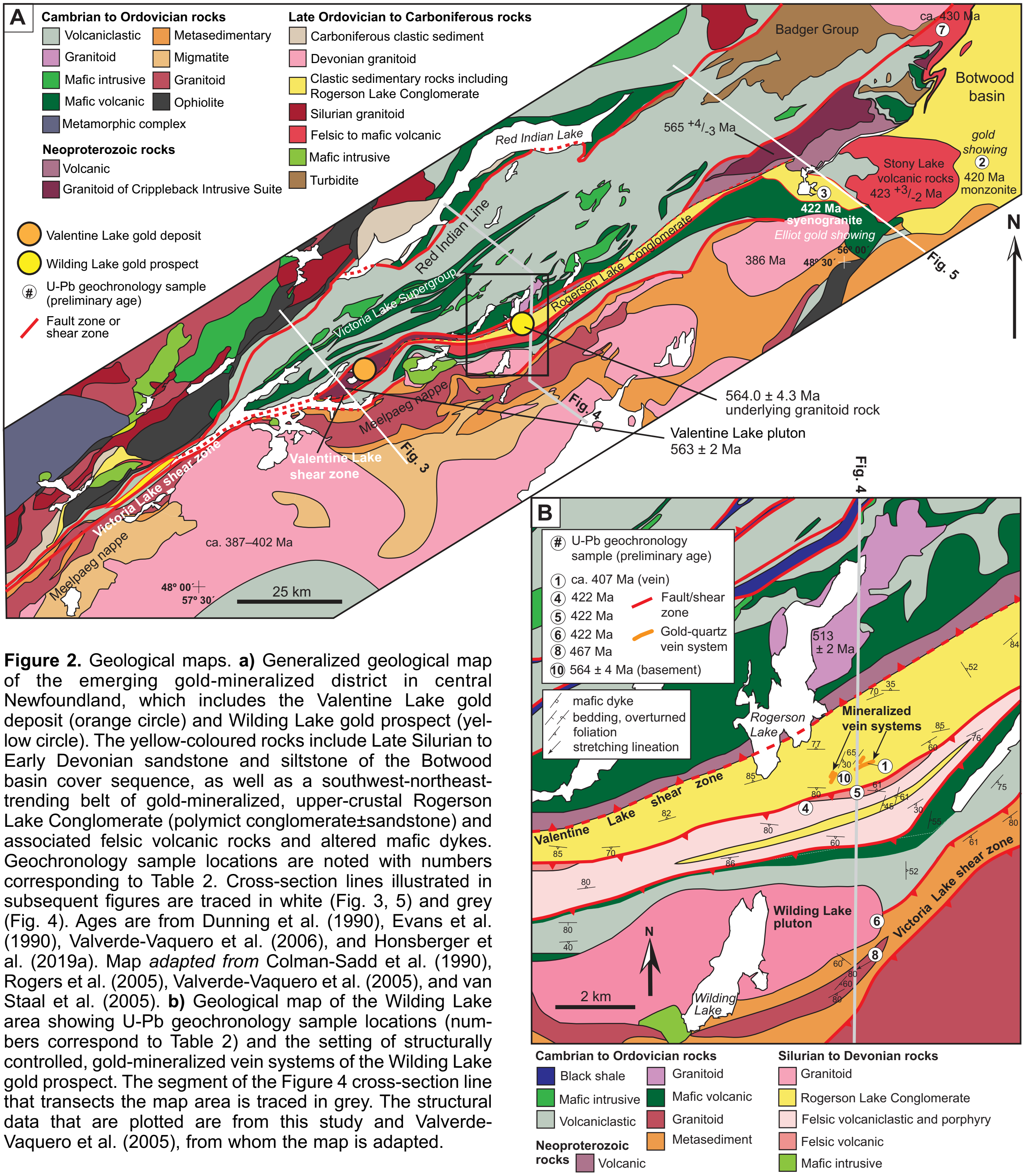

Figure 2. Geological maps. **a)** Generalized geological map of the emerging gold-mineralized district in central Newfoundland, which includes the Valentine Lake gold deposit (orange circle) and Wilding Lake gold prospect (yellow circle). The yellow-coloured rocks include Late Silurian to Early Devonian sandstone and siltstone of the Botwood basin cover sequence, as well as a southwest-northeast-trending belt of gold-mineralized, upper-crustal Rogerson Lake Conglomerate (polymict conglomerate±sandstone) and associated felsic volcanic rocks and altered mafic dykes. Geochronology sample locations are noted with numbers corresponding to Table 2. Cross-section lines illustrated in subsequent figures are traced in white (Fig. 3, 5) and grey (Fig. 4). Ages are from Dunning et al. (1990), Evans et al. (1990), Valverde-Vaquero et al. (2006), and Honsberger et al. (2019a). Map *adapted from* Colman-Sadd et al. (1990), Rogers et al. (2005), Valverde-Vaquero et al. (2005), and van Staal et al. (2005). **b)** Geological map of the Wilding Lake area showing U-Pb geochronology sample locations (numbers correspond to Table 2) and the setting of structurally controlled, gold-mineralized vein systems of the Wilding Lake gold prospect. The segment of the Figure 4 cross-section line that transects the map area is traced in grey. The structural data that are plotted are from this study and Valverde-Vaquero et al. (2005), from whom the map is adapted.

and Victoria Lake shear zone (Fig. 1). The Cape Ray fault zone is a steeply eastward-dipping, oblique reverse high-strain zone that is approximately 100 km long and several metres wide (Dubé and Lauzière, 1996, 1997; Dubé et al., 1996) and correlates with the Red Indian Line to the northeast (*see* Valverde-Vaquero et al., 2006). The Cape Ray fault zone is delineated by a panel of Ordovician bimodal volcanic rocks and gold-mineralized clastic sedimentary rocks of the Windsor Point Group, including mylonitized polymict conglomerate, greywacke, and siltstone (Dubé and Lauzière, 1996, 1997; Dubé et al., 1996). The northeastern extension of the Cape Ray fault zone splays into two major fault zones, the Red Indian Line in the west and the Victoria Lake shear zone in the east (Fig. 1).

Structural Cross-Sections

For more than 200 km along strike, the gold-mineralized, crustal-scale fault corridor in central Newfoundland is delineated by deformed panels of polymict conglomerate—a distinctive synorogenic unit known as the Rogerson Lake Conglomerate—and magmatic rocks that non-conformably overlie Pan-African basement granitoid rocks (Valverde-Vaquero et al., 2005). To further understand the structural architecture of this prospective gold belt, field data from the Rogerson Lake Conglomerate corridor was utilized to construct regional cross-sections over an approximately 100 km tract between Valentine Lake in the southwest and the Botwood Group (basin) in the northeast (Fig. 3–5). Figure 4 is a detailed structural cross-section that transects the Wilding Lake gold prospect in the central part of the district, whereas figures 3 and 5 are more generalized geological cross-sections from the areas of the Valentine Lake gold deposit in the southwest and the Elliot gold showing in the northeast, respectively. The overarching master fault system controlling orogenic gold mineralization is interpreted to be a southeast-dipping, northwest-directed, listric fault zone that correlates with the Victoria Lake shear zone and splays thereof (Fig. 3–5).

