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Strontium and neodymium isotope ratios in the Fraser River, British Columbia: a riverine transect across the Cordilleran orogen

Eion M. Cameron [a,b,*], Kéiko Hattori [b]

[a] Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada
[b] Ottawa–Carleton Geoscience Centre and University of Ottawa, Ottawa, ON K1N 6N5, Canada

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Abstract

The Fraser is the largest undammed river to traverse the North American Cordillera. Its source is in Precambrian/Palaeozoic sedimentary rocks of the Rocky Mountains, at the margin of the North American Craton, from where it flows west across accreted ensimatic terranes, to the young magmatic arc of the Coast Range. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ in suspended matter from the Fraser and its tributaries outline a mixing curve between two end members, (a) LILE-rich cratonic material with $^{87}Sr/^{86}Sr$ ~ 0.77 and ε_{Nd} (0) ~ -23 and an Archaean crustal residence age and (b) material from mantle-derived igneous rocks with $^{87}Sr/^{86}Sr$ ~ 0.704 and ε_{Nd} (0) $\sim +4$ and a crustal residence age of ~ 0.6 Ga. In the eastern, ensialic region, dissolved Sr is less radiogenic than Sr in suspended matter, because of the contribution of dissolved Sr from Rb-poor carbonate rocks. As the Fraser flows west over younger terranes, this relationship inverts, with dissolved Sr more radiogenic. Inversion reflects a difference in the transport behaviour of dissolved and suspended material. Dissolved Sr from upstream, with a radiogenic signature, remains in solution, whereas the suspended load from upstream tends to fall out where the current decreases, to be replaced by local, less radiogenic material. For riverborne fluxes entering the ocean at active margins, compositions of conservative dissolved elements, such as Sr, represent both the interior craton and the outer orogen, while elements carried mainly in suspended form, such as Nd, are biased towards the outer orogen.

Keywords: River; Strontium; Neodymium; Isotope

1. Introduction

Strontium in the oceans is well mixed and its composition is determined by the dissolved riverine flux and exchange during seawater penetration along ocean ridges (Palmer and Edmond, 1992). The behaviour of Nd is more complex. A large proportion of 'dissolved' Nd is in colloidal form, which undergoes coagulation in estuaries (Sholkovitz, 1995). The flux of dissolved Nd in rivers is small relative to the total flux of the dissolved and suspended phases (Goldstein and Jacobsen, 1987, 1988; Sholkovitz, 1995). In seawater, Nd may be dissolved from river-suspended material (Sholkovitz, 1995). In this paper we consider only the isotopic composition of Nd in the suspended material from the Fraser. Neodymium has a short residence time in the oceans, which

* Corresponding author.

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permits variations in isotopic composition between oceans. Thus Nd in the Pacific is more radiogenic than in the Atlantic (Piepgras et al., 1979), because of a preponderance of active margins around the Pacific and many island arcs. While rivers traversing active margins significantly influence ocean isotopic signatures, there have been no detailed studies of their Nd and Sr isotope geochemistry. The Fraser River is a typical large river of an active margin, draining an area of 238,000 km^2, with a mean annual discharge of 3630 m^3/s. Its source is in ancient cratonic terrane and dissects younger orogenic belts on its way to the coast. The main stem Fraser is the largest undammed river that traverses the North American Cordillera. Given that dams interrupt the transport of suspended matter, this river reasonably represents conditions existing prior to industrialisation.

2. Geology of the Fraser watershed

The source of the Fraser is in the Foreland Belt (Fig. 1), an easterly-thinning prism of Upper Proterozoic and Palaeozoic clastic and carbonate sedimentary rocks along the margin of the North American Craton. To the west, the Omineca Belt contains sedimentary and metasedimentary rocks of mainly Late Proterozoic age deposited upon and in part derived from a thinning ramp of Precambrian basement extending west from the craton (Ross and Parrish, 1991; Cook et al., 1991). While the Foreland Belt is entirely ensialic, the Omineca Belt contains rocks that are transitional to the ensimatic belts to the west. These include igneous rocks with a mantle component and a small area of accreted oceanic terrane. Armstrong's (Armstrong, 1988) 0.704 contour of initial $^{87}Sr/^{86}Sr$ ratios for Mesozoic igneous rocks roughly parallels the boundary of the Omineca and Intermontane belts. East of the contour, igneous rocks with higher ratios incorporated crustal material, whereas areas to the west are underlain by ensimatic crust.

The Intermontane Belt is a collage of accreted terranes that became joined to the craton margin in Mesozoic time, comprised mainly of volcanic and sedimentary rocks of Late Triassic to early Tertiary age intruded by I-type granitoids. Based on Nd isotope evidence, the Stikine terrane, which forms the largest part of this belt, is of mantle origin (Samson et al., 1989). Finally, the Coast Belt is an Andean-type magmatic arc, with Jurassic to Tertiary plutonic rocks of average quartz–diorite composition (Armstrong, 1988) and Cretaceous to Tertiary volcanic rocks and Permian to Cretaceous metamorphic rocks. A large area within the southwest portion of the watershed is covered by basaltic rocks ranging from 15 Ma to post-glacial in age. In terms of area, the Foreland Belt comprises 6% of the Fraser watershed, the Omineca 22%, the Intermontane 58% and the Coast Belt 14%.

