Aley Carbonatite: A Paleozoic Iron Oxide Copper Gold (IOCG) Deposit in North-Central British Columbia?

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INTRODUCTION

Iron oxide copper gold (IOCG) deposits are recognized world-wide and include a number of world-class, high-tonnage, low-grade Cu-Au deposits that are typically hosted in intrusive-hydrothermal breccias and include the Mesoproterozoic Olympic Dam (Australia) and Igarape-Bahia Alemao (Brazil) deposits (Hitzman *et al*., 1992). In the Canadian Cordillera, numerous Mesoproterozoic breccia bodies in the Yukon, collectively known as the Wernecke Breccias, have associated IOCG mineralization (Fig. 1; Thorkelson *et al*., 2001). Despite their economic significance, the origins and paragenesis of IOCG deposits, and hence mineral deposit models and related exploration strategies for IOCG deposits, continue to be debated (Hauck, 1990). In the Canadian Cordillera, exploration for IOCG deposits has focused on Proterozoic strata in the Yukon and adjacent portions of the Northwest Territories.

We report on recent mapping of the western margin of the Aley carbonatite complex of northeastern British Columbia (Fig. 1, 2). The Aley carbonatite is one of a series of carbonatite complexes that intrudes little-metamorphosed continental margin strata of the Canadian Cordillera foreland belt (Fig. 1). Of these complexes, the Aley carbonatite complex is of particular interest due to its anomalously high concentrations of Nb_2O_5 and its spatial association with the Ospika pipe, an ultramafic lamprophyric diatreme breccia pipe that has been previously investigated as a possible diamond exploration target (Fig. 2). Although carbonatites have traditionally been explored primarily for their rare earth element (REE) potential, Groves and Vielreicher (2001), based on their work on the Palabora carbonatite of South Africa, recently proposed a link between IOCG deposits and carbonatites. After summarizing the characteristics of carbonatites and IOCG deposits, we present the results of recent detailed (1:5000-scale) mapping across the western margin of Aley carbonatite. Should the Aley carbonatite prove to host significant IOCG mineralization, it would suggest that the series of carbonatite complexes that characterize the Canadian Cordilleran Foreland Belt may constitute a significant, newly recognized IOCG province.

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CARBONATITES AND IOCG DEPOSITS

Carbonatites are igneous rocks consisting of >50% magmatic carbonate. Although most common in Precambrian cratonic regions, carbonatites are known world-wide, range in age from the Archean to the present (Woolley, 1989) and are interpreted to be genetically and spatially associated with continental rifts (Bailey, 1977). Burke *et al*. (2003), based on a compilation of African carbonatite occurrences, have suggested that deformed carbonatite complexes occur along and characterize relict sutures where oceans adjacent to rifted continental margins have been closed. Johnston *et al*. (2003) suggested that carbonatite complexes of the Cordilleran foreland may lie along and mark a cryptic suture separating a far-travelled ribbon continent to the west (Johnston, 2001) from autochthonous North American strata to the east. Repeated carbonatite magmatism spanning hundreds of millions of years characterizes some small regions (Bailey, 1977). All carbonatites commonly occur together with alkaline igneous rocks as part of an alkaline intrusive series that includes olivine-free nephelinites, syenites and pyroxenites. Rarely, carbonatites are spatially associated with kimberlite.

Carbonatite mineralogy ranges from calcite (soivite) to dolomite carbonatites (raugaugite). Zoned carbonatite intrusions with calcite rims and dolomite cores have been documented. Important accessory phases commonly include pyroxene, magnetite and hematite, and apatite. Fenitization, consisting of Na metasomatic alteration of the host wallrocks, is commonly observed adjacent to carbonatite intrusions. Economic concentrations of REE, particularly Nb, used in the production of stainless steel and high-strength metallic alloys, make carbonatites attractive exploration targets. The Palaboro carbonatite of South Africa hosts an economic magnetite-copper-phosphate-REE deposit (Eriksson, 1989).