The Neoproterozoic Valentine Lake pluton (Fig. 2a; Evans et al., 1990; trondhjemite, tonalite, gabbro, and mafic dykes), which hosts the Valentine Lake gold deposit (total measured and indicated resources of 54.86 million tonnes at 1.75 grams/tonne gold: Marathon Gold Corp., 2020), is juxtaposed against Late Silurian to Early Devonian Rogerson Lake Conglomerate in the overall structural footwall of the Victoria Lake shear zone (Fig. 2, 3). The northwest-directed Victoria Lake shear zone accommodated Early Devonian emplacement of the Meelpaeg nappe, composed dominantly of high-grade Cambrian to Ordovician metamorphosed sedimentary and granitoid rocks of the Gander Zone, including migmatite and the ca. 467 Ma Peter Strides granitoid suite (Fig. 3–5; Valverde-Vaquero et al., 2006). The structure separating Rogerson Lake Conglomerate from basement granitoid rocks is a steeply northwest-dipping, second-order reverse sinistral shear splay known as the Valentine Lake shear zone (Fig. 2–3; Lincoln et al., 2018). Structurally controlled, gold-bearing quartz-tourmaline-pyrite (QTP) vein systems along the Valentine Lake shear zone have been compared to orogenic quartz-carbonate-tourmaline veins at the Val-d'Or mining camp of the Abitibi greenstone belt (Dunsworth and Walford, 2018; Lincoln et al., 2018).

Table 1. Summary of major gold-mineralized fault zones, central Newfoundland[1].

Terrane	Fault zone	Silurian synorogenic sequence	Notable gold showing/ deposit/mine	Historic/active (years in operation)	Gold resource estimate	Age of synorogenic magmatism (Ma)	Method	Age of gold mineralization (Ma)	Method	References
Humber Zone	Doucers Valley fault zone	Sop's Arm Group	Browning Mine	Historic (1903–1906)	150 oz	434.3 ± 1.1	U-Pb, zircon	374 ± 1	^{40}Ar-^{39}Ar, muscovite	Kerr (2006); Sandeman and Dunning (2016)
Dunnage Zone Notre Dame Subzone	Baie Verte Line	Topsails Suite	Ming's Bight, Goldenville Mine, first gold discovery in Newfoundland Pine Cove/ Stog'er Tight/Nugget Pond	Historic and active (1870s–present)	863,500 t at 2.07 g/t (indicated, Pine Cove)	ca. 433–425	U-Pb, zircon	420 ± 5 (Stog'er Tight); 375 ± 8 (Nugget Pond)	U-Pb, zircon; xenotime	Poulsen et al. (2000); Ramezani (2000); Sangster et al. (2007); van Staal et al. (2014)
Dunnage Zone Notre Dame/ Exploits Subzone	Cape Ray fault zone	Windsor Point Group[2]	Cape Ray deposit, under-developed	Active (1976–present)	450,000 t at 10.1 g/t (mineable reserve)	468.0 ± 1; 453 +5/-4	U-Pb, zircon	ca. 407–384	crosscutting relationships	This study; Dubé and Lauziere (1996, 1997) Dubé et al. (1996)
Dunnage Zone Exploits Subzone	Victoria Lake shear zone	Botwood Group Rogerson Lake Conglomerate	Valentine Lake deposit; Wilding Lake prospect	Active (1960s–present)	54.86 Mt at 1.75 g/t (measured and indicated)	424–418; 422 in Rogerson Lake Conglomerate corridor	U-Pb, zircon	407 ± 1.1	U-Pb, rutile	This study; Dunning et al. (1990); McNicoll et al. (2006); Sandeman et al. (2017)
Gander Zone	Cinq Cerf fault zone	La Poile Group	Hope Brook deposit[3]	Historic (1984–1997)	11.2 Mt at 4.54 g/t (indicated)	429 ± 2 to 418 +2/-1.5	U-Pb, zircon	578–574[3]	crosscutting relationships	Dubé et al. (1995); O'Brien (1989); O'Brien et al. (1993)

Notes: [1]Listed in order from northwest to southeast. [2]Ordovician synorogenic sequence. [3]High-sulphidation epithermal gold deposit.

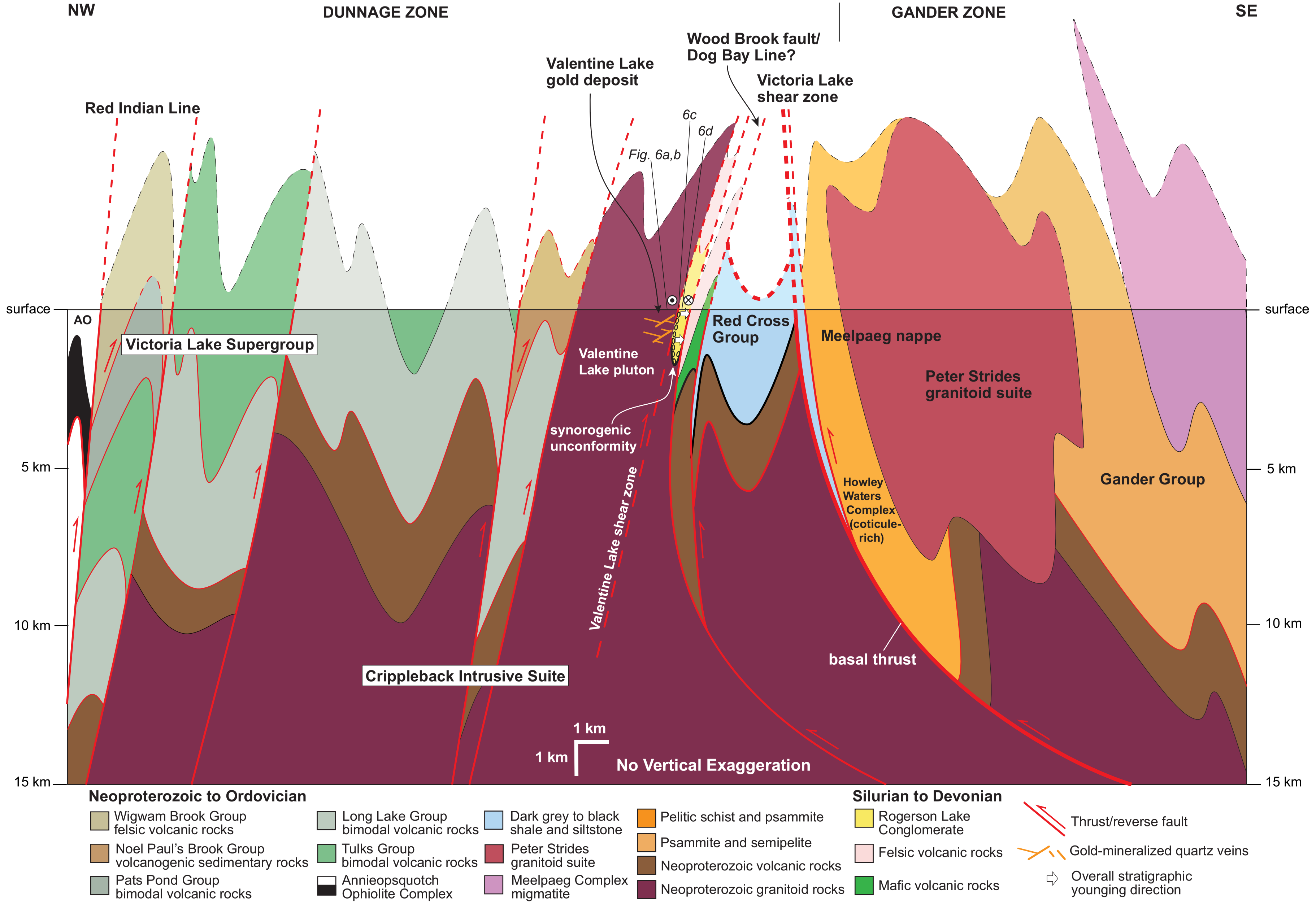

Figure 3. Generalized geological cross-section transecting the Valentine Lake gold deposit. The locations of the field photographs that are shown in Figure 6 are noted. A panel of synorogenic Rogerson Lake Conglomerate is coloured yellow.

