



Structural geology of the eastern Nadaleen trend, Yukon Territory, Canada: Implications for recently discovered sedimentary rock-hosted gold



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ABSTRACT

Recently discovered gold-rich mineral deposits in the eastern Nadaleen trend of northeastern Yukon Territory occur in unmetamorphosed Neoproterozoic carbonate and siliciclastic rocks and their location is partly controlled by structures. Regional deformation largely resulted from mid-Cretaceous NNE-vergent, thin-skinned fold-thrust activity. However, structures in the eastern Nadaleen trend are more complex and include strike-slip and reverse faults, and SSW-, W-, and E-plunging folds. Local structures are cospatial with regional geologic features, including (1) an E-striking structural triangle zone defined by oppositely dipping reverse faults that verge toward the eastern Nadaleen trend, (2) a transition zone between Paleozoic Ogilvie platform rocks in the north to Selwyn basin rocks in the south, and (3) a change in regional deformation character from west to east, whereby to the west, rocks in the south are more deformed than rocks in the north, whereas to the east, rocks show no obvious change in deformation style. The structural complexity within the eastern Nadaleen trend probably resulted from these regional geological features and was further complicated by local competency contrasts between rock units. The cospatial location of the regional geological features may have been caused by a pre-existing, W-trending subsurface basement structure. Reverse faults bounding the E-striking triangle zone may have acted as low permeability aquitards that directed mineralizing fluids up-dip into reactive carbonate stratigraphy in the eastern Nadaleen trend. Gold-rich mineral deposits in the eastern Nadaleen trend occur preferentially in SSW-plunging anticlines and near faults, both of which probably influenced the migration of mineralizing fluid.

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1. Introduction

Sedimentary rock-hosted gold deposits in ATAC Resources Ltd.'s (ATAC) Nadaleen trend occurs in intensely deformed, unmetamorphosed shelf to off-shelf carbonate and siliciclastic rocks located immediately north of the interface between the Paleozoic Ogilvie platform and Selwyn basin and at the eastern edges of the multi-hundred km-scale Dawson thrust and Kathleen Lakes fault (Fig. 1) (Moynihan, 2016). The area is located in northeastern Yukon Territory, 185 km ENE of Mayo, the nearest community, and in the eastern part of the Rackla gold belt (Fig. 1a, b). The Anubis and Osiris gold clusters, including the Anubis, Conrad, Ibis (formerly Isis East), and Osiris/Sunrise gold-rich mineral deposits (Fig. 1c, d), were discovered within the

trend between 2010 and 2015. No official resource estimates for the deposits exist currently, but abundant gold has been discovered within drill holes (e.g., 42.93 m of 18.44 g/t gold at the Conrad deposit) and surface trenches (www.atacresources.com).

We investigated the structural setting of the eastern Nadaleen trend that includes the Conrad, Ibis, and Osiris/Sunrise deposits to assess the structural controls that contributed to the distribution and concentration of gold in the area. SSW-trending anticlines host gold in the Osiris/Sunrise and Ibis deposits (Fig. 1d) in a region that is otherwise dominated by W- and WNW-trending structures (Fig. 1c). Gold in the Conrad deposit (Fig. 1d) has previously been interpreted as occurring within (1) an E-W striking, brittle-ductile shear zone, primarily based on a regional lineament analysis (Venessa Bennett, 2012, ATAC Resources Ltd. internal report), and (2) a WNW-trending doubly plunging anticline, based on the apparent subsurface geometry of the Conrad limestone and the trace of gold mineralization in drill core (www.atacresources.com; Tucker et al., 2013). Within the context of regional

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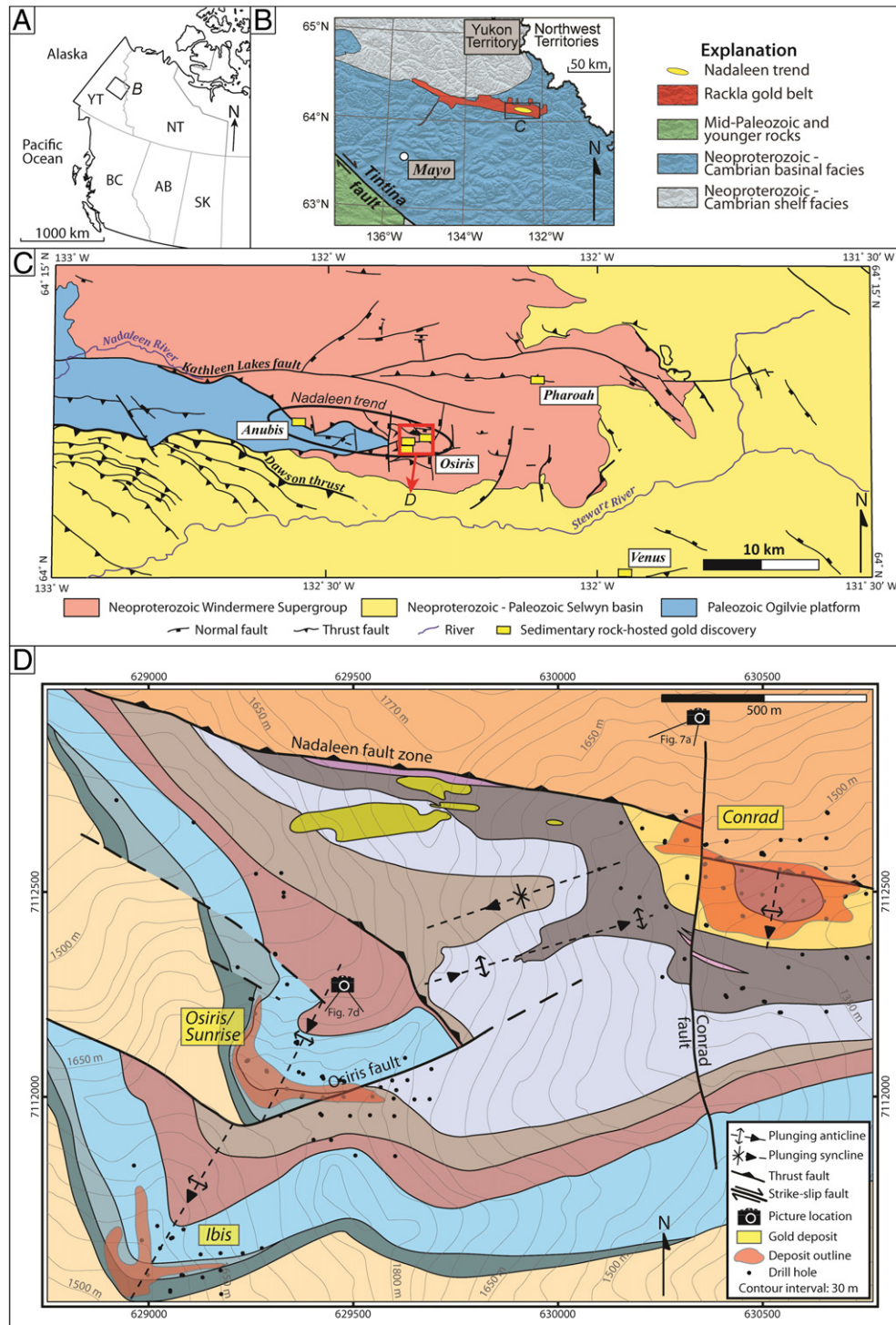


Fig. 1. A. Map of western Canada, showing location of (B). B. Generalized geologic map of northeastern Yukon Territory showing the outline of the Rackla gold belt, the Nadaleen trend, and the location of (C). C. Regional map showing sediment-hosted gold zones, reverse and normal faults, and regional stratigraphic domains. Red box outlines the eastern Nadaleen trend study area (D). Modified from Moynihan et al. (2014). D. Geologic map of the eastern Nadaleen trend showing local stratigraphy, structures, and generalized outlines of gold-rich mineral deposits projected to surface from drilling results. See Fig. 2 for color explanation and stratigraphic description.

geology, both of these interpreted geometries are unique to the eastern Nadaleen trend.

The aim of this study was to reveal the structural setting of the gold deposits in the eastern Nadaleen trend (Fig. 1c), using a multi-scale approach. We investigated the structural architecture in the Conrad deposit through detailed surface mapping of the poorly exposed, structurally complicated outcrops and through analysis of several

oriented drill cores. Surface structural mapping of other gold deposits in the eastern Nadaleen trend was also conducted to determine the structural setting of each deposit, and the structural history of the area. Finally, fold and fault trends from 1:50,000 scale regional quadrangle maps (Moynihan et al., 2014) were analyzed in order to interpret our results in a regional context, and to investigate the potential controls of regional structures on gold mineralization.

2. Geologic background

2.1. Stratigraphy

Rocks within the eastern Nadaleen trend correlate to Neoproterozoic-Cambrian Windermere Supergroup (Moynihan, 2016). These rocks were deposited on Paleo- to Neoproterozoic basement that consists of (from young to old) the Mackenzie Mountains Supergroup, the Pinguicula Group, and the Wernecke Supergroup (Thorkelson et al., 2001, 2005). Windermere Supergroup rocks are generally characterized by coarse, immature siliciclastic rocks interpreted to have been deposited during the first (723–716 Ma) of two rift phases that broke up the supercontinent Rodinia (Lund et al., 2003; MacDonald et al., 2010, 2012; Turner, 2011). The second phase of rifting (570–540 Ma) is interpreted to have opened the paleo-Pacific Ocean and initiated passive margin sedimentation on the Ogilvie platform and in Selwyn basin (Abbott, 1997; Colpron et al., 2002; Nelson et al., 2013). Rocks associated with the Ogilvie platform include fossiliferous limestone and dolostone of the Road River Group and the Bouvette Formation that are not observed south of the Dawson thrust fault (Moynihan, 2016). Selwyn basin rocks include siliciclastics, silty carbonates, and mafic volcanics of the Gull Lake, Old Cabin, Elmer Creek, and Steele Formations that are largely observed south of the Dawson thrust. These marked changes in sedimentary rock facies across the Dawson thrust fault (Fig. 1C) suggest the fault originated as a basin-bounding normal fault (proto-Dawson thrust) that profoundly influenced Paleozoic basin architecture (Abbott, 1997; Colpron et al., 2002; MacDonald et al., 2012; Mair et al., 2006; Moynihan, 2016). The location and trace of the Dawson thrust may have been controlled by the ancestral Dawson fault, an interpreted subsurface basement fault, based on (1) stratigraphic relationships adjacent to the fault, (2) igneous sills (Upper Paleozoic) and volcanic rocks (Cambrian-Devonian) that concentrate near the fault, and (3) the westerly trend of the fault that differs from the strong NW-trending structural grain present throughout western Canada (Abbott, 1990, 1997; Green, 1972). After the second phase of Neoproterozoic rifting, passive margin sedimentation and tectonic quiescence characterized the region through the mid-Mesozoic (Creaser et al., 1999; Hansen, 1990; Nelson et al., 2013).

