Geochronological and lithogeochemical studies of intrusive rocks in the Nahanni region, southwestern Northwest Territories and southeastern Yukon

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ABSTRACT

Magmatism in the Nahanni region, which defines the eastern extent of the Tintina Gold Province, is generally associated with tungsten mineralization and/or gold-copper-antimony-bismuth-lead-zinc metal occurrences. Intrusions are subalkaline, granitic to granodioritic, and contain several types of textural variations and highly evolved phases. The intrusions range from large composite batholiths to small stocks with associated felsic dykes and veins. Initial U-Pb and Ar-Ar geochronology reveals ages of 97.5-95 Ma with short (0.5-1.5 m.y.) cooling periods, although the intrusion associated with the Cantung tungsten-skarn orebody cooled over a relatively long period (3 m.y.). Magmatism in the area has been interpreted as crustally derived, however, the rare earth element primitive-mantle-normalized profile revealed negative niobium, tantalum and titanium anomalies suggesting an arc-type setting. Furthermore, the granites lack volumetrically significant, primary peraluminous mineralogies characteristic of S-type granites.

RÉSUMÉ

Dans la région de Nahanni, le magmatisme qui détermine la limite est de la Province aurifère de Tintina est généralement associé à une minéralisation en tungstène et/ou à des occurrences minérales d'or-cuivre-antimoine-bismuth-plomb-zinc. Les intrusions sont subalcalines, de granitiques à granodioritiques, contient plusieurs types de variations texturales et se répartissent en plusieurs phases très complexes. Les intrusions varient de grands batholithes composites à de petits stocks auxquels sont associés des dykes et des filons felsiques. La géochronologie initiale U-Pb et Ar-Ar révèle des âges de 97,5 à 95 Ma avec de brèves périodes (0,5 à 1,5 Ma) de refroidissement, bien qu'une période relativement longue (3 Ma) ait été nécessaire au refroidissement de l'intrusion associée au corps minéralisé de skarn tungsténifère de Cantung. On interprète le magmatisme de la région comme étant d'origine crustale. Cependant, le profil en terres rares normalisé au manteau primitif révèle des anomalies négatives en Nb, Ta et Ti, indiquant un cadre de type arc. De plus, les granites sont exempts d'importants volumes des principaux minéraux hyperalumineux, caractéristiques des granites de type S.

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INTRODUCTION

A study of intrusive rocks and the potential for related mineralization in southwestern Northwest Territories and southeastern Yukon was initiated as one component of the 2004-2006 Nahanni Mineral and Energy Resource Assessment (MERA). The study area covers the South Nahanni River watershed, which originates in the eastern Selwyn Mountains and transects the southern Mackenzie Mountains in the Northwest Territories (Fig. 1). Magmatism in the study area is confined to the western portion of the watershed near the Yukon border, however, sampling was extended outside the watershed to include several more intrusions further west within Yukon (Fig. 2). Intrusions in the study area represent the southeastern extent of the Tintina Gold Province (TGP), an elongate band of Early to Late Cretaceous magmatism that extends northwest from the study area across Yukon and into central Alaska (Fig. 1). The TGP is characterized by numerous precious and base metal occurrences and deposits that are spatially and genetically related to well defined, metalliferous, mid- and Late Cretaceous plutonic suites (Mortensen *et al.*, 2000). A few intrusion-related deposits are present within the study area, but the rugged topography and lack of road access has hindered exploration efforts to date. The potential for additional intrusion-related mineralization in much of the study area has not been previously investigated in detail despite the presence of widespread mineral occurrences.

Figure 2. *(next page) Mid-Cretaceous granitic intrusions (grey) within, and adjacent to, the Nahanni MERA study area. Radiometric ages (Ma) are reported for several granitoids sampled in 2003 (large closed circles) as ID-TIMS U-Pb (U) and Ar-Ar (A) ages, with 2-sigma errors in brackets. Locations for the 2003 and 2005 samples currently being analyzed for U-Pb geochronology by the laser ablation ICP-MS method are indicated by open circles. Sample locations from Heffernan (2004) for which geochronological analyses are available are also indicated. The Cantung mine area, outlined with a dashed line, is expanded in the inset for greater detail. Figure 3 photo locations are plotted as the figure notation in a box. NWT mineral occurrence locations from the NORMIN database, www.nwtgeoscience.ca/normin. Map modified from Gordey and Makepeace (2003).*

