Large-Scale Crust Formation and Lithosphere Modification Beneath Middle to Late Cenozoic Calderas and Volcanic Fields, Western North America

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Over 500,000 km$^3$ of intermediate- to silicic-composition ash flow tuffs and lavas were erupted from large-volume volcanic fields in western North America during the middle to late Cenozoic. Of the commonly used isotope systems, Nd isotope data provide the best constraint on the proportions of crust and mantle components in the tuffs; all tuffs that have been studied contain a major, often dominant, mantle component. The proportion of mantle to crustal components is best constrained for ash flow tuffs that were erupted on Precambrian crust. There is no simple correlation between inception of extensional faulting with development of calderas, although all calderas formed in or adjacent to regions that ultimately underwent crustal extension to some degree. Similarly, there are no first-order correlations between the proportion of mantle-derived component in the silicic magmas and the tectonic setting. The common thread to all caldera complexes is that they are generated by large fluxes of mantle-derived basaltic magmas. Detailed isotopic and petrologic studies of several caldera complexes indicate that the silicic magmas were fundamentally derived by fractional crystallization of mantle-derived magmas, accompanied by assimilation of continental crust. Cenozoic caldera-related magmatism in western North America represents a major episode of crustal growth and hybridization; crustal growth rates in the Cenozoic may rival those that occurred in the Proterozoic during initial crust formation. New results of petrologic and isotopic studies of multicyclic caldera complexes in the northern Rio Grande rift region, in addition to several other areas of the western United States, confirm previous models that predict large changes in O, Sr, and Nd isotope compositions of the crust during formation. Continuous injection of basaltic magmas results in an increase in the mean density of the crust, which may be reflected in upward movement of the locus of silicic magma evolution in the crust; such changes may be monitored in areas underlain by ancient crust using Pb isotope ratios if the crust is stratified in U/Pb ratios. If accompanied by assimilation, crystallization of mantle-derived magmas that stall near the crust-mantle boundary will return crustal components to the mantle in the form of mafic and ultramafic cumulates, in addition to producing a petrologically complex crust-mantle boundary. This model can explain many geophysical characteristics of the crust and upper mantle in western North America and supports the conclusions of many recent studies of lower crustal xenoliths, which propose recent magmatic underplating in tectonically active regions.

INTRODUCTION

Over 500,000 km$^3$ of ash flow tuffs have been erupted onto the surface of western North America during the middle to late Cenozoic, approximately equally distributed between the western United States and Mexico [Mackin, 1960; Smith, 1960; McDowell and Clabaugh, 1979; Swanson and McDowell, 1984; Lipman, 1984]. Taking into account the voluminous plutonic rocks that underlie volcanic centers [Crisp, 1984; Lipman, 1984; Shaw, 1985], as much as 5,000,000 km$^3$ of intermediate- to silicic-composition magmas may have been associated with this Cenozoic volcanism. Voluminous, caldera-related Cenozoic volcanism in western North America began at 49 Ma in the Challis volcanic field of central Idaho [Cater et al., 1973] and swept southwest along an accretion front [e.g., Armstrong et al., 1969; Best et al., 1989]. Caldera complexes in the northeastern Great Basin formed at 35-30 Ma, whereas calderas in central and western Nevada formed at 30-20 Ma. Calderas at the western and southern margins of the Great Basin formed less than 20 m.y. ago. Large caldera complexes also developed at 40-23 Ma along the eastern margins of what is now the Colorado Plateau [e.g., Stuckless and Sheridan, 1971; Steven and Lipman, 1976; Ratté et al., 1984; Elston, 1984; Pallister and du Bray, 1989; Lipman et al., 1986]. Caldera-related volcanism in the Trans-Pecos Texas region occurred at 38-28 Ma [Henry and Price, 1984], and the large volume of ash flow tuffs that belong to the Upper Volcanic Supergroup of the Sierra Madre Occidental were erupted at 34-23 Ma [McDowell and Clabaugh, 1979; Swanson and McDowell, 1984]. Volcanism in the Mojave and northern Sonoran Deserts began at 30 Ma and migrated northward over a 20-m.y. period but produced relatively few calderas [Glasner and Supplee, 1982]. Well-known young (≤ 2 Ma) calderas in the western United States include those in the Yellowstone and Jemez volcanic fields, as well as the Long Valley caldera [Christiansen and Blank, 1972; Smith et al., 1970; Bailey et al., 1976], and these lie along the outer margins of the caldera-related volcanism in the western United States. Cenozoic caldera complexes in western North America formed in a diverse range of tectonic settings. Although Gans et al. [1989] propose that major volcanic episodes are related to periods of extension in the Great Basin, detailed studies of a large number of stratigraphic sections in the eastern Great Basin indicate that caldera-related volcanism
in the region is not associated with extension [Taylor et al., 1989; Best and Christiansen, this issue]. Several large-volume caldera complexes formed significantly prior to extension or in areas that underwent little extension, including the Sawatch Range calderas in central Colorado, the central Sierra Madre Occidental calderas, and the Marysvale, San Juan, and parts of the Mogollon-Datil volcanic fields [e.g., Lipman et al., 1970; McDowell and Clabaugh, 1979; Steven et al., 1984; Cather and Johnson, 1986; Shannon, 1988]. Early caldera-related eruptions in the southwestern Nevada volcanic field began approximately contemporaneous with initiation of extension [Ekren et al., 1968], and ash flow tuffs were erupted for another 8 m.y. [Byers et al., 1989]. The McDermitt, Jemez, and Long Valley calderas formed after initiation of extension (see Rytuba and McKee [1984] and references above). Regardless of the tectonic setting in which calderas were formed, all developed within or adjacent to areas that underwent mid-Miocene to Quaternary extensional faulting.

Geologists have long debated if silicic magmas are generated primarily by crystal fractionation of basaltic magmas or partial melting of the crust [e.g., Daly, 1914; Bowen, 1915; Holmes, 1932]. Early Sr isotope analyses of ash-flow tuffs in the Great Basin have been used to support both crystal fractionation and crustal melting models [Noble and Hedge, 1969; Scott et al., 1971; McKee et al., 1972; Noble et al., 1973; Stuckless and O'Neil, 1973]. In the first Pb isotope study of a large-volume caldera complex, Lipman et al. [1978] highlight the strong influence of the crust on caldera-related magmatism.

This report summarizes Nd isotope data for silicic rocks from middle to late Cenozoic calderas and volcanic fields from western North America (Figure 1). The data highlight the large mantle component in the ash flow tuffs, which, based on detailed study of several caldera complexes, is interpreted to reflect fractional crystallization of large volumes of basaltic magmas, accompanied by interaction with continental crust. Of the three commonly used radiogenic isotope systems, Rb-Sr, Sm-Nd, U-Th-Pb, determination of the relative proportions of crust and mantle components is probably least ambiguous using Nd isotope ratios. Neodymium contents of mantle-derived basalts and continental crust are similar, and where the basement consists of Precambrian crust, the Nd isotope compositions of the crust and mantle are often distinct. Present-day 87Sr/86Sr ratios of low-Rb lower crust may be similar to those of the modern mantle, which would disguise a crustal component. Conversely, the low-Sr contents of highly evolved rhyolites make their Sr isotope ratios susceptible to modification by even minor amounts of late stage assimilation of radiogenic upper crust; this would overemphasize a crustal component. Lead isotope ratios of intermediate- to silicic-composition rocks are probably dominated by crustal compositions, given the relatively high Pb contents of the crust as compared to mantle-derived basalts. Temporal variations at several multicyclic caldera complexes are discussed, with particular emphasis on the northern Rio Grande rift region. Data from multicyclic systems provide strong evidence for extensive hybridization of the lithosphere and formation of new crust, and broad consideration of available Nd isotope data for silicic volcanic rocks throughout western North America suggests that these processes were common at many volcanic centers.