The Fraser watershed extends over three physiographic regions. The Coast Mountains, roughly coincident with the Coast Belt, have high precipitation and block the moist winds that move east from the Pacific, giving the Interior Plateau a dry climate. The Eastern Mountains region, comprising the Foreland Belt and the eastern margin of the Omineca Belt, has a moderate to high precipitation. Winter freezing, when precipitation falls mainly as snow, followed by snowmelt, gives rise to considerable seasonal variation in river flow: low in the winter, peaking in the early summer.

The headwaters of the Fraser in the Rocky Mountains are fast-flowing and pass through Moose Lake, the only lake along its course. There is a sharp change of gradient as the river enters and flows northwest along the flat-bottomed floor of the Rocky Mountain Trench, which is the boundary between the Foreland and Omineca belts (Fig. 1). It then bends south, flowing swiftly between high gravel banks, before passing through the Coast Range in a deep, rocky canyon. After leaving the Coast Range the estuary of the Fraser begins downstream of Hope (Fig. 1). There are no dams on the Fraser or on its principal tributary, the Thompson. There are dams on two tributaries, the upper part of the Nechako (see Kenney Dam Diversion, Fig. 1) and on the Bridge River.

From the Rocky Mountain Trench to the where it enters the Coast Range, the Fraser flows through a frequently thick sequence of tills and other glacial sediments, overlain by fluviatile, aeolian and colluvial sediments. The glacial sediments were deposited by the Cordilleran Ice Sheet, which covered the whole region during glacial maxima. Suspended ma-

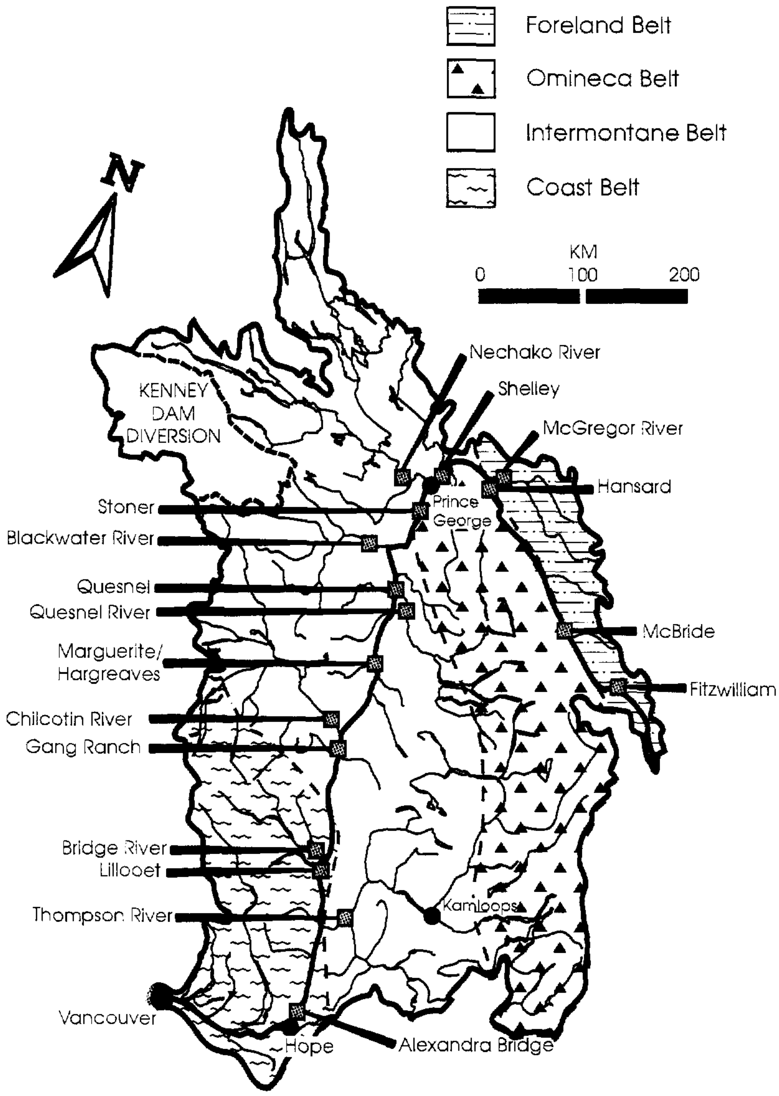

Fig. 1. Map of the Fraser River watershed showing sampling sites on the Fraser and its principal tributaries. Geological belts from Wheeler et al. (1991).

terial derived from these sediments gives the Fraser waters a turbid appearance, particularly during flood. Waters of the tributary rivers contain less suspended material, the result of flowing along rocky mountain courses or through lakes. At Hope the Fraser has a mean annual flow of 2700 m^3/s and has a mean annual suspended matter content of 210 ppm (Milliman, 1980). Most suspended material is carried during the early to mid stages of the period of high discharge (~ 1 May to 1 July at Hope) and is mainly sand, whereas in the latter part of this period and at other times suspended matter is mainly fine silt and clay (Milliman, 1980).

