

Nd isotopic evidence for the antiquity of the Wyoming province

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ABSTRACT

Sm-Nd isotopic data on Late Archean age metasedimentary rocks from around the Wyoming province yield ϵ_{Nd} values at 2.6 Ga from -12.9 to $+3.3$, which correspond to depleted mantle model ages of 2.7 to 3.8 Ga. These results indicate that crust of a wide variety of ages was exposed and eroding in Late Archean time. The predominance of Middle Archean model ages suggests that continental crust was extensive in the Wyoming province by this time. No resolvable correlation exists between initial ϵ_{Nd} value and geographic location or depositional environment of the metasedimentary rock samples; thus, there is no indication that any part of the province was established at a time different from the rest. The Nd isotopic characteristics of Archean rocks from the Wyoming province contrast with those of the Superior province, confirming that, although their Proterozoic evolution has been parallel, the two cratons did not share a common Archean history.

INTRODUCTION

Recent geochronological research has provided evidence of crust at least as old or older than 3.8 Ga in a number of Precambrian provinces around the world, including Australia, the Slave province, and Labrador. Ancient crust also appears to have been present in the Wyoming province, where zircon crystals as old as 3.8 Ga have been documented in a migmatite from the Wind River Range (Aleinikoff et al., 1989), and detrital zircons from the Beartooth Mountains have been dated at 3.96 Ga (Mueller et al., 1992). It is uncertain, however, how widespread Early Archean age crust was in the Wyoming province. Other evidence of material older than 3 Ga is limited and comes mainly from the northwestern part of the province (e.g., Nunes and Tilton, 1971; Stevenson and Patchett, 1990) and from the Granite Mountains (Fischer and Stacey, 1986). The volume of Early to Middle Archean age crust present in the Wyoming province is difficult to determine because Archean rocks are exposed only in the cores of late Mesozoic-early Tertiary Laramide uplifts; these exposures represent <10% of the area of the Wyoming province. Moreover, the Archean exposures are dominated by Late Archean granitoids and granite gneisses that obliterated much of the earlier geologic record.

I have documented the prevalence of Early and Middle Archean crust across the Wyoming province by examining the Sm-Nd isotopic characteristics of Late Archean metasedimentary rocks deposited prior to the emplacement of Late Archean granitoids. The rare-earth characteristics of fine-grained sediments are thought to reflect those of the exposed and eroding surface of the continental crust. As such, their Nd isotopic compositions provide a composite of the Nd isotopic character of their source areas. The Archean metasedimentary rocks studied here represent aggregates of detritus from the Wyoming craton, almost certainly including parts that are no longer exposed. Therefore, they represent a way to recover information about more of the Archean continental crust than can be investigated directly. The initial isotopic ratios of these sediments and their model crustal-residence ages indicate whether parts of the crust exposed in Late Archean time were largely juvenile or whether ancient materials dominated Late Archean detritus.

Farmer and DePaolo (1984) first used Nd isotopic data to identify age provinces within Precambrian continental crust. They analyzed Phanerozoic granites, the Nd isotopic signatures of which were assumed to reflect the age of the crust through which they ascended.

The geographic pattern of ϵ_{Nd} values and Nd model ages that emerged was used to delineate crust-formation age provinces. Many subsequent studies have adopted this approach, while emphasizing the importance of identifying granitoids that are pure crustal melts. Abstracts by Peterman and Futa (1987, 1988) used Nd isotopic data from felsic crystalline rocks to compare the Wyoming and Superior provinces. My study differs from those above in that it examines metasedimentary rocks that represent composites of the subaerial crust instead of granitoids that represent a vertical sampling through the crust, which perhaps include an upper-mantle component. The Nd isotopic data from the Late Archean metasedimentary rocks presented here, together with ϵ_{Nd} data from Late Archean igneous rocks, are used to assess the antiquity of the Wyoming province.

SAMPLES

The 23 samples of Archean metasedimentary rocks analyzed in this study were collected from the Beartooth, Madison, Gravelly, Wind River, Owl Creek, Granite, Laramie, and Hartville uplifts (Fig. 1). All samples have been variably metamorphosed from greenschist to granulite facies. They have major element compositions within the range typical of post-Archean shales and modern turbidite mudstones and sandstones. In general, the metasediment samples can be divided into three types. The first are those associated with greenstone-belt successions in the southern Wind River Range and the central Laramie Mountains. The second type appear to represent continental platform deposits such as those in the ranges of southwest Montana and the Hartville uplift where metacarbonates and shales predominate. The third type of metasedimentary samples includes those from the northern Wind River, Owl Creek, and Granite mountains. They are found as inclusions and disrupted belts within high-grade gneisses, and their depositional environment has not been determined. Intrusive contacts of Late Archean granitoids provide minimum depositional ages of 2.7 to 2.6 Ga for most samples; in addition, the depositional age of samples from the central Laramie Mountains is delimited by a 2.64 ± 0.01 Ga age on a rhyolite from the same supracrustal succession (Snyder et al., 1988).