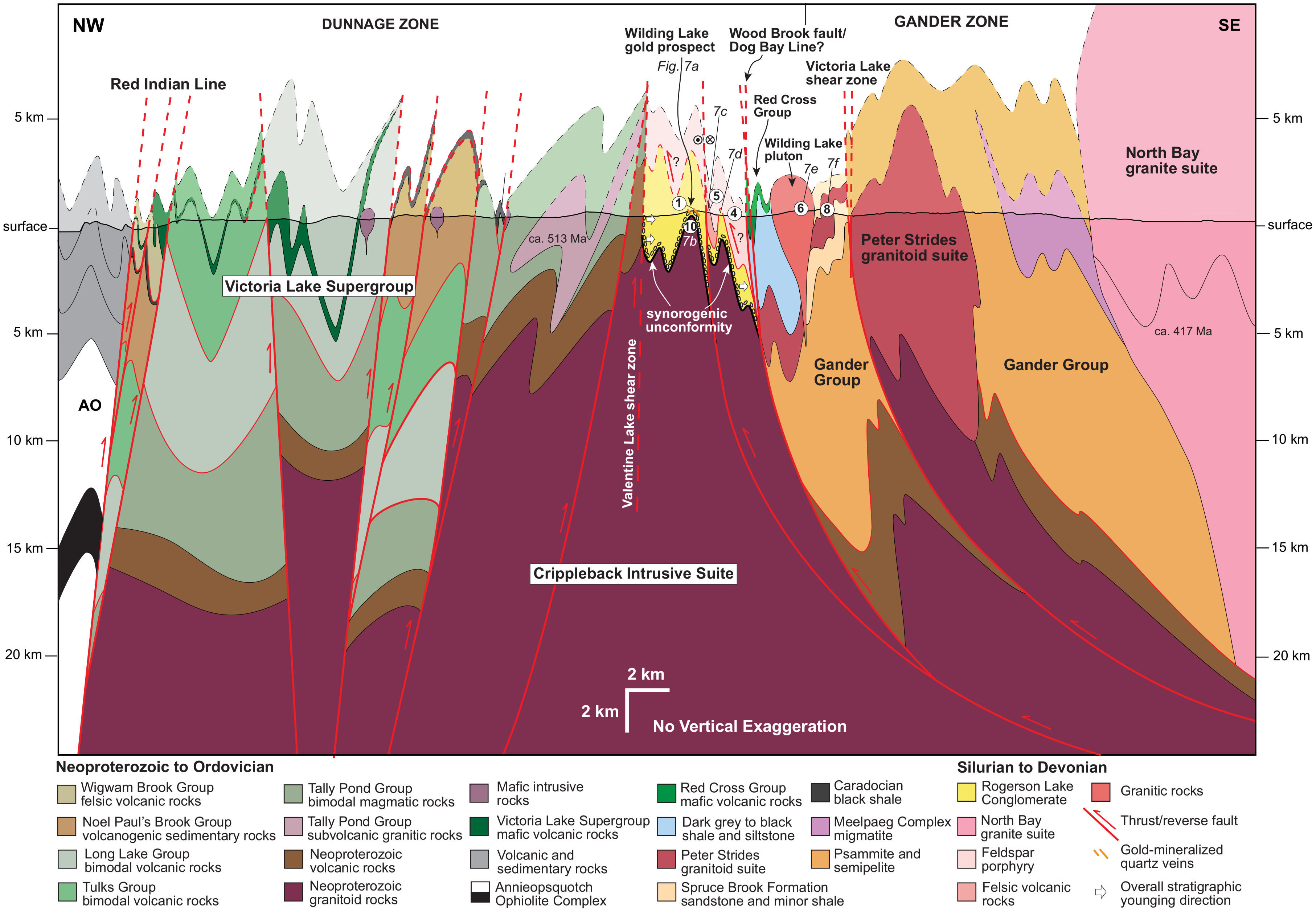

Figure 4. Detailed structural cross-section transecting the Wilding Lake gold prospect, with Rogerson Lake Conglomerate in yellow. The locations of the field and sample photographs that are shown in Figure 7 are noted. Ages are from Evans et al. (1990) and Valverde-Vaquero et al. (2005).

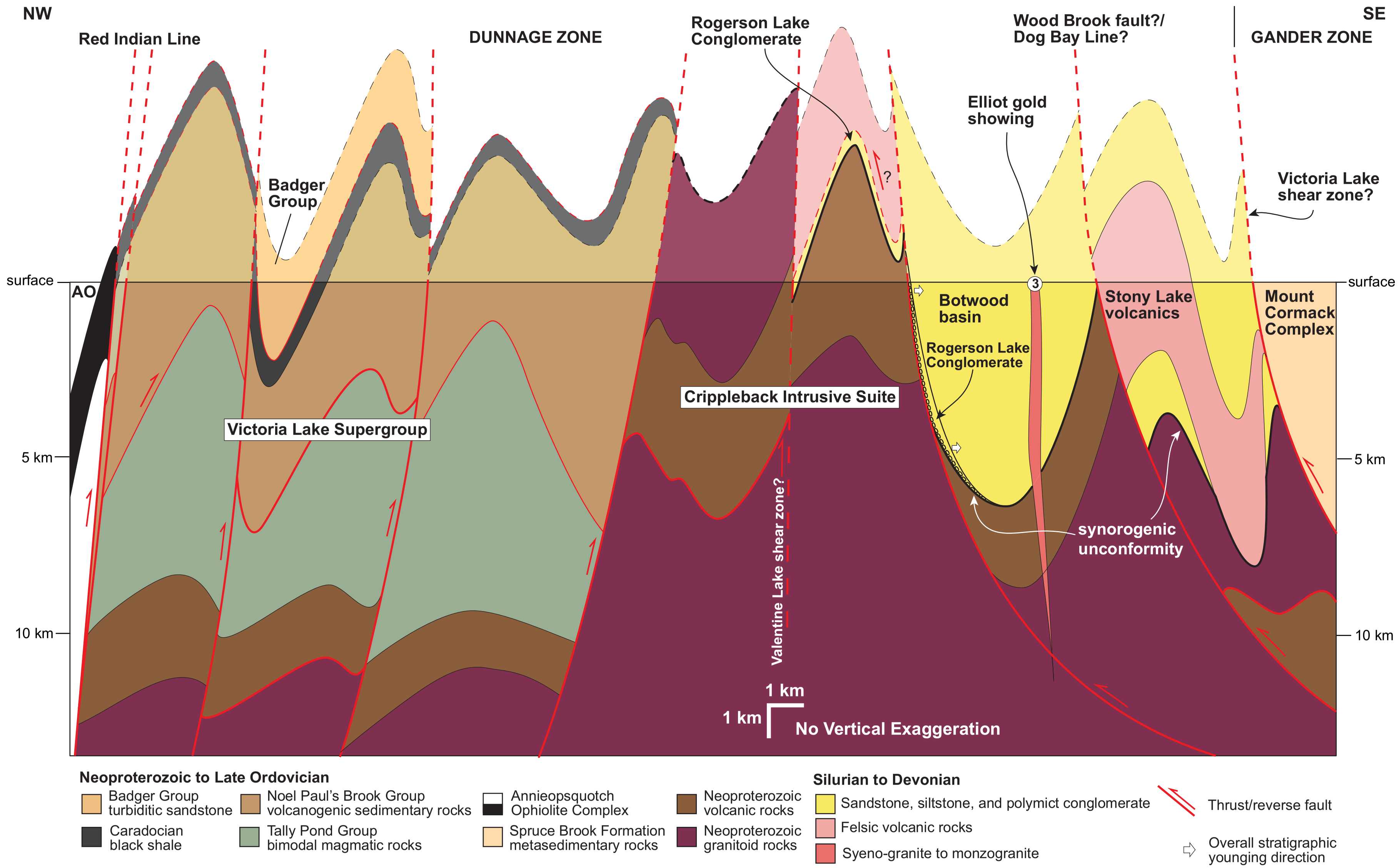

Figure 5. Generalized geological cross-section transecting the Elliot gold showing. Rocks of the Botwood basin and associated Rogerson Lake Conglomerate are in yellow.

