Laser ablation ICP-MS U-Pb zircon ages for Cretaceous plutonic rocks in the Logtung and Thirtymile Range areas of southern Yukon

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ABSTRACT

Plutonic rocks of Early and mid-Cretaceous age are associated with tungsten-molybdenum porphyry- and skarn-style mineralization in the Logtung area (Yukon MINFILE 105B 039, Deklerk and Traynor, 2005) in southwestern Wolf Lake map area (105B), and with tin-tungsten (-copper, lead, zinc) skarn mineralization at the Mindy and Ork occurrences (Yukon MINFILE 105C 038 and 054, respectively, Deklerk and Traynor, 2005) in the Thirtymile Range in eastern Teslin map area (105C). We have determined laser ablation U-Pb zircon ages of 109.4 ± 0.9 Ma and 110.5 ± 0.8 Ma for two samples of a biotite monzogranite stock that is inferred to be comagmatic with the felsic dyke system that partially hosts the Logtung mineralization. The latter sample is from the same locality from which a U-Pb zircon age of ~58 Ma was previously reported for zircons inferred to be hydrothermal in origin. Two separate phases of the Thirtymile Stock gave U-Pb ages of 102.7 ± 1.1 Ma and 100.9 ± 1.4 Ma.

RÉSUMÉ

Des roches plutoniques datant du Crétacé moyen au Crétacé supérieur sont associées à du porphyre renfermant du tungstène et du molybdène ainsi qu'à la minéralisation typique des skarns dans la région de Logtung (MINFILE 105B 039) au sud-ouest de la région de la carte Wolf Lake (105B), ainsi qu'au skarn minéralisé en étain et tungstène (-cuivre, plomb, zinc) des indices Mindy et Ork (MINFILE 105C 038 et 054, respectivement) dans la chaîne Thirtymile située dans la partie orientale de la région de la carte Teslin (105C). Nous avons déterminé par datation des zircons à l'U/Pb des âges de 109,4 ± 0,9 Ma et de 110,5 ± 0,8 Ma pour deux échantillons d'un stock de monzogranite à biotite que l'on déduit contemporain du magmatisme ayant engendré le réseau de filons intrusifs renfermant en partie la minéralisation de Logtung. Le dernier de ces deux échantillons provient du même emplacement où une datation antérieure à l'U/Pb de zircons qui seraient d'origine hydrothermale a fourni une âge d'environ 58 Ma. Deux phases distinctes du stock Thirtymile ont fourni des âges U/Pb de 102,7 ± 1,1 Ma et 100,9 ± 1,4 Ma.

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INTRODUCTION

Plutonic rocks are widespread in the Cassiar Terrane in southeastern and south-central Yukon (Fig. 1). Most of these are of Early to mid-Cretaceous age and have been included within the Cassiar Plutonic Suite of Mortensen *et al.* (2000) or the Anvil-Hyland-Cassiar belt of Hart (2004) and Hart *et al.* (2004). The broad range of lithological and geochemical compositions of these plutons and their diverse metallogenic signatures (including tungsten skarns, tin skarns and greisens, lead-zinc-silver-rich veins and tungsten-molybdenum porphyries; e.g., Liverton and Alderton, 1994; Driver *et al.*, 2000; Liverton and Botelho, 2001; Liverton *et al.*, 2001, 2005), together with the wide range of isotopic ages previously reported for various intrusions in the Cassiar Terrane, however, indicates that more than one plutonic suite is present.

Most published isotopic ages for this region were calculated using K-Ar or Rb-Sr methods, and some of these ages have likely been disturbed by subsequent re-heating events. Several recent studies employing the more robust U-Pb dating method on zircons and/or monazite (e.g., Stevens *et al.*, 1993; Liverton *et al.*, 2005; Mortensen *et al.*, 2006) have demonstrated that most intrusive rocks in this area were emplaced 115-97 Ma, but that two older intrusive suites, one giving Early Jurassic crystallization ages and one giving Late Permian ages, are also present. Mihalynuk and Heaman (2002) also reported a U-Pb age of 58 ± 6 Ma for zircons recovered from a hydrothermally altered sample of monzonite from the Logtung W-Mo porphyry occurrence (Fig. 1) that they interpreted to have been hydrothermal in origin.

