New U-Pb geochronology of Early Cretaceous porphyry and skarn mineralization in southwest Yukon

Steve Israel[1]
Yukon Geological Survey, Whitehorse, YT

Rosie Cobbett
Archer Cathro and Associates (1981) Ltd.

Jim Mortensen
University of British Columbia, Vancouver, BC

Israel, S., Cobbett, R., and Mortensen, J., 2012. New U-Pb geochronology of Early Cretaceous porphyry and skarn mineralization in southwest Yukon. *In:* Yukon Exploration and Geology 2011, K.E. MacFarlane and P.J. Sack (eds.), Yukon Geological Survey, p. 91-102.

ABSTRACT

New U-Pb geochronological analyses of zircon and garnet found within intrusive rocks and skarn indicate that porphyry copper-gold and gold-copper skarn mineralization is associated with the Early Cretaceous Kluane Ranges suite in southwest Yukon. The Nikki porphyry property, located ~25 km south of Beaver Creek, is characterized by Paleozoic to Triassic rocks of Wrangellia intruded by *ca.* 125 Ma intermediate intrusions of the Kluane Ranges suite. High copper and anomalous gold values associated with intrusions are considered to be related to high-level porphyry-style mineralization. The Arn property, located ~15 km to the southeast of the Nikki, is characterized by gold and copper mineralization associated with skarn developed at the margin of intrusions thought to be the Kluane Ranges suite and Triassic carbonate of the Chitistone Limestone. No ages for the intrusions exist and age of mineralization was not well constrained. New U-Pb analyses of garnet and titanite from the skarn indicate that the skarn mineralization occurred at *ca.* 123 Ma.

The new data suggests that skarn mineralization is associated with Early Cretaceous intrusion of the Kluane Ranges suite and that porphyry mineralization at the Nikki property is the same age as skarn mineralization at the Arn. This indicates that the Kluane Ranges suite is highly prospective for both porphyry and skarn type mineralization elsewhere in southwest Yukon.

[1] *steve.israel@gov.yk.ca*

INTRODUCTION

Southwest Yukon is well-endowed with placer gold mineralization and native copper found in creeks and in fractures within rocks, as well as elevated values of copper and gold in regional geochemical surveys. Some of these anomalous values have been associated with Triassic mafic-ultramafic intrusions and their volcanic equivalents; however, these rocks cannot account for all the mineralization known in southwest Yukon. The Early Cretaceous Kluane Ranges suite, which consists mainly of diorite, quartz-diorite and granodiorite, is another possible mineralizer in the region; however, the possible relationship to mineralization in southwest Yukon is not very well understood. Two properties in southwest Yukon, near the Alaska border south of Beaver Creek, include mineralization that is thought to be related to the Kluane Ranges suite. One of these occurrences (Arn; Yukon occurrence 115K 048) comprises skarn mineralization, and the other (Nikki; Yukon occurrence 115K 082) includes porphyry copper mineralization. A regional Early Cretaceous emplacement age for the Kluane Ranges suite is mainly defined by K-Ar ages from hornblende and biotite found within the intrusive bodies, and by one TIMS age on zircon. These ages range from *ca.* 124 to 112 Ma, with a 122 Ma U-Pb TIMS date (Dodds and Campbell, 1988; Israel, unpublished data).

The Arn property (Fig. 1) is characterized by a copper-gold skarn developed within rocks of Wrangellia. Skarn mineralization at the Arn occurs near the intrusive contact between Triassic carbonate of the Chitistone Limestone and the Kluane Ranges suite. On the Nikki property (Fig. 1) porphyry copper mineralization is related to a quartz-diorite of the Kluane Ranges suite. The relationships between the two mineralizing systems have not been assessed previously, although it has been suspected they are of similar age.

This paper presents new mapping and zircon ages from the Nikki property and titanite and garnet ages from the skarn mineralization at the Arn property. The new data indicates that mineralization at the Arn and Nikki are both related to Kluane Ranges suite intrusions and occurred between 123 and 125 Ma. The new U-Pb data also shows the effectiveness of using garnet for dating skarn systems.

Figure 1. *Location of the Nikki and Arn properties shown by red dots, black box indicates location of Figure 2. HJ-Haines Junction; BC-Beaver Creek.*

REGIONAL GEOLOGY

The region around the Nikki and Arn properties is characterized by Mississippian through to Triassic volcanic and sedimentary strata of Wrangellia, which are overlain by Jura-Cretaceous sedimentary rocks of the Dezadeash Formation (Israel *et al.*, 2007). The area is dissected by the Miles Creek fault, which separates the Jura-Cretaceous rocks to the south from the main Wrangellian sequence to the north (Fig. 2). This fault likely has some normal displacement associated with it and is probably linked to deformation along the Denali fault in the Cenozoic. North of the Miles Creek fault, rocks of Wrangellia are folded and cut by northeast directed thrust faults. Folds are tight and in places overturned towards the northeast. South of the Miles Creek fault, the geology is not as well understood and is broadly divided into Paleozoic volcaniclastic rocks of the Station Creek Formation, Triassic volcanic rocks of the Nikolai formation, Triassic carbonates of the Chitistone Limestone and Jura-Cretaceous turbidites of the Dezadeash Formation. Much of the geology has been compiled from existing 1:250 000 scale mapping and does not show the detailed structural and stratigraphic relationships north of the fault. The rocks south of the fault are intruded by large bodies of the Kluane Ranges suite; north of the fault smaller intrusive bodies of both Triassic and Cretaceous ages are found (Fig. 2).

NORTHWEST ARN PROPERTY GEOLOGY

The approximate location of the Arn claims is shown in Figure 2. Mapping for this project covered the western part of the claim block. The geology of this study area is similar to that described for the rest of the property (Eaton, 2003; 2004; Fig. 3).

The lowermost stratigraphic unit within the Arn property is a dark green to black, fine-grained, locally vesicular or amygdaloidal, and locally pillowed, strongly magnetic basalt (unit mTRb) (Fig. 4) that crops out along a knife-edged ridge on the west side of the mapped area. Sitting above this, and to the north, is a horizon of grey, laminated to thin-bedded limestone (unit lTRl) that is locally converted to marble (unit lTRm) near the contact with intrusive rocks (Fig. 5). The limestone appears to dip shallowly to the north and is at most a few hundred metres thick. Above, and to the north of the limestone, is a relatively flat laying package of thin bedded, very fine grained, green and beige, banded tuffs (Fig. 6). The tuffs make up the highest part of the mountain in the northwest corner of the property. Contacts between the basalt, limestone, and tuff are inferred to be conformable; however the abundance of dikes and sills intruding this package obscures most of the exposed contacts. To the north and east of the layered rocks a grey, medium-grained diorite intrudes the layered rocks (unit Kd).

