Cratonic Basement in Northeastern British Columbia: New U-Pb Geochronological Results and their Significance for Diamond Exploration

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ABSTRACT

This study was proposed to enhance our understanding of crystalline basement in northeastern British Columbia. Seven new U-Pb zircon ages for this area are reported from samples of drill cuttings. Samples B5 (1854 ± 6 Ma) and B25 (minimum age 1.75 Ga; inherited zircon 1.89–2.23 Ga) are located within but near the edge of the Nova Terrane, as it is currently defined. Sample B2 plots within the Kiskatinaw Terrane and samples B11 (1994 ± 7 Ma), B12 (1993 ± 7 Ma) and B14 (1993 ± 7 Ma) plot within the Ksituan Terrane. Sample B34 (1859 ± 10 Ma) is located near the British Columbia – Yukon Border, and occurs within the Fort Simpson Terrane. The samples from the Nova Terrane returned Paleoproterozoic ages and thus did not confirm the popular interpretation that assigns an Archean age to the Nova Terrane. The age indicated by the inherited zircon from sample B25 is similar to the 2.0 and 2.3 Ga ages previously reported for the Buffalo Head Terrane, which is believed to be reworked Archean basement. This finding is important from an exploration point of view, since the Buffalo Head Terrane in neighbouring Alberta hosts diamondiferous kimberlites.

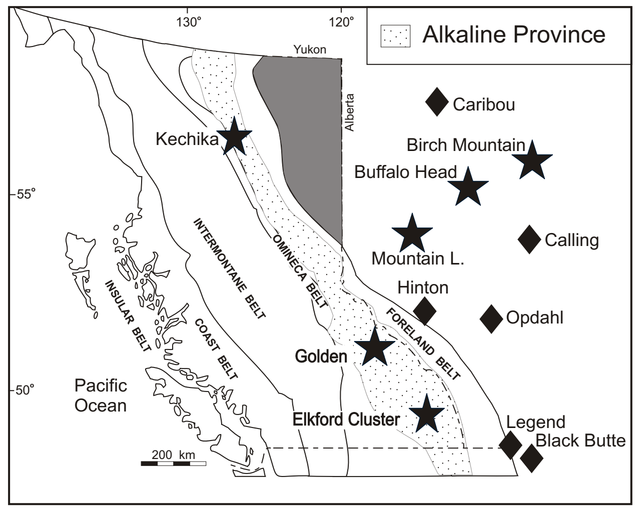

Figure 1: Morphogeological belts of the Canadian Cordillera; British Columbia's alkaline province shown in stipple; stars indicate primary diamond occurrences and lozenges represent alluvial diamond occurrences reported in the literature (*modified from* Simandl, 2004). Shaded area indicates British Columbia's portion of the Western Canada Sedimentary Basin, located northeast of the Foreland Belt. Basement underlying this and the adjacent area in Alberta is shown in more detail in the Figure 2. Location of belts according to Gabrielse et al. (1991).

INTRODUCTION

Major diamond-producing areas, such as the Diavik and Ekati mines in the Northwest Territories, are located within old stable cratons and conform to Clifford's rule, as considered by Janse (1994). Such areas host most of the known, large, primary diamond orebodies (Helmstaed, 1993). The Argyle mine (Australia), which is located within a mobile zone near the edge of the craton, is the only major exception (O'Neill *et al.,* 2003). Northeastern British Columbia (Fig. 1) is underlain by the Laurentian craton and is located east of the Foreland Belt (Gabrielse *et al.*, 1991; Monger and Price; 2002). It has been located near the edge of the Laurentian craton since the break-up of the Rodinia supercontinent more than 530 m.y. ago (Monger and Price, 2002).

All diamond occurrences reported in British Columbia (Northcote, 1983a, b; Anonymous, 1994; McCallum (1994); Allan, 1999, 2002;Roberts, 2002) are located within the British Columbia alkaline province (Fig. 1). This belt-shaped province follows the Omineca-Foreland belt boundary and the Rocky Mountain Trench, and is characterized by a variety of alkaline rocks, including carbonatites, nepheline syenites and kimberlites (Pell, 1994; Simandl, 2004). It is reported to coincide with an abrupt thickening of the crust and continental lithosphere, which persists and thickens eastward (Hyndman and Lewis, 1999). The rocks east and west of the British Columbia alkaline province (Fig. 1) have received very little attention from the diamond exploration industry, with the exception of a few isolated projects in the Peace River area, as exemplified by Stapleton (1997).

This paper concentrates on the Precambrian basement terranes in northeastern British Columbia (Fig. 2), situated between the British Columbia alkaline province and diamond discoveries within the Buffalo Head Terrane, Alberta. Current continental masses are a mosaic of welded

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fragments of ancient continents and accreted terrains, and it is possible that a portion of the Precambrian crystalline basement in eastern British Columbia was previously associated with a deep cratonic keel similar to that described by Haggerty (1986), Mitchell (1991), Kirkley *et al.* (1991) and Helmstaedt and Gurney (1995). It is possible that diamonds formed in Paleoproterozoic time or that the old basement fragments were displaced relative to their position of origin and dissociated from their keel, but they may still host potential diamond transporters, such as kimberlites, lamproites and lamprophyres (Simandl, 2004). Any information about the tectonic history, structure, petrological, geophysical and geochemical characteristics, including age, are important for understanding the basement terranes and are of interest in diamond exploration.