In view of the renewed interest in a variety of intrusion-related styles of mineralization in the Cassiar Terrane, a more complete understanding of temporal, geochemical and metallogenic evolution of magmatism in this region is desired. To this end, we have been carrying out a series of focused studies aimed at better constraining the ages, metallogenic associations and paleotectonic settings of

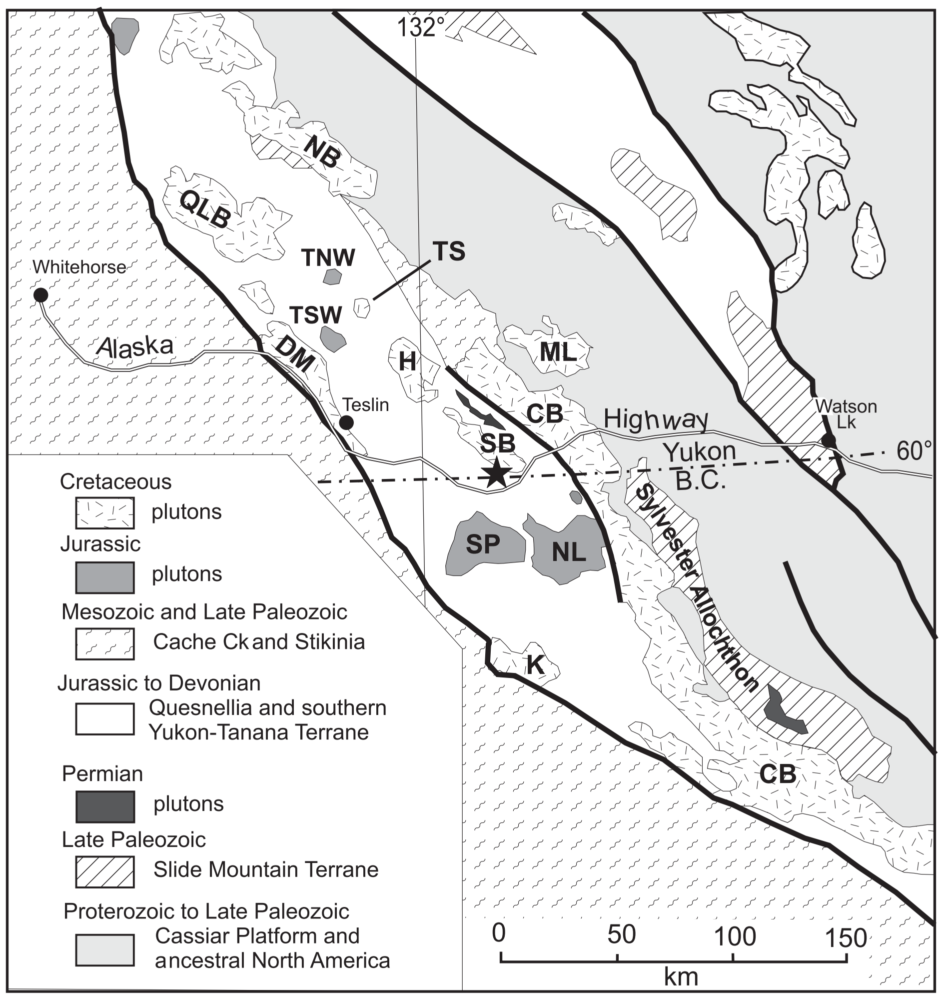

Figure 1. *Simplified geology of southern Yukon and northern British Columbia, with major plutons labelled.*
CB=Cassiar Batholith
SP=Simpson Peak pluton
NL=Nome Lake pluton
K= Klinkit pluton
SB=Seagull Batholith
ML=Marker Lake Batholith
H=Hake Batholith
DM=Deadman pluton
QLB=Quiet Lake Batholith
NB=Nisutlin Batholith
TNW=Thirtymile pluton northwest
TSW=Thirtymile pluton southwest
TS=Thirtymile Stock
Star shows the location of the Logtung area (see Fig. 2).

various intrusions in the Cassiar Terrane (e.g., Mortensen and Gabites, 2002; Liverton *et al.*, 2005; Mortensen *et al.*, 2006). In this contribution we report four new U-Pb zircon ages for two samples of intrusive rocks in the vicinity of the Logtung tungsten-molybdenum porphyry occurrence (Yukon MINFILE 105B 039, Deklerk and Traynor, 2005) in the southwest part of the Wolf Lake sheet, including a resampling of the unit previously dated by Mihalynuk and Heaman (2002), and two lithofacies of the Thirtymile Stock, in the Thirtymile Range, in the east part of the Teslin 1:50 000 mapsheet 105C/9 (Fig. 1).

