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Isotopic characteristics of mantle sources for Quaternary continental alkaline magmas in the northern Canadian Cordillera

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Abstract

Three mantle compositions are identified as potential source end members for Quaternary to recent alkaline volcanic rocks from Fort Selkirk, Llangorse–Hirschfeld, Alligator Lake and Mt. Edziza in the northern Canadian Cordillera. These are: (1) an amphibole-rich source, characterised by unradiogenic Sr, Nd and Pb, from which the olivine nephelinite lavas formed, (2) the continental lithospheric mantle which is characterised by high $^{207}Pb/^{204}Pb$ and appears to be involved in the formation of the alkali olivine basalts of Fort Selkirk, and (3) a mantle with radiogenic Pb and unradiogenic Sr (HIMU-type) represented by lavas from Mt. Edziza.

The Mt. Edziza volcano is the largest of the volcanic centres in the region, and is considered to reflect melting of sublithospheric mantle of HIMU composition below central British Columbia. Incipient melting of amphibole-veined subcontinental mantle lithosphere resulted from plume upwelling and/or transtensional pressure release and produced the small nephelinite to olivine basalt centres of the northern Cordilleran Province. The source of the nephelinite magmas is slightly more radiogenic than present-day Pacific MORB, and is best represented by the most depleted component of the Aleutian magmas. This suggests enrichment of the subcontinental lithosphere in the northern Cordillera by melts of this isotopic composition during Cretaceous subduction.

The Alligator Lake complex is anomalous and characterised by the most radiogenic lavas. Despite the presence of crustal xenoliths there is no clear geochemical signature for crustal contamination and, in contrast to the other volcanic centres which were erupted through the Intermontain Belt, the lavas of this centre may have been derived from a highly radiogenic lithospheric mantle beneath the Coast Plutonic complex.

1. Introduction

Alkaline and subalkaline basalt in both continental and oceanic settings commonly occur in close association, but often their geochemical characteristics require different mantle source regions [1,2]. In oceanic settings highly alkaline magmas are erupted at the onset of construction of a volcanic island, as a capping to the subalkaline shield, and in the rejuvenation stage after shield erosion [3,4]. In this setting there is a relationship between the volume of material produced and its alkalinity as the voluminous magmatism in the shield-building phase swamps the trace element characteristics of small-degree partial melts produced upon incipient melting of asthenospheric or lithospheric mantle [1]. Upwelling mantle in continental regions produces a similar spectrum of lava compositions [4–6]. However, interaction with continental crust and

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continental lithospheric mantle may result in more extreme end-member compositions in terms of both isotopic and elemental abundances. In the continental environment the possibility of mapping volcanic complexes in three dimensions and undertaking regional studies on the subcontinental scale may contribute to a better understanding of the temporal and spatial variation in the magma source regions and reservoirs.

In this paper we present isotope and trace element data for a series of Quaternary to recent mafic centres from the Canadian Cordillera in northern British Columbia and Yukon. The largest volcanic centre in the region, Mt. Edziza, records 10 Ma of volcanism ranging from subalkaline basalt and hawaiite to alkali–olivine basalt, with minor peralkaline–felsic magmas [7]. There are numerous other smaller volcanic centres ranging in composition from highly Si-undersaturated nephelinites (normative Ne up to 25%) to Hy-normative basalts. This volcanic province extends more than 1000 km N–S and 400 km NE–SW, crossing five accreted terrane boundaries and the western limit of ancestral North America (Figs. 1 and 2).

The geochemical data indicate a complex interplay between (i) nonradiogenic but highly alkaline melts derived from partial melts of amphibole in the subcontinental lithosphere [5,6], (ii) alkali olivine basalt (AOB) closely related to the

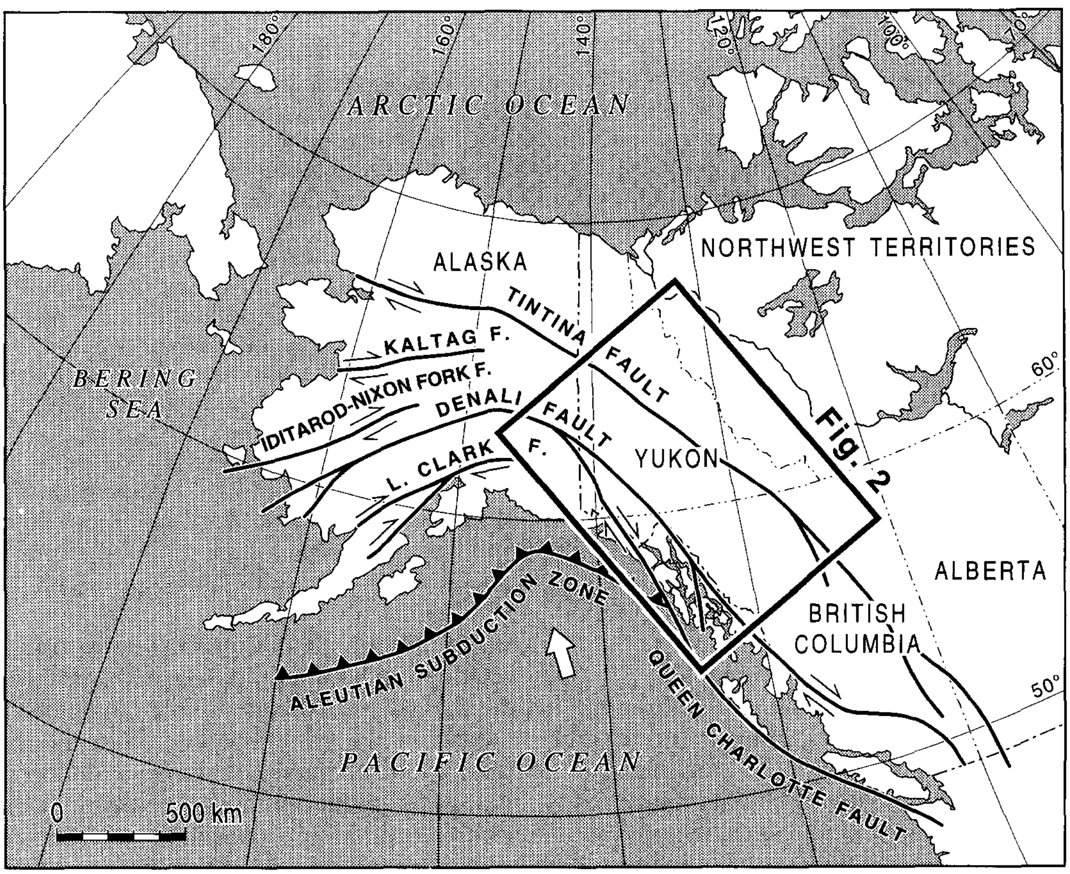

Fig. 1. Location of the study area in the Canadian Cordillera, showing the position of the present subduction zone and major fault zones.

nephelinites, which are derived from, or have interacted with subcontinental lithosphere and/or the upwelling mantle, and (iii) magmas centered on Mt. Edziza which were derived from actively upwelling mantle with distinct Pb and Sr isotope components. Just as the alkalinity of melts in the oceanic OIB suites is reflected in the volume of erupted magma and an evolving tectonic context, in the northern Canadian Cordillera we demonstrate the effects of incipient melting of lithospheric mantle (in this case 'continental' mantle accreted during the Mesozoic–Tertiary period) in producing the olivine nephelinite (OL-NEPH)–AOB spectrum and the distinct character of the plume magmas of the Edziza complex.