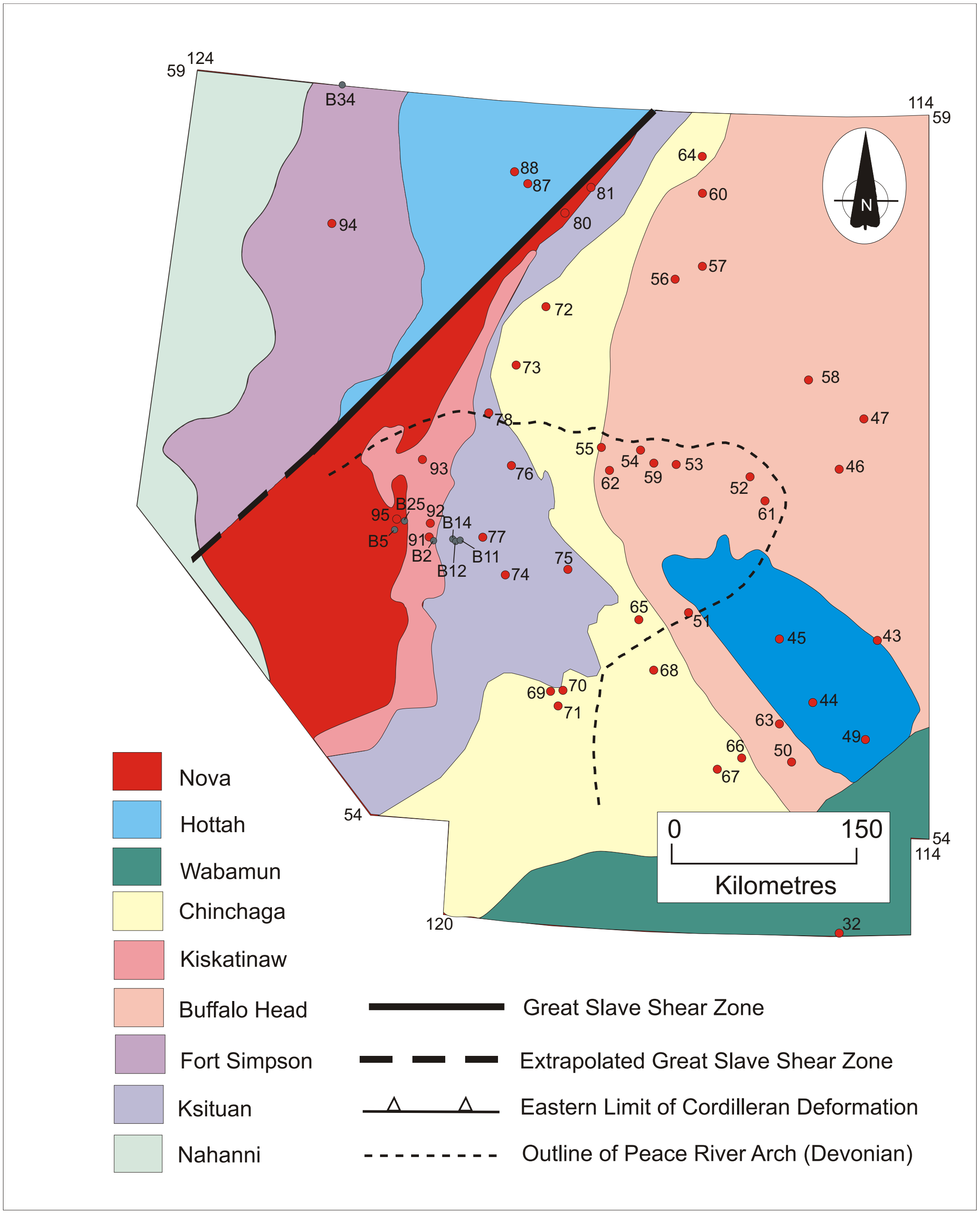

Figure 2: Generalized tectonic map of basement in northeast British Columbia and adjacent Alberta. The Nova Terrane is commonly interpreted as a sliver of Archean Slave craton (Villeneuve *et al.,*1993). Samples that were submitted for radiometric dating and are discussed in the text are identified by numbers B2, B5, B11, B12, B14, B25 and B34. Dates for the remaining samples and their locations are provided by Villeneuve *et al.* (1993).

PRECAMBRIAN BASEMENT IN NORTHEASTERN BRITISH COLUMBIA

Along the Alberta border (Fig. 2), the basement terranes hidden beneath the cover sequence are defined and extrapolated based on a combination of potential-field geophysics combined with limited radiometric dating and petrological studies of oil and gas well cuttings from northern Alberta. These wells are unevenly distributed, forming tight clusters in areas of highest oil and gas potential. Consequently, the interpretation based on the work of Hoffman (1988, 1989) and Ross *et al.* (1991, 1995), with minor subsequent modification, is still in use (Gehrels and Ross, 1998; McNicoll *et al*., 2000; Pilkington *et al*., 2000).

