

# A Cretaceous back-arc basin in the Coast Belt of the northern Canadian Cordillera: evidence from geochemical and neodymium isotope characteristics of the Kluane metamorphic assemblage, southwest Yukon

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**Abstract:** The Coast Belt of the northern Cordillera in Canada is the locus of the boundary between accreted and ancient North American margin rocks. The largest exposure of metasedimentary rocks in the Coast Belt is the Kluane metamorphic assemblage (KMA), a northwest-striking belt 160 km long of graphitic mica–quartz schist and gneiss with minor interfoliated olivine serpentinite. The KMA does not appear to correlate with other sedimentary or metamorphic rock assemblages in the Canadian Cordillera. To determine its tectonic setting and protolith provenance, we analyzed trace element, rare earth elements, and neodymium isotope compositions of the KMA, of the adjacent pericratonic Aishihik metamorphic suite (AMS) of the Yukon–Tanana terrane, and of adjacent slates of the Dezadeash Formation (DF), filling a Late Jurassic – Early Cretaceous flysch basin. The  $\epsilon\text{Nd}(0)$  values of analyzed KMA samples range from  $-1.4$  to  $-5.6$  and depleted mantle model ages ( $T_{\text{DM}}$ ) range from 1.16 to 1.45 Ga. KMA samples are intermediate between more evolved AMS samples (average  $\epsilon\text{Nd}(0) -25$ ,  $T_{\text{DM}} = 2.6$  Ga) and more juvenile DF samples ( $\epsilon\text{Nd}(0) = +1.9$ ,  $T_{\text{DM}} = 0.95$  Ga). The intermediate characteristics of the KMA samples cannot be linked to a known source region and are interpreted to reflect homogeneous mixing from predominantly juvenile and minor evolved sedimentary sources. A compatible tectonic setting is a back-arc basin within influence of a continental source. Eastward subduction of the KMA beneath ancient North America collapsed the back-arc basin by latest Cretaceous time.

**Résumé :** Le Domaine côtier de la Cordillère septentrionale canadienne est le lieu de la limite entre les roches accrétées et les roches de l'ancienne marge nord-américaine. Le plus grand affleurement de roches métasédimentaires du Domaine côtier est l'assemblage métamorphique de Kluane (KMA), une ceinture de direction nord-ouest, longue de 160 km, et composée de schiste graphitique à mica et quartz et de gneiss ainsi qu'une légère intercalation de serpentinite à olivine. Le KMA ne semble pas être en corrélation avec d'autres assemblages de roches métamorphiques ou sédimentaires de la Cordillère canadienne. Afin de déterminer sa situation tectonique et sa provenance protolithique, nous avons analysé des éléments traces, des éléments de terres rares et des compositions de l'isotope néodyme du KMA, de la suite métamorphique adjacente péricratonique d'Aishihik (AMS), du terrane Yukon–Tanana et des schistes ardoisiers adjacents de la Formation de Dezadeash (DF), qui remplissent un bassin flysch du Jurassique tardif – Crétacé précoce. Les valeurs  $\epsilon\text{Nd}(0)$  d'échantillons du KMA analysés varient de  $-1,4$  à  $-5,6$  et des âges typiques pour le manteau appauvri ( $T_{\text{DM}}$ ) varient de 1.16 à 1.45 Ga. Les échantillons de KMA sont intermédiaires entre les échantillons AMS plus évolués (moyenne  $\epsilon\text{Nd}(0) -25$ ,  $T_{\text{DM}} = 2,6$  Ga) et les échantillons DF plus jeunes ( $\epsilon\text{Nd}(0) = +1,9$ ,  $T_{\text{DM}} = 0,95$  Ga). Les caractéristiques intermédiaires des échantillons du KMA ne peuvent pas être reliés à une région-source connue et elles sont interprétées comme le reflet d'un mixage homogène de sources à prédominance juvéniles et des sources évoluées plus mineures. Une position tectonique compatible serait un bassin d'arrière arc à l'intérieur de la zone d'influence d'une source continentale. La subduction vers l'est du KMA sous l'ancienne Amérique du Nord a écrasé le bassin d'arrière arc vers la toute fin du Crétacé.

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## Introduction

The Coast Belt of the Canadian Cordillera is a plutonic-metamorphic belt comprising Late Cretaceous – Early Tertiary plutonic and medium- to high-grade metamorphic rocks. It has been interpreted to mark the boundary between rocks of North American affinity and magmatic arc rocks presumed to have been accreted to the ancient margin (Gabrielse et al. 1991). Knowledge of the tectonic affinity and protolith of the metamorphic rocks, the ability to distinguish autochthonous (North American) from possible exotic metamorphic rocks, and the capacity to identify accreted terranes of potentially different origin are essential to understanding the tectonic evolution of the belt and the Canadian Cordillera. The Kluane metamorphic assemblage (KMA) in the northernmost part of the Coast Belt in Canada is an enigmatic body of metamorphic rocks more than 3000 km<sup>2</sup> in area, which has received little study until now. It has lithological, structural, and metamorphic characteristics that preclude correlation with either the accreted crust or the ancient continental margin. On the most recent tectonic assemblage map of the Canadian Cordillera (Wheeler et al. 1991), the entire area is simply shown as undivided metamorphic rocks.

To define the KMA's role in the evolution of the Cordillera, we conducted geochemical and isotopic studies of the KMA and of adjacent assemblages, the sedimentary Dezadeash Formation (DF) and the metamorphic Aishihik metamorphic suite (AMS). Our results of trace-element and Nd isotope analyses show that the KMA, AMS, and DF have distinct provenances. Juvenile characteristics and young crustal residence ages of the DF suggest an origin at or near a volcanic arc; evolved characteristics and late Archean crustal residence ages for the AMS suggest an ancient cratonic source. Results from the KMA are intermediate between the DF and AMS, indicating possible mixing of predominantly juvenile crust with evolved sources. We propose an evolution model compatible with deposition in a back-arc basin along an outer continental margin that closed during the Late Cretaceous accretion of oceanic terranes against North America.

## Geology of the southwestern Yukon

The northern Coast Belt in the Yukon comprises Eocene granodiorite of the Ruby Range batholith and mica-quartz schist of the Kluane metamorphic assemblage (Fig. 1). To the southwest, the Shakwak Trench is the locus of the Denali fault zone and of recent reverse faulting (Mezger 1997). It obscures the contact of the KMA with the Insular Belt, arc, and oceanic rocks interpreted to have been accreted to North America during the late Mesozoic (Rubin et al. 1990). To the northeast, the Ruby Range batholith intrudes metamorphic assemblages of broad North American margin affinity, the Yukon-Tanana and Nisling terranes (Mortensen 1992; Johnston et al. 1996).

The 160 km long belt of the KMA is one of the most extensive metamorphic terrains of the Canadian Cordillera. Its rock types differ from those of other metamorphic sequences of the orogen (Tempelman-Kluit 1974; Erdmer 1991) and include graphitic mica-chlorite-quartz schist and garnetiferous sillimanite-cordierite-quartz gneiss with minor orthoamphibole-biotite-plagioclase-quartz gneiss. Plagioclase porphyroblasts up

to one centimetre across are characteristic of the mica-quartz schist. Fine graphitic layers in the plagioclase give it a dusty grey appearance and are interpreted as the trace of primary laminations and early crenulation cleavage. Mica-quartz schist of the KMA was originally subdivided into an epidote- and (or) calcite-bearing calcic unit and an epidote-free aluminous unit (Muller 1967; Erdmer 1991; Mezger 1997). However, whole-rock and isotope characteristics of the KMA determined in this study show no significant differences between the units. Interfoliated with the schist are isolated, lens-shaped bodies of serpentinized dunite underlying areas up to 1.5 × 15 km. Locally, minor decimetre- to metre-thick boudinaged layers of coarse-grained actinolite and actinolite-epidote-chlorite schist are interlayered with mica-chlorite-quartz schist. Conspicuously absent are the calc-silicate rocks, marble, and quartzite that are common constituents of the Yukon-Tanana and Nisling terranes (Mortensen 1992; Johnston and Timmerman 1994).