**The Lower Crust**

Contrasts between Nd isotope ratios of the crust and mantle are greatest where the crust is Precambrian in age. The largest body of Nd isotope and rare earth element (REE) data for Proterozoic rocks in western North America exists for those exposed in Colorado and New Mexico, and the majority of these rocks have low Sm/Nd ratios. Many Early Proterozoic tholeiite lavas have low Sm/Nd ratios, in addition to all mafic calc-alkaline rocks yet analyzed, and these would produce low present-day εNd values (Figures 2a and 2b). Some Early Proterozoic tholeiite lavas that are associated with bimodal greenstone sequences have high Sm/Nd ratios, however, which have produced positive
Fig. 2. Predicted present-day $\varepsilon_{Nd}$ values for Proterozoic rocks in Colorado and New Mexico, based on measured Sm and Nd concentrations. Source for oldest rocks assumed to be depleted mantle at 1800 Ma [DePaolo, 1981a]. Younger rocks assumed to have been derived from depleted mantle as it evolved to a present-day $\varepsilon_{Nd}$ value of -14. The peak at $\varepsilon_{Nd}$ = -13 in the predicted histogram (Figure 2g) is the same as that measured for intermediate- to silicic-composition rocks [DePaolo, 1981a; Nelson and DePaolo, 1985]; similar rocks in southeastern Arizona are predicted to have an average present-day $\varepsilon_{Nd}$ value of -15 [Condie et al., 1985]. Additional data from Barker et al. [1976b], Condie and Budding [1979], Condie and Nuter [1981], Condie and McCrink [1982], Nelson and DePaolo [1984], Boardman and Condie [1986], Knoiper and Condie [1988], Robertson and Condie [1989], and Stein and Crock [1990].

Fig. 3. Predicted present-day $\varepsilon_{Nd}$ values for Proterozoic mafic lower crust, assuming crust had REE contents similar to those of Cenozoic continental basalts from the western United States. Calculated assuming crust was derived from depleted mantle at 1800 Ma [DePaolo, 1981a] and using Sm/Nd ratios measured for mafic Cenozoic lavas erupted through Proterozoic basement in the southwestern United States. Data from Phelps et al. [1983], Alibert et al. [1986], Crowe et al. [1986], Duncan et al. [1986], Kempton et al. [1987], Johnson and Lipman [1988], Duncan et al. [1989], Witek et al. [1989], Thompson et al. [this issue] and R. Thompson (unpublished data, 1990).
of exposed Proterozoic crust [Esperanca et al., 1988; Ruiz et al., 1988a; K.L. Cameron et al., submitted manuscript, 1991]. If the xenoliths represent Proterozoic lower crust, the majority of these data for Cenozoic ash flow tuff from western North America can be explained largely by melting of the crust, as noted by Ruiz et al. [1988a]. Mafic xenoliths at the Geronimo volcanic field, New Mexico, and at La Olivina, Chihuahua, however, are interpreted to reflect recent intrusion of mantle-derived magmas and associated cumulates into the deep crust [Kempton et al., 1990; K.L. Cameron et al., submitted manuscript, 1991]. In contrast, xenoliths from Arizona and eastern Mexico that have high present-day $e_{Nd}$ values have been interpreted to reflect lower crust that is Proterozoic in age [Esperanca et al., 1988; Ruiz et al., 1988a]. This interpretation is based on Nd and Pb-Pb model ages. Interpretation of these model ages as indicating a Proterozoic age for the xenoliths has been recently debated, however, highlighting the difficulty of using xenoliths to constrain the isotopic compositions of the Proterozoic lower crust [Cameron and Robinson, 1990; Esperanca et al., 1990; Johnson, 1990; Ruiz et al., 1990].

In summary, it appears likely that the Proterozoic lower crust prior to initiation of Cenozoic magmatism had low $e_{Nd}$ values that were similar to those of exposed basement rocks, consistent with the observation that most granulite-facies rocks have low and rather consistent Sm/Nd ratios [e.g., Weaver and Tarney, 1980; Ben Othman et al., 1984]. Although the crust is probably vertically zoned in major element and Sr and Pb isotope compositions, it is probably relatively homogeneous in Nd isotope compositions. This is consistent with Nd isotope data for peraluminous granites from the southwestern United States, which have an average present-day $e_{Nd}$ value of -14, and are thought to dominantly record lower and middle crust Nd isotope compositions [Farmer and DePaolo, 1984; Bennett and DePaolo, 1987; J. Wooden and C. Johnson, unpublished data, 1989]. Moreover, studies of crustally contaminated mafic- and intermediate-composition lavas in the northern Rio Grande rift suggest that the Proterozoic lower crust in the region has low present-day $e_{Nd}$ values [Johnson and Thompson, this issue].

**MIDDLE TO LATE CENOZOIC CALDERAS AND VOLCANIC FIELDS**

Neodymium isotope data are now available for caldera complexes and volcanic fields that span nearly the entire age range and tectonic setting of the middle to late Cenozoic volcanic episode that covered much of western North America. Discussion of calderas and volcanic fields is divided into three groups, based on basement age and tectonic setting: (1) Phanerozoic basement and at the margin of the Precambrian craton, which includes extended and non-extended regions, (2) the highly extended Great Basin and Mojave Desert regions, which are underlain by Proterozoic basement, and (3) the modestly extended Rio Grande rift region, which is also underlain by Proterozoic basement (Figure 1).

**On Phanerozoic Basement and Precambrian Craton Margin**

West-east traverses across northern Mexico and the Mexican Neovolcanic Belt provide a comparison of magmas erupted on Phanerozoic basement in the west with those erupted on Proterozoic basement in the east. The voluminous tuffs of the Sierra Madre Occidental in central Mexico were probably erupted largely on Phanerozoic basement, although the nature of the basement is uncertain [e.g., Campa and Coney, 1983]. The McDermitt and Long Valley calderas provide a comparison of large-volume ash flow tuffs that were erupted just west and east, respectively, of the Precambrian craton margin in the western United States.

**Northern Mexico.** Oligocene dacite lavas in northwestern Mexico in the Batopilas region of the Sierra Madre Occidental and mid-Miocene to Quaternary lavas in Baja California Sur have high $e_{Nd}$ values (+0.2 to +4.8) that overlap those of Oligocene mafic lavas in the region (Figure 4, northwestern field), suggesting that they evolved largely by crystal fractionation of mantle-derived basaltic magmas [Cameron and Cameron, 1985; Cameron et al., 1989]. These lavas, however, are not underlain by Precambrian crust but probably by Mesozoic and younger plutonic, volcanic, and sedimentary complexes [Campa and Coney, 1983], and there may be little contrast in Nd isotope compositions between basement and mantle-derived magmas.

Lavas in northeast Mexico in the Chinati Mountains, San Antonio, and Sierra los Cajones regions, in addition to an ash flow tuff near Sierra Virulento, are similar in age and major element compositions to lavas in northwestern Mexico but were erupted on Precambrian basement [e.g., Campa and Coney, 1983]. The northeastern silicic rocks have $e_{Nd}$ values that are similar to those of the western lavas, varying from +0.1 to -2.0 (Figure 4, northeastern fields and symbols [Cameron and Cameron, 1985]). Temporally related mafic lavas have $e_{Nd}$ values of -2.2 to +3.5 [Cameron et al., 1989]. These rocks were probably erupted through Proterozoic basement rocks that have low present-day $e_{Nd}$ values of -14 to -4, as indicated by pelitic and granulitic xenoliths from La Olivina and exposed basement at Novillo [Cameron and Cameron, 1985; Ruiz et al., 1988a,b; K.L. Cameron et al., submitted manuscript, 1991]. As Cameron and Cameron [1985] note, the high $e_{Nd}$ values of the silicic volcanic rocks are consistent with generation by crystal fractionation of mafic magmas, accompanied by little crustal assimilation.

**Mexican Neovolcanic Belt.** The Sierra La Primavera center lies near the western margin of the Mexican Neovolcanic Belt and Quaternary volcanism at this center included the 40 km$^3$ Tala Tuff [Mahood, 1981]. The Sierra La Primavera center is probably underlain by Mesozoic and Cenozoic basement [Campa and Coney, 1983]. Mahood and Halliday [1988] report a restricted range of $e_{Nd}$ values for all Sierra La Primavera rocks of +4.8 to +5.8 (Figure 4), including an older basalt. Mahood and Halliday [1988] reject crystal fractionation of basaltic magmas as the mechanism for producing the silicic magmas, based primarily on arguments that the volume of parental basalt and associated cumulates would be excessive, and instead favor partial melting of Mesozoic or Cenozoic plutonic rocks.
The Los Humeros volcanic center erupted ~220 km$^3$ of basalt to high-SiO$_2$ rhyolite magma at 0.47-0.02 Ma and was associated with three caldera-forming eruptions [Ferriz and Mahood, 1984]. This center lies near the eastern margin of the Mexican Neovolcanic Belt and occupies the border between Proterozoic rocks that are part of the eastern margin of the Sierra Madre terrane and Paleozoic rocks of the Coahuila terrane [Campa and Coney, 1983]. Proterozoic basement rocks are exposed to the northwest at Molango and south at Oaxaca, and these rocks have low present-day $\varepsilon_{Nd}$ values of -16 to -6 (Figure 4) [Ruiz et al., 1988b]. $\varepsilon_{Nd}$ values of mafic- to silicic-composition rocks at Los Humeros vary from +4.1 to -1.4 and decrease with increasing SiO$_2$ contents (Figure 4 [Verma, 1983]). These variations are interpreted by Verma [1983] as reflecting generation of the silicic rocks primarily by crystal fractionation of mafic parental magmas, accompanied by little assimilation of crust.