The terranes in northeastern British Columbia are, from southwest to northeast, the Wabamun High (accreted terrane), Buffalo Head (accreted terrane), Chinchaga Low (accreted terrane), Ksituan High (magmatic arc), Kiscatinaw Low (accreted terrane), Nova (possible Archean basement?), Hottah (accreted terrane), Fort Simpson (magmatic arc) and Nahanni (uncertain age and origin). The characteristics of the key terranes (including their ages) are summarized below.

The most intriguing and controversial aspect of the prevailing interpretation (Fig. 2) is that the Nova Terrane, which is assigned an Archaean age, is interpreted as a possible sliver of the Slave Craton, based on mylonites from Imperial Rainbow Lake (Alberta), which are dated at 2808 ± 30 Ma.

BUFFALO HEAD TERRANE

The Buffalo Head Terrane (BHT) consists mainly of metaplutonic and, to a lesser extent, metavolcanic and metasedimentary rocks. The U–Pb zircon ages for the magmatic rocks range from 2324 to 1990 Ma (Villeneuve *et al*., 1993). Dioritic to granitic rocks are dated at 2324 to 2072 Ma. Monazite and zircon ages from granulite in the Chinchaga Domain and BHT suggest that a metamorphic event occurred at 2017 Ma, followed by the intrusion of granitic rocks from 1990 to 1998 Ma. The younger magmatism is interpreted to be penecontemporaneous with collision of the Buffalo Head and Chinchaga terranes (Ross and Eaton, 2002). Neodymium isotope data suggest that the Buffalo Head Terrane formed as a result of reworking of Archean crust (McNicoll *et al*., 2000). This terrane hosts a number of barren and diamondiferous kimberlites (Carlson *et al*., 1999).

CHINCHAGA TERRANE

The Chinchaga Terrane is an aeromagnetic low, separating the Buffalo Head Terrane from the Ksituan Terrane. It consists of metaplutonic rocks that recrystallized at 2.19 to 2.08 Ga, overlapping with ages reported from the Buffalo Head Terrane (Ross and Eaton, 2002). Argon-argon ages suggest that this terrane has a similar cooling history to that of the BHT. Neodymium isotope data from the Chinchaga indicate a recycling of Archean crust, similar to that observed in the BHT (Theriault and Ross 1991; McNicoll *et al*., 2000).

KSITUAN TERRANE

This terrane is characterized by an aeromagnetic high and consists mainly of metaplutonic rocks dated at 1986 to 1900 Ma (U-Pb zircon), younger than rocks within the Buffalo Head and Chinchaga terranes. Uranium-lead geochronology of titanite suggests that these rocks cooled to 600°C by 1885 Ma (Ross *et al*,. 2002).

KISKATINAW TERRANE

This terrane has an aeromagnetic low signature, with U-Pb ages that are similar to those of the Ksituan Terrane. The terrane is interpreted as a shear zone separating the Ksituan from the Nova Terrane (Ross *et al*., 2002). Loss of magnetization may be deformation or alteration induced.

NOVA TERRANE

The Nova Terrane is an aeromagnetic high bounded by the Hay River Fault and the Liskatinaw Terrane. In Alberta, mafic gneiss and metarhyolite within this terrane give late Archean U-Pb ages of 2808 and 1990 Ma, respectively (Ross and Eaton, 2002).

HOTTAH TERRANE

This terrane coincides with an aeromagnetic low that grades eastward into the Great Bear Arc aeromagnetic high in northern Alberta. Rock types intercepted by drillholes are plutonic rocks and calcsilicate gneiss (Villeneuve *et al*., 1993). The same authors stated that 1.92 Ga is a typical date from this terrane.

WABAMUN TERRANE

The Wabamun Terrane is characterized by a positive aeromagnetic signature with an internal fabric that consists of oval-shaped positive domains surrounded by magnetic lows. It is believed to consist largely of undeformed magmatic rocks. Villeneuve et al. (1993) reported a single age of 2.32 Ga.

FORT SIMPSON TERRANE

This terrane forms a magnetic high with ovoid internal structures. It is interpreted as a calcalkaline plutonic complex. The three dates available, all from biotite granites, range from 1.84 to 1.85 Ga. (Villeneuve *et al*., 1991; Ross *et al*,. 2000).

NAHANNI TERRANE

The Nahanni magnetic low is interpreted as thinned Fort Simpson basement (Cook *et al*., 1999); however, granite clasts from the Coates Lake diatreme indicate a crystallization age of 1100 to 1175 Ma (Jefferson and Parrish, 1989).

SAMPLE SELECTION, SAMPLE PREPARATION AND ANALYTICAL PROCEDURES

There are no outcrops of Precambrian basement within the study area, and less than 100 boreholes drilled for oil and gas in the area are reported to have reached the basement. Most of these boreholes are clustered in areas that were subject to the most intense oil and gas exploration. Cuttings from basement are available from a limited number of holes. Basement cuttings were collected, carefully handpicked to avoid cavings (contamination) from overlying shale and limestone units, crushed, and the heavy mineral fraction was separated using both heavy liquids and magnetic separation with a Frantz™ isodynamic separator. Zircons were recovered from seven of the nine samples processed.