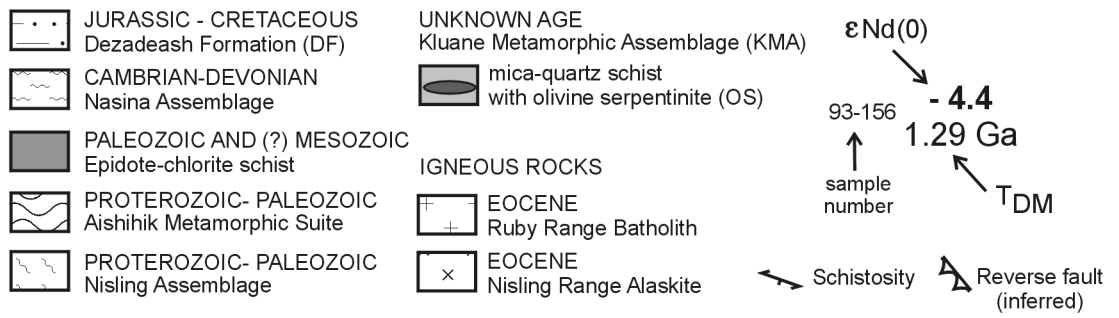
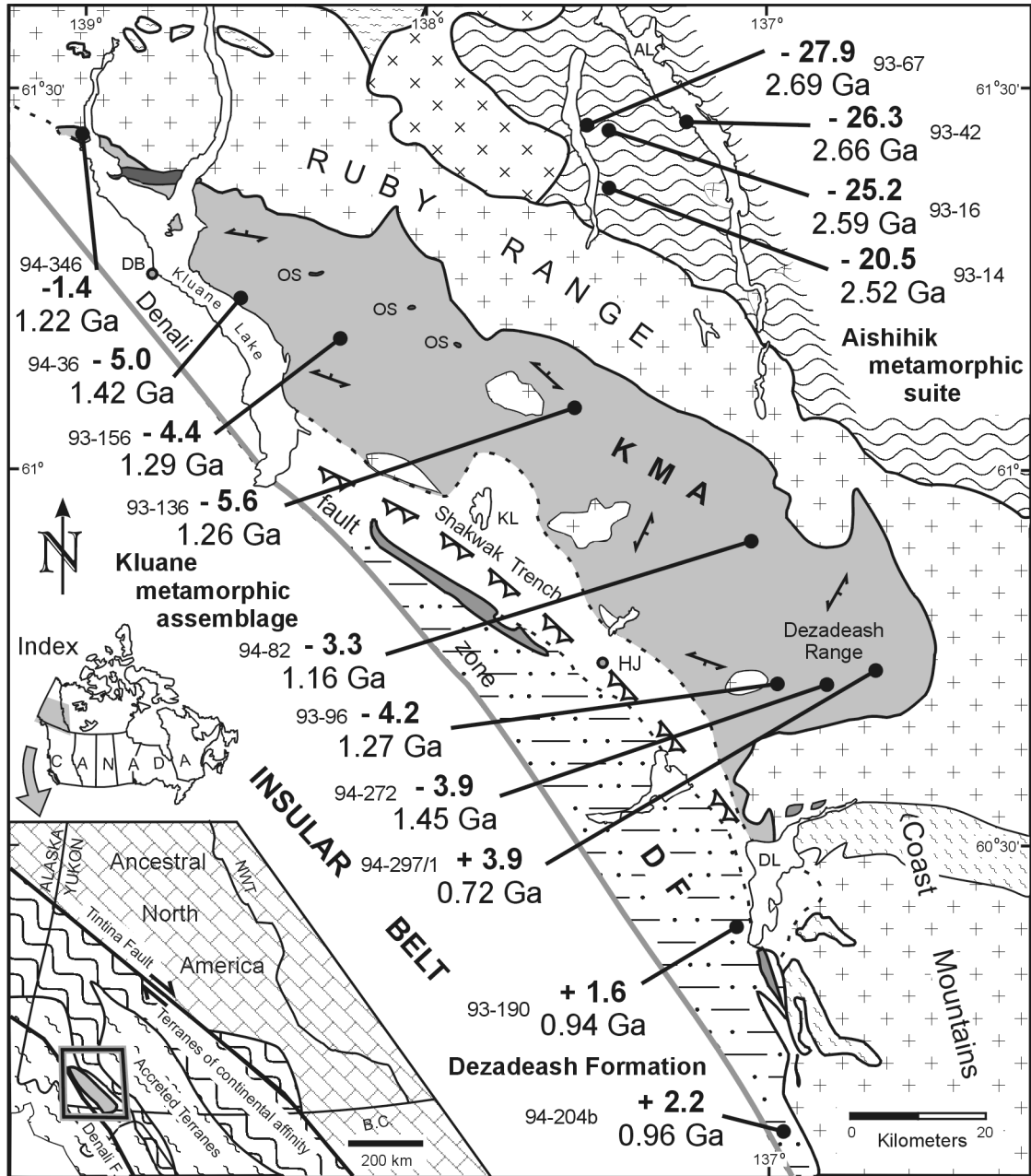
Schistosity in the KMA is defined by chlorite and muscovite at lower metamorphic grade and biotite at higher grade. The orientation of schistosity and mineral stretching lineation in the KMA varies little over areas of tens of square kilometres. In the western part of the KMA, schistosity defines a moderately steep, north-northeast-dipping homocline, with a structural thickness near 12 km. East of Kloo Lake, there is a gently east-southeast-plunging map-scale open antiform. Lineation plunges generally shallowly to the east. Ductile strain is recorded by a pervasive mylonitic fabric; well-developed shear-sense indicators are common (Mezger 1996, 1997). A minimum age of ductile deformation is indicated by a crosscutting 72 Ma biotite granite dyke (J. Mortensen, personal communication, 1997).

Prior to the Eocene emplacement of the Ruby Range batholith, the KMA experienced amphibolite-facies regional metamorphism coeval with mylonitization. This is inferred to have occurred in the Late Cretaceous, when the KMA underplated the AMS and was accreted to the continental margin (Mezger 1997). The sill-like Ruby Range batholith imposed a wide hot-side-up metamorphic aureole on the KMA. Near the batholith, the growth of static cordierite partly obliterated schistosity and mineral lineation. Geothermobarometric data show that regional metamorphism occurred at 20–25 km depth, and later contact metamorphism at 15–17 km depth (Mezger 1997). Available K–Ar and <sup>40</sup>Ar/<sup>39</sup>Ar data from biotite and muscovite and U–Pb monazite ages from mica-quartz schist for the KMA range from 57 to 40 Ma and have been interpreted to record cooling following intrusion of the Ruby Range batholith (Erdmer and Mortensen 1993).

In the eastern Dezadeash Range, Erdmer (1991) proposed a faulted contact between graphitic mica schist in the west and cordierite-biotite gneiss in the east originally assigned to the Nisling terrane. The mapped contact can be shown to coincide with a cordierite-in isograd and has been reinterpreted as a metamorphic-grade transition within the KMA rather than a terrane boundary (Mezger 1997). Lithologic unit continuity across the boundary is confirmed by the isotopic data presented here.

Across the Shakwak Trench, to the southwest, occur interbedded sandstone and shale with minor conglomerate and limestone of the Dezadeash Formation, interpreted as

**Fig. 1.** Geology of the southwestern Yukon east of the Denali fault (after Dodds and Campbell 1992; Johnston and Erdmer 1995; Mezger 1997) and its setting in the tectonic framework of the northern Canadian Cordillera. Sample localities and Nd isotopic data are shown.



AL: Aishihik Lake, DB: Destruction Bay, DL: Dezaeash Lake, HJ: Haines Junction, KL: Kloo Lake

volcanogenic flysch. Late Jurassic to Early Cretaceous fossils in the DF have been used to support correlation with the Gravina–Nutzotin Belt of Alaska that formed during amalgamation of accreted oceanic rocks to the west (Eisbacher 1976). Eisbacher (1976) interpreted the KMA as a metamorphosed equivalent of the DF.

The third assemblage analyzed in this study is the Aishihik metamorphic suite to the northeast of the Ruby Range batholith. The AMS includes mica–quartz schist, micaceous quartzite, quartzite, calc-silicate, marble, amphibolite, metabasite, and other metaigneous rocks. Johnston and Timmerman (1994) interpreted the AMS as Late Proterozoic to Paleozoic continental margin and off-shelf strata, part of the Nisling and Nasina assemblages of the Yukon–Tanana terrane.

## Analytical studies

Rare earth elements (REE) and other elements, such as Y, Th, Zr, Hf, Nb, Ti, Sc, and Co, are generally considered immobile during low- and medium-grade metamorphism (e.g., Bhatia 1985; Taylor and McLennan 1985; Bhatia and Crook 1986). Ratios between compatible elements (e.g., V, Sc, Co) and incompatible elements (e.g., light REE (LREE)) can be used to distinguish sedimentary protolith provenance (Bhatia and Crook 1986). The increasing abundance of trace elements that are concentrated in heavy minerals, such as Zr, indicates multiple recycling phases and higher sedimentary maturity of the protolith. Normalized REE, La/Sc–Th/Sc, La–Th–Sc, and Th–Zr/10–Sc plots are used to distinguish tectonic settings (Taylor and McLennan 1985; Bhatia and Crook 1986).