Central Mexico. Although only a very small fraction of the voluminous ash flow tuffs and lavas of the Upper Volcanic Supergroup of the Sierra Madre Occidental have been studied in detail, rocks near Zacatecas have a relatively restricted range of $\varepsilon_{Nd}$ values, from -2.3 to +1.4 (Figure 4) [Verma, 1984]. These rocks crop out in the western Sierra Madre terrain, which may be underlain by Phanerozoic rocks [Campa and Coney, 1983]. Verma [1984] suggests that the silicic rocks are dominated by a crustal component, although uncertainties in constraining basement compositions make calculation of the relative contributions of crust and mantle difficult. If a basalt listed by Verma [1984] that has an $\varepsilon_{Nd}$ value of +1.4 is more representative of the mantle composition than the value of +7 assumed by Verma [1984], the proportion of mantle in the silicic rocks would be considerably higher than previously estimated.

McDermitt. Seven major ash flow tuffs, totalling over 1700 km$^3$, were erupted from four overlapping and nested calderas of the McDermitt caldera complex and three satellite calderas between 16.1 and 15 Ma [Rytuba and McKee, 1984]. All of the tuffs are peralkaline rhyolite or comendite and are part of a sequence of mid-Miocene alkaline caldera complexes that developed along the western and southern margins of the Great Basin [Noble and Parker, 1974]. The McDermitt volcanic field was developed on Phanerozoic basement and lies west of the 87Sr/86Sr=0.706 line for plutonic rocks that is interpreted to reflect the western limit of Precambrian basement (Figure 1) [Kistler and Peterman, 1973, 1978].

The Tuffs of Double H and Members 2 and 3 of Long Ridge, the first two tuffs of the McDermitt caldera complex, have $\varepsilon_{Nd}$ values of +2.0 to +6.4 [Tegtmeyer and Farmer, 1990]. The lowest $\varepsilon_{Nd}$ values are interpreted to reflect late stage assimilation in the pre-eruptive magma chamber [Tegtmeyer and Farmer, 1990], indicating that magmas parental to the ash flow magmas had $\varepsilon_{Nd}$ values $>$+6, and that the local crust had $\varepsilon_{Nd}$ values $<$+2. The highest $\varepsilon_{Nd}$ values (least contaminated at late stages) overlap those of the underlying Steens Basalt ($\varepsilon_{Nd}$=+4.1 to +6.9 [Carlson and Hart, 1987]). Probable basement rocks include Mesozoic and Tertiary plutonic rocks of the northwestern Great Basin which lie immediately south of the McDermitt field and have present-day $\varepsilon_{Nd}$ values of -6.4 to +1.4 [Farmer and DePaolo, 1983, 1984], or Paleozoic sedimentary rocks that have present-day $\varepsilon_{Nd}$ values $<$-11 [Farmer, 1985].
magnas that were least contaminated by late stage assimilation suggest a dominant mantle component in the silicic magmas.

Long Valley. Greater than 600 km³ of high-SiO₂ rhyolite was erupted as the Bishop Tuff from the Long Valley caldera at 0.7 Ma [Bailey et al., 1976]. Premonitory volcanism included eruption of small volume mafic- and intermediate-composition lavas between 3.2 and 2.6 Ma [Bailey et al., 1976], followed by eruption of ~15 km³ of high-SiO₂ rhyolite at Glass Mountain between 2.1 and 0.8 Ma [Metz and Mahood, 1985]. Neodymium isotope data form a striking trend of increasing εNd values with decreasing age for silicic rocks at Glass Mountain, the Bishop Tuff, and Mono Craters (Figure 5). Older lavas at Glass Mountain (1.35 Ma) have εNd values of -3.9 to -2.6, whereas younger lavas (1.06 Ma) have higher εNd values of -1.2 to -0.8 (Figure 5) [Halliday et al., 1989]. Although the Bishop Tuff magma chamber was thermally and chemically zoned [Hildreth, 1979], εNd values of the tuff are constant at -1.2 to -0.8 (Figure 5) [Halliday et al., 1984], and identical to the younger Glass Mountain lavas. The Inyo-Mono craters chain contains the youngest silicic lavas and domes in the region, and these rocks have εNd values of -1.4 to +0.9 [Sampson and Cameron, 1987; Kelleher and Cameron, 1990]. Pliocene and Quaternary basalts and andesites from the Long Valley area have εNd values of -2.5 to +2.9, similar to those of the silicic rocks [Ormerod et al., 1988; Kelleher and Cameron, 1990].

Because the Long Valley caldera is located just east the 87Sr/86Sr=0.706 line [Kistler and Peterman, 1973, 1978], it is inferred to be underlain by Proterozoic and Phanerozoic basement rocks. The caldera partly collapsed into Mesozoic granitic rocks of the Sierra Nevada batholith, and the granitic rocks that lie east of the 0.706 line have present-day εNd values of -8.6 to -3.6 [DePaolo, 1981b]. Paleozoic sedimentary rocks intruded by the Sierra Nevada batholith have present-day εNd values of -11.8 to -3.4 [DePaolo, 1981b]. These data suggest that the silicic volcanic rocks in the Long Valley region, including the Bishop Tuff, contain a large mantle component and that this component increased with continued magmatism in the area.

On Highly Extended Proterozoic Basement

This region includes several multicyclic caldera complexes that were associated with basaltic volcanism and Proterozoic basement that had unusual isotopic compositions. The basement of the Mojave Desert is 200-400 m.y. older than that of the central Great Basin, and this is reflected in markedly lower present-day εNd values for Precambrian rocks. The basement underlying the northeastern Great Basin probably also has present-day εNd values that are lower than those of the central Great Basin, due to the proximity of the Archean craton. εNd values for basaltic lavas in the Great Basin and Mojave Desert range from very low values (down to -11) for the Sierran Province rocks to relatively high values (up to +9) for young basalts of the central Great Basin and eastern Mojave Desert.

Mojave Desert. Ash flow magmatism was rare in the Mojave Desert region compared to the adjacent Basin and Range. The 18.5 Ma Peach Springs Tuff is the only regionally extensive Cenozoic ash flow tuff in the Mojave Desert area, and it represents at least several hundred cubic kilo-

![Fig. 5. (a) εNd-SiO₂ variations for Cenozoic volcanic rocks and Mesozoic plutons in eastern California that lie east of 87Sr/86Sr=0.706 line, on Proterozoic basement. OVB, Owens Valley basalts; SPB, Sierran Province basalts; SNP, Sierra Nevada plutons that crop out east of 87Sr/86Sr=0.706 line; MMP, Mojave metaluminous plutons; MPP, Mojave peraluminous plutons; PST, Peach Springs Tuff; OGM, older Glass Mountain lavas; YGM, younger Glass Mountain lavas. (b) Histogram for present-day εNd values of exposed basement rocks in eastern California. Data from DePaolo [1981b], Menzies et al. [1983], Farmer and DePaolo [1983, 1984], Nelson and DePaolo [1985], Bennett and DePaolo [1987], Ormerod et al. [1988], Musselwhite et al. [1989], Farmer et al. [1989], Halliday et al. [1984, 1989], Kelleher and Cameron, [1990], J. Wooden and C. Johnson (unpublished data, 1989) and C. Johnson, (unpublished data, 1990).]
meters of silicic magma, based on estimated outflow volumes alone [Glazner et al., 1986; Nielson et al., 1990]. The Peach Springs Tuff probably erupted from a source in the eastern Mojave Desert, near the intersection of the California-Nevada-Arizona borders [Hillhouse and Wells, 1991], several million years after a period of short-lived, though voluminous, intermediate-composition volcanism in the region [e.g., Armstrong and Higgins, 1973; Glazner, 1990]. Two glass samples from pumice in the lower Peach Springs Tuff have $\varepsilon_{Nd}$ values of -11.7 and -11.0 (C. Johnson, unpublished data, 1990), similar to the average present-day $\varepsilon_{Nd}$ values of metaluminous Mesozoic granites from the Mojave Desert region (Figure 5) [Farmer and DePaolo, 1983, 1984; J. Wooden and C. Johnson, unpublished data, 1989].