Iron oxide copper gold deposits occur in a variety of brecciated hostrocks, but are all associated with potassic anorogenic granitoid plutons, and are spatially associated with crustal-scale faults that mark cratonic margins (Hitzman *et al*., 1992). Most known IOCG deposits are Paleo- to Mesoproterozoic. Host breccia bodies are typically steeply plunging pipe-like bodies that consist of fresh to entirely metasomatized country-rock fragments. Metasomatism locally extends into unbrecciated wallrocks. Hostrocks range from older sedimentary and volcanic strata to much older gneiss complexes, and rarely

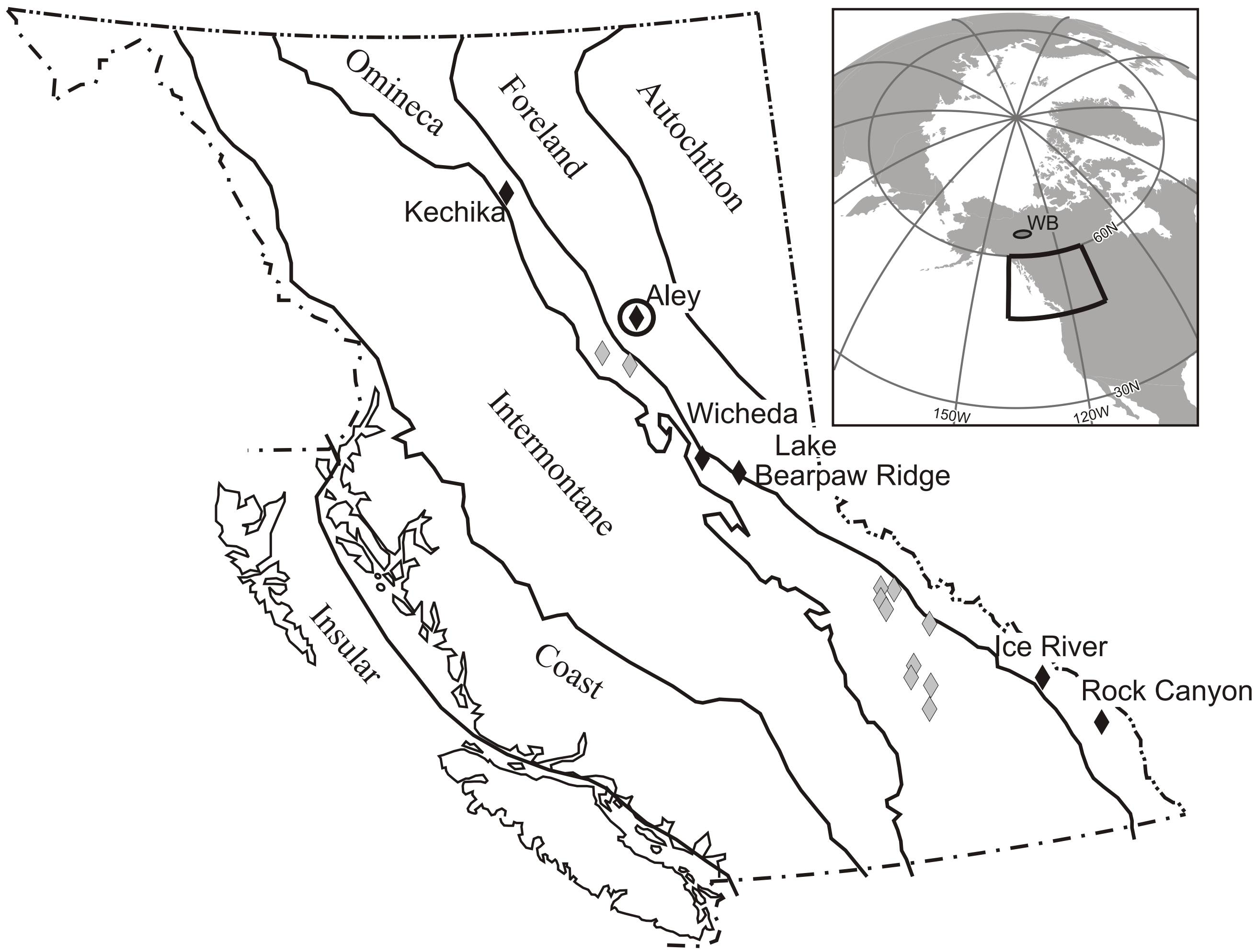

Figure 1 – Distribution of known carbonatite complexes in the Foreland and Omineca belts of British Columbia, in part after Pell (1994). Black diamonds indicate carbonatites emplaced into layered strata thought to have been deposited along the ancient continental platform and slope of western North America, and include the Aley carbonatite (circled). Grey diamonds indicate carbonatites hosted by metamorphosed strata of probable Precambrian age. Distribution of the Wernecke Breccia bodies is indicated on the inset map.

