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Contrasting responses of Rb–Sr systematics to regional and contact metamorphism, Laramie Mountains, Wyoming, USA

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ABSTRACT Archean supracrustal sequences of pelitic, quartzitic, calcareous and mafic compositions in the central Laramie Mountains, Wyoming, have been affected by two metamorphic events: a 1.78 Ga amphibolite-grade regional metamorphism, and a 1.43 Ga contact metamorphism resulting from the intrusion of the Laramie Anorthosite Complex (LAC). Rb–Sr whole-rock isotopic data from both outside and within the LAC contact aureole define a linear array that lies along a 1.78 Ga isochron. This date has been independently established as the time of amphibolite facies regional metamorphism associated with collision of the Archean Wyoming province and the Proterozoic Colorado province along the Cheyenne belt. The Rb–Sr isotopic data require that Sr was redistributed during regional metamorphism on a scale of at least tens of metres. Although within the 2 km-wide aureole of LAC the pelitic rocks were thermally metamorphosed at temperatures greater than 800 °C, none of the whole-rock Rb–Sr data from samples within the LAC aureole show evidence of resetting at 1.43 Ga. It is interpreted that the regional metamorphism involved fluid transport which facilitated Sr isotopic resetting, whereas the contact metamorphism occurred in a relatively dry environment in which isotopic mobility was restricted to centimetre-scale or less. Rb–Sr data for biotite, feldspar and whole rock from a regional metamorphosed pelitic schist give an isochron age of 1450 ± 40 Ma, which is interpreted as a cooling age resulting from crustal uplift. Rb–Sr data for biotite, quartz + feldspar and whole rock from a pelitic schist affected by contact metamorphism give an isochron age of 1420 ± 43 Ma, the time of isotopic re-equilibration in response either to crustal uplift or to both contact metamorphism and crustal uplift. This study demonstrates that although the response of isotopic systems to metamorphism is complex, isotopic data provide insight into metamorphic processes that is difficult to obtain by other means.

Key words: contact metamorphism; Laramie Mountains; Rb–Sr and Sm–Nd isotopes; regional metamorphism.

INTRODUCTION

Isotopic systems can be sensitive indicators of metamorphic processes, including mineral growth, fluid movement, and deformation (e.g. Bickle *et al.*, 1995; Frost & Frost, 1995; Scheuber *et al.*, 1995). Previous studies indicate that redistribution of parent–daughter elements and concomitant partial or complete equilibration of isotopic systems can occur on mineral to regional size domains. Thus, depending on the scale of equilibration relative to that chosen for sampling, isotopic systems can monitor processes ranging from those relating to the original protolith to those occurring during the youngest metamorphism. Some studies (e.g. Hofmann & Grauert, 1973; Krogh & Davis, 1973; Grauert *et al.*, 1974; Hänny *et al.*, 1975; Steiger *et al.*, 1976; O'Hara & Gromet, 1983) have shown that Sr isotopic equilibration was not reached over distances of more than centimetres during amphibolite facies regional metamorphism. On the other hand, reports of many well-fitted Rb–Sr isochrons giving the time of metamorphism of regionally metamorphosed rocks suggest that Sr isotopic equilibration can take place on a regional scale (e.g. Allsopp *et al.*, 1968; Montigny & Faure, 1969; Peterman & Hildreth, 1978; Clauer & Kroner, 1979; Graham, 1985). Similarly, Sr isotopic equilibration in mylonite zones has been reported on scales of few metres (Odom & Fullagar, 1973; Hickman, 1984) to hundreds of metres (Turek & Peterman, 1971; Kamineni *et al.*, 1990). Hickman & Glassley (1984) showed that the scale of whole-rock Rb–Sr isotopic resetting in a shear zone varied from few metres to kilometres depending upon the scale of fluid migration. Bickle *et al.* (1988) reported Sr isotopic equilibration on a scale of tens of metres during hydrothermal metamorphism in the Pyrenees, and concluded that profound equilibration of the $^{87}Sr/^{86}Sr$ ratio of large volumes of the crust can occur during regional metamorphism. Frost & Frost (1995) demonstrated that, during contact metamorphic dehydration of amphibolite, both Rb–Sr and Sm–Nd mineral isochrons may be reset, even in rocks outside zones of shearing and grain-size reduction.

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The present investigation documents pervasive Sr isotopic redistribution in pelitic schists during a regional metamorphic event, and that a later high-temperature contact metamorphic event had no discernible effect on the whole-rock isotopic systematics. We document that the composition of the protolith, the metamorphic reactions taking place, and the nature and scale of fluid flow play a crucial role in the process of isotopic redistribution during metamorphism. This kind of study is possible in the central Laramie Mountains because: (i) there was a period of 800 Ma between the time of deposition (2.64 Ga) of the pelitic schists and the regional metamorphism (*c.* 1.78 Ga) during which isotopic disequilibrium built up between domains of different Rb/Sr ratios; (ii) the age of the regional metamorphism is well known, and correlates with a major orogenic event in the region; (iii) the time of the later contact metamorphism is constrained by the precisely known age of the intrusive body; and (iv) thermobarometric information on the contact aureole is available.

Geological setting

The Laramie Mountains of eastern Wyoming are a Precambrian-cored Laramide uplift (Fig. 1). The northern two-thirds of the range is occupied by Archean granite–gneiss and supracrustal sequences, all of which are cut by 2010 ± 10 Ma mafic dykes (Cox *et al.*, 1995). The largest belt of supracrustal rocks, known as the Elmers Rock greenstone belt (Graff *et al.*, 1982), is constrained in age by a U–Pb zircon date of 2637 ± 10 Ma on a rhyolite within the supracrustal sequence (Snyder, 1984), and by the 2.62 Ga Squaw Mountain granite that intrudes the supracrustal rocks along their eastern margin (Verts *et al.*, 1996; Fig. 1). The rock types in the supracrustal belt include marble, calc-silicate rock, quartzite, metagraywacke, metaconglomerate, pelitic schist, amphibolite, amphibole–kyanite schist and iron formation.