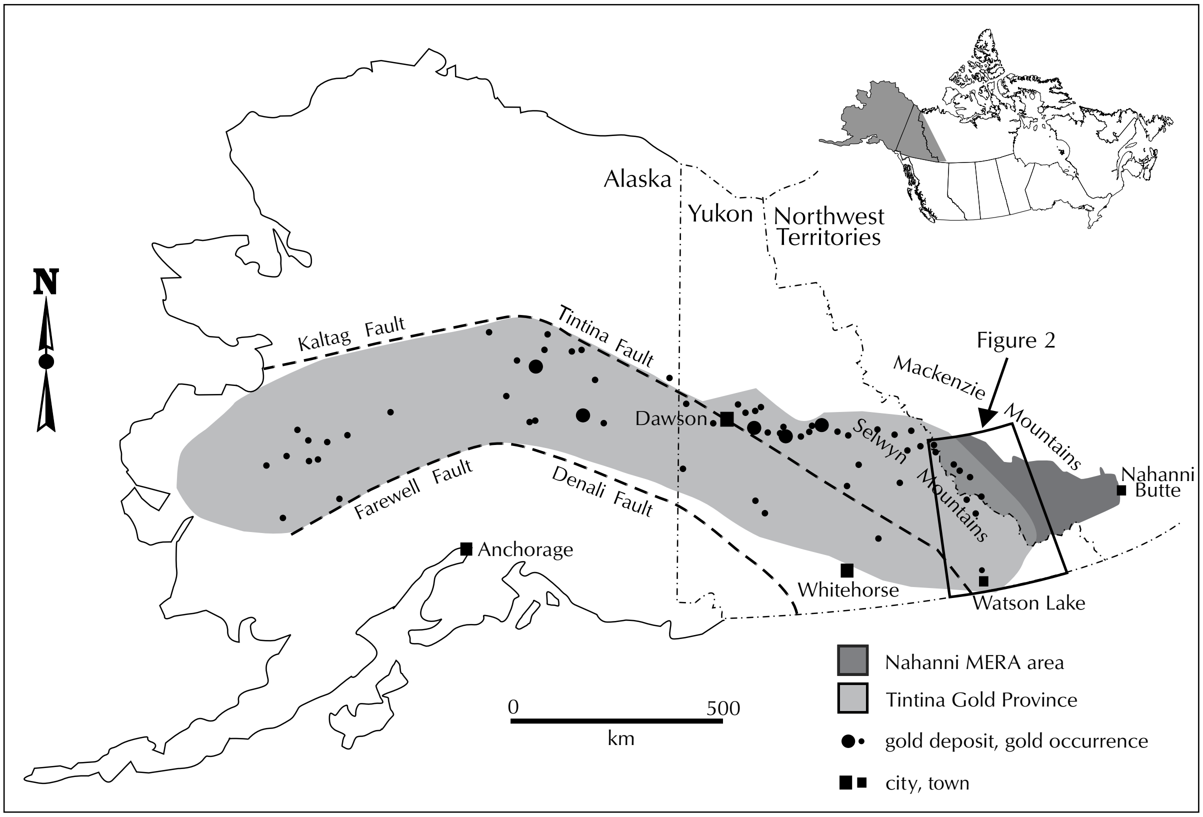

Figure 1. *Location of the Nahanni MERA study area (dark grey), relative to Alaska, Yukon, and Northwest Territories. The Tintina Gold Province (TGP) is shaded in light grey and the area where the MERA and TGP areas overlap is shaded in medium grey. The location of Figure 2 is outlined in black. Map modified from Mortensen et al. (2000).*

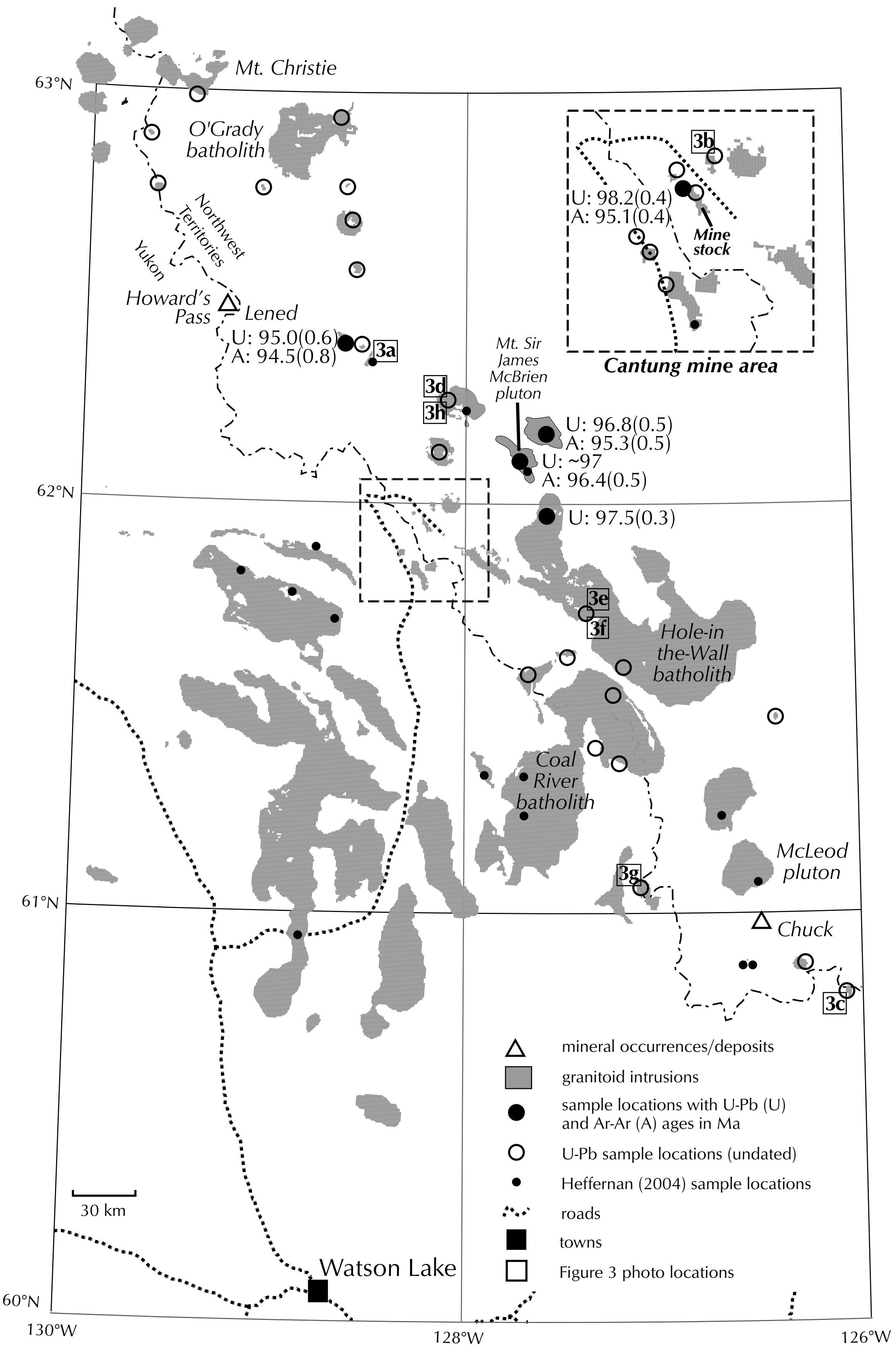

Figure 2. *(caption on facing page)*

Mineralization in the study area (Fig. 2) comprises five main deposit styles: (1) syngenetic sediment-hosted base metals (e.g., Howard's Pass zinc-lead, Yukon MINFILE 105I 012, Deklerk and Traynor, 2005); (2) fault-controlled, vein-hosted base metals (e.g., Prairie Creek zinc-lead-silver quartz-carbonate vein, NORMIN.DB 095FNE 0001-0003, 0009-0013); (3) placer gold originating from disseminated sediment or intrusive-hosted gold (e.g., Selina Creek placer; Chuck gold-showing, NORMIN.DB 095DNE 0007-0010); (4) intrusion-related proximal skarn, or distal quartz vein hosted base/precious metals (e.g., Lened tungsten-skarn, NORMIN.DB 105ISE 0003); and (5) intrusion-related or hosted precious/base metals and precious stones in evolved intrusive phases (e.g., Mt. Christie copper-lead-arsenic quartz veins; O'Grady gem tourmaline in miarolitic cavities). The most significant mineralization styles with respect to this study are placer, intrusion-related and intrusion-hosted mineralization. These mineralization styles consist of placer gold potentially derived from intrusion-related bedrock sources; intrusion- and sediment-hosted mineralized quartz veins or stockworks; intrusion-hosted sheeted gossanous fractures (± quartz veins) with anomalous precious and base metal contents; precious stones hosted in quartz veins or miarolitic cavities; and skarn mineralization in country rock adjacent to intrusions. Economically significant tungsten skarn deposits (e.g., Cantung mine, Fig. 2) and abundant tungsten (e.g., Lened showing, Fig. 2), copper, lead and zinc showings, many of which have been drilled, are spatially associated with the intrusions in the western portion of the MERA area. However, in much of the study area, the potential for intrusion-related precious and/or base metal mineralization is still uncertain.