The nature of the source region and tectonic affinity are further constrained by neodymium isotope analysis, which provides information on the isotopic evolution of the protolith and the homogeneity of mixing during sedimentation (DePaolo 1988; Frost and Coombs 1989). Although the depositional age of the protolith is unknown, the “depleted mantle model age” provides an average crustal residence age of the protolith components involved (McLennan and Hemming 1992). Nd isotope studies can help to constrain tectonic setting and possible protolith provenance in the accreted portion of the northern Cordillera, as shown for example by Jackson et al. (1991), Samson et al. (1991), Creaser et al. (1997), and Patchett and Gehrels (1998).

Seven mica–quartz schist and gneiss samples and one orthoamphibole gneiss sample representative of the KMA were selected for geochemical and Nd isotope analysis. In addition, two graphitic slate samples of the DF and four mica–quartz schist samples of the AMS (units PAMqb and PAMfs of Johnston and Timmerman 1994) were analyzed for the purpose of comparison. Sample locations and descriptions are given in Table 1.

Samples were crushed to gravel size avoiding contact with metal and subsequently pulverized to ~35 µm size using an agate grinder and a tungsten carbide swing mill. Major and trace elements were determined at Washington State University, Pullman, Wash., by X-ray fluorescence (XRF) and inductively coupled plasma – mass spectrometry (ICP–MS), respectively, as described by Hooper et al. (1993), Knaack et

al. (1994), and Johnson et al. (1999). Analytical results are listed in Table 2.

Neodymium isotope analyses were obtained at the Radiogenic Isotope Facility of the University of Alberta, Edmonton, Alta. Sample powders were weighed, totally spiked with a  $^{150}\text{Nd}$ – $^{149}\text{Sm}$  tracer solution, and dissolved in a 5:1 mix of HF–HNO<sub>3</sub> in sealed Teflon™ vessels at 160°C for ~120 h. Resultant fluorite solutes were evaporated to dryness, converted to chloride by adding 6 N HCl, and heated at 160°C for 24 h. Chloride solutes were evaporated to dryness and dissolved in 0.75 N HCl, and filtered to remove graphite. REE were separated as a group by standard cation chromatography. Subsequent separation of Nd from Sm was done using HDEHP chromatography. The purified Nd and Sm fractions were analyzed for isotopic composition using VG354 and Micromass MM30 mass spectrometers, respectively. Measured isotopic ratios were corrected for mass discrimination and fractionation by normalizing to the following ratios:  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  and  $^{152}\text{Sm}/^{154}\text{Sm} = 1.17537$ . During the course of this study, a dissolution of the spiked standard rock BCR-1 yielded  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512634 \pm 0.000009$  ( $\epsilon\text{Nd} = -1$ ) and  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1378$ . A spiked aliquot of the La Jolla Nd isotopic standard had a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of  $0.511848 \pm 0.000008$  after separation of Nd from spike Sm by HDEHP chromatography. Multiple analyses of an unspiked in-house Nd isotopic standard ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.511054$ ) yielded an external reproducibility of 0.000016 (2σ), which is taken as the minimum uncertainty estimate for the analyzed samples of this study. Additionally, all totally spiked samples were monitored for recovered  $^{145}\text{Nd}/^{144}\text{Nd}$ , which was determined to be 0.348407 for the average analyzed samples. These results are in good agreement with previously published data (Thirlwall 1991).

## Results

The SiO<sub>2</sub> contents of samples of the Kluane metamorphic assemblage, Aishihik metamorphic suite, and Dezadeash Formation range from 59 to 75 wt.%. The three assemblages are indistinguishable in terms of their SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratios, which range from 3 to 6. K<sub>2</sub>O/Na<sub>2</sub>O ratios of 2–4.5 for the AMS and 0.45–1.8 for the KMA and DF samples place them in the lithic arenite field and greywacke fields of Pettijohn et al. (1987), respectively. This may indicate a higher sedimentary maturity of AMS rocks compared to the KMA and DF. Major-element contents can distinguish the pericratonic AMS from the KMA and DF, but cannot discriminate between the KMA and DF. Because of the mobility of major elements at increasing metamorphic grade, these results have to be considered with caution.

DF samples have moderate Eu anomalies ( $\text{Eu}/\text{Eu}^* = 0.72$  and 0.82), the least LREE-enrichment ( $\text{La}_\text{N}/\text{Yb}_\text{N} \sim 3.6$ ), and ΣREE (57 and 87 ppm) close to bulk continental crust (87 ppm). In contrast, Phanerozoic first-cycle volcanogenic sediments derived from andesite or basalt of magmatic island arcs do not display a negative Eu anomaly (Taylor and McLennan 1985), and thus the modest negative Eu anomalies observed in the DF indicate a more felsic source.

The most evolved characteristics are displayed by three AMS samples with a strong negative Eu anomaly ( $\text{Eu}/\text{Eu}^*$

**Table 1.** Sample localities.

Sample	Rock type	Locality
<b>Kluane metamorphic assemblage</b>		
93-96	Graphitic garnet–sillimanite–biotite schist	136°57'36", 60°42'15"
93-136	Graphitic staurolite–chlorite–biotite schist	137°33'20", 61°03'30"
93-156	Graphitic muscovite–chlorite schist	138°16'00", 61°12'20"
94-36	Graphitic muscovite–chlorite schist	138°36'30", 61°14'10"
94-82	Sillimanite–cordierite–biotite gneiss	137°01'10", 60°54'10"
94-272	Biotite–quartz gneiss	136°46'20", 60°42'40"
94-297/1	Orthoamphibole–biotite gneiss	136°42'20", 60°43'55"
94-346	Graphitic garnet–staurolite–biotite schist	139°04'00", 61°26'12"
<b>Dezadeash Formation</b>		
94-190	Graphite slate	137°02'40", 60°23'05"
94-204b	Garnetiferous graphite slate	137°56'30", 60°06'30"
<b>Aishihik metamorphic suite</b>		
93-14	Staurolite–garnet–mica schist (PAMfs)	137°10'40", 61°23'45"
93-16	Biotite–muscovite schist (PAMqb)	137°29'00", 61°23'20"
93-42	Biotite–muscovite schist (PAMqb)	137°28'20", 61°26'30"
93-67	Sillimanite–garnet–mica schist (PAMqb)	137°27'30", 61°23'00"

~0.6–0.7),  $La_N/Yb_N$  ratios of 12–13, and high  $\Sigma REE$  (120–280 ppm). The REE pattern is similar to that of post-Archean sedimentary rocks (PAAS) derived from felsic upper crust (Fig. 2). Sample 93-14 has more juvenile characteristics than other AMS samples, with a less pronounced Eu anomaly (0.87) and less enrichment in LREE ( $La_N/Yb_N = 5.6$ ), comparable to KMA samples.

Kluane metamorphic assemblage samples show patterns and characteristics intermediate between the evolved AMS and the more primitive DF rocks (Fig. 2).  $Eu/Eu^*$  ranges from 0.69 to 1.09, and LREE are moderately enriched over heavy REE (HREE) ( $La_N/Yb_N = 4.4–7.3$ ). The  $\Sigma REE$  ranges from 63–160 ppm. The lowest  $\Sigma REE$ , the least LREE enrichment, and a positive Eu anomaly were observed in the orthoamphibole-rich gneiss (sample 94-297/1) from the KMA.

Generally, Th, Zr, Sc, and REE contents display a linear correlation between the relatively primitive DF and the strongly evolved AMS samples. The KMA samples occupy a position between the AMS and DF (Fig. 3). AMS samples have La/Sc values of 1.3–5.6 and Th/Sc of 0.8–2, near or above the upper continental crust average, while the lower ratios of the DF (La/Sc = 0.6, Th/Sc = 0.12) are similar to bulk continental crust. KMA samples have ratios between upper and bulk continental crust (La/Sc = 1.3–2.1, Th/Sc = 0.3–0.5) (Figs. 3a, 3b). Exceptions are the orthoamphibole schist sample of the KMA (94-297/1), which falls in the DF field, and the AMS sample 93-14, which plots close to the KMA. On La–Sc–Th and Th–Zr/10–Sc ternary plots (Figs. 3c, 3d), DF samples and KMA sample 94-297/1 plot near the bulk continental crust or within the “oceanic arc” field of Bhatia and Crook (1986); AMS samples near the upper continental crust average within the “continental margin” and “continental arc” fields; and KMA samples plot between both averages, within the “continental arc” field.

REE and trace-element characteristics may record two geochemical end members, an evolved felsic continental crust source for the AMS, and a more juvenile basaltic to andesitic source for the DF. The data show that the KMA is

not likely the metamorphosed DF as suggested by Eisbacher (1976), but instead is derived from a different protolith or is formed of variable mixtures of the protoliths for the DF and AMS, as discussed below.