INTRUSIVE ROCKS IN THE LOGTUNG AREA

The oldest intrusion in the Logtung area (preliminary Early Jurassic U-Pb zircon age; Mortensen, unpublished data) is a zoned diorite which locally grades to granodiorite, and predates mineralization. Two diorite intrusions, each approximately 0.5 x 1 km, intrude the metasedimentary country rocks to the northeast and southwest of the main monzogranite body and felsic dyke complex (Fig. 2). Primary mineralogy consists of hornblende and plagioclase, with minor quartz, biotite, clinopyroxene and K-feldspar. In places, textures become porphyritic with hornblende phenocrysts up to 8 mm, but the main diorite is dominantly heterogeneous and equigranular, with an average grain size of 1-2 mm. A sporadic aureole consisting of early reaction skarns is associated with this unit up to 30 m from the contacts (Noble *et al.*, 1984). The reaction skarns contain biotite and disseminated sulphide minerals including pyrrhotite and chalcopyrite. Disseminated sulphide minerals (possibly including molybdenite and chalcopyrite) have also been observed within the diorite near the contact.

The main intrusive body associated with the felsic dyke system and tungsten-molybdenum mineralization is a biotite monzogranite stock, approximately 2 km^2 in area. The slightly elongate monzogranite dips ~45˚ to the northwest below the felsic dyke system. It is characterized by a high silica content (74.6 – 77.5% SiO_2), 3% modal biotite, a molar $Al_2O_3/(Na_2O+K_2O+CaO)$ ratio of 1.00 and maximum W and Mo concentrations of 510 ppm and 235 ppm, respectively (Stewart, 1983). Accessory minerals include fluorite, scheelite, ilmenite, pyrite, zircon, allanite, apatite and beryl. Porphyritic textures dominate throughout the body; however, there is a fine-grained (1-5 mm) contact phase up to 90 m across, and satellite dykes associated with the intrusion are (rarely) pegmatitic. Hydrothermal alteration is variable in intensity throughout

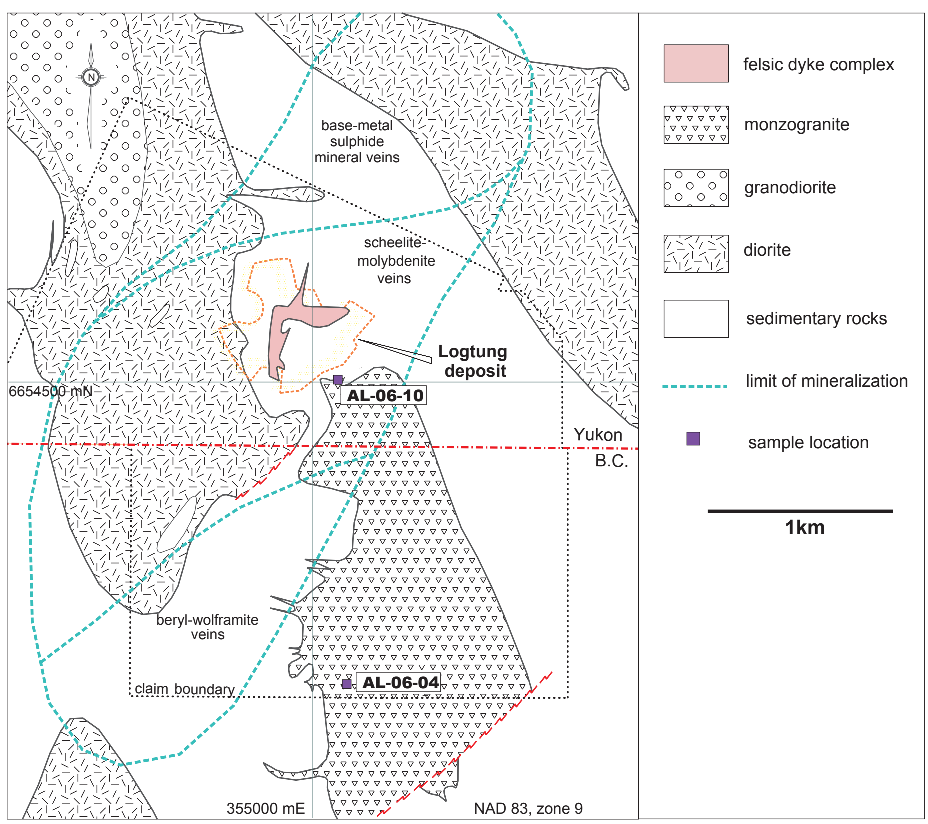

Figure 2. *Geology of southwestern Wolf Lake map area showing location of Logtung deposit and geochronological samples.*

the monzogranite stock, and consists of feldspar replacement by sericite, calcite and fluorite; and scheelite and biotite replacement by chlorite.