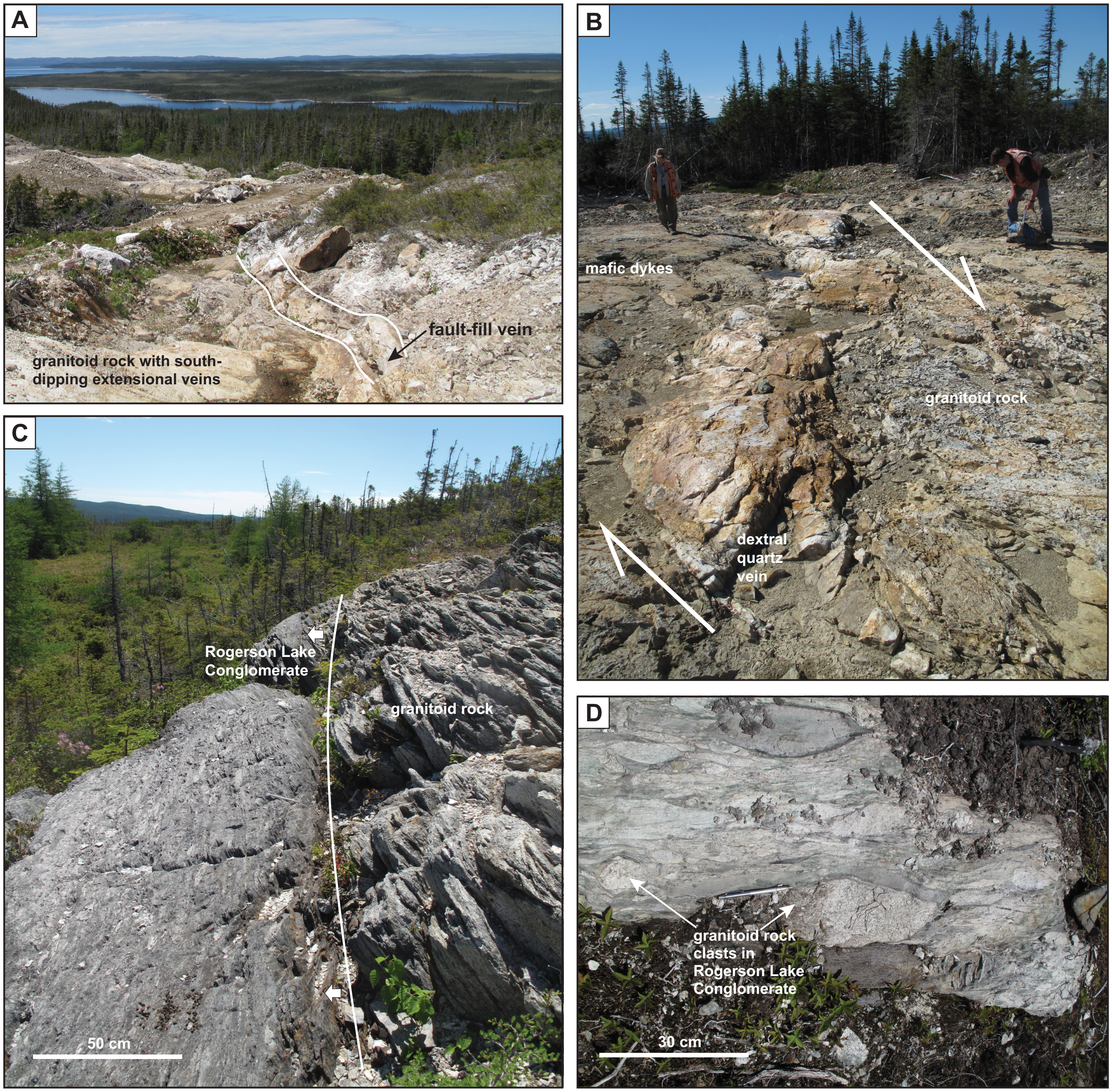

Figure 6. Field photographs from the Valentine Lake gold deposit. Refer to Figure 3 for photograph locations. **a)** A northwest-dipping fault-fill vein cutting gold-mineralized Neoproterozoic granitoid rock (Valentine Lake pluton, looking southwest). **b)** Quartz vein showing dextral motion and cutting the Valentine Lake pluton and mafic dykes (looking west). **c)** Contact between the Rogerson Lake Conglomerate (left, southeast) and the Valentine Lake pluton (right, northwest). **d)** Coarse-grained granitoid rock clasts in Rogerson Lake Conglomerate, shown near the contact with the Valentine Lake pluton.

The gold-mineralized Valentine Lake shear zone is a steeply northwest-dipping, reverse sinistral shear zone that cuts the Valentine Lake pluton and juxtaposes it against a panel of Late Silurian to Early Devonian Rogerson Lake Conglomerate and associated magmatic rocks (Fig. 3, 6; Lincoln et al., 2018). The Valentine Lake gold deposit is hosted within a network of fault-fill and extensional quartz vein sets along the Valentine Lake shear zone (Fig. 3, 6), with the bulk of gold mineralization hosted by the Valentine Lake pluton. Farther east from the Valentine Lake shear zone, northwest-directed, crustal-scale faults, including the Victoria Lake shear zone, imbricate Ordovician to Late Silurian sedimentary, volcanic, and volcaniclastic (Red Cross Group) rocks of the eastern-most Dunnage Zone. The fault zone marking the boundary between the Red Cross Group and the sedimentary-volcanic sequence immediately to the west correlates with the Wood Brook fault (Fig. 3; Valverde-Vaquero et al., 2006) in the southwest, and the Dog Bay Line (Williams et al.,