comprise coeval anorogenic granitoids. Mineralization is characterized by low-grade copper and gold mineralization in magnetite and hematite. Magnetite and hematite occur as a cement binding together breccia fragments, as breccia fragments, and as a texture-destroying metasomatic alteration of wallrock fragments. Anomalous enrichment in light REE, F and P, and Ag, As, Ba, Co, Mo, Nb, Ni, Th, and U is common. Evidence of early carbonate alteration is rare, although carbonates are commonly replaced by younger sulphide minerals, and the extent of early carbonate fluxing may be underestimated. Carbon dioxide is a common component of the ore fluids (Groves and Vielreicher, 2001)

ALEY CARBONATITE

The Aley carbonatite complex was mapped as part of a regional-scale (1:250 000) mapping program by Thompson (1989) and in detail by Maeder (1986, 1987). The main components of the complex are 1) an oval shaped intrusion 3.0 km in diameter along its long north-south axis and characterized by a massive, coarsely crystalline dolomite carbonatite core; 2) spatially associated lamprophyre dikes; 3) a mantle of rocks that have previously been referred to as 'amphibolite' (Mader, 1987; Pell, 1994) and mapped as a continuous body that completely encloses the intrusion; 4) an outer fenite zone, previously interpreted as Na-metasomatized wallrocks; and 5) cleaved argillaceous limestone and dolomitic limestone of the host wallrocks (Fig. 2). We first discuss the wallrocks, then the 'amphibolite' mantle, and finally the carbonatite and its associated lamprophyres.

Regional mapping has established the stratigraphic succession into which the carbonatite was intruded, and the relationship of the carbonatite to regional facies boundaries (Thompson, 1989). Slaty limestones and calcareous slate of the Cambrian to Ordovician Kechika Formation host the carbonatite complex. Stratigraphically overlying the Kechika Formation in the vicinity of the Aley carbonatite are light grey dolostones of the Middle Ordovician Skoki Formation (Fig. 2). The dolostones include a dark green