The focus of this study is to identify intrusions or intrusive phases that have significant potential for genetically related mineralization within the Nahanni MERA area. This contribution will provide preliminary interpretations of magnetic susceptibility and lithogeochemical data recently obtained for several of the intrusive rocks from the study area. In addition, initial U-Pb (zircon and monazite) and Ar-Ar (biotite) ages for several of the intrusions within the study area are reported and discussed. Finally, this paper will describe ongoing and future work aimed at defining the potential of intrusion-related mineralization in the study area. This study builds on previous studies of intrusive rocks in the region (Heffernan, 2004), intrusive rocks in the immediate vicinity of the Cantung mine (Rasmussen, 2004), as well as regional geological studies in the northern Cordillera (Gordey and Anderson, 1993; Mortensen *et al.*, 2000; Lang *et al.*, 2001; Jefferson and Spirito, 2003; Hart *et al.*, 2004).

GEOLOGIC OVERVIEW

The study area is underlain by Neoproterozoic (~800 Ma) to Late Cretaceous (~100 Ma) platformal to basinal strata that was deposited along the western margin of the early North American continent. The sedimentary rocks were intruded by minor Devonian (350 Ma) granitoid rocks and subsequently deformed into fold and thrust belts spanning the Middle Jurassic to Cretaceous time periods. During the mid-Cretaceous, a later magmatic event in this portion of the northern Cordillera was interpreted to be a result of syn- to post-collisional partial melting of miogeoclinal strata within the thickened crustal material (Woodsworth *et al.*, 1991). Mid-Cretaceous, felsic intrusive rocks underlie a significant portion of the MERA area and range from large batholithic bodies (e.g., the Coal River and Hole-in-the-Wall batholiths), to small stocks (e.g., the Mine stock, Cantung mine) and contemporaneous felsic dykes (Fig. 2). Most of the mid-Cretaceous intrusions have relatively restricted mineralogies and have been classified on this basis by Anderson (1983) as biotite-hornblende-bearing, biotite-bearing, and biotite-muscovite-bearing plutons.

Plutonic contacts are shallow- to steep-dipping, but dominantly conformable to, and typically overlain by, the adjacent strata (Fig. 3a). Adjacent, sub-parallel or concentric dykes and sills are commonly observed along the margins of the intrusions, intruding both plutonic and sedimentary rocks (Fig. 3b). Several textural variations, ranging from fine-grained, dioritic, quartz-feldspar porphyry phases (Fig. 3c), to K-feldspar megacrystic granite and syenite phases (Fig. 3d), are observed within the intrusions. Development of one or more late, volatile-rich phases in many of the felsic intrusions is indicated by the presence of the following: 1) miarolitic cavities in granites (Fig. 3e); 2) leucocratic dykes infilled with graphic-textured tourmaline (Fig. 3f); 3) quartz-(tourmaline) veins and aplite-pegmatite dykes (Fig. 3g); 4) sheeted gossanous fractures cutting plutons (Fig. 3h); and 5), one example of a late-stage, marginal breccia in the Circular stock at the Cantung mine. Many of the intrusions are composite; this is established from both internal contacts and textural, mineralogical, and magnetic susceptibility variations, or by age differences between different portions of the larger intrusions.