Of significance are the numerous intermediate to mafic dikes and sills that cut through the layered rocks. Textures of these bodies vary from fine grained to very coarsely porphyritic (hornblende, pyroxene and plagioclase phenocrysts). Intermediate, fine-grained dikes and feldspar porphyry dikes both cut hornblende ± pyroxene porphyry dikes. Both porphyritic dikes and intermediate composition dikes cut the diorite pluton, as does a light green, sugary felsite dike. Xenoliths of mafic and intermediate blocks, similar to the dikes in outcrop, occur within a medium-grained diorite, but are only recognized in float.

Lens shaped, discontinuous skarn horizons are common throughout the Arn property. Skarn horizons are commonly spatially associated with limestone, are rarely found within the basalt, and are always associated with intermediate or mafic dikes and sills believed to be associated with the Kluane Ranges suite intrusions. Within the mapped area, skarn minerals consist of varying amounts of garnet, epidote, pyroxene, magnetite, pyrite, and pyrrhotite.

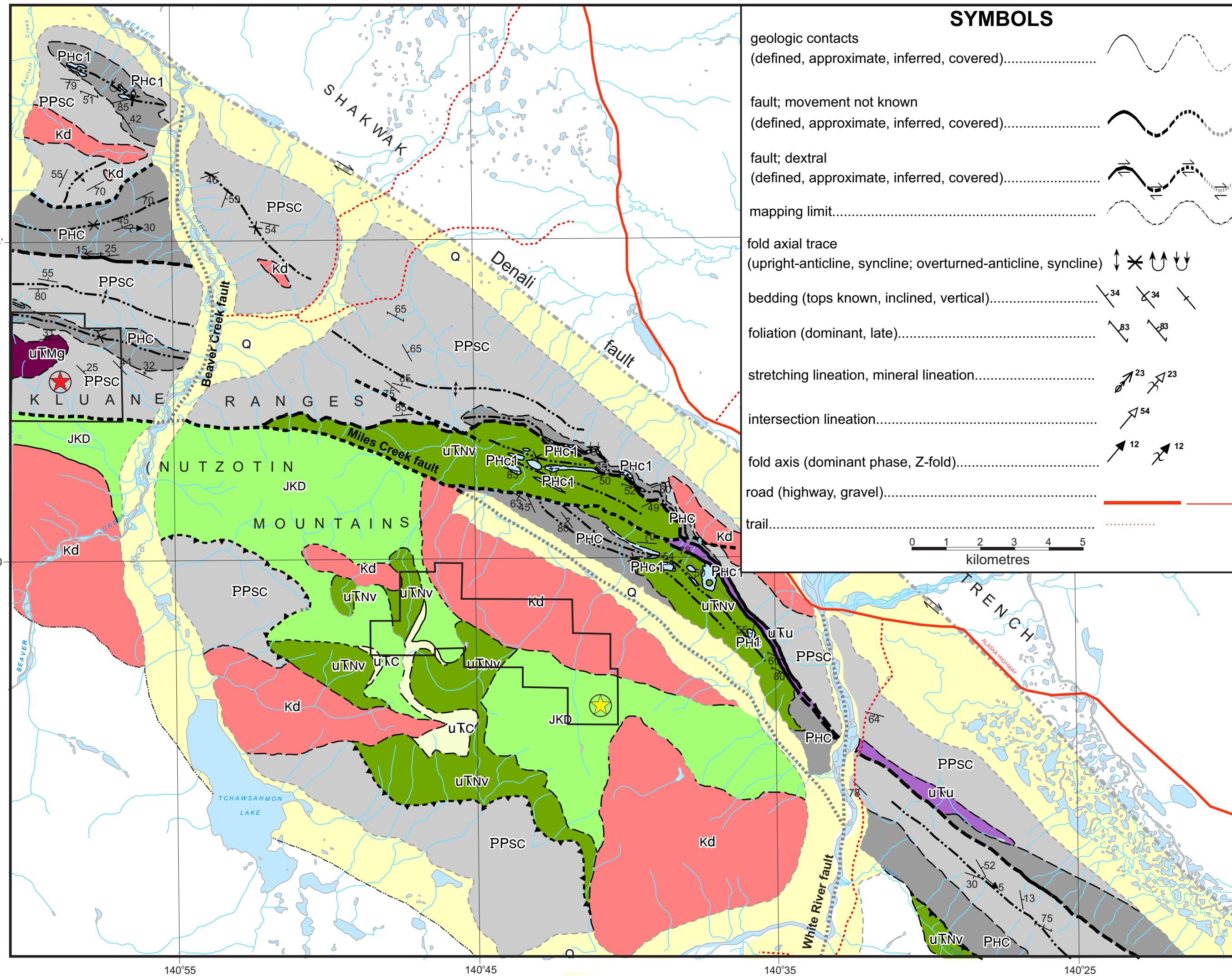
To the east of the mapped area, still within the Arn property boundary, previous workers have recorded a wide variety of skarn minerals associated with grey, bedded limestone, and basalt, cut by intermediate dikes. Skarn assemblages in this area are typically made up of varying amounts of garnet, epidote, magnetite-amphibole, pyrrhotite and pyrite (Eaton, 2004). Copper and gold mineralization is found within pyrrhotite and pyrite rich skarns that occur within the basalts and less commonly within intermediate dikes near limestone bodies (Eaton, 2004).

NIKKI PROPERTY GEOLOGY

The Nikki property is characterized by layered sedimentary rocks of probable Permian age that have been intruded by Triassic Maple Creek gabbro and Early Cretaceous intrusions (Fig. 7).

Layered rocks mapped within the Nikki property boundary comprise banded tuffs, sandstone, siltstone and shale. The tuffs are made up of beige, light and dark green bands and are interlayered with green, volcaniclastic sandstone and siltstone. The volcaniclastic rocks grade upwards into dark grey siltstone with interbeds of fossiliferous shale. This becomes shale-rich and then finally passes up into shale interbedded with medium-grained arkose and lithic sandstone. Rare fining upwards sequences within the sandstone beds indicate this package of rocks is structurally upright (Fig. 8). This entire succession has been assigned to the Permian Hasen Creek Formation based on lithological similarities to Hasen Creek rocks mapped nearby (Fig. 2; Israel *et al.*, 2007).

