Nd- and Pb-isotope variations in the multicyclic central caldera cluster of the San Juan volcanic field, Colorado, and implications for crustal hybridization

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ABSTRACT
The $\varepsilon_{Nd}$ values for six large-volume (100–3000 km$^3$) ash-flow tuffs and associated lavas from the multicyclic central caldera cluster of the San Juan volcanic field in south-central Colorado are between those of Proterozoic crust in the region and mantle-derived basaltic magmas, and the values generally become progressively higher in progressively younger tuffs and lavas. The increase in the $\varepsilon_{Nd}$ values of the tuffs, from $\sim$8.0 to $\sim$6.0 with decreasing age, can be modeled by assimilation and crystal fractionation of a mantle-derived magma, accompanied by an increase of $\sim$4 units in $\varepsilon_{Nd}$ values of the assimilated crust. The postulated increase in $\varepsilon_{Nd}$ values of the crust is envisioned to have occurred by hybridization of the crust through continued injection of mantle-derived magmas during the life of the magmatic system. Decreasing $^{206}$Pb/$^{207}$Pb ratios observed in progressively younger tuffs following the initiation of caldera-related volcanism cannot, however, be solely explained by addition of mantle-derived magmas to the crust, but are more likely to reflect the transfer of lower-crustal Pb into the upper crust as the magmatic system evolved. Input of large volumes ($\sim$300 000 km$^3$) in the San Juan volcanic field of mantle-derived magma resulted in extensive hybridization of preexisting crust, suggesting that large-scale silicic volcanism involves generation of large quantities of new crust.

INTRODUCTION
Most workers agree that generation of large volumes of silicic magmas, commonly erupted as ash-flow tuffs, requires injection of substantial volumes of basaltic magmas into the crust (e.g., Hildreth, 1981), suggesting that most silicic volcanic centers and bimodal basalt-rhyolite fields are fundamentally basaltic (Christiansen and Lipman, 1972). The role of basaltic magmas in generating silicic magmas varies among models, from those in which mantle-derived magmas serve primarily as a heat source for generating silicic magmas by crustal anatexis (e.g., Huppert and Sparks, 1988; Chappell and Stevens, 1988) to those that call upon crustal assimilation coupled with fractional crystallization of mantle-derived magmas to produce silicic magmas (e.g., Cameron and Cameron, 1985; Musselwhite et al., 1989; Johnson et al., 1990). Although recent isotopic data on continental volcanic rocks indicate large crustal components (e.g., Hildreth and Moorabath, 1988), several ash-flow tuffs from western North America have $\varepsilon_{Nd}$ values between those of regional crust and mantle, suggesting that these evolved rocks contain significant mantle components as well (Johnson, 1991).

Herein we present new Pb-isotope data and the first Nd-isotope data for Oligocene ash-flow tuffs and related lavas of the San Juan volcanic field, Colorado. The multicyclic central San Juan caldera cluster provides an excellent locality to test the model proposed by Johnson et al. (1990) that progressive modification of crustal Sr- and Nd-isotope ratios may occur beneath large caldera complexes by repeated injection of mantle-derived magmas.

GEOLOGIC SETTING
The San Juan volcanic field is the largest remnant of a composite, mid-Tertiary volcanic field that covered much of the southern Rocky Mountains (Steven, 1975). More than 40 000 km$^3$ of magma were erupted between 35 and 25 Ma in the San Juan field (Lipman et al., 1970). About two-thirds of the total volume of rocks in the San Juan field consists of predominantly intermediate-composition lavas of the Conejos Formation that were erupted between 35 and 30 Ma (Lipman et al., 1970). Approximately 15 intermediate- to silicic-composition, large-volume ash-flow tuffs were erupted from three distinct caldera clusters between 30 and 26 Ma (Fig. 1; Steven and Lipman, 1976; Lipman, 1989). The oldest ash-flow tuffs were erupted from two caldera clusters in the southeast and west between 30 and 27.5 Ma (Fig. 1; Steven and Lipman, 1976; Lipman, 1989). The largest volumes of ash-flow tuffs in the San Juan field were erupted between 28.3 and 26.1 Ma from six calderas from the central caldera cluster (Lanphere, 1988; Lipman et al., 1989), producing $\sim$11 ash-flow tuffs that represent $\sim$7000 km$^3$ of magma (Table 1; Steven and Lipman, 1976; Lipman et al., 1989).