The entire region underwent regional metamorphism associated with the accretion of Proterozoic island arcs to the Archean Wyoming province along the Cheyenne belt between 1780 and 1760 Ma (Premo & van Schmus, 1989; Chamberlain *et al.*, 1993; Resor *et al.*, 1996). The collision involved northward thrusting of successively deeper-level rocks of the island arc system onto the Wyoming craton, resulting in tectonic burial of the craton within 150 km of the suture (Karlstrom & Houston, 1984). A break in regional metamorphic grade occurs across the Laramie Peak shear zone, which is located about 60 km north of the Cheyenne belt (Fig. 1). This discontinuity has been interpreted as the northern boundary of a crustal block that underwent decom-

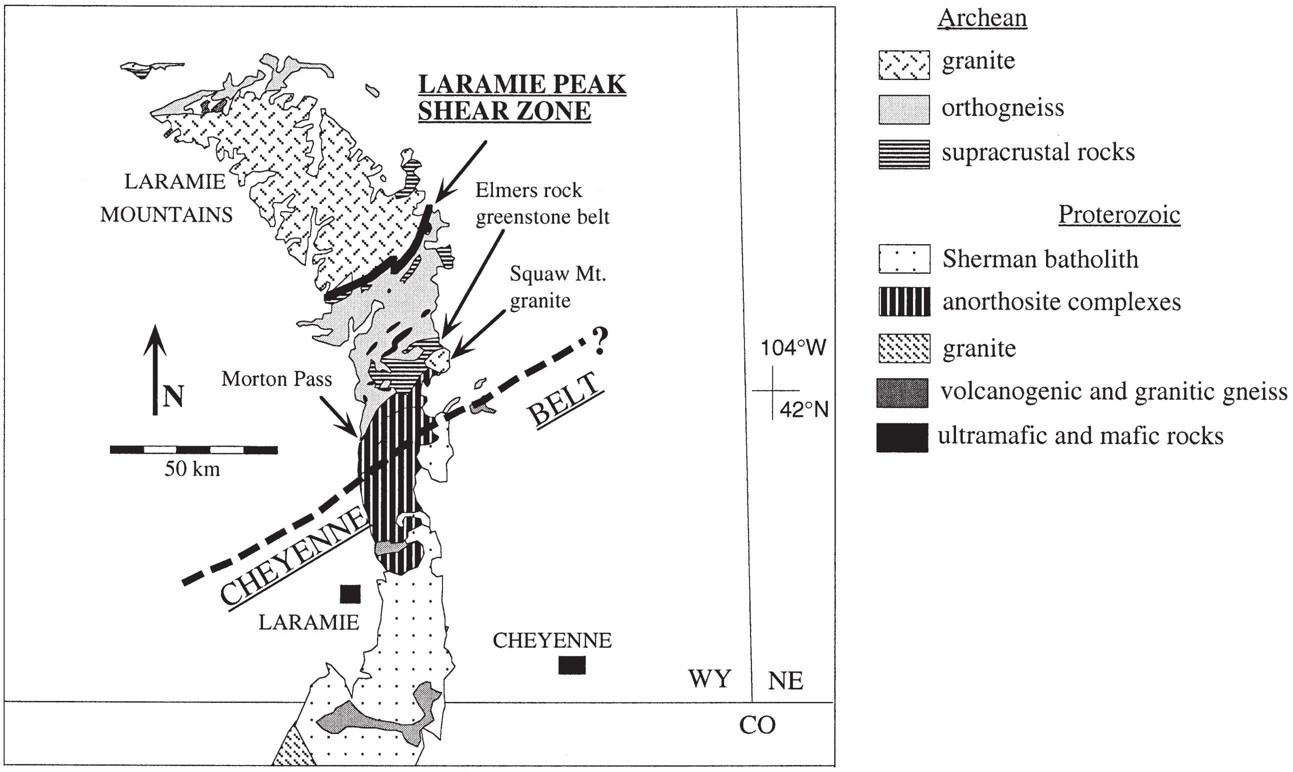

Fig. 1. Generalized geological map of the Laramie Mountains, showing the area of Archean high-grade gneiss and supracrustal rocks in the central Laramie Mountains bounded on the north by the Laramie Peak shear zone and on the south by the 1.43 Ga Laramie Anorthosite Complex. Regional metamorphism of the central Laramie Mountains is associated with collision of Proterozoic island arc terranes against the Archean Wyoming province along the Cheyenne belt.

pression and uplift immediately following regional metamorphism (Chamberlain *et al.*, 1993). The metamorphic conditions north of the Laramie Peak shear zone are andalusite grade with pelitic assemblages involving chloritoid–garnet–andalusite, and a peak pressure around 2 kbar (Patel *et al.*, 1999). South of this shear zone, the metamorphic grade is uniformly high as recorded by the amphibolite-grade pelitic assemblage quartz–biotite–garnet–kyanite–staurolite. In metabasites, the assemblage is hornblende–plagioclase–garnet ± quartz. Both assemblages are consistent with the results of thermobarometry indicating that pressures were 7 kbar or higher and temperatures exceeded 650 °C (Chamberlain *et al.*, 1993; Patel *et al.*, 1999). These rocks, especially the pelitic schists, have strong penetrative schistosity. Deformation has almost everywhere destroyed the original contacts of the granite–gneiss complex and supracrustal rocks.

The latest Precambrian thermal event in the Laramie Mountains was the emplacement of the Laramie Anorthosite Complex (LAC) and the contemporaneous Sherman batholith. The LAC consists of anorthositic and associated monzonitic and syenitic bodies, dated at 1.44–1.43 Ga (Scoates & Chamberlain, 1995). The youngest body of the LAC is the Red Mountain pluton for which Verts *et al.* (1996) obtained a precise U–Pb zircon age of 1431 ± 1 Ma. The Red Mountain pluton intrudes the Elmers Rock greenstone belt along its northern margin, where Archean supracrustal rocks are deformed and contact-metamorphosed (Fig. 2). In this locality, four contact metamorphic zones based on pelitic assemblages can be defined. In order of increasing metamorphic grade these are: andalusite–sillimanite–kyanite, K-feldspar–cordierite–sillimanite, K-feldspar–cordierite–garnet, and feldspar–cordierite–orthopyroxene zones (Snyder *et al.*, in press; Fig. 3). The maximum temperatures attained within the contact aureole are in excess of 800 °C (Grant & Frost, 1990).

Sample descriptions

Nine samples of pelitic schist were collected from the contact aureole of the Red Mountain pluton along Bluegrass Creek (Fig. 3). Two additional samples were collected at Morton Pass, where the intrusion of the Sybille monzosyenite pluton of the LAC produced contact metamorphism of similar grade to the Bluegrass Creek area (Fig. 2; Russ-Nabelek, 1989; Grant & Frost, 1990). Samples of one pelitic schist and one metabasite were collected from the regional metamorphic terrane north of Bluegrass Creek (Fig. 2) The mineral assemblages of the analysed pelitic schist samples are given in Table 1.