Tungsten-molybdenum mineralization is most intensely centred on the felsic dyke system, which is inferred to be associated with the monzogranite stock. The system consists of an irregularly shaped bilobate intrusion, approximately 500 m across, which outcrops on both sides of the northeast-trending Logtung ridge, a topographical high between the two diorite intrusions. The felsite is porphyritic, with a high SiO_2 content (75.1-76.7 wt%), and tungsten/molybdenum values similar to the monzogranite. Quartz, plagioclase, K-feldspar and spessartine garnet phenocrysts (all up to 1.5 mm) are set in a fine-grained felsite groundmass (~0.06-0.09 mm) (Stewart, 1983). Ribbon-banded material consisting of alternating layers (1-4 mm thick) of quartz, apatite needles and felsite locally developed in the main felsite body. Areas of coarsely crystalline, monomineralic massive quartz also occur. Alteration is similar to the monzogranite; however, the felsic dyke system is crosscut by a system of thin (~1-3 mm) quartz-molybdenite veins. In places, the felsite is fractured, with pyrite and molybdenite infilling. A contact aureole ~70 m wide affects the reaction skarns intruded by the felsite.

THIRTYMILE STOCK

The Thirtymile Stock, together with the Hake Batholith and Seagull Batholith (Fig. 1), have been described as a 'sub-suite' of the Cassiar intrusions. Rb-Sr dating yielded an isochron age of 101 ± 5.6 Ma for the megacrystic lithofacies of the Thirtymile Stock and an errorchron (interpreted as a cooling age) of 98.3 ± 2.9 Ma for the marginal facies of the Hake Batholith (Liverton *et al.*, 2001). All of the intrusions are highly fractionated metaluminous to weakly peraluminous one-mica granites *sensu stricto*, with only the least-evolved facies of the Thirtymile Stock (porphyry) displaying any hornblende or titanite. The Thirtymile Stock conveniently contains four lithofacies (Fig. 3) that span the complete compositional range of these intrusions (Liverton and Alderton, 1994). These include the Li-mica leucogranite and the following three biotite-bearing lithofacies: porphyry, megacrystic granite and even-grained granite. The Li-mica leucogranite is a zinnwaldite-topaz-fluorite alkali granite that forms the smallest areal extent in the Thirtymile Stock and occurs as various small sills and dykes peripheral to the stock. A lithology virtually identical to the Li-mica leucogranite exists in the apophyses of the Ork Stock, 4 km to the south. The chemistry of these granites is distinctive in their progression from relatively 'evolved' compositions (Thornton-Tuttle indices, 'D' of 86.8 (porphyry, specimen POR) to 96.2 in the biotite-bearing facies; Thornton and