Sm-Nd ISOTOPIC RESULTS

Sm and Nd concentration data, Nd isotopic ratio and calculated model ages are presented in Table 1. There is no obvious correlation

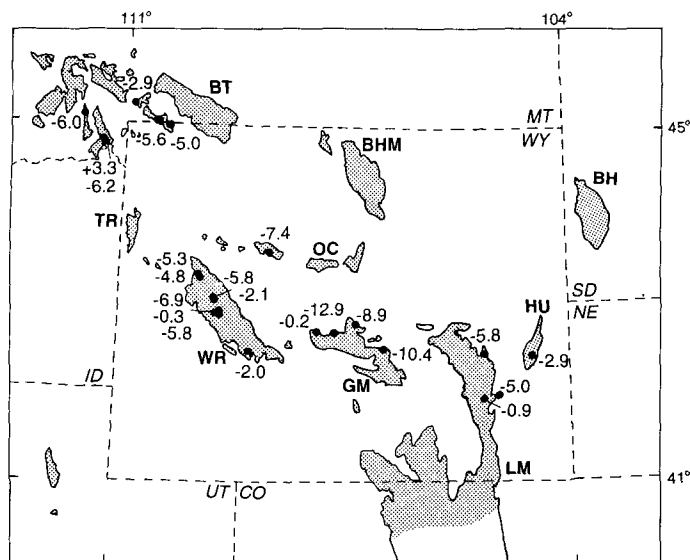


Figure 1. Sketch map showing Precambrian outcrop (dot pattern) exposed in cores of Laramide uplifts in Wyoming and adjacent states. Solid circles indicate location of metasedimentary rock samples analyzed in this study. Numbers are ϵ_{Nd} values at 2.6 Ga. BT = Beartooth Mountains, TR = Teton Range, BHM = Bighorn Mountains, OC = Owl Creek Mountains, WR = Wind River Range, GM = Granite Mountains, BH = Black Hills, HU = Hartville uplift, LM = Laramie Mountains.

between mineralogy and Sm and Nd abundance evident in these samples. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios vary from 0.0915 to 0.130, plus two samples with higher ratios of 0.171 and 0.160 (Fig. 2A). With these two exceptions, the Sm/Nd ratios are typical of mudstones and shales. The average value for the entire data set, 0.119, is indistinguishable from the average value of 0.120 obtained by Dia et al. (1990) from a compilation of $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of clastic sedimentary rocks taken from the literature.

Present-day $^{143}\text{Nd}/^{144}\text{Nd}$ ratios range from 0.510176 to 0.511703, and correspond to ϵ_{Nd}^0 values of -48.0 to -18.2 . Subsequent to Late Archean plutonism, known geologic events are limited largely to uplift and fracturing of these rocks during formation of the ancestral Rocky Mountains and the Laramide uplifts that exposed the rocks we observe today. It appears unlikely that any post-Archean geologic event affected the Nd isotope systematics of these rocks, and thus the Nd isotopic ratio of the metasedimentary rocks at their minimum depositional age of 2.6 Ga can be calculated based upon the present-day Sm/Nd and Nd isotopic ratios (Table 1). ϵ_{Nd} values at 2.6 Ga vary between -12.9 and $+3.3$, and 16 of 23 samples have values within 3 epsilon units of the mean, $\epsilon_{Nd} = -4.8$ (Fig. 2B).

Model Nd crustal-residence ages (T_{CR}) calculated relative to the depleted-mantle model of Goldstein et al. (1984) vary from 2.7 to 3.8 Ga (Table 1, Fig. 2C). These model ages represent the average time at which the precursors of the sediment were extracted from a de-