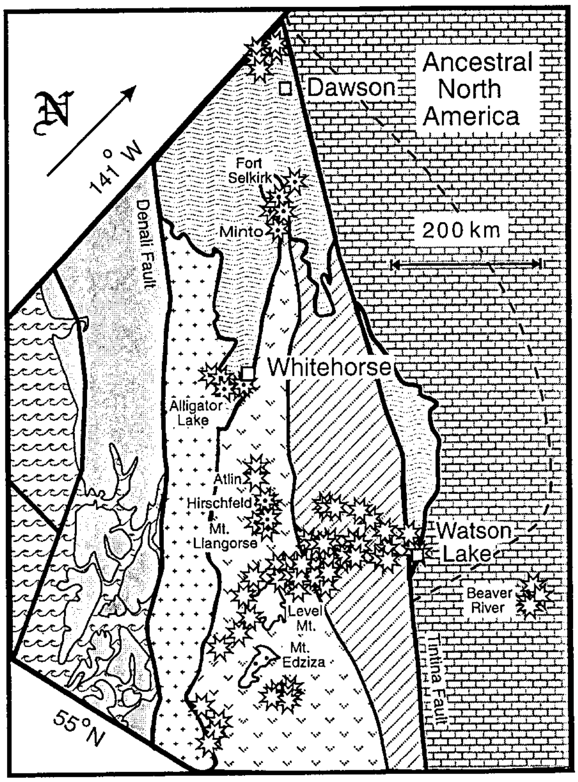

Fig. 2. Simplified map illustrating the regional geological context. Stars = Quaternary to Recent alkaline volcanic centres (dots = sampled localities). Terranes: Light grey = Insular Superterrane; plus signs = Coast Plutonic complex; V = Intermontane Belt; oblique shading = Omenica Belt; wavy lines = Yukon Crystalline Terrane; brick pattern = ancestral North America; dashed line = limit of the Omenica Belt.

2. Geological setting and geochemical characteristics of the lavas

Extension in late Tertiary to recent times resulted in a series of volcanic centres along the entire length of the North American Cordillera reflecting a post-Mesozoic transtensional regime along most of the Cordillera (Figs. 1 and 2). Recent tectonic extension and associated volcanism in the southern Canadian Cordillera and the U.S. is largely a consequence of the North American plate overriding the extensional ridge axis, while that in the northern Canadian Cordillera appears to reflect transtension associated with major dextral transcurrent displacements [8].

In northern British Columbia the Stikine volcanic belt comprises the two large shield complexes of Mt. Edziza and Level Mountain [7,9] and a series of small volcanic centres [5,6,10] extending northward from the Mt. Edziza complex to the Yukon–Alaska border and northeast over the ancestral North American craton (Fig. 2). In this paper, we present isotopic data from the Mt. Edziza, Hirschfeld, Llangorse and Fort Selkirk centres, which lie in the Intermontane Belt, and for the Alligator Lake centre which erupted through the Coast Plutonic complex (Figs. 1 and 2). Samples selected for isotopic analyses cover the entire spectrum of mafic magmas for each centre (Fig. 3). The main characteristics of each centre are summarised below:

(i) *Mt. Edziza*: The Mt. Edziza complex is the largest centre, and has been described in detail by Souther [7] and Souther et al. [11]. The volcanic activity spans approximately 10 Ma and is characterised by the eruption of AOB, Hy-normative basalt and hawaiites, with minor differentated rocks of trachytic and mildly peralkaline rhyolite and Si-undersaturated phonolite composition. Hawaiitic lavas form the base of the volcanic shield [12], and are overlain by the thin mafic Hy-normative flows of the Armadillo Formation. The final eruptive stage of Mt. Edziza (Big Raven Formation) is characterised by AOB.

(ii) *Alligator Lake*: This complex has been described by Eiché et al. [10]. It comprises 0.5 km^3 of lavas of basanite to quartz-normative (QZ-NORM) basalt composition, which have erupted as lavas of differing trace element abundances from two distinct vents. The complex is located 30 km southwest of Whitehorse, close to a major terrane boundary (Figs. 1 and 2), and overlies Cretaceous granites of the Coast Plutonic complex. Both granite and spinel lherzolite xenoliths are found within the lavas of the complex. The granitic xenoliths are alkali-feldspar granites and monzogranites and display granophyric textures as well as a number of features indicative of disequilibrium and partial melting [10]. The spinel lherzolite xenoliths range in composition from fertile lherzolite to refractory harburgite and most likely represent samples of the continental lithospheric mantle under the Yukon [13,14]. At Alligator Lake, QZ-NORM lavas occur near the top of the volcanic stratigraphy, while the most Si-undersaturated lavas are basanite with less than 15% normative Ne and occur near the base of the succession.

(iii) *Hirschfeld–Llangorse region*: Several volcanic centres occur as necks and lavas in a region located close to the Yukon–British Columbia border (Fig. 2). A spectrum from OL-NEPH to AOB (most of this spectum bears spinel lherzolite xenoliths) characterises these centres. The Hirschfeld centre is a 0.5 km wide plug which displays a spectacular outward zonation from AOB to OL-NEPH, and is the focus of a model for the origin of alkaline series lavas developed by Francis and Ludden [6].

(iv) *Fort Selkirk region*: This region was described by Francis and Ludden [5]. OL-NEPH (up to 25% normative Ne, Table 2) erupted from three separate vents. The lavas from each vent become less Si-undersaturated with time, but the youngest flows have an OL-NEPH composition. Valley-filling AOB flows in the Pelly River region separate the vents, and grade from basanite to Hy-normative basalt. These lavas erupted from the same vent that later erupted OL-NEPH at Volcano Mountain. The Minto Landing centre to the south of the Fort Selkirk (Fig. 2) has not been described in detail, but consists of four small volcanic necks ranging from basanite to OL-NEPH.