3. Sampling and analysis

Ten sites on the Fraser and seven sites on its principal tributaries (Fig. 1) were sampled in late July, 1993, towards the end of the period of high discharge, when the waters contained moderately

Table 1

Elemental and isotopic data for waters and suspended material from the Fraser River and its principal tributaries (± is 2σ error)

Station	Dissolved			Suspended material											
	Sr (ppb)	Rb (ppb)	$^{87}Sr/^{86}Sr$	Sr (ppm)	Rb (ppm)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	T_{CR} Sr (Ga)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd} (0)	T_{CR} Nd (Ga)	$\varepsilon Sr_{diss} - \varepsilon Sr_{susp}$
Fraser, Fitzwilliam	39	0.12	0.751349±09	139	200	0.772408±60	4.19	1.18	14.93	79.6	0.113	0.511435±23	−23.5	2.59	−299
Fraser, McBride	96	1.36	0.726804±07	127	124	0.747322±11	2.84	1.12	5.23	28.6	0.111	0.511560±11	−21.0	2.34	−291
Fraser, Hansard	114	1.06	0.723610±08	106	81.1	0.738092±11	2.22	1.14	5.30	28.0	0.114	0.511554±12	−21.1	2.44	−205
Fraser, Shelly	98	0.75	0.721035±08	142	107	0.734015±15	2.19	1.03	5.08	27.2	0.113	0.511680±20	−18.7	2.22	−184
Fraser, Stoner	88	0.61	0.716368±07	155	83.9	0.724149±15	1.57	0.99	4.79	26.0	0.111	0.511741±35	−17.5	2.09	−110
Fraser, Quesnel	86	0.65	0.715300±07	178	67.7	0.714304±25	1.10	0.78	5.21	26.6	0.118	0.512073±12	−11.0	1.72	+14
Fraser, Marguerite	95	0.65	0.715114±09	217	79.1	0.713862±50	1.06	0.79	5.21	25.9	0.122	0.512022±45	−12.0	1.87	+18
Fraser, Gang Ranch	91	0.60	0.713939±08	279	57.8	0.711256±28	0.60	1.11	3.55	17.8	0.120	0.512302±18	−6.6	1.39	+38
Fraser, Lillooet	94	0.60	0.713706±10	242	55.9	0.709360±25	0.67	0.77	3.90	19.8	0.119	0.512172±22	−9.1	1.57	+62
Fraser, Alexandra Br.	85	0.83	0.712707±08	249	44.9	0.709775±20	0.52	1.07	3.37	16.2	0.126	0.512253±12	−7.5	1.56	+42
McGregor River	62	0.35	0.719104±10	128	89.9	0.722672±60	2.03	0.71	4.87	25.9	0.114	0.511729±10	−17.7	2.16	−51
Nechako River	64	0.37	0.705026±10	276	39.0	0.705387±22	0.41	0.54	4.51	22.4	0.122	0.512699±14	1.2	0.75	−5
Quesnel River	126	0.46	0.714486±34	266 [a]	110 [a]	0.714005±40	1.20	0.69	5.41 [a]	27.4 [a]	0.119	0.511847±20	−15.4	2.10	+7
Blackwater River	65	1.40	0.704510±07	231	27.0	0.704498±22	0.34	0.45	5.54	24.6	0.136	0.512611±20	−0.5	1.06	0
Chilcotin River	56	0.44	0.704253±08	332	31.2	0.704225±12	0.27	0.50	3.39	14.8	0.138	0.512859±15	4.3	0.59	0
Bridge River	115	0.35	0.704847±09												
Thompson River	70	1.23	0.712170±06	323 [a]	72.7 [a]	0.707890±22	0.65	0.61	4.96 [a]	23.9 [a]	0.125	0.512476±12	−3.2	1.16	+61

[a] Analysis by isotopic dilution.

high amounts of suspended matter as silt and clay. Where possible, surface waters were collected from the centre of bridges, well below inflows of major tributaries. The possibility that tributary waters do not mix because of laminar flow is minimized over much of the length of the Fraser because of turbulent flow conditions. Samples were filtered through a 0.45-μm filter (Millipore, type HAWP). These samples were used for isotopic analysis of dissolved Sr and for Sr and Nd in suspended material.

For Nd and Sr isotopic analysis, dried suspended matter was scraped from filters and approximately 10 to 40 mg of material dissolved using $HF–HClO_4$ (10:1) in Savillex screw-top Teflon vials at 200°C. Because of the fine grain size of suspended matter, the reaction was fast and clear solutions were obtained within several hours, but the vessel was kept at 200°C overnight to ensure complete dissolution. Samples were then dried at 200°C to remove $HClO_4$ and reacted with 6 *N* HCl, followed by evaporation to dryness. Reaction with HCl and evaporation to dryness was repeated twice and the sample was dissolved in 2.5 *N* HCl for cation separation using Bio Rad AG 50 W-X8 (200–400 mesh). Strontium and REE were eluted with 2.5 *N* HCl and 6.1 *N* HCl, respectively. Nd and Sm were separated from other REE using a Teflon powder resin coated with di-ethylhexyl orthophosphoric acid. Total chemical blanks are less than < 0.1 ng for Nd and < 0.05 ng for Sr, negligible in comparison to the minimum amounts of Sr (1000 ng) and Nd (148 ng) present in the sample aliquots.