ISOTOPIC DATA
The $\varepsilon_{Nd}$ values of lavas and ash-flow tuffs from the central San Juan caldera cluster generally increase $\sim$2 $\varepsilon_{Nd}$ units with decreasing age and do not correlate with rock type (Table 2, Fig. 2). The $\varepsilon_{Nd}$ values of lavas and tuffs from the central caldera cluster are significantly higher than the majority of Proterozoic granitic and metamorphic rocks from Colorado.

Figure 1. Study area; stipple pattern is San Juan volcanic field (adapted from Steven and Lipman, 1976; Lipman et al., 1989); solid lines with hachures indicate caldera boundaries (dashed where inferred). SL = San Luis, LG = La Garita, B = Bachelor, C = Creede, SR = South River, MH = Mount Hope. Western and eastern caldera clusters also shown (unlabeled).
and northern New Mexico (Fig. 2, DePaolo, 1981; Nelson and DePaolo, 1984, 1985). The Grizzly Peak Tuff, erupted northeast of the San Juan field, has \( \epsilon_{Nd} \) values of \(-13\) to \(-11\), indicating interaction with Proterozoic crust that had \( \epsilon_{Nd} \) values of \(-16\) (Johnson and Fridrich, 1990). Most exposed Proterozoic rocks in Colorado and New Mexico have low Sm/Nd ratios (e.g., Condie, 1986), suggesting that much of the Proterozoic crust in the region has present-day \( \epsilon_{Nd} \) values of \(-10\). Samples plotted in Figure 2 with present-day \( \epsilon_{Nd} \) values are generally from the Tijeras greenstone belt of central New Mexico, which contains rocks of unusually high Sm/Nd ratios; the Dubois greenstone sequence north of the San Juan field has present-day \( \epsilon_{Nd} \) values of \(-12\) to \(+3\) (Nelson and DePaolo, 1984).

Primitive mantle-derived magmas produced during the evolution of the San Juan volcanic field probably had \( \epsilon_{Nd} \) values between 0 and \(-4\), as indicated by 26 Ma basaltic dikes from the nearby San Luis Hills (C. Johnson and R. Thompson, unpublished data).

Lipman et al. (1978) noted that the \( {206}\text{Pb} / {204}\text{Pb} \) ratios for the earliest ash-flow tuffs erupted in all three caldera clusters are substantially higher than those of the precalddera ( Conejos age) lavas. In contrast, \( {206}\text{Pb} / {204}\text{Pb} \) ratios in the younger tuffs and lavas steadily decrease with decreasing age. Our more extensive data set for the central caldera cluster confirms this trend (Table 2, Fig. 3). Lipman et al. (1978) also noted that the early and late ash-flow tuffs from the central caldera cluster that have the least radiogenic Sr- and Pb-isotope ratios (e.g., Fish Canyon and Snowshoe Mountain, respectively) tend to have normative Q-A-Bo compositions that define a high-pressure fractionation trend, although the exact depths of equilibration are controversial (Whitney and Stormer, 1985; Stormer et al., 1987; Grunder and Boden, 1987; Johnson and Rutherford, 1989). The intermediate-age ash-flow tuffs (Mammouth Mountain, Carpenter Ridge, and Wason Park Tuffs) have more radiogenic Sr- and Pb-isotope ratios and tend to have normative Q-Ab compositions that define a low-pressure fractionation trend.

Primitive basaltic of the Hinsdale Formation on the west side of the Rio Grande rift and in the San Luis Hills have \( {206}\text{Pb} / {204}\text{Pb} \) ratios of \(-18.2\), suggesting that this value represents the mantle value for the region (Doe et al., 1969; C. Johnson and R. Thompson, unpublished data). The \( {206}\text{Pb} / {204}\text{Pb} \) ratios for exposed Proterozoic rocks in the region vary from 17 to 33 and do not correlate with rock type; most rocks have \( {206}\text{Pb} / {204}\text{Pb} \) ratios of \(-19\) (J. Wooden, C. Johnson, and J. Reed, Jr., unpublished data).