Windermere Supergroup rocks observed within the eastern Nadaleen trend have been divided into three distinct stratigraphic sequences named (from oldest to youngest) Nadaleen North, Conrad, and Osiris. The oldest rocks are siliciclastic rocks in the Nadaleen North unit that correlate to the Mesoproterozoic Ice Brook Formation (Fig. 2) (Moynihan, 2016). These rocks are juxtaposed against the southward-younging Conrad and Osiris stratigraphic sequences to the south across the Nadaleen fault zone (Figs. 1d, 2). The Conrad sequence is primarily composed of fine-grained siliciclastic rocks and lesser carbonate rocks and carbonate conglomerate units. The overlying Osiris stratigraphic sequence is dominated by carbonate rocks with lesser siliciclastic rocks and also contains carbonate conglomerate units. All rocks in the Conrad sequence correlate with the undivided Nadaleen Formation and Osiris sequence rocks correlate to the Stenbraten Member of the Nadaleen Formation, and with the Gametrail and Blueflower Formations, all of which are of late Neoproterozoic age (Fig. 2) (Moynihan, 2016). The boundary between the Conrad and Osiris stratigraphic sequences is defined by a color difference between the gray shale of the Conrad sequence and the overlying maroon Osiris shale. The contact relationship is unclear as it is unexposed and may be conformable. Gabbro dikes (ca. 74–65 Ma; Venessa Bennett, 2013, ATAC Resources Ltd. internal report; Tucker, 2015) occur adjacent to the Nadaleen fault zone (Fig. 1d).

2.2. Regional deformation

Disruption of the passive margin occurred during the Late Triassic to Early Jurassic as a result of eastward subduction and island arc collision

with the western margin of the continent, marking the onset of Cordilleran deformation (Nelson et al., 2013). Heterogeneous strain affected the entire continental margin and as a result, N-vergent, thin-skinned thrust faults and folds formed throughout the Selwyn basin and Ogilvie platform (Evenchick et al., 2007; Gehrels et al., 2009; Mair et al., 2006; Murphy, 1997; Nelson et al., 2013). Earlier normal faults, such as the proto-Dawson thrust, were inverted such that basinal facies in the south were juxtaposed against platformal rocks in the north, west of the eastern Nadaleen trend (Fig. 1C) (Evenchick et al., 2007; Gehrels et al., 2009; Mair et al., 2006; Moynihan, 2016; Murphy, 1997; Nelson et al., 2013). The Kathleen Lakes fault (Fig. 1c) north of the Nadaleen trend is strike-parallel to the Dawson thrust and may have formed during the same deformation event. The movement sense and dip direction of the Kathleen Lakes fault are unclear over the extent of the fault, but may accommodate strike-slip and/or reverse offset (Moynihan, 2016). Igneous activity of varying Mesozoic and early Cenozoic ages occurred near the plate margin (e.g., Cretaceous to early Cenozoic Coast plutonic belt) and throughout the Selwyn basin (Gordey and Anderson, 1993; Monger et al., 1982; Monger and McNicoll, 1993; Murphy, 1997; Nelson et al., 2013) and Ogilvie platform (Moynihan, 2016). Igneous rocks within the Selwyn basin include the Tombstone (94–90 Ma) and McQuesten (67–61 Ma) plutonic suites (Murphy, 1997). Granitic aplite and pegmatite in the Rau trend in the western Rackla gold belt are considered to be related to the McQuesten plutonic suite and yielded 62–59 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages (Kingston et al., 2009). Gabbro dikes dated using $^{40}\text{Ar}/^{39}\text{Ar}$ (hornblende) and U/Pb (zircon) from the eastern Nadaleen trend are enigmatic in that they give ages of $\sim 74.4 \pm 1.0$ Ma (Tucker, 2015) that do not fit with these regional data.

2.3. Mineralization

Mineral deposits in the region include carbonate-hosted disseminated gold (Carlin-type), sediment-hosted Mississippi valley-type Pb-Zn, Sedex-style Zn-Pb-Ag, vein-hosted polymetallic Ag-Pb-Zn +/- Au, and carbonate replacement, intrusion-related Au-W (Arehart et al., 2013; Tucker et al., 2013; Tucker, 2015; Moynihan, 2016). Gold in the eastern Nadaleen trend occurs as microscopic and sub-microscopic particles primarily in disseminated to semi-massive pyrite in carbonate rocks although some gold occurs in siliciclastic rocks (Arehart et al., 2013; Tucker et al., 2013; Tucker, 2015). Gold in the Conrad deposit occurs in limestone and overlying siliciclastic rocks in the Conrad stratigraphic sequence and gold in the Ibis and Osiris/Sunrise deposits occur in limestone and dolostone of the Osiris stratigraphic sequence (Fig. 2). Alteration types in the Conrad deposit consist of decalcification and brecciation with subsequent silicification (Tucker et al., 2013). The Conrad deposit features fine-grained, ore-stage, disseminated arsenic-bearing pyrite and abundant late-ore stage, open-space filling minerals including realgar, orpiment, illite, fluorite, and calcite (Tucker et al., 2013). The alteration types, replacement and open-space filling ore and gangue minerals, gold-related element association of arsenic, mercury, and thallium, as well as the structural and stratigraphic position of the Conrad deposit and other gold deposits within the region led Arehart et al. (2013) and Tucker et al. (2013) to interpret the Conrad deposit as a 'Carlin-type deposit' similar to prolific sedimentary rock-hosted gold deposits that occur in Nevada. Gabbro dikes at the Conrad deposit are locally hydrothermally altered and mineralized in a manner consistent with Carlin-type deposits (Tucker et al., 2013; Tucker, 2015).

3. Results

3.1. Oriented drill core

Structural data were collected from oriented drill core in the Conrad deposit. The Reflex® oriented core device was used during drilling and each drilled interval was marked with a 'bottom mark' showing the side

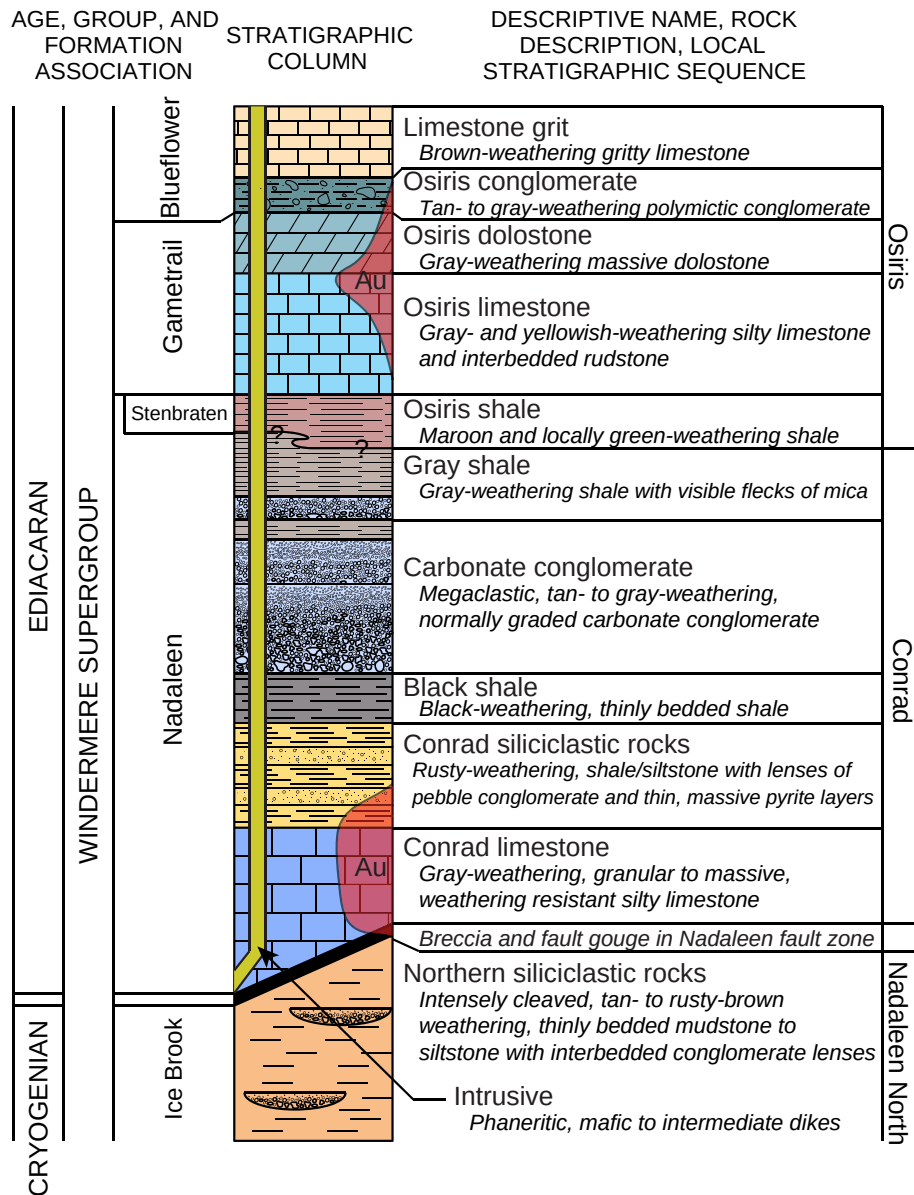


Fig. 2. Eastern Nadaleen trend stratigraphic column showing relative thicknesses as preserved today and the rock types that host gold (Au). Rock ages, group, and formation associations are from Moynihan (2016). Northern siliciclastic rocks are separated from the Conrad limestone by rocks of the Nadaleen fault zone.

of the core that points down in a non-vertical hole. After drilling, the core was reassembled to its original downhole state, the bottom mark was traced along the outside of the core with a tungsten carbide scribe, and a Reflex® goniometer was used to extract bedding and foliation orientations. Data not included into our analysis included data from zones where the bottom marks from consecutive drilled intervals did not correlate, which frequently occurred in highly fractured, mineralized, and/or altered zones where piecing the core together to its original downhole state was not possible. Data was collected on 53% of the intervals where oriented drill core was taken. Minor error may have been introduced during core reassembly, scribing of the bottom mark, and the thickness of the marker used to mark the bottom mark, but we do not believe that affected our data set significantly.

Plan view maps in Fig. 3 show rock units, outlines of mineralized rocks, drill hole intersections, and structural data from oriented drill core at six levels below the surface of the Conrad deposit. The original elevation datum used for the depths was 1503.2 m, defining the drill collar with the highest elevation. The 100 – 200 m plan view map (Fig. 3), for example, displays data collected from elevations between

1403.2 – 1303.2 m. Geologic contacts were interpreted from all 99 drill holes. Equal-area lower-hemisphere projections were constructed using OSXStereonet (Cardozo and Allmendinger, 2011) and show poles to bedding planes and best-fit great circles defined with a Bingham axial distribution (Bingham, 1974). On the plan view maps, colored drill intersections define where structural data shown in Fig. 4 were collected.