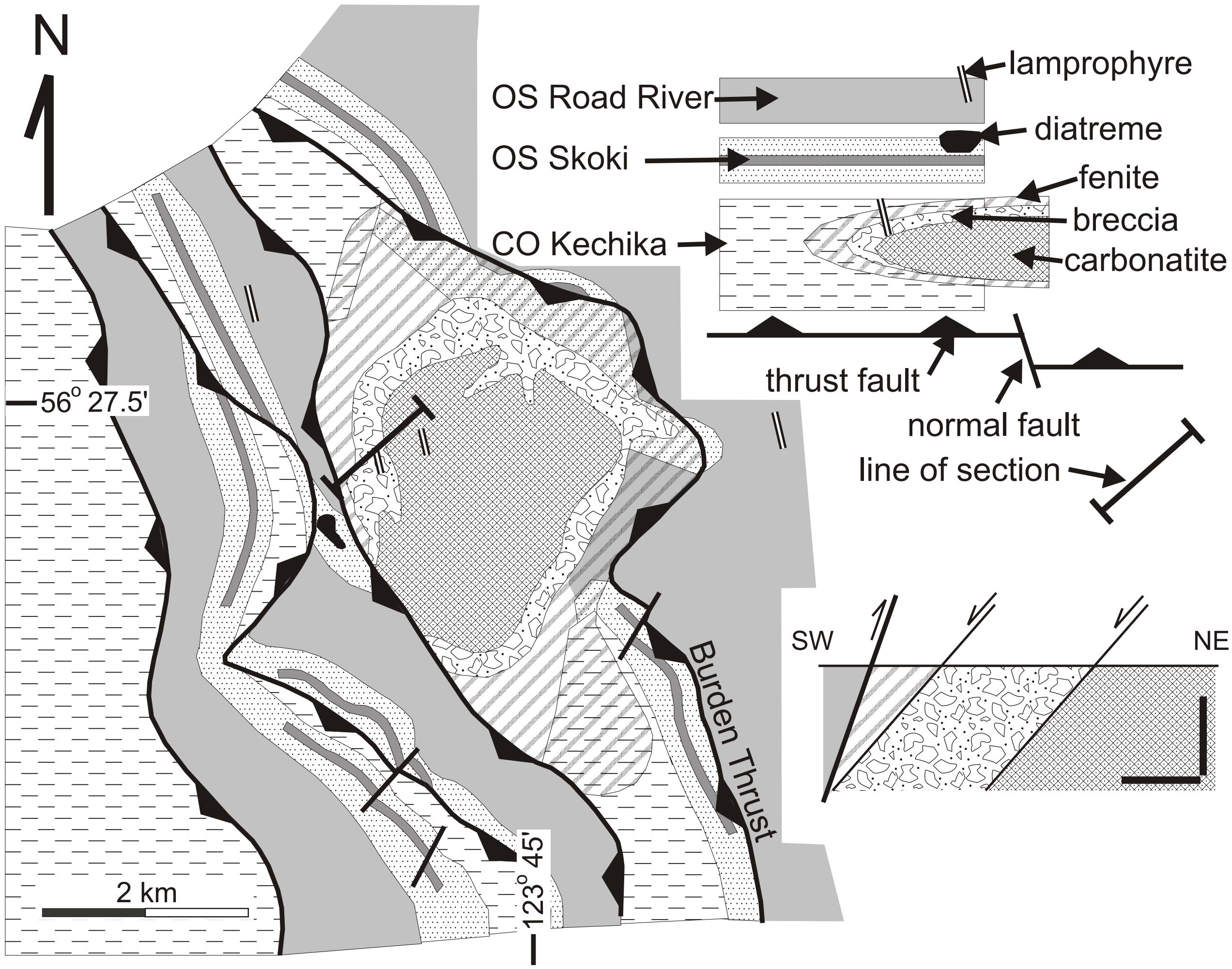

Figure 2 – Detailed geology of the Aley carbonatite (in part after Mader, 1987 and Thompson, 1989). See Figure 1 for location. The grey marker unit contained in the Skoki Formation is an alkalic basalt layer. The diatreme that intrudes the Skoki Formation west of the carbonatite is the Ospika Pipe. Schematic cross-section at lower right shows the relationships between the fenite, breccia and carbonatite; black bars represent 250 m on the cross-section. Abbreviations: OS, Ordovician-Silurian; CO, Cambrian-Ordovician.

weathering alkaline basalt that thins away from the Aley carbonatite to the north and south (Fig. 2). Pyle and Barnes (2001) identified carbonatite ocelli in samples of the basalt collected to the north of the Aley carbonatite (D. Canil, personal communication, 2001). The Skoki Formation passes both upsection and to the west into shales, calcareous shales and sandstones of the basinal Road River Group (Fig. 2). The transition from carbonates of the Skoki Formation to shales of the Middle Ordovician to Middle Devonian Road River Group has been interpreted as a facies boundary where shallow-water platform and shelf carbonates pass westward into deep water shales of the continental slope and adjacent basin (Cecile and Norford, 1979; Pyle and Barnes, 2001). Hence, the Aley carbonatite intruded along or close to the ancient western margin of the North American continent.

FENITE ZONE

Kechika Formation rocks within 500 m map distance of the intrusion are characterized by a bleached to cream-white weathering colour, have been mapped as ‘fenites’, and have been interpreted as sedimentary rocks metasomatized during carbonatite intrusion by the addition of Na_2O, K_2O, MgO and Fe_2O_3 (Mader, 1987; Pell, 1994). Two distinct rock types characterize the fenite zone: coarsely crystalline dolomite and finely laminated dolostone. Coarsely crystalline dolomite is texturally and mineralogically identical to the dolomitic carbonatite intrusion and occurs as massive, lamination-parallel layers 5 to 100 cm thick that we interpret as intrusive carbonatite sills. Finely laminated dolostones that host the sills are characterized by wavy, anastomosing laminations that appear mylonitic. Contacts with unaltered and nonlaminated (nonmylonitized?) Kechika Formation rocks are gradational over short distances and are commonly sharp. These relationships suggest to us that the fenitized zone is a structurally distinct package of rocks with an uncertain relationship to adjacent rocks of the Kechika Formation. We believe that at least some of the fenitized rocks are mylonitized carbonatite of the intrusion. Interleaving of massive and mylonitized carbonatite suggests that intrusion was synkinematic and involved the development of highly strained rocks.

MANTLING BRECCIA

The carbonatite intrusion is mapped as being everywhere isolated from the fenite zone by a mantle of amphibolite (Fig. 2; Mader, 1987). Pell (1994) noted that, locally at least, the amphibolite was characterized by breccia. Our mapping focused on the western margin of the carbonatite, where the intrusion is separated from the fenite zone by a thick and continuous breccia body that forms a steeply west-dipping sheet. The breccia is grey, matrix supported and heterogeneous (Fig. 3). Clasts range in size from sand-sized particles to blocks >1 m in diameter, are well rounded but not spherical, and are commonly characterized by bleached (altered) margins (Fig. 3a). A weak foliation defined by alignment of the largest clasts is locally evident and parallels the steep west dip of the breccia body. The majority of the clasts consist of quartzite or microcrystalline leucosyenite. Limestone clasts, presumably derived from the adjacent country rocks, are common. Neither the quartzite nor the leucosyenite is mapped in the vicinity of the Aley carbonatite and the source of these abundant clasts is unknown. Clasts of hematite-magnetite, carbonatite and aphanitic 'greenstone' are rare.