Neodymium isotope data indicate distinct provenances for the KMA, AMS, and DF. Because the depositional ages of the KMA and the AMS are not known, Nd isotope data are reported as present-day “epsilon parameters,”  $\epsilon Nd(0)$  (DePaolo and Wasserburg 1976). Nd isotopic compositions are given in Table 3 and plotted in Fig. 1.

The four AMS samples have strongly negative  $\epsilon Nd(0)$  values ranging from –20.5 to –27.9 and Archean model ages of 2.52–2.69 Ga, indicating derivation from ancient crust. The DF samples have  $\epsilon Nd(0)$  values of +1.6 and +2.2 and younger Late Proterozoic model ages ( $T_{DM} = 0.94$  and 0.96 Ga), suggesting a relatively juvenile protolith. Initial  $\epsilon Nd$  values for the time corresponding to the deposition of the DF (~140 Ma; Eisbacher 1976) are +2.6 and +3.0. Mica–quartz schists of the KMA record small variation in  $\epsilon Nd(0)$ , ranging from –5.6 to –1.4. There is no correlation of  $\epsilon Nd(0)$  with structural level or along-strike location (Fig. 1).  $T_{DM}$  ages range from 1.16 to 1.45 Ga, intermediate between AMS and DF values, with the exception of the orthoamphibole gneiss sample 94-297/1, which has the most juvenile composition of all analyzed samples ( $\epsilon Nd(0) = +3.9$ ) and the youngest model age ( $T_{DM} = 0.72$  Ga).

$^{147}Sm/^{144}Nd$  ratios are negatively correlated with  $\epsilon Nd(0)$ . AMS samples have  $^{147}Sm/^{144}Nd$  ratios ranging from 0.104 to 0.119, whereas the DF samples have ratios of 0.142 and 0.148. The  $^{147}Sm/^{144}Nd$  ratios of KMA samples vary from 0.123 to 0.144 (Fig. 4). Negative correlation of  $\epsilon Nd(0)$  with Th/Sc, La/Sc, and  $La_N/Yb_N$  place the AMS near Precambrian continental crust composition and the DF close to average arc volcanic rocks, while the KMA plots in an intermediate position close to the DF (Fig. 5). The location of the KMA samples near a line that joins the AMS and DF samples may indicate formation of the KMA by mixing AMS with DF or mixing of their protoliths.

**Table 2.** Major-, trace-, and rare-element abundances of metamorphic (KMA, AMS) and sedimentary (DF) rocks of the southwestern Yukon.

Sample:	93-96	93-136	93-156	94-36	94-82	94-272	94-297	94-346	94-190	94-204b	93-16	93-67	93-14	93-42
Unit:	Kluane metamorphic assemblage (KMA)								DF		AMS			
<b>Major elements (wt.%)</b>														
SiO <sub>2</sub>	64.41	70.11	63.34	64.49	65.58	64.55	61.14	59.20	62.84	62.86	63.71	74.49	59.46	62.73
Al <sub>2</sub> O <sub>3</sub>	19.30	14.77	18.54	16.36	16.33	16.77	17.37	18.31	17.01	17.99	17.91	13.74	18.84	20.25
TiO <sub>2</sub>	0.90	0.73	0.94	0.84	0.84	0.86	0.77	1.17	0.65	0.77	0.95	0.61	1.14	0.84
FeO	6.48	5.42	6.43	6.15	6.38	6.21	6.59	8.01	5.18	6.08	6.39	4.36	6.85	5.97
MnO	0.11	0.09	0.09	0.07	0.09	0.11	0.09	0.10	0.09	0.12	0.07	0.05	0.10	0.09
CaO	1.16	1.67	0.94	0.92	2.23	2.99	5.41	2.62	3.13	3.49	0.94	0.56	2.22	0.82
MgO	2.95	2.24	2.61	3.26	2.64	2.22	3.81	3.10	2.22	2.42	2.27	1.60	2.36	2.05
K <sub>2</sub> O	3.06	2.02	2.88	1.33	2.22	2.28	1.48	2.80	4.01	2.30	5.28	3.42	4.87	4.79
Na <sub>2</sub> O	1.69	2.25	2.35	4.21	2.34	3.03	3.22	3.37	2.70	4.09	1.44	1.03	2.34	1.08
P <sub>2</sub> O <sub>5</sub>	0.09	0.12	0.20	0.11	0.15	0.56	0.33	0.15	0.13	0.16	0.17	0.07	0.11	0.12
Total	100.14	99.43	98.32	97.95	98.80	99.58	100.21	98.83	97.96	100.27	99.13	99.94	98.30	98.74
<b>Trace elements (ppm)</b>														
Ba	1309	708	918	451	787	704	487	847	1112	918	940	641	2522	826
Rb	96.7	67.4	93.4	42.0	69.9	79.3	39.6	87.4	88.9	57.6	211.4	128.1	136.7	166.8
Cs	4.16	3.75	4.72	2.46	4.18	3.79	1.37	5.74	2.78	2.82	6.88	3.86	5.00	4.52
Sr*	235	250	224	194	280	344	634	379	320	481	153	170	191	126
Pb	7.25	13.36	13.50	8.11	14.43	14.28	19.46	13.32	13.16	11.50	17.73	17.91	15.16	28.30
Th	7.78	5.25	6.78	5.76	5.68	6.85	1.25	4.76	1.63	2.96	15.68	15.74	14.72	16.18
U	2.77	2.14	2.24	2.14	1.98	2.28	0.91	2.18	1.13	1.81	3.30	2.66	2.73	3.28
Zr*	171	141	167	137	152	170	98	174	82	134	236	248	236	147
Nb	13.6	10.39	12.92	10.55	10.26	11.84	5.76	13.35	4.83	7.00	31.88	14.77	27.41	20.24
Hf	4.82	3.61	4.70	3.76	4.23	4.48	2.21	4.68	2.00	3.55	6.87	7.16	7.10	4.29
Y	23.82	19.87	24.79	23.41	22.29	41.42	17.76	28.97	16.27	28.48	36.05	24.35	28.36	37.69
La	26.56	21.53	23.34	23.10	23.57	29.62	10.62	20.87	8.76	14.29	59.78	44.67	23.15	64.18
Ce	50.56	41.42	44.78	43.76	45.14	59.27	21.51	41.60	19.53	28.39	108.16	85.95	49.41	120.21
Pr	5.61	4.82	5.13	4.96	5.17	7.05	2.73	5.04	2.60	3.75	11.72	9.01	5.22	13.21
Nd	22.06	19.38	20.80	19.84	21.05	28.97	12.33	21.55	11.59	16.54	44.31	33.48	20.55	49.77
Sm	5.00	4.35	4.89	4.73	4.70	7.47	3.26	5.48	2.73	4.56	8.91	6.50	4.66	9.94
Eu	1.06	1.13	1.16	1.35	1.34	1.78	1.12	1.66	0.67	1.22	1.60	1.28	1.23	1.68
Gd	4.39	3.67	4.38	4.58	4.33	7.0	3.04	5.30	2.95	4.55	7.22	4.97	4.05	7.98
Tb	0.75	0.62	0.73	0.78	0.71	1.31	0.53	0.89	0.51	0.82	1.16	0.78	0.76	1.22
Dy	4.44	3.65	4.43	4.53	4.18	7.81	3.22	5.47	2.99	5.22	6.83	4.52	4.97	7.15
Ho	0.94	0.76	0.92	0.93	0.83	1.53	0.66	1.11	0.60	1.08	1.36	0.90	1.07	1.40
Er	2.68	2.15	2.70	2.50	2.31	4.18	1.89	3.00	1.72	3.15	3.61	2.39	3.02	3.72
Tm	0.37	0.30	0.42	0.36	0.35	0.53	0.25	0.43	0.23	0.43	0.53	0.36	0.46	0.53
Yb	2.54	1.98	2.67	2.21	2.33	3.26	1.63	2.75	1.51	2.81	3.35	2.21	2.79	3.28
Lu	0.42	0.32	0.43	0.35	0.37	0.49	0.27	0.43	0.24	0.46	0.52	0.34	0.43	0.48
Sc*	19	17	16	11	10	20	19	15	16	21	14	8	18	17
V*	181	155	187	195	177	171	160	241	127	195	89	55	122	102
Cr*	113	115	95	135	135	111	38	173	55	54	62	34	77	57
Ni*	23	34	31	60	43	40	22	65	47	29	37	24	15	35
Cu*	17	16	34	77	58	34	68	11	60	8	14	4	32	22
Zn*	138	116	116	96	123	109	92	192	75	106	108	61	75	103
Ga*	24	14	21	21	18	20	19	15	16	27	24	18	26	28

**Note:** DF, Dezadeash Formation; AMS, Aishihik metamorphic suite. Major-element analyses performed by XRF. Trace elements denoted with \* performed by XRF, all others by ICP-MS. Analyses by Washington State University; details are given by Hooper et al. (1993).