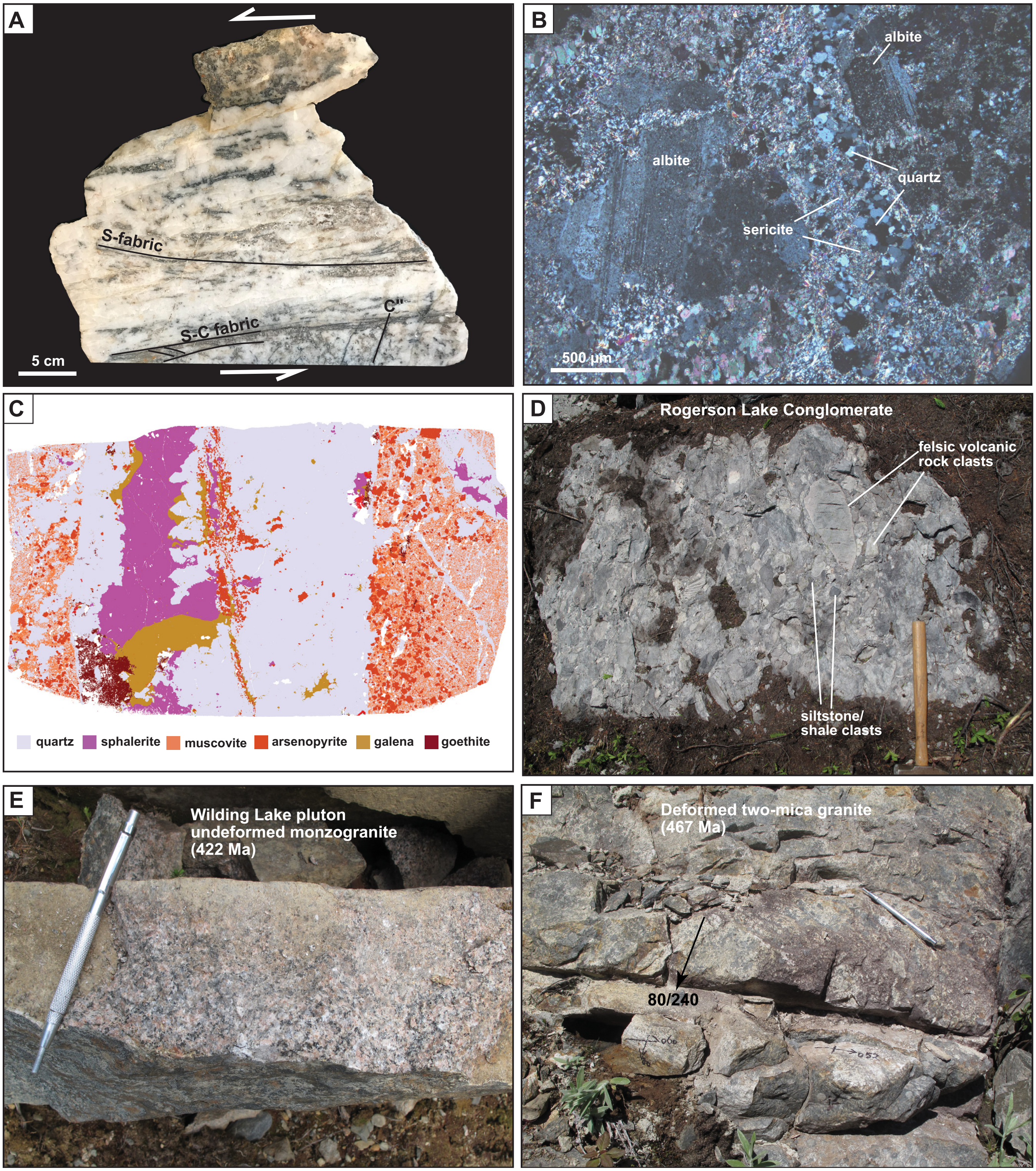

Figure 7. Field and sample photographs. Refer to Figure 4 for locations and Table 2 for descriptions and locations of the geochronology samples. **a)** A quartz vein sample from the Wilding Lake gold prospect displaying sinistral S-C fabrics. **b)** A microphotograph of altered Neoproterozoic basement tonalite (ca. 564 Ma) underlying the Wilding Lake gold prospect (geochronology sample #10). **c)** Scanning electron microscope-mineral liberation analyzer image of a mineralized vein cutting felsic volcanic rock (422 Ma), Wilding Lake gold prospect. The thin section image is ~46 mm long. **d)** Southern panel of Rogerson Lake Conglomerate near Wilding Lake containing coarse-grained clasts of felsic volcanic and sedimentary rocks. **e)** Undeformed two-mica monzogranite, Wilding Lake pluton (422 Ma: geochronology sample #6). **f)** Strongly deformed, two mica granite (467 Ma) displaying steeply southwest-dipping stretching lineations (black arrow), which is consistent with reverse motion towards the northeast (geochronology sample #8).

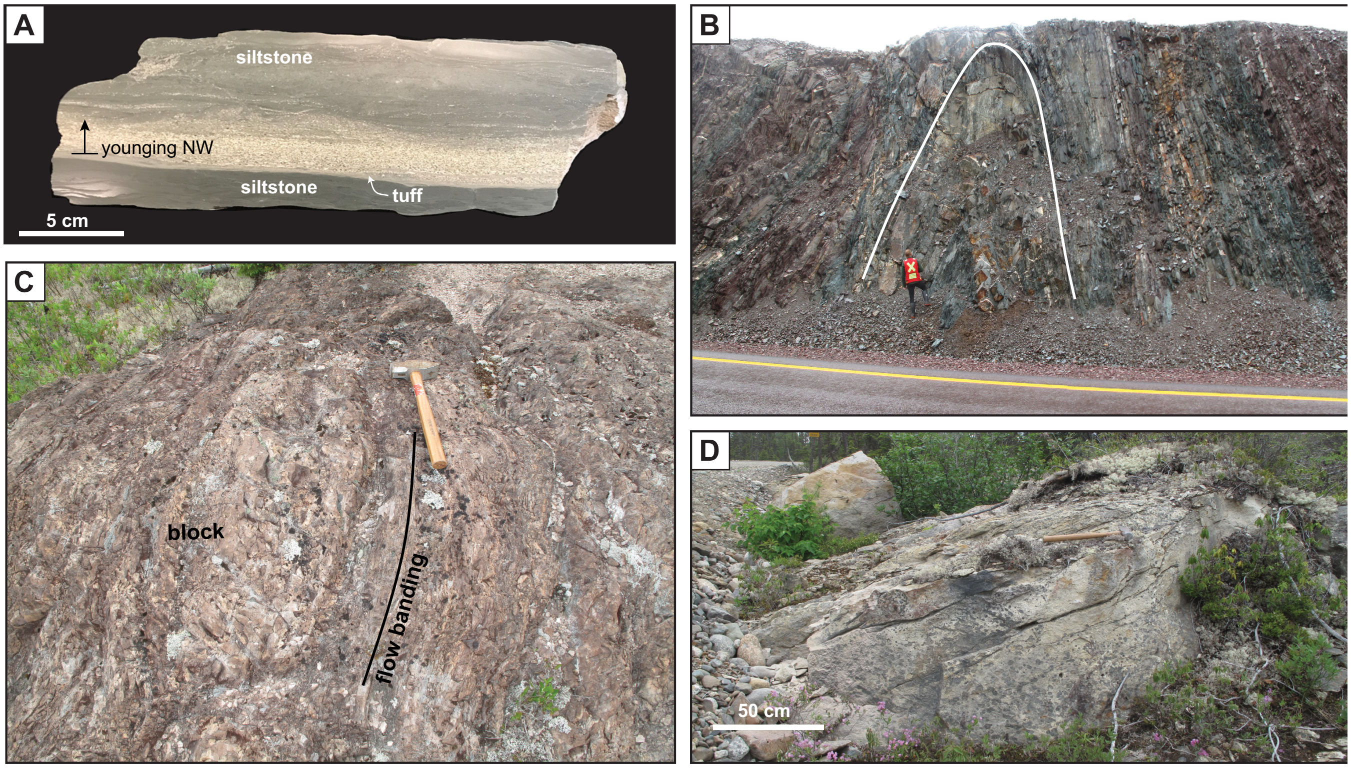

Figure 8. Field and sample photographs. *See* Figure 4 for locations and Table 2 for descriptions and locations of the geochronology samples. **a)** Sample of northwest-younging, stratified tuffite interlayered within siltstone of the Botwood basin (geochronology sample #11). **b)** Folded sequence of interlayered sandstone, siltstone, and tuffite from the Botwood basin. **c)** Autobrecciated, flow-banded rhyolite (ca. 430 Ma) dome of the Hodges Hill magmatic suite. **d)** Moderately deformed Late Silurian Stony Lake felsic volcanic rocks.

1993) in north-central Newfoundland. The Dog Bay Line is interpreted to represent the terminal suture of the Iapetus Ocean basin system (Williams et al., 1993; Pollock et al., 2007). West of the Valentine Lake pluton, Cambrian to Ordovician rocks of the Victoria Lake Supergroup (van Staal et al., 2005) are tectonically imbricated along steeply northwest-dipping, southeast-verging faults that record displacement before and during the Middle Ordovician (Zagorevski et al., 2007).

The structurally controlled Wilding Lake gold prospect (Honsberger et al., 2020a,b) occurs within a deformed panel of mineralized Rogerson Lake Conglomerate and associated felsic volcanic rocks and altered mafic dykes that unconformably overlie Neoproterozoic basement tonalite (Fig. 4, 7a–d; Honsberger et al., 2020b). It is yet to be determined if the contact between the overall southeast-younging Rogerson Lake Conglomerate sequence and overlying felsic volcanic rocks is a stratigraphic or structural boundary (*see* "?" in Fig. 4). The base of the Rogerson Lake Conglomerate sequence (western contact of syn-orogenic unconformity) is sheared along a vertical structural contact that correlates with the Valentine Lake shear zone to the southwest. This structure marks a transition from an overall northwest-verging thrust system in the southeast to an overall southeast-verging thrust system in the northwest, where subduction-related Cambrian arc volcanic rocks of the Tally Pond Group are preserved (Fig. 4). The Late Silurian Wilding Lake pluton (Fig. 7e) intrudes Ordovician and older, deformed sedimentary, volcanic, and plutonic (Fig. 7f) rocks of the Gander and Red Cross groups in the footwall of the Victoria Lake shear zone. Farther southeast, the Early Devonian North Bay granite suite (ca. 417 Ma: *see* Valverde-Vaquero et al., 2005) intrudes rocks of the Gander Group.