The range of compositions studied is shown in the alkali–silica diagram (Fig. 3) and in terms of Nb/Zr in Fig. 5. The most Ne-rich magmas were erupted in the Volcano Mountain and the Hirch-

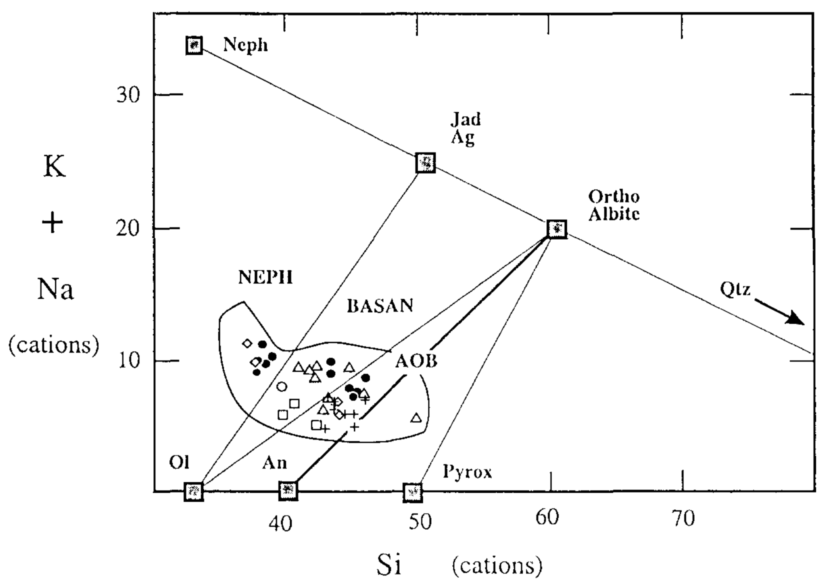

Fig. 3. Alkali–silica diagram showing the range of compositions for the samples analysed for their isotopic compositions. The fields delimit the composition of all the Quaternary centres in Yukon and northern British Colombia [5,6,10] [unpublished data]. ● = Fort Selkirk; ○ = Minto Landing; ◇ = Hirschfeld; □ = Llangorse; △ = Alligator Lake; + = Mt.Edziza.

Table 1
Pb, Sr and Nd isotopic ratios of all alkali basalt samples

LOCALITY	SAMPLE	LEGEND	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	87Sr/86Sr	143Nd/144Nd
FORT SELKIRK	PY-6	AOB	18.939	15.603	38.480	0.70331	0.51307
	PY-10	AOB				0.70333	0.51302
	PY-16	AOB	19.060	15.603	38.568	0.70337	
	PY-34	AOB	19.119	15.588	38.622		
	W-2	BASAN				0.70308	0.51308
	FS-153	BASAN	18.792	15.520	38.125	0.70314	
	VM-5	OL-NEPH	18.763	15.524	38.143	0.70296	0.51312
	VM-6	OL-NEPH	18.770	15.517	38.134	0.70296	0.51311
	VM-14	OL-NEPH	18.752	15.490	38.076	0.70301	0.51311
	GR-14	OL-NEPH	18.796	15.522	38.080		
	DF-40	OL-NEPH	18.791	15.517	38.050	0.70301	0.51230
MINTO LANDING	MI-10	BASAN	19.035	15.544	38.471	0.70286	0.51302
HIRSCHFELD	HF-3	OL-NEPH	18.818	15.496	38.113	0.70292	0.51300
	HF-5	Hy-NORM	19.001	15.545	38.368	0.70305	
	HF-11	OL-NEPH	18.838	15.525	38.171		
	HF-50	AOB	19.047	15.577	38.478		
LLANGORSE	LG-7	AOB	19.066	15.553	38.408	0.70309	
	LG-2	BASAN				0.70295	0.51300
	LG-5	BASAN	18.914	15.530	38.262		0.51302
ALLIGATOR	AL-119	BASAN	18.862	15.538	38.269	0.70396	0.51292
LAKE	AL-140	BASAN	18.908	15.561	38.400	0.70392	
	AL-143	BASAN				0.70392	0.51295
	AL-163	BASAN	18.977	15.581	38.489		
	AL-244	BASAN	18.816	15.544	38.269		
	AL-171	AOB	18.926	15.573	38.436	0.70386	
	AL-187	AOB				0.70392	0.51293
	AL-199	AOB	18.925	15.553	38.385	0.70388	
	AL-183	Hy-NORM	19.023	15.565	38.388		
	AL-208	Qz-NORM	18.988	15.587	38.509	0.70396	0.51299
	AL-105	granitoid XE.	19.269	15.636	38.867	0.70325	
MT.EDZIZA	EZ-3	Hy-NORM	19.339	15.570	38.680	0.70306	0.51307
	EZ-23	Hy-NORM	19.175	15.556	38.562	0.70293	
	EZ-20	AOB	19.289	15.596	38.669	0.70314	
	EZ-32b	Hy-NORM	19.272	15.532	38.525	0.70276	0.51301
	EZ-34	Hy-NORM				0.70297	0.51299
	EZ-37	Hy-NORM	19.200	15.534	38.516	0.70284	0.51294
	EZ-39	AOB	19.341	15.594	38.694	0.70289	0.51296
	ML-38	Hy-NORM	19.270	15.571	38.666	0.70335	
	SE-44	Hy-NORM	19.259	15.547	38.589	0.70291	0.51299

AOB = alkali-olivine basalt; Hy-NORM = hypersthene-normative; BASAN = basanite; OL-NEPH = olivine-nephelinite; Qz-NORM = quartz-normative; XE = xenolith. Pb was purified following the technique of [35] and analysed by TIMS. A fractionation correction of 0.09%/amu was applied to the measured Pb ratios as determined by repeated measurements of the NBS SRM 981 standard. The 2σ incertainties are 0.2, 0.3 and 0.4% for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ respectively. Sr and Nd were purified following the technique of [36]. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ uncertainties are ± 0.00005 and ± 0.00003 respectively. Total blanks are 60 pg for Pb, 200 pg for Sr and 400 pg for Nd, and negligable in all cases.