The U-Pb ages of the zircons were determined using the sensitive high-resolution ion microprobe (SHRIMP) at the J.C. Roddick Ion Microprobe Laboratory, Geological Survey of Canada. Analytical procedures followed those described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Briefly, zircons were cast in 2.5 cm diameter epoxy mounts (GSC #333) along with fragments of the GSC laboratory standard zircon (z6266, with $^{206}Pb/^{238}U$ age = 559 Ma). The midsections of the zircons were exposed using 9, 6, and 1 µm diamond compound, and the internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized with cathodoluminescence (CL) and back-scattered electrons (BSE) using a Cambridge Instruments scanning electron microscope. Mount surfaces were evaporatively coated with 10 nm of high purity Au. Analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. Two different sized spots were used for analysis, one ~ 25 µm in diameter and another ~16 µm in diameter, with a beam currents of ~9 and ~1.6 nA, respectively. The count rates of ten isotopes of Zr^+, U^+, Th^+, and Pb^+ in zircon were sequentially measured over seven scans with a single electron multiplier and a pulse counting system with deadtime of 35 ns. Offline data processing was accomplished using customized in-house software. The 1 external errors of $^{206}Pb/^{238}U$ ratios reported in the accompanying data table incorporate a 1.4 to 2.0% (for larger spot and smaller spot, respectively) error in calibrating the standard zircon (*see* Stern and Amelin, 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the measured ^{204}Pb and composition of the surface gold coating (Stern, 1997). Isoplot v. 3.00 (Ludwig, 2003) was used to generate concordia plots and calculate weighted means.

SAMPLE LOCATIONS AND U-PB DATING RESULTS

Zircons were recovered from seven samples: B2, B5, B11, B12, B14, B25 and B34. Sample locations are indicated on Figure 2 and the sample descriptions are summarized in Table 1. Samples B5 and B25 are located within but near the edge of Nova Terrane, as currently defined. Sample B2 plots within the Kiskatinaw Terrane and samples B11, B12 and B14 plot within the Ksituan Terrane. Sample B34, which is located near the British Columbia –Yukon boundary, occurs within the Fort Simpson Terrane. The results of U-Pb analyses are systematically described below and displayed on Figures 3 to 9.

U-PB AGE RESULTS

Sample B2: Kiskatinaw Terrane; cuttings of granitic basement. Zircons comprise a homogeneous population of euhedral to subhedral prismatic grains with broad oscillatory zoning typical of igneous crystals. Analyses of 13 individual zircon grains yielded a single age population with a weighted mean $^{207}Pb/^{206}Pb$ age of 1903 ± 7 Ma (Fig. 3), interpreted as the crystallization age of the sample. Evidence for older zircon in the form of inherited cores was not observed using BSE imaging.

Sample B11: Ksituan Terrane; cuttings of granitic basement. Zircons in this sample are euhedral to subhedral, equant to short prisms with well-developed oscillatory zoning. Some zones of presumably higher U content are altered

TABLE 1. DESCRIPTIONS OF SAMPLES DATED USING SENSITIVE HIGH-RESOLUTION ION MICROPROBE (SHRIMP).

Sample	Description of drillhole cuttings
B2	Crystalline basement (granitic composition) *Mineralogy: biotite, quartz, slight chloritization, feldspars (some altered)* *cavings: limestone/shale < 15% of the vial*
B5	Crystalline basement (granite) *Mineralogy: biotite, quartz, phlogopite, feldspar, sulphides, trace green mineral (epidote or amphibole, less likely pyroxene)* *cavings: < 15%*
B11	Crystalline basement (granite) *Mineralogy: chlorizited biotite, quartz, feldspar, chlorite* *cavings: < 10%*
B12	Crystalline basement (granitic composition, possibly orthogneiss) *Mineralogy: quartz, feldspar, biotite, zircon, titanite, trace of phlogopite (~90-95%)* *cavings: < 5% limestone*
B14	Crystalline basement (granite) *Mineralogy: quartz, altered feldspar, epidote, biotite, chlorite, unknown brown mineral, sediment, some grains look like quartzite* *cavings: limestone/shale < 10%*
B25	Crystalline basement (granite/gneiss, possibly quartzite fragments) *Mineralogy: feldspar, quartz, mica is aligned in some grains* *cavings: 15%*
B34	Crystalline basement (granite) *Mineralogy: biotite, lots of quartz, some feldspar, trace muscovite* *cavings: < 10%*

and these areas were avoided during the analyses. A total of twelve analyses yielded variably discordant data that define a discordia line with an upper intercept age of 1994 ± 7 Ma (Fig. 4). This is interpreted as the igneous age of the sample. The discordance in the data may in part reflect the poor quality of many of the zircon crystals. No inherited component was recognized.

Sample B12: Ksituan Terrane; cuttings of granitic basement. Zircons recovered from this sample are dominantly prismatic with moderate terminations and concentric growth zoning in BSE images. The igneous age of 1993 ± 7 Ma is interpreted from the weighted mean $^{207}Pb/^{206}Pb$ age of the twelve least discordant analyses (Fig. 5), with the most discordant fraction excluded from the calculation.