Northeast of the Wilding Lake section, mineralized syenogranite (422 Ma; *see below*) near Sandy Lake (a locality known as the "Elliot gold showing") intrudes deformed sandstone, siltstone, conglomerate, and associated tuffite of the Late Silurian – Early Devonian Botwood basin (Fig. 5, 8a,b). In this area and farther northeast, the panel of Rogerson Lake Conglomerate is not well preserved, interpreted to be related to deeper erosion of Neoproterozoic basement blocks composed of volcanic and granitoid rocks of the Sandy Brook Group (Rogers et al., 2006) and Crippleback Intrusive Suite (Evans et al., 1990), respectively. However, Silurian felsic magmatic rocks, including those of the Hodges Hill suite and the younger Mount Peyton/Fogo suite (van Staal et al, 2014; Sandeman et al., 2017), including the Stony Lake volcanic rocks, are well pre-

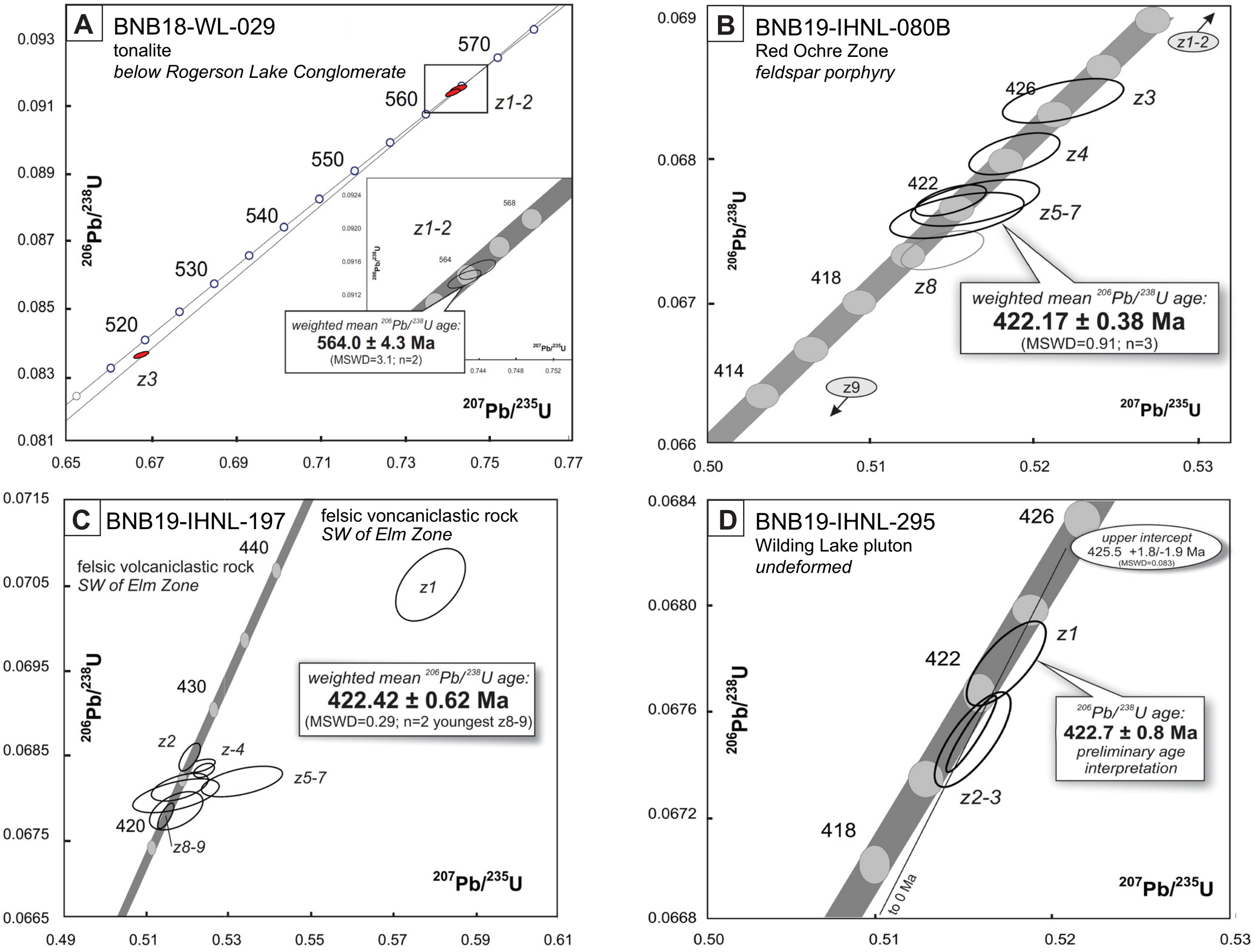

Figure 9. U-Pb Concordia diagrams for rocks from the Wilding Lake prospect and pluton: **a)** geochronology sample #10, **b)** geochronology sample #4, **c)** geochronology sample #5, and **d)** geochronology sample #6. *See* Figure 4 for locations and Table 2 for descriptions and locations of the geochronology samples.

served as structural domes (Fig. 5, 8c,d). Forthcoming high-precision U-Pb zircon geochronology on stratified, northwest-younging tuff layers within the sandstone and siltstone sequences of the Botwood basin (Fig. 8a) will help constrain the timing of synorogenic sedimentation and magmatism in north-central Newfoundland. High-grade metamorphic rocks of the Mount Cormack Complex (i.e. Ganderia; Fig. 5) tectonically bury rocks of the eastern Dunnage Zone along a northwest-directed thrust structure correlative with the Victoria Lake shear zone.

PRELIMINARY U-PB GEOCHRONOLOGY

Methods

Single zircon grains from 11 samples from central Newfoundland were dated by chemical abrasion – isotope dilution – thermal ionization mass spectrometry (CA-ID-TIMS) at the Jack Satterly Geochronology Laboratory, University of Toronto, following the methods described in Mattinson (2005). Age calculations were performed using ISOPLOT (Ludwig, 2008). Preliminary U-Pb geochronological data and analytical notes are presented in Table 2.

Results

Figure 9 shows a selection of four standard U-Pb concordia diagrams for the following units: Neoproterozoic basement tonalite, Late Silurian feldspar porphyry and felsic volcanic rocks of the Wilding Lake gold prospect, and Late Silurian monzonite of the Wilding Lake pluton. Results yield preliminary weighted mean $^{206}Pb/^{238}U$ zircon ages of 564.0 ± 4.3 Ma for basement tonalite (Table 2, sample #10), 422.17 ± 0.38 Ma for feldspar porphyry (sample #4), 422.42 ± 0.62 Ma for felsic volcanic rock (sample #5), and 422.7 ± 0.8 Ma for undeformed monzonite of the Wilding Lake pluton (sample #6). Other preliminary ages are listed in Table 2 and include monzonite (sample #2) and syenogranite (sample #3) intrusions in the Botwood basin, northeast of Wilding Lake, that yield preliminary zircon ages of

Table 2. Preliminary U-Pb zircon and rutile geochronological data.