Isotopic measurements were on a multi-collector thermal ionization mass spectrometer (Finnigan MAT 261), and the ratios for Sr and Nd isotopes were normalized to $^{86}Sr/^{88}Sr$ of 0.1194 and $^{146}Nd/^{144}Nd$ of 0.7219. During the course of isotopic analysis, measurements of NBS987 and E and A standards gave $^{87}Sr/^{86}Sr$ of 0.710270 ± 19 ($N = 20$) and 0.708048 ± 17 ($N = 11$), respectively. $^{143}Nd/^{144}Nd$ of La Jolla is 0.511868 ± 17 ($N = 35$). Goldstein et al. (1984) found a difference of 0.7 ε-values for duplicate samples from the Ganges and 0.4 between the fine and bulk fractions from the Amazon. Considering this sampling variation in ε_{Nd}, plus possible seasonal variation in the suspended phases, mass spectrometer runs were terminated after collecting 50 to 60 ratio measurements.

Concentrations of Sr, Rb, Nd and Sm in two samples (identified in Table 1) were determined by thermal ionization mass spectrometry. This entailed isotope dilution using mixed spikes of $^{84}Sr–^{87}Rb$ and $^{148}Nd–^{149}Sm$ added to the samples before digestion. For the remaining samples, the concentrations of these elements were determined by ICP–MS measurements carried out as part of a broader study of the geochemistry of the Fraser. For the ICP–MS analyses, 1 ml HNO_3 and 3 ml HCl was added to the filtered particulates in a polypropylene tube. All acids were Ultrex. After sitting overnight, tubes were heated at 90°C for 1.5 h. Then 5 ml of a 5:3:2 $HF–HClO_4–HNO_3$ mixture was added and heated for 1 h at 90°C with the tube capped. The solution was transferred to a Teflon beaker and heated at 70°C overnight. The temperature was increased to 125°C until dryness. The material was re-dissolved with 1.5 ml HNO_3 and water added to make a 30-ml volume, then analyzed using a VG PlasmaQuad 2 Plus ICP–MS with concentric nebulisation. Strontium was analyzed using an ISA Instruments ICP–ES. Data for Nd and Sm were used to estimate crustal residence time (T_{CR}) (Table 1). This estimate appears to be relatively insensitive to methods of chemical extraction. Data for Nd and Sm concentrations in the particulate material using a partial (HNO_3–HCl) extraction were also available. These gave values of T_{CR} that ranged from 0.8% less to 6% greater than that obtained from the $HF–HClO_4–HNO_3$ treatment.

4. Results

For the suspended matter, elemental concentrations of Rb, Sr, Sm and Nd and isotopic data for Sr and Nd are listed in Table 1, together with isotopic data for dissolved Sr and the elemental abundances for dissolved Sr and Rb in the waters, the latter from Cameron et al. (1995). Crustal residence time (T_{CR}) was calculated with respect to the evolution of the depleted mantle (DM), assuming a linear evolution of DM in $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ from the origin of the earth to the present. The values for $^{143}Nd/^{144}Nd$, $^{147}Sm/^{144}Nd$, $^{87}Sr/^{86}Sr$, $^{87}Rb/^{86}Sr$ of DM used for the calculation are 0.513151 ($\varepsilon_{Nd}(0) = +10$), 0.2136, 0.702706 and 0.05852, respectively. ε-notation for $^{87}Sr/^{86}Sr$ and for $^{143}Nd/^{144}Nd$

were calculated using bulk earth values of 0.704755 and 0.512638, respectively.

5. Interpretation

5.1. Nd- and Sr-isotopes in suspended matter

The watershed of the first station on the Fraser at Fitzwilliam (Fig. 1) is entirely underlain by Upper Proterozoic to Ordovician clastic and carbonate sedimentary rocks of the Foreland Belt. From exposures elsewhere (McDonough and Parrish, 1991), these are known to rest on a basement of granitoid gneiss, which was a source of detritus for the sedimentary rocks (e.g., Ghosh and Lambert, 1989). In Fig. 2 we compare ε_{Nd} (0) versus $^{147}Sm/^{144}Nd$ for suspended matter from the Fraser at Fitzwilliam with similar data for Upper Proterozoic to Ordovician clastic sediments from southeastern British Columbia (Burwash et al., 1988; Ghosh and Lambert, 1989). Samples of clastic sedimentary rocks display a wide range in $^{147}Sm/^{144}Nd$, whereas the suspended matter is in the middle of the range, close to the average exposed upper crust of 0.114 (Goldstein and Jacobsen, 1988). This suggests that suspended material in the river is a well homogenised mixture of detritus from different rock types in the local watershed. The suspended matter from Fitzwilliam has a late Archaean T_{CR} of about 2.62 Ga, within the range of the clastic sedimentary units shown in Fig. 2.

The data given in Table 1 also show a broad tendency for $^{147}Sm/^{144}Nd$ in the suspended material to increase as ε_{Nd} (0) increases and T_{CR} decreases. This observation for a single river system conforms to the trend established over a variety of rivers by Goldstein and Jacobsen (1988).