The Woods Mountains volcanic center contains one of the few calderas recognized in the Mojave Desert region. The 15.8 Ma caldera-forming Wild Horse Mesa Tuff (~80 km$^3$ magma equivalent) largely consists of peralkaline rhyolite, but mingled rhyolite and trachyte pumices in the upper parts of the tuff are thought to reflect tapping of more mafic magma at depth [McCurry, 1988]. Trachyte and rhyolite have similar $\varepsilon_{Nd}$ values of -7.5 to -6.2 (Figure 5), which have been interpreted as reflecting extensive crystal fractionation of mantle-derived magmas and 20 to 40 wt % crustal assimilation [Musselwhite et al., 1989]. Postcaldera mafic lavas (11.2-10.2 Ma) that unconformably overlie the tuff have $\varepsilon_{Nd}$ values of -4.2 to +2.4 [Musselwhite et al., 1989]. The Peach Springs Tuff and Wild Horse Mesa Tuff erupted from the same general vicinity, and although current isotopic data are sparse, their Nd isotope compositions are suggestive of a trend of increasing $\varepsilon_{Nd}$ with decreasing age (Figure 5).

Precambrian basement rocks in the Mojave Desert region have present-day $\varepsilon_{Nd}$ values that are significantly lower than those of Tertiary lavas and tuffs, including the Peach Springs Tuff (Figure 5). Proterozoic rocks have Nd $T_{DM}$ ages of 2.3-2.0 Ga, and low present-day $\varepsilon_{Nd}$ values of -24.1 to -9.9 (Figure 5) [Nelson and DePaolo, 1985; Bennett and DePaolo, 1987; Musselwhite et al., 1989]. These low values suggest that the ash flow tuffs contain a large mantle component, particularly the younger Wild Horse Mesa Tuff.

Southwest Nevada Volcanic Field. Five major calderas developed at 14-6.5 Ma in southwest Nevada, accompanied by eruption of >5000 km$^3$ of ash flow tuffs [e.g., Byers et al., 1989]. The 14.3-11.4 Ma Timber Mountain-Oasis Valley caldera complex produced >4000 km$^3$ of calc-alkaline and alkali-calcic ash flow tuffs [Byers et al., 1976a, 1976b; Christiansen et al., 1977; Broxton et al., 1989] which are intercalated with peralkaline tuffs of the slightly older Silvertown volcanic field [Orkild et al., 1969; Sargent and Orkild, 1973; Sawyer and Sargent, 1989] and overlain by peralkaline tuffs of the 7.5 Ma Black Mountain caldera [Christiansen and Noble, 1968; Noble and Christiansen, 1968; Vogel et al., 1989]. The last caldera to form in the field is the ~6.5 Ma Stonewall Mountain caldera [Ekren et al., 1971; Weiss and Noble, 1989]. Early volcanism in the volcanic field correlates with the onset of regional extension [Ekren et al., 1968].

In one of the first detailed Nd isotope studies of a multicyclic caldera complex, Farmer et al. [1991] present important data which document significant temporal varia-

ations of $\varepsilon_{Nd}$ values for silicic rocks from the Timber Mountain-Oasis Valley complex. Early extracaldera (14 Ma) intermediate- and silicic-composition lavas have the lowest $\varepsilon_{Nd}$ values of the complex (-13 to -12; Figure 6), whereas the large-volume ash flow tuffs have $\varepsilon_{Nd}$ values that increase to -9 with decreasing age (Figure 6). Caldera-related mafic- and silicic-composition lavas have $\varepsilon_{Nd}$ values that are similar to those of the tuffs, in contrast to the early lavas.

Basaltic volcanism in the region largely occurred after the peak in ash flow tuff eruptions at -11 Ma [Crowe et al., 1986; Byers et al., 1989], and Nd isotope data appear to be bimodally distributed between -10.4 to -7.8 and -13 to +3.7 (Figure 6) [Farmer et al., 1989, 1991]. Other mid-Miocene and younger mafic lavas in the region include those of the "Sierran Province basalts" (Figure 6); see also Figure 5), and those of northwest Arizona (Figure 6) [Alibert et al., 1986]. Proterozoic rocks in southern Nevada, northern Arizona, and eastern California generally have present-day $\varepsilon_{Nd}$ values ≤ -16 (Figure 6), significantly lower than those of ash flow tuffs from the Timber Mountain-Oasis Valley complex, implying a large mantle component in the tuffs.

Kane Springs Wash. The Kane Springs Wash volcanic center in eastern Nevada was active from 14 to 13 Ma, and mafic lavas both underlie and overlie lavas and tuffs of the center, at 16-15 Ma and 13-11 Ma, respectively [Novak, 1984]. Extension-related faulting largely postdates the younger mafic lavas. The Kane Wash Tuff erupted at 14 Ma and represents >130 km$^3$ of metaluminous and mildly peralkaline rhyolite magma [Novak and Mahood, 1986]. Two Nd isotope analyses of Kane Wash Tuff indicate that it has relatively high $\varepsilon_{Nd}$ values of -6.9 and -6.7 (Figure 6) [Novak, 1985; Leeman and Hawkesworth, 1986]. Precaldera trachyte and postcaldera lavas have similar values, between -6.4 and -5.3. Extracaldera basalts have $\varepsilon_{Nd}$ values of -8.3 to -2.0, and a precaldera tholeiite lava has an $\varepsilon_{Nd}$ value of -10.4. Trachytic lavas, common in both the precaldera and postcaldera volcanic sequence, are probably similar to the magmas that were parental to the Kane Wash Tuff magma. Novak and Mahood [1986] suggest that compositional and isotopic variations in the intermediate-composition rocks are best explained by assimilation/fractional crystallization (AFC) of alkali basalt magmas, accompanied by relatively small amounts of crustal assimilation; continued crystal fractionation is thought to be the primary mechanism for producing the Kane Wash Tuff magma.

Kalamazoo. Forty to 35 Ma andesite to rhyolite lavas underlie the regional Kalamazoo Tuff in northeastern Nevada and northwestern Utah [Gans et al., 1989]. The pretuff lavas generally predate initiation of regional extension in the area, which occurred at ~36 Ma. The dacite to rhyolite Kalamazoo Tuff erupted >500 km$^3$ of magma at 35 Ma from an inferred source in or adjacent to the Schell Creek Range and is overlain by an equally voluminous sequence of dacite lavas [Gans et al., 1989]. $\varepsilon_{Nd}$ values of pretuff andesite and dacite lavas decrease with increasing SiO$_2$ contents, from -7.4 to -16.0 (Figure 7) [Gans et al. 1989]. Two samples of the Kalamazoo Tuff have slightly lower $\varepsilon_{Nd}$ values of -17.7 and -16.7 (Figure 7); a postcaldera dacite has a similar $\varepsilon_{Nd}$ value of -16.5. These relations are interpreted by Gans et al. [1989] as reflecting AFC of mantle-derived basaltic magmas, involving assimilation of >50 wt % crust.
This interpretation is consistent with variations in Nd isotope compositions of probable mantle-derived magmas and crust. The \( e_{\text{Nd}} \) value of the most mafic Kalamazoo lava may be similar to that of the Oligocene mantle in the region, and lies within the range of the low-\( e_{\text{Nd}} \) group of younger mafic lavas in the Timber Mountain-Oasis Valley caldera complex region (Figure 7; see also Figure 6) [Farmer et al., 1989, 1991]. Few Proterozoic rocks in the region have been analyzed for Nd isotope ratios, but two rocks from the Ruby Mountains to the west have present-day \( e_{\text{Nd}} \) values of -16 and -23.8 [Farmer and DePaolo, 1983]. Late Precambrian and early Paleozoic miogeoclinal sedimentary rocks in the Deep Creek and Schell Creek Ranges have present-day \( e_{\text{Nd}} \) values of -18 to -11, and those in the Pilot Range and Ruby Range have present-day \( e_{\text{Nd}} \) values of -26 to -18 (Figure 7) [Farmer, 1985] and probably indicate a low-\( e_{\text{Nd}} \) basement at depth. Low \( e_{\text{Nd}} \) values for the basement are predicted, considering the proximity to Archean crust which is inferred to extend south to within 50 km of the Kalamazoo sequence [e.g., Bryant, 1988]. These factors indicate that it is likely that basement rocks under the Kalamazoo rocks have present-day \( e_{\text{Nd}} \) values that are significantly lower than those of Precambrian rocks in Colorado, New Mexico, and the central Great Basin.