#	Rock unit	Sample Number	Easting (m)	Northern (m)	Description	New U-Pb age (Ma)	Method[1]	Event	References
1	Mineralized quartz vein	BNB18-IHNL-180	518452	5368270	Goethite-altered pyrite-bearing (±Au) hydrothermal quartz vein cutting Rogerson Lake Conglomerate, Wilding Lake prospect	407.0 ± 4.0	U-Pb, rutile	Gold mineralization	This study
2	Paradise Lake monzonite	BNB18-IHNL-008	600796	5398557	Locally deformed and strongly altered, medium-grained monzonite at Paradise Lake, intrudes Botwood basin	420.0 ± 0.77	U-Pb, zircon	Mount Peyton felsic pulse	This study; *see also* Sandeman et al. (2017)
3	Elliot syenogranite	BNB19-IHNL-317	570646	5392646	Grey to pinkish grey, medium-grained, altered and mineralized syenogranite to monzogranite, Elliot gold showing	422.06 ± 0.47	U-Pb, zircon	Mount Peyton felsic pulse	This study; *see also* Sandeman et al. (2017)
4	Red Ochre feldspar porphyry	BNB19-IHNL-080B	516703	5367285	Mineralized feldspar porphyry, Wilding Lake prospect	422.17 ± 0.38	U-Pb, zircon	Felsic magmatism	This study
5	Third Spot felsic volcanic rock	BNB19-IHNL-197	518246	5367610	Fine-grained felsic volcanic, Wilding Lake prospect	422.42 ± 0.62	U-Pb, zircon	Felsic magmatism	This study
6	Wilding Lake pluton	BNB18-IHNL-295	519328	5363230	Light grey to pink, medium-grained, undeformed two mica monzogranite	422.7 ± 0.8	U-Pb, zircon	Felsic magmatism	This study
7	Red Cliffs rhyolite dome	BNB19-IHNL-092	591846	5423816	Flow-banded, fine-grained rhyolite dome, near quarry area in Grand Falls	429.5 ± 1.0	U-Pb, zircon	Hodges Hill felsic pulse	This study
8	Deformed granitoid rock	BNB19-IHNL-294	518837	5362019	Grey to grey-pink, medium-grained, foliated two mica granite along Granite Lake, south-side up shear indicators	467.41 ± 0.47	U-Pb, zircon	Peter Strides Granitoid Suite?	This study; *see also* Valverde-Vaquero et al. (2006)
9	Windsor Point felsic tuff	BNB19-IHNL-287	329506	5276517	Grey to tan, fine-grained, laminated, felsic to intermediate, pyroclastic tuff layer intercalated with pillow basalts younging to the northwest, Cape Ray	468.0 ± 1	U-Pb, zircon	Windsor Point extensional magmatism	This study; *see also* Dunning et al. (1990)
10	Basement tonalite	BNB18-WL-029 (drill core)	517453	5367934	Medium-grained, mineralized tonalite underlying Rogerson Lake Conglomerate, Wilding Lake prospect	564.0 ± 4.3	U-Pb, zircon	Crippleback intrusive suite	This study; *see also* Evans et al. (1990) and Honsberger et al. (2019b)
11	Felsic tuffite	BNB19-IHNL-291	612845	5431548	~3 cm wide, stratified tuffite layer, Wigwam Group, Botwood basin	in progress	U-Pb, zircon	Mount Peyton felsic pulse?	This study

Notes: [1]CA-ID-TIMS on single rutile and zircon grains, or small fragments thereof.

420.0 ± 0.77 Ma and 422.06 ± 0.47 Ma, respectively. An autobrecciated, flow-banded rhyolite dome west of the Botwood basin in Grand Falls (sample #7, Fig. 2a, 8c) records an older pulse of Silurian felsic magmatism at ca. 430 Ma (Table 2). A deformed granitoid rock that occurs immediately to the south of the Wilding Lake pluton is dated at 467 Ma (sample #8), which is the same age, within error, as felsic tuff (sample #9) interlayered with mafic volcanic rocks of the Windsor Point Group at Cape Ray. Hydrothermal rutile from an extensional quartz vein cutting Rogerson Lake Conglomerate from the Wilding Lake gold prospect yielded a preliminary ^{206}Pb/^{238}U age of 407 ± 4 Ma.

DISCUSSION

Orogenic gold mineralization in central Newfoundland occurs within footwall blocks along the length of an overall northwest-directed thrust system that exhumes high-grade rocks of Ganderia (Fig. 3–5). The Victoria Lake shear zone and correlative fault zones in central Newfoundland (Fig. 3–5) were, therefore, critical structures for controlling gold-bearing hydrothermal fluid flow, gold deposition, and tectonically burying and preserving gold mineralization in footwall blocks. The Valentine Lake gold deposit is preserved in an exhumed Neoproterozoic basement block (Valentine Lake pluton) where the northwest-directed fault system is steepened and overturned (Fig. 3). The Valentine Lake shear zone may be a secondary southeast-directed structure that was active during compression related to the overturning of the main fault system (Fig. 3).

Preliminary U-Pb zircon and rutile geochronology (Fig. 9, Table 2), combined with regional structural cross-sections (Fig. 3–5), constrain the critical phase of tectonism and associated hydrothermal fluid circulation for orogenic gold mineralization in central Newfoundland between ca. 424 and 407 Ma, with the main pulse of felsic magmatism in the southern Botwood basin and correlative Rogerson Lake Conglomerate sequence at ca. 422 Ma and hydrothermal gold mineralization between ca. 415 and 407 Ma. In addition to our samples, Late Silurian magmatic rocks of the Botwood basin sequence include the Stony Lake felsic volcanic rocks (Fig. 2a, 8d; 423 +3/-2: Dunning et al., 1990; 422 ± 2 Ma: McNicoll et al., 2008), mafic dykes, and mineralized bimodal rocks of the Mount Peyton Intrusive Suite (Fig. 1), which have been dated between 424 and 418 Ma (Sandeman et al., 2017). Field and structural relationships combined with geochronological results suggest that the magmatic pulse at ca. 422 Ma in central Newfoundland, as well as associated synorogenic sedimentation, are a result of transient lithospheric extension following the main phase of Salinic compressional deformation (433–426 Ma: van Staal et al., 2014), before emplacement of the Meelpaeg nappe during the Acadian Orogeny in the Early Devonian (e.g. Valverde-Vaquero et al., 2006; van Staal et al., 2014). Late Silurian magmatism in the gold-mineralized Ordovician Windsor Point Group along the southern coast at Cape Ray (Dubé et al., 1996) provides further evidence of an extension-related magmatic event. Metamorphic monazite in exhumed rocks of the Meelpaeg nappe in central Newfoundland and correlative rocks at Cape Ray are dated at ca. 420 Ma (Owen, 1992; Valverde-Vaquero et al., 2006) and ca. 415 Ma (Dubé et al., 1996), respectively, which places maximum age constraints on northwest-directed, Early Devonian thrust reactivation of faults that were initially extensional. This implies that the vein structures hosting gold mineralization in central Newfoundland formed during deformation associated with the Acadian Orogeny.

At Valentine Lake and Wilding Lake, orogenic gold mineralization is hosted within dominantly reverse sinistral shear vein systems characterized by fault-fill and extensional vein sets that cut Late Silurian to Early Devonian Rogerson Lake Conglomerate, Late Silurian volcanic rocks, and underlying Neoproterozoic basement granitoid rocks (Lincoln et al., 2018; Honsberger et al., 2020b). Furthermore, these main shear vein systems are in turn overprinted by at least three generations of younger gold-mineralized vein sets associated with subsequent local episodes of horizontal extension, oblique compression, and minor late dextral strike-slip (Honsberger et al., 2019b, 2020b). A preliminary age of ca. 407 ± 4 Ma (Table 2, this study) from hydro-thermal rutile in a crosscutting vein with overall dextral asymmetry on the Wilding Lake prospect provides a minimum age for the formation of the main auriferous shear vein system cutting Rogerson Lake Conglomerate. Assuming the initial phase of transient lithospheric extension terminated by 418 Ma (youngest Mount Peyton rocks: Sandeman et al., 2017) and that the youngest gold mineralization event occurred at ca. 407 Ma (U-Pb rutile), northwest-directed, Early Devonian progressive deformation related to quartz-gold vein development lasted for approximately 10 million years, between ca. 418 and 407 Ma. This is consistent with reverse sinistral and dextral shearing and associated orogenic gold mineralization that occured between 415 and 386 Ma along the Cape Ray fault zone (Dubé and Lauzière, 1996, 1997; Dubé et al., 1996) and Acadian Orogeny deformation between 415 and 410 Ma along the Dog Bay Line in north-central Newfoundland (McNicoll et al., 2006), which is slightly younger than the reverse sinistral inversion of the Silurian La Poile basin that occured between ca. 429 and 418 Ma along the Cinq Cerf fault zone in southwestern Newfoundland (Fig. 1; O'Brien et al., 1993).