Bedding poles from some oriented drill holes indicate fold geometries with moderate to steep plunges towards the south, west, or north (Fig. 4a, b, c, resp.), while those from other drill holes show subvertical ENE-planar bedding (Fig. 4d, e). The NNE-dipping Nadaleen fault zone cuts off the Conrad deposit to the N (Fig. 3), and foliation within the fault zone has an best-fit orientation of 277°/67° (Fig. 4f). The latest structural feature is the N-trending Conrad fault that offsets all rock units in a right-lateral sense (Fig. 3). Slickensides with dextral-sense lineations and drag folds were observed in a decimeter-scale fault at a location consistent with the projected surface location of the Conrad fault based on drill core data. The Conrad fault is therefore interpreted as a dominantly dextral strike-slip fault. Geologic contacts

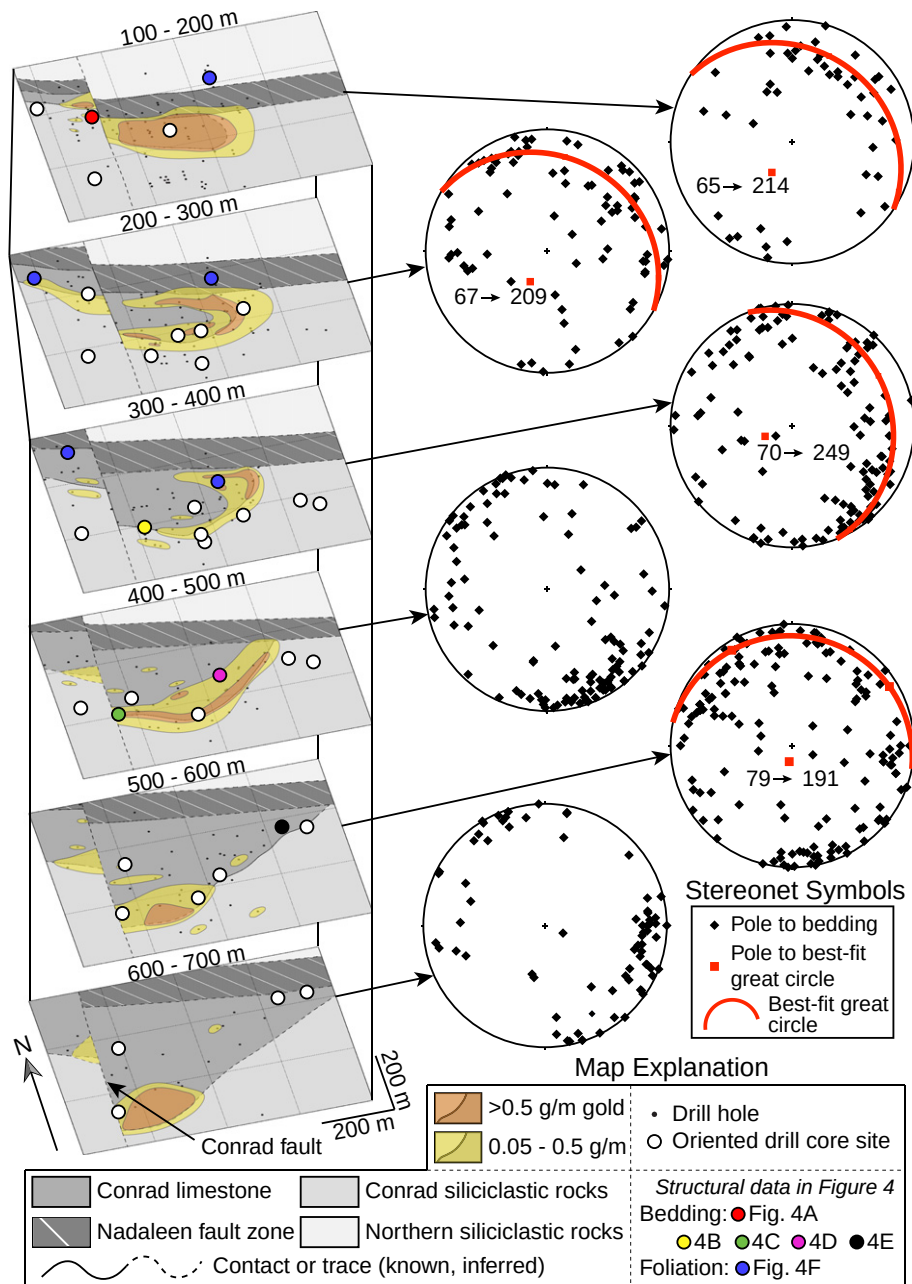


Fig. 3. Map stack through the Conrad gold deposit showing rock type, average intersected gold grade, and basic (black dots) and oriented (filled circles) drill core sites. Structural data collected from each map in the map stack are shown in the equal-area lower-hemisphere projections. Great circles are indicated where poles show a fold geometry. The great circle orientation was determined with a Bingham axial distribution (Bingham, 1974) in OSXStereonet (Cardozo and Allmendinger, 2011).

between limestone and siliciclastic rocks in map view in the top two maps (100 – 300 m) outline an apparent ESE-trending fold, while all sections below this (300 – 700 m) suggest a SSW-trending fold. However, poles to bedding (Fig. 3) generally outline a great circle suggesting that most levels, including the top levels, may be characterized by steeply SSW- to WSW-plunging folds (fold axes represented by red dots in equal-area lower-hemisphere projections in Fig. 3) that steepen with increasing depth. Scatter in the data most likely reflects unresolvable error associated with data collection from oriented drill core. Structural data more commonly reflect a folded geometry adjacent to the Conrad fault (Fig. 4a, b, c), while planar bedding is more commonly observed away from the Conrad fault (Fig. 4d, e). Although map patterns and outlines of mineralized rocks near the top of the mineral deposit suggest the presence of an E-W oriented anticline, structural data do not provide evidence for this interpretation.

3.2. Surface mapping

The geology of the eastern Nadaleen trend is dominated by moderately to steeply S- to SSW-plunging anticlines that host the Osiris/Sunrise, Ibis, and Conrad gold deposits (Figs. 1d, 5). The generally E-trending Osiris fault offsets the Ibis and Osiris anticlines and juxtaposes the carbonate conglomerate unit against itself, resulting in a large apparent thickening of this unit between the Conrad and Osiris/Sunrise deposits (Figs. 1d, 5, 6, 7a). The Osiris and Conrad stratigraphic sequences are truncated to the N by the NNE-dipping Nadaleen fault zone (Figs. 1d, 5, 6). Gabbroic dikes occur along and south of the Nadaleen fault zone (Figs. 1d, 5, 6). Surface outcrop structural mapping was completed at 1:1500 scale and structural subdomains (Fig. 5) were defined by structural similarity and/or orientation. The surface structural geology is described below by

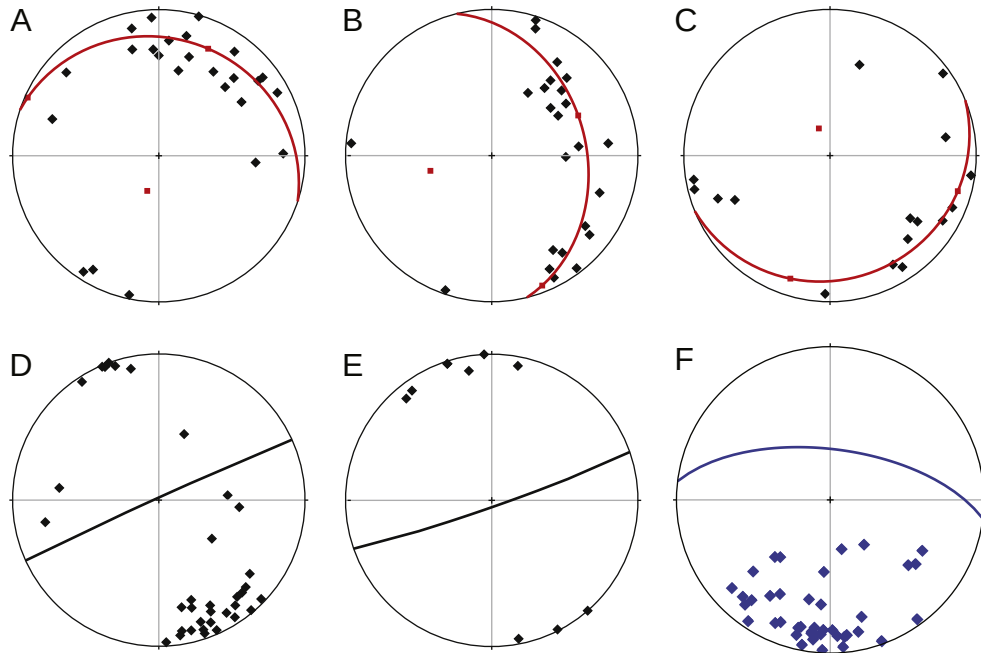


Fig. 4. Equal-area lower-hemisphere projections of structural data from oriented drill core within select intervals at the Conrad deposit. Poles to bedding suggest folded geometry from: A. Drill hole 156 ($70^{\circ} \rightarrow 198^{\circ}$) in the 100 – 200 m map (red circle; Fig. 3); B. Drill hole 157 ($54^{\circ} \rightarrow 225^{\circ}$) in the 300 – 400 m map (yellow circle; Fig. 3); C. Drill hole 148 ($74^{\circ} \rightarrow 338^{\circ}$) in the 400 – 500 m map (green circle; Fig. 3). Poles to bedding suggest planar geometry from: D. Drill hole 119 ($246^{\circ}/89^{\circ}$) in the 400 – 500 m map (purple circle; Fig. 3); E. Drill hole 193 ($061^{\circ}/77^{\circ}$) in the 500 – 600 m map (purple circle; Fig. 3). The black great circles in (D) and (E) show the best-fit orientations of planar bedding. Best-fit great circle orientations were determined with a Bingham axial distribution (Bingham, 1974) in OSXStereonet (Cardozo and Allmendinger, 2011). F. Poles to foliation data collected from all oriented drill holes intersecting the Nadaleen fault zone (blue circles; Fig. 3) show a best-fit orientation of $277^{\circ}/67^{\circ}$ (blue great circle).

