EUB/AGS Geo-Note 2003-37

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Alberta Energy and Utilities Board

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AGS

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Radiogenic Isotope Geochemistry of Kimberlitic Rocks in Northern Alberta: Constraints for Source of Magmatism and Emplacement Age

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November 2003

Eccles, D.R., Heaman, L.M. and Creaser, R.A. (2003): Radiogenic isotope geochemistry of kimberlitic rocks in northern Alberta: constraints for source of magmatism and emplacement age; Alberta Energy and Utilities Board, EUB/AGS Geo-Note 2003-37.

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Published November 2003 by:
Alberta Energy and Utilities Board
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Acknowledgments

Rick Richardson, Reg Olson and Mark Fenton of the Alberta Geological Survey, and Bob Luth and Thomas Stachel of the University of Alberta are thanked for their intuitive discussion regarding the direction and goals of this project.

Several laboratory technicians and research assistants at the University of Alberta worked on the samples from preparation to mass spectrometer analysis. For this we thank Curtis Chmilar, Laura Raynor, Kelly Nixon and Stacey Hagen for their demonstrated care and precision.

Abstract

Kimberlitic rocks from the K4 and K6, and Legend, Phoenix and Kendu pipes from the Buffalo Head Hills and Birch Mountains fields, respectively, in the northern Alberta kimberlite province (NAKP) were selected for radiogenic isotopic analysis, including Rb-Sr, Sm-Nd and Pb-Pb on whole rock, U-Pb on perovskite and rutile, Sr on perovskite and Rb-Sr on mica (phlogopite).

Good correlations between whole-rock $\in$Nd, $^{87}Sr/^{86}Sr$ and Pb-isotopes, in conjunction with enriched incompatible elements and low contamination index ($SiO_2 + Al_2O_3 + Na_2O/MgO + K_2O$), suggest the isotopic content of the NAKP kimberlitic rocks can be used to make relevant observations on the mantle source characteristics in northern Alberta. Thus, the difference in isotopic character between the northern Alberta pipes must reflect chemical differences in their mantle source rocks, which may, for example, be derived from differing sources in a heterogeneous mantle or by the mixing of two or more components of vastly differing isotopic characteristics.

The K6 pipe (Buffalo Head Hills) is representative of melts derived from a depleted mantle and plot in the field for South African Group I kimberlites. The Phoenix and Legend pipes (Birch Mountains) have similar $\in$Nd to K6, but more radiogenic $^{87}Sr/^{86}Sr$, possibly related to their evolved nature. The K4 (Buffalo Head Hills) and Kendu (Birch Mountains) pipes contain lower $\in$Nd, higher $^{87}Sr/^{86}Sr$, and less radiogenic Pb isotopic ratios, and therefore contain: 1) at least some contribution from an old source region enriched in Rb/Sr and light rare-earth element (LREE; low U/Pb and Sm/Nd) material, 2) crustal contamination, or 3) both.

A compilation of known biostratigraphic and isotopic dates show the emplacement age of the NAKP is Late Cretaceous (Coniacian to Maastrichtian). The isotopic results for mineral separates analyzed in this study provided a robust emplacement age for the Phoenix pipe, 77.6±1.1 Ma by U-Pb perovskite. This date is older than previously reported ages of 70.3±1.6 and 70.9±0.4 Ma by U-Pb perovskite and Rb-Sr phlogopite, respectively (Aravanis, 1999). The variance in ages is possibly the result of separate eruption events, which have subsequently mixed in the crater environment.

1 Introduction

Kimberlitic rocks were first discovered in northern Alberta during 1989-1990, when Monpros Limited (the then Canadian exploration subsidiary company of De Beers) discovered the Mountain Lake pipes in northwestern Alberta. To March 2003, 48 ultramafic pipes have been discovered in 3 separate areas of the northern Alberta kimberlite province (NAKP): 2 pipes in the Mountain Lake cluster (northwestern Alberta), 38 pipes in the Buffalo Head Hills field (north-central Alberta), and 8 pipes in the Birch Mountains field (northeastern Alberta). These pipes comprise mainly crater volcaniclastic kimberlitic rocks with varying amounts of mantle material.

This report is the third in a series intended to investigate the petrogenesis of kimberlitic rocks in Alberta. Previously, Eccles and Luth (2001) documented the major and trace element whole-rock geochemical content of 83 samples from the three separate kimberlitic clusters or fields. They suggested a kimberlite magma evolution 'trend-line' may be used to reflect the compositional evolution from primitive to evolved kimberlite magmas in Alberta. Eccles (2002) grouped these whole-rock geochemical data into five separate 'groups,' based on similar whole-rock geochemical compositions, and selected one pipe in each 'group' for detailed petrographic interpretation. This report uses the same sample set as Eccles (2002) for isotopic analyses (Table 1), which includes pipes K4 and K6 (Buffalo Head Hills) and Legend, Phoenix and Kendu (Birch Mountains).

Table 1. Samples selected for isotope analysis.

Sample number	Pipe name (general area)*	Drill hole number	Depth (m)	Easting (m)	Northing (m)	Zone
ABK-01	K4A (BHH)	4A-02	49.15	578380	6301519	11
ABK-02	K4B (BHH)	4B-01	140.65	578464	6300991	11
ABK-05	K6 (BHH)	6-02	110.15	585550	6308383	11
ABK-29	K6 (BHH)	Outcrop	0 - surface	585317	6308651	11
ABK-59	Legend (BM)	98DH-LE01	44.00	386200	6340600	12
ABK-68	Legend (BM)	98DH-LE01	187.00	386200	6340600	12
ABK-75	Phoenix (BM)	98DH-PH01	105.00	351500	6330580	12
ABK-76	Phoenix (BM)	98DH-PH01	130.00	351500	6330580	12
ABK-81	Kendu (BM)	Kendu	102.00	368567	6353618	12
ABK-82	Kendu (BM)	Kendu	127.25	368567	6353618	12

* BHH – Buffalo Head Hills, north-central Alberta; BM – Birch Mountains, northeastern Alberta

Because kimberlitic rocks were only discovered in Alberta during the last decade, little to no research has been reported on their emplacement ages or isotopic composition. To date, no whole-rock Rb-Sr, Sm-Nd or Pb-Pb isotopic analyses have been reported, and few radiometric kimberlite emplacement ages have been reported. The latter is particularly true for the Buffalo Head Hills field, where emplacement U-Pb perovskite ages of between 86 ± 3 Ma and 88 ± 5 Ma are reported for only three of the 38 pipes (Carlson et al., 1999; Skelton et al., 2003).

The primary objective of this report, therefore, is to sample, analyze and report on the isotopic compositions of selected northern Alberta kimberlitic rocks from the Buffalo Head Hills and Birch Mountains fields. The results from this study are intended to provide evidence for the nature of their mantle source(s), and thus the genesis of Alberta kimberlites, and to constrain the emplacement age of selected NAKP pipes.

2 Application of Radiogenic Isotopes to Kimberlite Research and Exploration

Isotopic tracers represent a particularly powerful tool for geochemical studies of mantle-derived kimberlite magma. Two principal groups of kimberlites have been recognized based primarily on the mineralogical, geochemical and isotopic characteristics of South African kimberlites (e.g., Smith et al. 1985; Mitchell, 1986). The application of radiogenic isotopes (e.g., Smith, 1983), in particular, have shown a distinct compositional 'gap' occurs between the two kimberlite groups. Group I (basaltic) kimberlites possess isotopic characteristics similar to many ocean island basalts (OIBs) and are believed to be derived from very small-degree partial melts that originate in comparatively 'fertile' asthenospheric sources. In contrast, Group II (micaceous) kimberlites have more radiogenic initial $^{87}Sr/^{86}Sr$ and lower $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ ratios and represent Group I-type rocks that have been subsequently contaminated to different degrees in the large-ion, lithophile element-enriched, but refractory subcontinental lithosphere. This mixing model, originally proposed for kimberlite genesis by Nixon et al. (1981) can also serve as a unifying petrogenetic model for other ultramafic sources (e.g., lamproite and possibly carbonatite). On this basis, any major chemical differences in isotopic character between kimberlitic rocks in the NAKP may reflect substantial chemical differences in their mantle source rocks and can shed new light on their genesis.

In addition to mantle processes, radiogenic isotopes can provide reliable data on the emplacement age of individual pipes. Knowledge of the ages of kimberlite and related intrusions, clusters and provinces provides a basis for evaluating the controls on magma genesis and eruption mechanisms (e.g., Le Roex, 1986; Heaman et al., in press). Furthermore, variations in diamond content relative to emplacement age can help to direct exploration companies to areas of high potential.

3 Isotopic Geochemistry and Analytical Techniques

Because the composition and alteration variability of kimberlite precludes the application of a single isotopic technique to all occurrences, the best approach to determining the primary isotopic composition of kimberlite is separate measurements using multiple isotopic systems. If present, separated primary magmatic mineral phases may provide more robust results than whole-rock samples because they represent a more direct sample of fresh material unaffected by possible alteration with the host kimberlite. Thus, a variety of radiometric methods were completed on selected Alberta kimberlitic rocks, including Rb-Sr, Sm-Nd and Pb-Pb on whole rock, U-Pb on perovskite and rutile, Sr on perovskite and Rb-Sr on mica (phlogopite).