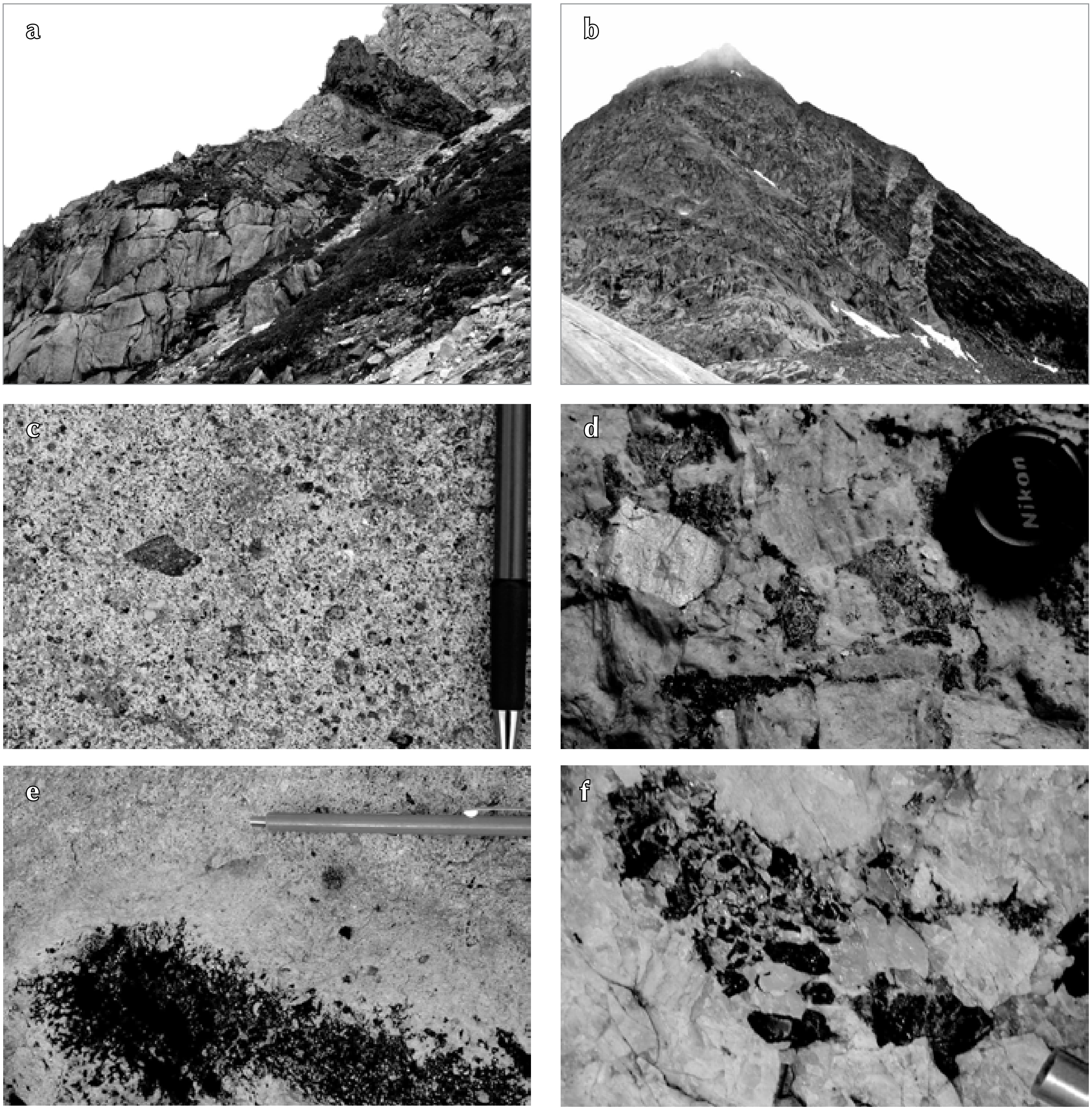

Figure 3. *Photographs of structural and textural features of instrusive rocks (photo locations displayed on Figure 2).* ***(a)*** *Stepped pluton-country rock (lower left half of photo) with overlying strata dipping to the right (upper right half of photo); dark beds are mineralized skarn (outcrop is ~20 m high).* ***(b)*** *Stepped pluton-country rock contact with marginal dykes (granite is on left side of photo; bedding in country rock is sub-parallel to slope of hill; hill expresses ~100 m of relief).* ***(c)*** *Fine-grained, dioritic, quartz-feldspar porphyry phase (pen for scale).* ***(d)*** *Granitic, K-feldspar megacrystic phase; K-feldspar grains are represented by the large white phenocrysts (lens cap is 3 cm across).* ***(e)*** *Miarolitic cavity with aplitic margin and infilled with coarse-grained schorl, in granite (pen magnet for scale).* ***(f)*** *Relatively fine-grained pegmatitic dyke with graphic-textured K-feldspar and schorl (pen magnet tip for scale in bottom right corner of photograph).*

(Figure 3 continued on next page.)

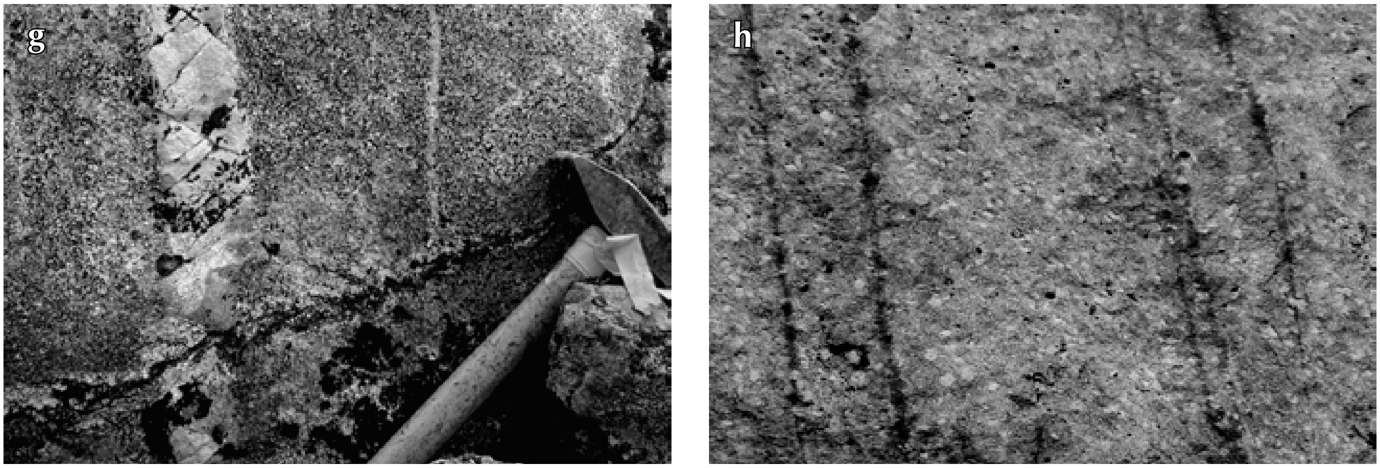

Figure 3. *(continued)* ***(g)*** *Aplite dyke (vertical) cross-cut by quartz-tourmaline vein with gossanous margin (sub-horizontal) in garnet-muscovite-bearing granite (hammer for scale).* ***(h)*** *Typical sheeted, sub-vertical, gossanous fracture set cutting granitic pluton (0.25- and 1-m spacing between fractures).*

PRELIMINARY RESULTS

MAGNETIC SUSCEPTIBILITY

Average magnetic susceptibility was measured in the field for many of the intrusive phases. Measured magnetic susceptibility values are based on an average of 10, randomly oriented readings on flat surfaces of each sample using a KT-9 Kappameter. Values ranged widely between intrusive phases within a single pluton, therefore the magnetic susceptibility of only the dominant intrusive phase in each pluton was selected for interpretation. In general, most of the magnetic susceptibility values are less than 0.5 ($x10^{-3}$ SI units), but several intrusions have values as high as 16.4.

LITHOGEOCHEMISTRY

A total of 51 plutonic and aplitic samples collected during the 2003 and 2005 field seasons were analysed for major, trace and rare earth element composition by ALS Chemex Labs Ltd., North Vancouver. Major element oxides were obtained by both X-ray fluorescence and inductively coupled plasma atomic emission spectroscopy (ICP-AES), and trace and rare earth element concentrations were determined through a combination of ICP-AES and inductively coupled plasma mass spectroscopy (ICP-MS). The accuracy reproducibility of the analyses at the ALS Chemex facility was monitored by repeat analyses of several in-house standards of known composition.

The major element data suggests that intrusions in the study area are predominantly granitic and granodioritic in composition as is shown by the total alkali-silica diagram (Le Bas *et al.*, 1986; Fig. 4a). Samples that plot within the diorite field and low SiO_2 end of the granodiorite field are dominantly fine-grained porphyry phases. Magmatism in the area is subalkaline according to the Irvine and Baragar (1971) classification (Fig. 4a) and the felsic intrusions have a low to moderate peraluminous signature using Shand's Index, after Maniar and Piccoli (1989; Fig. 4b). Many of the northernmost and easternmost intrusions that have more alkaline compositions plot as distinctly metaluminous or weakly peraluminous; several of these intrusions are dioritic porphyries and K-feldspar porphyritic syenites (Fig. 4a,b). The extended trace element diagram of the plutonic bodies, normalized to the primitive mantle values of Sun and McDonough (1989), has a steep profile with distinct negative Ba, Nb, Ta, P, and Ti anomalies and a strong positive Pb anomaly (Fig. 5). On two tectonic discrimination diagrams (Y+Nb *vs.* Rb and Yb+Ta *vs.* Rb; Pearce *et al.*, 1984), the granitoids plot on the border between the volcanic arc granite (VAG) and syn-collisional granite (syn-COLG) fields (Fig. 6).