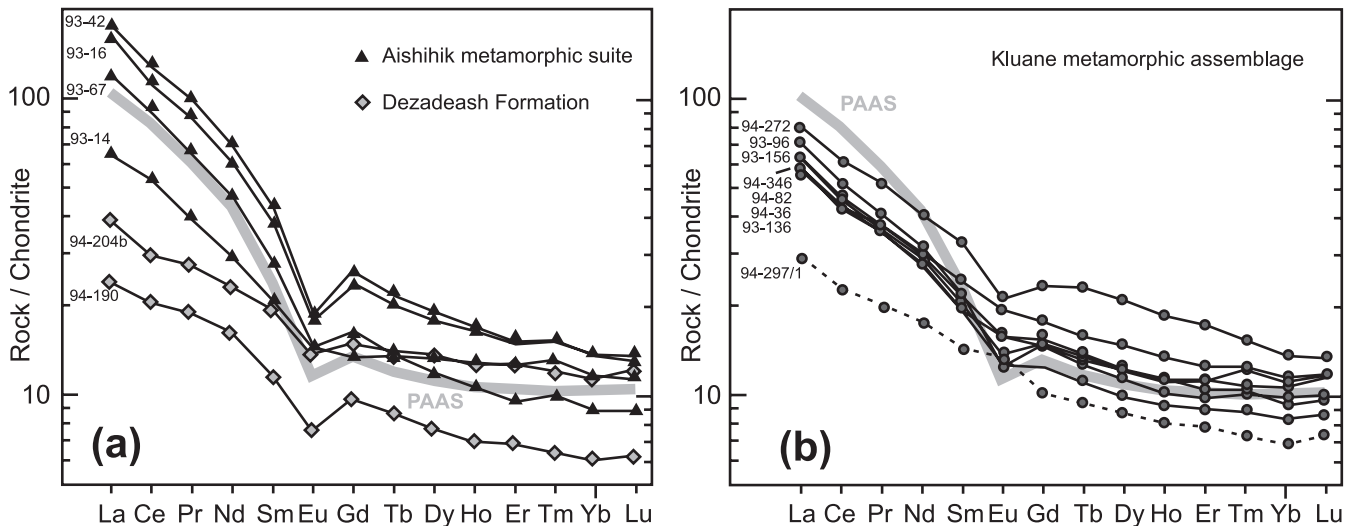
## Protolith provenance and regional correlation

### Aishihik metamorphic suite

Trace-element geochemistry,  $\epsilon\text{Nd}(0)$  values, and Archean  $T_{\text{DM}}$  ages show an ancient cratonic protolith for the AMS. The AMS has been correlated with continental margin strata

of the Nisling assemblage, which forms part of the Nisling terrane (Wheeler and McFeely 1991; Mortensen 1992; Johnston and Erdmer 1995). Plutonic and volcanic rocks in the buried Precambrian basement of Alberta and British Columbia have yielded  $T_{\text{DM}}$  ages of 2.46–2.83 Ga and  $\epsilon\text{Nd}(0) = -27$  (Frost and O'Nions 1984; Thériault and Ross 1991). Volcanic and plutonic rocks of the Wopmay Orogen in the

**Fig. 2.** REE plots of the (a) AMS and DF, and (b) KMA. The DF samples are the least evolved, having the shallowest slope. Samples of the AMS have similar patterns, a steep slope and clearly negative Eu anomalies. Samples of the KMA have a homogeneous composition, intermediate between the AMS and the DF. Sample 94-297/1, which is an orthoamphibole gneiss (dashed line) has a slightly positive Eu anomaly and shallow slope, similar to DF samples. Chondritic normalizing factors and post-Archean average Australian shale (PAAS) curve are from Taylor and McLennan (1985).



Northwest Territories have yielded an average  $\epsilon\text{Nd}(0)$  of  $\sim -25$  and model ages between 2.0 and 2.4 Ga (Bowring and Podosek 1989). These basement rock data overlap with the AMS samples on the  $\epsilon\text{Nd}(0) - {}^{147}\text{Sm}/{}^{144}\text{Nd}$  plot (Fig. 4). We conclude that the Precambrian basement of Alberta, British Columbia, and the Wopmay Orogen represents the most likely source regions for the AMS on the North American continent.

Studies of plutonic and metamorphic rocks of the Yukon–Tanana terrane in eastern Alaska have yielded  $\epsilon\text{Nd}(0)$  values of  $-27$  to  $-16$  and model ages of 1.9–2.3 Ga, matching the AMS data (McCulloch and Wasserburg 1978; Aleinikoff et al. 1981; Bennett and Hansen 1988).

Broader ranges of  $\epsilon\text{Nd}(0)$  values and  $T_{\text{DM}}$  ages,  $-28$  to  $+2$  and  $\sim 0.6$  to 2.8 Ga, respectively, were obtained from other metamorphic assemblages associated with the Yukon–Tanana terrane: the Tracy Arm, Endicott Arm, Port Houghton, and Ruth assemblages of the western margin of the Coast Plutonic Complex in southeastern Alaska, and the Nisutlin assemblage in the Teslin tectonic zone in southern central Yukon (Fig. 4; Samson et al. 1991; Creaser et al. 1997). These have been interpreted as indicating mixed source terranes ranging from late Archean to Cambrian, as indicated by 0.5–3.0 Ga detrital zircon grains (Gehrels et al. 1991; Samson et al. 1991), or mixed magmatic arc and ancient North American continental crust in the Nisutlin assemblage (Creaser et al. 1997). The Nd isotopic, REE compositions, and model ages of the most evolved Yukon and southeastern Alaska samples are very similar to those of the AMS (Fig. 4), suggesting a similar protolith. However, this does not necessarily imply the same depositional age, since multiple recycling or several depositional phases cannot at present be resolved by such studies in medium-grade metamorphic rocks.

From the limited data set and spatial distribution of AMS samples, it is possible that, unlike other metamorphic assemblages of the Yukon–Tanana terrane, the AMS is derived

from Archean crust without influences of less evolved or younger sources.

#### Dezadeash Formation

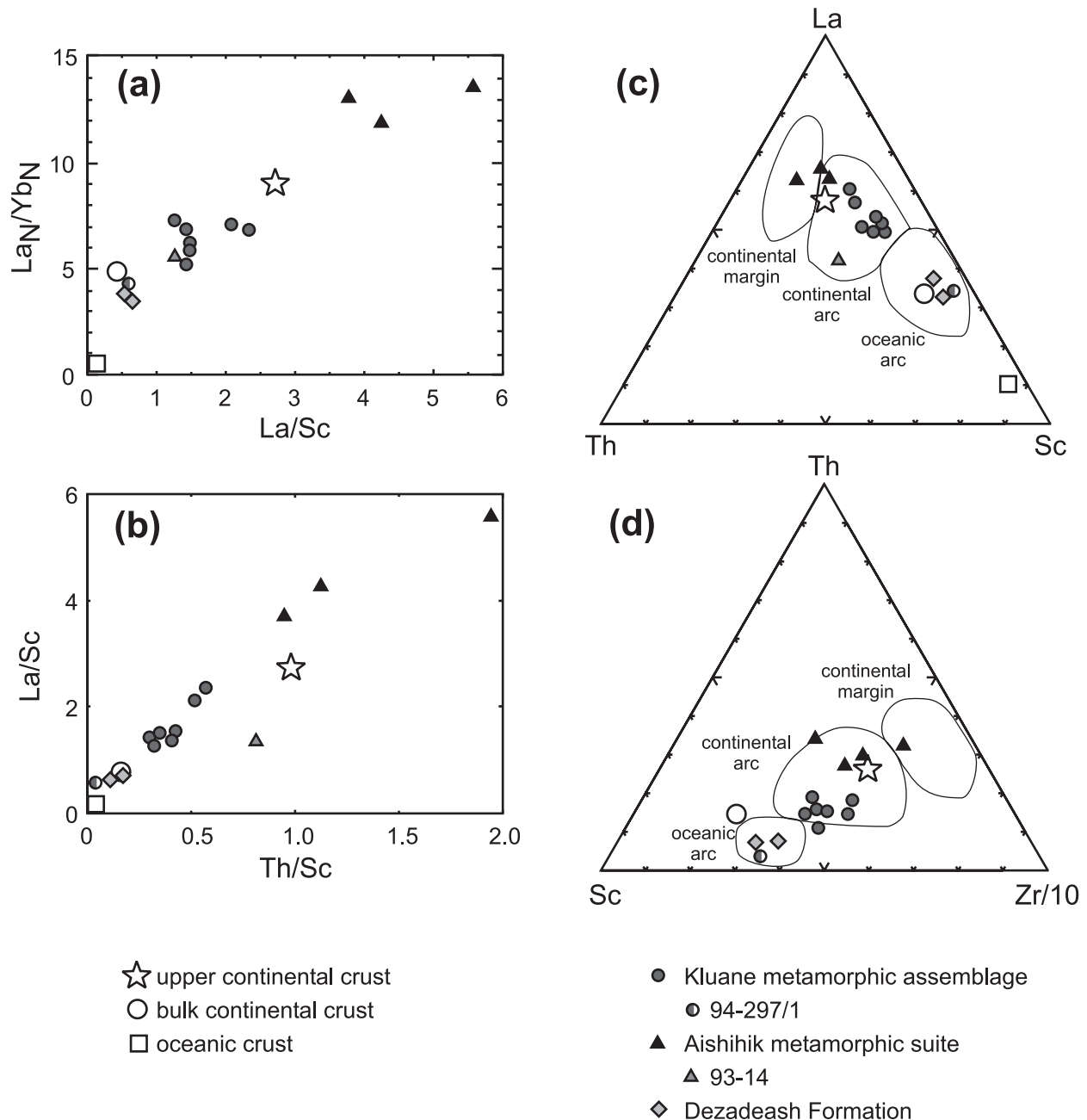
The isotopic data from the DF support the correlation of the DF with the Late Jurassic – Early Cretaceous Gravina–Nutzotin Belt (see Monger et al. 1991). The  $\epsilon\text{Nd}(0)$  values and  $T_{\text{DM}}$  ages of the DF are comparable to those for Gravina Belt rocks in southeastern Alaska ( $\epsilon\text{Nd}(0) = -2$  to  $+3.3$ ,  $T_{\text{DM}} = 0.5$ – $0.9$  Ga), and for the Alexander ( $\epsilon\text{Nd}(0) = -4$  to  $+3$ ) and Wrangellia ( $\epsilon\text{Nd}(0) = 0$  to  $+6$ ) terranes (Fig. 4) (Samson et al. 1989, 1990, 1991). The lower  $\epsilon\text{Nd}(0)$  values of DF sedimentary rocks compared to igneous rocks and sediments derived from juvenile crust indicates contribution from older crustal material. This could be either a small amount of ancient continental crust, similar to the protolith of the AMS, or a large amount of recycled material possibly from the oldest parts of the Alexander terrane (Samson et al. 1989). In the first case, the DF could have been part of the same sedimentary basin as the proto-KMA, but farther from the continental source (see discussion below).