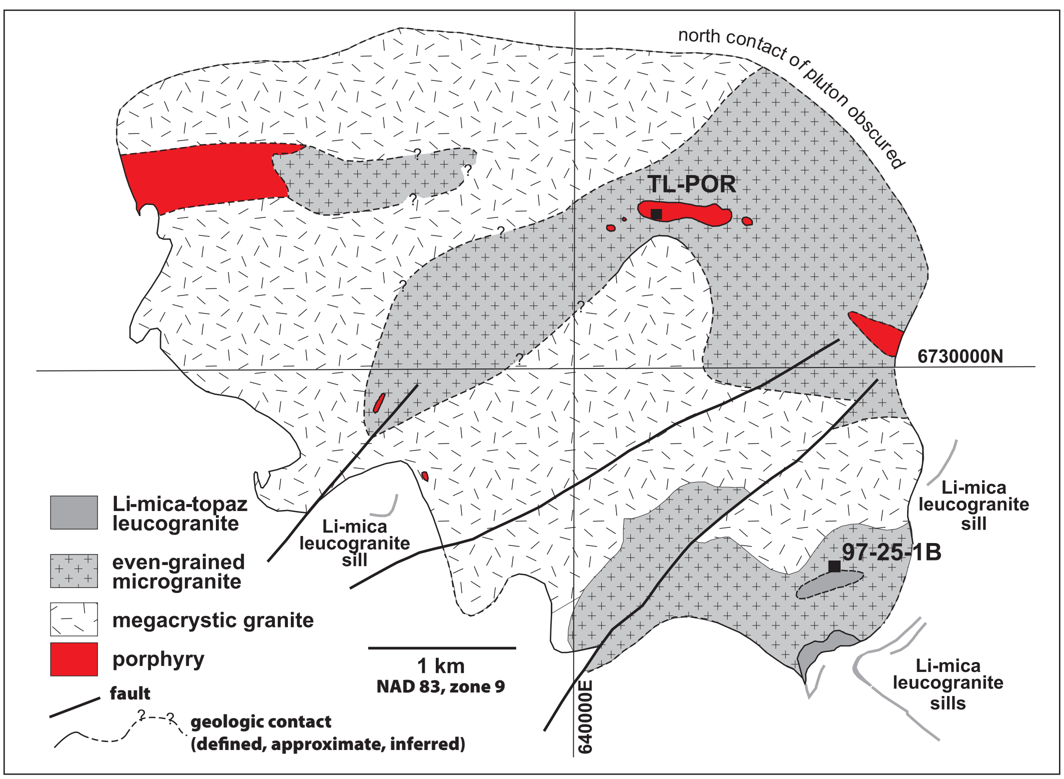

Figure 3. *Simplified geology of the Thirtymile Stock.*

Tuttle, 1960) to an extremely fractionated final lithofacies (D= 99.4 in the Ork stock). This final lithofacies has Rb/Sr ratios to >7000, and trace element compositions that fall in the 'A-type' or 'within-plate' fields of tectonic discriminant diagrams. Biotite compositions indicate that these granites are reduced-type, plotting between the nickel-nickel oxide (NNO) and quartz-fayalite-magnetite (QFM) buffers, with some below the QFM oxygen fugacity buffers (Liverton and Botelho, 2001). The Sr_i ratio of 0.7074 for the Thirtymile megacrystic facies indicates that these are I-type granites. The reduced nature and elevated halogen contents of the magma from which these granites were derived are reflected in peripheral mineralization: tin-fluorine-boron greisen-skarn at the Mindy prospect (Yukon MINFILE 105C 038, Deklerk and Traynor, 2005), tin-fluorine skarn at the Ork stock and nearby un-named scheelite-bearing skarns. The chemical signature of these granites being transitional between I-types and anorogenic granites is consistent with their generation in a late-tectonic extensional setting, which fits the H_{LO} ('Hybrid Late Orogenic') classification of Barbarin (1990).

U-PB GEOCHRONOLOGY

In this study we determined U-Pb crystallization ages for 1) two intrusive units in the vicinity of the Logtung tungsten-molybdenum porphyry occurrence (Yukon MINFILE 105B 039, Deklerk and Traynor, 2005) in the southwest part of the Wolf Lake mapsheet and 2) two lithofacies of the Thirtymile Stock in the Thirtymile Range of the Teslin mapsheet (Figs. 1 and 3) using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) methods. All of the analytical work was done at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia.

METHODOLOGY

The methodology used for LA-ICP-MS U-Pb dating at the PCIGR has been described by Mortensen *et al.* (2006). Minor modifications to the dating method in this study include using a 116 Ma in-house zircon as an external standard rather than the ~1100 Ma FC-1 standard, using higher laser power (60%) for the ablation, and collecting data in mixed analog and ion counting mode, with the strongest isotopic peaks (for ^{238}U and ^{232}Th) being counted in analog mode and the other weaker peaks in ion counting mode. These changes have resulted in substantially stronger ion beams and much-improved counting statistics, leading to better precision and accuracy on individual analyses. In this study, a total of 20 line scans were collected for each sample. The time-resolved signal from each analysis was carefully examined, and portions of the signal that likely reflect the effects of post-crystallization Pb-loss and/or the presence of older inherited zircon cores were excluded from calculation of the final isotopic ratios. Data from some analyses are thought to indicate that the entire scan covered portions of zircon that had experienced at least minor Pb-loss or were entirely on inherited core material. These analyses were not included in the final age calculation. Interpreted crystallization ages are based on a weighted average of the calculated $^{206}Pb/^{238}U$ ages for 10-20 individual analyses from each sample. Errors for the calculated ages are given at the 2 sigma level using the method of Ludwig (2003).