**ORIGIN OF ISOOTYPE VARIATIONS AND EVOLUTION OF THE CRUST**

The low \( \epsilon_{Nd} \) values of the tuffs and lavas indicate that these rocks contain a substantial crustal component, although the general increase in \( \epsilon_{Nd} \) values of the tuffs and caldera-related lavas with decreasing age suggests an increasing proportion of mantle Nd in the younger rocks. Coupled assimilation and fractional crystallization involving 50% to 85% crystallization and assimilation to crystallization ratios \( R \) of \(-0.4\) can produce the \( \epsilon_{Nd} \) values of the early tuffs and lavas, provided that the assimilated Proterozoic crust had \( \epsilon_{Nd} \) values of \(-12\) (Fig. 4). Calculations indicate that the increase of 2 \( \epsilon_{Nd} \) units between the Fish Canyon Tuff and Snowshoe Mountain Tuff can be explained by an increase of \(-4 \epsilon_{Nd} \) units for the assimilated crust, assuming the mineral/melt distribution coefficient \( D_{\text{Mafic}} \) and \( R \) values remain relatively constant (Fig. 4); we consider these assumptions reasonable given their compositional similarity. The increasing component of mantle Nd in successively younger rocks may not necessarily indicate a decrease in the amount of crust assimilated during generation of successive tuffs, but rather an increase in the proportion of recent mantle-derived Nd in the assimilated crustal component.

Although low \( \epsilon_{Nd} \) values of precalddera Conejos lavas (Fig. 2) indicate that these rocks contain substantial crustal components, some Conejos magmas are too mafic (as low as 54 wt% SiO\(_2\)) to have been generated entirely by crustal melting. Low \( \epsilon_{Nd} \) values in relative mafic pumice (55 wt% SiO\(_2\), \( \epsilon_{Nd} = -7.0 \); L. Ricciuti and C. Johnson, unpublished data) in the Carpenter Ridge Tuff also suggest that at least this tuff cannot have been derived solely by crustal melting. It is unlikely that mixing of magmas is responsible for the observed trends in the isotopic data, since there is no apparent correlation between \( \epsilon_{Nd} \) values and magma composition.

We propose that the ash-flow tuffs were generated by assimilation and fractional crystallization of mantle-derived basaltic magmas. Assimilation and fractional crystallization of mafic parental magmas generally lead to an increased Nd concentrations owing to the incompatible nature of Nd.

### TABLE 2. ISOTOPE DATA FOR THE CENTRAL CALDERA COMPLEX, SAN JUAN VOLCANIC FIELD

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Age (Ma)</th>
<th>Sample</th>
<th>Material</th>
<th>Sm/Nd</th>
<th>( \epsilon_{Nd} )</th>
<th>( \epsilon_{Nd,Mafic} )</th>
<th>( \epsilon_{Nd,Reas} )</th>
<th>( \epsilon_{Nd,Min} )</th>
<th>( \epsilon_{Nd,Pl} )</th>
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<tbody>
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<td>Tcm</td>
<td>26.15</td>
<td>LR8669</td>
<td>Clinopyroxene</td>
<td>0.2388</td>
<td>0.512262</td>
<td>214</td>
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<td>18.315</td>
</tr>
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<td>206</td>
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<td>20.4</td>
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</tr>
<tr>
<td>lava</td>
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<td>Tcm</td>
<td>Whole rock</td>
<td>0.2610</td>
<td>0.512252</td>
<td>200</td>
<td>-7.0</td>
<td>20.4</td>
<td>18.417</td>
</tr>
<tr>
<td>lava</td>
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<td>Tcm</td>
<td>Whole rock</td>
<td>0.2610</td>
<td>0.512252</td>
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<tr>
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<td>Tcm</td>
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<tr>
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<td>Tcm</td>
<td>Whole rock</td>
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<td>0.512252</td>
<td>240</td>
<td>-7.0</td>
<td>20.4</td>
<td>18.417</td>
</tr>
<tr>
<td>lava</td>
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<td>Tcm</td>
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<td>0.2610</td>
<td>0.512252</td>
<td>250</td>
<td>-7.0</td>
<td>20.4</td>
<td>18.417</td>
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<td>Tcm</td>
<td>Whole rock</td>
<td>0.2610</td>
<td>0.512252</td>
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<tr>
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<tr>
<td>lava</td>
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<td>Tcm</td>
<td>Whole rock</td>
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<td>0.512252</td>
<td>280</td>
<td>-7.0</td>
<td>20.4</td>
<td>18.417</td>
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### TABLE 1. STRATIGRAPHY AND CHARACTERISTICS OF CENTRAL CALDERA CLUSTER TUFFS, SAN JUAN VOLCANIC FIELD