3.1 Whole-Rock Sm-Nd, Rb-Sr and Pb-Pb

Whole-rock isotopic analyses offer a quick and cost-effective method involving limited sample preparation, and provide data on a number of isotopic systems:

- The Rb-Sr system is applicable because the kimberlite is highly potassic and information on initial $^{87}Sr/^{86}Sr$ ratios has been found useful in interpreting the history of the Earth's crust and mantle.
- The Sm-Nd system is relatively resilient to geological disturbances, such as metamorphism and weathering (e.g., Barovich and Patchett, 1992).
- The Pb-Pb system offers an opportunity to determine mantle isochron ages without the effects of parent-daughter fractionation during partial melting and is most helpful in differentiating mantle sources with contrasting U-Pb compositions.

The analytical procedures are summarized as follows:

- Pulverize sample to -150 mesh using a chrome-steel ring-and-puck pulverizer at ACME Analytical Laboratories Ltd., Vancouver, British Columbia.
- Samples were weighed and spiked with mixed ^{149}Sm-^{150}Nd and ^{87}Rb-^{84}Sr tracers and placed on a hot plate (ca. 150º C) for five days.
- Rb and Sr were separated using standard cation exchange chromatography.
- Pb was extracted using standard anion chromatography.
- Sm and Nd were extracted using isotope dilution mass spectrometry.

Isotope ratios were measured on a VG 354 and Micromass S54 multi-collector thermal ionization mass spectrometers. All errors are reported at the 2σ level. Analytical details for whole-rock Rb-Sr, Pb and Sm-Nd isotopic analysis can also be found in the following references: Holmden et al. (1996), Yamashita et al. (1999) and Unterschutz et al. (2002).

3.2 U-Pb Perovskite/Rutile

Kimberlite emplacement ages can be effectively determined by U-Pb analysis of matrix perovskite (e.g., Heaman, 1989; Heaman and Kjarsgaard, 2000), which contains high-U contents (up to 200 ppm) and typically provides good precision and accuracy. However, the small grain size (often <50 μm) of the mineral in many instances renders mineral separation extremely difficult. We also investigated the feasibility of U-Pb mantle rutile dating for one sample from the Kendu pipe.

The separation and analytical technique for U-Pb perovskite and rutile can be summarized as follows:

- Perovskite/rutile was isolated from 0.1 to 1 kg samples by pulverization using standard crushing (Jaw crusher and Bico disk mill), heavy liquid separation (Methylene Iodide), and magnetic separation (Frantz).
- Perovskite/rutile was hand-picked under a binocular microscope at high magnification to ensure that grains with inclusions, alteration or other imperfections could be excluded.
- Each fraction was weighed and washed in warm, 4N HNO_3 for one hour at ca. 50º C, given a one-minute rinse in an ultrasonic bath, and then triple rinsed with distilled H_2O followed by distilled acetone prior to dissolution in TFE Teflon bombs.
- The fractions were spiked using a mixed ^{205}Pb-^{235}U tracer solution and dissolved in a mixture of HF and 7N HNO_3 at 230º C for 5 days.
- Prior to column chemistry, the samples were equilibrated in 3.1N HCl for 12 hours.
- Uranium and lead were purified using an HBr procedure (Heaman, 1989).
- The purified uranium and lead were loaded onto outgassed Re filaments, with a mixture of silica gel and phosphoric acid, and were analyzed on a VG 354 mass spectrometer in single Daly photomultiplier dector mode. All errors are reported at the 2σ level.

3.3 Rb-Sr Phlogopite

Rb-Sr analysis of phlogopite is a well-established dating technique for kimberlite (e.g., Smith et al., 1985; Allsopp et al., 1989). Phlogopite is present in many kimberlites as fine-grained groundmass phlogopite and coarser-grained macrocrysts. The latter are easier to date by virtue of their larger size, ease of separation and lower common Sr content (more radiogenic Sr). Limitations of the technique include contamination from inherited crustal micas, secondary alteration and presence of strontium-rich inclusions.

The separation and analytical technique for Rb-Sr phlogopite analysis can be summarized as follows.

- The samples were crushed in a jaw crusher to less than 2 cm.
- Phlogopite crystals were hand-picked in ethanol under microbinoculars, and grains free of visible alteration selected for analysis were dried and weighed.
- The samples were leached in a 0.75N HCl ultrasonic bath for 30 minutes at room temperature to extract carbonate material following an adopted leaching method of Brown et al. (1989).
- The HCl supernatant was decanted and residue washed twice in H_2O prior to addition of a mixed ^{84}Sr-^{87}Rb spike.
- The leached fraction was dissolved in Savillex capsules in 24N HF and 16N HNO_3 at ca. 150º C for 12 hours, dried down, dissolved in 6N HCl at 80º C for 12 hours and evaporated to dryness.
- Prior to column chemistry, the dried samples were re-dissolved in oxalic and HCl acid. Rb and Sr were separated using conventional cation exchange chromatography.

Purified Rb and Sr aliquots were loaded onto single rhenium filaments and coated with H_3PO_4 and tantalum gel. The Rb and Sr aliquots were analysed on the VG 354 and Micromass S54 thermal ionization mass spectrometers. All errors are reported at the 2σ level.

4 Whole-Rock Results and Considerations for Alteration and Contamination

Ten samples from five pipes (K4, K6, Legend, Phoenix and Kendu) were analyzed for whole-rock Sm-Nd, Rb-Sr and Pb-Pb isotopes. Their initial isotopic ratios were calculated using ages of 86 and 76 Ma for samples from the Buffalo Head Hills and Birch Mountains fields, respectively (ages based on dates from Aravanis, 1999 and Skelton et al., 2003). The results, which are presented in Table 2, have wide initial isotopic ranges: $^{87}Sr/^{86}Sr$ compositions vary between 0.704 to 0.709, $\in$Nd between –7.4 to +2.7, $^{206}Pb/^{204}Pb$ between 18.2 to 19.8, $^{207}Pb/^{204}Pb$ between 15.49 to 15.58 and $^{208}Pb/^{204}Pb$ between 38.61 to 41.06. The diagrams of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ (Figure 1) and isotopic Pb ratios (Figure 2) show that the isotopic compositions of samples from the same pipe or cluster (i.e., samples ABK01 and ABK02 from the K4A and K4B pipes) have similar isotopic ratios and, thus, indicate that the whole rock isotopic values obtained for the pipes selected in this study are reproducible.

Before the results of the whole rock isotopic analyses are used to make inferences on mantle source composition in the NAKP, however, the degree and type of alteration and contamination, which could occur during disequilibrium in the mantle, mantle metasomatism, magma transport and eruption, and/or post depositionally, must be considered.

The Phoenix pipe was selected to test kimberlite whole-rock contamination because of the abundance and ease of separation of the cognate minerals (e.g., perovskite). Independent Sr isotope analysis on perovskite can help clarify whether the whole-rock isotopic signature is of mantle source or a contaminated mantle source. That is, if the whole-rock and unaltered perovskite Sr-isotope ratios are identical, then the whole-rock isotopic signature must be directly related to its mantle source. Minimally altered perovskite from sample ABK76 has a significantly lower $^{87}Sr/^{86}Sr$ ratio (0.704786±0.000018) than the whole rock, which has initial $^{87}Sr/^{86}Sr$ ratios of between 0.70576 and 0.70556. Because perovskite best reflects the primary isotopic composition of the Phoenix kimberlite and the perovskite and whole rock $^{87}Sr/^{86}Sr$ ratios are in disequilibrium, it is likely that the Phoenix kimberlite is contaminated.

It is also possible, therefore, that other NAKP pipes with radiogenic values of $^{87}Sr/^{86}Sr$, such as those exhibited by the Legend, K4 and Kendu pipes (Table 2, Figure 1), have also been subjected to varying degrees of alteration and contamination. Possible sources for contamination with the focus on Sr are

Table 2A. Rb-Sr whole-rock isotopic data for selected Alberta kimberlites.

	Pipe	Rb	Sr			$^{87}Sr/^{86}Sr$	Uncertainty	Initial	
Sample	name	(ppm)	(ppm)		$^{87}Rb/^{86}Sr$	corrected*	+/- 2sm	$^{87}Sr/^{86}Sr$	
ABK01	K4A	2.14	295.72		0.0210	0.70673	0.00001	0.70671	
ABK02	K4B	6.81	452.42		0.0436	0.70626	0.00001	0.70621	
ABK05	K6	9.56	515.33		0.0537	0.70406	0.00002	0.70400	
ABK29	K6	29.78	928.65		0.0928	0.70434	0.00001	0.70423	
ABK59	Legend	37.53	878.38		0.1236	0.70521	0.00001	0.70508	
ABK68	Legend	30.27	543.40		0.1612	0.70645	0.00001	0.70628	
ABK75	Phoenix	36.99	1273.17		0.0841	0.70585	0.00001	0.70576	
ABK76	Phoenix	3.67	118.69		0.0896	0.70565	0.00001	0.70556	
ABK81	Kendu	4.11	42.72		0.2786	0.70778	0.00001	0.70749	
ABK82	Kendu	32.38	407.46		0.2300	0.70879	0.00001	0.70856	
* Sr correction S54 Multi Dynamic									

Table 2B. Sm-Nd whole-rock isotopic data for selected Alberta kimberlites.