SAMPLE LOCATIONS AND DESCRIPTIONS

Two samples of the monzogranite stock were collected from the Logtung area. Sample AL-06-04 was obtained from the main monzogranite body (UTM 355284E, 6653271N; zone 9; all locations given use the NAD83 datum) south of the defined deposit boundary (Fig. 2). Approximately 15 kg of coarse-grained material was collected, with primary mineralogy consisting of quartz, plagioclase, K-feldspar and biotite. Minor garnet and accessory pale blue beryl, black tourmaline and fluorite are also present. Textures are porphyritic, with quartz phenocrysts up to 5 mm and euhedral K-feldspar crystals up to 1.0 cm in length. The groundmass is equigranular, with grains ~0.5-1.5 mm. Although relatively unaltered, there is evidence of minor replacement of feldspar by fluorite.

Sample AL-06-10 (~20 kg) was obtained from approximately the same location (UTM 354631E, 6655505N, zone 9; Fig. 2) as that of Mihalynuk and Heaman (2002), near the contact with the metasedimentary country rock. The primary mineralogy consists of quartz-plagioclase, K-feldspar and biotite, with accessory garnet. Although the monzogranite at this locality is also porphyritic, the average size of phenocrysts is smaller (~5-8 mm) than that of the previous sample, with an average groundmass grain size of ~0.3-1.0 mm. This sample is more intensely altered than AL-06-04, with sericite replacing feldspar.

Two samples were analysed from two separate phases of the Thirtymile Stock (Fig. 3). The geochemically least-evolved portion of the stock comprises a fine-grained seriate-textured granodiorite locally with 1-cm-sized potassium feldspar phenocrysts that grades into a similar groundmass containing cumulates of potassium feldspar megacrysts in metre-scale masses. Sample TL-POR (640568E, 6731078N, zone 9) is from the latter phase. Sample 97-25-1B (611778E, 6728670N, zone 9) is the most evolved lithofacies of the stock, which consists of even-grained biotite granite. Sample sizes ranged from 3-15 kg each.

ANALYTICAL RESULTS

The two samples of monzonite from the Logtung area each yielded a moderate amount of zircon, which consisted of clear, colourless to pale yellow, stubby prisms with multifaceted terminations. Many of the grains were fractured and contained abundant clear bubble- and rod-shaped inclusions. A total of 21 individual analyses were done on zircons from sample AL-06-04 (Fig. 4a). One grain yielded an older (~125 Ma) age that appears to reflect the presence of inherited zircon throughout the entire analysis; three grains gave slightly younger ages and are interpreted to have suffered Pb-loss throughout (Table 1). A weighted average of the $^{206}Pb/^{238}U$ ages of the remaining 17 analyses gives an age of 109.4 ± 0.9 Ma, which is interpreted to be a reasonable estimate of the crystallization age of the sample. Twenty analyses were obtained from the second sample (AL-06-10; Fig. 4b, Table 1); a weighted average $^{206}Pb/^{238}U$ age of 110.5 ±