Samples from the regional metamorphic terrane

The pelitic schists in the regionally metamorphosed terrane are characterized by the amphibolite-grade assemblage quartz–biotite–garnet–kyanite–sillimanite–staurolite–rutile–ilmenite (K + S zone in Fig. 3). Muscovite is present in many samples, but is texturally late and is interpreted as the result of retrogression. The mineral assemblages in the pelitic schist prior to the 1.78 Ga regional metamorphism are poorly known. A pelitic schist from the Esterbrook area, north of the Laramie Peak shear zone, has the assemblage quartz–muscovite–chlorite–garnet–chloritoid–andalusite. This assemblage formed at pressures of c. 2 kbar and temperatures of *c.* 560 °C (Patel *et al.*, 1999). We interpret this assemblage to be

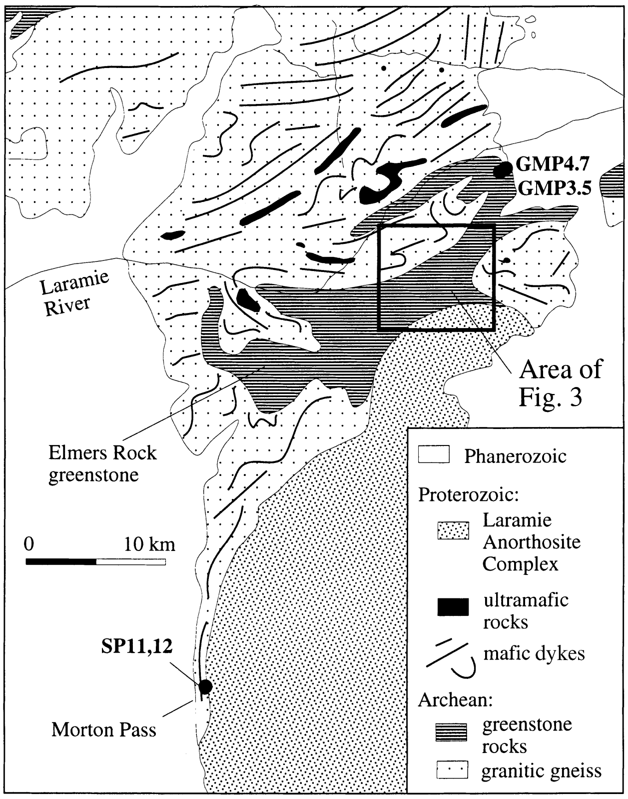

Fig. 2. Geological sketch map of the central Laramie Mountains, modified from Snyder (1984), showing the location of Elmers rock greenstone belt and Morton Pass, the areas from which samples of pelitic schist were collected. GMP3.5 and GMP4.7 are samples of pelitic schist and metabasite, respectively. SP11 and SP12 are pelitic schist samples from the contact aureole at Morton Pass. Samples SP1–9 are from the area outlined by the box; an enlargement of this area is shown in Fig. 3.

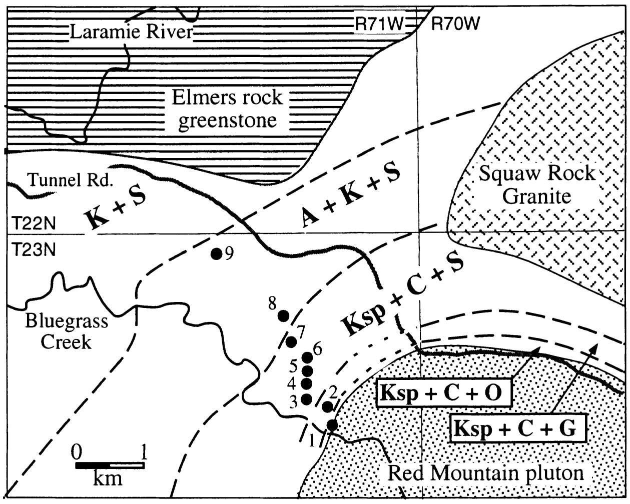

Fig. 3. Enlargement of the map area from which contact metamorphosed pelitic schist samples SP1–9 were collected, showing the contact metamorphic zones defined by Snyder *et al.* (in press). K, kyanite; S, sillimanite; A, andalusite; Ksp, K-feldspar; C, cordierite; O, orthopyroxene; G, garnet.

Table 1. Pelitic assemblages in the contact aureole of the Larantie Anorthosite Complex.

Sample	Grt	Ky	And	Sil	St	Pl	Kfs	Crd	Opx	SPl	Ms	Chl	llm
Regionally metamorphosed terrane													
GMP3.5				x	x	x		x					
SP15						x					x		
Andalusite–kyanite–sillimanite zone													
SP9	x	x	x	x	x	x		x					
SP8	x	x	x			x		x			x	x	x
SP7	x					x		x			x	x	x
K-feldspar–cordierite–sillimanite zone													
SP6	x		x	x	x	x		x		x	x	x	x
SP5			x	x		x	x				x	x	
SP4			x	x		x	x	x			x		x
SP3			x	x			x	x			x		x
K-feldspar–cordierite–garnet zone													
SP2	x		x	x		x	x	x		x	x		x
SP12				x		x	x	x		x			
K-feldspar–cordierite–orthopyroxene zone													
SP1	x		x			x	x	x	x	x			x
SP11						x	x	x	x	x			

All samples contain quartz and biotite. Samples SP11 and SP12 are from the Morton Pass area; all other samples are from the Bluegrass Creek area.

the result of an Archean-age metamorphism, and therefore it represents the assemblage that probably was present before the 1.78 Ga regional metamorphism that affected the Elmers rock greenstone belt. We infer that during this Proterozoic-age regional metamorphism, muscovite was removed from the rock through one or more muscovite-consuming reactions that are common in prograde metamorphism of pelitic rocks (Spear, 1993). Samples of regionally metamorphosed pelitic schist selected for isotopic analysis include SP15, collected 8 km from the contact with the Red Mountain pluton, and sample GMP3.5 located 9 km from the contact. A metabasite sample GMP4.7 located near to sample GMP3.5 north of Squaw Mountain was also analysed.