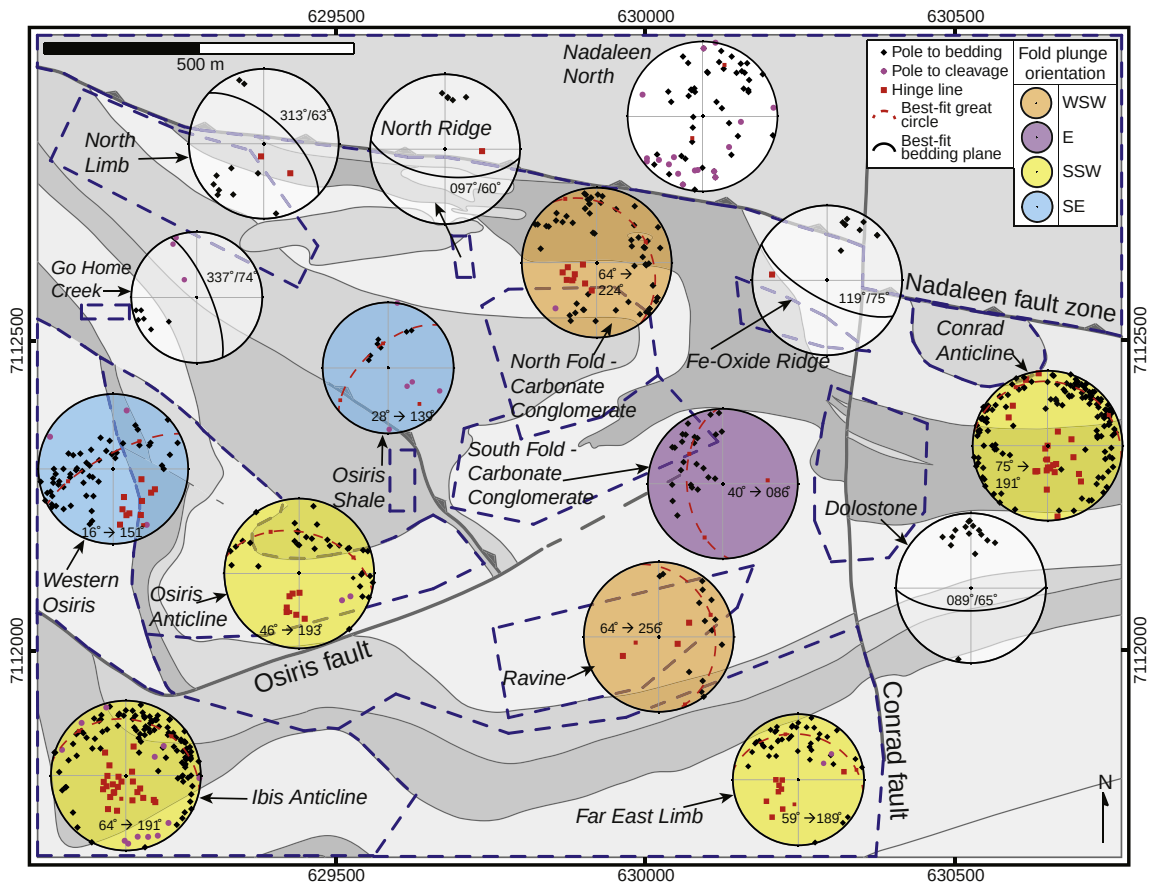


Fig. 5. Grayscale map of the eastern Nadaleen trend (from Fig. 1D) showing structural domains, domain names, and equal-area lower-hemisphere projections of structural data and best-fit great circle orientations. Best-fit great circle orientations were determined with a Bingham axial distribution (Bingham, 1974) in OSXStereonet (Cardozo and Allmendinger, 2011). Colors of equal-area lower-hemisphere projections reflect general fold orientations.

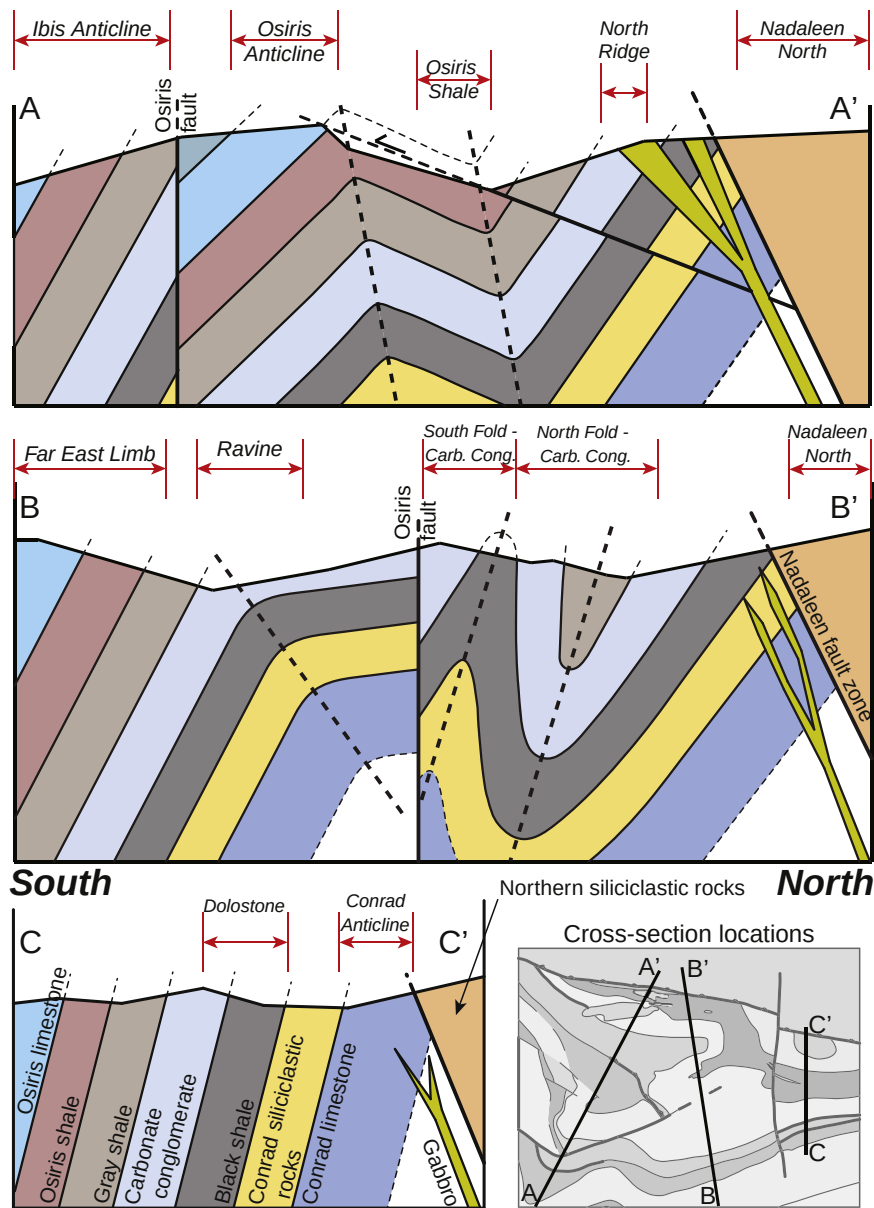


Fig. 6. Interpreted geologic cross sections and location map. Intersected structural domain names indicated above the sections. Colors as in Fig. 2.

stratigraphic sequence: structural domains in the Nadaleen North stratigraphic sequence are described first followed by the Conrad and Osiris sequences.

The most characteristic structural feature within the Nadaleen North structural subdomain is strong cleavage (Fig. 5) that is most commonly oriented parallel to foliated rocks in the Nadaleen fault zone (277°) (Figs. 4f, 7b). Rocks exhibit intense pencil cleavage adjacent to the Nadaleen fault zone. Poles to bedding are scattered and may reflect unresolvable structures in the monotonous rocks and/or more than one phase of folding (Fig. 5). An best-fit strike of bedding (294°) is still preserved and may be similar to the average strike of foliation in the Nadaleen fault zone.

In the Conrad stratigraphic sequence, rocks are characterized by map- to hand sample-scale, open to tight chevron folds in a variety of orientations. Centimeter- to meter-scale folds exist in the North Limb, North Ridge, and the Fe-oxide Ridge structural subdomains (Figs. 5, 7c). Steeply SSW-plunging folds occur throughout the Conrad Anticline subdomain (Figs. 5, 7e). The North Fold – Carbonate Conglomerate and South Fold – Carbonate Conglomerate subdomains show a map-scale anticline-syncline pair with fold axes plunging in opposite directions

(Figs. 5, 7a). Gabbroic intrusive rocks are largely undeformed and display chilled margins.

Deformed Osiris sequence rocks are characterized by map- to hand sample-scale, open to tight chevron folds in several orientations. Bedding in the Go Home Creek subdomain is overturned (Fig. 5). The axial traces of the Osiris Anticline and Ibis Anticline subdomains occur in similar orientations and are nearly in alignment. The Osiris fault is characterized by fault gouge and breccia and offsets the Osiris and Ibis anticlines. The SE limb of the Osiris Anticline subdomain dips moderately to the south and the NW limb is generally sub-vertical and SSW-trending (Fig. 5). The NW limb of the Ibis Anticline subdomain dips steeply to the WSW and the SE limb dips steeply to the SSW (Fig. 5). The Osiris Anticline and Ibis Anticline subdomains contain centimeter- to meter-scale parasitic folds (Fig. 7d) in an orientation similar to the map-scale fold.

3.3. Quadrangle map analysis

The orientations of reverse faults and fold axial traces throughout the Nadaleen region were compiled from regional geologic maps