The Hasen Creek Formation has been intruded by granodiorite that has been divided into three sub-units based on mineralogical variability within the mapped area. Salt and pepper, medium-grained, biotite-hornblende granodiorite to diorite (unit EKK, Fig. 7) crops out in the southeast corner of the map area and appears to be relatively unaltered. In the southwest corner of the map sheet a pinkish, medium-grained granodiorite is composed of quartz and plagioclase with biotite and hornblende altered to chlorite and what appears to be interstitial potassium feldspar (unit EKK2, Fig. 7). A band of purplish-grey, medium to coarse-grained, highly magnetic gabbro to diorite crops out north of the altered granodiorite. This body contains varying amounts of magnetite and locally significant amounts of secondary (?) biotite (unit EKK1, Fig. 7).



LEGEND

QUATERNARY

Q unconsolidated glacial, glaciofluvial and glaciolacustrine deposits; fluviatile silt, sand and gravel, and local volcanic ash, in part with cover of soil and organic deposits

INTRUSIVE ROCKS

EARLY CRETACEOUS

Kd KLUANE RANGES SUITE: medium to coarse-grained, unfoliated, hornblende-biotite, diorite to biotite granodiorite; salt and pepper appearance

LATE TRIASSIC

uTrMg MAPLE CREEK GABBRO: medium to coarse-grained, massive to foliated, dark-grey weathered and fresh, pyroxene gabbro; rare olivine phenocrysts

uTru KLUANE MAFIC-ULTRAMAFIC COMPLEX: fine to medium-grained, dark-grey weathered pyroxene gabbro; dark-green/black weathered peridotite, pyroxenite and rare dunite, locally strongly serpentinized and altered

LAYERED ROCKS

UPPER TRIASSIC(?) - JURASSIC

Dezadeash Formation

JKD interbedded light to dark buff-grey lithic greywacke, sandstone and siltstone, thin dark grey shale, argillite, phyllite and conglomerate; rare tuff horizons; may include Late Triassic McCarthy Formation, well bedded calcareous mudstone and black fetid carbonate

TRIASSIC

uTrC CHITISTONE LIMESTONE: light beige to light grey carbonate; massive to brecciated and locally bedded; noticeable absence of macrofossils distinguishes this unit from Paleozoic limestones; includes abundant dark green/maroon basalt clasts near contact with underlying Nikolai formation; may include Late Triassic McCarthy Formation, well bedded calcareous mudstones and black fetid carbonate

Nikolai formation

uTrNv dark green/maroon weathered and fresh, massive to locally foliated, amygdaloidal and vesicular basalt flows; rare pillows, volcanic breccia and conglomerate locally developed near base of unit; breccia and conglomerate contain clasts of sedimentary and volcanic rocks of underlying Hasen Creek and Station Creek formations as well as rounded volcanic clasts typical of the Nikolai basalts

PENNSYLVANIAN - PERMIAN

Skolai Group

Hasen Creek Formation

PHc1 light to medium grey, massive to bedded fossiliferous limestone; fossils include corals and crinoids

PHC interbedded, dark-grey and brown weathered siltstone, mudstone and medium to coarse-grained sandstone; lower part contains volcaniclastic sandstones, tuffs and rare basaltic flows; rare dark-grey to black chert beds and pebble conglomerate

Station Creek Formation

PPSC interbedded volcanic breccia, agglomerate and volcaniclastic sandstone; intercalated light-grey weathered, dark-green to black fresh, pyroxene-phyric basalt flows; dark grey to black siltstone and light to dark-grey limestone found near contact with Hasen Creek Formation

Figure 2. *Regional geological map of the area surrounding the Nikki (red star) and Arn (yellow star) properties, modified from Israel et al., (2007).*

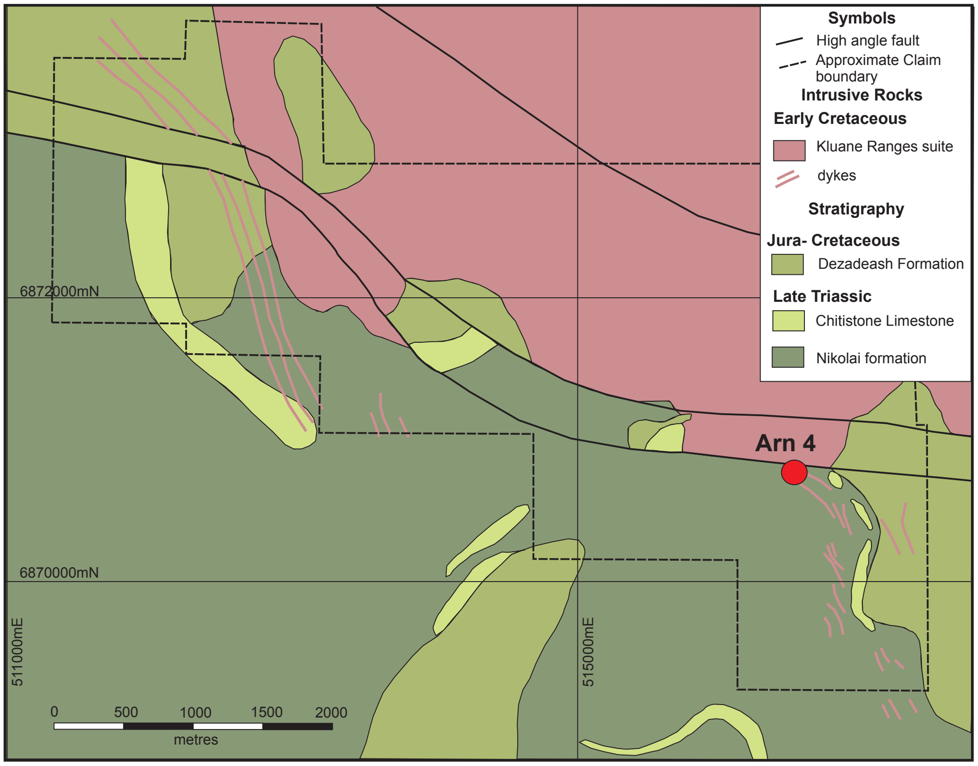


Figure 3. *Simplified geology of the Arn property, modified from Eaton (2004).*

Figure 4. *Basalt from the Arn property.*

Figure 5. *Layered limestone/marble found on the Arn property.*

Figure 6. *Banded tuff found at the stratigraphically highest level at the Arn property.*