The matrix varies between a magmatic microsyenite and a clastic mix of sand-sized particles of quartzite and grey, aphanitic lithic clasts of uncertain lithology. The microsyenite consists of interlocking, euhedral feldspar (or possibly nepheline) microlites that appear igneous in origin. Both the clastic and microsyenite matrix are commonly characterized by hematite and hematite-magnetite cement. Hematite forms asymmetric, laminated mantles on many of the clasts and locally penetrates into clasts along fractures (Fig. 3b,c) that cut across matrix and clasts. Previous geochemical studies, summarized in Pell (1994), indicate that the syenite clasts are characterized by light REE enrichment similar to, but not as strongly developed as, the that of Aley carbonatite. The matrix is anomalously Na and K-rich, but otherwise geochemically similar to fenite zones marginal to many carbonatite intrusions (Pell, 1994).

Sheets of highly foliated and lineated, orange-weathering carbonatite are common in the breccia. These carbonatite sheets appear to locally host rare singular clasts. The foliation is defined by wavy laminations and by discontinuous layers rich in rods of white, coarsely crystalline saddle dolomite. The lineation is defined by 1–10 mm long rods of saddle dolomite that plunge steeply down-dip to the west (Fig. 3d). At one locality, the foliation was defined by alignment of abundant, highly altered orthopyroxene 'plates' 1 cm across. The sheet-like geometry of the foliated carbonatites and the presence of altered orthopyroxene crystals imply that the carbonatite sheets originated as dikes or sills that intruded the breccia. In one instance a sheet of foliated carbonatite rooted into a west-dipping extensional shear zone (Fig. 3e). The close spatial relationship between shear zones and foliated carbonatite sheets may indicate that carbonatite intrusion was synkinematic with extensional (top down to the west) shearing and that the presence of the carbonatite magma promoted and localized shear zones within the breccia. In addition to the sheared carbonatite sheets, orange-weathering, discordant dikes and sills of massive carbonatite are common throughout the breccia body, although they appear more abundant adjacent to the contact with the main body of the underlying Aley carbonatite. These carbonatite dikes narrow and branch upward away from the underlying intrusion (Fig. 3f), suggesting that the breccia body predated and formed the roof above the intruding Aley carbonatite.

Argillaceous limestones of the Ordovician Skoki Formation immediately west of and in fault contact with the mantling breccia are intruded by a breccia pipe (Ospika pipe). Although distinguishable from the mantling breccia due to the presence of abundant phlogopite, the Ospika pipe breccia is otherwise similar to and probably genetically related to the mantling breccia. Both breccias are characterized by a similar suite of clasts, the presence of bleached reaction rims on the clasts, a heterogeneous igneous matrix that locally consists of pyroxene-phyric carbonatite, and crosscutting carbonatite dikes that postdate breccia emplacement.

ALEY CARBONATITE

The Aley intrusion consists of bright orange weathering crystalline dolomite, and sits structurally beneath and is in sharp contact with the overlying breccia body. The carbonatite-breccia contact consists of a highly sheared zone, ranging from 1 to >10 m wide, of structurally intermixed breccia, green schist, hematite layers and carbonatite. Kinematic indicators, including asymmetric folds, extensional shears, and a crenulation cleavage, imply that deformation occurred during top-down-to-the-west shearing. The presence of interfoliated layers of highly strained and unstrained carbonatite indicates that extensional shearing was coeval with intrusion. The core of the intrusion consists of weakly foliated to unstrained, coarsely crystalline dolomite. The orange colour appears to result from abundant disseminated hematite. The foliation commonly dips steeply to the west to northwest, parallel to the contact with the overlying breccia body. Previous geochemical studies (Pell, 1994) have established that the carbonatite is strongly enriched in phosphorus (>11% P_2O_5) and light REE. Concentrations of Nb_2O_5 alone locally exceed 2%.

The age of the carbonatite intrusion is constrained as being younger than the enclosing Late Cambrian to Middle Ordovician Kechika Formation. An alkalic volcanic layer in the Ordovician Skoki Formation, which is locally characterized by carbonatite ocelli, thins away from the carbonatite to the north and south. The spatial association of this alkalic volcanic unit with its carbonatitic affinity may indicate that volcanism and intrusion were cogenetic, requiring a mid-Ordovician age for the Aley carbonatite. Alternatively, the close spatial association of the volcanic layer and the intrusion may be another example of repeated carbonatitic magmatism in one locality over long periods of time.