	Sm	Nd			$^{143}Nd/^{144}Nd$	Uncertainty		Epsilon	
Sample	(ppm)	(ppm)		$^{147}Sm/^{144}Nd$	corrected*	+/- 2sm	TDM	NdT	
ABK01	0.74	6.55		0.0683	0.51221	0.0000096	1.00215	-7.0	
ABK02	2.54	25.26		0.0607	0.51218	0.0000103	0.97458	-7.3	
ABK 05	11.11	94.21		0.0713	0.51270	0.0000069	0.50059	2.5	
ABK 29	8.90	74.93		0.0719	0.51271	0.0000076	0.49004	2.7	
ABK 59	10.79	92.43		0.0706	0.51259	0.0000063	0.61027	0.2	
ABK 68	8.42	71.63		0.0710	0.51258	0.0000102	0.62324	0.0	
ABK 75	26.66	242.18		0.0666	0.51267	0.0000073	0.50926	1.8	
ABK 76	27.02	245.83		0.0665	0.51267	0.0000073	0.50979	1.8	
ABK 81	8.43	62.02		0.0822	0.51226	0.0000060	1.04534	-6.3	
ABK 82	6.81	49.39		0.0833	0.51238	0.0000064	0.91267	-4.0	
* Nd correction S54 Multi Dynamic									

Table 2C. Pb-Pb whole-rock isotopic data for selected Alberta kimberlites.

				206/204	207/204	208/204	206/204	207/204	208/204
Sample	U	Th	Pb	corrected	corrected	corrected	initial	initial	initial
ABK 01	1.3	5.5	<3	19.135	15.566	39.447	19.130	15.565	39.440
ABK 02	2	9.5	4	19.123	15.486	39.757	19.119	15.486	39.750
ABK 05	3.9	23.2	8	19.530	15.550	39.886	19.526	15.550	39.877
ABK 29	3.1	18.1	5	19.418	15.544	39.685	19.412	15.544	39.675
ABK 59	6	37.7	11	19.673	15.578	40.249	19.669	15.578	40.241
ABK 68	5.3	31.1	8	19.724	15.576	40.248	19.719	15.576	40.238
ABK 75	8.5	88	12	19.828	15.577	41.077	19.822	15.577	41.059
ABK 76	8.9	85.9	11	19.764	15.578	40.866	19.758	15.578	40.847
ABK 81	2.4	26.6	9	18.238	15.500	39.602	18.236	15.500	39.595
ABK 82	2	14.7	8	18.203	15.490	38.616	18.201	15.490	38.611

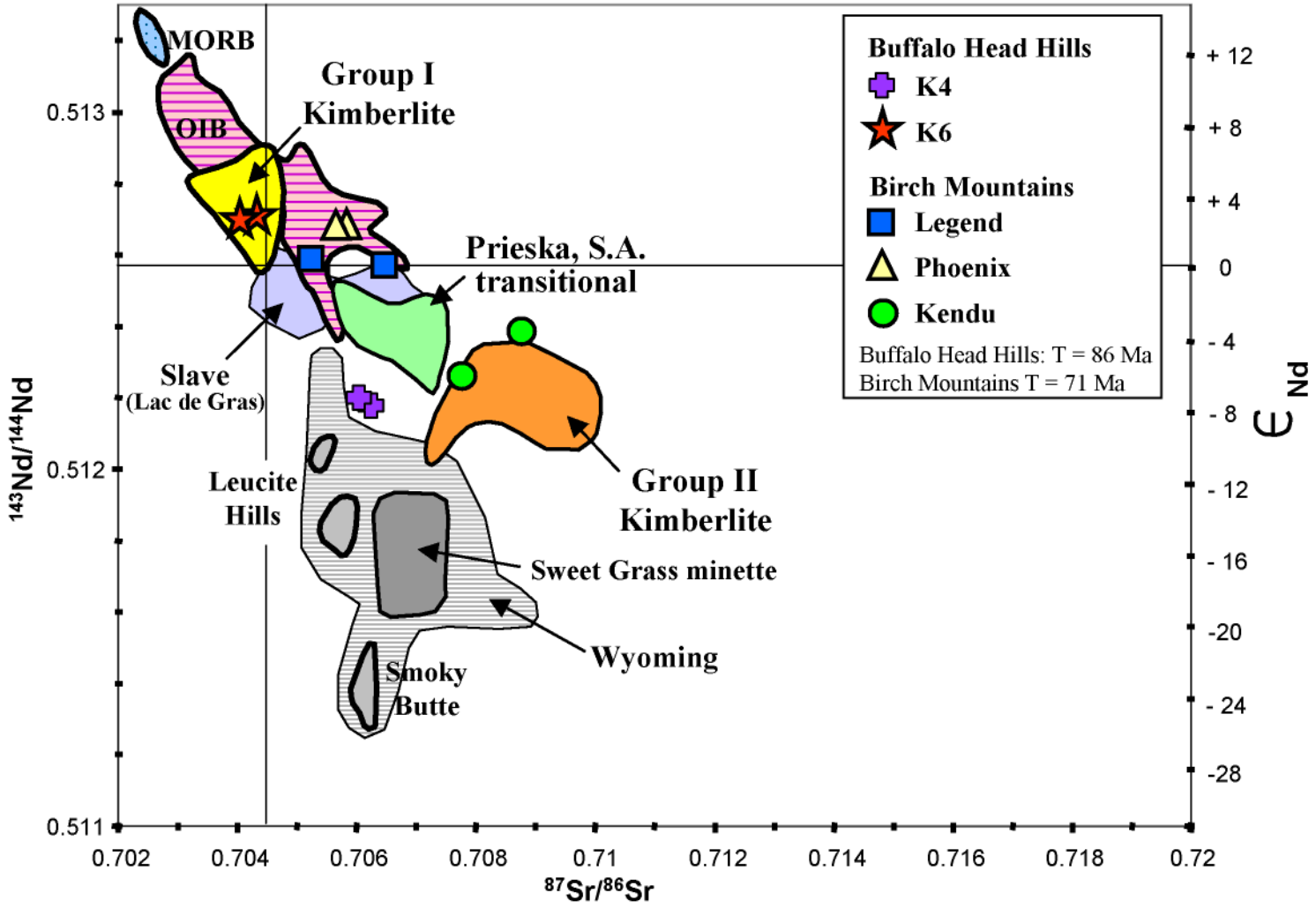

Figure 1. Nd-Sr isotope variations from selected kimberlitic rocks in northern Alberta. Group I and II kimberlite fields from Mitchell (1986); Prieska transitional kimberlite field from Skinner et al. (1994); Slave Lac de Gras field from Dowall et al. (2000); Wyoming ultrapotassic fields from Vollmer et al. (1984) and O'Brien et al. (1995); Sweet Grass minette from Buhlmann (1996). See Mitchell (1986) for mid-oceanic ridges (MORB) and oceanic islands (OIB) references.