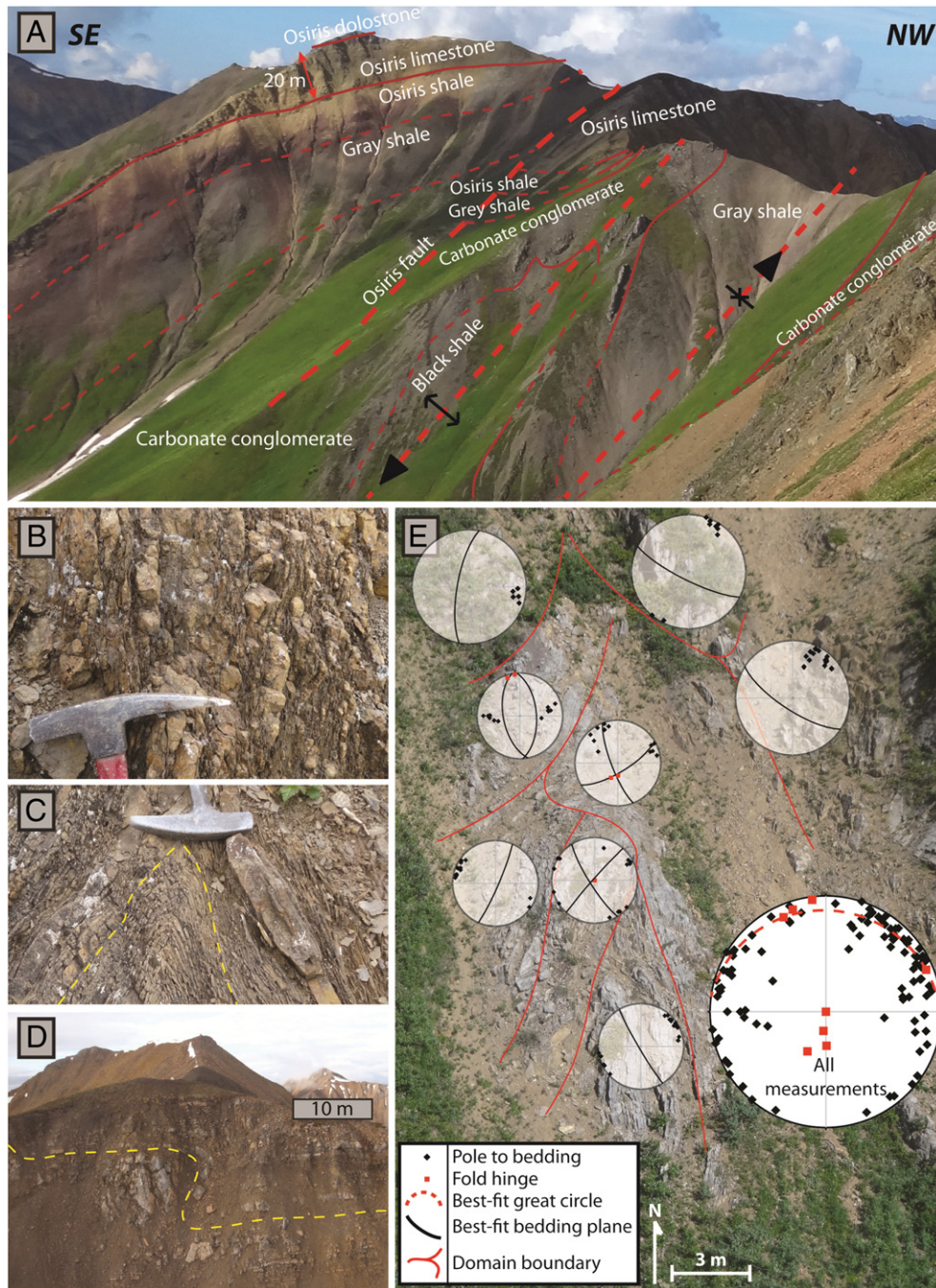


Fig. 7. Outcrop photos within the eastern Nadaleen trend. A. Rock units, exposed and inferred contacts, and fault and fold traces within the eastern Nadaleen trend. Photo location defined in Fig. 1D. B. Scaly foliation and elongate clasts in fault rock of Nadaleen fault zone. C. Close chevron folds in Conrad siliciclastic rocks on Fe-Oxide Ridge structural subdomain (see Fig. 5). D. Parasitic fold in the Osiris limestone on the SE limb of the Osiris Anticline structural subdomain, looking south. Photo location defined in Fig. 1D. E. Detailed structure map of a well-exposed and representative outcrop of Conrad limestone in the Conrad Anticline subdomain, looking north. Best-fit great circle orientations were determined with a Bingham axial distribution (Bingham, 1974) in OSXStereonet (Cardozo and Allmendinger, 2011).

(Moynihan et al., 2014) and are summarized here using regional structural domains (Fig. 8). The term reverse fault is used as opposed to thrust fault because the dips are not published in Moynihan et al. (2014). Reverse faults in the Overlap Assemblage, Upper Plate Dawson Fault, and Eastern Nadaleen structural domains generally reflect N- to NW-vergence, while S-vergent reverse faults occur in the Nadaleen Area, North of Nadaleen, and Northeast Nadaleen structural domains. No map-scale reverse faults have been documented in the Northwest structural domain (Moynihan et al., 2014).

Fold trends throughout the Nadaleen region show marked deviations from regional trends at and north of the eastern Nadaleen trend.

Folds in the Northwest, Overlap Assemblage, Upper Plate Dawson Fault, Northeast Nadaleen, and Eastern Nadaleen structural domains generally trend ESE to SE, whereas folds in the North of Nadaleen and Nadaleen Area domains trend NE to E (Fig. 8).

4. Discussion

4.1. Deformation history

Map-scale structures at the eastern Nadaleen trend include: (1) moderately to steeply S- to SSW-plunging anticlines, (2) WSW-, SE-,

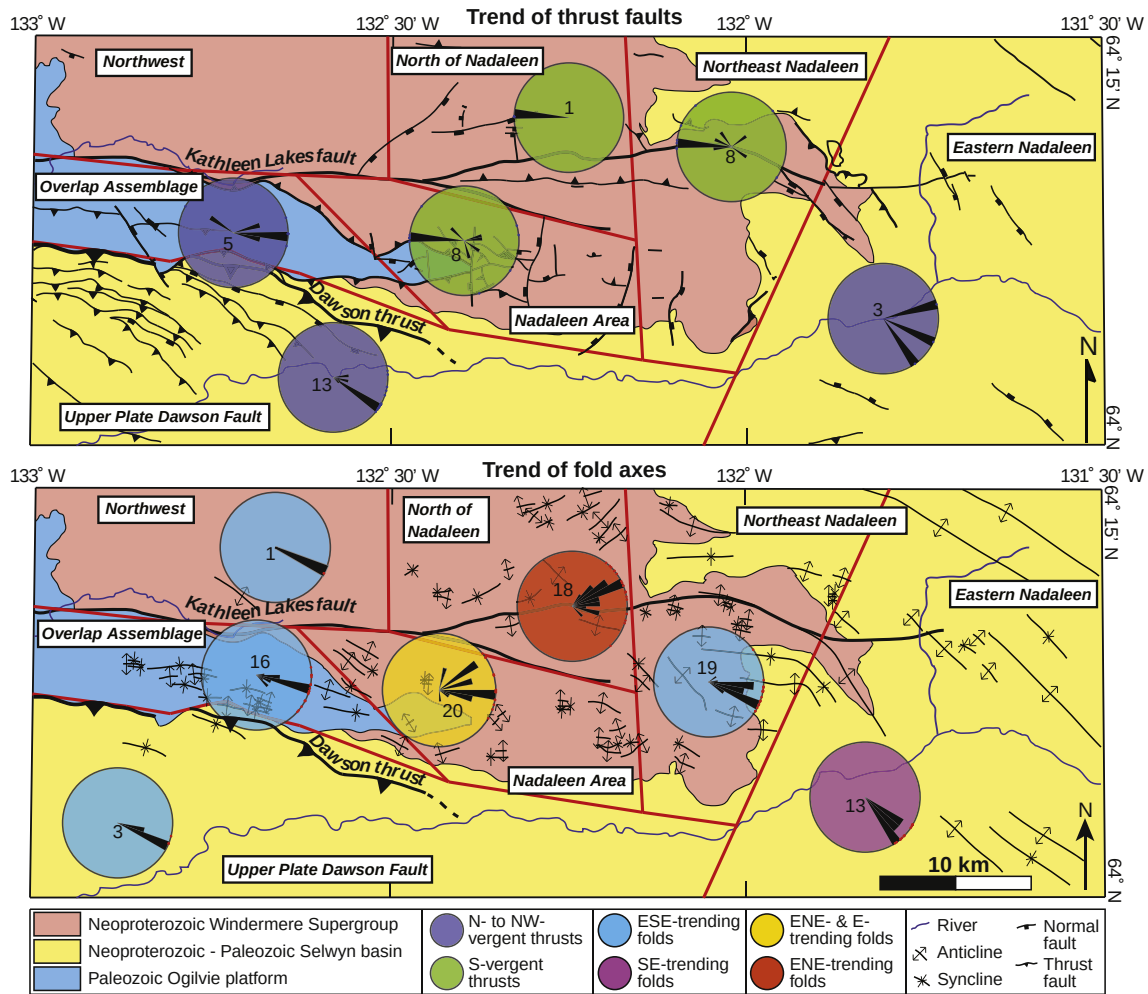


Fig. 8. Reverse fault strike (American right-hand rule) and fold axial trace orientation analysis of regional quadrangle maps near the Nadaleen trend. Dips and plunges were not published on the maps and therefore are not recorded here. Map location defined in Fig. 1b. Modified from Moynihan et al. (2014).

and E-plunging folds, (3) the E-trending Osiris fault, (4) the NNE-dipping Nadaleen fault zone, and (5) the late N-trending Conrad fault (Figs. 1d, 5). Slickenside lineations on an outcropping fault in the Conrad siliciclastic rocks and offset rock units from drill core intersections indicate the Conrad fault accommodated dominantly dextral strike-slip movement. The high-angle Nadaleen fault zone juxtaposes the older Nadaleen North stratigraphic sequence in the north against the younger Conrad and Osiris stratigraphic sequences in the south. Juxtaposition relationships, a steep dip, and enigmatic shear sense indicators suggest the Nadaleen fault zone is a reverse fault with a history of overprinting deformation. Folded rocks in the Conrad and Osiris stratigraphic sequences are offset along the sub-planar Nadaleen fault zone, indicating folding occurred prior to formation of the Nadaleen fault zone. The Osiris fault is sub-vertical, separates the Ibis and Osiris anticlines in map view, and ends less than ~1.5 km east of the Osiris and Ibis anticlines. The shear sense along the Osiris fault remains unclear, but may be explained by north-side-down slip where the Osiris and Ibis anticlines were originally one continuous anticline (Moynihan, 2016) or by dextral movement so that the Osiris and Ibis anticlines were originally two adjacent anticlines as part of one fold system.

Observed structures within the Conrad and Osiris stratigraphic sequences south of the Nadaleen fault zone may be schematically reconstructed in three ways: (1) W-vergent folding and contemporaneous or subsequent top-to-the-W thrust faulting along the Osiris fault, followed by tilting to the south; (2) W-vergent folding followed by tilting to the south followed by right-lateral strike-slip faulting along

the Osiris fault; or (3) tilting to the SSW followed by WNW-ESE shortening that resulted in folding and contemporaneous or subsequent strike-slip faulting along Osiris fault. The first two models require top-to-the-W transport to form the SSW-plunging folds, which is not a regionally recognized deformation event. The third model can be explained by regionally recognized deformation patterns (as explained below) and is therefore our preferred model.

In our preferred model (third model above), the rocks were initially tilted to the SSW (Fig. 9: D₁), potentially as a result of NNE-SSW directed shortening consistent with large regional thrust faults and folds related to mid-Cretaceous NNE-directed fold-thrust deformation (Evenchick et al., 2007; Gehrels et al., 2009; Mortensen, 1982; Murphy, 1997; Nelson and Colpron, 2007; Nelson et al., 2013; Roots, 1997; Stephens et al., 2004). Subsequent to tilting, WNW-ESE shortening folded the tilted rocks into moderately to steeply SSW-plunging Z-folds such as the Osiris and Ibis anticlines (Fig. 9: Early D₂). Further shortening led to brittle faulting along the Osiris fault (Fig. 9: Late D₂). Right-lateral offset of ~500 m along Osiris fault caused the apparent spatial continuity between the axial traces of the Osiris and Ibis anticlines (Fig. 9: Late D₂). NE-trending folds have been recognized north of the eastern Nadaleen trend (Moynihan, 2016) and may be related to this WNW-ESE shortening (Fig. 8). Rheological contrasts between competent limestone units and weak shale units resulted in local thickening of the Osiris shale and gray shale units in the hinge zone of the Osiris anticline during Late D₂. We interpret that local thickening also caused: (1) rotation of the northern fold in the carbonate conglomerate rocks from an