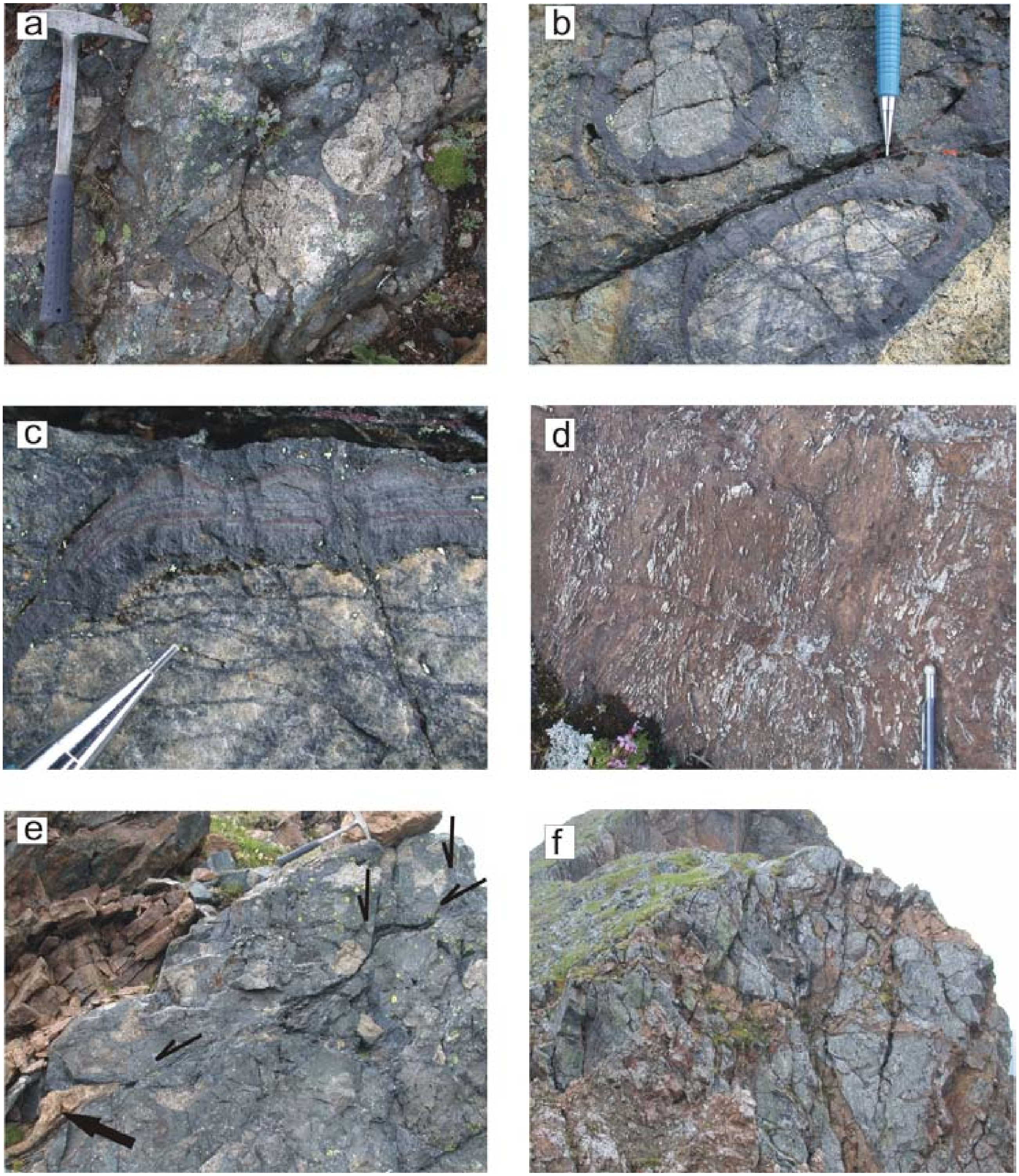

Figure 3. **a)** Rounded, elongate syenite clasts (light grey) in dark grey, hematitic microsyenite matrix. **b)** Syenite and quartzite clasts enclosed in laminated hematite-magnetite mantles within a hematitic microsyenite matrix; note that hematite-magnetite mantles are asymmetric and appear to penetrate into the clasts along fracture planes. **c)** Close-up of laminated hematite-magnetite mantle. **d)** Foliated and lineated orange-weathering carbonatite sheet within the mantling breccia; light grey saddle dolomite forms resistant, elongate lenses that define a steeply westward plunging, down-dip lineation. **e)** Breccia cut by down-dip to the west extensional shear zone (asymmetric arrows indicate sense of shear); note extensional domino-faulting of breccia in the hangingwall of the extensional shear, and the carbonatite sheet (black arrow) at lower left that defines the down-dip continuation of the extensional shear; **f)** 30 m high cliff face exposure of breccia immediately above the upper contact of the Aley carbonatite intrusion; upward-branching carbonatite dikes that root downward into the carbonatite pluton intrude the grey-weathering breccia.