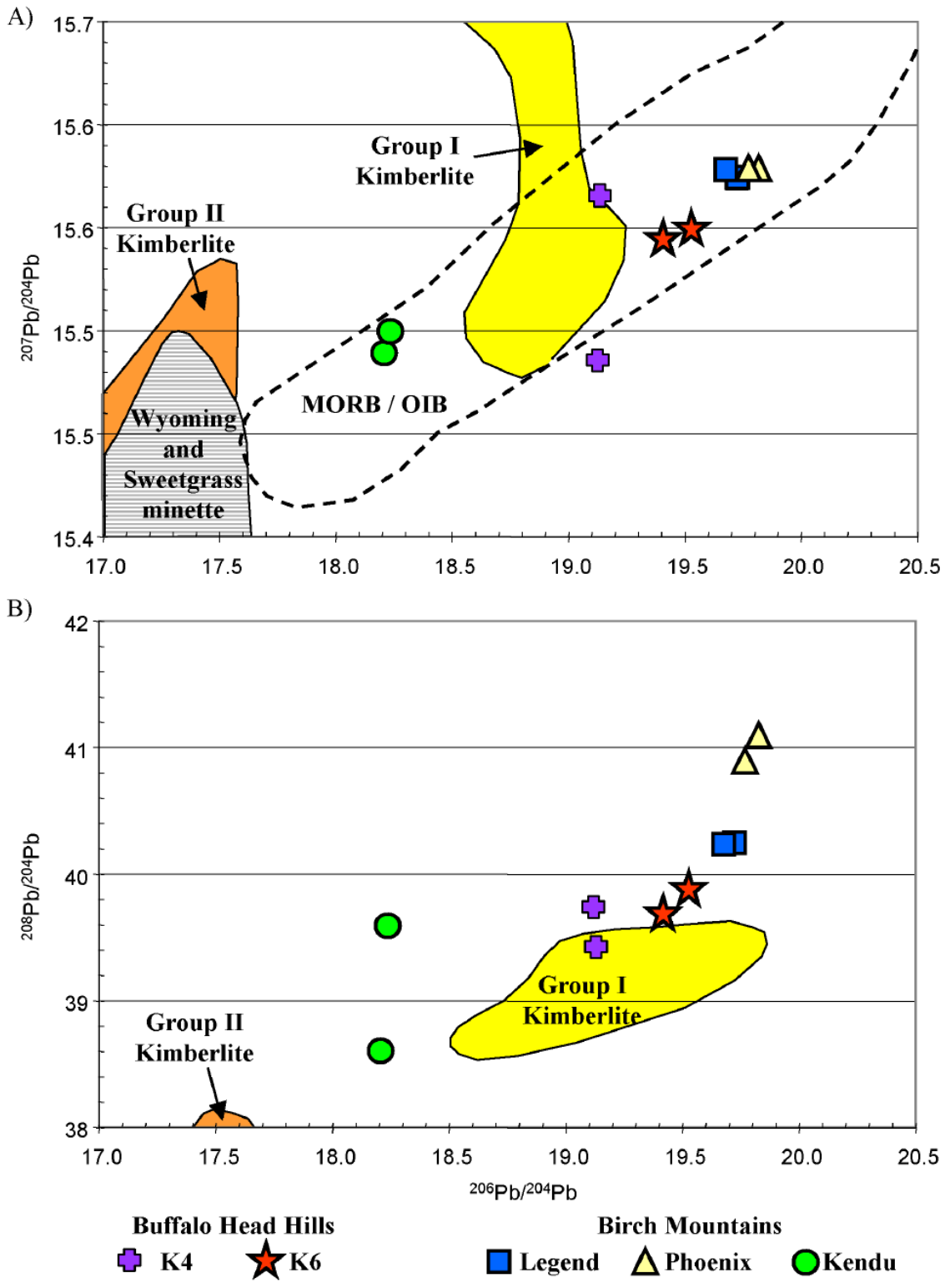

Figure 2. Isotopic composition of Pb from kimberlitic rocks in northern Alberta. A) $^{207}Pb/^{204}Pb$ versus $^{205}Pb/^{204}Pb$, B) $^{208}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$. Kimberlite fields from Mitchell (1995); Wyoming and Sweetgrass field from O'Brien et al. (1995) and Buhlmann (1996); see Mitchell (1995) for mid-oceanic ridges (MORB) and oceanic islands (OIB) references.

discussed below, including influence on the NAKP kimberlitic rocks by assimilation of country rock, disequilibrium in the mantle, mantle metasomatism and/or groundwater contamination. This discussion will provide some basis regarding the extent to which contamination will influence any interpretations about the nature of the mantle source compositions in northern Alberta.

4.1 Assimilation by Country Rock

The volatile-rich nature of kimberlite magmas causes rapid ascent through the crust. This, coupled with their high incompatible-element concentrations (e.g., Nd and Sm), may mean these magmas are very resistant to isotopic modification by crustal contamination. Typical kimberlites have initial Sr isotope ratios in the range of 0.706 to 0.716 (e.g., Barrett and Berg, 1975; Mitchell, 1986). Because exceptionally fresh kimberlite rocks were believed to have ratios as low as approximately 0.704 (Berg and Allsopp, 1972), crustal xenolith contamination was initially considered to influence kimberlite samples with higher radiogenic $^{87}Sr/^{86}Sr$ ratios. Contradictory evidence, however, suggested that trace element and radiogenic isotope composition of kimberlite primarily reflects mantle rather than crustal processes. For example, Paul (1979) showed that 'fresh' Indian kimberlite had higher initial $^{87}Sr/^{86}Sr$ (0.7102 to 0.7142) ratios than those classified as altered (0.7036 to 0.7073), and Smith (1983) reported that kimberlite samples with petrographic evidence for alteration and contamination do not generally show major isotopic changes. A plausible explanation for this is that kimberlite incompatible elements are enriched to the extent that any crustal contamination effect on kimberlitic rocks would be masked by the 5 to 10 times higher Nd and Sr abundances in these magmas compared to common crustal rocks (e.g., McCulloch et al., 1983).

The NAKP rocks analyzed in this study have whole-rock geochemical Sr contents of between 43 and 1273 ppm (average 546). In contrast, northern Alberta Late Cretaceous shale contains an average of 167 ppm Sr (n = 122; Dufresne et al., 2001), and northeastern Alberta Devonian carbonate contains an average of 244 ppm Sr (n = 141; Eccles et al., 2001; D.R. Eccles and D.I. Panu, work in progress, 2003). Based on these values, the NAKP kimberlitic rocks would have to have high assimilation (e.g., 50%) from Alberta basin country rocks, and for the samples analyzed in this study, there is no petrographic or geochemical evidence to support this. For example, northern Alberta kimberlitic rocks have high Mg# and Ni contents, low contamination index (C.I.) values, and the abundance of incompatible elements is extremely high relative to their abundance in common crustal rocks.

To test for mixing relationships, the NAKP rocks are plotted on the $^{87}Sr/^{86}Sr$ versus 1/Sr mixing relation diagram of Faure (1986) together with estimated fields for Alberta shale and carbonate sedimentary rocks (Figure 3). Because of the limited data, two contrasting arguments can be presented. First, the NAKP kimberlitic rocks, which have considerably lower $^{87}Sr/^{86}Sr$ and higher Sr, probably do not show any linear array with the shale and carbonate fields, and thus, crustal contamination by bulk assimilation is unlikely to be responsible for the observed $^{87}Sr/^{86}Sr$ enrichment of the Phoenix whole-rock samples or the isotopic variation between pipes. Alternatively, an approximate linear array, with two samples falling off the trend, can be interpreted from Figure 3 with samples from the Kendu, K4 and one sample from the Legend pipe plotting on the upper end (higher $^{87}Sr/^{86}Sr$) of a kimberlite-shale/carbonate mixing line. Based on petrographic evidence, the latter theory is unlikely. Nevertheless, multiple interpretations provide justification for future analyses in conjunction with detailed petrography, particularly from other pipes in the NAKP.

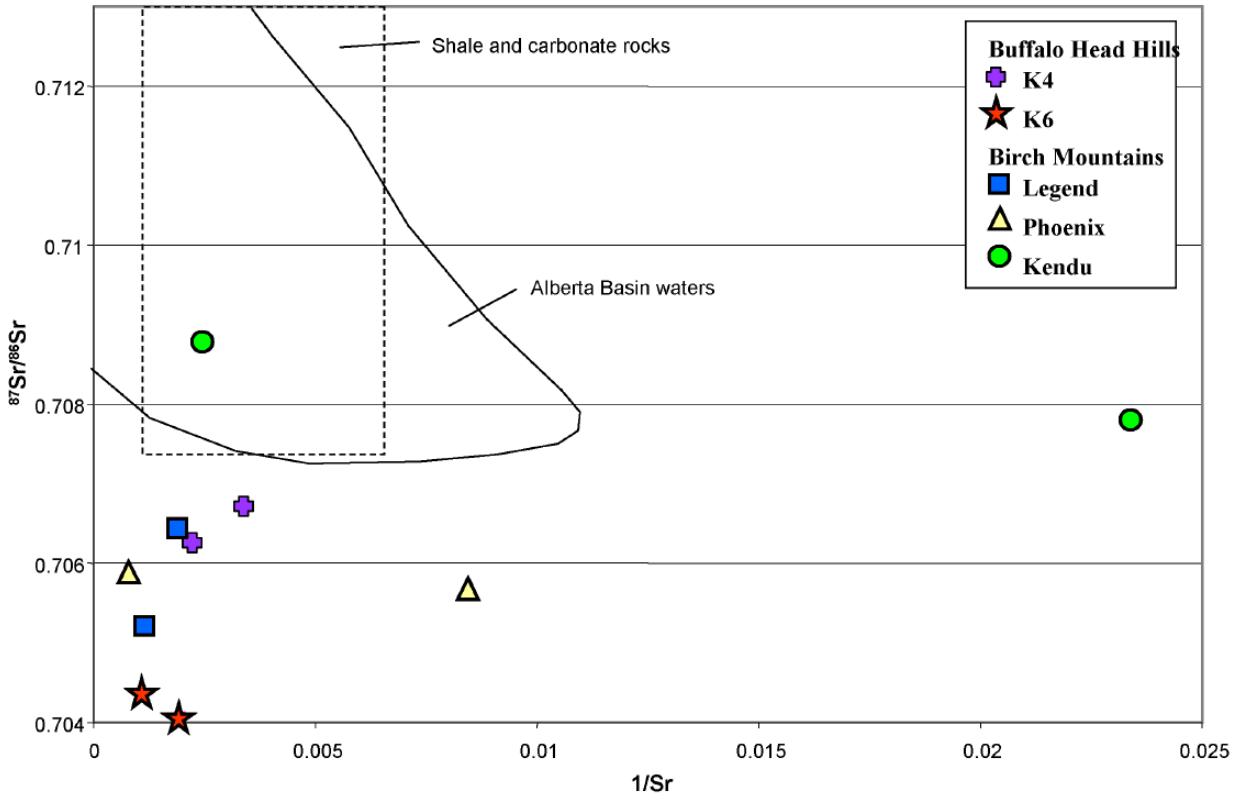

Figure 3. $^{87}Sr/^{86}Sr$ versus 1/Sr plot for kimberlitic rocks in northern Alberta, Alberta shale and carbonate sedimentary rocks and Alberta basin waters. The field for shale and carbonate rocks is estimated from the bedrock studies of Connolly (1990), Dufresne et al. (2001), Eccles et al. (2001) and D.R. Eccles and D.I. Pana (work in progress, 2003). The field for Alberta Basin waters is the Groups I and II basin water fields of Connolly et al. (1990).