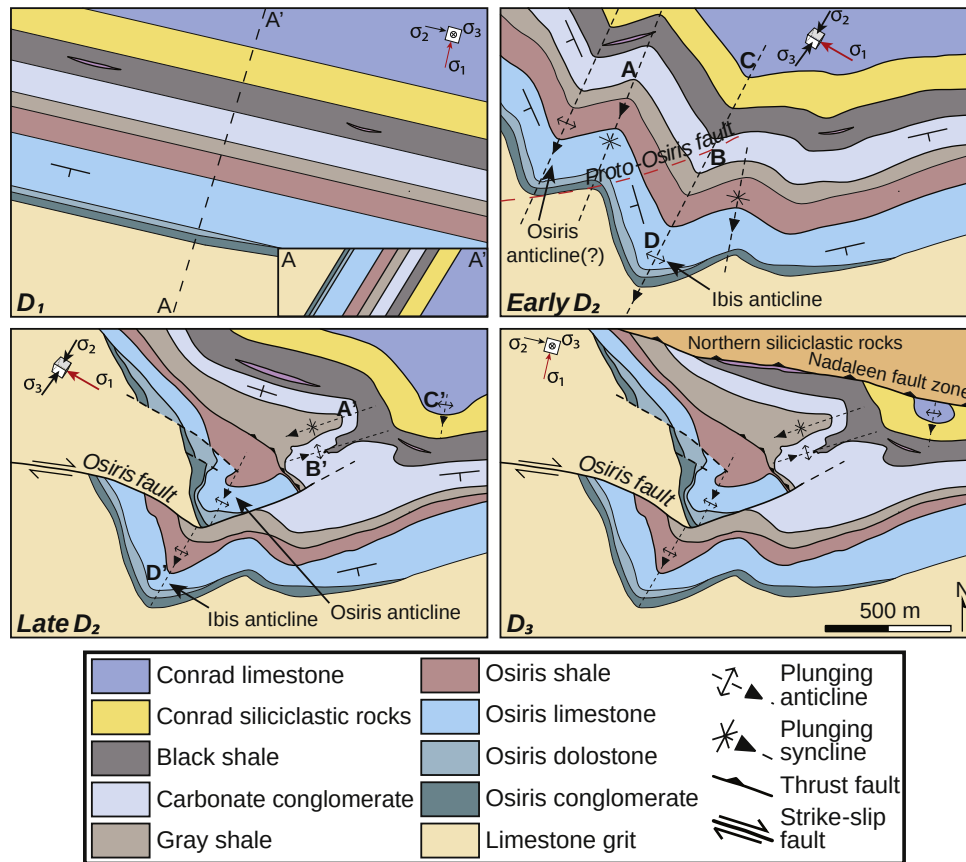


Fig. 9. Schematic structural reconstruction of the eastern Nadaleen trend including interpreted principal stress axes visualized on a cube for each map. See text for discussion. Scale and north arrow for all maps shown in bottom right of bottom right-hand map.

originally SW-trending fold axis orientation (A; Fig. 9: Early D_2) to a WSW-trending fold axis orientation (A'; Fig. 9: Late D_2), (2) tilting and rotation of the southern fold in the carbonate conglomerate from SW-trending, SW-plunging (B; Fig. 9: Early D_2) to WSW-trending, E-plunging (B'; Fig. 9: Late D_2), and (3) eastward translation of the Conrad anticline (C-C'; Fig. 9). Subsequent or coeval N-S directed shortening (Fig. 9: D_3) then resulted in the activation of the Nadaleen fault zone. S-vergent reverse faults similar to the Nadaleen fault zone have been recognized north of the eastern Nadaleen trend (Fig. 8) (Moynihan, 2016). Gabbroic dikes (ca. 74–65 Ma; Venessa Bennett, 2013, ATAC Resources Ltd. internal report; Tucker, 2015) primarily occur in the immediate footwall of the Nadaleen fault zone and have not been observed north of the fault zone; however, clasts of gabbro are incorporated into the Nadaleen fault zone (Tucker, 2015). These relationships suggest that the Nadaleen fault zone structurally controlled dike intrusion into the footwall of the fault only, and that the fault remained active after intrusion. Sericitic alteration and locally abundant pyrite and trace realgar mineralization in the dikes indicate that dike intrusion occurred before Conrad gold mineralization (Tucker, 2015). The final phase of deformation is dextral strike-slip faulting along the north-trending Conrad fault (D_4) that offsets all rock types and may offset mineralized rocks (Fig. 3).

This sequence of deformation events, including the style and orientation of local faulting and folding, thickening of units, and rotation of structures is unique to the eastern Nadaleen trend and is significantly different from regional structures. However, several other structurally complex zones are observed regionally and are interpreted to result from deformation imposed on rheologically heterogeneous sedimentary rocks (Cecile, 2000; Gabrielse, 1967; Gordy and Thompson, 1991; Mair et al., 2006; McMechan et al., 1991; Norris, 1974; Stockwell, 1969). Below, we integrate our local structural observations in the

eastern Nadaleen trend with regionally observed structures in order to understand why the observed sequence of deformation events has not been observed anywhere else regionally, and to potentially explain why gold occurs in the area.

4.2. The Nadaleen triangle zone

Reverse faults north and south of the eastern Nadaleen trend (Fig. 8) dip away from and show vergence toward the eastern Nadaleen trend. The orientations and motion sense of these oppositely verging faults are consistent with NNE-vergent fold-thrust deformation that commenced in the Late Triassic to Early Jurassic (Evenchick et al., 2007; Gehrels et al., 2009; Mair et al., 2006; Murphy, 1997; Nelson et al., 2013), making it likely that they formed coevally. This structural setting is similar to triangle zone geometry; similar structures are most common at the foreland margins of fold-thrust belts (Couzens and Wiltchko, 1996; Gordy et al., 1977; Jones, 1996) and have been observed above basement structures such as normal faults (Çemen et al., 2002; Woodward, 1985). They have been studied in great detail, because of the role they can play in trapping hydrocarbons (Couzens-Schultz et al., 2003; MacKay, 1996; Zapata and Allmendinger, 1996). An interpreted analog to the triangle zone across the eastern Nadaleen trend occurs in the Wilburton gas field of southeastern Oklahoma, USA (Fig. 10). Similar to the eastern Nadaleen trend, the Wilburton triangle zone is characterized by oppositely verging thrust faults, the stratigraphy is composed of rocks of widely variable competency, and thrust fault imbrication occurs against the primary foreland-directed detachment fault (Çemen et al., 2002; Woodward, 1985). The Wilburton triangle is interpreted to lie above a basement normal fault (Çemen et al., 2002; Woodward, 1985), which

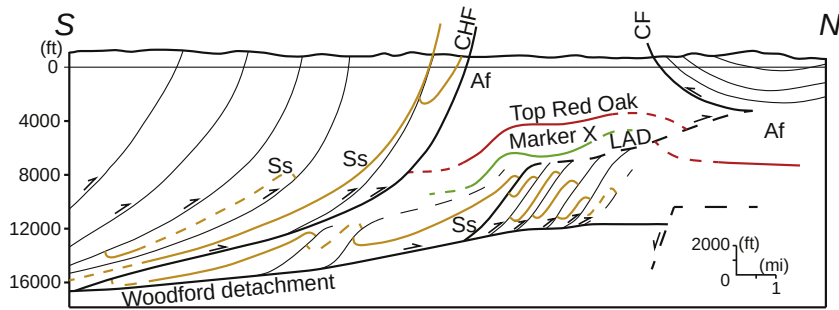


Fig. 10. Cross-section of a triangle zone in the Wilburton gas field of the Arkoma basin in southeastern Oklahoma derived from surface structural mapping, well logs, and 2D seismic data. Abbreviations: CF – Carbon fault, CHF – Choctaw fault, LAD – Lower Atoka detachment, Ss – Spiro sandstone, Af – Atoka formation. Modified from Çemen et al. (2002).

may also be true for the eastern Nadaleen trend. The N-vergent Dawson thrust at the eastern Nadaleen trend may be analogous to the Choctaw Fault of the Wilburton triangle. The Nadaleen fault zone or other south vergent reverse faults (Kathleen Lakes fault?) north of the eastern Nadaleen trend may be analogous to the Wilburton triangle's Carbon Fault (Fig. 10). Structures within the triangle zone may have controlled mineralizing fluid migration similar to gas migration in the Wilburton gas field, and perhaps explain the localities of mineralization.

The eastern Nadaleen trend triangle zone is a discrete feature and is generally confined to the eastern Nadaleen trend; south vergent thrust faults to the north terminate to the west and north vergent thrust faults to the south terminate to the east (Fig. 8). A number of other major regional-scale geologic transitions have existed within this area over geologic time. First, the Proterozoic basin architecture markedly changes near the eastern Nadaleen trend (Figs. 1c, 8). West of the triangle zone, the transition between the Ogilvie platform to the north and Selwyn basin to the south is interpreted to have been abrupt, defined by offset along a basin bounding fault (proto-Dawson thrust) (Abbott, 1997; Macdonald et al., 2012; Mair et al., 2006; Norris, 1997). East of the eastern Nadaleen trend triangle zone, where the basin bounding fault did not exist, the transition between platform and basin is interpreted to have been gradual (Abbott, 1997; Norris, 1997). Second, Paleozoic Ogilvie platform shelf-carbonate facies are transitional to the south and east with basinal facies of the Selwyn basin (Figs. 1c, 8). Third, the Dawson thrust and Kathleen Lakes fault both terminate proximal to the eastern Nadaleen trend (Figs. 1c, 8). Fourth, fold axis orientations change from SSE- and SE-trending to the west, south, and east of the eastern Nadaleen trend, to NE- and E- trending at and north of the area (Fig. 8). The changes in regional geologic trends across the eastern Nadaleen trend are discussed in more detail below.

West of the eastern Nadaleen trend, numerous reverse faults and fold axial traces in the Upper Plate Dawson thrust and Overlap Assemblage structural domains (Fig. 8) are parallel to structures elsewhere in the Selwyn basin that formed during Mesozoic fold-thrust deformation (Evenchick et al., 2007; Gehrels et al., 2009; Mortensen, 1982; Murphy, 1997; Nelson and Colpron, 2007; Nelson et al., 2013; Roots, 1997; Stephens et al., 2004). In the Northwest structural domain, no map-scale reverse faults have been documented and mapped folds trend ESE (Fig. 8) (Moynihan et al., 2014). Thus, west of the eastern Nadaleen trend, the number of reverse faults and folds, and therefore the amount of strain, decreases significantly to the north, with little strain north of the Overlap Assemblage structural domain. East of the eastern Nadaleen trend, fold orientations in the Eastern Nadaleen and Northeast Nadaleen structural domains dominantly reflect NNE-vergent deformation and S-vergent structures have not been documented. Thus, east of the eastern Nadaleen trend, strain does not decrease significantly towards the north. The orientations of reverse fault and fold axes in the Nadaleen Area and North of Nadaleen structural domains dominantly suggest S-vergent deformation, a characteristic not observed beyond these two structural domains.

Regional structures west of, east of, and at the eastern Nadaleen trend are each unique. We interpret that their differences result from the influence of an unexposed W-trending obstruction that may not extend east of the eastern Nadaleen trend (Fig. 11). This hypothesized obstruction may have presented a barrier to NNE-directed fold-thrust movement west of the eastern Nadaleen trend, shielding the Northwest structural domain from accumulating significant strain (Fig. 11; Western Domain). Across the eastern Nadaleen trend, the effects of the obstruction may have diminished just enough to result in a minor barrier to NNE-directed fold-thrust movement, permitting translated rocks to override the barrier and detach rocks in the foreland to form a triangle zone similar to the Wilburton gas field example (Figs. 10, 11; Central Domain). East of the eastern Nadaleen trend, the obstruction does not exist and fold-thrust movement occurs throughout (Fig. 11; Eastern Domain).