**Rio Grande Rift Region**

Several large-volume caldera complexes formed adjacent to the Rio Grande rift, from the Sawatch Range, Colorado, to the U.S.-Mexico border; these calderas erupted >25,000 km\(^2\) of ash flow tuffs from 36 Ma to 1 Ma. A large body of Nd isotope data exists for the calderas of the northern rift region in Colorado and northern New Mexico. A large dataset of O, Sr, and Pb isotopic ratios is also available for these rocks and forms the primary basis for discussion later in this paper on the origin of ash flow tuff magmas and temporal and compositional variations in large, multicyclic caldera complexes.

**Northern Area.** An exceptionally large middle Tertiary volcanic field is exposed in the northern Rio Grande rift region in southern Colorado and northern New Mexico [Steven, 1975]. The Grizzly Peak Tuff erupted >600 km\(^3\) of dominantly rhyolite magma at 34 Ma from the Grizzly Peak caldera, which is the northernmost of three calderas that formed during the Oligocene in the Sawatch Range [Fridrich et al., 1991]. Although the Sawatch Range calderas currently occupy the western side of the northern Rio Grande rift, they formed 8-10 m.y. prior to development of regional extension in the area [Epis and Chapin, 1975; Scott, 1975; Taylor, 1975; Shannon et al., 1987]. Eruption of the Grizzly Peak Tuff tapped an exceptionally large compositional range, from 57 to 77 wt % SiO\(_2\) [Fridrich and Mahood, 1987]. \( e_{\text{Nd}} \) values of the tuff range from -13.0 to -11.3 (Figure 8) and are interpreted to reflect AFC of mantle-derived basaltic magmas that assimilated 20-40 wt % crust which had \( e_{\text{Nd}} \) values ≤ -20; such crust is typical of ~1400 Ma Silver Plume-type intrusions in the region [Johnson and Fridrich, 1990]. Although the \( e_{\text{Nd}} \) values of the Grizzly Peak Tuff are relatively low, the mafic parts of the tuff have SiO\(_2\) contents that are too low to have
been produced by melting of most crustal rocks [Johnson and Fridrich, 1990].

Early precaldera volcanism at the San Juan volcanic field consisted of eruption of voluminous (>25,000 km³) intermediate-composition lavas contemporaneous with formation of the nearby Sawatch Range calderas and continued to 30 Ma [Lipman et al., 1970, 1978; Lipman, 1989]. $\epsilon_{Nd}$ values of these lavas range from -9 to -6 and generally decrease with increasing SiO$_2$ contents (Figure 8) [Riciputi and Johnson, 1990; Colucci et al., this issue]. Ash flow eruptions began at 30 Ma and continued until 23 Ma, resulting in emplacement of approximately 15 major ash flow tuffs and as many calderas; the total volume of ash flow tuff magma erupted exceeded 10,000 km³ [Steven and Lipman, 1976; Lipman, 1989]. More than 6000 km³ of largely dacite and rhyolite ash flow tuffs were erupted from at least six calderas in the central caldera complex at 28-26 Ma, including the >3000 km³ Fish Canyon Tuff. The central tuffs and related lavas have $\epsilon_{Nd}$ values between -8 and -6 and are interpreted to contain a large mantle component [Riciputi and Johnson, 1990].

Precaldera volcanism at the Latir volcanic field was contemporaneous with the peak in ash flow tuff magmatism in the nearby San Juan field, at 28 Ma [Lipman et al., 1986]. Early magmatism in the Latir field consisted of approximately ~1000 km³ of intermediate- to silicic-composition lavas and related shallow intrusions, followed by eruption of 500-1000 km³ of high-SiO$_2$ peralkaline rhyolite as the Amalia Tuff [Lipman, 1983, 1988; Johnson and Lipman, 1988]. The Questa caldera formed during initiation of regional extension at 26 Ma [Lipman et al., 1986; Hagstrum and Lipman, 1986]. Postcaldera magmatism is preserved as lavas on a horst in the Rio Grande rift [Thompson et al., 1986], and as intermediate- to silicic-composition intrusive rocks as young as 19 Ma on the east side of the rift [Lipman et al., 1986]. $\epsilon_{Nd}$ values of the precaldera lavas vary from -1.8 to -7.3 and generally decrease with increasing SiO$_2$ contents (Figure 8) [Johnson et al., 1990]. The Amalia Tuff and related lavas and resurgent intrusions

![Fig. 8. (a) $\epsilon_{Nd}$-SiO$_2$ variations for Cenozoic volcanic rocks of the composite volcanic field that is exposed in the northern Rio Grande rift region [Steven, 1975]. SLH1 and SLH2, mantle sources for early rift (26 Ma) basalts at San Luis Hills; LVF, precaldera lavas of the Latir volcanic field; ESJL, early San Juan lavas; NWCOB, Miocene to Quaternary basalts from northwestern Colorado. (b) Histogram for present-day $\epsilon_{Nd}$ values of exposed basement rocks in the northern Rio Grande rift region. Data from DePaolo [1981a], Nelson and DePaolo [1984, 1985], Leat et al. [1988, 1989, 1990], Johnson et al. [1990], Johnson and Fridrich [1990], Riciputi and Johnson [1990], Colucci et al., this issue; Johnson and Thompson, this issue], and L. Riciputi and C. Johnson, (unpublished data, 1990).](image_url)
have \( e_{Nd} \) values of -5.9 to -6.9 (Figure 8) [Johnson et al., 1990]. Postcaldera intrusions generally have \( e_{Nd} \) values of -4 to -7 and are interpreted to reflect the waning stages of the magmatic system. Detailed petrologic, chemical, and isotopic studies of the Latir field indicate that most of the evolved magmas were generated by AFC of mantle-derived basaltic magmas [Johnson and Lipman, 1988; Johnson et al., 1990].

Primitive basalts in the northern Rio Grande rift region were erupted after initiation of regional extension within, and along the margins of, the broad middle-Tertiary volcanic field that includes the Sawatch Range calderas and the San Juan and Latir volcanic fields [Steven, 1975]. \( e_{Nd} \) values of primitive, early-extension lavas at San Luis Hills form two clusters at -4 and 0 (Figure 8) [Johnson and Thompson, this issue]; this may be the range of values of magmas that were parental to the ash-flow tuff magmas. Miocene and younger mafic lavas erupted northwest of the Rio Grande rift have \( e_{Nd} \) values of -4 to -8 and may represent melts derived from enriched lithospheric mantle [Leat et al., 1988, 1989, 1990]. Present-day \( e_{Nd} \) values of most Proterozoic rocks in Colorado and New Mexico range from -16 to -10, although values as low as -24 are found in LREE-rich, 1400 Ma anorogenic granites (Figure 8) [DePaolo, 1981a; Nelson and DePaolo, 1984, 1985].

The relatively high \( e_{Nd} \) values of the San Juan and Latir ash-flow tuffs suggest a large mantle component in the magmas. Although the Grizzly Peak Tuff has \( e_{Nd} \) values that overlap those of average Proterozoic crust in the region, Johnson and Fridrich [1990] conclude that the magmas interacted with crust that had \( e_{Nd} \leq 20 \). Johnson and Thompson [this issue] conclude that the lower crust beneath the northern Rio Grande rift region must have \( e_{Nd} \leq -12 \), based on studies of contaminated lavas at San Luis Hills. \( e_{Nd} \) values of the southern Rocky Mountain ash flow tuffs increase with decreasing age, both in a regional context and within the large multicyclic central caldera cluster of the San Juan field. These important temporal variations are discussed below.