Suspended matter in the Fraser's headwaters at Fitzwilliam have unusually high contents of Rb and Nd, with Rb/Sr > 1, Nd/Sr > 0.5 (Fig. 3A), compared to average upper continental ratios of 0.32 for Rb/Sr and 0.07 for Nd/Sr (Taylor and McLennan, 1985). Examination of this sample by SEM showed an abundance of muscovite, which is common in the clastic sedimentary rocks of the western Rockies (R.R. Parrish, pers. commun., 1995). Retention of Rb relative to Sr in solid products of weathering is evidenced by high values for Rb/Sr in suspended matter compared to the same ratio for dissolved cations (Fig. 4). Suspended matter in the Fraser shows a steady decrease in Rb/Sr (Fig. 4) and Nd/Sr downstream (Fig. 3A), due to the increasing contributions from mafic volcanic rocks in these ensimatic terranes. Mafic rocks contain pyroxenes, calcic plagioclase and amphiboles, which are high in Sr and easily weathered. The increasingly ensimatic

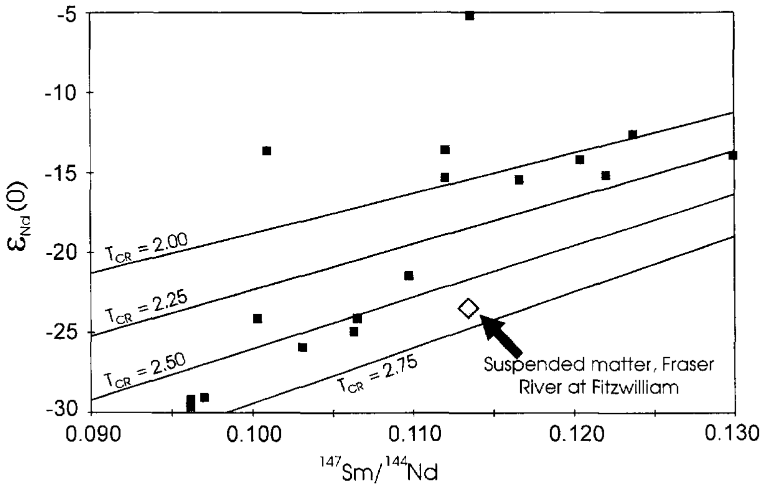

Fig. 2. Plot of ε_{Nd} (0) versus $^{147}Sm/^{144}Nd$ for suspended matter in the Fraser River at Fitzwilliam and for Upper Proterozoic and Palaeozoic clastic sedimentary rocks from southeastern British Columbia (Burwash et al., 1988; Ghosh and Lambert, 1989), together with crustal residence age (*TCR*) reference isochrons.

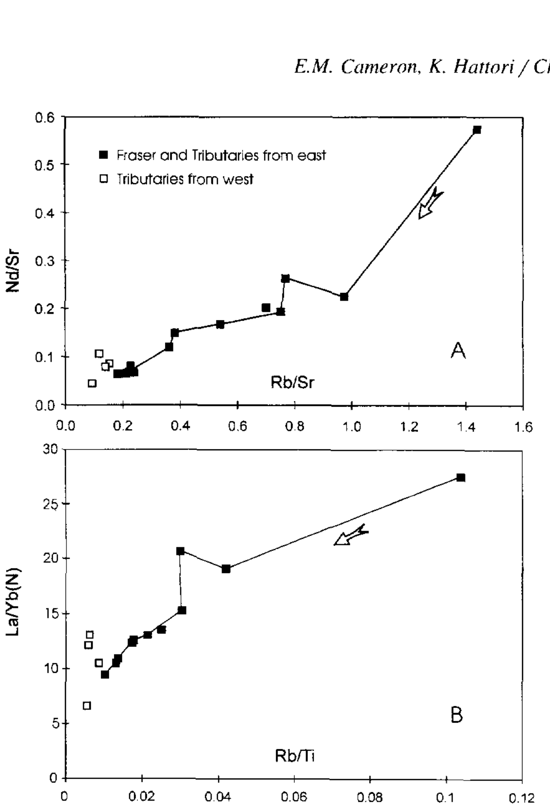

Fig. 3. (A) Nd/Sr versus Rb/Sr and (B) La/Yb(N) versus Rb/Ti for suspended matter in the Fraser River (symbols connected by line) and tributaries. Arrow indicates direction of flow. The cluster of four solid squares in the lower left of plot (A) are for the Gang Ranch, Lillooet, and Alexandra Bridge stations on the Fraser and for the Thompson River. Data for La and Yb were normalized using the chondrite values from McDonough and Sun (1995).

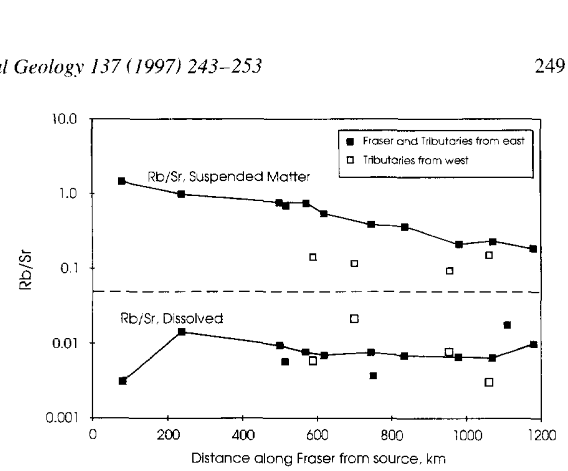

Fig. 4. Rb/Sr ratios for dissolved material and for suspended matter in the Fraser River (symbols connected by line) and tributaries.

nature of the western terranes is also demonstrated by the plot of La/Yb(N) versus Rb/Ti (Fig. 3B). Mafic rocks show lower La/Yb ratios, lower Rb and higher Ti than felsic rocks.