Potential reasons for the interpreted obstruction may include rheological heterogeneity between competent platform rocks of the Ogilvie platform and less competent basin rocks of the Selwyn basin and/or the presence of a subsurface structure, such as a basement normal fault similar to the Wilburton gas field (Fig. 10). The cospatial location and abrupt nature of both the Neoproterozoic to Paleozoic platform-to-basin transition and Paleozoic platform rocks (Fig. 1c) (Abbott, 1997; Macdonald et al., 2012; Mair et al., 2006; Norris, 1997) may suggest control by a pre-existing or syn-sedimentary structure. Subsurface structures control the location of abrupt shelf margins elsewhere, including the uplifted margin of southwestern Norway (Fig. 3a, b of Gabrielsen et al., 2010) and the Cretaceous to recent shelf margin of offshore Florida in the eastern Gulf of Mexico (Dobson and Buffler, 1991, their Fig. 3; Sawyer et al., 1991, their Fig. 14). If the location of abrupt platform-to-basin transitions within the Nadaleen region were indeed controlled by a deeper fault, the same structure is also likely to be the reason for the later obstruction. Therefore, the obstruction was probably not caused by rheological heterogeneity alone. A potential basement structure may be the previously interpreted ancestral Dawson Fault (Fig. 11) (Abbott, 1997), which may have influenced deformation in a way similar to how the basement normal fault influenced the structural geometry in the Wilburton gas field (Fig. 10). Because the fault potentially controlled Neoproterozoic and Paleozoic basin architecture, as well as mid-Cretaceous deformation patterns, it probably formed early in the geologic history of the region (early Neoproterozoic?) and affected sedimentation and structural deformation through the mid-Cretaceous.

4.3. Mineralizing fluid migration and potential controls

Our work and work by others (e.g., unpublished mapping by ATAC Resources, Ltd.) in the eastern Nadaleen trend indicate that the major gold discoveries (Conrad, Ibis, Osiris/Sunrise) are hosted within hinge zones of moderately to steeply S- to SSW-plunging anticlines and not within the hinge zones of synclines and/or folds in other orientations.

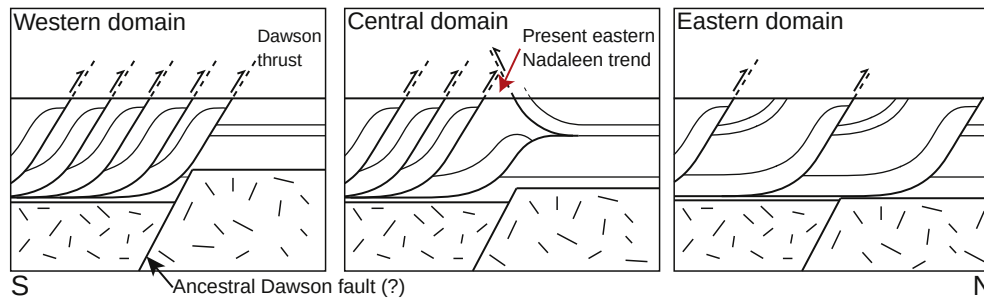


Fig. 11. Schematic cross-sections showing a western domain where foreland-directed fold-thrust motion is obstructed towards the north, a middle domain where the eastern Nadaleen trend triangle zone is located, and an eastern domain where deformation is unobstructed, possibly due to change in displacement along the interpreted ancestral Dawson fault. See text for discussion.

The deposits occur in close association to faults with variable shear sense. This suggests that faults at the eastern Nadaleen trend may have been important conduits for the mineralizing fluid and the hinge zones of anticlines may have been locations of increased fluid-rock interaction. At a regional scale, SSW-plunging anticlines are not commonly recognized, and other structures may have influenced the mineralizing fluid flow path.

The triangle zone across the eastern Nadaleen trend may have behaved as a regional-scale funnel that channeled the mineralizing fluid upward into structural highs. This model is similar to those for hydrocarbon migration and accumulation, like the Wilburton gas field (Fig. 10) and other triangle zones throughout the world (Couzens-Schultz et al., 2003; MacKay, 1996; Zapata and Allmendinger, 1996). At the eastern Nadaleen trend, gold-rich mineralizing fluid may have migrated updip along the base of the Dawson thrust, using the thrust sheet as a regional aquitard.

4.4. Structural similarities with Carlin-type deposits in Nevada

Major Carlin-type gold deposits in Nevada are generally located in the footwall of multi-hundred km-scale thrust faults, particularly the Roberts Mountain thrust, that are interpreted as regional aquitards (Cline et al., 2005; Rhys et al., 2015). Gold deposits are typically located near extensional faults that may be reactivated earlier reverse faults that propagated along limbs of anticlines (Cline et al., 2005; Rhys et al., 2015). Extensional faults offset mineral deposits and Miocene and younger rocks suggesting part of the normal movement postdates Carlin-type gold mineralization (cf. Cline et al., 2005). The deposits formed between ~42 and 36 Ma, coeval with the beginning of NW- to W-directed regional extension (Cline et al., 2005 and references therein). This early phase of extension is considered minor relative to later extension (e.g. Colgan et al., 2010; Henry et al., 2001; Ressel and Henry, 2006). However, this early normal reactivation of reverse structures may have enhanced the permeability of the structural network that permitted pervasive mineralizing fluid circulation through the crust (Cline et al., 2005; Rhys et al., 2015).

Regionally, the Carlin-type gold deposits within the Nadaleen trend occur in the footwall of the Dawson thrust, a fault comparable in scale to the Roberts Mountain thrust in Nevada. Similar to the Roberts Mountain thrust, the Dawson thrust places basinal facies of the Selwyn basin over carbonate strata of the Ogilvie platform and the fault surface may behave as a regional aquitard. The eastern Nadaleen trend Carlin-type deposits may occur within a structural triangle zone, a similar setting as has been previously interpreted for a Carlin-type deposit (Rain mine) in the Carlin trend (Essman, 2010). The eastern Nadaleen trend gold deposits are closely associated with anticlines, similar to the Twin Creeks deposit in the Getchell trend (Stenger et al., 1998), and occur near faults similar to most Carlin-type deposits in Nevada. The faults predate mineralization and probably influenced the migration paths of the mineralizing fluids. In summary, except for a lack of widespread extension in the eastern Nadaleen trend, the regional and local structural setting of

the eastern Nadaleen trend gold deposits is similar to Carlin-type deposits in Nevada.

5. Conclusion

The local structural complexity within the eastern Nadaleen trend includes generally SSW-dipping bedding, several hundred-meter scale, open to tight chevron folds that plunge moderately to steeply to the SSW, WSW, SE, or E, the E-trending Osiris fault, the steeply NNE-dipping Nadaleen fault zone and the late N-trending Conrad fault. These are interpreted to have resulted from: NNE-SSW directed shortening (D_1), NW-SE directed shortening (D_2), N-S directed shortening (D_3) and minor N-trending strike-slip faulting (D_4). Gabbroic dikes intruded after the onset of D_3 and gold mineralization occurred after D_3 and probably before D_4 .

Oppositely verging reverse faults indicate that an east-striking triangle zone exists across the eastern Nadaleen trend. This triangle zone does not extend to the west or east. Rocks to the west show multiple NNE-verging structures in the south and only one mapped fold in the north, whereas deformed rocks to the east consistently show NNE-vergence. The structural architecture of the region may be influenced by a subsurface structure such as the interpreted ancestral Dawson fault at and west of the eastern Nadaleen trend. Such a subsurface structure may have obstructed fold-thrust movement to the west, and presented a minor obstruction at the eastern Nadaleen trend resulting in the formation of a triangle zone. NNE-directed transport was unobstructed to the east.

The eastern Nadaleen trend triangle zone is believed to have behaved as a structural funnel that channeled gold-rich mineralizing fluid upward into favorable structures in the eastern Nadaleen trend. The primary detachment faults may have acted as regional aquitards for ascending mineralizing fluid. Gold-bearing rocks within the triangle zone are concentrated in moderately to steeply SSW-plunging anticlines adjacent to faults, both of which may have been effective conduits for the mineralizing fluid.

