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 $e_{Nd}$ 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 $e_{Nd}$ 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 $e_{Nd}$ 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 $e_{Nd}$ 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 green-schist 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...
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 $^{144}\text{Nd}^{144}\text{Nd}$ ratios range from 0.511076 to 0.511703, and correspond to $\epsilon_{\text{Nd}}$ 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). $\epsilon_{\text{Nd}}$ 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, $\epsilon_{\text{Nd}} = −4.8$ (Fig. 2B).

Model Nd crustal-residence ages ($T_{\text{Cr}}$) 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

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**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 $\epsilon_{\text{Nd}}$ 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.

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

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type of rock</th>
<th>Location</th>
<th>$^{147}\text{Sm}^{144}\text{Nd}$</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>$^{147}\text{Sm}^{144}\text{Nd}$</th>
<th>$T_{\text{Cr}}$ (Ga)</th>
<th>$\epsilon_{\text{Nd}}$ (2.6 Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beartooth</td>
<td>Biotite</td>
<td>45°0' 110°35'</td>
<td>0.510786 (24)</td>
<td>2.925</td>
<td>17.06</td>
<td>0.1036</td>
<td>3.3</td>
<td>−5.0</td>
</tr>
<tr>
<td>Wind River Range</td>
<td>Biotite</td>
<td>45°0' 110°35'</td>
<td>0.510921 (19)</td>
<td>4.571</td>
<td>24.38</td>
<td>0.1134</td>
<td>3.4</td>
<td>−5.6</td>
</tr>
<tr>
<td>Madison Range</td>
<td>Garnet biotite</td>
<td>5°11'56&quot; 110°58'40&quot;</td>
<td>0.511196 (29)</td>
<td>4.377</td>
<td>21.87</td>
<td>0.1213</td>
<td>3.2</td>
<td>−2.9</td>
</tr>
<tr>
<td>Gravelly Range</td>
<td>Garnet biotite</td>
<td>44°41'20&quot; 111°23'27&quot;</td>
<td>0.511668 (14)</td>
<td>6.306</td>
<td>29.23</td>
<td>0.1304</td>
<td>2.7</td>
<td>+3.3</td>
</tr>
<tr>
<td>Owl Creek</td>
<td>Garnet biotite</td>
<td>44°41'30&quot; 111°23'20&quot;</td>
<td>0.510930 (31)</td>
<td>7.442</td>
<td>38.94</td>
<td>0.1155</td>
<td>3.4</td>
<td>−6.2</td>
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<tr>
<td>OC-1</td>
<td>Garnet biotite</td>
<td>45°07'08&quot; 111°44'03&quot;</td>
<td>0.510937 (29)</td>
<td>4.678</td>
<td>24.46</td>
<td>0.1156</td>
<td>3.4</td>
<td>−6.0</td>
</tr>
<tr>
<td>Wind River</td>
<td>Garnet biotite</td>
<td>43°34'39&quot; 108°40'42&quot;</td>
<td>0.510790 (23)</td>
<td>4.135</td>
<td>22.51</td>
<td>0.1110</td>
<td>3.5</td>
<td>−7.4</td>
</tr>
<tr>
<td>WP-1</td>
<td>Cordierite biotite</td>
<td>47°20'28&quot; 109°44'38&quot;</td>
<td>0.510945 (17)</td>
<td>1.877</td>
<td>10.11</td>
<td>0.1222</td>
<td>3.3</td>
<td>−4.8</td>
</tr>
<tr>
<td>WPN1-3</td>
<td>Garnet cordierite biotite</td>
<td>47°08'45&quot; 109°34'20&quot;</td>
<td>0.510940 (27)</td>
<td>8.541</td>
<td>44.86</td>
<td>0.1151</td>
<td>3.4</td>
<td>−5.8</td>
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<td>DM38-28</td>
<td>Garnet cordierite biotite</td>
<td>47°08'55&quot; 109°34'06&quot;</td>
<td>0.511332 (33)</td>
<td>5.310</td>
<td>25.34</td>
<td>0.1267</td>
<td>3.2</td>
<td>−2.1</td>
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<tr>
<td>AR-7a</td>
<td>Garnet biotite</td>
<td>42°27'19&quot; 108°53'34&quot;</td>
<td>0.511285 (19)</td>
<td>4.960</td>
<td>24.20</td>
<td>0.1239</td>
<td>3.1</td>
<td>−2.0</td>
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<tr>
<td>Laramie Mountains</td>
<td>Cordierite biotite</td>
<td>42°39'01&quot; 107°54'29&quot;</td>
<td>0.511173 (24)</td>
<td>4.179</td>
<td>22.56</td>
<td>0.1200</td>
<td>3.0</td>
<td>−0.2</td>
</tr>
<tr>
<td>WP-14</td>
<td>Garnet cordierite biotite</td>
<td>45°18'34&quot; 107°19'58&quot;</td>
<td>0.511746 (12)</td>
<td>1.556</td>
<td>5.491</td>
<td>0.1713</td>
<td>3.0</td>
<td>−9.9</td>
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<tr>
<td>WP-15</td>
<td>Garnet biotite</td>
<td>42°28'41&quot; 106°52'21&quot;</td>
<td>0.510767 (21)</td>
<td>3.227</td>
<td>16.48</td>
<td>0.1184</td>
<td>3.8</td>
<td>−10.4</td>
</tr>
<tr>
<td>WP-28</td>
<td>Chloritoid</td>
<td>42°28'47&quot; 105°18'04&quot;</td>
<td>0.511703 (13)</td>
<td>2.463</td>
<td>9.335</td>
<td>0.1595</td>
<td>−5.8</td>
<td></td>
</tr>
<tr>
<td>WP-36</td>
<td>Sillimanite staurolite biotite</td>
<td>41°56'45&quot; 105°08'55&quot;</td>
<td>0.510965 (21)</td>
<td>4.873</td>
<td>25.81</td>
<td>0.1141</td>
<td>3.3</td>
<td>−5.0</td>
</tr>
<tr>
<td>WP-38</td>
<td>Sillimanite kyanite andalusite</td>
<td>41°54'38&quot; 105°20'03&quot;</td>
<td>0.511032 (22)</td>
<td>5.397</td>
<td>30.88</td>
<td>0.1057</td>
<td>3.0</td>
<td>−5.9</td>
</tr>
<tr>
<td>Hartville uplift</td>
<td>Sillimanite biotite</td>
<td>42°19'23&quot; 104°41'25&quot;</td>
<td>0.51077 (14)</td>
<td>3.957</td>
<td>20.92</td>
<td>0.1143</td>
<td>3.2</td>
<td>−2.9</td>
</tr>
</tbody>
</table>