Sample B14: Ksituan Terrane; cuttings of granitic basement. This sample yielded only a small number of zircons (~25). The grains are prismatic with fine to broad oscillatory zoning. No evidence for inherited cores was observed. Many of the crystals are altered and heavily fractured. Analyses were selectively located on unaltered domains and a weighted mean $^{207}Pb/^{206}Pb$ age of 1993 ± 5 Ma is interpreted as the igneous crystallization age (Fig. 6). The most discordant analysis was excluded from the calculation.

Sample B5: Nova Terrane; cuttings of granitic rock. Zircons recovered from this sample define a homogeneous population of prismatic zircons with broad diffuse zoning observed in BSE images. No evidence of inherited cores was noted in the approximately 47 grains imaged. An igneous crystallization age of 1855 ± 6 Ma was calculated from the weighted mean of 12 $^{207}Pb/^{206}Pb$ age determinations (Fig. 7).

Sample B25: Nova Terrane; cuttings of granitic basement. Zircons in this sample are dominantly prismatic with fine to diffuse oscillatory growth zoning. The analyses show a very large range in U and Th content, with individual analyses ranging from concordant to almost 70% discordant (Fig. 8), the more discordant grains containing higher U contents of up to 3400 ppm. It is likely that the Pb/U calibration for these analyses is unreliable due to the high U contents and variable matrix effects. The age results did not yield a definitive interpretation. Ages for the less

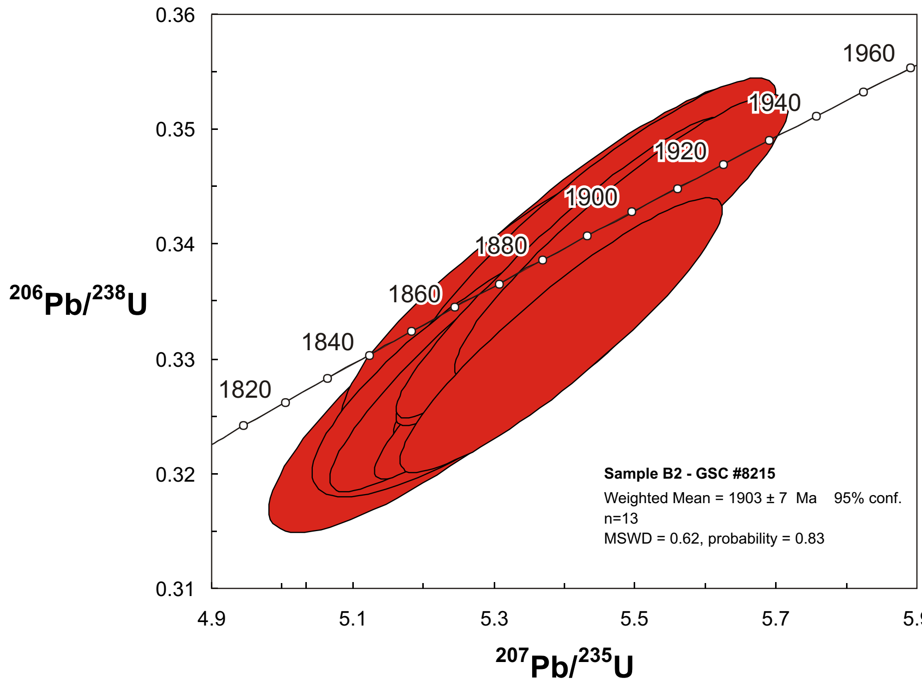

Figure 3. Interpretation of SHRIMP analytical data, sample B2; see text for explanations

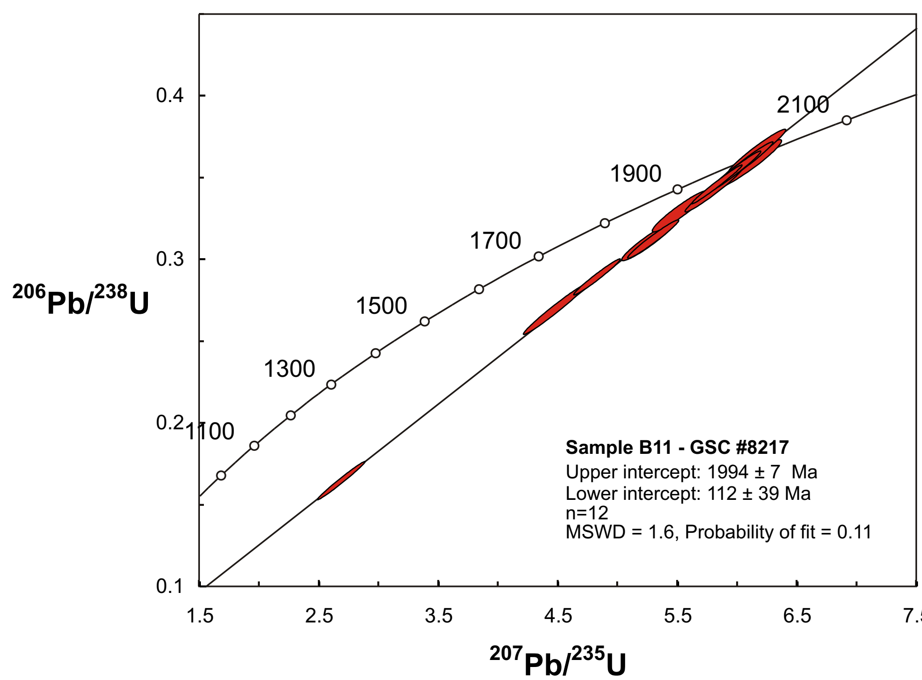

Figure 4. Interpretation of SHRIMP analytical data, sample B11; see text for explanations.