TABLE 1. Sm-Nd ISOTOPIC DATA FOR ARCHEAN METASEDIMENTARY ROCKS FROM THE WYOMING PROVINCE

Sample	Type of schist	Location (lat, N) (long, W)		$^{143}\text{Nd}/^{144}\text{Nd}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	T_{CR} (Ga)	ϵ_{Nd} (2.6 Ga)
Beartooth Mountains									
80-20	Biotite	45°0'	110°35'	0.510786 (24)	2.925	17.06	0.1036	3.3	-5.0
79-3	Biotite	45°4'	110°39'	0.510921 (19)	4.571	24.38	0.1134	3.4	-5.6
4-44	Garnet biotite	5°11'56"	110°58'49"	0.511196 (29)	4.377	21.81	0.1213	3.2	-2.9
Madison Range									
WS-84	Garnet biotite	44°41'20"	111°23'27"	0.511668 (14)	6.306	29.23	0.1304	2.7	+3.3
WS-86	Garnet biotite	44°41'30"	111°23'30"	0.510930 (31)	7.442	38.94	0.1155	3.4	-6.2
Gravelly Range									
AV-14	Biotite	45°07'08"	111°44'03"	0.510939 (27)	4.678	24.46	0.1156	3.4	-6.0
Owl Creek Mountains									
OC-1	Garnet biotite	43°34'39"	108°40'42"	0.510790 (23)	4.135	22.51	0.1110	3.5	-7.4
Wind River Range									
WP-1	Cordierite biotite	43°20'28"	109°44'38"	0.510945 (17)	1.877	10.11	0.1122	3.3	-4.8
FPN81-3	Garnet cordierite biotite	43°08'45"	109°34'20"	0.510940 (27)	8.541	44.86	0.1151	3.4	-5.8
FPN81-11b	Garnet orthopyroxene biotite	43°08'55"	109°34'06"	0.511332 (33)	5.310	25.34	0.1267	3.2	-2.1
DM83-28	Garnet cordierite biotite	43°21'	109°44'	0.510950 (19)	9.375	49.69	0.1140	3.3	-5.3
4CF-8*	Garnet biotite	42°56'05"	109°25'09"	0.510756 (21)	3.161	17.79	0.1074	3.4	-6.9
4CF-37*	Garnet biotite	42°55'20"	109°25'09"	0.511094 (05)	9.283	52.17	0.1076	2.9	-0.3
4CF-53*	Garnet biotite	42°55'55"	109°27'57"	0.510961 (24)	6.802	35.40	0.1162	3.4	-5.8
AR-7a	Biotite	42°27'19"	108°57'34"	0.511285 (19)	4.960	24.20	0.1239	3.1	-2.0
Granite Mountains									
WP-3	Cordierite biotite	42°39'01"	107°54'29"	0.511173 (24)	4.179	22.56	0.1120	3.0	-0.2
WP-7	Sillimanite muscovite biotite	42°37'51"	107°32'17"	0.510176 (22)	7.097	46.86	0.0915	3.7	-12.9
WP-14	Garnet cordierite biotite	42°38'24"	107°19'58"	0.511746 (12)	1.556	5.491	0.1713	--	-8.9
WP-15	Garnet biotite	42°28'41"	106°52'21"	0.510767 (21)	3.227	16.48	0.1184	3.8	-10.4
Laramie Mountains									
WP-28	Chloritoid	42°28'47"	105°18'04"	0.511703 (13)	2.463	9.335	0.1595	--	-5.8
WP-36	Sillimanite staurolite biotite	41°56'45"	105°08'55"	0.510965 (21)	4.873	25.81	0.1141	3.3	-5.0
WP-38	Sillimanite kyanite andalusite	41°54'38"	105°20'03"	0.511032 (22)	5.397	30.88	0.1057	3.0	-0.9
Hartville uplift									
WP-35	Sillimanite biotite	42°19'23"	104°41'25"	0.511077 (14)	3.957	20.92	0.1143	3.2	-2.9

Note: Rare earth separations and isotope ratio measurements were performed at the University of Wyoming following procedures outlined by Frost and Coombs (1989). Two standard errors on Nd isotope ratio (in parentheses) refer to final two decimal places. $^{143}\text{Nd}/^{144}\text{Nd}$ ratio normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. During the period these analyses were done the LaJolla standard gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.511837 \pm 0.000018$ (1σ), which is 15 ppm lower than the accepted value. Each analysis above has been adjusted upward by 15 ppm. Crustal-residence ages are not calculated for samples with $^{147}\text{Sm}/^{144}\text{Nd} > 0.15$.

*Data from Koesterer et al (1987).

pleted mantle, weighted by the amount of Nd in each source. The calculation assumes that the Sm/Nd ratio has not been substantially affected by diagenesis (Awwiller and Mack, 1991) or metamorphism and partial melting. Because it is not possible to determine precisely to what extent these assumptions are justified, model ages are used here only to corroborate interpretations based upon the 2.6 Ga ϵ_{Nd} data. As with the 2.6 Ga ϵ_{Nd} data, the variation in crustal-residence age is limited: 16 of 23 samples have model ages of 3.1 to 3.5 Ga.