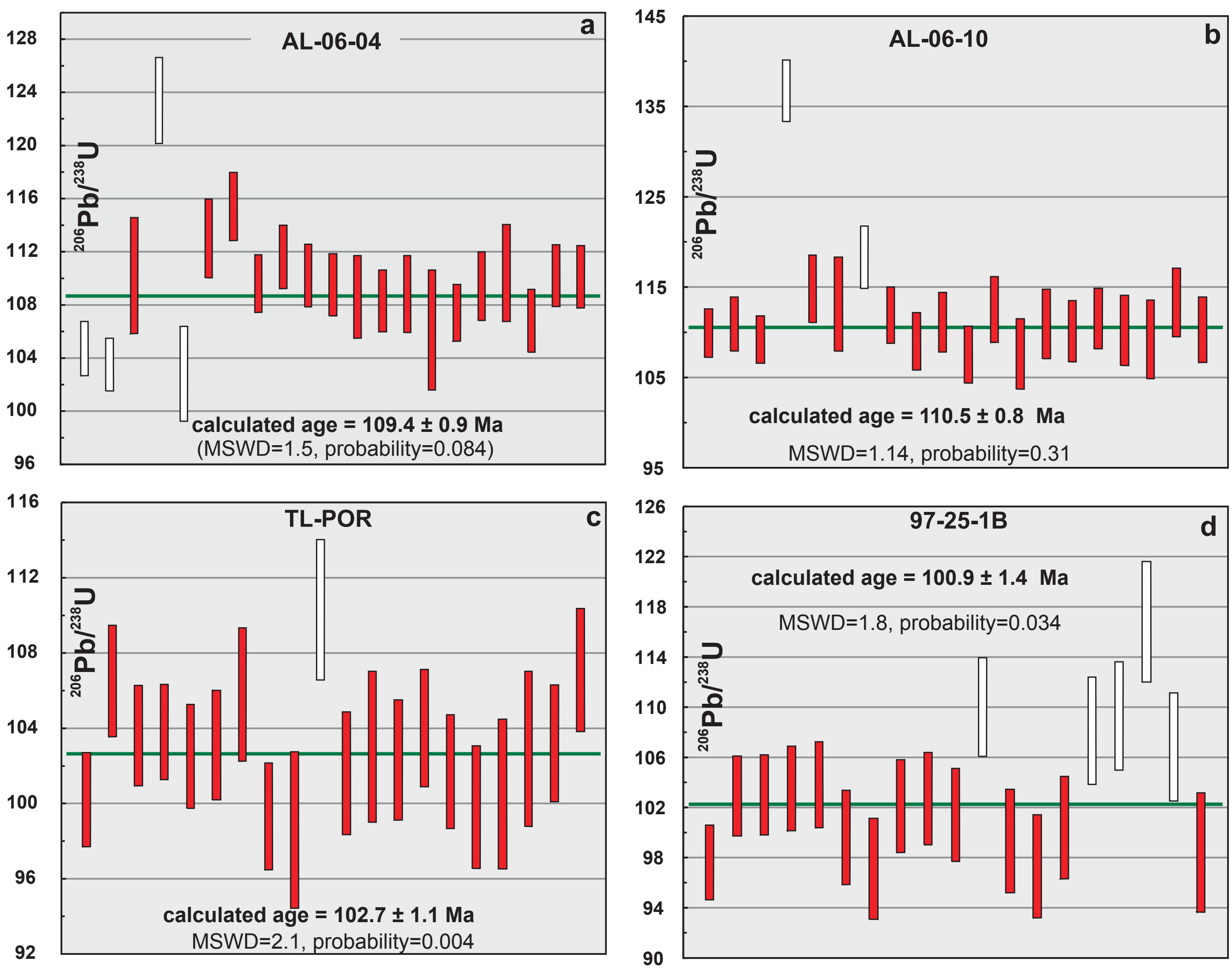

Figure 4. *Plot of $^{206}Pb/^{238}U$ ages for individual LA-ICP-MS analyses from two samples from the Logtung area **(a, b)** and two samples of the Thirtymile Stock **(c, d)**. Open bars are analyses that were excluded from the calculated weighted average age. MSWD = mean square of weighted deviates.*

0.8 Ma is based on a total of 18 individual analyses. Two analyses give slightly older ages, apparently due to the presence of minor inherited zircon.

The two Thirtymile Stock samples yielded abundant zircon that mainly formed square, stubby to elongate prismatic grains with simple terminations. Most of the zircon grains were fractured and contained abundant fine clear inclusions. No inherited cores were observed. The most colourless, least fractured and inclusion-free grains were selected from each sample for analysis. Nineteen out of a total of 20 analyses from sample TL-POR (Table 1) yield a weighted average $^{206}Pb/^{238}U$ age of 102.7 ± 1.1 Ma (Fig. 4c), which gives the crystallization age of the sample. One analysis yields a slightly older age,

Table 1. *LA-ICP-MS U-Pb analytical data for samples from the Logtung area and the Thirtymile Stock.*

Sample number	$^{206}Pb/^{238}U$ age	Error (1σ)
AL-06-04-1	104.7	1.02
AL-06-04-2	103.5	0.99
AL-06-04-3	110.2	2.18
AL-06-04-4	123.4	1.62
AL-06-04-5	102.8	1.78
AL-06-04-6	113	1.47
AL-06-04-7	115.4	1.28
AL-06-04-8	109.6	1.09
AL-06-04-9	111.6	1.19
AL-06-04-10	110.2	1.18
AL-06-04-11	109.5	1.18
AL-06-04-12	108.6	1.56
AL-06-04-13	108.3	1.16
AL-06-04-14	108.8	1.45
AL-06-04-15	106.1	2.26
AL-06-04-16	107.4	1.07
AL-06-04-17	109.4	1.29
AL-06-04-18	110.4	1.82
AL-06-04-19	106.8	1.18
AL-06-04-20	110.2	1.17
AL-06-04-21	110.1	1.17
AL-06-10-1	109.9	1.35
AL-06-10-2	110.9	1.51
AL-06-10-3	109.2	1.31
AL-06-10-4	136.7	1.71
AL-06-10-5	114.8	1.88
AL-06-10-6	113.1	2.6
AL-06-10-7	118.3	1.73
AL-06-10-8	111.9	1.56
AL-06-10-9	109	1.59
AL-06-10-10	111.1	1.64
AL-06-10-11	107.5	1.57
AL-06-10-12	112.5	1.83
AL-06-10-13	107.6	1.94
AL-06-10-14	110.9	1.92
AL-06-10-15	110.1	1.69
AL-06-10-16	111.5	1.68
AL-06-10-17	110.2	1.95
AL-06-10-18	109.2	2.17
AL-06-10-19	113.3	1.9