#### Kluane metamorphic assemblage

The geochemical and isotopic characteristics of the KMA define it as a remarkably homogeneous sequence when compared to the Yukon–Tanana terrane. The homogeneity confirms petrological evidence that the contact between the KMA and the Nisling terrane is not a terrane boundary but simply a metamorphic isograd within a coherent assemblage.

North American continental crust can be ruled out as single protolith provenance because of its distinct geochemical and isotopic characteristics (Fig. 4). Parts of the Yukon–Tanana terrane, such as the Nisutlin assemblage or the southeastern Alaska assemblages, are compatible with the most evolved KMA results. However, internal variation of these assemblages is large ( $\epsilon\text{Nd}(0) = -28$  to  $+2$ ) (Samson et al. 1991; Creaser et al. 1997), and a resulting sediment would

**Fig. 3.** The relationship between REE and Sc, Th, and Zr can be used to distinguish KMA, AMS, and DF samples. (a)  $\text{La}_N/\text{Yb}_N$  vs.  $\text{La}/\text{Sc}$ , and (b)  $\text{La}/\text{Sc}$  vs.  $\text{Th}/\text{Sc}$  diagrams show that samples of DF and KMA (94-297/1) plot close to the bulk continental crust composition; AMS samples lie closer to the average upper continental crust, except for sample 93-14, which is either (i) in the KMA field, or (ii) off a linear correlation trend; mica schist samples of the KMA lie on a linear trend between AMS and DF. (c, d) Tectonic setting discrimination diagrams for clastic sedimentary rocks (Bhatia and Crook 1986) indicate that DF samples and KMA sample 94-297/1 plot in the oceanic arc field near the bulk continental crust composition, KMA in the continental arc field, and AMS in both the continental arc and continental margin fields. Upper continental, bulk continental, and oceanic crust values are from Taylor and McLennan (1985).



either record similar variation or have more evolved characteristics than the KMA (Fig. 4).

Alternatively, the KMA could have been entirely derived from the older and more evolved parts of Phanerozoic accreted terranes to the west. However, oceanic and arc terranes (e.g., Alexander terrane) to the west are unlikely to be the sole source, as their oldest known rocks are Late Pro-

terozoic (Souther 1991), and their  $T_{DM}$  ages of 0.5–0.9 Ga (Samson et al. 1991) are significantly younger than those of the KMA (1.2–1.5 Ga).

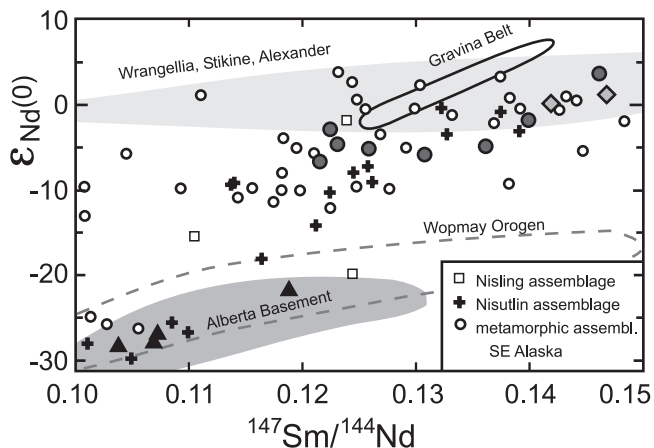
The only group of rocks with geochemical and isotope characteristics similar to the mica–quartz schist of the KMA are biotite–hornblende granodiorite and diorite of the Dawson Range batholith, part of the late Early Cretaceous

**Table 3.** Sm and Nd concentration and isotope data for metamorphic and sedimentary rocks of the SW Yukon.

Sample	Rock	Sm (ppm)	Nd (ppm)	$\frac{^{147}\text{Sm}}{^{144}\text{Nd}}$	$\frac{^{143}\text{Nd}}{^{144}\text{Nd}}$	$\epsilon\text{Nd}(0)$	$\epsilon\text{Nd}(140)$	$T_{\text{DM}}(\text{Ga})$
93-96	KMA	4.86	23.53	0.1250	0.512422±7	-4.2	—	1.27
93-136	KMA	4.19	20.52	0.1234	0.512352±9	-5.6	—	1.37
93-156	KMA	4.54	21.91	0.1253	0.512415±12	-4.4	—	1.29
94-36	KMA	4.22	19.58	0.1303	0.512383±9	-5.0	—	1.42
94-82	KMA	4.18	20.65	0.1225	0.512468±11	-3.3	—	1.16
94-272	KMA	7.24	31.83	0.1375	0.512437±9	-3.9	—	1.45
94-297/1	KMA	3.00	12.57	0.1444	0.512836±9	+3.9	—	0.72
94-346	KMA	4.87	21.08	0.1400	0.512569±11	-1.4	—	1.22
94-190	DF	2.91	12.37	0.1421	0.512719±12	+1.6	+2.6	0.94
94-204b	DF	4.32	17.76	0.1479	0.512748±10	+2.2	+3.0	0.96
93-16	AMS	8.62	48.61	0.1072	0.511344±13	-25.2	—	2.59
93-67	AMS	6.11	35.57	0.1038	0.511209±10	-27.9	—	2.69
93-14	AMS	4.25	21.58	0.1190	0.511589±9	-20.5	—	2.52
93-42	AMS	9.39	53.08	0.1070	0.511291±16	-26.3	—	2.66

**Note:**  $^{143}\text{Nd}/^{144}\text{Nd}$  uncertainties are quoted as  $2\sigma_m$ .  $\epsilon\text{Nd}(0) = (^{143}\text{Nd}/^{144}\text{Nd}_{\text{meas}}/^{143}\text{Nd}/^{144}\text{Nd}_{\text{Chur}} - 1) \times 10^4$ ; present-day  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{Chur}} = 0.512638$ , normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  (DePaolo and Wasserburg 1976).  $T_{\text{DM}} = 1/\lambda \times \ln((^{143}\text{Nd}/^{144}\text{Nd}_{\text{meas}} - ^{143}\text{Nd}/^{144}\text{Nd}_{\text{mantle}})/(^{147}\text{Sm}/^{144}\text{Nd}_{\text{meas}} - ^{147}\text{Sm}/^{144}\text{Nd}_{\text{mantle}}) + 1)$  (DePaolo 1981); Goldstein et al. (1984) values for  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{mantle}} = 0.513163$  and  $^{147}\text{Sm}/^{144}\text{Nd}_{\text{mantle}} = 0.2138$ .