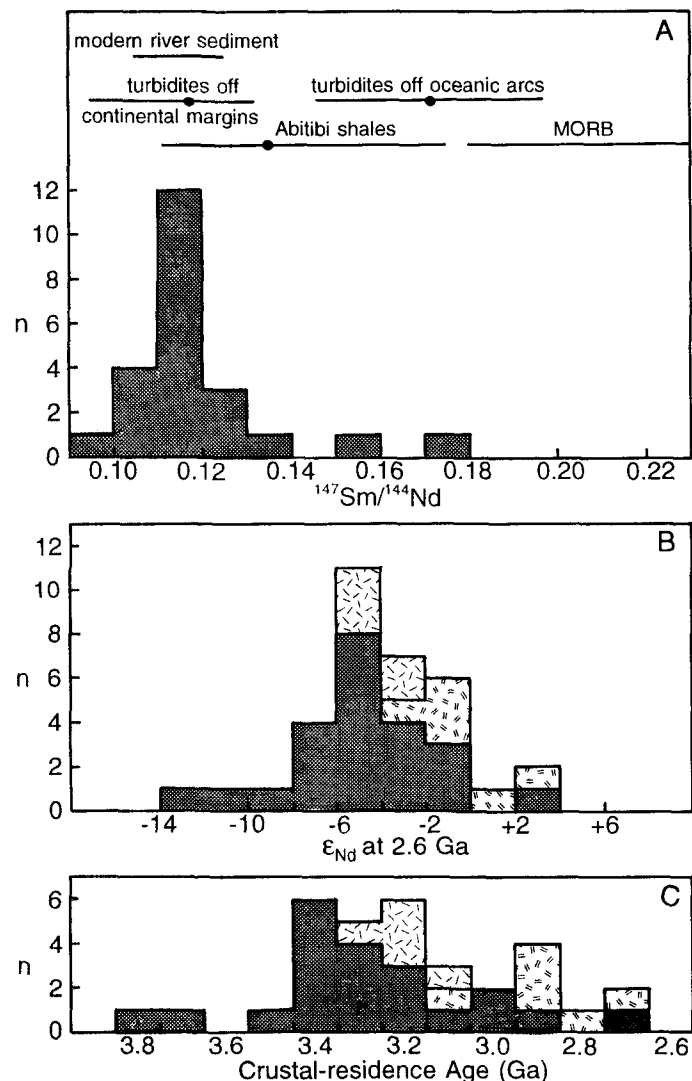


Figure 2. A: Histogram of $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of metasedimentary rocks analyzed in this study. Range of $^{147}\text{Sm}/^{144}\text{Nd}$ values for modern turbidites derived from continental arcs and passive margins, for modern and Permian turbidites from island-arc settings, for modern sediment from major rivers, for shales from Abitibi belt and for mid-ocean ridge basalt (MORB) are shown for comparison. Data from this study and from McLennan et al. (1990), Dia et al. (1990), Goldstein et al. (1984), and Frost and Coombs (1989). **B:** Histogram of ϵ_{Nd} values at 2.6 Ga for Archean rocks from Wyoming province. Shaded area represents metasedimentary rocks of this study; random double-dash pattern = Late Archean granitoid rocks of Wind River Range reported by Koesterer et al. (1987); random single-dash pattern = Late Archean granitoids and amphibolites from Beartooth Mountains reported by Wooden and Mueller (1988). Beartooth Mountains Nd isotope ratio data were adjusted by -0.00008 and renormalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. **C:** Histogram of Nd model crustal-residence ages for Archean rocks from Wyoming province. Patterns and data sources as in B.

DISCUSSION AND CONCLUSIONS

The Sm-Nd isotopic data presented here represent convincing evidence for the presence of ancient, evolved crust throughout the Wyoming province.