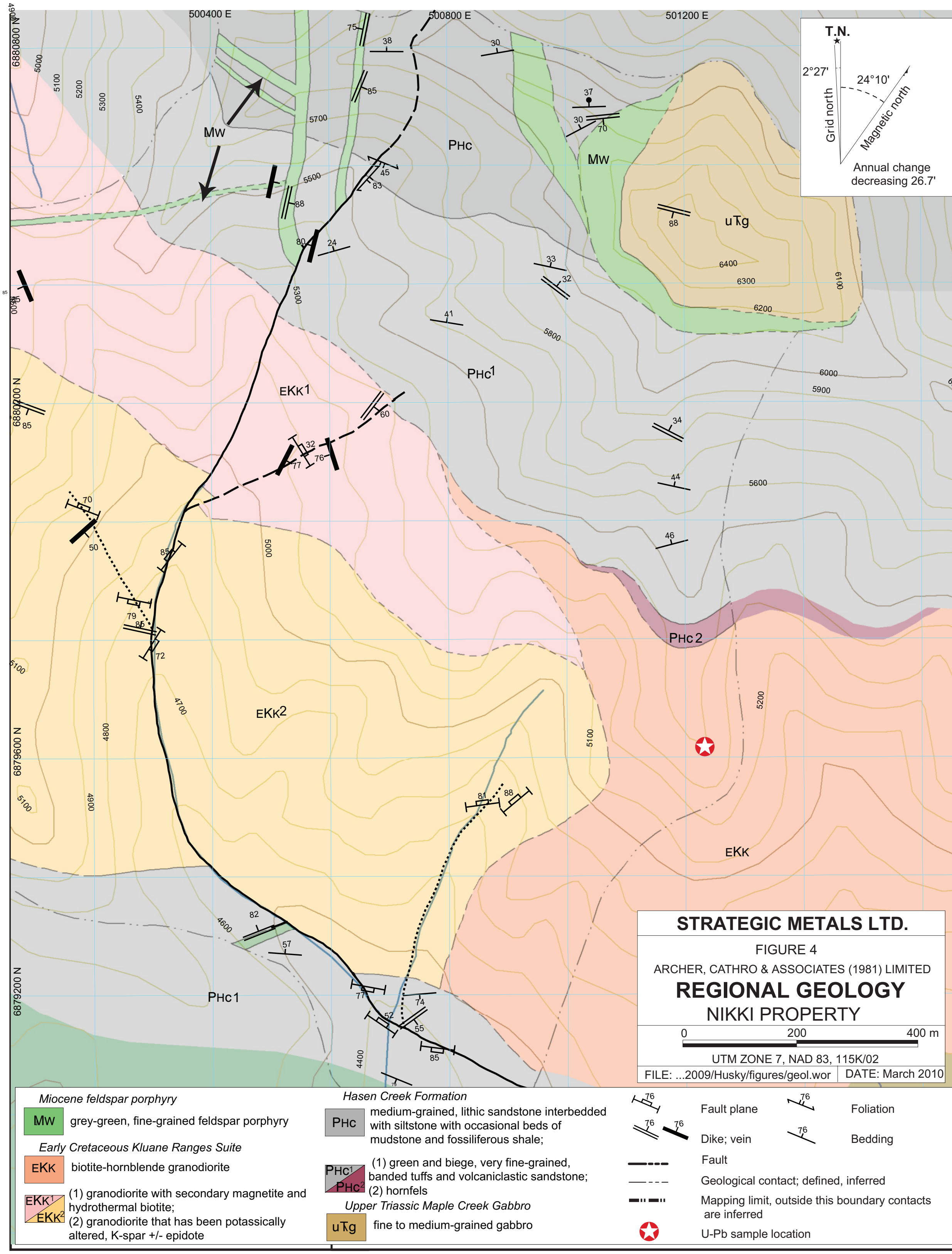


Figure 7. *Simplified geology of the Nikki property.*

Figure 8. *Fining upwards graded beds in arkosic/lithic sandstone at the Nikki property.*

Figure 9. *Orange weathered clay within a brittle fault on the Nikki property.*

In the northeast corner of the Nikki property a rugged mountain peak is composed of fine to medium-grained gabbro that has not been dated but has been assigned to the upper Triassic Maple Creek Gabbro based on regional geology (Fig. 2).

Both the layered rocks and the plutons are commonly cut by feldspar ± quartz porphyry dikes that range in thickness from 2 to 40 m, intermediate to mafic composition, pyroxene-porphyry dikes and grey-green, fine-grained, intermediate composition dikes. The age of these dikes is unknown; they either represent a later phase of the Kluane Ranges suite or younger, possibly Oligocene or Miocene intrusions similar to those that have been found elsewhere in the region.

The main gully that runs north-south through the centre of the property follows the trace of a steeply dipping brittle fault. Where exposed, the fault comprises zones of crushed rock and clay that range in thickness from 20 to 50 cm (Fig. 9). Splays off the main fault occur both to the northwest and northeast, but cannot be traced for very long distances. This fault appears to have a component of dextral strike slip motion because contacts are offset by as much as 150 metres. The orientation of gouge and crushed rock zones measured at a variety of locations can be grouped into two orientations, suggesting they may form a conjugate set. The dominant set of fault plane measurements strikes northeast and dips steeply to the southeast. A minor set of faults strikes east-southeast and dips steeply to the south. Exposures of the fault zone exhibit very rusty weathered rock and locally contain copper carbonate staining (Fig. 10).