discordant analyses range from 1.89 to 2.23 Ga, an age range that is interpreted to indicate a significant inherited component in the sample. Three analyses yielded similar $^{207}Pb/^{206}Pb$ ages of ~1.75 Ga, but these ages are extremely discordant and therefore provide only a minimum age for the sample. A maximum age is estimated for the cluster of analyses at ~1.9 Ga. The pre–2.0 Ga zircons are interpreted as inherited.

Sample: B34: Fort Simpson Terrane; cuttings of granitic basement. Zircons from this sample are dominated by prismatic morphologies with prominent oscillatory growth zoning evident in BSE images. A total of 13 analyses define a simple discordia line with the upper intercept age of 1859 ± 10 Ma interpreted as the crystallization age of the rock (Fig. 9). No evidence for an older inherited component is noted in this sample.

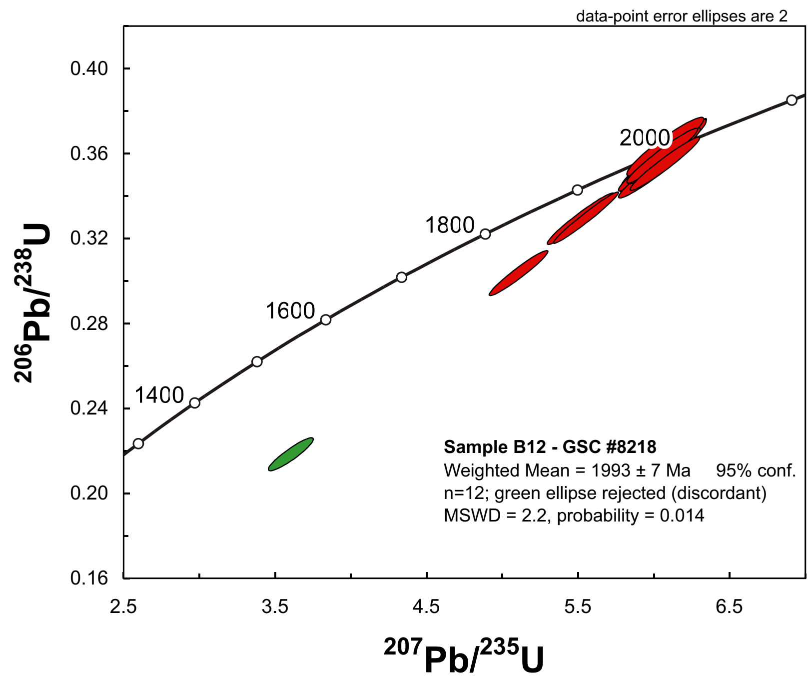

Figure 5 Interpretation of SHRIMP analytical data, sample B12; see text for explanations.

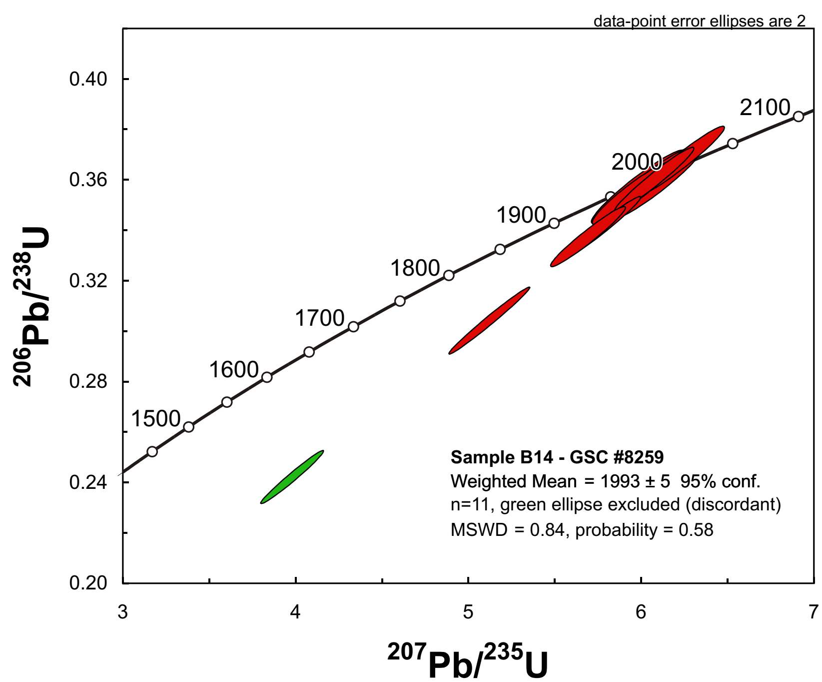

Figure 6 Interpretation of SHRIMP analytical data, sample B14; see text for explanations.