1. The Sm/Nd ratios of the Archean metasedimentary samples suggest derivation from a compositionally mature craton. Ratios of $0.0915 \geq ^{147}\text{Sm}/^{144}\text{Nd} \geq 0.130$ are typical of continental crust and are similar to the range exhibited by turbidite deposits dominated by continental detritus, as in passive-margin and continental-arc settings (Fig. 2A). They are lower than Sm/Nd ratios typical of Holocene and Permian turbidite deposits from oceanic-arc settings. The Archean metasedimentary rocks from Wyoming also have lower Sm/Nd ratios than do shale samples of comparable age from the Abitibi belt of the Superior province (Fig. 2A). As such, the Sm-Nd data from Archean metasedimentary rocks corroborate other evidence that many of the Archean rocks of the Wyoming province were geochemically evolved. For example, moderately potassic granitoids are more prevalent than tonalite (Frost and Frost, 1993), granitoids from the Wind River, Granite, and Beartooth mountains have relatively radiogenic initial Pb compositions (see compilation by Wooden and Mueller, 1988), and all but the oldest granitic gneisses have initial Sr isotope ratios that are more radiogenic than bulk earth values (Frost and Frost, 1993).

2. Negative ϵ_{Nd} values at 2.6 Ga, which correspond to Early to Middle Archean Nd crustal-residence ages, suggest that almost all of these Late Archean metasedimentary rocks were derived from exposed crust that was, on average, extracted from depleted mantle several hundred million years earlier. Only one sample, WS-84, had an ϵ_{Nd} value at 2.6 Ga which approached contemporary depleted mantle values, indicating that it was probably derived predominantly from juvenile crust. Published Nd isotopic data for Late Archean intrusive rocks from the Wind River Range and Beartooth Mountains (Fig. 2, B and C) have ϵ_{Nd} values at 2.6 Ga that range from $+3.1$ to -5.3 , which overlaps the radiogenic part of the metasedimentary spectrum. Likewise, the Nd model ages for the intrusive rocks ($T_{CR} = 2.7$ to 3.3 Ga) are within the range of metasedimentary model ages but are concentrated at the young end. The large range in both ϵ_{Nd} and T_{CR} values shown in Figure 2, B and C, suggests that both depleted mantle-juvenile crust and much older crustal source materials were incorporated into the metasedimentary rocks and granitoids. Given the wide range of ϵ_{Nd} values for Wyoming province continental crust at 2.6 Ga of -12.9 to $+3.3$, it is not necessary to invoke an origin for Late Archean plutonic and volcanic rocks from enriched mantle with ϵ_{Nd} of around 0 as has been proposed (Wooden and Mueller, 1988; Mueller and D'Arcy, 1990).

3. There is no correlation between ϵ_{Nd} values and geographic location. A range of ϵ_{Nd} values for 2.6 Ga is found within each uplift of the Wyoming province for which there are multiple analyses (Fig. 1). There is also no correlation between ϵ_{Nd} values and apparent depositional environment. Although supracrustal sequences of presumed greenstone affinity have been interpreted to represent Late Archean juvenile crust (Peterman, 1979; Peterman and Futa, 1988; Mueller and D'Arcy, 1990), samples from those successions in the southern Wind River Range and central Laramie Mountains do not have distinct Nd isotopic characteristics. No large areas of juvenile crust appear to be sampled by these or by any of the other metasedimentary rocks analyzed here. Although it remains possible that the Wyoming province grew by accretion of crustal blocks of different ages, such a pattern cannot be discerned from the data presented in this study. Metasedimentary rocks from all parts of the province provide evidence for the presence of continental crust of Middle Archean age or older.

4. Despite early speculation that the Wyoming and Superior

cratons may have been contiguous in Archean time (e.g., Peterman, 1979), the lithological and chronological differences between the two are now clearer. The Archean history of the Wyoming province is very different from that of the Superior province. The Superior province was formed primarily by the amalgamation of belts of greenstone supracrustal successions and volcano-plutonic rocks. The basement rocks of the Late Archean supracrustal sequences are not much older than the depositional age of the successions, and few rocks older than 3.1 Ga have been documented (Card, 1990). The absence of supracrustal rocks and basement gneiss samples with Nd model ages much in excess of depositional or crystallization ages is consistent with a model of crust formation followed almost immediately by amalgamation (Peterman and Futa, 1987, 1988; Dia et al., 1990). The growth of the Superior province is more analogous to that of the Proterozoic Colorado province, where mafic and felsic volcanic supracrustal sequences were derived from mantle or juvenile crustal sources in the absence of older continental crust, and were sutured to the southern margin of the Wyoming province soon after formation (Reed et al., 1987). If the Wyoming province was formed by such a mechanism, then it developed much earlier in the Early or Middle Archean. In any case, the metasedimentary rocks examined here clearly are not equivalent to Superior and Colorado greenstone-belt associations. Although the Wyoming and Superior provinces share a similar Proterozoic history, their Archean evolution is not parallel. The Nd isotopic data presented herein confirm that crust formation throughout the Wyoming province predates that of the Superior province.

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