**Fig. 4.**  $\epsilon\text{Nd}(0)$  versus  $^{147}\text{Sm}/^{144}\text{Nd}$  of the samples under investigation compared to other data from the northern Cordillera. The DF samples fall into the field of sedimentary and igneous rocks of the Alexander, Wrangellia, and Stikine terranes, and the Gravina Belt (Samson et al. 1989, 1990, 1991). The AMS samples plot in the same field as Archean rocks of the Alberta basement (Thériault and Ross 1991). Other metamorphic rocks include the Nisutlin assemblage of the Teslin tectonic zone in the Yukon (Creaser et al. 1997), the Nisling assemblage of northern British Columbia (Jackson et al. 1991), and smaller metamorphic assemblages along the western margin of the Coast Plutonic Complex in southeastern Alaska (Samson et al. 1991).



(111–99 Ma) Whitehorse – Coffee Creek suite (Mortensen et al. 2000). The Dawson Range batholith is 300 km long and 60 km wide, and exposed approximately 100 km north of the present-day KMA. Recent Nd isotope study has yielded  $\epsilon\text{Nd}(0)$  values of  $-8.6$  to  $-5.4$  and  $T_{\text{DM}}$  of 1.13–1.53 Ga (Selby et al. 1999), similar to values obtained from the KMA. Trace-element characteristics are also similar, as shown in the Th/Sc, La/Sc ratios (Figs. 5b, 5c). Eu/Eu\* ra-

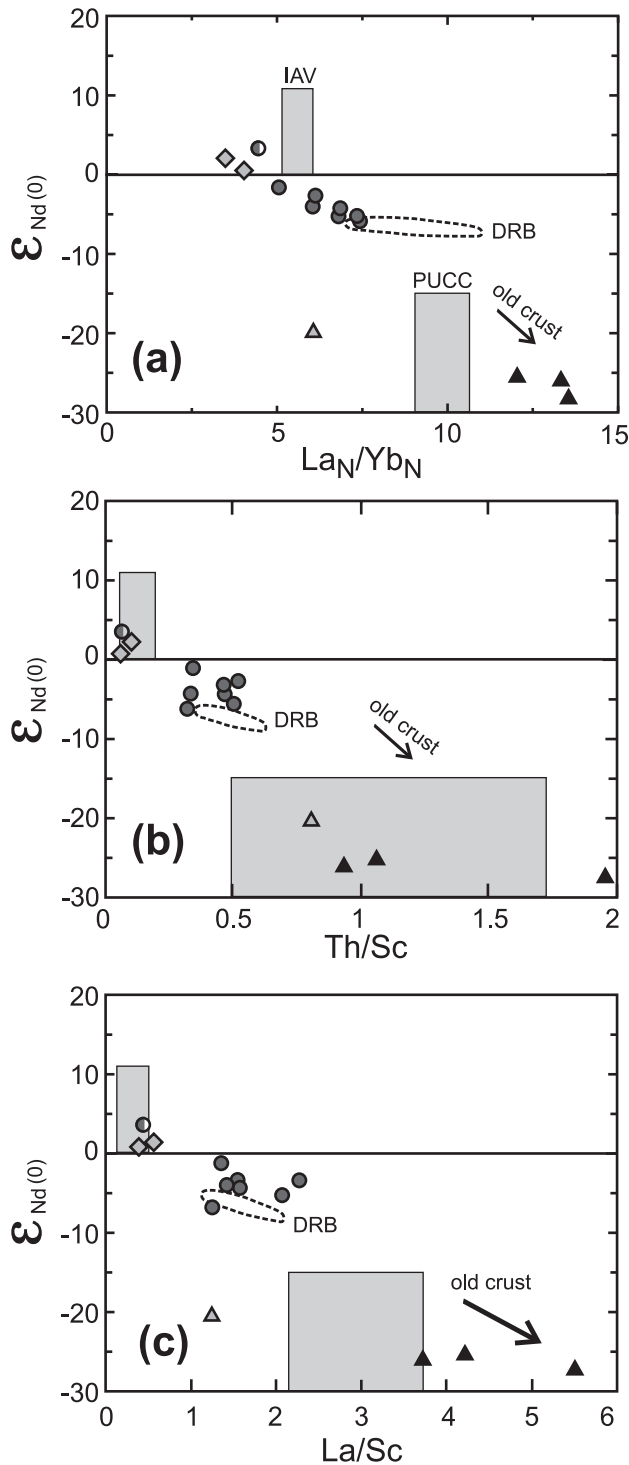
tios of 0.85–1.44 are somewhat higher than those of the KMA (0.69–1.09). LREE are more enriched over HREE ( $\text{La}_N/\text{Yb}_N = 7.1$ –10.8) compared to KMA samples (Fig. 5a) (Selby et al. 1999).

Alternatively, the sedimentary protolith of the KMA was derived from multiple sources. Nd isotope and trace-element discrimination plots (Figs. 3, 5) show that the mica–quartz schists of the KMA could be derived from mixed accreted (e.g., the DF) and North American (e.g., the AMS) terranes. This would require detritus from a volcanic arc to be mixed with material derived from an ancient continent. The existence of a volcanic arc is implied by the distinctive orthoamphibole gneiss (sample 94-297/1), with relatively juvenile andesitic characteristics ( $\epsilon\text{Nd}(0)$  of +3.9 and  $T_{\text{DM}}$  of 720 Ma), and is also compatible with the composition of igneous rocks of the Wrangellia and Alexander terranes (Samson et al. 1989, 1990). Andesite is common in the Alexander terrane and occurs nearby southwest of Dezadeash Lake (e.g., in the Field Creek volcanic strata of Cambrian age; Dodds and Campbell 1992).

### Tectonic setting of the sedimentary protolith of the KMA

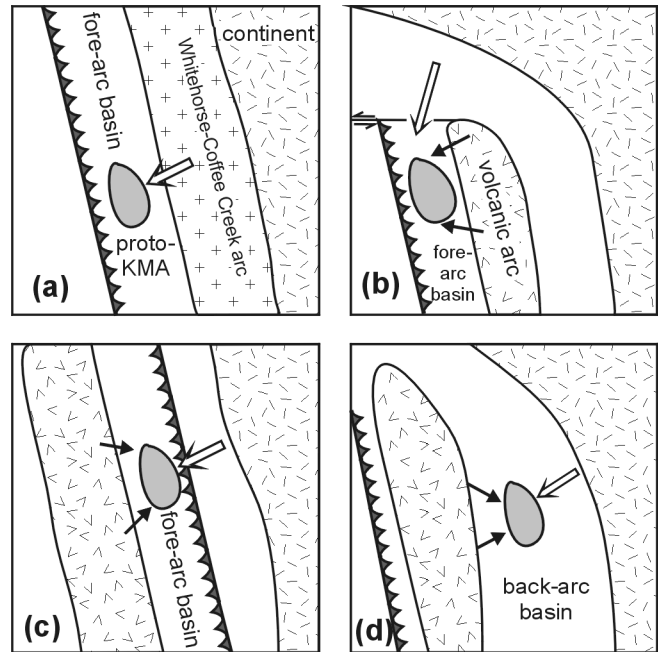
Deformation, metamorphism, and accretionary tectonism have obliterated depositional environment information about the protolith of the KMA. The absence of recognizable clasts and the presence of pervasive graphite suggest that the protolith was a fine-grained pelitic rock with significant residual organic matter. Interlayered with the KMA schist units are layers of actinolite rock and orthoamphibole gneiss that imply proximity to a volcanogenic source. The interfoliated lenses of serpentinized dunite are inferred to represent fragments of oceanic crust that were tectonically juxtaposed with the schist prior to accretion onto North America (Mezger 2000). A minimum age of accretion is given by a latest Cretaceous (72 Ma) biotite granite dyke, as-

**Fig. 5.** (a)  $La_N/Yb_N$ , (b) Th/Sc, and (c) La/Sc vs.  $\epsilon_{Nd}(0)$ . AMS samples plot near the Precambrian upper continental crust (PUC) field, whereas DF samples plot close to the island-arc volcanic field (IAV). The KMA orthoamphibole gneiss plots close to the DF samples. KMA samples lie on a line that joins the DF and AMS clusters, implying a possible origin of the KMA by mixing protoliths of the DF and AMS. Three granodiorite samples from the Dawson Range batholith (DRB) overlap with KMA schist (Selby et al. 1999). Same symbols as in Fig. 3. Average present-day volcanic arc Nd composition is



after Faure (1986). Precambrian upper continental crust range is adapted from Taylor and McLennan (1985), and McLennan and Hemming (1992).