<table>
<thead>
<tr>
<th>Tuff Unit</th>
<th>Symbol*</th>
<th>Caldera</th>
<th>Volume (cm(^3))</th>
<th>Composition†</th>
</tr>
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<tbody>
<tr>
<td>Cochitieta Creek</td>
<td>Tcm</td>
<td>San Luis</td>
<td>50-100</td>
<td>R to SD</td>
</tr>
<tr>
<td>Nelson Mtn.</td>
<td>Tcm</td>
<td>San Luis</td>
<td>100-500</td>
<td>R to D</td>
</tr>
<tr>
<td>Cebolla Creek</td>
<td>Tcm</td>
<td>San Luis</td>
<td>50-100</td>
<td>R to SD</td>
</tr>
<tr>
<td>Rascal Creek</td>
<td>Tcm</td>
<td>San Luis</td>
<td>&lt;50</td>
<td>R to SD</td>
</tr>
<tr>
<td>Snowshoe Mtn.</td>
<td>Tcm</td>
<td>Creede &gt;500</td>
<td>SD to A</td>
<td></td>
</tr>
<tr>
<td>Wason Park</td>
<td>Tcm</td>
<td>South River &gt;500</td>
<td>R to SD</td>
<td></td>
</tr>
<tr>
<td>Blue Creek</td>
<td>Tcm</td>
<td>unknown &gt;500</td>
<td>R to SD</td>
<td></td>
</tr>
<tr>
<td>Carpenter Ridge</td>
<td>Tcm</td>
<td>Bachelor &gt;1000</td>
<td>R to SD</td>
<td></td>
</tr>
<tr>
<td>Mammouth Mtn.</td>
<td>Tcm</td>
<td>Bachelor</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Fish Canyon</td>
<td>Tcm</td>
<td>La Garza &gt;1000</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

### Note:
- * Used in Figures 2 and 3.
- † R = rhyolite, SD = silicic dacite, D = dacite, A = andesite.
- § An intracaldera upper member of the Carpenter Ridge Tuff.

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causing Nd-isotope ratios to reach a steady-state composition in intermediate- to silicic-composition magmas (Johnson et al., 1990). This process may explain the similarity of \( \epsilon_{Nd} \) values for tuffs and lavas of a particular age relative to a wide compositional range of up to 10 wt% SiO\(_2\). The \( \epsilon_{Nd} \) value of the evolved steady-state composition largely depends on the value of \( R \) and the isotopic composition of the assimilated crust. Assuming that the \( \epsilon_{Nd} \) value of the assimilated crust remains constant, the increase in the \( \epsilon_{Nd} \) values of the younger tuffs and lavas might be explained by decreasing both \( D_{Nd} \) and the \( R \) values (Fig. 4), but such systematic changes seem unlikely given the compositional and petrographic variability among the tuffs and lavas. Moreover, if any systematic change in the amount of assimilation occurred through time, assimilation would be expected to increase as the mean temperature of the crust increased with continued magmatic activity, producing a trend of decreasing \( \epsilon_{Nd} \) values through time, which is the opposite of the observed trend. The increasing \( \epsilon_{Nd} \) values of the younger volcanic rocks are interpreted to reflect a change in the \( \epsilon_{Nd} \) value of the assimilated crust toward mantle compositions, although the temporal isotopic variations may also be explained by melting of increasingly hybridized crust. We envision that either of these processes could be accomplished through progressive hybridization of the crustal column by input of mantle-derived Nd into the crust as the magmatic system evolves, similar to the model proposed by Johnson et al. (1990).