4.2 Mantle Disequilibrium Melting

Barret and Berg (1975) suggested that assimilation of high Sr, high $^{87}Sr/^{86}Sr$, mantle-derived, highly calcitic phlogopite nodules can also produce high $^{87}Sr/^{86}Sr$ ratios, especially for apparently fresh micaceous kimberlites. The Kendu pipe has significantly higher modal phlogopite than all pipes studied, and therefore, the high phlogopite content may be coincident with Kendu having the highest initial $^{87}Sr/^{86}Sr$ ratios (0.7058 and 0.7086). ^{87}Sr isotope-enrichment might occur if mantle temperatures were not hot enough to ensure diffusional homogenization of Sr isotopic ratios between different mantle minerals (e.g., phlogopite versus perovskite). This seems unlikely because, at temperatures above 350º C, phlogopite is an open system for Sr diffusion, so radiogenic Sr will not accumulate.

4.3 Mantle Metasomatism

Another potential process that can explain the isotopic and trace element characteristics in the NAKP kimberlitic rocks is mantle metasomatism. Introduction of metasomatizing, large-ion lithophile (LIL) element-enriched, fluids from a region with long-term Rb/Sr enrichment relative to Bulk Earth (e.g., sediment recycling in a subduction zone) into a long-term depleted mantle source for a few tens of millions of years before magma generation would: 1) be insufficient time to affect the Nd isotopic signature, and 2) transfer a radiogenic Sr isotope signature to the magma.

This model may shed some light on the radiogenic Sr-isotope signature of the Birch Mountains field pipes, because whole-rock geochemical and petrographic evidence presented by Eccles and Luth (2001) and Eccles (2002) suggest that pipes in this field are composed of evolved, enriched kimberlite magma.

4.4 Assimilation by Ground and Formation Waters

Barrett and Berg (1975) reported that $^{87}Sr/^{86}Sr$ ratios in kimberlite rocks could be increased by interaction with groundwater. In northeastern Alberta, Lower Cretaceous aquifers and Quaternary-Tertiary buried channel aquifers contain between 0.1 and 54.5 ppm Sr and average 6.4 ppm Sr (n = 42; calculation from mg/L to ppm assumes a water density of 1 kg/L) with $^{87}Sr/^{86}Sr$ values that generally fall within a range of 0.709 to 0.707 (Lemay, 2002). Based on these values, the same argument used for country rock assimilation could be used; however, the exposure of crater- and diatreme-type volcaniclastic rocks to waters in a basin environment can be seen as being subject to prolonged alteration.

Furthermore, Connolly (1990) reported that stable ($\delta^{18}O$, $\delta^{13}C$) and radiogenic isotopes ($^{87}Sr/^{86}Sr$) in central Alberta indicate that meteoric waters influence limestone/dolostone, shale and authigenic carbonate cements in the Alberta Basin. These formation waters are probably related to gravity-driven meteoric waters subsequent to the Laramide Orogeny. Group I formation waters (0.7076 to 0.7129) dominate and appear to be strongly influenced by Devonian shales. Importantly, Connolly (1990) suggests that volcanic rock sources are responsible for relatively low $^{87}Sr/^{86}Sr$ ratios (0.7058) for waters and diagenetic minerals in the upper Lower and Upper Cretaceous stratigraphic units, and therefore, develop a negative-trend on the $^{87}Sr/^{86}Sr$ versus 1/Sr plot (Figure 3). If this negative trend is extrapolated into lower $^{87}Sr/^{86}Sr$ and higher 1/Sr space on Figure 3, then there is clearly a scattering or triangular pattern developed in conjunction with the NAKP kimberlitic rocks that would attest to their lack of association with the basin brines.

Crater- and diatreme-type volcaniclastic rocks in the NAKP may be particularly susceptible to influx by waters. Because these pipes are partially to totally altered to serpentine, and serpentinization is partly attributed to meteoric water circulation, the influence of ground and meteoric waters seems likely, although its exact influence on the NAKP volcaniclastic rocks is unknown at this time.

In summary, it is likely the majority of the NAKP kimberlitic rocks analyzed in this study have radiogenic Sr isotopic ratios influenced by some form of contamination. The most likely agent for whole-rock radiogenic ^{87}Sr contamination of the northern Alberta kimberlitic rocks is modal metasomatism or formation/meteoric water. It is still important to recognize, however, that good correlations exist between $\in Nd$ and Pb-isotopes (Figures 1 and 2). This observation, in conjunction with enriched incompatible elements and low C.I., suggests the isotopic content of the NAKP kimberlitic rocks can still be used to make relevant observations on the mantle source characteristics in northern Alberta.

5 Whole-Rock Isotopic Tracing

Radiogenic Sr and Pb, and Nd whole-rock isotopic compositions of the NAKP rocks relative to mid-ocean ridge basalt (MORB) indicate the sources of these components have had long and complex histories. On the Nd-Sr plot, NAKP rocks plot within or between the fields previously defined for Groups I and II South African kimberlite.

With respect to Bulk Earth, samples from the K6 kimberlite may be the most primitive and are characterized by low $^{87}Sr/^{86}Sr$ (0.70400 to 0.70423) and positive $\in Nd$ (+2.5 to +2.7) plotting within the field for South African Group I kimberlites (Figure 1). The K6 pipe has slightly more radiogenic Pb isotope compositions (19.41 to 19.53 $^{206}Pb/^{204}Pb$ and 39.68 to 39.88 $^{208}Pb/^{204}Pb$) compared to Group I kimberlite (Figure 2). The Legend and Phoenix pipes have similar $\in Nd$ (+0.0 to +1.8), but more radiogenic initial $^{87}Sr/^{86}Sr$ compositions (0.70508 to 0.70628) and Pb isotope ratios (e.g., 40.24 to 41.06 $^{208}Pb/^{204}Pb$) in comparison to the K6 pipe and the field for Group I kimberlite. The Legend and Phoenix pipes could, therefore, be derived from an enriched reservoir in comparison to the K6 pipe.

The K4 and Kendu pipes have higher $^{87}Sr/^{86}Sr$ (0.70778 to 0.70879) and lower $\in Nd$ (-4.0 to –6.3) than Bulk Earth and plot within the enriched, bottom right quadrant of the Nd-Sr diagram (Figure 1). In contrast to $^{87}Sr/^{86}Sr$, the K4 and Kendu pipes are characterized by less radiogenic Pb-isotope ratios in comparison to the K6, Legend and Phoenix pipes (Figure 1). Analyses from the K4 pipe plot within or near to the Pb-isotopic composition of Group I kimberlite, and Kendu plots closer to the Group II kimberlite and Wyoming craton fields. These results suggest, therefore, that the Kendu and possibly K4 pipes contain at least some contribution from an old source region enriched in Rb/Sr and light rare-earth element (LREE) (low U/Pb and Sm/Nd) material, which most observers would place within the lithosphere, be it subcontinental mantle or the continental crust.

6 Description of Mineral Separates Selected for Dating

Nine perovskite samples and four rutile samples were selected from four different pipes (K6, Legend, Phoenix and Kendu) for U-Pb analysis. The location and description of the samples are presented in Table 3.

Four phlogopite samples were selected from the Phoenix and Kendu pipes for Rb-Sr analysis. The location and description of the samples are presented in Table 3.