Samples from within the 1.43 Ga contact aureole

All other samples of pelitic schist collected for this study were subjected to both the 1.78 Ga regional metamorphic event and to contact metamorphism associated with the intrusion of the Red Mountain pluton and the Laramie Anorthosite Complex. Samples SP8 and 9 are from the lowest-grade portion of the contact aureole, where the all three aluminosilicate minerals, andalusite, kyanite and sillimanite, may be found (Fig. 3). This zone has been identified as the kyanite + sillimanite zone by Snyder *et al.* (in press). Andalusite that forms as reaction rims around kyanite and staurolite is interpreted as having formed during contact metamorphism (Grant & Frost, 1990). Within *c.* 1.7 km of the contact with the Red Mountain pluton, the regional metamorphic minerals kyanite and staurolite disappear, coincident with the appearance of K-feldspar according to the reaction:

$$\mathrm{Ms + Qtz = aluminosilicate + Kfs + H_2O} \qquad (1)$$

Sample SP7 is from this innermost portion of the kyanite + sillimanite zone. Inwards towards the pluton from this reaction is the K-feldspar–cordierite–sillimanite zone, from which samples SP3–6 were collected. Within this zone, K-feldspar, cordierite and sillimanite co-exist with biotite, quartz and plagioclase. Hercynite is common, but is usually within cordierite as pseudomorphs after staurolite, and may not be in equilibrium with quartz. Andalusite may be present.

Within about 400 m of the contact, aluminosilicates disappear from the metapelitic schists and the common assemblage becomes K-feldspar–biotite–cordierite–garnet (Ksp–C–G zone on Fig. 3). Partial melting, as evidenced by the appearance of pink leucosome, begins at slightly lower grades than the K-feldspar–cordierite–garnet zone. With melting, muscovite and relict andalusite disappear from the rocks. Sample SP2 represents the K-feldspar–cordierite–garnet zone in the Bluegrass Creek area. Metapelitic schist sample SP12 from Morton Pass contains the assemblage quartz–plagioclase–K-feldspar–cordierite–biotite–sillimanite–spinel, and is equivalent in contact metamorphic grade to sample SP2.

Within 100–150 m of the contact, orthopyroxene appears in the pelitic rocks, and the common assemblage becomes K-feldspar–cordierite–orthopyroxene–biotite. This assemblage is diagnostic of pyroxene hornfels facies and indicates that the maximum temperature attained in the contact aureole was above 800 °C (Pattison & Tracy, 1991). Sample SP1 is from the K-feldspar–cordierite–orthopyroxene zone (Fig. 3). SP11 from Morton Pass contains the assemblage plagioclase–K-feldspar–cordierite–biotite–orthopyroxene–spinel, and is equivalent in grade to sample SP1.

ANALYTICAL DETAILS

Samples were crushed between tungsten carbide plates and powdered using a tungsten carbide ring mill. Mineral separates were obtained using conventional heavy liquid techniques, and were hand-picked for purity. Whole rock powders were heated in air to 600 °C to remove graphite before dissolving in HF–cHNO_3 and HCl. The samples were split and spiked with separate ^{87}Rb and ^{84}Sr tracers, and with a mixed ^{149}Sm and ^{146}Nd spike. Rb, Sr, Sm and Nd were separated using standard ion-exchange procedures. All isotopic ratios were measured on a VG sector single collector mass spectrometer at the University of Wyoming. Isotopic measurements were corrected for fractionation by normalizing the observed ^{86}Sr/^{88}Sr ratios to 0.1194 and the ^{146}Nd/^{144}Nd ratios to 0.7219. Replicate analyses yielded 0.1% precision for Sm and Nd concentrations, and 2% precision for Rb and Sr concentrations.

The program ISOPLOT (Ludwig, 1988) was used for all isochron calculations. Best-fit lines to the data were drawn assuming that variation in ^{87}Sr/^{86}Sr is independent of ^{87}Rb/^{86}Sr (model III of McIntyre *et al.*, 1966). All errors are quoted at 2 σ limits. The analytical results are given in Table 2.

RESULTS

Whole-rock isotopic results

The Sm–Nd isotopic compositions of pelitic schist samples do not vary greatly, although there is a positive correlation of ^{147}Sm/^{144}Nd with ^{143}Nd/^{144}Nd (Fig. 4). The addition of the regionally metamorphosed metabasite sample to the dataset results in an array that lies along a reference isochron of 2640 Ma, the best estimate for the depositional age of the supracrustal rocks (Fig. 4). The scatter of the data points at least in part reflects original heterogeneities in the provenance of the metapelites, and the fact that the metabasite sample and the pelitic schist samples together lie along a Late Archean reference isochron suggests that their Nd isotopic compositions at 2640 Ma were similar. Later tectonothermal events apparently did not produce whole-rock Nd isotopic equilibration. In view of the apparent immobility of Sm and Nd during metamorphism, calculated ε_{Nd} values at 2.64 Ga may accurately reproduce initial ε_{Nd}. These fall in the range of +0.6 to −6.9. Nd crustal residence model ages vary from 2.94 to 3.55 Ga for the pelitic schists. These initial ε_{Nd} and T_{CR} values are typical of Late Archean metasedimentary rocks from around the Wyoming province (Koesterer *et al.*, 1987; Frost, 1993; Frost *et al.*, 1998).

In contrast to the Sm–Nd system, the Rb–Sr whole-

Table 2. Rb-Sr and Sm-Nd isotopic data.