**Fig. 6.** Possible tectonic settings for the protolith of the KMA: (a) one of the single-source models; (b)–(d) various scenarios for multiple-source models. See text for discussion.

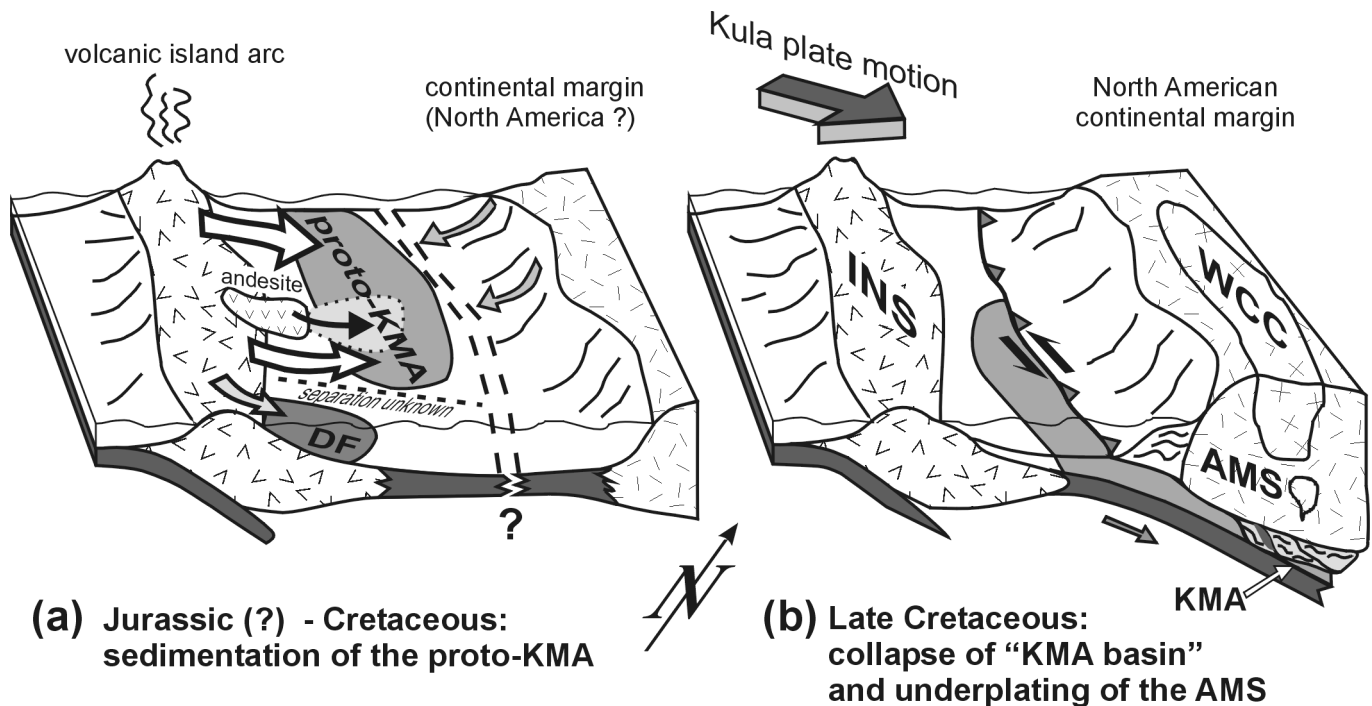


sociated with the early mafic phase of the Ruby Range batholith, which truncates penetrative fabrics of the KMA schist (Mezger 1997). Detrital zircon grains occur in samples of the KMA and could provide more information on the age of potential protoliths, but the grains observed are both scarce and too small to be reliably analyzed by presently available analytical techniques ( $\leq 20 \mu\text{m}$ ).

Given these constraints, we now discuss single- and multiple-source models for the sedimentary protolith of the KMA. Detritus from the eroded Dawson Range batholith have geochemical and isotopic characteristics compatible with the KMA schist and form a possible single source. However, additional input is necessary to account for the ubiquitous graphite. Derivation from a single source does not constrain the tectonic setting and can include deposition in either a fore-arc basin (Fig. 6a), a deep sea trench, or a back-arc basin proximal to the magmatic arc represented by the Dawson Range batholith. Fore-arc basin sediments are generally located inboard a trench slope break and are deposited onto an accretionary wedge. It is difficult here to find a process that would allow only fragments of oceanic crust to be tectonically interleaved during the subduction of the fore-arc basin, without involvement of the associated oceanic or accretionary wedge sediments. The same problem arises with deposition only in a deep sea trench; some trace of oceanic sediment would remain in the vicinity of the ultramafic lenses in the KMA.

The Dawson Range batholith as a single source for the KMA would limit deposition of the KMA to Late Creta-

**Fig. 7.** Postulated tectonic evolution model for the KMA in the late Mesozoic. Coeval deposition of DF and proto-KMA is speculative. See text for discussion. INS, Insular Superterrane; WCC, Whitehorse – Coffee Creek arc.



ceous time. The emplacement of the batholith at 100–90 Ma, followed by rapid uplift and erosion, would have preceded deposition of the proto-KMA and ductile deformation prior to 72 Ma.

Tectonic models based on multiple protolith provenances, that is, both juvenile and evolved, can be proposed. A first possibility is that the protolith of the KMA was deposited in a fore-arc basin outboard of a volcanic arc, with continental detritus transported trench-parallel from a source to either the north or south (Fig. 6b). However, present regional geological relations do not show evidence of volcanic-arc rocks inboard of the KMA. Another possible setting is a fore-arc basin, with the arc in the west and the continent in the east, and westward subduction (Fig. 6c). However, subsequent underplating of the KMA against North America would necessitate a reversal of subduction polarity, for which there is no evidence.

The geological evolution we consider the most likely initiates with deposition of the proto-KMA in a back-arc basin situated inboard (east of) a volcanic arc and outboard (west of) the North American continental margin (Figs. 6d, 7a). The isotopic and petrographic homogeneity of the KMA suggest that the original sediments were an unusually uniform mix of predominantly juvenile and minor mature detritus throughout deposition. The homogeneous mixing of fine detritus occurred in a highly restricted and highly reducing basinal environment that preserved significant organic material. The accretion of the KMA against the continental margin resulted from eastward subduction beneath the AMS (Fig. 7b); the polarity of subduction is inferred from mineral lineation and other non-coaxial strain indicators in mylonite (Mezger 1996, 1997). The KMA did not experience more than one phase of penetrative ductile deformation. This strongly suggests that collapse of the KMA basin occurred

in the Late Cretaceous (95–80 Ma), a time when the postulated Kula (Pacific) plate was moving eastward relative to North America at this latitude (Engebretson et al. 1995). If the Whitehorse – Coffee Creek arc contributed to the sedimentation of the KMA, then the basin was still active by 110 Ma. However, if the Whitehorse – Coffee Creek arc was related to the subduction of the KMA beneath the continental margin, then the minimum age of the KMA back-arc basin would be late Early Cretaceous (~110 Ma). In that case, the protolith of the KMA could be of the same age as the DF (~135–160 Ma), and could have been part of the same basin, although compositionally distinct.

## Conclusions

- (1) The Kluane metamorphic assemblage, the Aishihik metamorphic suite, and the Dezadeash Formation are distinguished by their trace-element, REE, and neodymium isotope characteristics. Their present spatial proximity in the northern Coast Belt of the Canadian Cordillera is the result of tectonic juxtaposition.
- (2) Strongly negative  $\epsilon_{\text{Nd}}(0)$  values and late Archean crustal residence ages of the AMS are comparable to those of metamorphic rocks of the Yukon–Tanana terrane and of the buried Precambrian basement of northwestern North America, which is entirely compatible with derivation from continental North America.
- (3) Rocks of the DF display trace-element and REE patterns, Nd isotope characteristics, and late Middle Proterozoic model ages indicating a predominant arc source. Some clastic input from evolved crust, either continental North America or possibly older parts of oceanic assemblages, such as the Alexander terrane,

produced Nd isotope compositions slightly lower than depleted mantle.

- (4) The KMA, situated between the AMS and the DF, has intermediate isotopic characteristics and may have formed by mixing of detritus from Archean and juvenile sources. The KMA is not simply a metamorphosed equivalent of the DF. As original spatial relations between the KMA, AMS and DF are unknown, the KMA could be the result of mixing of AMS and DF rocks, or mixing of their protoliths, or of similar but unrelated protoliths. Alternatively, the KMA is derived from the Dawson Range batholith to the north, which has similar geochemical and isotope characteristics, but lacks an obvious source of organic material.
- (5) A compatible tectonic setting of the KMA is a back-arc basin distal to a continental source and proximal to a volcanic arc. If the depositional ages of the KMA and DF are similar, the DF could have been deposited in the same basin, but closer to the arc.

## Acknowledgments

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