The high $^{87}Sr/^{86}Sr$ ratio for suspended material in the Fraser at Fitzwilliam (Fig. 5) is consistent with the high Rb/Sr ratio and the age of the source rocks. T_{CR} for Rb–Sr is, however, much younger than T_{CR} for Sm–Nd similar to what has been demonstrated for other river systems (Goldstein and Jacobsen, 1988; Négrel et al., 1993). This is explained by incoherent behaviour of Rb and Sr, with preferential retention of Rb over Sr in mature clastic sediments and in riverine suspended matter (Fig. 3A). Suspended matter from Fitzwilliam can be considered the ensialic end member determining the isotopic and chemical composition of suspended matter in the Fraser system. As the river moves west to the coast, there is an increasing contribution of ensimatic, younger crust in accreted terranes. The ensimatic end member is considered to be suspended material derived from plutonic and volcanic rocks of the Coast Plutonic Complex (CPC). Cui and Russell (1995) studied a transect through this complex at the latitude of the lower Fraser and partly within its watershed. A plot of the measured values for $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ in rocks from the CPC is shown in Fig. 6. The CPC consists mainly of mantle-derived material, with little or no crustal additions (Cui and Russell, 1995). Suspended matter from the Chilcotin

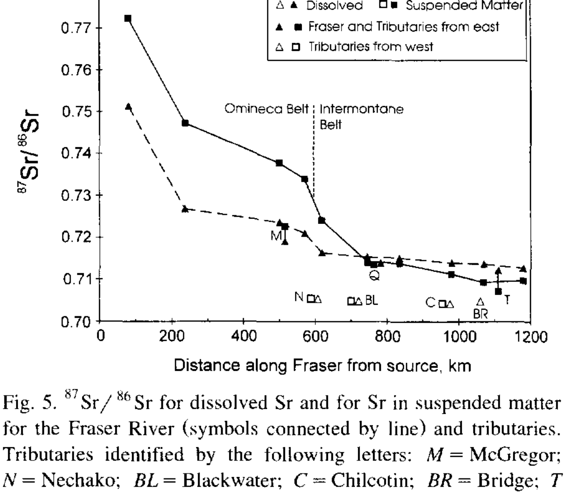

Fig. 5. $^{87}Sr/^{86}Sr$ for dissolved Sr and for Sr in suspended matter for the Fraser River (symbols connected by line) and tributaries. Tributaries identified by the following letters: *M* = McGregor; *N* = Nechako; *BL* = Blackwater; *C* = Chilcotin; *BR* = Bridge; *T* = Thompson.

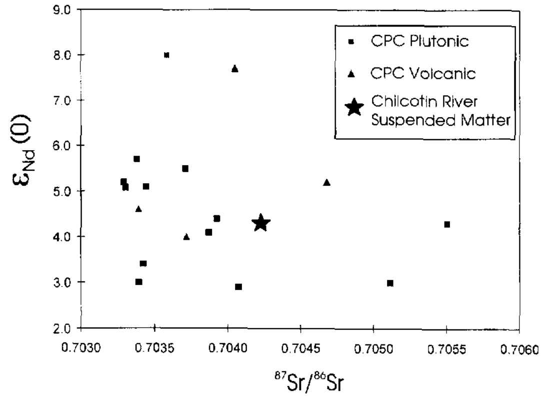

Fig. 6. ε_{Nd} (0) versus $^{87}Sr/^{86}Sr$ (measured ratios) for plutonic and volcanic rocks from the Coast Plutonic Complex (*CPC*) (Cui and Russell, 1995) and for suspended matter from the Chilcotin River.

River, which drains the Coast and Intermontane belts, plots within the cluster of ε_{Nd} (0)–$^{87}Sr/^{86}Sr$ values for the CPC (Fig. 6). Using both elemental abundances and isotopic data for Sr and Nd in the mixing calculations, suspended matter from the Fraser at Fitzwilliam and from the Chilcotin are used as end members for the mixing curve of ε_{Nd} (0) versus $^{87}Sr/^{86}Sr$ (Fig. 7). As it progresses downstream, suspended matter in the Fraser and in its tributaries follows a reasonable approximation to this curve.