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	±	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	±	T(CR)(Ga)**
Contact aureole at Bluegrass Creek											
SP1WR	56.9	107.0	1.548	0.763768	(24)	5.99	35.97	0.1006	0.510838	(15)	3.1
SPI Opx	3.2	8.4	1.109	0.748928	(54)	2.25	12.90	0.1054	0.510859	(31)	
SPI Bt	189.0	7.4	87.40	2.54598	(42)	5.46	33.40	0.0988	0.510851	(20)	
SPI PI	24.8	269.4	0.267	0.738227	(13)	2.30	19.61	0.0925	0.510725	(13)	
SP2WR	211.0	68.9	9.068	0.935894	(22)	16.57	75.76	0.1322	0.511427	(19)	3.2
SP3WR	88.2	18.2	14.62	1.119154	(20)	10.38	58.65	0.1070	0.510808	(25)	3.32
SP4WR	71.1	88.2	2.352	0.790364	(13)	7.41	45.06	0.0994	0.510805	(11)	3.11
SP5WR	90.0	77.9	3.379	0.821487	(15)	5.37	31.06	0.1045	0.510862	(16)	3.17
SP6WR	45.0	60.5	2.166	0.777584	(20)	6.73	37.16	0.1094	0.510820	(12)	3.38
SP7WR	160.0	57.5	8.231	0.947011	(15)	4.64	25.05	0.1197	0.510947	(11)	3.55
SP8WR	79.0	43.7	5.297	0.853851	(26)	4.52	24.14	0.1132	0.510990	(9)	3.26
SP9WR	90.4	156.4	1.680	0.757370	(17)	4.48	23.87	0.1134	0.511215	(15)	2.93
Contact aureole at Morton Pass											
SP11WR	88.0	216.6	1.180	0.753056	(15)	3.87	23.24	0.1006	0.510921	(20)	2.99
SP12WR	103.4	131.9	2.285	0.792452	(16)	4.17	23.26	0.1084	0.511111	(9)	2.94
Regional metamorphic terrane											
SP15WR	100.6	35.8	8.311	0.936898	(21)	2.40	13.17	0.1102	0.511010	(13)	3.13
SP15Ms	137.0	11.1	39.15	1.67766	(29)	2.62	13.20	0.1193	0.510905	(66)	
SPI5Bt	306.2	4.1	391.1	8.89819	(99)				0.511031	(29)	
SP15Qtz + Pl	1.3	40.7	0.095	0.766018	(28)	0.70	3.520	0.1204	0.51097	(16)	
GMP3.5WR	68.9	55.2	3.653	0.828540	(28)						
GMP4.7WR*	1.8	32.3	0.161	0.722698	(26)	3.38	11.05	0.1850	0.51233	(13)	

WR, whole rock. * GMP4.7 is a metabasite sample; all others are pelitic schists. ** Nd model 'crustal residence ages' (TCCR) are calculated using the mantle model of Goldstein *et al.* (1984). Model age not calculated for samples with $^{147}Sm/^{144}Nd > 0.15$. Analytical uncertainties (±) refer to the fifth and sixth decimal places of the Sr and Nd isotopic ratio measurements.

rock data define greater variation in isotopic composition, and form a positively correlated array on a Rb–Sr isochron diagram. This array does not have a slope corresponding to an Archean age; instead, the data lie along a 1.78 Ga reference isochron (Fig. 5). It thus appears that the Rb–Sr isotopic system in the whole-rock samples has been strongly affected by the regional metamorphic event at 1.78 Ga. If during metamorphism isotopic equilibration were complete, it would result in metabasites and pelitic schists defining a single isochron, as is approximated by the array shown in Fig. 5. However, complete isotopic homogenization was not achieved: the MSWD of 23.7 is substantially greater than that attributable to analytical uncertainties alone and indicates the presence in the data of some geologically induced dispersion.

The whole-rock Rb–Sr data presented here place some limits on the length scale across which Sr was redistributed during metamorphism. The samples that define an array with a slope corresponding to *c.* 1.78 Ga are from localities separated by many kilometres. Thus,

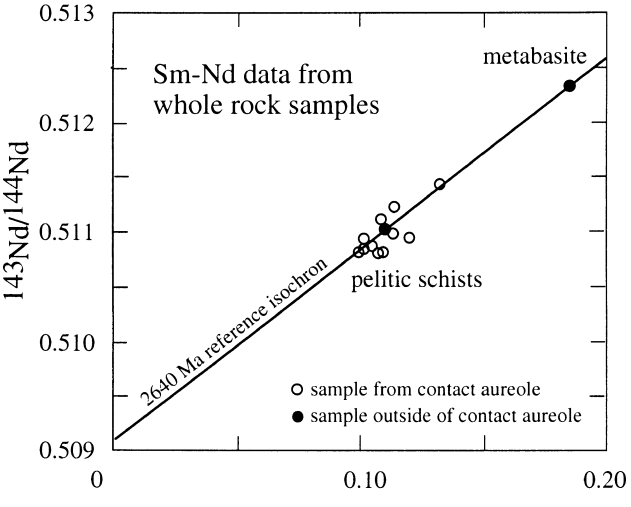

Fig. 4. Sm–Nd isochron diagram for whole-rock samples from contact aureole (○) and regional metamorphic terrane (●).

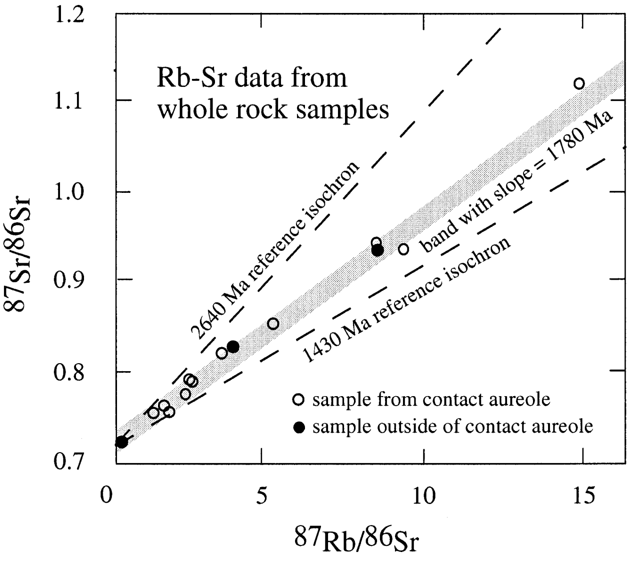

Fig. 5. Rb–Sr isochron diagram for whole-rock samples from contact aureole (○) and regional metamorphic terrane (●). Samples scatter about a slope corresponding to an age of 1780 Ma, the time of regional metamorphism. Reference isochron slopes corresponding to 2640 Ma, the time of deposition of the supracrustal rocks, and to 1430 Ma, the time of contact metamorphism, are shown for comparison.