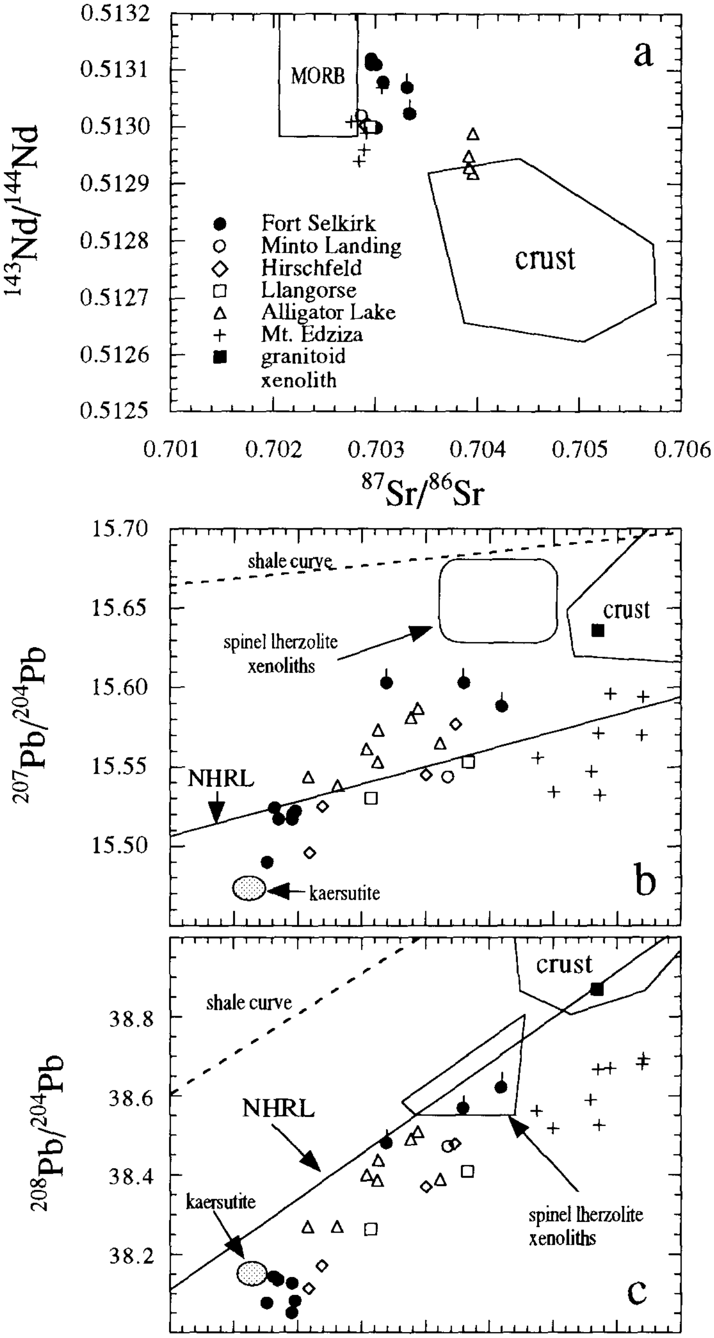

Fig. 4. (a) $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram showing the alkali basalt data compared with the field for MORB and present-day composition of crust [15]. (b–d) $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagrams in which the data are compared to the composition of spinel lherzolite and granitoid xenoliths hosted by the Alligator Lake basalts [13], crust [17–19], kaersutite megacrysts from Nunivak Island [16], the Northern Hemisphere Reference Line (NHRL [20]) and the shale Pb evolution curve for the Canadian Cordillera [21]. Ticked dots = Pelly valley-filling lavas.

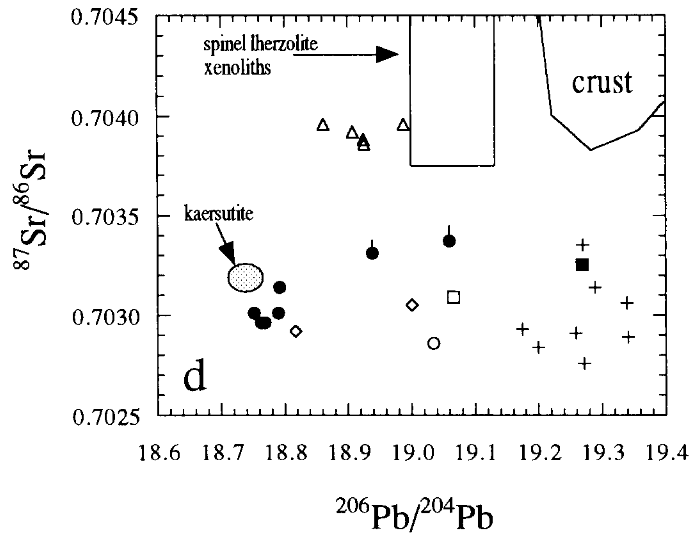

Fig. 4 (continued).

feld–Llangorse region. All centres comprise AOB, while the larger centres also have hawaiite and minor felsic end members. The centres exhibit a range from a low Nb/Zr end member characterised by the Mt. Edziza complex towards two high Nb/Zr end members [6], one characterised by the Minto complex and including the Alligator Lake complex, and the other characterised by the most Si-undersaturated lavas of Fort Selkirk and the Llangorse field.

Francis and Ludden [5,6] interpret the petrogenesis of these lavas in terms of residual mantle amphibole for the most Si-undersaturated lavas and melting of a lherzolite component for the AOB and Hy-normative magmas; crustal contamination is considered to have played an insignificant role in the petrogenesis of the mafic lavas. In this paper, we evaluate the petrogenesis of lavas from these volcanic centres using an isotopic database of 33 samples spanning the OL-NEPH to olivine basalt spectrum.

3. Isotope results

Pb, Sr and Nd isotopic compositions for all the volcanic rocks and a granitoid xenolith are presented in Table 1 and Fig. 4. Selected trace element data, MgO and normative values are presented in Table 2. Complete geochemical data are available on request, some of which are also given in Francis and Ludden [5,6]. The analytical conditions for the isotope determinations are given in Table 1 and for the trace element determinations in Francis and Ludden [6] and in Table 2.

Fig. 4a displays the isotope results in a $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram in which fields for MORB and for Phanerozoic lithologies from the Alexander (Insular Superterrane) and Stikine terranes (Intermontain Belt) [15] have been plotted for comparison. The isotopic composition of these two terranes overlap and their radiogenic character, as seen in Fig. 4a, most likely represents the mean composition of the crust through which the Quaternary alkaline basalts erupted. Most of the lavas analysed fall between the MORB and the crustal fields but do not define a single trend in the diagram and thus require more than two sources. A trend towards a low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ end member is defined by lavas from the Mt. Edziza complex, but includes some lavas from the other centres. The most Si-undersaturated lavas always have the least radiogenic compositions (high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$) and plot close

Table 2
Foid, hyper and MgO (%) and selected trace element (ppm) abundances for alkali basalt samples analysed for isotope composition