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. $^{147}\text{Sm}^{144}\text{Nd}$/Sm-Nd ratio normalized to $^{147}\text{Sm}^{144}\text{Nd}$ = 0.7219. During the period these analyses were done the LaJolla standard gave $^{143}\text{Nd}^{144}\text{Nd}$ = 0.51837 (±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 $^{147}\text{Sm}^{144}\text{Nd}$/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 εNd
data. As with the 2.6 Ga εNd data, the variation in crustal-residence age
is limited: 16 of 23 samples have model ages of 3.1 to 3.5 Ga.

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
0.9915 ± 147Sm/144Nd = 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 set-
tings (Fig. 2A). They are lower than Sm/Nd ratios typical of Hol-
ocene 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 evi-
dence that many of the Archean rocks of the Wyoming province were
depositionally mature. For example, moderately potassic grani-
toids are more prevalent than tonalite (Frost and Frost, 1993), grain-
toids 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 εNd 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 ex-
posed crust that was, on average, extracted from depleted mantle
several hundred million years earlier. Only one sample, WS-84, had
an εNd 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
invasive rocks from the Wind River Range and Beartooth Mountains
(Fig. 2, B and C) have εNd 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 (TcR
= 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 εNd
and TcR values shown in Figure 2, B and C, suggests that both
deposited mantle-juvenile crust and much older crustal source ma-
terials were incorporated into the metasedimentary rocks and gran-
toids. Given the wide range of εNd values for Wyoming province
crustal Nd 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 εNd of around 0 as has been proposed (Wooden

3. There is no correlation between εNd values and geographic
location. A range of εNd 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 εNd values and apparent
depositional environment. Although supracrustal sequences of pre-
sumed 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 metased-
imentary 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

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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 successions 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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REFERENCES CITED

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