one possibility is that Sr redistribution took place on the kilometre scale, resulting in nearly complete homogenization of the Sr isotopic ratio across this extensive terrane. However, such large-scale redistribution is not required. As pointed out by Roddick & Compston (1977), isotopic equilibration need take place only within sub-volumes of a terrane such that each sub-volume has the same mean Rb/Sr, and thus $^{87}Sr/^{86}Sr$, as the entire terrane. Information on the minimum distance across which Sr redistribution took place in the central Laramie Mountains is provided by data from metabasite sample GMP4.7. This sample has the lowest $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ of the data set. However, its $^{87}Sr/^{86}Sr$ of 0.7227 is much higher than the $^{87}Sr/^{86}Sr$ of correlative metabasites in the Morton Pass area, which range from 0.7028 to 0.7097. The more radiogenic isotopic composition of GMP4.7 cannot be accounted for by a difference in Rb/Sr ratio and therefore different postcrystallization accumulation of radiogenic Sr. Moreover, the initial $^{87}Sr/^{86}Sr$ of 0.723 at 1.78 Ga defined by the data is intermediate between the lower Sr isotopic ratio expected for amphibolitic rocks and the higher Sr isotopic ratio that would result if redistribution of Sr occurred only within Archean metapelitic rocks. We suggest that the elevated $^{87}Sr/^{86}Sr$ of the metabasite sample results from the exchange of Sr from pelitic schists, which at 1.78 Ga contain more radiogenic $^{87}Sr/^{86}Sr$ than the metabasites. The metabasite sample is located 35 m from the contact with pelitic schists, thus this distance represents a minimum length scale for isotopic redistribution.

Mineral isotopic results

Rb–Sr and Sm–Nd analyses were made on orthopyroxene, feldspar and biotite separates from a sample from the contact aureole (SP1), and on muscovite, biotite and quartz + feldspar separates from a sample from the regional metamorphic terrane (SP15).

Having established that the Rb–Sr whole-rock system was affected by regional metamorphism at 1.78 Ga, a mineral isochron for the regional metamorphic sample SP15 is also expected to give the same age if the minerals were closed subsequent to metamorphism. However, the biotite, quartz + feldspar and whole-rock data of sample SP15 together define a Rb–Sr isochron (Fig. 6) with an date of 1450 ± 40 Ma (MSWD = 0). The muscovite analysis of sample SP15 deviates from the above mineral isochron, and gives a muscovite–whole-rock date of 1670 ± 84 Ma. The younger of these two dates coincides with the intrusion age of the LAC, suggesting the possibility that this mineral isochron records the age of contact metamorphism. However, the sample SP15 is from a locality *c.* 8 km away from the contact aureole and does not exhibit any sign of mineralogical or textural changes suggestive of contact metamorphism. Furthermore, Verts *et al.* (1996) calculated that there would have been no increase in temperature for country rocks more than 5 km from the contact of the LAC. Therefore, resetting due to contact metamorphism does not appear to explain the 1450 Ma mineral date obtained from sample SP15.

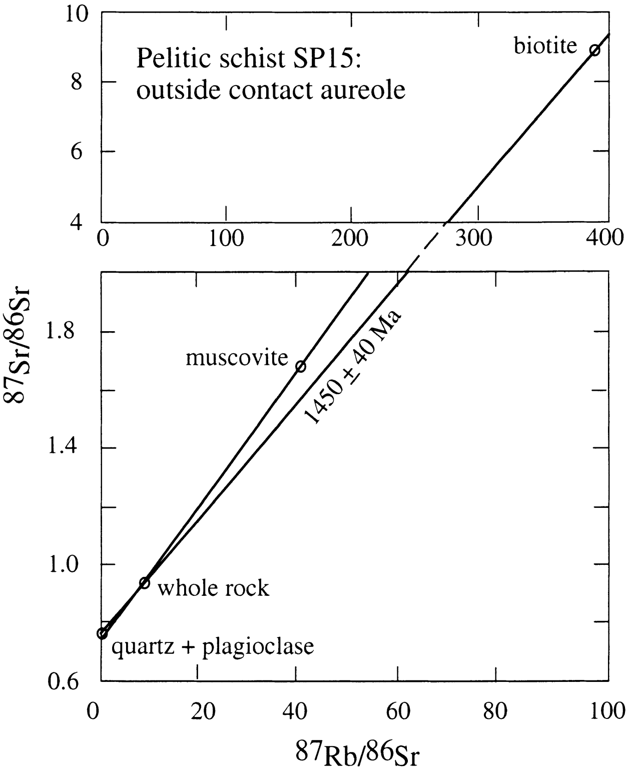

Fig. 6. Rb–Sr isochron diagram for minerals of the regional metamorphosed pelite sample SP15. The 1450 ± 40 Ma isochron is defined by biotite, whole rock and quartz + feldspar, and has an MSWD of 0. The muscovite–whole rock slope corresponds to a date of 1670 Ma.

An alternative preferred interpretation of these mineral dates is that they represent cooling ages for times at which the rocks were uplifted through the blocking temperatures for Sr of the minerals. Experimentally calibrated data for the blocking temperatures of biotite and muscovite are not available; however, based upon comparisons with other isotopic mineral systems, temperatures of 500 ± 50 °C (muscovite) and 300 ± 50 °C (biotite) have been suggested (e.g. Hanson & Gast, 1967; Jager, 1979). Hills & Armstrong (1974) and Peterman & Hildreth (1978) reported reset K–Ar and Rb–Sr mineral dates mostly in the range of 1600–1400 Ma for Archean rocks in a zone some 120 km wide north of the Cheyenne belt covering all the Precambrian mountain ranges of southern Wyoming province. These authors interpreted these reset mineral dates as cooling ages, and postulated crustal uplift and erosion of several kilometres during 1600–1400 Ma. Our mineral isochron results from the regional metamorphic sample SP15 conform to this interpretation.

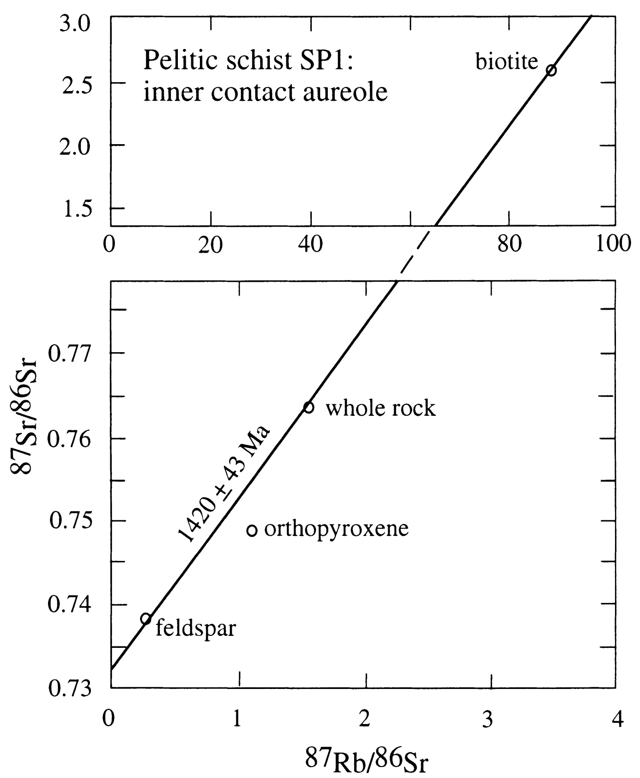

Fig. 7. Rb–Sr isochron diagram for minerals of the contact metamorphosed pelite sample SP1 from Bluegrass Creek. The 1420 ± 43 Ma isochron is defined by biotite, whole rock and feldspar, and has an MSWD of 1.56.