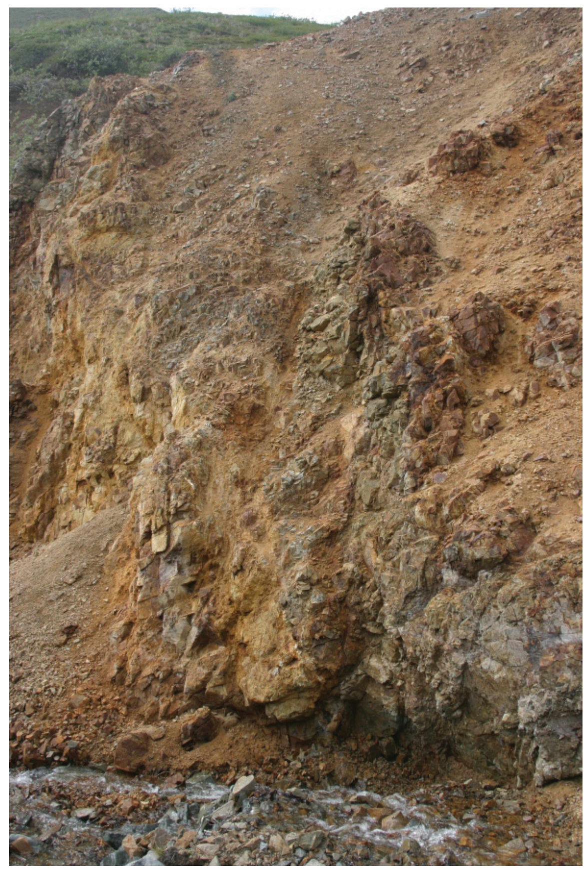


Figure 10. *Moderately mineralized brittle fault on the Nikki property.*

Mineralization at the Nikki property is believed to be porphyry copper-gold, with some anomalous molybdenum, and probably associated with high level intrusions of the Kluane Ranges suite (Eaton, 2005). A large copper and gold soil geochemical anomaly on the Nikki property was identified during work in 2004 and was subsequently followed up in this study with bedrock geological mapping.

GEOCHRONOLOGY

Samples from the Nikki and Arn properties were analysed using U-Pb zircon techniques at Memorial University of Newfoundland (MUN) and U-Pb titanite and garnet techniques at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, in order to test the age of mineralization. Analytical techniques employed at MUN followed Bennett and Tubrett (2010), and at PCIGR methods used followed Mortensen *et al.* (1995).

NIKKI

A sample of hornblende, quartz-diorite from the Nikki property, associated with mineralization, was obtained during mapping. This sample was analysed at MUN using LAM-ICPMS to obtain an age for the intrusions at the property and the age of mineralization. Analytical data are shown in Appendix A. Zircons from the sample were imaged using cathodoluminescence and display oscillatory zoning and no cores or metamorphic rims. A total of 24 zircons were analysed with the best 17 returning a mean average age of 125.08 ± 0.77 Ma (Fig. 11). We interpret this age as the crystallization age of the intrusion and also the age of the porphyry style mineralization associated with the intrusion.

ARN

Precisely dating mineralized skarns is hampered by the fact that minerals amenable to ^{40}Ar-^{39}Ar dating are commonly absent, and in many cases, as at the Arn, the temporal relationship between the mineralization and intrusive rock phases that could be dated by ^{40}Ar-^{39}Ar or U-Pb methods is unclear. However, Meinert *et al.* (2001) successfully employed U-Pb methods to directly date inclusion-free garnets from several copper skarns. In this study we have used U-Pb dating of both garnet and titanite from within mineralized skarn at the Arn property to establish the age of skarn formation. Garnet in mineralized skarn at the Arn

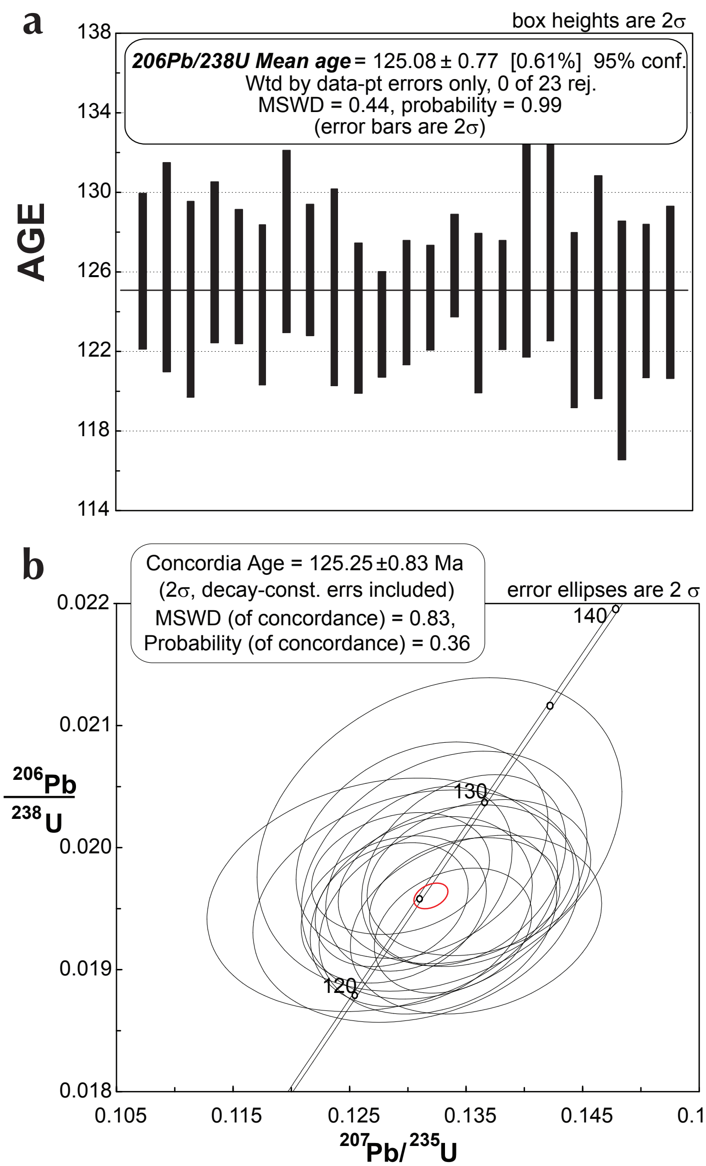


Figure 11. *U-Pb zircon ages from quartz-diorite samples at the Nikki property,* ***(a)*** *weighted mean of zircon ages,* ***(b)*** *U-Pb zircon concordia diagram.*

property is typically compositionally zoned from grossular-rich cores to more andraditic rims (Miller, 2004). Titanite occurs together with prismatic hornblende grains within calcite.

Selected samples of skarn material from diamond drillhole Arn 4, drilled adjacent to the Arn fault (Eaton, 2003; 2004; Fig. 3), were crushed and ground to fine sand size, and then garnet and/or titanite was concentrated using a combination of heavy liquids and magnetic separation methods. The best, clearest, inclusion-free grains available were carefully hand-picked under a binocular microscope. Analytical data are reported in Appendix B. All errors in interpreted ages are given at the 2 sigma level.

Sample JM-14. Two fractions of clear, pinkish-brown garnet were analysed. Both yield concordant analyses with overlapping error envelopes (Fig. 12a). The interpreted age of 123.3 ± 0.9 Ma is based on the total range of $^{206}Pb/^{238}U$ ages for the two garnet fractions.