Central Area. Volcanic rocks of the Jemez volcanic field range from mid-Miocene to Quaternary in age. Early volcanism consisted of ~13 to ~7 Ma basalt through rhyolite composition lavas [Smith et al., 1970; Gardner et al., 1986]. The precaldera basalts and andesites have \( e_{Nd} \) values of -1.5 to +0.5 [Loeffler and Futa, 1985], slightly lower than those of temporally related tholeiite and alkali basalts in the region [Perry et al., 1987]. Younger andesite and dacite lavas of the Tschicoma Formation (~7 to ~4 Ma) have \( e_{Nd} \) values of -3.0 to -0.8, and the 2 Ma El Rechuelos rhyolite has \( e_{Nd} \) values between -3.5 and -1.2 [Loeffler and Futa, 1985]. The Otowi Member and Tshirege Member of the Bandelier Tuff erupted at 1.4 and 1.1 Ma, respectively, and represent >600 km\(^2\) of mildly peralkaline rhyolite [Smith, 1979]; these magmas were erupted after block faulting had established the Rio Grande depression. One pumice sample from the Guaje Pumice Bed of the Otowi Member has an \( e_{Nd} \) value of -0.3, and one pumice sample from the lower part of the Tshirege Member has an \( e_{Nd} \) value of -2.3 [C. Johnson, unpublished data, 1990]. The relatively high \( e_{Nd} \) values of the tuffs, as compared to Proterozoic basement in New Mexico (Figure 8), suggests a large mantle component.

### Silicic Magmatism and Relations to Evolution of the Lithosphere

\( e_{Nd} \) values of Cenozoic ash flow tuffs from western North America are closely related to those of the local mantle, as estimated by caldera-related mafic lavas, or those that erupted shortly after caldera magmatism (Figure 9). \( e_{Nd} \) values of the tuffs also correlate with those of the local basement, indicating both crustal and mantle influences on the isotopic compositions of the silicic rocks (Figure 9). Although the Nd isotope composition of the crust is likely to be variable and the composition of the lower crust remains uncertain, it is relatively homogeneous as compared to Sr and Pb isotope variations, and therefore Nd isotope ratios provide the best constraint possible on the proportion of mantle and crustal components in the tuffs. Where low \( e_{Nd} \) values of mafic lavas are due primarily to low-\( e_{Nd} \) lithospheric mantle [e.g., Fitton et al., 1988; Kempson et al., this issue], and not crustal contamination, the proportion of crust in the ash flow tuffs based on inspection of Figure 9b will be overestimated.

Detailed studies of several caldera complexes support an origin for the ash flow tuffs that involve assimilation/fractional crystallization (AFC [DePaolo, 1981c]) of basaltic magmas, and it is proposed below that this may be generally applicable to most calderas. This conclusion requires large volumes of basaltic magmas, and evidence for this is discussed below. Finally, the significance of temporal variations in isotope compositions of multicyclic caldera complexes is discussed in terms of models for mass transfer in the lithosphere and recent crustal growth.

Given the evidence that the ash flow tuffs discussed here are not exclusively melts of ancient crust, three models can explain the Nd isotope data for the silicic rocks: (1) evolution primarily by assimilation of continental crust and fractional crystallization of mantle-derived basaltic magmas, (2) melting of precursor mafic magmas that had stalled deep in the crust but had assimilated crust so that their isotopic compositions are midway between the ancient crust and mantle, and (3) mixing between mantle-derived magmas and melts of ancient crust.

Detailed petrologic and isotopic studies of caldera complexes that contain mafic- and intermediate-composition precaldera lavas suggest that AFC involving basaltic parental magmas may be the dominant process in several large-volume caldera complexes. Examples include volcanic rocks at Los Humeros [Verma, 1983], Zacatecas [Verma, 1984], Kane Springs Wash [Novak, 1985; Novak and Mahood, 1986; Leeman and Hawkesworth, 1986], Kalamazoo [Gans et al., 1989], Timber Mountain-Oasis Valley [Farmer et al., 1991], Latir [Johnson and Lipman, 1988; Johnson et al., 1990], San Juan [Lipman et al., 1978; Ricopiuti and Johnson, 1990], and Grizzly Peak [Johnson and Fridrich, 1990]. In most of these cases, the calculations indicate that the tuffs contain >50 wt % mantle-derived material. A particularly strong case for AFC of parental basalts can be made for the Grizzly Peak Tuff, which is zoned to co-genetic compositions that are too mafic to be partial melts of most crustal rocks (57-77 wt % SiO\(_2\) [Fridrich and Mahood, 1987; Johnson and Fridrich, 1990].

The magma chamber of the Carpenter Ridge Tuff also apparently contained silicic and mafic compositions (down to 55 wt % SiO\(_2\), Figure 8) that had similar Nd isotope ratios
ratios, whereas ash-flow tuffs have similar or higher end values and 2⁰6pb/2⁰4pb ratios. Whereas mafic parts of the tuff as well [Johnson and Fridrich, unpublished data, 1990]. Interpretation of Nd isotope ratios is probably not a major reservoir in this area as mechanism for determining the Nd isotope compositions of andesitic lavas at the Timber Mountain-Oasis Valley complex [Farmer et al., 1991], the Kane Springs Wash caldera [Novak, 1985; Leeman and Hawkesworth, 1986], and the San Juan volcanic field [Riciputi and John- son, 1990; Colucci et al., this issue]. Special pleading is required to explain the relatively high εNd values of the mafic rocks as reflecting melting of contaminated precursor basalts, while simultaneously explaining the lower εNd values of the mafic precaldera lavas as the result of crustally contaminated mantle-derived magmas.

Fig. 9. (a) Summary of ranges in Nd isotope compositions of silicic volcanic rocks (mostly ash flow tuffs) and those of basaltic magmas that erupted contemporaneous with silicic volcanism or are postulated to have been parental magmas to the silicic rocks. AT, Amalia Tuff; BT, Bishop Tuff; GPT, Grizzly Peak Tuff; J, Jemez; KAL, Kalamazoo; KSW, Kane Springs Wash; MCD, McDermitt; E MEX, eastern Mexico; W MEX, western Mexico; PST, Peach Springs Tuff; SJ, San Juan; TMOV, Timber Mountain-Oasis Valley; WM, Woods Mountains. Dashed lines indicate ash flow tuffs from the northern Rio Grande rift. Silicic rocks that have Nd isotope compositions that plot farthest from the 1:1 line probably have the largest crustal components. (b) Summary of ranges in Nd isotope compositions of silicic volcanic rocks (mostly ash flow tuffs) and those of the regional crust. Silicic rocks that have Nd isotope compositions which plot farthest from the 1:1 line probably have the largest mantle components. Labels and lines as in Figure 9a. Data for the Bandelier Tuff of the Jemez volcanic field and Peach Springs Tuff from C. Johnson (unpublished data, 1990).

[Riciputi and Johnson, 1990; L. Riciputi and C. Johnson, unpublished data, 1990]. Interpretation of Nd isotope variations in volcanic centers that only erupted silicic magmas are more ambiguous because the nature of mafic-magma differentiation is unknown. For example, the silicic parts of the Grizzly Peak Tuff have very low εNd values (-11 to -12; Figure 8) that might have been interpreted as reflecting crustal melting, had these values not been found in the mafic parts of the tuff as well [Johnson and Fridrich, 1990]. It remains difficult, however, to estimate the relative proportions of crust and mantle components in ash flow tuffs that were erupted through basement that may not have a large isotopic contrast with the mantle, such as much of the Sierra Madre Occidental and at least the western part of the Mexican Neovolcanic belt.

Several caldera complexes erupted mafic lavas that have εNd values that are lower than those of the ash flow tuffs, which is best explained by an AFC model and not crustal melting. Examples include the Timber Mountain-Oasis Valley complex [Farmer et al., 1991], the Kane Springs Wash caldera [Novak, 1985; Leeman and Hawkesworth, 1986], and the San Juan volcanic field [Riciputi and John- son, 1990; Colucci et al., this issue]. Special pleading is required to explain the relatively high εNd values of the silicic rocks as reflecting melting of contaminated precursor basalts, while simultaneously explaining the lower εNd values of the mafic precaldera lavas as the result of crustally contaminated mantle-derived magmas.