LOCALITY	SAMPLE	Foid	Hyper	MgO	Rb	Sr	Th	U	Nb	Zr	La	Nd	Sm
FORT SELKIRK	PY-6	3.33		8.9	24	614	2.8	0.8	38	167	23.3	20.5	5.8
	PY-10	0.73		9.9	22	549	2.7	0.8	34	158	19.8	18.2	5.5
	PY-16	0.18		9.7	22	545	2.3	0.8	33	158	19.6	17.7	5.4
	PY-34	2.40		5.6	27	735			42	196	22.5	22.6	6.2
	W-2	7.18		9.4	22	924	4.1	1.4	65	258	35.6	34.0	8.3
	FS-153	10.48		8.8	22	944	4.4	1.0	65	242	38.5	30.0	8.5
	VM-5	25.08		11.5	22	1345	6.6	2.1	88	337	64.2	47.9	11.5
	VM-6	19.66		14.0	20	1111	5.5	1.8	73	285	52.6	40.6	10.1
	VM-14	20.38		11.9	22	1140	5.4	2.2	75	289	52.3	40.8	10.5
	GR-14	25.46		12.5	28	869	5.9	2.1	89	321	53.2	46.0	11.1
	DF-40	20.35		11.9	13	1395	8.9	2.6	105	427	76.5	67.0	14.9
MINTO LANDING	MI-10	14.23		9.4	51	914	6.0	1.6	71	226	52.8	36.2	8.1
HIRSCHFELD	HF-3	27.76		11.7	28	1392	7.5	1.9	76	286	74.6	54.7	12.5
	HF-5		2.72	10.3	17	558	2.4	0.8	26	150	20.3	20.0	5.0
	HF-11	34.78		10.9	30	1409	7.7	2.1	88	293	80.5	62.0	14.2
LLANGORSE	LG-7	1.39		11.3	17	597	2.7	0.8	29	165	24.5	21.9	5.7
	LG-2	8.57		10.2	27	689	3.0	0.9	39	199	29.6	25.5	6.5
	LG-5	7.39		13.3	16	1988	5.6	1.7	57	271	57.7	43.1	9.9
ALLIGATOR	AL-119	5.81		6.5	41	1040	2.7		42	174	34.1	26.1	7.0
LAKE	AL-140	11.43		10.6	59	951			44	176			
	AL-143	12.14		13.2	50	1028	4.0		48	177	40.2	30.4	7.6
	AL-163	9.70		11.3	55	996	4.0		47	187	39.7	29.9	7.7
	AL-244	9.26		7.8	42	811	3.3		43	164	30.7	26.1	7.0
	AL-171	3.66		11.5			2.4				24.3	18.8	5.5
	AL-187	4.44		11.0	32	592	2.3		30	124	21.3	17.7	5.3
	AL-199	2.98		14.4									
	AL-183		2.29	6.8	23	667	1.4			167	20.4	20.1	5.8
	AL-208		20.72	6.8	24	304	1.0		18	83	9.4	7.9	2.7
	AL-105				133	37	16.2		19	237	32.8	21.8	5.8
MT.EDZIZA	EZ-3		9.60	7.1	11	505	1.1	0.3	19	166	17.4	19.3	5.7
	EZ-23		1.30	5.4	13	571	1.5	0.4	30	176	21.9	25.0	7.1
	EZ-20	0.63		4.5	19	606	1.6	0.4	30	254	26.9	29.4	8.2
	EZ-32b		18.05	6.5	4	376	1.1	0.2	18	144	13.7	15.1	5.1
	EZ-37		7.89	6.6	11	460	1.1	0.3	26	177	18.4	19.7	5.9
	EZ-39	2.18		8.6	21	548	2.8	0.6	34	220	25.6	22.6	6.5
	ML-38		6.01	12.1	11	422	1.7	0.4	22	144	16.7	18.0	4.8
	SE-44		4.69		21	475			33	172			

Foid and Hyper = normative feldspathoids and hypersthene respectively, calculated in oxygen units assuming $Fe^{3+}/Fe_{tot} = 0.15$. Mg, Rb, Sr, Zr and Nb were analysed by XRF with uncertainties better than 5% (Mg < 1%). Other trace elements were analysed by INNA with uncertainties better than 5% for La, Nd and Sm and 10% for Th and U.

to MORB whereas lavas from the Alligator Lake complex fall close to, or within, the crustal field.

Diverse source reservoirs for the lavas are also supported by their Pb isotopic compositions (Figs. 4b and c). In addition to the results from the Quaternary centres, the isotopic compositions of spinel lherzolite xenoliths from Alligator Lake [13], kaersutite megacrysts from Nunivak Island

(Alaska) [16], various Phanerozoic lithologies from Alaska, Yukon and northern British Colombia [17–19], the Northern Hemisphere Reference Line (NHRL [20]) and the shale Pb evolution curve for the Canadian Cordillera [21] are shown for comparison. All of the lavas studied have Pb isotopic ratios that fall close to the NHRL and display lower $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than the mean composition of shales from the Canadian Cordillera (Figs. 4b and c). The nephelinites define the least radiogenic compositions and are similar to a kaersutite megacryst from Nunivak Island. Basanites and AOB are generally more radiogenic than the nephelinites (e.g., Fort Selkirk