Sample JM-28B. Two fractions of pinkish-brown garnet were analysed. Although both analyses are concordant there is a greater range of $^{206}Pb/^{238}U$ ages for the two fractions (Fig. 12b). An age of 122.9 ± 0.8 Ma is assigned based on the total range of $^{206}Pb/^{238}U$ ages for the two fractions.

Sample ARN-16. Two fractions of clear, very pale pink garnet were analysed. Both yield slightly discordant analyses with a total range of $^{206}Pb/^{238}U$ ages of 123.6 ± 0.8 Ma. The sample also yielded abundant clear, very pale yellow fragments of originally relatively large, subhedral to euhedral titanite. Two fractions of titanite were also analysed; one fraction yielded a concordant analysis and the second yielded a somewhat reversely discordant analysis (Appendix B; Fig. 12c). A $^{238}U/^{206}Pb$ isochron age of 124.0 ± 0.8 Ma was obtained for the garnet and titanite analyses, with a MSWD of 4.1 and a calculated initial $^{206}Pb/^{204}Pb$ ratio of 18.0 (Fig. 13a).

Sample JM-16. Both garnet and titanite were analysed from this sample. The garnet was pale pinkish-brown. Two fractions of garnet and three fractions of titanite yield a considerable scatter in $^{206}Pb/^{238}U$ ages (Table 2; Fig. 12d); however a relatively imprecise $^{238}U/^{206}Pb$ isochron age of 125.5 ± 4.2 Ma was obtained for the garnet and titanite analyses. The calculated regression has a MSWD of 219 and a calculated initial $^{206}Pb/^{204}Pb$ ratio of 19.7 (Fig. 13b).

The ages obtained for the four samples of Arn skarn material are in excellent agreement and collectively indicate that the skarn formed at about 123 Ma.

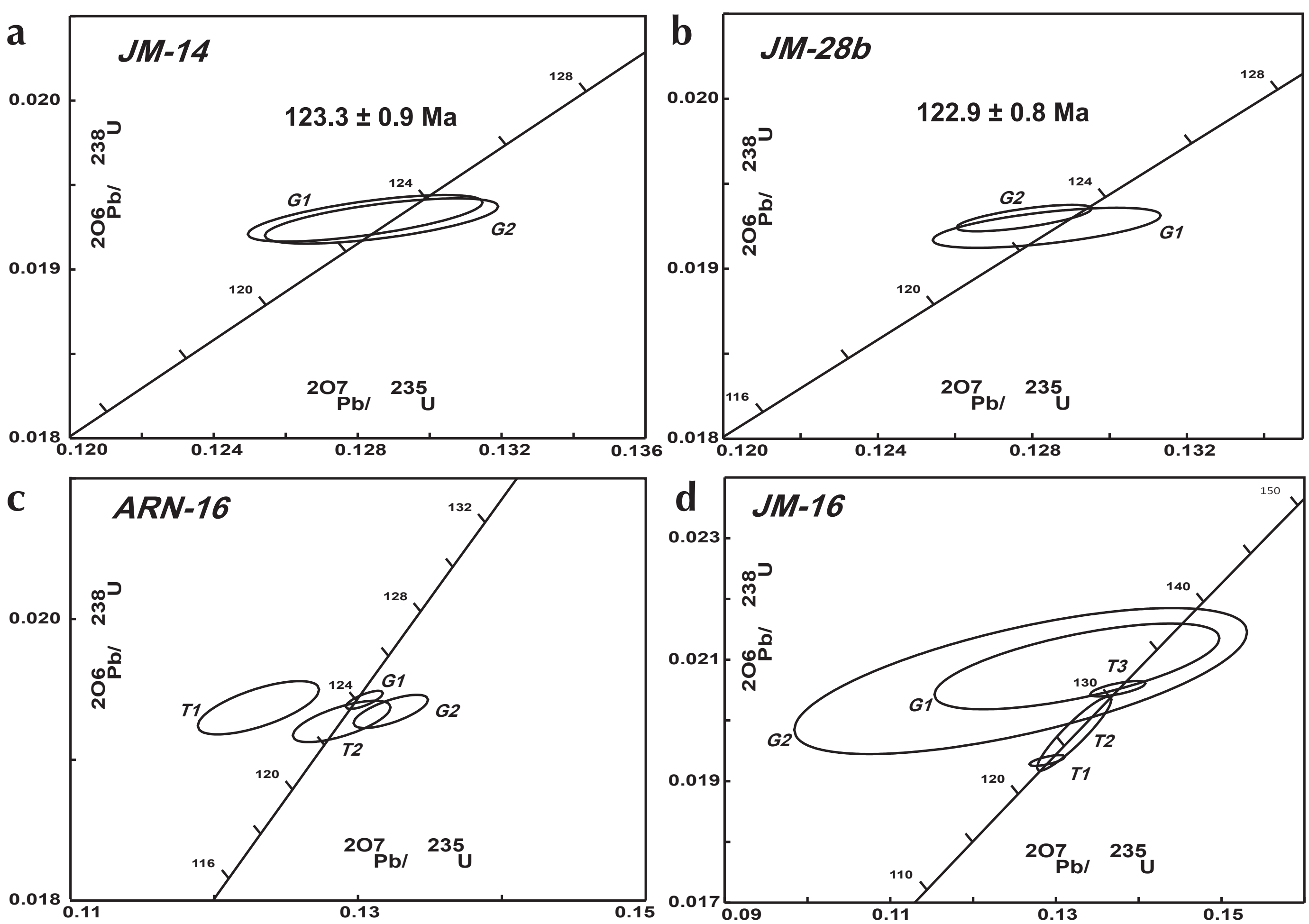


Figure 12. *U-Pb concordia diagrams for garnet and titanite from the Arn skarn samples;* ***(a)*** *JM-14,* ***(b)*** *JM-28b,* ***(c)*** *ARN-16, and* ***(d)*** *JM-16.*