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References

- Abbott, G., 1990. Preliminary results of the stratigraphy and structure of the Mt. Westman map area, central Yukon. *Curr. Res. Geol. Surv. Can. E* 15–22.
- Abbott, G., 1997. Geology of the upper Hart River area, eastern Ogilvie Mountains, Yukon Territory (116A/10, 116A/11). *Yukon Geol. Surv. Bull.* 9, 1–92.
- Arehart, G., Ressel, M., Carne, R., Muntean, J., 2013. A comparison of Carlin-type deposits in Nevada and Yukon. *Soc. Econ. Geol. Spec. Publ.* 17, 389–402.
- Bennett, V., 2012. Synthesis report, Rackla gold project, east central Yukon, Canada. ATAC Resources Internal Report pp. 1–57.
- Bennet, V., 2013. U-Pb geochronology report, Rackla gold project, east central Yukon, Canada. ATAC Resources Internal Report pp. 1–44.
- Bingham, C., 1974. An antipodally symmetric distribution on the sphere. *Ann. Stat.* 2, 1201–1225.
- Cardozo, N., Allmendinger, R., 2011. OSXStereonet 1.9.
- Cecile, M.P., 2000. The geology of the northeastern Nidderly Lake map area, east central Yukon and adjacent Northwest Territories. *Geol. Surv. Can. Bull.* 553, 1–122.
- Çemen, I., Sagnak, A., Akthar, S., 2002. Geometry of the triangle zone and duplex structure in the Wilburton gas field area of the Arkoma Basin, southeastern Oklahoma. *Okla. Geol. Surv. Circ.* 104, 87–98.
- Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M., Hickey, K.A., 2005. Carlin-type gold deposits in Nevada: critical geologic characteristics and viable models. *Econ. Geol.* 100th Anniv. vol. 100, pp. 451–484.
- Colgan, J.P., Howard, K.A., Fleck, R.J., Wooden, J.L., 2010. Rapid middle Miocene extension and unroofing of the southern Ruby Mountains, Nevada. *Tectonics* 29 (TC6022), 1–38.
- Colpron, M., Logan, J., Mortensen, J.K., 2002. U-Pb age constraint for late Neoproterozoic rifting and initiation of the lower Paleozoic passive margin of western Laurentia. *Can. J. Earth Sci.* 39, 133–143.
- Couzens, B.A., Wiltshko, D.V., 1996. The control of mechanical stratigraphy on the formation of triangle zones. *Bull. Can. Pet. Geol.* 44, 165–179.
- Couzens-Schultz, B.A., Vendeville, B.C., Wiltshko, D.C., 2003. Duplex style and triangle zone formation: Insights from physical modeling. *J. Struct. Geol.* 25, 1623–1644.
- Creaser, R.A., Goodwin-Bell, J.A.S., Erdmer, P., 1999. Geochemical and Nd isotopic constraints for the origin of eclogite protoliths, northern Cordillera: Implications for the Paleozoic tectonic evolution of the Yukon-Tanana terrane. *Can. J. Earth Sci.* 36, 1697–1709.
- Dobson, L.M., Buffler, R.T., 1991. Basement rocks and structure, northeast Gulf of Mexico. *Trans. Gulf Coast Assoc. Geol. Soc.* 41, 191–206.
- Essman, J., 2010. Rain revisited: New structural and stratigraphic insights and their implications for Carlin-type deposits. In: Steininger, R., Pennell, B. (Eds.), *Great Basin Evolution and Metallogeny*. *Geol. Soc. Nev. Symp. Proc.*, pp. 511–535.
- Evenchick, C.A., McMechan, M.E., McNicoll, V.J., Carr, S.D., 2007. A synthesis of the Jurassic–Cretaceous tectonic evolution of the central and southeastern Canadian Cordillera: Exploring links across the orogeny. *Geol. Soc. Am. Spec. Pap.* 433, 117–145.
- Gabrielse, H., 1967. Tectonic evolution of the northern Canadian Cordillera. *Can. J. Earth Sci.* 4, 271–298.
- Gabrielsen, R.H., Faleide, J.I., Pascal, C., Braathen, A., Nystuen, J.P., Etzelmueller, B., O'Donnell, S., 2010. Latest Caledonian to Present tectonomorphological development of southern Norway. *Mar. Pet. Geol.* 27, 709–723.
- Gehrels, G., Rusmore, M., Woodsworth, G., Crawford, M., Andronikos, C., Hollister, L., Patchett, J., Ducea, M., Butler, R., Klepeis, K., Davidson, C., Friedman, R., Haggart, J., Mahoney, B., Crawford, W., Pearson, D., Girardi, J., 2009. U-Th-Pb geochronology of the Coast Mountains batholith in north-coastal British Columbia: Constraints on age and tectonic evolution. *Geol. Soc. Am. Bull.* 121, 1341–1361.
- Gordey, S.P., Anderson, R.G., 1993. Evolution of the northern Cordilleran miogeocline, Nahanni map area (1051), Yukon and Northwest Territories. *Geol. Surv. Can. Mem.* 428, 1–214.
- Gordey, S.P., Thompson, R.L., 1991. Structural styles. In: Gabrielse, H., Yorath, C.J. (Eds.), *Geology of the Cordilleran orogen in Canada*. *Geol. Surv. Can., Geol. of Can.* 4, pp. 625–630.
- Gordy, P.L., Frey, F.R., Norris, D.K., 1977. Geological guide for the Canadian Society of Petroleum Geologists 1977 Waterton-Glacier Park Field Conference. *Can. Soc. Pet. Geol.*, Calgary.
- Green, L.H., 1972. Geology of Nash Creek, Larsen Creek and Dawson map-areas. *Yukon Geol. Surv. Can. Mem.* 364, 1–157.
- Hansen, V.L., 1990. Yukon-Tanana terrane: A partial acquittal. *Geology* 18, 365–369.
- Henry, C.D., Faulds, J.E., Boden, D.R., Ressel, M.W., 2001. Timing and styles of Cenozoic extension near the Carlin trend, northeastern Nevada: Implications for the formation of Carlin-type gold deposits. *Geol. Soc. Nev. Spec. Pub.* 33, 115–128.
- Jones, P.B., 1996. Triangle zone geometry, terminology and kinematics. *Bull. Can. Pet. Geol.* 44, 139–152.
- Kingston, S., Mortensen, J., Dumala, M., Gabites, J., 2009. Ar-Ar geochronology and Pb isotopic constraints on the origin of the Rau gold-rich carbonate replacement deposit, central Yukon. In: MacFarlane, K.E., Weston, L.H., Blackburn, L.R. (Eds.), *Yukon Exploration and Geology 2009*. *Yukon Geol. Surv.*, pp. 213–222.
- Lund, K., Aleinikoff, J.N., Evans, K.V., Fanning, C.M., 2003. SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchronicity of Sturtian glacial deposits. *Geol. Soc. Am. Bull.* 115, 349–372.
- MacDonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss, J.V., Cohen, P.A., Johnston, D.T., Schrag, D.P., 2010. Calibrating the Cryogenian. *Science* 327, 1241–1243.
- MacDonald, F.A., Halverson, G.P., Strauss, J.V., Smith, E.F., Cox, G., Sperling, E.A., Roots, C.F., 2012. Early Neoproterozoic basin formation in Yukon, Canada: Implications for the make-up and break-up of Rodinia. *Geosci. Can.* 39, 77–99.
- MacKay, P.A., 1996. The Highwood structure: A tectonic wedge at the foreland edge of the southern Canadian Cordillera. *Bull. Can. Pet. Geol.* 44, 215–232.
- Mair, J.L., Hart, C.J.R., Stephens, J.R., 2006. Deformation history of the northwestern Selwyn basin, Yukon, Canada: Implications for orogen evolution and mid-Cretaceous magmatism. *Geol. Soc. Am. Bull.* 118, 304–323.
- McMechan, M.E., Thompson, R.L., Cook, D.G., Gabrielse, H., Yorath, C.J., 1991. Foreland Belt. In: Gabrielse, H., Yorath, C.J. (Eds.), *Geology of the Cordilleran orogen in Canada*. *Geol. Soc. Am., Geology of North America Series*, pp. 571–678.
- Monger, J.W.H., McNicoll, V.J., 1993. New U-Pb dates from southwestern Coast belt, British Columbia. *Geol. Surv. Can. Pap.* 93-2, 119–126.
- Monger, J.W.H., Price, R.A., Tempelman-Kluit, D.J., 1982. Tectonic accretion and the origin of the two major metamorphic and tectonic belts in the Canadian Cordillera. *Geology* 10, 70–75.
- Mortensen, J.K., 1982. Geological setting and tectonic significance of Mississippian felsic metavolcanic rocks in the Pelly Mountains, southeastern Yukon Territory. *Can. J. Earth Sci.* 19, 8–22.
- Moynihan, D., 2016. Bedrock geology compilation of the eastern Rackla belt, east-central Yukon: Yukon Geological Survey open-file report 2016-2, 1:75,000 scale.
- Moynihan, D., Colpron, M., Israel, S., Abbott, G., 2014. Geology of the eastern Rackla belt, east-central Yukon. Poster presented at 2014 Mineral Exploration Roundup (January 27, 2014).
- Murphy, D.C., 1997. Geology of the McQuesten River region, northern McQuesten and Mayo map areas, Yukon Territory. *Yukon Geol. Surv. Bull.* 6, 1–95.
- Nelson, J.L., Colpron, M., 2007. Tectonics and metallogeny of the Canadian and Alaskan Cordillera, 1.8 Ga to present. In: Goodfellow, W.D. (Ed.), *Mineral deposits of Canada: A synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods*. *Miner. Depos. Div., Geol. Assoc. Can. Spec. Pub.* 5, pp. 755–791.
- Nelson, J.L., Colpron, M., Israel, S., 2013. The cordillera of British Columbia, Yukon and Alaska: Tectonics and metallogeny. In: Colpron, M., Bissig, T., Rusk, B.G., Thompson, J.F.H. (Eds.), *Tectonics, metallogeny and discovery. The North American cordillera and similar accretionary settings*. *Soc. Econ. Geol. Spec. Pub.* 17, 53–109.
- Norris, D.K., 1974. Structural geometry and geological history of the northern Canadian Cordillera. *Proc. First Natl. Conv., Can. Soc. Explor. Geophys.*, Calgary, pp. 18–45.
- Norris, D.K., 1997. Geology and mineral and hydrocarbon potential of northern Yukon Territory and northwestern District of Mackenzie. *Geol. Surv. Can., Ottawa*.
- Ressel, M.W., Henry, C.D., 2006. Igneous geology of the Carlin trend, Nevada: Development of the Eocene plutonic complex and significance for Carlin-type gold deposits. *Econ. Geol.* 101, 347–383.
- Rhys, D., Valli, F., Burgess, R., Heitt, D., Griesel, G., Hart, K., 2015. Controls of fault and fold geometry on the distribution of gold mineralization on the Carlin trend. *New Concepts and Discoveries*. *Geol. Soc. Nev. 2015 Symp. DEStech Publications, Inc.*, pp. 333–389.
- Roots, C.F., 1997. Geology of the Mayo map area, Yukon Territory, 105M. *Explor. Geol. Serv. Div., INAC, Geosci. Bull.* 7, pp. 1–81.
- Sawyer, D.S., Buffler, R.T., Pilger Jr., R.H., 1991. The crust under the Gulf of Mexico. In: Salvador, A. (Ed.), *The Gulf of Mexico Basin*. *Geol. Soc. Am., The Geol. of N. Am. J.*, pp. 53–72.
- Stenger, D.P., Kesler, S.E., Peltonen, D.R., Tapper, C.J., 1998. Deposition of gold in Carlin-type deposits: the role of sulfidation and decarbonation at Twin Creeks, Nevada. *Econ. Geol.* 93, 201–215.
- Stephens, J.R., Mair, J.L., Oliver, N.H.S., Hart, C.J.R., Baker, T., 2004. Structural and mechanical controls on intrusion-related deposits of the Tombstone gold belt, Yukon, Canada, with comparisons to other vein-hosted ore-deposit types. *J. Struct. Geol.* 26, 1025–1041.
- Stockwell, C.H., 1969. Tectonic map of Canada, prepared by Tectonic Map of Canada Committee (scale 1:5,000,000). *Geol. Surv. Can.*
- Thorkelson, D.J., Mortensen, J.K., Davidson, G.J., Creaser, R.A., Perez, W.A., Abbott, J.G., 2001. Mesoproterozoic intrusive breccias in Yukon, Canada: The role of hydrothermal systems in reconstructions of North America and Australia. In: Bartley, J.K., Kah, L.C. (Eds.), *The Mesoproterozoic Earth–Ocean System of Rodinia*. *Precambrian Res.* 11, pp. 31–56.
- Thorkelson, D.J., Abbott, G.J., Mortensen, J.K., Creaser, R.A., Villeneuve, M.E., McNicoll, V.J., Layer, P.W., 2005. Early and Middle Proterozoic evolution of Yukon, Canada. *Can. J. Earth Sci.* 42, 1045–1071.
- Tucker, M.J., 2015. Geology, mineralization and geochronology of the Conrad zone Carlin-type gold prospect, east-central Yukon Territory, Canada (Unpublished MS thesis) University of British Columbia.
- Tucker, M.J., Hart, C.J.R., Carne, R.C., 2013. Geology, alteration, and mineralization of the Carlin-type Conrad zone, Yukon. In: MacFarlane, K.E., Nordling, M.G., Sack, P.J. (Eds.), *Yukon Exploration and Geology 2012*. *Yukon Geol. Surv.*, pp. 163–178.
- Turner, E.C., 2011. Stratigraphy of the Mackenzie Mountains supergroup in the Wernecke Mountains, Yukon. In: MacFarlane, K.E., Weston, L.H., Relf, C. (Eds.), *Yukon Exploration and Geology 2010*. *Yukon Geol. Surv.*, pp. 207–231.
- Woodward, N.B., 1985. Valley and ridge thrust belt: Balanced cross-sections, Pennsylvania to Alabama. *Univ. Tenn. Stud. Geol.* 12, 1–64.
- Zapata, T.R., Allmendinger, R.W., 1996. Thrust-front zone of the Precordillera, Argentina: A thick-skinned triangle zone. *Am. Assoc. Petrol. Geol. Bull.* 80, 359–381.