GEOCHRONOLOGY

Of the 51 samples collected for geochemical analysis, a total of 38 samples were selected for U-Pb dating (Fig. 2); many of these samples will also be dated by Ar-Ar, and (U-Th)-He geochronological analysis. The initial geochronological results for five of the plutonic samples

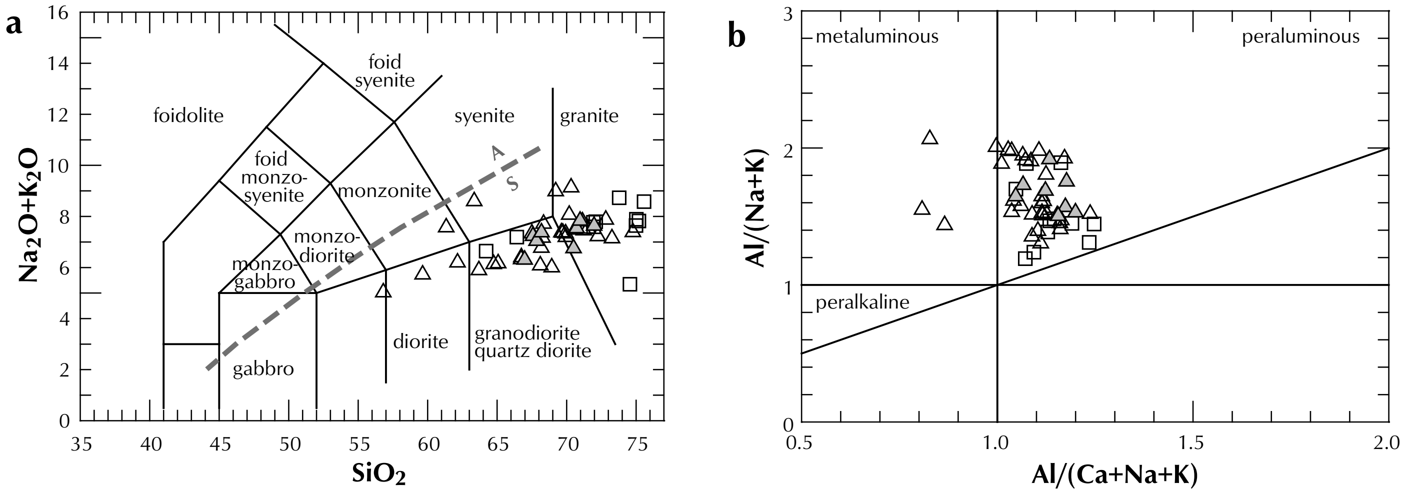

Figure 4. *Geochemistry of the plutonic and aplitic samples.* ***(a)*** *Silica versus total alkali plot (Le Bas et al., 1986) displaying the range of plutonic rock types sampled (2003 – grey triangles; 2005 – white triangles) and aplitic dykes sampled (white squares); n = 51. The Irvine and Baragar (1971) alkalic-subalkalic discrimination line is indicated by the grey dashed line (A = alkaline; S = subalkaline).* ***(b)*** *Al/(Ca+Na+K) versus Al/(Na+K) plot based on Shand's Index, after Maniar and Piccoli (1989); intrusions have a predominantly low to moderate peraluminous signature.*

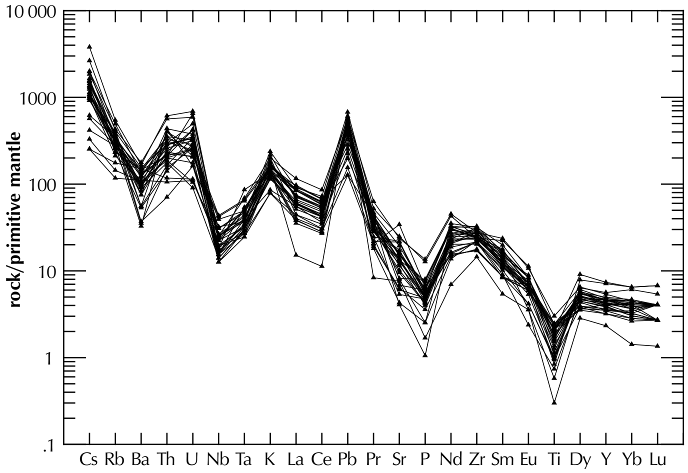

Figure 5. *Primitive-mantle-normalized extended trace element diagram of the 2005 plutonic samples; n = 31. Mantle-normalized values from Sun and McDonough, 1989.*

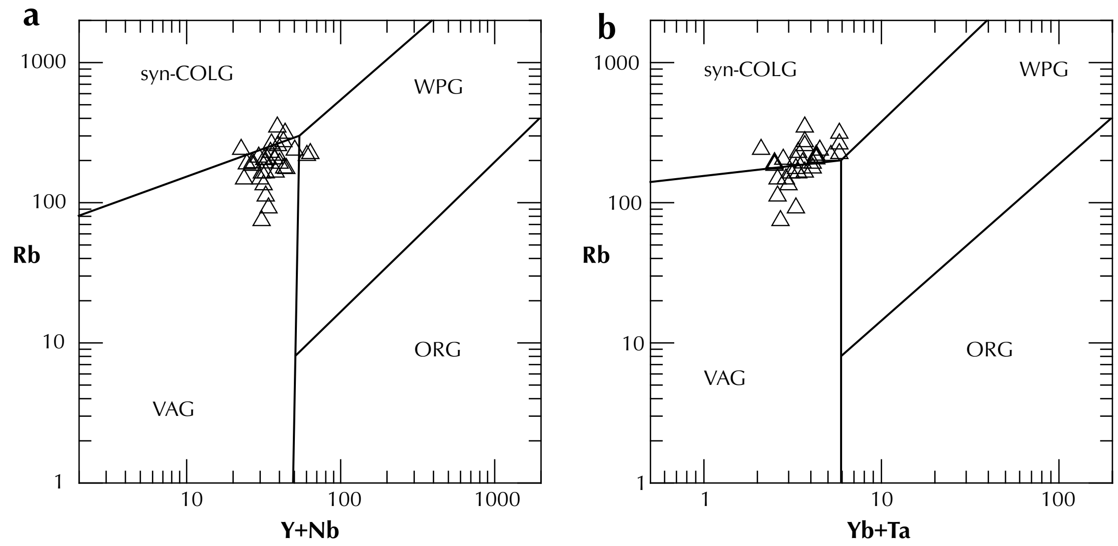

Figure 6. *Tectonic discrimination diagrams for 2005 plutonic samples; n = 31. Diagrams are after Pearce et al., 1984.* ***(a)*** *Y+Nb vs. Rb.* ***(b)*** *Yb+Ta vs. Rb.*

collected in 2003 are plotted in Figure 2, and include U-Pb zircon or monazite crystallization ages determined by the isotope dilution–thermal ionization mass spectrometry (ID-TIMS) method and four ^{40}Ar-^{39}Ar cooling ages for biotite. Zircon and monazite grains from the 2005 samples are currently being analysed for U-Pb geochronology by the laser ablation ICP-MS method.