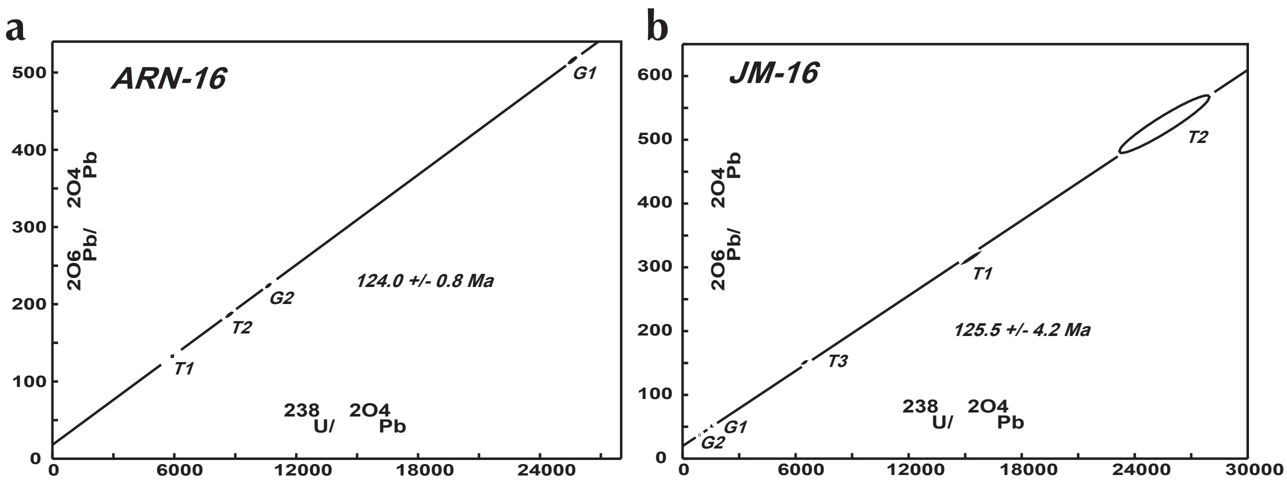


Figure 13. *U-Pb isochron diagrams for samples **(a)** ARN-16 and **(b)** JM-16.*

DISCUSSION

Geochronological results described here demonstrate that the porphyry style mineralization associated with intrusions at the Nikki property is the same age, within statistical error, as the skarn mineralization at the Arn property ~15 km to the southeast. We believe that intrusions responsible for both types of mineralization are associated with the Early Cretaceous Kluane Ranges suite. It is likely that both skarn and porphyry style mineralization is likely to be found associated with the Kluane Ranges suite elsewhere in southwest Yukon.

REFERENCES

Bennett, V. and Tubrett, M., 2010. U-Pb isotopic age dating by LAM ICP-MS, INCO Innovation Centre, Memorial University: Sample preparation methodology and analytical techniques. *In:* Yukon Exploration and Geology 2009, K.E. MacFarlane, L.H. Weston and L.R. Blackburn (eds.), Yukon Geological Survey, p. 47-55.

Dodds, C.J. and Campbell, R.B., 1988. Potassium-argon ages of mainly intrusive rocks in the Saint Elias Mountains, Yukon and British Columbia. Geological Survey of Canada, Paper 87-16, 43 p.

Eaton, W.D., 2003. Diamond drilling, prospecting and soil sampling on the Arn property. Yukon Territorial Assessment Report 094374.

Eaton, W.D., 2004. Geological mapping, soil sampling, prospecting and hand trenching on the Arn property. Yukon Territorial Assessment Report 094476.

Eaton, W.D., 2007. Prospecting, geological mapping, soil sampling and geophysical surveys at the Nikki property. Yukon Territorial Assessment Report 094527.

Israel, S., Cobbett, R. and Fozard, C., 2007. Bedrock geology of the Miles Ridge area, Yukon (parts of NTS 115F/15, 16 and 115K/1, 2) (1:50 000 scale). Yukon Geological Survey, Open File 2007-7.

Meinert, L.D., Nicolescu, S., Mortensen, J.K. and Cornell, D.H., 2001. U-Pb dating of hydrothermal garnets from skarn deposits – implications for petrogenesis and ore deposits. Geological Society of America, Abstracts with Program, v. 33.

Miller, J.L.P., 2004. U-Pb age and petrography of the ARN skarn occurrence in southwestern Yukon and the nature of contained gold. Unpublished B.A.Sc. thesis, University of British Columbia, 30 p.

Mortensen, J.K., Ghosh, D. and Ferri, F., 1995. U-Pb age constraints of intrusive rocks associated with copper-gold porphyry deposits in the Canadian Cordillera. *In:* Porphyry deposits of the northwestern Cordillera of North America, T.G. Shroeter (ed.), Canadian Institute of Mining and Metallurgy, Special Volume 46, p. 142-158.