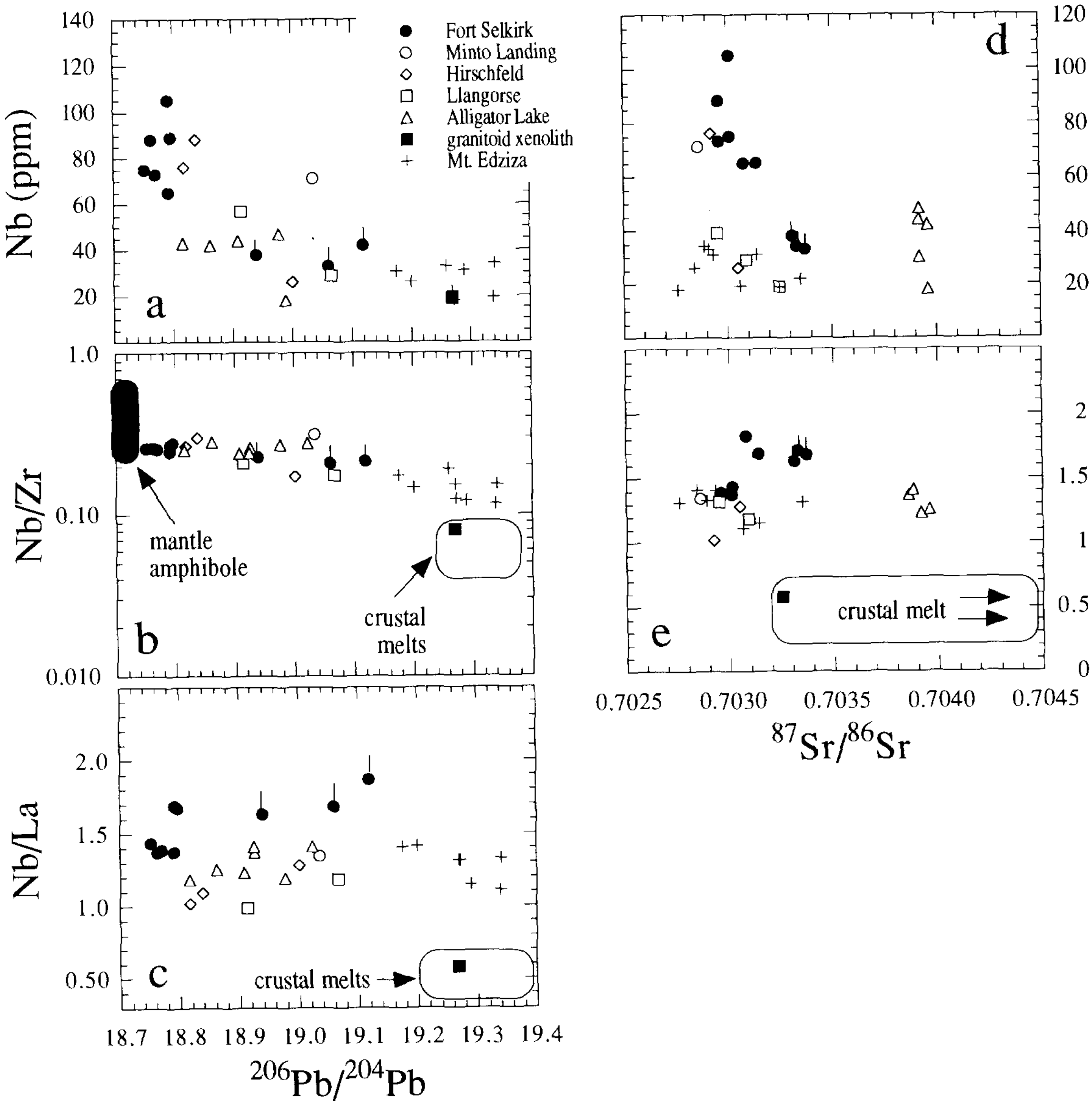

Fig. 5. Diagrams showing relationships between trace elements (Nb, Zr and La) and Pb and Sr isotopic compositions for all the lavas. The field for crustal melts is defined from the composition of granitoids in the area [10,17–19,38], and for mantle amphibole from [16,22].

and Hirschfeld). Mt. Edziza lavas define distinct Pb isotope values and have higher $^{206}Pb/^{204}Pb$ (19.18–19.34) at equivalent values of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than any of the other volcanic complexes. A granitic xenolith from Alligator Lake falls within the crustal field in both Figs. 4b and c. The spinel lherzolite xenoliths from Alligator Lake have a significantly higher $^{207}Pb/^{204}Pb$ than volcanic rocks with comparable $^{206}Pb/^{204}Pb$.

There is no systematic variation of $^{87}Sr/^{86}Sr$ with $^{206}Pb/^{204}Pb$ (Fig. 4d). The nephelinite lavas form a distinct population with unradiogenic values similar to kaersutite from the Nunivak Island. The Mt. Edziza samples also show low $^{87}Sr/^{86}Sr$ but have high $^{206}Pb/^{204}Pb$. The Alligator Lake lavas define a third pole characterised by intermediate $^{206}Pb/^{204}Pb$ and high $^{87}Sr/^{86}Sr$ and close to the compositional field of the spinel lherzolite xenoliths from the same centre. The granitic xenolith from Alligator Lake displays a relatively unradiogenic Sr isotopic composition compared to other crustal rocks in the area and falls in the field for Mt. Edziza lavas. The position of Alligator Lake lavas in this diagram precludes simple mixing between the OL-NEPH reservoir and the granitoid basement (represented by the granitic xenolith) as an origin for the Alligator Lake rocks. However, if the composition of the crust in the area is similar to the field shown in Fig. 4d, the radiogenic Sr isotopic character of Alligator Lake lavas compared to the other centres may result from crustal assimilation. Basanite and AOB from the remaining centres have compositions intermediate between OL-NEPH and the Mt. Edziza lavas. The lherzolitic lithosphere, as characterised by the Alligator Lake mantle xenoliths, does not appear to represent a major source reservoir except for the lavas of the Pelly sequence of Fort Selkirk, which display higher $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{204}Pb$ than that of other basanites and AOB.

4. Trace element–isotope correlations

In general, the absence of simple correlations between Sr, Nd and Pb suggests the involvement of at least three sources in the generation of the alkaline magmas in Yukon and northern British Colombia. In order to evaluate further the nature of the source reservoirs, isotope–trace element relationships have been investigated in Fig. 5, in which estimates for the composition of mantle amphibole and crustal melts are also shown.

La and Nb abundances are positively correlated for all the lavas and Nb/La is consistently greater than the chondritic ratio. The Alligator Lake granitoid xenolith falls clearly out of the volcanic trend as do estimates for crustal melts, thus precluding any significant contribution of La and Nb to the magmas from crustal reservoirs (Fig. 5). Both Nb content and Nb/Zr are negatively correlated with the $^{206}Pb/^{204}Pb$. The OL-NEPH lavas represent an end member characterised by unradiogenic Pb, high Nb and Nb/Zr (Figs. 5a and b) and also low $^{87}Sr/^{86}Sr$ (Fig. 5d); these lavas also fall close to the field of mantle amphibole [16,22]. Mt. Edziza lavas represent a low Nb and Nb/Zr end member, but with radiogenic Pb and unradiogenic Sr isotope compositions.

In terms of Nb/La vs. $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ (Figs. 5c and e), neither is there a simple mixing relationship between OL-NEPH and Mt. Edziza lavas, nor do any of the lavas show an obvious trend towards crustal compositions. In Fig. 5c, comparison of the least Si-undersaturated lavas relative to the more evolved lavas (AOBs or Hy-normative basalts) in any centre shows a trend towards higher La/Nb with increasing Si-saturation. This is especially evident for the Fort Selkirk centre (closed symbols) and also for the Alligator lake complex, despite the radiogenic character of the Nd and Sr isotopes in this centre. Thus, even for the Alligator Lake centre, evidence for a crustal component is at best ambiguous.

5. Discussion

As for most continental alkaline magma suites [2,4], the Pb, Sr and Nd isotopic compositions and their relationships with trace elements suggest that multiple magma sources and mixing processes were involved in their formation. In the northern Canadian Cordillera, however, some systematic relationships are observed and certain volcanic centres can be grouped on the basis of their trace element and isotopic compositions, permitting the distinction between lithospheric and deeper mantle sources. The Fort Selkirk, Hirschfeld and Llangorse volcanic fields display similar geochemical characteristics and may have been produced from different proportions of similar mantle sources. Although lavas from Alligator Lake display similar correlations between trace element and Pb isotopic compositions, their relatively uniform and high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ compared to the other alkali basalts in the area suggests a distinct source with respect to Sr and Nd isotopes. Similarly, the Mt. Edziza lavas are distinct in defining a subvertical trend in the $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram (Fig. 4a) and in having a relatively uniform, but radiogenic, $^{206}Pb/^{204}Pb$ ratios and plotting as an extreme Pb isotope end member. In the following sections we elaborate on these general observations for individual centres and compare the overall isotopic variation with the major isotope reservoirs of the northern Pacific region.