DISCUSSION

The magnetic susceptibility data provides an indication of the redox state for granitoid intrusions sampled in the study area. Based on work by Hart *et al.* (2004) in Alaska and Yukon, the mid-Cretaceous intrusions in the northern Cordillera with magnetic susceptibility values less than 0.5 (x10^{-3} SI units) are interpreted to reflect reduced ilmenite-series granitoids, and greater than 0.5 are interpreted to reflect more oxidized magnetite-series granitoids. The majority of the intrusions in the MERA study area are classified as ilmenite-series granitoids. However, several of the intrusions, particularly at the northern and eastern extremities of the study area, have magnetic susceptibility values greater than 0.5, which classifies these intrusions as magnetite-series granitoids. The ilmenite/magnetite-series classification of granitic magmatism is linked to the type of mineralization that may be associated with an intrusion. In the Tintina Gold Province (TGP) throughout Yukon and Alaska, ilmenite-series magmatism is generally associated with tungsten, antimony, gold, silver-lead-zinc polymetallic veins, and tin mineralization related to very reduced intrusions. In contrast, magnetite-series magmatism is associated with copper-gold-iron(-molybdenum), and alkalic intrusion-related uranium-thorium(-copper-gold) enrichment (Hart *et al.*, 2004). The dominantly reduced, subalkaline intrusions within the study area are, therefore, most prospective for tungsten-antimony-gold-lead-zinc(-tin) mineralization, which is consistent with the majority of known intrusion-related mineral occurrences; however, there is some potential for mineralization typically associated with magnetite-series granitoids in outermost portions of the study area.

One important aspect of the lithogeochemical results is the constraint on the source of the granitoids. Granitic magmatism in the inboard portion of the northern Cordillera has been interpreted by several authors to be dominantly S-type, post-collisional magmatism produced by crustal thickening and subsequent melting in the outer miogeoclinal strata, followed by upper crustal extension late in the orogeny (Woodsworth *et al.*, 1991; Hart *et al.*, 2004). Consistent with S-type magmas, accessory apatite, zircon, and ilmenite are abundant in the intrusions within the study area, and monazite and tourmaline may even be present in place of zircon and biotite, respectively. However, field observations and lithogeochemical data indicate that the majority of intrusions in the study area lack clear S-type characteristics, such as a strong peraluminosity and a diagnostic mineralogy (e.g., aluminous minerals), that are typically associated with magmas sourced from sedimentary material (e.g., shale or greywacke) (Christiansen and Keith, 1996). Magmatic aluminous minerals, such as muscovite and especially garnet, are rare in the majority of the intrusions, and where observed, appear to be volumetrically insignificant. Also, the observed negative niobium, tantalum and titanium anomalies on the extended trace element diagram (Fig. 5) are more characteristic of I-type magmas formed in subduction zone environments, and these magmas, in general, are derived from igneous source material (Christiansen and Keith, 1996). Other studies have also noted similarly anomalous geochemical signatures (van Middelaar, 1988; Driver *et al.*, 2000; Mortensen *et al.*, 2000; Lang *et al.*, 2001; Heffernan, 2004; Rasmussen, 2004), but most researchers have postulated a crustally derived origin for the mid-Cretaceous magmatism in the area. An alternative interpretation based on recent work has demonstrated that I-type geochemical signatures may also result from partial melting of rocks that initially formed in a subduction zone environment, or from partial melting of immature sedimentary rocks eroded from arc material (Christiansen and Keith, 1996; Morris *et al.*, 2000). Thus, tectonic discrimination plots such as that of Pearce *et al.* (1984), which suggest a volcanic arc setting for at least some of the Nahanni MERA area intrusions, must be used with caution.

The U-Pb zircon and monazite age results for five of the samples collected for this study (Fig. 2), together with those reported by Heffernan (2004) for the adjoining area to the southwest, indicate a narrow range of mid-Cretaceous crystallization ages of plutonic rocks within the region. These ages, together with lithological and geochemical characteristics of the rocks, permit individual intrusions in the study area to be correlated with three of the plutonic suites defined in the TGP further to the northwest by Mortensen *et al.* (2000). Metaluminous to weakly peraluminous intrusions with crystallization ages of 95-89 Ma are correlated with the Tombstone suite, those with ages in the 98-96 Ma range are correlated with the Tay River suite, and intrusions with more strongly peraluminous compositions and crystallization ages of 97-92 Ma are assigned to the Tungsten suite. In the TGP, the metallogenic associations of these three suites are distinct: Tombstone suite intrusions are associated with gold and bismuth mineralization, commonly as structurally controlled sets of sheeted veins (e.g., Dublin Gulch), as well as tungsten skarns (e.g., Ray Gulch) and silver-lead-zinc veins (e.g., Keno Hill); Tay River suite intrusions are generally not associated with mineralization; and Tungsten suite intrusions are associated with tungsten skarn mineralization (e.g., MacTung; Deklerk and Traynor, 2005).

In the study area, metallogenic associations are more complex. In particular, tungsten skarns (together with volumetrically insignificant sheeted, tungsten-rich, gossanous fractures or veins) are associated with moderately peraluminous intrusions of the Tungsten suite (e.g., the Lened pluton), but also occur with intrusions assigned to the Tay River suite in terms of age and mineralogy (e.g., the Mine stock, Cantung mine). For example, biotite is the only primary mica observed in the main intrusions at the Cantung mine; although muscovite and, rarely, garnet occur in highly fractionated aplitic dykes, they are secondary mineral phases (Rasmussen, 2004). In fact, the Mine stock at Cantung is only moderately peraluminous with an aluminum saturation index, or Al/(Ca+Na+K) ratio, of ~1.1. In addition, the U-Pb zircon age of 98.2 ± 0.4 Ma for the Mine stock (Fig. 2) is significantly older than plutons adjacent to tungsten-skarn mineralization farther to the north at Lened (95.0 ± 0.6 Ma, the Lened pluton; this study) and MacTung (95.4 Ma, the Cirque Lake pluton; Mortensen, unpublished data). Although it is possible that younger intrusions are responsible for mineralization at MacTung, an older mineralization age of 97.5 ± 0.5 Ma (Re-Os isochron age, molybdenite; Selby *et al*., 2003) indicates that an older unidentified intrusion closer in age to the Mine stock at the Cantung mine is a more likely source for the metals. Many of the intrusions with related tungsten mineralization provided the basis for the initial definition of the Tungsten suite (Mortensen *et al*., 2000); however, the actual metallogenic, mineralogical, lithogeochemical and geochronological relationships observed appear to be somewhat more complicated. Although the Cantung mine rates within the 90th percentile of tungsten-skarn deposits based on grade (Lentz, 1998) and is one of the two most significant tungsten resources in the TGP, the older age of the Mine stock intrusion, combined with a low peraluminous geochemical signature and a lack of primary aluminous minerals, indicate that this intrusion is not a member of the Tungsten suite. The nature and origin of the Tungsten suite and its relationship with tungsten mineralization in the southeastern Yukon and southwestern Northwest Territories is still uncertain and it appears that this suite may have to be redefined.