DISCUSSION

Six of the seven samples yielded reliable age information, with Paleoproterozoic ages that fall within three age groupings: ~1990, ~1900 and ~1850 Ma. Although sample B25 did not yield a reliable age estimate, it is most likely Paleoproterozoic and, perhaps most significantly, contains zircon that indicates interaction with ~2.0–2.3 Ga crust.

Sample B34 is from within the area of the Fort Simpson Terrane (Fig. 2), which is defined mainly as a magnetic high and interpreted as a calcalkaline plutonic complex. The 1859 ±10 Ma age of the sample is older than a previously published age of 1845 ± 1 Ma for the Fort Simpson Terrane in British Columbia (locality 94; Villeneuve *et al.,* 1993). Two ages from the Fort Simpson Terrane in the Northwest Territories are 1.84 and 1.85 Ga (Villeneuve e*t al.,* 1991; Ross *et al.,* 2000). The results for sample B34 support previous geophysical interpretations that extend the Fort Simpson Terrane from northeastern British Columbia all the way to the Northwest Territories (e.g., Aspler *et al.* 2003).

Samples B11, B12 and B14 occur within the Ksituan Terrane. The three samples give consistent ages of 1994 ± 7, 1993 ± 7and 1993 ± 5 Ma. These ages are slightly older than the results of Ross and Eaton (1900 to 1986 Ma, 2004) but still within the proposed range because of associated uncertainties. Dates in the Ksituan Terrane are in the same range as the Kiskatinaw dates reported by Villeneuve *et al.* (1993), and there is no distinction in age between these terranes. Samples B5 and B25 are located within the Nova Terrane (Fig. 2) near its boundary with the Kiskatinaw Terrane. The 1854 ± 6 Ma age for sample B5 is similar to Kiskatinaw ages previously reported by Villeneuve *et al.* (1993).

Sample B25 provided an unexpected result and is extremely important. Three highly discordant analyses yield similar $^{207}Pb/^{206}Pb$ ages of ~1.75 Ga, and constrain the minimum age for this sample. The most concordant analyses range in age from 1.89 to 2.23 Ga, indicating a significant inherited component in the sample. A maximum age is estimated for the cluster of analyses at ~1.9 Ga. This result suggests that rocks within at least a portion of the Nova Terrane contain zircons with characteristics similar to those of the Buffalo Head and Chinchaga terranes. The Buffalo Head Terrane is believed to consist mainly of Paleoproterozoic rocks (2.0 to 2.3Ga) intruded by a magmatic event at ~1.96 Ga (Villeneuve *et al.,* 1993). Archean magmatic ages are not documented in the diamondiferous kimberlite-bearing Buffalo Head Terrane as they have been in the Nova Terrane in Alberta (Ross and Eaton, 2002). However, U-Pb upper intercept ages in some Buffalo Head rocks and Nd isotopic data are interpreted to indicate Archean inheritance (Villeneuve *et al.,* 1993).

The difference between samples B25 and B5 is striking and requires additional consideration. Our results do not support the hypothesis that the Nova Terrane is a sliver of the Archean Slave craton (Fig. 2). Basement samples located centrally within the Nova Terrane are lacking, so some caution should be exercised.

Other approaches, such as Nd isotopic analyses, could be used to further compare sample B25 with existing data from the Buffalo Head and Chinchaga terranes in Alberta, where Nd data suggest that these terranes formed on a foundation consisting of Archean crust

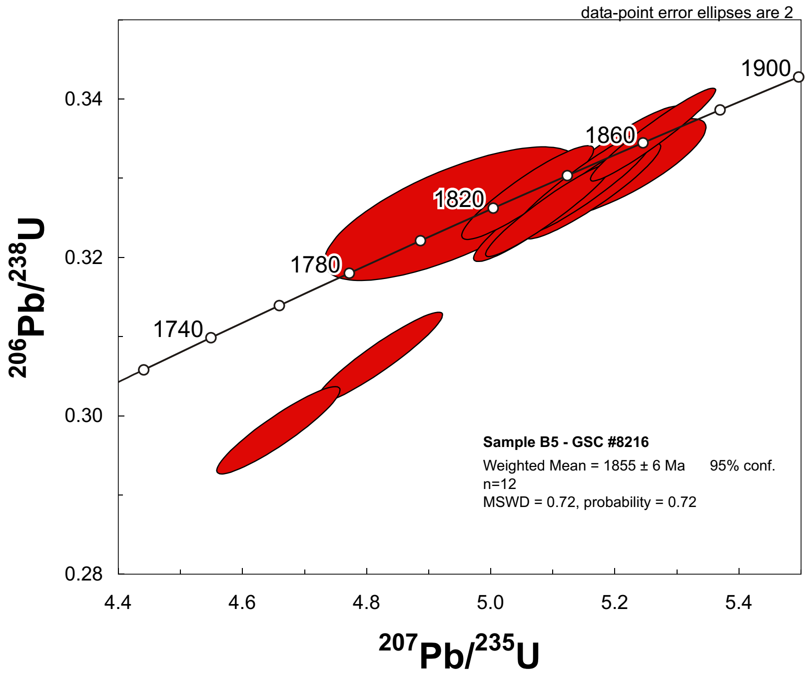

Figure 7. Interpretation of SHRIMP analytical data, sample B5; see text for explanations