6.1 Perovskite and Rutile

Perovskite is present as pinkish-brown, subhedral, rounded crystals. Of the pipes sampled in this study, the Phoenix pipe contained the best perovskite in terms of abundance, size and preservation. The perovskite grains typically occur as isolated grains, but also occur as mantles on xenocrystic ilmenite. The size of perovskite crystals varies appreciably between pipes. In kimberlite K6, perovskite occurs as very small (typically <3 μm), rounded crystals that, in places, dominant the opaque mineral suite. In the Phoenix pipe, abundant (up to 5 vol. %), unusually large perovskite averages 0.8 mm and is up to 0.12 mm in diameter. The perovskite in the Phoenix pipe is large enough for it to survive alteration, but the very small perovskite crystals in the K6 and Kendu pipes may be altered possibly to a titanium dioxide (TiO_2) phase (e.g., rutile, anatase or ilmenite). Mineral separates of perovskite from the Phoenix pipe are coated by a whitish, carbonate-rich alteration material that, when combined with ilmenite, have a salt-and-pepper appearance. Fresh rutile and highly altered ‘perovskite-like’ grains were picked from the Kendu pipe. The Kendu rutile is characterized by two different morphological and colour populations: dark brown to black subhedral grains and amber to light orange angular fragments. The rutile was selected on the supposition that the U-Pb system in mantle rutile is reset while at temperatures of approximately 1200º C, and therefore, may provide a robust age for Kendu pipe emplacement.

6.2 Phlogopite Rb-Sr

Phlogopite is a minor constituent of the K4 and K6 pipes, generally forming <3 vol. % of the mineral assemblage with macrocrysts up to 10 mm in length and normally quite dispersed. The modal amount of phlogopite in the Birch Mountain pipes varies from nonexistent (Legend pipe) to moderate (up to 8 vol. % in the Phoenix pipe) to high with autoliths of up to 40 vol. % (Kendu pipe). Because of a limited amount of sample material from the Buffalo Head Hills pipes, phlogopite in this study was limited to the Phoenix and Kendu pipes.

In thin section, phlogopite typically occurs as subhedral to euhedral laths that range in length from 0.05 to 0.1 mm and have a length/breadth ratio of 2.5 to 3.5. With the exception of the Kendu pipe, phlogopite grains are typically randomly oriented and isolated. The phlogopite is partially altered and its idiomorphic character slightly modified by varied degrees of corroded margins. This may be related to the late-stage development of the phlogopite or alteration, which when present, occurs as chlorite at the grain margins and along cleavage planes.

Table 3A. Samples selected for U-Pb perovskite and rutile isotopic analysis.

Sample number	Pipe name (general area)*	Drillhole number	Depth (m)	Easting (m)	Northing (m)	Zone	Mineral separate	Paramagnetic fraction (A)	Number of grains	Description
ABK-29-1	K6 (BHH)	Outcrop	0-outcrop	585317	6308651	11	Perovskite?	0.4	35	Dark black, irregular grains with whitish alteration (possibly carbonate-coating on spinels)
ABK-29-2	K6 (BHH)	Outcrop	0-outcrop	585317	6308651	11	Perovskite?	0.3	150	Very small (<10 um), cubic, black grains; some with whitish alteration
ABK-59-1	Legend (BM)	98DH-LE01	44	386200	6340600	12	Perovskite?	0.45	100	Small (<20 um), cubic, black grains; some with whitish alteration
ABK-75-1	Phoenix (BM)	98DH-PH01	105	351500	6330580	12	Perovskite	0.6	25	Large, brown, broken and 'scorched' grains; no alteration
ABK-75-2	Phoenix (BM)	98DH-PH01	105	351500	6330580	12	Perovskite	0.6	50	Smaller, cubic to sub-rounded cubic, altered perovskite (salt [Ca-rich] and pepper [ilmenite] texture)
ABK-76-1	Phoenix (BM)	98DH-PH01	130	351500	6330580	12	Perovskite	0.45	40	Fresher than ABK-75; Large, black, cubic, lustrous grains with slight whitish alteration
ABK-76-2	Phoenix (BM)	98DH-PH01	130	351500	6330580	12	Perovskite	0.45	200	Smaller, cubic to sub-rounded, brown to black cubes
ABK-76-3	Phoenix (BM)	98DH-PH01	130	351500	6330580	12	Perovskite		50	Fresher than ABK-75; Large, brown, cubic grains with slight whitish alteration
ABK-81-1	Kendu (BM)	Kendu	102	368567	6353618	12	Perovskite	0.45	67	Large, sub-rounded to rounded, brownish-black, altered
ABK-82-1	Kendu (BM)	Kendu	127.25	368567	6353618	12	Rutile	0.6	27	Brown, semi-transparent and angular
ABK82-2	Kendu (BM)	Kendu	127.25	368567	6353618	12	Rutile			Light brown-orange (amber), semi-transparent and angular
ABK82-3	Kendu (BM)	Kendu	127.25	368567	6353618	12	Rutile			Light brown-orange (amber), semi-transparent, and angular
ABK82-4	Kendu (BM)	Kendu	127.25	368567	6353618	12	Rutile			Brown, semi-transparent and angular

Table 3B. Samples selected for Rb-Sr phlogopite isotopic analysis.

Sample number	Pipe name (general area)*	drillhole number	Depth (m)	Easting (m)	Northing (m)	Zone	Mineral separate	Description
ABK-75-1	Phoenix (BM)	98DH-PH01	105	351500	6330580	12	Phlogopite	Single, subhedral macrocrysts; sulphide and apatite inclusions
ABK-76-1	Phoenix (BM)	98DH-PH01	130	351500	6330580	12	Phlogopite	Single, subhedral macrocrysts; sulphide and apatite inclusions
ABK-81-1	Kendu (BM)	Kendu	102	368567	6353618	12	Phlogopite	Single, subhedral macrocrysts; minor chloritization
ABK-82-1	Kendu (BM)	Kendu	127.25	368567	6353618	12	Phlogopite	Single, subhedral macrocrysts; minor chloritization

* BHH – Buffalo Head Hills, north central Alberta; BM – Birch Mountains, northeastern Alberta

Zoning is typically confined to core-rim relationships; however, some zoning appears erratic or random so that a clear distinction between the core and rims is not always possible. These zoning irregularities may be due to reactions with late liquids and with local micro-environments that may have influenced the nature and extent of the reactions. No sieve-textured phlogopite mica is present. Inclusions of sulphide (pyrite) and apatite in phlogopite from the Phoenix pipe necessitated the need for a longer leach time to remove contaminants.

7 Emplacement Age Results

The results of isotopic analysis on mineral separates from this study are presented in Table 4. Of the 18 samples from four pipes (K6, Legend, Phoenix and Kendu) analyzed by U-Pb perovskite, U-Pb rutile or Rb-Sr phlogopite, only three U-Pb perovskite ages from the Phoenix pipe and one U-Pb rutile sample from Kendu yielded robust model ages (Table 4; Figure 4b).

Samples ABK76-1, ABK76-2 and ABK76-3 had acceptable U-Pb perovskite emplacement age $^{206}Pb/^{238}U$ dates of 77.1±1.1, 77.7±1.3 and 77.6±1.1 Ma (2σ level), respectively. Thus, a weighted average $^{206}Pb/^{238}U$ date of 77.6±1.1 Ma is recommended for the emplacement age for this sample from the Phoenix pipe.

The two morphologically different rutile ages have acceptable $^{238}U/^{204}Pb$ ratios (between 3000 and 7800), but initial $^{206}U/^{204}U$ ratios are too low, and hence, an exact emplacement age is not included in this report. The date interpreted as the current best estimate for the emplacement age of the Kendu pipe is from rutile sample ABK82-1b, which yielded a $^{206}Pb/^{238}U$ date of 79.4±1.6 Ma (2 sigma), with a proviso that it may be an upper age limit. Other Kendu rutile analysis yielded older U-Pb isotope ages (up to 93.0±0.3 Ma for sample ABK82-1; Figure 4c), and therefore, we cannot eliminate the possibility there may be an 'older' rutile component to the Kendu pipe.

The Rb and Sr concentrations of the phlogopite, which were measured relative to initial weight prior to leaching, did not yield high enough Rb/Sr ratios to be considered useful for model ages because model age calculations are quite sensitive to initial Sr composition used. The Rb concentrations are acceptable (between 170 and 383 ppm), but Sr is very high (up to 230 ppm) relative to Sr levels from successfully dated phlogopites (generally <50 ppm; R. Creaser, personal communication, 2003). In an attempt to reduce the Sr content, two samples (ABK75-RG and ABK76-RG) from the Phoenix pipe were re-analyzed after grinding the phlogopite and subjecting the pulverized phlogopite to a longer (4 hour) 0.75N HCl leach. The test did not work, as the Sr content in these samples increased, particularly for sample ABK75-RG (Table 4).

When the combined phlogopite and whole-rock isotopic data from the Phoenix and Kendu pipes are plotted on the Rb-Sr isochron diagram (Figure 5), their regression lines (mean square of weighted deviates [MSWD]) are greater than 37 700, and thus, meaningful dates using this method cannot be determined for the Phoenix and Kendu pipes. The phlogopite and whole-rock data were also plotted by sample on Figure 5. A three-point isochron for sample ABK75 yielded the 'best' model age of 69.4±0.09 Ma with an MSWD of 0.105. That is, the ABK75 phlogopite age is relatively close to the U-Pb perovskite dates of 70 and 79 Ma for the Phoenix pipe (Aravanis, 1999). As such, the use of phlogopite in determining ages for the northern Alberta pipes should be further studied.