For sample SP1, which comes from the contact aureole, feldspar, biotite and whole rock define a Rb–Sr isochron (Fig. 7) which gives a date of 1420 ± 43 Ma (MSWD = 1.56). The Rb–Sr result for orthopyroxene of sample SP1 falls below the 1420 Ma isochron (Fig. 7). This anomaly may be due to the presence of the retrograde mineral biotite found within and along the edges of some pyroxene grains, an effect also reported by Burton & O'Nions (1990). The date of 1420 ± 43 Ma is within error of the mineral date of sample SP15, and could also record the time of crustal uplift. However, the Rb–Sr mineral isochron is also in agreement with the age of the Red Mountain pluton in the Laramie Anorthosite Complex (Verts *et al.*, 1996) that produced the contact metamorphism. Frost & Frost (1995) documented that Rb–Sr and Sm–Nd mineral isochrons for metabasites at Morton Pass were reset during contact metamorphism. Sample SP1 was subject to equally high temperatures during the contact metamorphic event, and thus also could have re-equilibrated in response to the intrusion of the LAC. The 1420 Ma mineral date for the minerals of sample SP1 is thus likely to be the result of both contact metamorphism and crustal uplift.

Owing to the exceedingly small range in ^{147}Sm/^{144}Nd, the Sm–Nd results of the minerals do not provide any significant age constraints.

DISCUSSION

During metamorphism, the Rb–Sr and Sm–Nd isotopic systems behaved very differently in the pelitic schists described here than they did in metabasites at Morton Pass described by Frost & Frost (1995), even though the rocks in both studies were subjected to the same metamorphic conditions. Both rocks underwent at least two metamorphisms: amphibolite-grade regional metamorphism at 1.78 Ga, and high-grade contact metamorphism at 1.43 Ga. As described above, Sr isotopes in the whole-rock pelitic schist samples north of the Red Mountain pluton were redistributed during the 1.78 Ga metamorphism, but were unaffected by the contact metamorphism. In contrast, the Rb–Sr system in the metabasites at Morton Pass was strongly disturbed by contact metamorphism at 1.43 Ga, but was apparently unaffected by the 1.78 Ga metamorphism, because remnants of an Archean isochron array can be discerned in the least-metamorphosed samples (Frost & Frost, 1995). The Sm–Nd system also displays different behaviour in pelitic schists compared to metabasites. The Sm–Nd system was unaffected by metamorphism in the pelitic schists described in this paper, but during contact metamorphism of metabasites REEs were mobile and Nd isotopes were largely homogenized on the outcrop scale (Frost & Frost, 1995). These differences in isotopic behaviour provide important insights into the factors controlling isotopic mobility during metamorphism. These factors include: (i) presence of a fluid phase, (ii) the geochemical behaviour of parent and daughter isotopes, and (iii) availability of sites for parent and daughter isotopes in the various rock types involved in metamorphism.

Influences on the isotopic response to metamorphism

Presence of a fluid phase

Regional metamorphism typically occurs over a longer time scale in contrast to contact metamorphism which typically occurs over a shorter time scale (Spera, 1980). Thus, the difference in time scale of metamorphism might be called upon to explain the large difference in scale of isotopic equilibration observed in the central Laramie Mountains. However, as we discuss below, time scale alone cannot explain the different response of the Rb–Sr system during regional versus contact metamorphism. A more dominant factor controlling the scale of element migration is the presence or absence of a fluid phase.

The scale of isotopic equilibration resulting from thermal diffusion during metamorphism can be modelled using the Arrhenius equation, where the temperature dependence of the diffusion coefficient is given by $D = D_0 e^{-Q/RT}$. At 700 °C, the diffusion coefficient for $\mathrm{Sr} < 10^{-16}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ in crystalline phases (Brabander & Gilleti, 1991; Chen & DePaolo, 1991). Thus, from the relationship between transport distance and time, $x = (D_{Sr}t)^{1/2}$, the above values lead to transport distances of less than a centimetre on a geologically reasonable time scale of 10 Ma. The short transport distances predicted for diffusion are in accordance with the observations of Bickle *et al.* (1995), who documented diffusion distances of less than 1–7 cm between marble and silicate rocks in the East Humboldt Range, Nevada.

If deformation accompanies metamorphism, diffusion will be enhanced via strain-induced processes such as dislocation generation and movement, and grain boundary migration and sliding (Black *et al.*, 1979; Beach, 1980; Brodie, 1980). There is almost no direct information on grain boundary diffusion in rocks but it can be expected to play a significant role in circumstances where deformation is accommodated by mass transfer processes.

Rb–Sr isotope systematics during metamorphism involving fluid transport will differ from those where diffusive processes predominate (Hickman & Glassley, 1984). In such cases, isotopic equilibration can take place on scale of kilometres depending upon the nature and the scale of fluid transport. Devolatilization reactions in pelitic schists seem to be the most important source of aqueous fluid (e.g. Graham *et al.*, 1983; Yardley *et al.*, 1991). Walther & Orville (1982) estimated that the H_2O and CO_2 produced during devolatilization of an average pelite (2 mol of fluid per kg of pelite) will occupy about 12% of the rock at 500 °C and 5 kbar. Such a source implies generation of fluid on a scale of grain size, and thus can help explain pervasive isotopic equilibration via maintenance of grain-scale fluid–solid interaction.