Sample number	$^{206}Pb/^{238}U$ age	Error (1σ)
AL-06-10-20	110.3	1.81
TL-POR-1	100.2	1.25
TL-POR-2	106.5	1.48
TL-POR-3	103.6	1.34
TL-POR-4	103.8	1.27
TL-POR-5	102.5	1.38
TL-POR-6	103.1	1.46
TL-POR-7	105.8	1.77
TL-POR-8	99.3	1.42
TL-POR-9	98.6	2.08
TL-POR-10	110.3	1.86
TL-POR-11	101.6	1.63
TL-POR-12	103	2.01
TL-POR-13	102.3	1.6
TL-POR-14	104	1.56
TL-POR-15	101.7	1.51
TL-POR-16	99.8	1.63
TL-POR-17	100.5	1.99
TL-POR-18	102.9	2.06
TL-POR-19	103.2	1.55
TL-POR-20	107.1	1.63
97-25-1B-1	97.6	1.49
97-25-1B-2	102.9	1.59
97-25-1B-3	103	1.6
97-25-1B-4	103.5	1.7
97-25-1B-5	103.8	1.72
97-25-1B-6	99.6	1.88
97-25-1B-7	97.1	2.02
97-25-1B-8	102.1	1.85
97-25-1B-9	102.7	1.84
97-25-1B-10	101.4	1.86
97-25-1B-11	110	1.97
97-25-1B-12	99.3	2.06
97-25-1B-13	97.3	2.06
97-25-1B-14	100.4	2.04
97-25-1B-15	108.1	2.14
97-25-1B-16	109.3	2.16
97-25-1B-17	116.8	2.4
97-25-1B-18	106.8	2.16
97-25-1B-19	98.4	2.38

presumably reflecting minor inheritance. Sixteen of twenty analyses from sample 97-25-1B (Table 1) give a weighted average $^{206}Pb/^{238}U$ age of 100.9 ± 1.4 Ma (Fig. 4d), which gives the crystallization age of the sample. The four outliers give slightly older ages, indicating older inherited zircon cores were present.

DISCUSSION

Results from the Logtung area confirm previous work by K-Ar and Rb-Sr dating that suggested an age of ~110 Ma (e.g., Hunt and Roddick, 1987) for these bodies. The results that were reported previously by Mihalynuk and Heaman (2002) are difficult to explain. Our sample AL-06-10, which was collected from the same outcrop as that of Mihalynuk and Heaman (2002), did not contain any of the brownish zircons that yielded an apparent age of 58 Ma and were interpreted by Mihalynuk and Heaman (2002) to be of hydrothermal origin. Two samples of molybdenite from the Logtung deposit have yielded Re-Os ages that are identical to the U-Pb zircon ages that we report here (D. Selby, pers. comm., 2006); thus, the nature and origin of the ~58 Ma zircons in the Mihalynuk and Heaman sample is uncertain.

The Thirtymile Stock and other bodies in the Thirtymile Range (e.g., the Ork Stock) represent some of the most evolved mid-Cretaceous plutons in the Cassiar Terrane. The mineralogy of these bodies is substantially different from most other Cassiar Suite plutons, however, in that they contain both magnetite and titanite. This mineral assemblage is generally more typical of more oxidized magmas, although geochemical investigations of the Thirtymile and Ork stocks (Liverton and Alderton, 1994; Liverton and Botelho, 2001) indicate that the magmas were in fact moderately reduced. In the northern Cordillera they are closest in composition to the reduced I-type of the Tungsten Suite (Hart *et al.*, 2004), except for Sr_i and age. However, some relatively reduced granitoids have been noted in the northern part of the Cassiar Suite (Driver *et al.*, 2000), and the Sr_i ratio for the Thirtymile pluton is only just less than the lower values reported for that suite. Ages reported for the Anvil-Hyland-Cassiar intrusions (110-96 Ma, Hart *et al.*, 2004) overlap the 100.9-102.7 Ma age reported in this study.

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