At the point that the Fraser crosses into the Intermontane Belt, downstream from the station at Shelley (Fig. 7), suspended matter is roughly 55% along the ε_{Nd} (0)–$^{87}Sr/^{86}Sr$ mixing curve. By Quesnel, this has increased to 80% and the three downstream stations on the Fraser cluster in the 85–90% range. Thus suspended matter in the middle and lower Fraser is dominated by material from rocks of mantle origin and approach the isotopic composition of the rivers draining from the west over the Coast and Intermontane belts, the Chilcotin, Nechako and Blackwater rivers. Suspended matter in two of the tributaries draining from the east, the McGregor and Quesnel rivers, have an isotopic signature that indicates a significant contribution of cratonic material (Fig. 7). The Thompson River also drains from the east, with a significant portion of its watershed in the Omineca Belt. However, the Thompson, after passing through Kamloops (Fig. 1) widens into Kamloops Lake. The turbid waters that enter the east end of this lake are replaced by clear waters emerging from the west, with the eastern-derived suspended load largely deposited in the lake. From this lake to

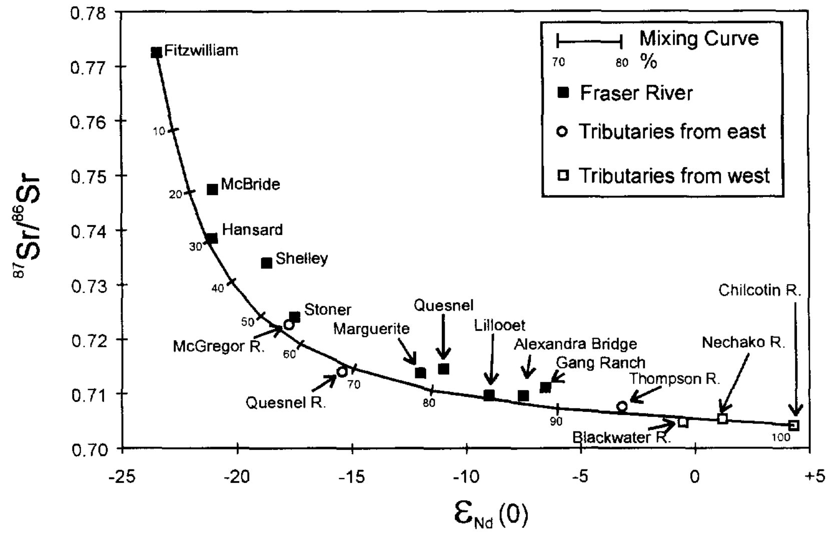

Fig. 7. Mixing curve for ε_{Nd} (0)–$^{87}Sr/^{86}Sr$ using suspended matter from the Fraser River at Fitzwilliam and from the Chilcotin River as end members representing areas of ancient crust and young crust, respectively. Superimposed is ε_{Nd} (0)–$^{87}Sr/^{86}Sr$ values for suspended matter in the Fraser River and tributaries.

its confluence with the Fraser, the Thompson picks up only a small amount of suspended material, all from the Intermontane Belt, with an isotopic composition (Fig. 7) similar to that of the western tributaries.

Given the importance of tills as a source of suspended material, to what extent is the spatial distribution of isotope ratios and elemental compositions of the river-suspended material modified by glacial dispersion? Any effects are not observable at the broad scale of sampling used for this study. For the main part of the Fraser watershed, lying within the Interior Plateau, and once covered by the Cordilleran Ice Sheet, dispersion of till from bedrock source is generally short, in the order of a few kilometres. It is this feature which makes feasible the use of till samples in geochemical exploration for mineral deposits. In the Nechako Plateau, Levson and Giles (1995) describe geochemical anomalies in till that spread 1000–1500 m from the mineralized source.

5.2. *Differences in isotopic composition of Sr in dissolved and suspended material*

Differences between the isotopic composition of Sr present as dissolved and suspended phases is shown in Fig. 5 and as ($\varepsilon Sr_{diss} - \varepsilon Sr_{susp}$) in Table 1. Throughout the Foreland and Omineca belts, dissolved Sr is significantly less radiogenic than Sr in suspended matter. This can be accounted for by Sr in the suspended material being entirely derived from the weathering of old, Rb-bearing silicate rocks, whereas the dissolved Sr also contains a component derived from Rb-poor sedimentary carbonate and sulphate minerals. Where rivers exclusively drain silicate rocks there is little difference in $^{87}Sr/^{86}Sr$ between the dissolved and suspended loads (Goldstein and Jacobsen, 1987). This is confirmed by data from the Chilcotin, Blackwater and Nechako that drain mainly silicate rocks and ($\varepsilon Sr_{diss} - \varepsilon Sr_{susp}$) of 0 to −5.

Values for ($\varepsilon Sr_{diss} - \varepsilon Sr_{susp}$) in the Fraser drop sharply after crossing from the Omineca into the Intermontane Belt, reflecting the change from sedimentary terrane containing carbonate rocks to ensimatic terranes. By the station at Quesnel, the ratio has inverted, with dissolved Sr more radiogenic, although the tributaries that enter the river have similar $^{87}Sr/^{86}Sr$ compositions for dissolved and suspended phases. The inversion relates to the different transport behaviours of dissolved and solid phases. For a dissolved constituent, such as Sr, present at low concentrations and with a weak tendency towards adsorption on solids, cations once dissolved will be retained as the river water moves downstream. The isotopic composition of Sr will thus represent the entire upstream basin. It is this characteristic that permits high $^{87}Sr/^{86}Sr$ waters from the Himalayas to be carried long distances to the coast and influence the composition of modern ocean water (Krishnaswami et al., 1992). The conservative behaviour of dissolved Sr can be demonstrated by the mass balance calculation in Table 2 obtained from water discharge and the elemental abundance and isotopic composition of dissolved Sr. For the final station on the Fraser at Alexandra Bridge, the estimated abundance and isotopic composition of Sr based on all upstream inputs is in good agreement with its measured composition.