Appendix A. *U-Pb analyses for sample 10-RC-038.*

								2 s %	2 s %	2 s %	AGES Ma						
Analysis	207/235	7/5 err	206/238	6/8 err	Rho	207/206	7/6 err	207/235	206/238	207/206	7/5 age	1 sigma	6/8 age	1sigma	Th_ppm	U_ppm	Th/U
no06a76	0.13095	0.00326	0.01974	0.00031	0.31388	0.04921	0.00131	4.99	3.13	5.33	125.0	2.9	126.0	2.0	86.2	241.3	0.36
no06a77	0.13312	0.00501	0.01977	0.00041	0.27889	0.04983	0.00197	7.52	4.20	7.89	126.9	4.5	126.2	2.6	181.2	328.6	0.55
no06a79	0.13071	0.00572	0.01952	0.00039	0.22766	0.04998	0.00245	8.75	3.98	9.82	124.7	5.1	124.6	2.5	86.2	178.3	0.48
no06a80	0.13480	0.00358	0.01981	0.00032	0.30414	0.05033	0.00154	5.31	3.23	6.10	128.4	3.2	126.5	2.0	119.8	297.9	0.40
no06a82	0.13414	0.00413	0.01970	0.00027	0.21940	0.04985	0.00132	6.16	2.70	5.29	127.8	3.7	125.8	1.7	150.1	361.8	0.41
no06a83	0.13115	0.00389	0.01948	0.00032	0.27523	0.05014	0.00175	5.94	3.27	6.98	125.1	3.5	124.3	2.0	123.4	231.4	0.53
no06a85	0.13122	0.00441	0.01998	0.00036	0.26934	0.04854	0.00170	6.73	3.62	7.00	125.2	4.0	127.5	2.3	83.6	225.3	0.37
no06a93	0.13610	0.00392	0.01975	0.00026	0.22939	0.05101	0.00169	5.76	2.64	6.61	129.6	3.5	126.1	1.7	110.7	357.0	0.31
no06a94	0.12781	0.00614	0.01961	0.00039	0.20727	0.04784	0.00215	9.62	3.99	8.97	122.1	5.5	125.2	2.5	197.1	318.0	0.62
no06a95	0.13585	0.00441	0.01937	0.00030	0.23826	0.05166	0.00164	6.49	3.09	6.37	129.3	3.9	123.7	1.9	190.6	420.0	0.45
no06a96	0.13388	0.00276	0.01932	0.00021	0.26323	0.05093	0.00111	4.12	2.17	4.36	127.6	2.5	123.4	1.3	473.2	547.6	0.86
no06a97	0.12880	0.00325	0.01949	0.00025	0.25057	0.04860	0.00135	5.04	2.53	5.57	123.0	2.9	124.5	1.6	520.4	576.3	0.90
no06a98	0.12861	0.00268	0.01953	0.00021	0.25488	0.04857	0.00119	4.17	2.13	4.92	122.9	2.4	124.7	1.3	474.0	548.3	0.86
no06a99	0.12937	0.00312	0.01979	0.00020	0.21369	0.04820	0.00124	4.82	2.06	5.13	123.5	2.8	126.3	1.3	420.4	503.7	0.83
no06a100	0.13258	0.00417	0.01941	0.00032	0.25913	0.05012	0.00182	6.28	3.26	7.25	126.4	3.7	123.9	2.0	684.1	635.4	1.08
no06a103	0.13488	0.00334	0.01955	0.00022	0.22294	0.05072	0.00125	4.96	2.21	4.94	128.5	3.0	124.8	1.4	440.6	559.4	0.79
no06a104	0.13272	0.00640	0.02011	0.00052	0.27081	0.04892	0.00235	9.64	5.22	9.63	126.5	5.7	128.3	3.3	53.2	133.0	0.40
no06a70*	0.11116	0.00465	0.01999	0.00040	0.23915	0.04170	0.00203	8.37	4.00	9.74	107.0	4.3	127.6	2.5	88.5	195.6	0.45
no06a78*	0.12202	0.00314	0.01935	0.00035	0.35008	0.04661	0.00124	5.14	3.60	5.34	116.9	2.8	123.6	2.2	94.2	271.8	0.35
no06a81*	0.11138	0.00419	0.01962	0.00044	0.30044	0.04210	0.00186	7.52	4.52	8.82	107.2	3.8	125.2	2.8	207.3	312.0	0.66
no06a84*	0.12489	0.00863	0.01919	0.00047	0.17862	0.04761	0.00332	13.82	4.94	13.93	119.5	7.8	122.5	3.0	91.8	278.1	0.33
no06a101*	0.11298	0.00362	0.01951	0.00030	0.24323	0.04278	0.00135	6.41	3.12	6.31	108.7	3.3	124.5	1.9	92.7	187.2	0.50
no06a102*	0.11752	0.00447	0.01957	0.00034	0.22970	0.04449	0.00177	7.61	3.50	7.94	112.8	4.1	125.0	2.2	124.1	237.0	0.52
no06a105*	0.12246	0.00595	0.01826	0.00041	0.22951	0.04955	0.00246	9.72	4.46	9.92	117.3	5.4	116.6	2.6	493.5	479.6	1.03

Note: samples with (*) were only used for 206Pb/238U mean age (Fig. 11 a)

Appendix B. *Arn U-Pb data.*

Sample Description[1]	Wt (mg) (mg)	U content (ppm)	Pb[2] content (ppm)	$^{206}Pb/^{204}Pb$ (meas.)[3]	total common Pb (pg)	%^{208}Pb[2]	$^{206}Pb/^{238}U$[4] (± % 1s)	$^{207}Pb/^{235}U$[4] (± % 1s)	$^{207}Pb/^{206}Pb$[4] (± % 1s)	$^{206}Pb/^{238}U$ age (Ma; ± % 2s)	$^{207}Pb/^{206}Pb$ age (Ma; ± % 2s)
Sample JM-14 (depth 47.6m)											
G1	0.688	11.9	0.21	179	60	0.89	0.01930(0.36)	0.1282(1.27)	0.04817(1.06)	123.3(0.9)	107.8(50.5)
G2	0.324	12.1	0.21	197	26	0.37	0.01929(0.35)	0.1287(1.26)	0.04838(1.07)	123.2(0.9)	118.0(50.6)
Sample JM-28 B (depth 12.5 m)											
G1	0.971	8.7	0.15	256	42	0.58	0.01924(0.31)	0.1284(1.15)	0.04839(0.99)	122.9(0.7)	118.3(46.5)
G2	0.588	20.2	0.35	344	37	0.01	0.01930(0.20)	0.1278(0.68)	0.04802(0.56)	123.2(0.5)	100.5(26.4)
Sample ARN-16											
G1	0.362	299	7.68	512	260	31.7	0.01943(0.17)	0.1304(0.50)	0.04870(0.39)	124.0(0.4)	133.5(18.1)
G2	0.213	87.9	2.27	220	109	32.1	0.01934(0.30)	0.1323(0.98)	0.04960(0.80)	123.5(0.7)	176.1(37.0)
T1	0.123	39.2	0.92	125	30	25.7	0.01937(0.50)	0.1231(1.71)	0.04609(1.43)	123.7(1.2)	2.1(69.1)
T2	0.067	75.5	1.88	182	67	30	0.01927(0.38)	0.1289(1.32)	0.04850(1.10)	123.1(0.9)	123.5(51.3)
Sample JM-16 (depth 45.0 m)											
G1	0.459	12.2	0.23	50.7	221	0.01	0.02089(1.69)	0.1324(6.49)	0.04602(5.52)	133.3(4.5)	-2(268.0)
G2	0.499	11.6	0.21	37.1	394	0.01	0.02065(2.91)	0.1257(10.9)	0.04417(9.18)	131.8(7.6)	-101(466)
T1	0.117	79.9	1.4	300	39	0.47	0.01934(0.23)	0.1289(0.83)	0.04835(0.69)	123.5(0.6)	116.6(32.5)
T2	0.056	69.1	1.24	434	11	0.58	0.01978(1.54)	0.1322(1.70)	0.04847(0.66)	126.3(3.9)	122.4(31.3)
T3	0.252	33.2	0.62	148	81	0.43	0.02052(0.31)	0.1375(1.21)	0.04859(1.02)	131.0(0.8)	127.9(48.2)

[1] G = garnet; T = titanite

[2] radiogenic Pb; corrected for blank, initial common Pb, and spike

[3] corrected for spike and fractionation

[4] corrected for blank Pb and U, and common Pb