Initial U-Pb zircon geochronological results for three separate felsic intrusions sampled underground at the Cantung mine place firm constraints on the timing of tungsten and trace amounts of localized molybdenum mineralization. The Mine stock underlying the orebody and a scheelite- and pyrrhotite-bearing aplite dyke that cuts the stock, yield essentially identical ages of 98.2 ± 0.4 Ma and 98.3 ± 0.3 Ma, respectively. A separate felsic dyke that intrudes underground along one of several low-displacement normal faults and cuts the massive orebody, but does not contain scheelite or pyrrhotite (only trace molybdenite) is younger at 97.4 ± 0.3 Ma. Combined, these results indicate that the main tungsten mineralization coincided with emplacement of the Mine stock and associated aplite dykes, which is consistent with the results of Rasmussen (2004). Subsequent molybdenum mineralization is associated with a slightly younger phase of felsic magmatism.

As noted earlier in this report, the presence of multiple phases in many of the intrusions is independent of the size of the intrusion, whether large batholiths or smaller stocks. One example of this is demonstrated by zircons from two sample locations in the Mt. Sir James McBrien pluton (Fig. 2) that yielded U-Pb crystallization ages of 97.7 ± 0.2 Ma (Heffernan, 2004) and 96.8 ± 0.5 Ma (this study). These ages, both resulting from ID-TIMS, are statistically different at the 2-sigma error level and indicate that this body is composed of more than one granitic phase of intrusion. Similarly, U-Pb zircon ages reported previously by Heffernan (2004) for two separate samples from the southern portion of Coal River batholith (Fig. 2; 95.6 ± 0.4 Ma and 96.9 ± 0.4 Ma) are also different outside of error. These results are not unexpected, particularly in larger intrusive bodies where several phases of plutonism are distinguished by defined ranges of magnetic susceptibilities. For example, continuous magnetic susceptibility measurements over a 3-km traverse near the northeastern contact of the McLeod pluton (Fig. 2) have resolved at least six mineralogically and texturally distinct phases with unique magnetic susceptibility value ranges between ~0.3 and ~25 (x10^{-3} SI units).

The ^{40}Ar-^{39}Ar results for biotite from various intrusions suggest moderately rapid, post-emplacement cooling from magmatic temperatures of 850-900°C (indicated by zircon saturation thermometry) to the closure temperature of the argon system in biotite (~300°C). Cooling periods for three of the five intrusions sampled are indicated by precise U-Pb (zircon and monazite) and Ar-Ar (biotite) ages ranging from 1-1.5 m.y. (Fig. 2). This suggests rapid cooling due to a relatively shallow level of emplacement in the crust, which has important implications for the probability of a long-lasting magmatic-hydrothermal system that could lead to significant mineralization. One exception to this is the Mine stock at the Cantung mine, which cooled over a longer period of approximately 3 m.y. This correlates well with recent data from Yuvan *et al.* (2004) that presents pressure estimates of 2-3 kilobars for mineralized quartz veins located about 500 m above the intrusive stock; elevated pressure conditions are expected for large tungsten deposits as crystallization at deeper crustal levels allows for the longer cooling periods that are generally considered necessary for significant tungsten mineralization (Keith *et al.*, 1989). Surprisingly, the Lened pluton, which is also associated with a large tungsten resource, cooled quickly from emplacement at approximately 95.0 Ma to about 300°C in less than 1 m.y. However, as most or all of the intrusions in the area are composite, and several compositional phases were recognized within the Lened pluton by Gordey and Anderson (1993), it is possible that the phase sampled for dating was not directly associated with the tungsten skarn mineralization.

WORK IN PROGRESS

In addition to the geochronological and geochemical aspects of this study, the authors are investigating halogen (F, Cl, S) contents in igneous apatites and micas within the various intrusions in order to determine which intrusive phases may have exsolved a potentially mineralizing volatile phase. Results of this study will help identify intrusions and regions within the Nahanni MERA area that have higher potential for intrusion-related mineralization. If proven successful, the scope of this portion of the study will be expanded to include intrusions northwest to the Macmillan Pass area and into a study area immediately to the southwest (see Heffernan, 2004).

Lead isotopic compositions will be determined for igneous feldspars from the intrusions and for sulphide minerals from many of the known mineral occurrences throughout the area, in order to test possible genetic relationships between mineralization and magmatism. These compositions will also help to determine the nature and origin (magmatic or sedimentary) of mineral occurrences that are not obviously associated with magmatism.

Some P-T-t studies, including investigations of metamorphic mineral assemblages in contact aureoles, as well as aluminum-in-hornblende geobarometry and (U-Th)-He dating of apatite, are underway to better constrain the depths of emplacement for various intrusions and their cooling histories. The resulting data will provide additional criteria useful in assessing which intrusions have good potential for genetically related mineralization.

A final aspect of the study will be the examination of the morphology and composition of placer gold grains from drainages in the MERA area, particularly the Selina Creek/ Caribou River region in the southwest portion of the study area. Over 40 panned samples (collected in 2005), together with grains obtained from heavy mineral concentrate samples for the Nahanni MERA area (collected in 2005), and panned grains previously recovered from the study area by C. Jefferson (collected in 1986 and 1987; Jefferson and Spirito, 2003) will be compared to a larger database of gold grain morphologies and compositions being compiled on placer gold from the Klondike (Mortensen *et al.*, 2005). The resulting data will be used to assess the style of lode mineralization from which the placer gold grains were derived, and the approximate distance that they traveled from their source.

CONCLUSIONS

The focus of this study is to determine which intrusions or intrusive phases within the Nahanni MERA area are genetically related to mineralization. To date, field observations, combined with lithogeochemistry and geochronology of intrusions within the study area, have provided a basic understanding of the widespread magmatism that underlies the region and extends northwest into the Tintina Gold Province. Initial mid-Cretaceous U-Pb zircon and monazite crystallization ages (97.5-95 Ma) allow us to classify the intrusions as Tungsten and/or Tay River suites, with short 0.5-1.5 m.y. cooling periods from magmatic temperatures (850-900°C) down to ~300°C for several of the intrusions. The exception to this is the Mine stock at the world-class Cantung tungsten mine, for which a longer cooling period

(~3 m.y.) indicates a deeper emplacement level. Several uncertainties have arisen from the initial data reported here, including what the source(s) of the granitoid melt were and how valid the definition of the Tungsten plutonic suite is. Further work is necessary to answer these, among other questions, the most important of which is: which of the intrusions in the Nahanni MERA area have significant potential for intrusion-related mineralization?

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REFERENCES

Anderson, R.G., 1983. Selwyn plutonic suite and its relationship to tungsten skarn mineralization, southeastern Yukon and District of Mackenzie. Current Research, Part B, Geological Survey of Canada, Paper 83-1B, p. 1151-163.