Pb-isotope ratios of all San Juan lavas and tuffs probably reflect those of the assimilated crust, given the low Pb contents of mantle-derived magmas and the large crustal components implied by the low \( \epsilon_{Nd} \) values. The \( ^{206}Pb/^{204}Pb \) ratios of the lower crust are generally lower than those of the mantle, as indicated by isotopic compositions of granulite-facies rocks and contaminated lavas in the Taos Plateau volcanic field (e.g., Gray and Owersby, 1972; Dungan et al., 1986). Galena mineralization in the central caldera cluster has \( ^{206}Pb/^{204}Pb \) ratios of 18.8 to 19.1 and probably reflects the average Pb-isotope composition of the uppermost crust (Doe et al., 1979). The jump from low \( ^{206}Pb/^{204}Pb \) ratios for precaldera Conejos lavas to more radiogenic ratios during initiation of caldera-related volcanism, followed by a steady decrease in the \( ^{206}Pb/^{204}Pb \) ratios of the younger tuffs and lavas may indicate a shift in the source of crustal contamination from deep to shallow levels in the crust, followed by a drop back to deeper levels, as suggested by Lipman et al. (1978). Alternatively, we interpret the steady decrease in \( ^{206}Pb/^{204}Pb \) ratios in younger ash-flow tuffs to reflect transfer of relatively nonradiogenic Pb from the lower crust into the upper crust as the magmatic system evolved. If mantle-derived magmas assimilated lower-crustal rocks beneath the San Juan volcanic field and then ascended to higher crustal levels and crystallized, the \( ^{206}Pb/^{204}Pb \) ratios of the newly hybridized upper crust would decrease. The extent to which Pb-isotope ratios of the upper crust are decreased by this process will depend largely on the volume of crust assimilated by mafic magmas in the lower crust. Injection of mantle-derived magmas will produce little change in the average isotopic ratios of the total crust, because of the low Pb contents of mantle-derived magmas (Johnson et al., 1990).

CONCLUSIONS

Isotopic data suggest that volcanism in the central San Juan caldera cluster was generated by large fluxes of mantle-derived magmas that assimilated the crust. Highly radiogenic Pb isotope ratios of the youngest lavas suggest that Pb migration from deep sources was responsible for the observed \( ^{206}Pb/^{204}Pb \) enrichment. Mantle-derived basaltic magmas are assumed to have \( \epsilon_{Nd} = 0, \) Nd = 20 ppm (see text). Crustal Nd contents are assumed to be constant at 30 ppm. Histogram of \( \epsilon_{Nd} \) values for tuffs and lavas plotted on right side of figure. Dashed lines indicate range of \( \epsilon_{Nd} \) values measured for early and late ash-flow tuffs and range in crustal \( \epsilon_{Nd} \) values required, assuming constant percentage crystallization and \( D_{Nd} \) and \( R \) values.
ilated substantial crust, resulting in a hybridized mixture of crust and mantle components at depth. Extension of assimilation–fractional crystallization calculations to the entire San Juan field suggests that 65,000 to 95,000 km$^3$ of mantle-derived magmas were injected into the crust to produce the observed volcanic rocks, assuming that 30% to 50% crystallization is required to produce the intermediate-composition Cenozoic lavas (total $\geq$25,000 km$^3$) and 60% to 80% crystallization is required to produce the caldera-related lavas and tufts (total $\geq$10,000 km$^3$). On the basis of gravity data, a large (75 by 150 km) batholith of intermediate-to-silicic composition rocks is interpreted to underlie much of the San Juan field (Plouff and Pakiser, 1972), suggesting that even larger volumes of mafic magma are required. This is consistent with suggestions by Crisp (1984) and Shaw (1985) that ratios of intrusive to extrusive magmas in volcanic systems may range from 4:1 to 16:1. By using a conservative ratio of 4:1, we find that more than 30,000 km$^3$ of primitive basaltic magmas may have been injected into the crust during the lifetime of the San Juan field. Assuming that the areal extent of magma injection was confined to the present area of the volcanic field (25,000 km$^2$) and that no material was returned to the mantle in the form of cumulate minerals, this amount of primitive magma would be equivalent to a net crustal thickening of ~12 km. However, it is likely that large volumes of cumulates from magmas crystallizing near the Moho would be recycled into the mantle, and such processes would produce substantially less crustal thickening (Johnson et al., 1990).

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