Lamprophyre dikes intrude the breccia body and Ordovician to Devonian Road River Group to the east of the carbonatite. If attributable to the same magmatic event that gave rise to the carbonatite, these lamprophyres would indicate a Devonian or younger age of intrusion. Two K-Ar ages on phlogopite separates the lamprophyre dikes yielded ages of 339 ± 12 and 349 ± 12 Ma (Maeder, 1986). We interpret these ages as reflecting cooling through the closure temperature for Ar in biotite-phlogopite and therefore interpret 345 Ma (Mississippian) as the minimum possible age of the lamprophyres.

STRUCTURAL GEOLOGY

The complex and its wallrocks are imbricated along a series of steeply west-dipping, east-verging thrust faults. The carbonatite occurs in the immediate hangingwall of the Burden thrust (Fig. 2), a major northwest-trending thrust fault that merges with the north-trending mountain front to the south where it defines the east limit of the Rocky Mountain structural province (Thompson, 1989). Kechika Formation rocks in the hangingwall of the Burden thrust north and south of the Aley carbonatite are folded, forming an overturned anticline with a steeply west-dipping axial surface. It remains unclear if the carbonatite is itself tightly folded in the core of this fold; although the dolomitic carbonatite in the core of the intrusion is weakly foliated, there is no indication of significant strain that one would commonly associate with the hinge of a tight, overturned fold. In addition, the symmetric ovoid shape of the carbonatite body and lack of any significant penetrative deformation or flow within the body argue against the intrusion having been tightly folded, and the upward branching geometry of carbonatite dikes that root into the roof of the intrusion all point to the intrusion being the right way up. How then to reconcile the folded nature of the Kechika Formation wallrocks north and south of the intrusion with the apparent lack of folding of the intrusion itself? It may be that the tight overturned fold roots into the fenite zone, which may be a mylonitic thrust, as opposed to a metasomatic aureole.

The Aley carbonatite and its host Kechika Formation rocks are thrust east over an overturned panel of shale of the Road River Group (Fig. 2). A biotite lamprophyre dike that intrudes the footwall Road River Group shales provides a link with lamprophyres that characterize the Aley carbonatite. To the west, Kechika Formation rocks carried in the Burden thrust sheet are interpreted as being overthrust by younger argillaceous limestones and calcareous shales of the Road River Group. Interpetation of this contact as a fault is consistent with the presence of fault rocks (gouge and disrupted and folded strata) and with the absence of the Skoki Formation, which is known to lie between and separate the Kechika Formation and Road River Group regionally. Interpreting the contact as a thrust fault, however, requires that younger (Road River) strata were thrust over older (Kechika) strata. Interpretation of the fault as a normal fault would be consistent with the younger over older relationship and with the absence of the Skoki Formation. Extensional, top down to the west shear zones have been observed in the breccia above the carbonatite and along the breccia-carbonatite contact (Fig. 3f). Interleaving of sheared and unstrained carbonatite, the rooting of sheared carbonatite into discrete shear zones, and truncation of extensional shears by unstrained carbonatite dikes imply that shearing was synintrusive and may have accommodated emplacement of the Aley carbonatite intrusion. It may be, therefore, that the fault zone bounding the Burden thrust sheet to the west is a Paleozoic extensional fault that developed during Aley carbonatite magmatism. Alternatively, the observed younger over older relationships and the absence of the Skoki Formation could be accomplished by having a thrust fault cut structurally upsection through an already overturned panel of rock, although this conflicts with our interpretation of the Aley carbonatite being right way up.

An isolated area underlain by rocks of the Skoki Formation, immediately west of the Aley carbonatite in the hangingwall of the fault forming the western margin of the Burden thrust sheet, hosts an ultramafic diatreme pipe, referred to as the Ospika diatreme. The diatreme has been prospected for diamond potential. Depending upon the nature of the fault bounding the western margin of the Burden thrust sheet, the Ospika pipe either originated to the west of the carbonatite (if the fault is a thrust) or structurally above the carbonatite (if the fault is a normal fault).