8 Compiled Ages of Kimberlitic Pipes in Northern Alberta

Table 5 is a compilation of available northern Alberta kimberlitic pipe emplacement ages. The emplacement age of the NAKP is Late Cretaceous (Coniacian to Maastrichtian). The K5, K7A and K14 kimberlites from the Buffalo Head Hills field have reported emplacement ages of 86±3 to 88±5 Ma by U-Pb perovskite (Carlson et al., 1999; Skelton et al., 2003; Heaman et al., in press). The Birch

Table 4. Results of U-Pb perovskite, U-Pb rutile, Rb-Sr phlogopite and Sr perovskite isotopic analysis for northern Alberta kimberlitic rocks. All errors reported to 1 sigma.

Table 4A. U-Pb perovskite and rutile.											Age	Age
Sample	**Weight (mg)**	**U (ppm)**	**Th (ppm)**	**Pb (ppm)**	**Th/U**	**TCPb (pg)**	**$^{206}Pb/^{204}Pb$**	**$^{207}Pb/^{206}Pb$**	**$^{207}Pb/^{235}U$**	**$^{206}Pb/^{238}U$**	**$^{207}Pb/^{235}U$**	**$^{206}Pb/^{238}U$**
K6 - perovskite												
ABK-29-1	78	19.9	1548.3	7.5	77.87	169	27	0.0393±96	0.0779±190	0.01436±31	76.1±17.8	91.9±2.0
ABK-29-2	12	28.6	450.9	2.8	15.76	32	21	0.0455±612	0.0203±286	0.00324±130	20.4±28.1	20.8±8.3
Legend - perovskite												
ABK-59-1	13	32.9	51.4	2.1	1.57	31	27	0.0399±163	0.0494±2060	0.00897±37	48.9±19.7	57.6±2.4
Phoenix -perovskite												
ABK-75-1	432	122.5	8305.5	37.0	67.80	3405	31	0.0385±67	0.0660±115	0.01242±19	64.9±10.9	79.6±1.2
ABK-75-1	235	112.5	2987.7	19.0	26.56	1823	29	0.0344±119	0.0556±195	0.01170±26	54.9±18.3	75.0±1.6
Phoenix - perovskite												
ABK-76-1	80	122.0	2301.1	16.4	18.86	586	31	0.0378±63	0.0627±104	0.01203±18	61.7±9.9	77.1±1.1
ABK-76-2	325	119.7	2078.5	15.4	17.37	2435	31	0.0420±83	0.0702±142	0.01213±21	68.9±13.4	77.7±1.3
ABK-76-3	128	131.0	3017.6	18.5	23.04	974	32	0.0433±62	0.0724±104	0.01211±17	71.0±9.8	77.6±1.1
Kendu - rutile												
ABK-82-1 rut	334	8.8	\	0.3	\	55	67	0.0509±19	0.1019±39	0.01453±5	98.6±3.6	93.0±0.3
ABK-82-2 rut	530	9.0	\	0.3	\	104	56	0.4819±23	0.0822±39	0.01239±13	80.2±3.7	79.4±0.8
ABK-82-3 rut	441	8.4	\	0.2	\	35	131	0.0532±12	0.1057±25	0.01440±6	101.9±2.3	92.2±0.4
ABK-82-4 rut	945	8.6	\	0.3	\	166	61	0.0528±20	0.0986±37	0.01354±12	95.5±3.4	86.7±0.8

Table 4B. Rb-Sr phlogopite.									
Sample	**Rb (ppm)**	**Sr (ppm)**	**$^{87}Rb/^{86}Sr$**	**$^{87}Sr/^{86}Sr$ corrected**	**Initial $^{87}Sr/^{86}Sr$**	**+-2sm**	**T Ma (0.7025)**	**T Ma (0.705)**	**T Ma (0.710)**
Phoenix									
ABK 75 RG	381.07	230.14	4.7932	0.710495	0.705658	0.000019	117.36	80.68	7.27
ABK-75-PHL3	383.19	80.10	13.8603	0.719431	0.705446	0.000040		73.29	
ABK 76 RG	367.85	61.30	17.3882	0.719067	0.701522	0.000016	67.06	56.95	36.71
ABK76-PH1-1	378.25	67.51	16.2325	0.718192	0.701813	0.000036		57.21	
Kendu									
ABK 81 phl-1	170.06	27.56	17.8834	0.723870	0.705826	0.000016	84.10	74.27	54.60
ABK 82 phl-1	310.31	93.86	9.5778	0.718440	0.708776	0.000096	117.10	98.75	62.03

Table 4C. Sr perovskite.										
Sample	**$^{87}Sr/^{86}Sr$ corrected**	**+-2sm**								
Phoenix										
ABK-75 Perov	0.704786	0.000019								
		Robust model ages								
		Recommended model age								

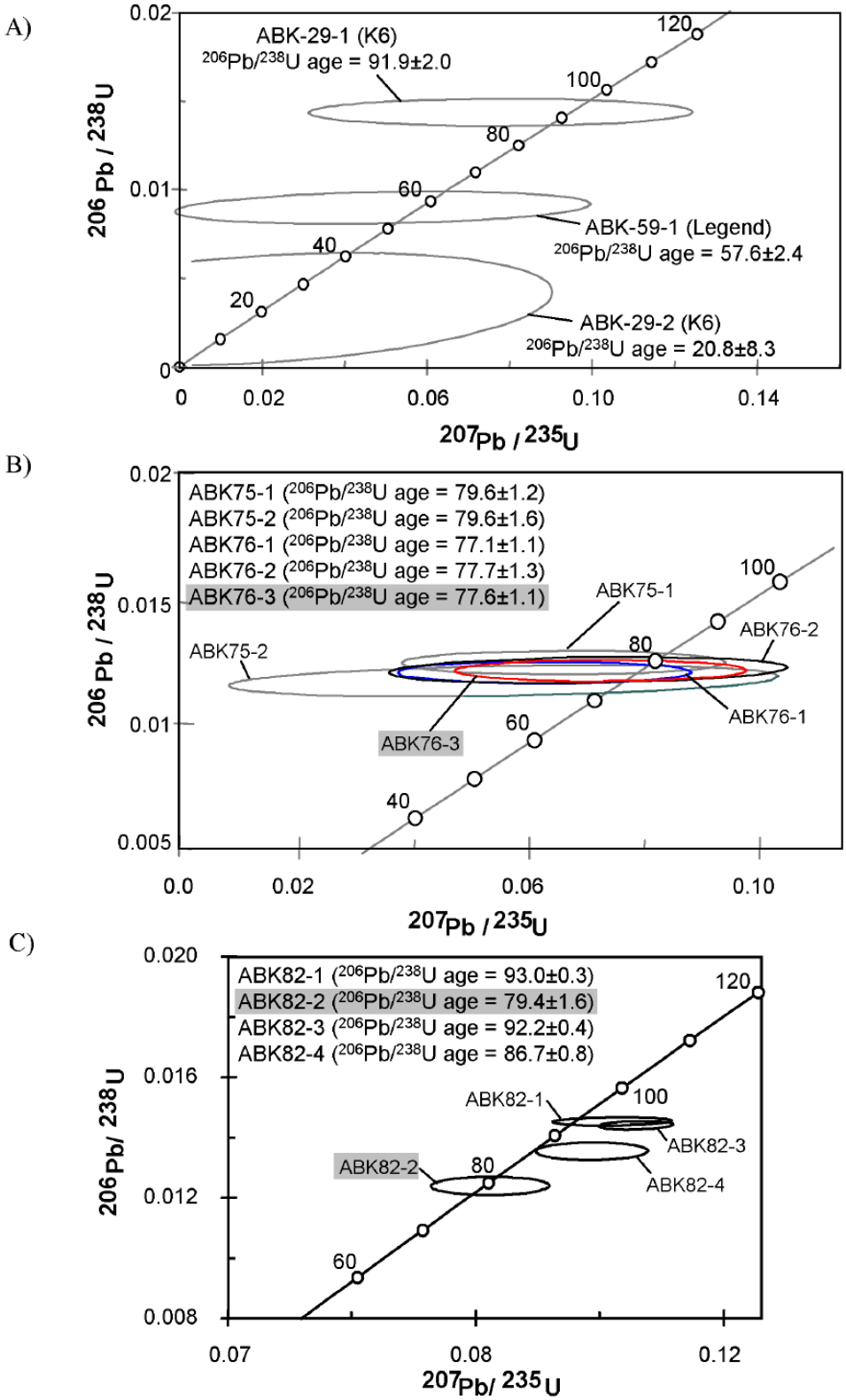

Figure 4. U-Pb concordia diagram for perovskite and rutile mineral separates from kimberlitic rocks in northern Alberta. A) perovskite from the K6 and Legend pipes; B) perovskite from the Phoenix pipe; and D) rutile from the Kendu pipe. The shaded samples are the recommended model age for Phoenix and the best estimate of the upper emplacement age for Kendu.