Christiansen, E.H. and Keith, J.D., 1996. Trace element systematics in silicic magmas: a metallogenic perspective. *In:* Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulfide Exploration, Geological Association of Canada, Short Course Notes, D.A. Wyman (ed.), vol. 12, p. 115-151.

Deklerk, R. and Traynor, S., 2005. Yukon MINFILE – A database of mineral occurrences. Yukon Geological Survey, CD-ROM.

Driver, L.A., Creaser, R.A., Chacko, T. and Erdmer, P., 2000. Petrogenesis of the Cretaceous Cassiar batholith, Yukon-British Columbia, Canada: implications for magmatism in the North American cordilleran interior. Geological Society of America Bulletin, vol. 112, p. 1119-1133.

Gordey, S.P. and Anderson, R.L., 1993. Evolution of the northern cordilleran miogeocline, Nahanni map area (105I), Yukon and Northwest Territories. Geological Survey of Canada, Memoir 428, 214 p.

Gordey, S.P. and Makepeace, A.J. (compilers), 2003. Yukon digital geology. Geological Survey of Canada, Open File 1749, and Exploration and Geological Services Division, Yukon Region, Open File 2003-9D.

Hart, C.J.R., Goldfarb, R.J., Lewis, L.L. and Mair, J.L., 2004. The northern cordilleran mid-Cretaceous plutonic province: ilmenite/magnetite-series granitoids and intrusion-related mineralization. Resource Geology, vol. 54, p. 253-280.

Heffernan, R.S., 2004. Temporal, geochemical, isotopic and metallogenic studies of mid-Cretaceous magmatism in the Tintina Gold Province, southeastern Yukon and southwestern Northwest Territories, Canada. Unpublished MSc thesis, University of British Columbia, Vancouver, BC, 83 p.

Irvine, T.N. and Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences, vol. 8, p. 523-548.

Jefferson, C.W. and Spirito, W.A. (eds.), 2003. Mineral and energy resource assessment of the Tlogotsho Plateau, Nahanni Karst, Ragged Ranges and adjacent areas under consideration for expansion of Nahanni National Park Reserve, Northwest Territories. Open File 1686, 1 CD-ROM.

Keith, J.D., van Middelaar, W., Clark, A.H. and Hodgson, C.J., 1989. Granitoid textures, compositions, and volatile fugacities associated with the formation of tungsten-dominated skarn deposits. *In:* Reviews in Economic Geology, J.A. Whitney and A.J. Naldrett (eds.), vol. 4: Ore Deposition Associated with Magmas, p. 235-250.

Lang, J., Thompson, J.F.H., Mortensen, J.K., Baker, T., Coulson, I., Duncan, R., Maloof, T., James, J.J., Friedman, R. and Lepitre, M., 2001. Regional and system-scale controls on the formation of copper and/or gold magmatic-hydrothermal mineralization. *In:* Mineral Deposit Research Unit Special Publication No. 2, J. Lang (ed.), Mineral Deposits Research Unit, 115 p.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology, vol. 27, p. 745-750.

Lentz, D.R. (comp.), 1998. Appendix: grade and tonnage models of skarns. *In:* Mineralized Intrusion-Related Skarn Systems, D.R. Lentz (ed.), Mineralogical Association of Canada Short Course Series, vol. 26, 663 p.

Maniar, P.D. and Piccoli, P.M., 1989. Tectonic discrimination of granitoids. Geological Society of America Bulletin, vol. 101, p. 635-643.

Morris, G.A., Larson, P.B. and Hooper, P.R., 2000. 'Subduction style' magmatism in a non-subduction setting: the Colville igneous complex, NE Washington State, USA. Journal of Petrology, vol. 41, p. 43-67.

Mortensen, J.K., Hart, C.J.R., Murphy, D.C. and Heffernan, S., 2000. Temporal evolution of Early and mid-Cretaceous magmatism in the Tintina Gold Belt. *In:* The Tintina Gold Belt: Concepts, Exploration and Discoveries, British Columbia and Yukon Chamber of Mines, Special Volume 2, J. Jambor (ed.), p. 49-57.

Mortensen, J.K., Chapman, R., LeBarge, W. and Jackson, L., 2005. Application of placer and lodegold geochemistry to gold exploration in western Yukon. *In:* Yukon Exploration and Geology 2004, D.S. Emond, L.L. Lewis and G.D. Bradshaw (eds.), Yukon Geological Survey, p. 205-212.

Mortensen, J.K., Chapman, R., LeBarge, W. and Crawford, E., 2006 (this volume). Compositional studies of placer and lode gold from western Yukon: Implications for lode sources. *In:* Yukon Exploration and Geology 2005, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 247-255.

Mortensen, J.K., Sluggett, C., Liverton, T. and Roots, C.F., 2006 (this volume). U-Pb zircon and monazite ages for the Seagull and Cassiar batholiths, Wolf Lake map area, southern Yukon. *In:* Yukon Exploration and Geology 2005, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 257-266.

NORMIN.DB – The Northern Minerals Database. Northwest Territories Geoscience office.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, vol. 25, p. 956-983.

Rasmussen, K.L., 2004. The aplitic dykes of the Cantung Mine, NWT: Petrology, geochemistry, and implications for the mineralization process. Unpublished BSc thesis, University of Calgary, Alberta, Canada, 128 p.

Selby, D., Creaser, R.A., Heaman, L.M. and Hart, C.J.R., 2003. Re-Os and U-Pb geochronology of the Clear Creek, Dublin Gulch, and Mactung deposits, Tombstone Gold Belt, Yukon, Canada: absolute timing relationships between plutonism and mineralization. Canadian Journal of Earth Sciences, vol. 40, no. 12, p. 1839-1852.

Sun, S.S. and McDonough, W.F., 1989. Chemical and isotope systematics of oceanic basalts: implications for mantle compositions and processes. *In:* Magmatism in Ocean Basins, Geological Society, London, Special Publications, A.D. Saunders, and M.J. Norry (eds.), vol. 42, p. 313-345.

Van Middelaar, W.T., 1988. Alteration and mica chemistry of the granitoid associated with the Cantung scheelite skarn, Tungsten, Northwest Territories, Canada. Unpublished PhD thesis, University of Georgia, Georgia, 245 p.

Woodsworth, G.J., Anderson, R.G. and Armstrong, R.L., 1991. Plutonic regimes. *In:* Geology of the Cordilleran Orogen in Canada, GSC Geology of Canada, H. Gabrielse and C.J. Yorath (eds.), no. 4, p. 491-531.

Yuvan, J.G., Shelton, K.L., Falck, H. and Marshall, D.D., 2004. High-grade quartz-scheelite veins in the Cantung mine, Northwest Territories: a late magmatic-hydrothermal event. 32nd Annual Yellowknife Geoscience Forum, November 16-18, Abstracts Volume, p. 85.