5.1. Fort Selkirk–Hirschfeld–Llangorse

Previous work on the Fort Selkirk volcanics led Francis and Ludden [5] to interpret their compositional spectrum as a result of mixing between melts of amphibole–garnet pyroxenite veins and partial melts of a lherzolite mantle. In a more recent re-evaluation of the trace element systematics of several OL-NEPH–AOB centres in the Yukon and a worldwide compilation of sodic alkaline magmas, Francis and Ludden [6] suggest the progressive melting of an amphibole-rich residue as the source of OL-NEPH magmas. Primitive basanite and AOB magmas are considered to result from the melting of a mantle source having variable proportions of residual amphibole. The advantage of this model is that a single source mantle intruded by amphibole-rich veins can be melted to produce the entire spectrum of lavas without resorting to extremely small degree partial melts required for alkaline magmas derived from a lherzolite mantle source [1]. Mantle xenoliths found in the volcanic centres of the northern Canadian Cordillera are surprisingly devoid of hydrous components, making this model difficult to test with isotope data. However, support for the model is provided by isotope data from amphibole–garnet–clinopyroxene and lherzolite xenoliths [23,24] and kaersutite megacrysts from Nunivak Island [16], both of which are hosted in AOB to basanite lavas. The similarity between the $^{87}Sr/^{86}Sr$ ratios of kaersutite and amphibole-rich xenoliths (0.7028–0.7032) and those of the Cordilleran OL-NEPH (0.7029–0.7030), and between the $^{206}Pb/^{204}Pb$ of kaersutite megacrysts (18.75) and OL-NEPH (18.75–18.79) (Fig. 4), supports the contention that the OL-NEPH lavas were produced by the melting of an amphibole-bearing source. Furthermore, analyses given in O'Reilly et al. [22] indicate that amphibole may be the dominant reservoir for Nb in the mantle and has significantly higher Nb/Zr ratios than coexisting clinopyroxene. Using the available $K_{d(amp)}$ for Nb and Zr [22,25], mantle amphibole melts should have high Nb/Zr ratios, in the range of that measured for the Ne-rich lavas. In contrast, using the $K_{d(cpx)}$ for Nb and Zr determined by Hauri et al. [26], lherzolite melts should display Nb/Zr ratios that are lower than any of those measured for alkali basalts in the area. These general relationships are evident in Fig. 5b where the least Si-undersaturated lavas have low Nb/Zr and the nephelinites have high Zr/Nb close to that of mantle amphibole. Furthermore the trend towards higher Nb/La, away from crustal compositions, for the more Si-saturated lavas from these centres is particularly evident for Fort Selkirk and supports the involvement of a lherzolite mantle source. Variations in Nb/La between centres are ascribed to differing extents of residual amhibole in the source regions by Francis and Ludden [6].

In terms of isotope composition the nephelinite component is unradiogenic in Sr, Nd and Pb isotopes, while the mantle component from which the AOBs were derived is somewhat more radiogenic. In Fort Selkirk the AOBs appear to be derived from a source more radiogenic than for Llangorse and Hirshfeld; the latter have characteristics similar to the Mt. Edziza source (Figs. 4b and d).

5.2. Alligator Lake

The high $^{87}Sr/^{86}Sr$ of the Alligator Lake lavas contrasts with that of the other alkali basalts in the area. This characteristic either reflects a distinct source for the primary magmas, or crustal contamination. Despite the fact that the granitic xenoliths from Alligator Lake display evidence for partial melting, such as heavily embayed grain boundaries, reaction rims at their contact with the host basalts and veinlets of glass, Eiché et al. [10] argued against differential crustal contamination to explain the difference between primitive AOB and basanite lavas because of the low concentrations of Sr, Nb, P and Ti in the granitoid xenolith relative to the primitive lavas. Also, the high $^{87}Sr/^{86}Sr$ and Sr abundance of the lavas, compared to that of the granitoid xenolith, makes extensive Sr exchange between primary lavas and these granitic xenoliths unlikely. Furthermore, all the lavas have Nb/La ratios which are higher than the chondritic ratio, and display a broad positive trend in the Nb/La vs. $^{206}Pb/^{204}Pb$, away from the compositional field of crustal melts. However, the unradiogenic Sr isotopic composition coupled with the very low Sr abundance (37 ppm) of the granitoid xenolith compared to available data for the Paleozoic to Mesozoic basement in Alaska and Yukon [15,17] may indicate that this xenolith is not representative of possible crustal contaminants. In the Pb isotope diagrams (Figs. 4b and c), lavas from Alligator Lake define a positive trend that would intersect the crustal field and the granitoid xenolith found within the alkali basalts. Interaction between primary lavas of Alligator Lake and a continental crust having radiogenic Sr and Pb isotopic compositions could explain both the trend in the Pb diagrams and the radiogenic Sr composition of the lavas. The Alligator Lake basalts fall in an intermediate position between the nephelinite magmas and the crustal field in the $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 4d), but the relatively low $^{206}Pb/^{204}Pb$ composition and high $^{87}Sr/^{86}Sr$ composition of the most Si-undersaturated basanite from Alligator Lake are difficult to reconcile with a contamination model, unless complete decoupling of the isotope systems is envisaged.

Thus, despite the presence of granitoid xenoliths [10], the Alligator Lake lavas may represent an enriched lithospheric source associated with the Coast Plutonic complex, as opposed to the Intermontane Belt through which all the other lavas studied here were erupted. Distinct chemical characteristics of alkali lavas erupted through different accreted terranes in the Yukon have been identified. For example, different trace element ratios for Quaternary alkali basalts erupted across the Tintina fault (Figs. 1 and 2) have been interpreted as reflecting a compositional contrast in the lithospheric upper mantle under different accreted terranes [27].

5.3. Mt. Edziza

Both trace element and isotope systematics indicate that the Mt. Edziza lavas are distinct from the other alkaline basalts, and in many diagrams these lavas appear to represent an end-member composition. The radiogenic Pb isotopic and nonradiogenic Sr isotopic character of Mt. Edziza lavas, and the fact that they fall close to or slightly under the NHRL in the Pb diagrams (Figs. 4b and c), suggests an affinity with the HIMU mantle component and precludes any important role for crustal assimilation. This affinity is supported by the position of the data points in the $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram of Fig. 4a, where they define a steep positive array between OL-NEPH compositions and HIMU fields. Geochemical characteristics, field relationships and geophysical constraints [6,7] suggest that Mt. Edziza may be centred on a mantle swell and be the result of a rising mantle plume similar to that responsible for the formation of Pacific seamounts and/or northeast Pacific MORB, both of which define an end-member composition comparable to Mt. Edziza [28,29].

6. Mantle sources

Three mantle components have been identified in the continental alkaline magmas of the northern Canadian Cordillera. They are (1) an unradiogenic Sr, Nd and Pb component from which OL-NEPH formed, (2) a lherzolite mantle characterised by high $^{207}Pb/^{204}Pb$ [13] that was probably involved in the formation of AOB from Fort Selkirk and (3) a radiogenic Pb–nonradiogenic Sr component (HIMU-type) represented by Mt. Edziza lavas.