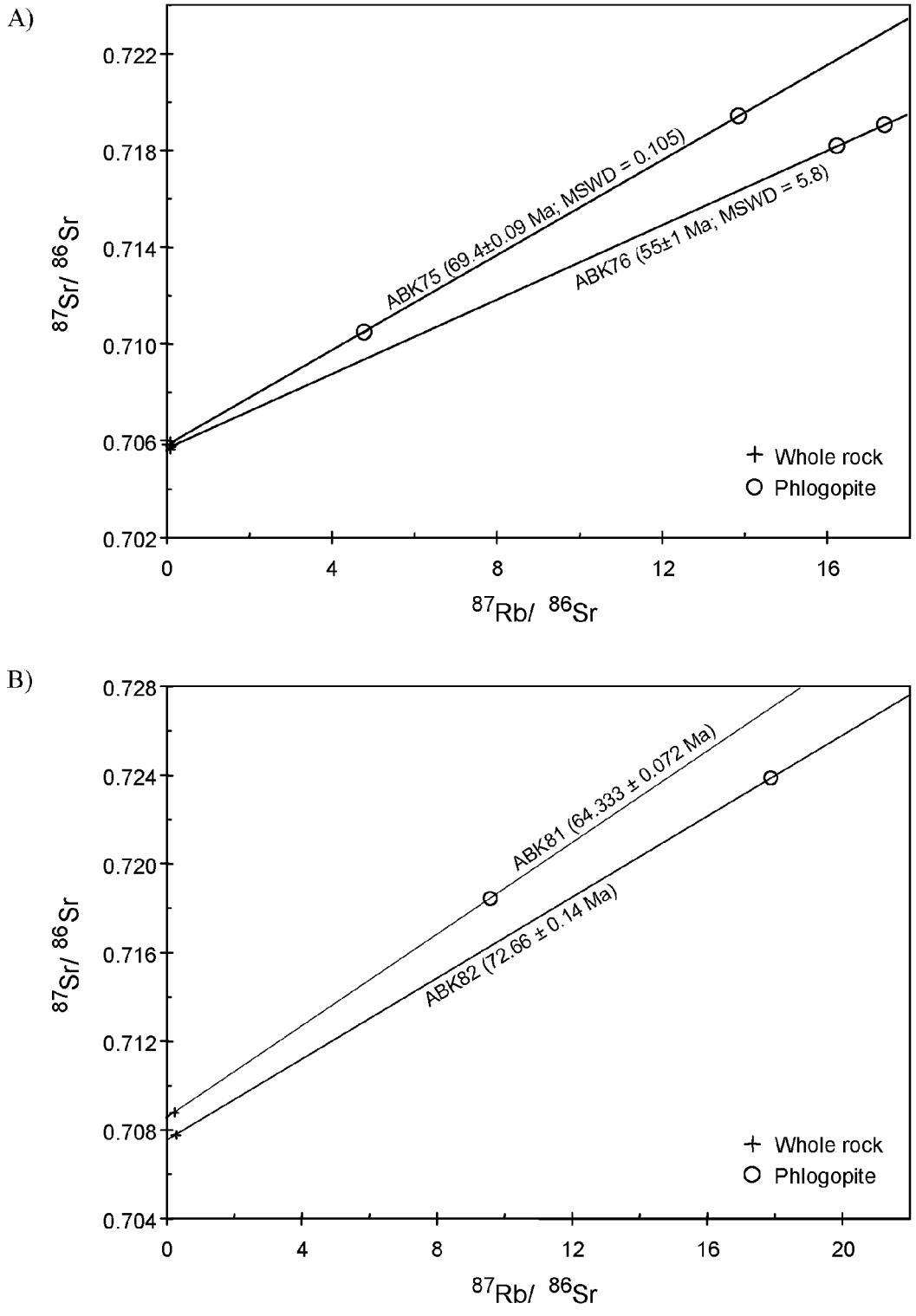

Figure 5. Rb-Sr isochron diagram for whole-rock and phlogopite macrocrysts from selected kimberlitic rocks in northern Alberta. A) three-point isochrons for samples ABK75 and ABK76 from the Phoenix pipe; and B) two-point isochrons for samples ABK81 and ABK82 from the Kendu pipe. Regression method from Ludwig (2000).

Table 5. Age compilation for northern Alberta kimberlitic rocks.

Area	Pipe	Depth (m)	Age (Ma)	Method	Reference
Mountain Lake	Mountain Lake	N/A	68	Palynology	Wood et al. (1998)
Mountain Lake	Mountain Lake North	Various depths	75 to 76	Palynology	Leckie et al. (1997)
Mountain Lake	Mountain Lake South	N/A	74±7 to 78±9	Apatite fission track (central age)	Leckie et al. (1997)
Mountain Lake	Mountain Lake North	N/A	72±7	Apatite fission track (central age)	Leckie et al. (1997)
Birch Mountain	Phoenix	113.9	70.3±1.6	U-Pb perovskite	Aravanis (1999)
Birch Mountain	Phoenix	113.9	70.9±0.4	Rb-Sr phlogopite	Aravanis (1999)
Birch Mountain	Phoenix	130.0	77.6±1.1	U-Pb perovskite	This study
Birch Mountain	Dragon	142.5	72.4±0.9	Rb-Sr phlogopite	Aravanis (1999)
Birch Mountain	Xena	157.4	72.6±2.1	Rb-Sr phlogopite	Aravanis (1999)
Birch Mountain	Valkyrie	158.2	75.8±2.7	U-Pb perovskite	Aravanis (1999)
Birch Mountain	Legend	29.8	77.6±0.8	Rb-Sr phlogopite	Aravanis (1999)
Birch Mountain	Kendu	127.3	79.4±1.6	U-Pb rutile	This study
Buffalo Head Hills	K7A	N/A	86±3	U-Pb perovskite	Skelton et al. (2003); Heaman et al. (in press)
Buffalo Head Hills	K14	N/A	88±5	U-Pb perovskite	Skelton et al. (2003); Heaman et al. (in press)
Buffalo Head Hills	K5	N/A	87±3	U-Pb perovskite	Skelton et al. (2003); Heaman et al. (in press)

N/A – Not available

Mountains pipes are younger: that is, the Phoenix, Dragon, Xena, Legend, Valkyrie and Kendu pipes have emplacement ages of 70.3±1.6 to 79.4±1.6 Ma, as determined by U-Pb perovskite/rutile and Rb-Sr phlogopite (Aravanis, 1999). The Mountain Lake pipes are similar in emplacement age to the Birch Mountains. Palynological results are consistent with emplacement ages for the Mountain Lake pipes of 76 and 68 Ma from *in situ* laminated sediments (Leckie et al., 1997) and from nonmarine sedimentary clasts (Wood et al., 1998), respectively.

9 Conclusions

Northern Alberta kimberlitic rocks analyzed in this study have whole-rock radiogenic Sr isotopic ratios influenced by contamination, most likely by modal metasomatism or interaction with formation/meteoric waters. Good correlations between $\in$Nd, $^{87}Sr/^{86}Sr$ and Pb-isotopes, in conjunction with enriched incompatible elements and low C.I., suggest the isotopic content of the NAKP kimberlitic rocks can still be used to make relevant observations on mantle source characteristics beneath northern Alberta.

In Nd-Sr space, the K6 pipe (Buffalo Head Hills) is representative of melts derived from a depleted mantle and plot in the field for South African Group I kimberlites. The Phoenix and Legend pipes (Birch Mountains) have similar $\in$Nd, but more radiogenic $^{87}Sr/^{86}Sr$, possibly related to their evolved nature. The K4 (Buffalo Head Hills) and Kendu (Birch Mountains) pipes contain lower $\in$Nd, higher $^{87}Sr/^{86}Sr$, and less radiogenic Pb ratios and, therefore, contain at least some contribution from an old mantle source region enriched in Rb/Sr and LREE (low U/Pb and Sm/Nd) material, crustal contamination, or both.

The majority of the samples did not yield robust emplacement ages. The limited success of emplacement dating is attributed to

- the lack of rock available from the Buffalo Head Hills for mineral processing and minerals separation;
- not having the right mineral constituents available in the rock, or in the case of perovskite, the mineral being too small to properly identify; and/or
- alteration problems associated with the mineral separates (e.g., incipient chloritization of phlogopite macrocrysts).

Isotopic analysis of mineral separates in this study provided two new emplacement ages for the Phoenix and Kendu pipes in the Birch Mountains kimberlite field. An emplacement age for the Phoenix pipe by perovskite U-Pb is 77.6±1.1 Ma. This date is older than previously reported ages of 70.3±1.6 and 70.9±0.4 Ma by U-Pb perovskite and Rb-Sr phlogopite, respectively (Aravanis, 1999). This is possibly the result of separate eruption events, which have subsequently mixed in the crater environment. The best estimate emplacement age for the Kendu pipe, which has not previously been dated, is 79.4±1.6 Ma by U-Pb rutile. Because the initial $^{206}U/^{204}U$ ratios are too low in Kendu rutile, an exact emplacement age is not included in this report, and this age should be considered as an upper limit emplacement age.

10 References

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