ECONOMIC GEOLOGY

Extensive exploration of the Aley carbonatite and the adjacent Ospika pipe, including surface mapping and diamond-drilling, has focused on the Nb_2O_5 and diamond potential, respectively. Concentrations of >0.6% Nb_2O_5 characterize large volumes of the carbonatite intrusion, with local concentrations of >2%, comparable to the 0.5–0.7% Nb_2O_5 grade of carbonatite mined near at St. Honoré, Quebec (Pell, 1994). High concentrations of light REE and phosphates further enhance the economic viability of the Aley carbonatite.

Ultrabasic diatremes similar to the Ospika pipe, located to the south (Golden) and north (Kechika), have yielded microdiamonds (Simandl, 2004). Exploration of the Ospika pipe has, however, so far failed to yield diamonds or diamond-indicator minerals (e.g., G8–G10 garnets).

Creeks draining the Aley carbonatite and the mantling breccia comprise an isolated placer gold province; no other significant placer gold deposit is known in British Columbia east of the Rocky Mountain Trench. Placer gold provinces elsewhere in the eastern Cordillera are commonly spatially associated with mid-Cretaceous granitoid plutons (Dawson *et al.*, 1991). No mid-Cretaceous plutons are known east of the Rocky Mountain Trench in northeastern British Columbia. The presence of the Aley carbonatite at the head of the creeks characterized by placer gold makes it likely that the carbonatite intrusion or its wallrocks is the source of the gold.

DISCUSSION AND CONCLUSIONS

The Aley carbonatite complex shares many of the traits of IOCG deposits. Intrusion was accommodated by and synkinematic with crustal extension. Spatial association with a long-lived, Paleozoic carbonate-to-shale facies boundary implies proximity to a major, continent-bounding fault system. The carbonatite postdated and was emplaced into and beneath a steeply plunging body of magmatic breccia. The spatially and genetically related Ospika pipe, located to the west of the carbonatite, also forms a steeply plunging breccia pipe. Significant metasomatism attended breccia emplacement: clasts of country rock exhibit bleached altered rims, and are mantled by, shot through and partially to wholly replaced by laminated to massive hematite and hematite-magnetite. Hematite and hematite-magnetite also occur as discrete fragments within the breccia, and as a ubiquitous cement phase present throughout the matrix. Locally, the breccia matrix consists of sheared carbonatite, implying significant carbonate-fluxing during breccia emplacement. The presence of a 'fenite zone' hosting the breccia may indicate that metasomatism extended into the unbrecciated country rock. Although potassic anorogenic granitoid plutons were not mapped in the vicinity of the carbonatite body, the presence of abundant microsyenite clasts in the breccia and the syenite-nephelinite character of the breccia matrix imply the presence of associated anorogenic magmatism. Previous exploration has demonstrated that the carbonatite is anomalously enriched in light REE, as well as phosphorus. No visible gold mineralization has been reported in the carbonatite or the mantling breccia. Low-grade gold mineralization is, however, implied by the presence of significant gold placers on the creeks draining the intrusive complex.

Interpretation of the Aley carbonatite as host to significant IOCG mineralization remains a largely untested model. The extent of related copper mineralization, a hallmark of IOCG deposits, remains entirely unknown, as does the amount of enrichment in other IOCG-associated elements (F, Ag, As, Ba, Co, Mo, Th and U). Fundamental constraints, such as the age of breccia formation and subsequent carbonatite intrusion, are lacking. It seems likely that the structural evolution of the carbonatite and the mantling breccia involves a synmagmatic extensional event and Late Cretaceous displacement along east-verging thrust faults. The geometry of extensional and thrust structures is, however, only broadly constrained, and the relationship of the carbonatite to these structures remains poorly understood.

Our observations from the Aley carbonatite lend support to the suggestion, first made by Groves and Vielreicher (2001), that carbonatites are an end member of the IOCG family of mineral deposits. All previously documented occurrences of IOCG mineralization are Proterozoic or older. Confirmation of significant IOCG mineralization at the Paleozoic Aley carbonatite would make it the youngest known IOCG occurrence in the world, and would imply that exploration for IOCG deposits should expand into post-Proterozoic terranes. From a Canadian perspective, the Aley carbonatite is but one of a series of Paleozoic carbonatites and alkaline complexes that extend the length of the Foreland Belt of the Cordilleran orogen, all of which may potentially host IOCG mineralization. Hence, exploration programs for IOCG deposits, which have to date focused on the Mesoproterozoic Wernecke Breccias of the Yukon and Northwest territories, might now find encouragement to expand into Paleozoic strata along the length of the Cordilleran Foreland.

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