In Figs. 6a and b the Cordilleran alkaline basalts are compared with other volcanic rocks in the area in $^{207}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagrams. Most of the alkaline basalts have low $^{207}Pb/^{204}Pb$ compared to sediments from the northern Pacific [30] and closely follow the NHRL [20]. Lavas from the Pelly sequence at Fort Selkirk, and from Alligator Lake, have Pb and Sr isotopic compositions above the NHRL, but similar to those of arc–transform magmatism in the Wrangell volcanic belt of the western Yukon [31]. Based on trace element and

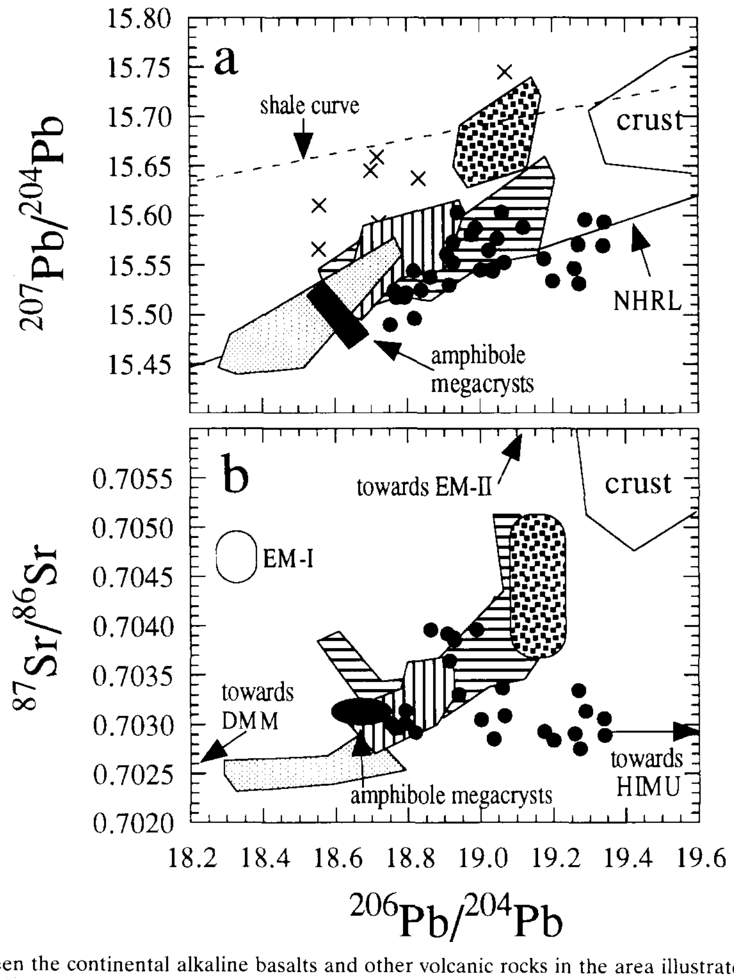

Fig. 6. Comparison between the continental alkaline basalts and other volcanic rocks in the area illustrated in $^{207}Pb/^{204}Pb$ (a) and $^{87}Sr/^{86}Sr$ (b) vs. $^{206}Pb/^{204}Pb$ diagrams. Symbols and data sources: ● = alkaline magmas [this study]; light grey = MORB from Juan de Fuca and Gorda ridges [32]; × = northern Pacific sediments [30]; crust [17–19]; vertical shading = Aleutian island arc [33,34]; dark grey = amphibole megacrysts from Nunivak Island [16]; horizontal shading = volcanic rocks from the Wrangell belt, Yukon [31]; stipple = spinel lherzolite xenoliths from Alligator Lake [13]. Compositional domains of depleted mantle (DMM), enriched mantle I and II (EMI and EMII) and HIMU mantle [37] are given for reference. Shale Pb evolution curve [21].

isotope systematics, Skulski et al. [31] argue that some rocks from the Wrangell belt having high $^{87}Sr/^{86}Sr$ must have a mantle source. Hence, a radiogenic mantle may be characteristic of the subcontinental lithosphere in the northwestern Canadian Cordillera and this component may be the source of the alkali basalts of Alligator Lake. Lithosphere of different composition and of different age would characterise the diverse terranes in the region and may explain variations in basanite–AOB composition between Alligator Lake (Coast Plutonic complex) and Fort Selkirk and Llangorse–Hirschfeld (Intermontain Belt).

Most of the MORB samples from the Juan de Fuca and Gorda ridges [32] are less radiogenic than the OL-NEPH lavas. Furthermore MORBs with comparable $^{206}Pb/^{204}Pb$ have higher $^{207}Pb/^{204}Pb$ and are similar to the least radiogenic arc lavas from the Aleutian Islands [33,34], but with slightly lower $^{87}Sr/^{86}Sr$ (0.7025–0.7028). With the exception of the Alligator Lake lavas the northern Cordilleran continental alkaline magmas define a horizontal trend in the $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram from the least radiogenic Aleutian arc domain towards a HIMU component. The nephelinites and mantle amphibole define compositions similar to the nonradiogenic end member that produced Aleutian Island arcs. The amphibole-rich veins may then have been formed from small-degree partial melts of asthenosphere injected into the subcontinental lithosphere during Mesozoic subduction.

7. Conclusions

During the Cenozoic and Quaternary, magmas from either the asthenosphere or a plume, but with HIMU characteristics, rose through the continental lithosphere and erupted to form the Mt. Edziza and Level Mountain volcanic centres. Small-volume eruptive centres, such as Fort Selkirk, Alligator Lake and Hirchfeld–Llangorse, traverse several terrane boundaries and were produced either as a result of the influx of magma from the subcontinental lithosphere, or as melts produced in response to pressure release associated with transtensional faulting in the northern Canadian Cordillera; both events are a result of ridge subduction and a transition from compressional to an extensional tectonic regime [8].

The distinct isotopic character of the Mt. Edziza lavas relative to the alkaline magmas of the other Cordilleran centres and an isotopic composition similar to Pacific Seamounts suggests that this centre reflects upwelling of Pacific mantle below central British Columbia. This mantle component has HIMU characterstics and is distinct from the lherzolite continental mantle lithosphere in the region. Melting of amphibole-bearing subcontinental lithospheric mantle resulted in the small OL-NEPH–AOB centres characteristic of the northern Cordilleran Province. The nephelinite source is slightly more radiogenic than present-day Pacific MORB and is best represented by the most depleted component of the Aleutian magmas, perhaps indicating an enrichment of the subcontinental lithosphere in the northern Cordillera by melts of this composition during Cretaceous subduction.

Differentiating subcontinental lithosphere sources and potential effects of crustal contamination is difficult. The AOB magmas of the Fort Selkirk appear to lie on a binary mixing trend between the nephelinite component and lherzolite xenoliths from the region, whereas other AOB and basanite lavas may originate from a mixture between the nephelinite component and an upwelling enriched mantle having high $^{206}Pb/^{204}Pb$ (Edziza-type). The Alligator Lake lavas are highly radiogenic and display evidence of crustal contamination, but may nonetheless represent a highly radiogenic mantle lithosphere associated with the Coast Plutonic complex, as opposed to the Intermontane Belt.

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