The behaviour of suspended matter is different from conservative dissolved phases. Where the velocity of the river water slows, some suspended load

Table 2
Mass balance calculations of elemental and isotopic compositions of dissolved Sr

River	Geol. belt	Water discharge	Sr (ppb)	εSr_{diss}
Fraser at Hansard	F, O	17.3	114	271
McGregor River	F	8.3	62	207
Quesnel River	O	8.7	126	138
Other Omineca Belt	O	2.8	126	138
Nechako River	I	10.5	64	7.5
Chilcotin River	I, C	3.6	56	−3.5
Other Intermontane/Coast	I, C	20.2 *	75	2.3
Thompson River	O, I	28.6	70	109
Estimated Fraser, Alexandra Br.	All	100.0	83	126
Measured Fraser, Alexandra Br.	All	100.0	85	117

Water discharge is expressed as a percentage of the discharge at Alexandra Bridge; discharge data represent averages over at least 10 years (Water Survey of Canada, 1991), except for (*), which is an estimate. For *Other Omineca Belt rivers*, the chemical data for Quesnel River are used and for *Other Intermontane / Coast Belt Rivers*, the average compositions of the Nechako, Chilcotin, Blackwater and Bridge rivers. Abbreviations for geological belts: F = Foreland, O = Omineca, I = Intermontane, C = Coast.

can be deposited; where the velocity increases, new material is added to suspension by erosion. Thus at any station, the composition of the suspended load is more representative of those terranes that lie immediately upstream than terranes that are more distant. At Quesnel and downstream, dissolved Sr is a mixture of high $^{87}Sr/^{86}Sr$ from the Foreland and Omineca belts with low $^{87}Sr/^{86}Sr$ supplied from the Intermontane and Coast belts, whereas the suspended matter is more representative of low $^{87}Sr/^{86}Sr$ material from the two younger belts. Values for ($\varepsilon Sr_{diss} - \varepsilon Sr_{susp}$) increase from +14 at Quesnel to a maximum of +62 at Lillooet, then drop after mixing with the Thompson River to +42 at the final station at Alexandra Bridge. The Thompson River is the only tributary with a significant positive value of +62. As was noted above, most of its suspended material is deposited within Kamloops Lake, a short distance upstream from the sampling station at Spences Bridge. The more radiogenic isotopic composition of dissolved Sr in the Thompson indicates the presence of Sr derived from its headwaters in the Omineca Belt, whereas suspended matter downstream of Kamloops Lake is entirely derived from the Intermontane Belt. Strontium dissolved in the Thompson significantly influences the Sr isotope composition of the Fraser downstream of their confluence, but because of the low turbidity of the Thompson, there is little effect on the suspended phase of the combined rivers.

6. Discussion and conclusions

The changing isotopic composition of suspended matter in the Fraser River from the source in the interior to the mouth mirrors the geological evolution of the orogen. Suspended matter in the headwaters has $^{87}Sr/^{86}Sr \sim 0.77$ and $\varepsilon_{Nd}(0) \sim -23$, and an Archaean crustal residence age from Sm–Nd data, indicating a derivation from the Precambrian craton. Downstream, where the Fraser crosses into younger ensimatic terranes that were accreted to the craton, suspended material displays a change towards a 'mantle' isotopic signature and young crustal residence ages.

Over the eastern, ensialic terranes, dissolved Sr is substantially less radiogenic than in the suspended phase, because of a significant contribution of Sr by dissolution of Sr-rich, Rb-poor carbonate rocks. Downstream this relation inverts, with dissolved Sr more radiogenic. Inversion reflects the different transport behaviours of dissolved and suspended phases. Part of the suspended load is deposited where the current slows, then, when the current increases, new material is eroded. Passage through a lake, such as Kamloops Lake on the Thompson, can result in the loss of the entire suspended load.

Thus suspended materials tend to be representative of the immediate environs of the sampling site. For a river that crosses an orogen, the suspended material that passes into the ocean, comes largely from the outer margin of the orogen. In contrast, conservative dissolved elements represent the isotopic composition of the entire drainage basin. For the downstream sections of the Fraser and the Thompson this leads to substantial differences in the isotopic composition of Sr in the dissolved and suspended phases, with the former more radiogenic from the interior, cratonic rocks.

Given the localized origin of the suspended material, it may appear unusual that $\varepsilon_{Nd}(0)$–$^{87}Sr/^{86}Sr$ shows a mixing relationship between two end members across four geologically distinct belts. The Foreland Belt and the Coast Belt represent the two end members. Yet the mixing relationship is apparent within the intervening Omineca and Intermontane belts, although their rock assemblages are different compared to each other and to the flanking belts. In spite of its diverse lithology, the Omineca Belt can be regarded as material from the Precambrian craton, with an admixture of juvenile material. Parts of the Intermontane Belt, which is mainly accreted oceanic–upper mantle material, may contain a recognisable continental basement signature. These observations of a mixing relationship across the orogen may be viewed as support for the observation that the edge of the continental basement is not a sharp feature, but rather as Ross (1991) observes, "a temporally and spatially variable feature that results from the interplay of crustal–mantle heterogeneities and tectonics during magma genesis in an actively telescoping plate margin."

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