The association of Ag, Cu, W, Mo, Sb, and B with Au in altered Late Silurian to Early Devonian Rogerson Lake Conglomerate, magmatic rocks, and structurally controlled vein sets in central Newfoundland may suggest Late Silurian magmatic fluid input to the surrounding rocks and encompassing fault system (e.g. Sandeman et al., 2017). Regardless, gold-bearing fluid circulation was structurally controlled by the crustal-scale, northwest-directed master fault system that may have reactivated Late Silurian extensional faults as thick-skinned thrusts in the Early Devonian. The undeformed Late Silurian Wilding Lake pluton (422 Ma) does not record Early Devonian deformation; potentially because of its competency and structural position in the centre of a fault block (Fig. 4). Nonetheless, the proposed evolution is explained by Late Silurian initiation of a southeast-dipping fault system, and associated synorogenic sedimentation and magmatism, resulting from transient lithospheric extension of the accreted Penobscot/Victoria/Popelogan arc during roll-back and break-off of an underlying, subducted Ganderian slab (e.g. Whalen et al., 2006; Zagorevski et al., 2007; van Staal et al., 2014). Early Devonian, northwest-directed, thick-skinned inversion and thrust reactivation are attributed to Acadian orogenesis that resulted from the collision of Avalonia with the trailing margin of Ganderia (e.g. van Staal and Barr, 2012).

Comparison with the Abitibi Greenstone Belt

The emerging structurally controlled Paleozoic gold district of central Newfoundland is remarkably similar to the world-class Archean Abitibi orogenic gold system in scale (Fig. 1), synorogenic sedimentary and magmatic rocks, structural architecture, style of mineralization, tectonic evolution, and process rates (e.g. Bleeker, 2015; Honsberger and Bleeker, 2018). One key difference between the districts, other than the Abitibi systems being 2.2 billion years older, is that the Abitibi system is considerably more prolific, having produced 170 Moz (~5300 metric tonnes) of gold (Dubé and Mercier-Langevin, 2019).The detailed model presented in Bleeker (2015) for the Abitibi system was used as the main source of comparison in the following discussion.

First, the gold-mineralized crustal-scale fault systems in both areas extend continuously for ≥200 km along-strike and cut deformed and metamorphosed “granite-greenstone” basement terranes, with synorogenic unconformities separating uplifted basement blocks from younger, overlying upper-crustal synorogenic sequences of sedimentary (Rogerson Lake Conglomerate and Botwood basin, Newfoundland; Timiskaming conglomerate, Abitibi greenstone belt) and syenitic to monzonitic magmatic rocks (e.g. central Newfoundland: Sandeman et al., 2017), of overall low-grade metamorphic grade. Second, the synorogenic sequences of polymict conglomerate and cross-bedded sandstone occur as deformed and truncated synformal panels that display overall stratigraphic younging directions that point towards the master fault systems (Fig. 3–5; Victoria Lake shear zone and correlatives, Newfoundland: Destor-Porcupine and Larder Lake- Cadillac fault zones, Abitibi). Third, structurally controlled gold mineralization in both areas is preserved in the overall structural footwalls of the overarching crustal-scale fault zones. Fourth, orogenic-style gold mineralization (e.g. Groves et al., 1998) is hosted within laminated fault-fill and extensional shear vein networks (e.g. Dubé and Gosselin, 2007), as well as in brittle, crosscutting vein sets that indicate a period of extensive fluid cycling. Fifth, both gold systems record a process chain involving early imbrication of volcano-sedimentary terranes, transient lithospheric extension and uplift of basement blocks, synorogenic sedimentation and calc-alkaline to transitional alkaline magmatism, inversion and tectonic burial of the synorogenic basin during thick-skinned thrust re-imbrication, and degeneration to late-stage strike-slip deformation. Sixth, the time between transient lithospheric extension and subsequent tectonic burial of synorogenic basins in both areas spans approximately 15 to 20 million years. This implies comparable tectonic rates for Archean and Paleozoic lithospheric processes that produce and preserve structurally controlled gold deposits within crustal-scale fault systems.

Our study highlights that transient extension and synorogenic magmatism are critical ingredients for producing orogenic gold mineralization. Extension increases the geothermal gradient, generates deep-rooted magmas, and minimizes long-term post-orogenic uplift and erosion, whereas synorogenic magmatism further increases the geothermal gradient and may contribute fluids to the fault system (e.g. Bleeker, 2015). Additionally, inversion and tectonic burial of synorogenic clastic basins, followed by erosion of the overlying hanging-wall blocks, is essential for minimizing erosion of footwall blocks and preserving gold deposits. Ultimately, this research demonstrates that a common and predictable set of structural, magmatic, and tectonic processes leading to orogenic gold mineralization have recurred over more than 2 billion years of Earth’s history (Goldfarb et al., 2005).

IMPLICATIONS FOR EXPLORATION

The present research has local, regional, and global implications for exploration for orogenic gold mineralization. On a local and regional scale in central Newfoundland, our study indicates that rocks in the footwall blocks of the Victoria Lake shear zone and associated splays, including Late Silurian to Early

Devonian Rogerson Lake Conglomerate, Late Silurian sub-alkaline to alkaline intermediate felsic magmatic rocks and altered mafic dykes, and Neoproterozoic basement granitoid rocks are highly prospective for orogenic gold mineralization for at least 200 km along-strike (Fig. 3–5). Accordingly, the occurrence of upper-crustal, altered Rogerson Lake Conglomerate with felsic magmatic rocks (±mafic dykes) is a key geological association within the gold-mineralized fault system of central Newfoundland. Future exploration may consider targeting Neoproterozoic basement granitoid rocks of the Crippleback Intrusive Suite along-strike of the fault corridor, as these rocks are presently underexplored (except the Valentine Lake pluton, the main host of the Valentine Lake deposit), occur in the overall footwall of the Victoria Lake shear zone and correlative structures, and are mechanically favourable, brittle host rocks; i.e., analogues to some of the granitoid and porphyry stocks along the major fault zones of the Abitibi greenstone belt.

The global implications of the present research include characterizing common geological settings and associated recurring processes for structurally controlled gold mineralization from the Archean to Paleozoic. Accordingly, the geological and structural relationships documented in our research can be utilized as first-order guides in gold exploration to target and explore prospective terranes of any age. More detailed comparisons of both Archean and these Paleozoic systems (e.g. magma associations and overall proportions; fluid inclusions; isotopic tracer studies) may contribute to more detailed process understanding.

ONGOING AND FUTURE WORK

Further high-precision U-Pb detrital zircon geochronology is required at a regional scale in central Newfoundland to determine if the contact between Late Silurian to Early Devonian synorogenic Rogerson Lake Conglomerate and overlying Late Silurian felsic volcanic rocks is a stratigraphic or structural boundary (*see* "?" in Fig. 3, 4). Furthermore, additional field-based structural studies of the Rogerson Lake Conglomerate and associated rocks in the Valentine Lake area will be important for testing and refining the overall architecture of the crustal-scale, gold-mineralized fault system. Considering the association of synorogenic magmatism with orogenic gold mineralization, an important next step in comparing and contrasting central Newfoundland with the Abitibi greenstone belt is to quantify the volume of synorogenic magmatism in both areas and assess how this may relate to differences in gold potential and endowment.

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