In contrast, the attainment of only centimetre-scale equilibration in the contact aureole of the Laramie Anorthosite Complex at 1.43 Ga is most probably due to the dry nature of the aureole (Grant & Frost, 1990). Water activity during contact metamorphism was low because: (i) the rocks were already partially dehydrated during the 1.78 Ga regional metamorphism before the contact metamorphism at 1.43 Ga; (ii) the monzonitic magmas of the Laramie Anorthosite Complex were hot (approximately 1030 °C) and water-undersaturated (Frost & Touret, 1989) so that horizontal outward movement of ‘igneous’ water from the crystallizing Laramie Anorthosite Complex into the aureole was negligible, and (iii) hydroscopic partial melts were present in the inner aureole, further reducing water activity. Spicuzza (1990) documented that water activity within the aureole decreases towards the contact. Crystalline diffusion between adjacent minerals was probably the only effective transport mechanism of elements during contact metamorphism, and no large-scale transport of aqueous fluid was involved. Petrological criteria such as the low variance nature of mineral assemblages and the localized nature of contact metamorphic reactions in rocks indicate a dry environment during the contact metamorphism (e.g. Thompson, 1983; Ridley & Dixon, 1984). Textural features observed within the outer margins of the aureole such as andalusite–spinel and cordierite–spinel knots after staurolite, and replacement of kyanite by andalusite, indicate that the metamorphic reactions during contact metamorphism were extremely localized.

An illustration of the importance of fluids, rather than duration of metamorphism, is provided by a comparison of the isotopic response of pelitic schists with that of metabasites within the contact aureole of the LAC at Morton Pass. Where these abut marble, the metabasites have undergone extreme dehydration, presumably due to the fluxing of CO_2-rich fluids out of the marbles. In these metabasites, Rb–Sr and Sm–Nd isotopic systems in both whole rocks and mineral separates had been partially to completely re-equilibrated at the time of contact metamorphism. The duration of heating and maximum temperatures attained in the metabasites are comparable to those of the metapelites, so it is clear that the difference between the two is that the metabasites reported by Frost & Frost (1995) were subjected to high fluid flux, whereas the pelitic hornfelses were not.

Geochemical behaviour of parent and daughter elements and site availability

Rb has a similar ionic charge and radius to K, hence Rb occurs primarily in K-bearing minerals by replacing K in the crystal lattice. Sr, on the other hand, occurs primarily in Ca-bearing minerals. ^{87}Sr, the product of radioactive decay of ^{87}Rb, has a higher ionic charge and much smaller ionic radius than Rb. This radiogenic ^{87}Sr is located in an unfavourable site in a mineral lattice from which it may be liberated during metamorphism.

In contrast to the different geochemical characteristics of parent and daughter elements in the Rb–Sr system, Sm and Nd are geochemically similar. Both rare earth elements, they have identical ionic charge and similar ionic radii. They are present in rock-forming minerals at the ppm level, and in addition are concentrated in accessory minerals such as monazite and apatite. The rare earth elements are among the more immobile elements during metamorphism. Even in cases in which Sm and Nd are affected by metamorphic processes, their geochemical similarity means that parent and daughter may not be fractionated and thus there may be little or no effect on Sm–Nd isotopic systematics.

These differences in geochemical behaviour between the Rb–Sr and Sm–Nd systems help explain the behaviour of different rock types during metamorphism. In particular, the availability of crystal lattice sites for Sr and Rb can affect the response of the Rb–Sr system in different rock types, and helps to explain the different behaviour of the Rb–Sr system in metabasite and metapelite in the central Laramie Mountains. In some rock types, especially those containing only a few minerals, it is possible that parent or daughter elements may be partitioned strongly into only one mineral. For example, the metabasites studied by Frost & Frost (1995) are composed primarily of plagioclase, hornblende and Fe–Ti oxides. In this rock, most of the Rb is held in hornblende and Sr is partitioned strongly into plagioclase. If, during metamorphism, hornblende breaks down and there is no mineral that takes up Rb, this element may be partitioned into the fluid phase. Plagioclase is the main host for Sr in these metabasites. Some radiogenic Sr liberated by the breakdown of hornblende may have been incorporated into feldspar, but most appears to have been removed in the fluid phase (Frost & Frost, 1995). Hence, the Rb–Sr system was reset during the 1.43 Ga contact metamorphism of metabasites by removal of radiogenic Sr from the rock via metamorphic fluids.

Pelitic schists typically contain a greater number of phases, and Rb and Sr are distributed amongst several minerals. In the pelitic schists from the Elmers rock greenstone belt, K-feldspar and garnet grown during contact metamorphism have appropriate sites to accommodate Rb and Sr liberated during metamorphism. This, coupled with the fluid-poor environment of contact metamorphism associated with the Laramie Anorthosite Complex, explains why the schists may remain closed to Rb and Sr on the hand sample scale, and why the Rb–Sr system in the pelitic rocks was not reset.

CONCLUSIONS

This study shows that the Rb–Sr whole-rock systematics of samples of pelitic schists collected throughout the central Laramie Mountains were strongly affected by amphibolite-grade regional metamorphism at 1.78 Ga. Because diffusion alone is ineffective, additional factors such as flow of aqueous fluid must have been involved during the 1.78 Ga regional metamorphism in order to cause widespread Sr isotopic redistribution on a scale of at least tens of metres. During the fluid-absent contact metamorphism at 1.43 Ga associated with the Laramie Anorthosite Complex, Sr isotopic mobility in pelitic schists was restricted to the centimetre scale or less. The importance of a fluid phase is highlighted by the contrasting response of the Rb–Sr system in metabasites that were fluxed by a CO_2-rich fluid during the same contact metamorphism: in these, the Rb–Sr isotopic system was reset (Frost & Frost, 1995).

The results above demonstrate that the behaviour of isotopic systems during metamorphism is complex. Given the dependence of isotopic response upon factors including those discussed above, it is not surprising that attempts to date metamorphism have met with varying success. Clearly it is important to design dating experiments carefully, for example, by dating minerals that are known to have grown during metamorphism (i.e. Resor *et al.*, 1996). On the other hand, the very complexity of isotopic responses means they may provide information that would not be obtained by other means. An example from the present study is the discovery that Sr from metabasites and pelitic schists within Elmers rock greenstone belt was redistributed during regional metamorphism, such that following metamorphism both rock types had similar $^{87}Sr/^{86}Sr$ ratios. This interaction between metabasites and pelitic schists could not have been detected using conventional approaches to describing metamorphism. Isotopic tracing of metamorphic processes will be most successful in areas that are well dated, and in which a substantial amount of time passed between the age of the protolith and the time of metamorphism.

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