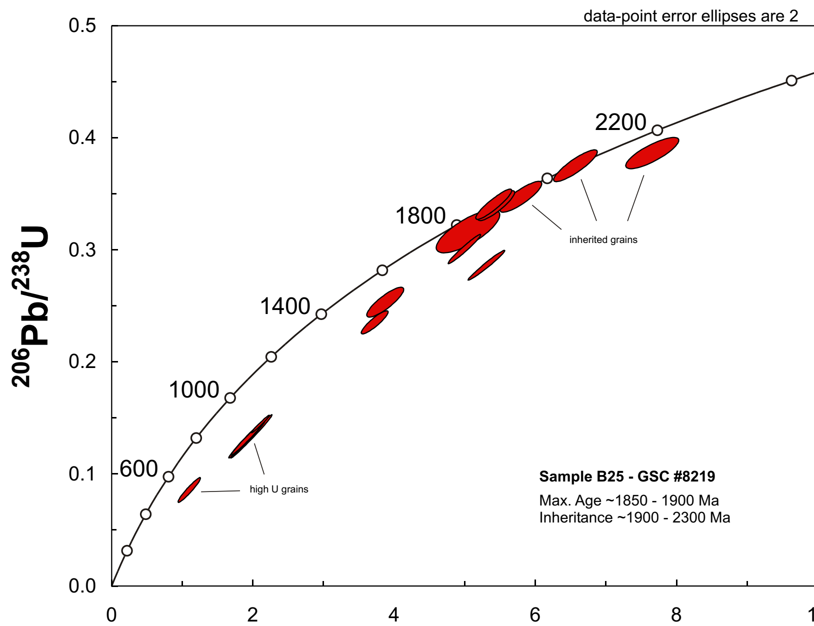

Figure 8. Interpretation of SHRIMP analytical data, sample B25; see text for explanations.

CONCLUSION

This study confirms the presence of Precambrian basement throughout the northeastern British Columbia study area. The dates of 1993 ± 5, 1993 ± 7 and 1994 ± 7 Ma within the Ksituan Terrane represent the timing of igneous activity, and these rocks must have intruded older basement, the age of which remains undetermined. Interpretation of $^{207}Pb/^{206}Pb$ zircon ages for the samples studied does not confirm the presence of Archean basement within the projected area of the Nova Terrane. Sample B25, located within but near the edge of the Nova Terrane, contains inherited zircon of ~2.0 to 2.2 Ga age, similar to rocks from the Buffalo Head and Chinchaga terranes. This is significant, because the Buffalo Head Terrane hosts diamond-bearing kimberlites in neighbouring Alberta. This indicates that basement of BHT age is present much farther west than previously proposed.

Future work, including Nd isotope analysis, could establish additional similarities or differences between the

Buffalo Head Terrane in Alberta and the Nova Terrane in British Columbia. A key question is whether Nova Terrane rocks were derived through recycling of Archean material. Additional dating and detailed geophysical interpretation are required to reconcile existing data. Based on similarities with the diamondiferous kimberlite-hosting BHT Terrane in Alberta, portions of northeastern British Columbia should be considered as legitimate but speculative diamond exploration areas.

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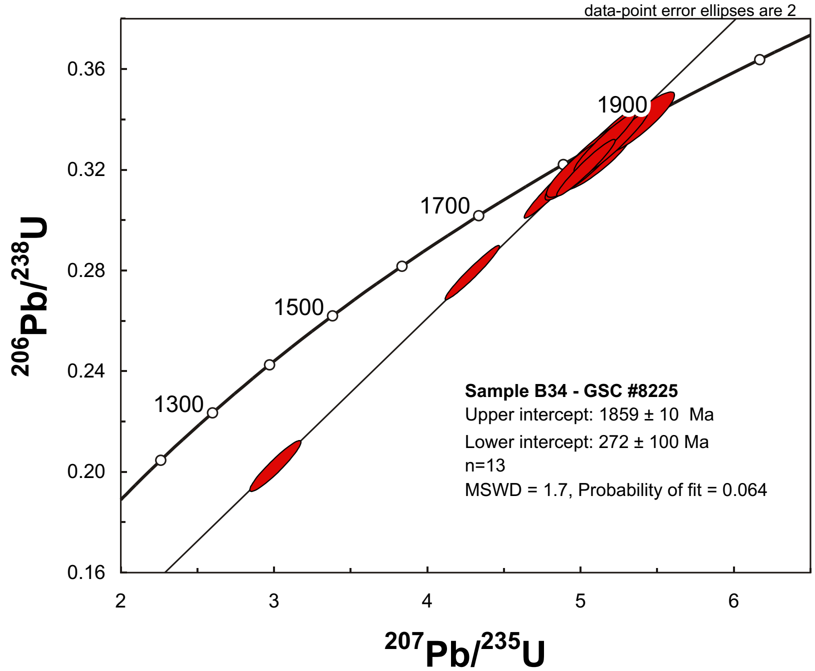

Figure 9 Interpretation of SHRIMP analytical data, Sample B34; see text for explanations.

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