Calling upon a relatively high-εNd lower crust as an explanation for deriving the ash flow tuffs by crystalline melting predicts that Nd and Pb isotope ratios of volcanic rocks should be anticorrelated. Magmas that were generated by partial melting of mafic lower crust that was not as LREE enriched as the exposed crust should have relatively high ⁴⁴Nd/⁴⁰Nd ratios but low ²⁰⁶Pb/²⁰⁴Pb ratios. This contrasts with the fact that mafic precaldera lavas in the Latir and San Juan volcanic fields have low εNd values and ²⁰⁶Pb/²⁰⁴Pb ratios, whereas ash-flow tuffs have similar or higher εNd values and markedly higher ²⁰⁶Pb/²⁰⁴Pb ratios [Lipman et al., 1978; Johnson et al., 1990; Riciputi and Johnson, 1990; Colucci et al., this issue]. Although a possible exception to this argument could involve melting of lower crust that is similar to that sampled by many high-grade xenoliths, which have radiogenic Pb isotope ratios [Esperanca et al., 1988; Rudnick and Goldstein, 1990; Kempton et al. 1990; K.L. Cameron et al., submitted manuscript, 1991], this is an unlikely scenario for ash flow tuffs in the northern Rio Grande rift region. A lower crust that has high ²⁰⁶Pb/²⁰⁴Pb ratios is probably not a major reservoir in this area as virtually all mafic- and intermediate-composition lavas that contain a crustal component have low ²⁰⁶Pb/²⁰⁴Pb ratios; this generalization applies to 34 Ma precaldera lavas to 3 Ma lavas of the Taos Plateau Volcanic field [references above and Dungan et al. [1986] and Johnson and Thompson [this issue]].

Hildreth and Moorbath [1988] convincingly demonstrate the strong influence of the crust on the chemical and isotopic compositions of Andean arc rocks and suggest that most of the evolved magmas were generated by mixing crustal and mantle melts in the lower crust. It seems likely that the “blending” of crustal melts and more primitive magmas that Hildreth and Moorbath [1988] envision in their “MASH” model occurs in most volcanic fields. Because the end-members that may be involved in mixing are probably not seen at the surface, it is difficult to evaluate the significance of this process in the caldera complexes of western North America. If magma mixing is the primary mechanism for determining the Nd isotope compositions of the ash flow tuffs, the tuffs contain mantle components that are equal to or exceed that of related intermediate-composition lavas at the Timber Mountain-Oasis Valley complex, the Kane Springs Wash caldera, and the San Juan and Latir volcanic fields.

The largest volumes of basaltic magma are required to generate silicic magmas in models 1 and 2 (above). Production of silicic magmas by AFC will require of the order of
10 km$^3$ of basalt magma to produce 1 km$^3$ of rhyolite magma. Although the contaminated precursor magmas envisioned in model 2 (above) probably involved less extensive crystallization than that required in the first model, additional basaltic magma is required to melt the contaminated precursor magmas; a mafic:silicic ratio of the order of 10:1 also seems appropriate for model 2.

Although smaller volumes of basaltic magma are required to generate silicic magmas in model 3 (above), the volumes are still substantial. Because the enthalpy of fusion for common silicate minerals in mafic and silicic rocks are similar within a factor of two [e.g., Robie et al., 1978], approximately 1 km$^3$ of basaltic magma will be required to generate 1 km$^3$ of rhyolitic magma by crustal anatexis; it seems likely that larger amounts of basaltic magma often will be required, because some mafic magmas may undergo only limited crystallization, and substantial heat losses may occur through convection and conduction. Additional basaltic magma is, of course, required for the mafic component involved in mixing. All three models, therefore, require substantial volumes of mafic magma to generate and sustain silicic volcanism at the caldera complexes discussed here. Distinction between these models require detailed petrologic studies of caldera complexes that contain premonitory mafic- and intermediate-composition lavas, so that possible genetic links between the silicic and mafic parts of the system can be tested.

Evidence for Basalt Underplating From Geophysical and Petrologic Studies of the Lower Crust

There is growing consensus that heat flow and seismic data obtained in the Basin and Range province are best explained by recent intrusion or underplating of basaltic magmas at or near the base of the continental crust. Reduced heat flow in the Basin and Range province is generally 50-100% greater than that in stable cratons and can be well explained by underplating the crust by mantle-derived basaltic magmas [Lachenbruch and Sass, 1978]. Lachenbruch and Sass [1978] note that if basaltic magma underplating is the primary mechanism for producing high heat flow in the western United States, then intrusion rates in the Basin and Range province must be of the order of flood basalt eruption rates in the Columbia Plateau.

The reflection Moho is relatively flat at depths of 30-35 km in the Basin and Range province, and this has been interpreted as indicating that the Moho is relatively young [Allmendinger et al., 1983, 1987; Klemperer et al., 1986]. The reflection Moho in the Basin and Range cuts across crustal sections that have had markedly different tectonic and accretionary histories, which included large-scale vertical movements in the crust, as well as large variations in the amount of extension recorded in upper crustal rocks [Allmendinger et al., 1983, 1987; Klemperer et al., 1986; McCarthy and Thompson, 1988; Thompson et al., 1989]. Where high-quality reflection and refraction data are available for coincident traverses, the reflection and refraction Moho occur at the same depths in the western United States within error of the determinations [e.g., Mooney and Brocher, 1987; W. Mooney, personal communication, 1989]. The relatively flat Basin and Range Moho contrasts strongly with that observed in other regions that have undergone large-scale tectonism, but accompanied by little magmatism or extension, such as in the Himalaya-Tibet orogenic belt (see review by Jarchow and Thompson [1989]).

Primary wave velocities ($V_p$) obtained in seismic refraction studies in the Basin and Range province and the Rio Grande rift region indicate that the middle crust commonly has $V_p$ that is generally lower (~6.2-6.4 km/s) than those of the middle crust under regions that have not be extended, such as the Great Basins [McCarthy and Thompson, 1988; Prodehl and Lipman, 1989; Mooney and Braile, 1989]. The lower crust in the Great Basin commonly appears strongly layered in reflection studies, and has relatively high $V_p$ of ~7.3-7.5 km/s in some areas [e.g., Mooney and Braile, 1989; Thompson et al., 1989; Smithson, 1989]. A high-velocity lower crust is missing, however, beneath the Mojave Desert and Arizona, along the PACE transect [McCarthy and Thompson, 1988]. It is notable that this region contains few documented Cenozoic calderas, in comparison to the Great Basin, although numerous Mesozoic calderas have been identified in southern Arizona [e.g., Lipman and Sawyer, 1985]. Klemperer et al. [1986] and Smithson [1989] note that a prominent reflector (X) lies ~4 km above the Moho in the Great Basin and suggest that this marks the boundary of a transition zone between the crust and mantle. Primary wave velocities in the upper 100 km of the mantle beneath the Basin and Range province are ~7.8 km/s, significantly lower than those under the adjacent Colorado Plateau (~8.0 to 8.2 km/s) [Thompson and Burke, 1974; Hauser and Lundy, 1989; Braile et al., 1989]. These characteristics suggest that the crust beneath large Cenozoic ash flow tuff fields is composed of large volumes of intermediate- to silicic-composition intrusive rocks in the middle crust, which are underlain by layered mafic sills in the lower crust, which in turn is underlain by upper mantle that has anomalously low $V_p$.

The relatively flat Moho, high lower crustal seismic velocities, and strong layered reflections in the lower crust of the Great Basin have been interpreted as indicating emplacement of large volumes of basaltic magmas and related cumulates into the lower crust, which would create a petrologically mixed boundary between the crust and mantle [e.g., Furlong and Fountain, 1986; Thompson et al., 1989]. Indeed, Klemperer [1989] argues that the seismic reflection and refraction data obtained in the Basin and Range province are best explained by underplating ~3x10$^6$ km$^3$ of basaltic magmas near the crust-mantle boundary during the Cenozoic and that significant crustal growth may occur by this mechanism. This is equivalent to addition of ~6 km of mantle-derived magma to the crust, averaged over the ~5x10$^3$ km$^2$ area of the preextension Basin and Range province. Furlong and Fountain [1986] calculate larger additions of basaltic magma at the base of the crust 10-15 km, based on thermal models of magma extraction from the mantle. Unfortunately, geophysical evidence for magmatic underplating cannot constrain if underplating occurred during caldera-related volcanism in the Great Basin or after most calderas formed.

Sufficiently deep crustal exposures are not available in the western United States to test models that involve large-scale intrusion into the lower crust of mafic magmas. Evidence for large mafic intrusions in the lower crust can be
found in other regions [e.g., Fountain and Salisbury, 1981]. For example, the large Border Ranges mafic-ultramafic complex, Alaska, demonstrates that some regions of the lower crust are dominated by cumulates that underlie more silicic plutonic and volcanic rocks [Burns, 1985]. Ultramafic xenoliths in island arc lavas have been interpreted as cumulates that were generated by crystal fractionation of island arc magmas [e.g., Debari et al., 1987]. Mass balance calculations based on cumulative xenolith abundances suggest that it is reasonable to expect the lower parts of island arcs to have a large cumulate component [Kay and Kay, 1985].

Early studies of crustal and mantle xenoliths in the western United States note the complexity of the lower crust and upper mantle [e.g., McGetchin and Silver, 1972]. McGetchin and Silver suggest that the crust-mantle boundary is a complex and diffuse zone that includes mafic and ultramafic regions in the lower crust, as well as unusually silicic regions in the uppermost mantle. Subsequent studies of xenoliths from other regions in the western United States have confirmed these observations [e.g., Wilshire et al., 1988; Kempton et al., 1990; K.L. Cameron et al., submitted manuscript, 1991]. Xenolith studies from other Cenozoic magmatic provinces support models for large-scale underplating of mantle-derived basaltic magmas and associated formation in the crust-mantle boundary [e.g., Wass and Hollis, 1983; Griffin and O’Reilly, 1987; Rudnick et al., 1986; Rudnick and Taylor, 1987; Rudnick and Williams, 1987].

Relations of Magma Sources and Tectonic Setting

Regardless of the tectonic setting in which large-volume ash flow tuff eruptions occurred in western North America, all of the silicic magmas contained a major mantle component, that in some cases appears to be >50%. Although the discussion above suggests that large volumes of mantle-derived basaltic magmas were emplaced into the crust in all regions of caldera formation in western North America, regardless of the amount of extension, injection of voluminous basaltic magmas is not uniformly correlated with the onset of extension and cannot, therefore, be called upon as the uniform driving mechanism for extension [e.g., Gans, 1987; Fountain, 1989]. The common thread to all caldera complexes is that when they are formed, they are fundamentally associated with large volumes of basaltic magma that were injected into the crust.

Temporal Evolution and Modification of the Crust

Sustained (10-20 m.y. duration) eruption of magma at many magmatic centers, including multiple caldera-forming eruptions, has led several workers to suggest that a general requirement for developing caldera complexes is a large flux of mantle-derived basaltic magma into the lower parts of the system [e.g., Christiansen and Lipman, 1972; Lachenbruch et al., 1976; Smith, 1979; Hildreth, 1981; Spéa and Crisp, 1981]. Based on detailed study of the Latir volcanic field, which was active for 9 m.y., Johnson et al. [1990] calculate that ~29,000 km² of basaltic magma were required to generate and sustain the magmatic system. Injection of large volumes of basaltic magma into the crust will produce large changes in Sr and Nd isotope compositions of the crust, and these changes reflect profound hybridization of ancient crust and mantle components in the crustal column. Johnson et al. [1990] calculate that Sr and Nd isotope ratios of the hybridized crust may shift ~80% and ~50% closer to those of the mantle, respectively, during evolution of the Latir volcanic field, which had a single caldera cycle. In contrast, Pb isotope ratios of the hybridized crust were estimated to shift only ~20% toward those of the mantle, due to the low Pb contents of mantle-derived basalts compared to those of the crust.

Temporal trends in Nd isotope compositions for ash flow tuffs of the multicyclic central caldera cluster of the San Juan volcanic field are remarkably similar to those predicted to occur in the crust based on models for the Latir volcanic field. As noted by Ricciuti and Johnson [1990], εNd values of ash flow tuffs from the central caldera cluster increase by ~2 units with decreasing age; this trend can be modeled by a shift of ~8 εNd units of the isotopic composition of the crust toward mantle compositions as a result of continued injection of basaltic magmas. Additional data have identified two trends in the central caldera cluster. Relatively rapid shifts in Nd isotope compositions of ash flow tuffs from the San Luis caldera complex may reflect rapid injection of mafic magmas into the lower parts of this multicyclic system (Figure 10). Ash flow tuffs that define the younger end of the main trend for tuffs of the central cluster, as well as those for the San Luis caldera complex, have εNd values that are higher than those of most precaldera intermediate-composition lavas (Figure 10), strongly supporting an increasing mantle component in the crust during evolution of the volcanic field.

Temporal variations for ash flow tuffs in the northern Rio Grande rift region follow those that occur within the San Juan volcanic field (Figure 11). Eruption of the Grizzly Peak Tuff occurred contemporaneous with early precaldera volcanism in the nearby San Juan field, and ash flow magmatism in the central San Juan caldera cluster temporally overlaps precaldera and caldera-related volcanism at the nearby Latir volcanic field [Lipman et al., 1970, 1986; Fridrich et al., 1991]. The youngest caldera in the San Juan field erupted 3 m.y. after formation of the Questa caldera in the Latir field [Lipman et al., 1970, 1986]. These factors indicate that caldera-related magmatism in the northern Rio Grande rift region may be broadly considered part of the same coeval volcanic field [e.g., Steven, 1975]. Similar temporal variations in isotopic compositions are well documented at the Timber Mountain-Oasis Valley caldera complex, where εNd values of ash-flow tuffs that did not undergo late stage roof assimilation increase 1.2 εNd units over a 2-m.y. period (Figure 6) [Farmer et al., 1991]. εNd values for silicic rocks in the Long Valley area generally increase 4 εNd units over 2-m.y. period (Figure 5) [Halliday et al., 1984, 1989; Sampson and Cameron, 1987; Kelleher and Cameron, 1990]. Although the Peach Springs Tuff and Wild Horse Mesa Tuff in the eastern Mojave Desert are not part of the same magmatic system, they probably erupted from the same region, and the markedly higher εNd values of the younger Wild Horse Mesa Tuff may reflect an increasing mantle component in the crust of the region during late Cenozoic magmatism (Figure 5) [Musselwhite et al., 1989; C. Johnson, unpublished data, 1990]. Further work on other multicyclic caldera complexes are needed to test if
the temporal variations noted here are common, particularly in the caldera complexes of the Great Basin, Sierra Madre Occidental, and Mogollon-Datil volcanic field.

Although models presented by Johnson et al. [1990] predict only small changes in the Pb isotope compositions of the crust during continued injection of mantle-derived basalt, large variations in Pb isotope ratios for precaldera and caldera-related volcanism and postcaldera ore deposition have been noted for the San Juan volcanic field (Figure 12) [Lipman et al., 1978; Doe et al., 1979; Riciputi and Johnson, 1990; Colucci et al., this issue]. The low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of precaldera lavas have been interpreted by the above workers to reflect interaction with the lower crust, and the markedly higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the ash flow tuffs are interpreted to reflect a larger upper crustal component. Riciputi and Johnson [1990] suggest that the decrease in $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the younger ash flow tuffs of the central caldera cluster can be interpreted as due to transport of nonradiogenic lower crustal Pb into the middle and upper parts of the magmatic system during continued magmatism. This decrease in $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the ash flow tuffs contrasts with the very high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios that characterize postcaldera ore leads (Figure 12) [Doe et al., 1979] which presumably reflect the Pb isotope compositions of the upper crust in the vicinity of the ash-flow magma chambers that had not been hybridized.

$^{206}\text{Pb}/^{204}\text{Pb}$ ratios for ash flow tuffs in the northern Rio Grande rift region generally increase with decreasing age (Figure 13), suggesting that the evolved magmas interacted with progressively more evolved, and presumably more shallow, Proterozoic crust. That the younger ash flow tuffs in the central caldera cluster of the San Juan field do not follow this trend may indicate that transfer of lower crustal Pb to the upper crust may only occur in multicyclic caldera complexes, where crust hybridization and magma fluxes are concentrated in areaally restricted regions. In contrast to the ash flow tuffs, $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of mafic- and intermediate-composition lavas in the region remain low (Figure 13), and this may reflect restriction of large-scale interac-
tion between mantle-derived magmas and crust to the lower

Temporal changes in O and Sr isotope ratios for ash flow
tuffs in the northern Rio Grande rift region are also consist-
ent with an increasing mantle component in the hybridized
crust. $\delta^{18}O$ values for ash flow tuff samples that did not
interact with meteoric water decrease 2.5% with decreasing
age for the Grizzly Peak, San Juan, and Latir ash flow
tuffs [Larson and Taylor, 1986; Johnson et al., 1990; John-
son and Fridrich, 1990]. Similar, but larger, decreases in
$\delta^{18}O$ values of 4% over a 3-m.y. period occurred for ash flow
tuffs from the Sonoma volcanic field in western California
[Johnson and O'Neil, 1984]; these variations are inter-
preted as reflecting replacement of the original Mesozoic
sedimentary crust in western California with mafic intru-
sions that were associated with the late Cenozoic tuffs.
Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the most mafic parts of the ash
flow tuffs in the northern Rio Grande rift region decrease
with decreasing age from 0.7099 for the Grizzly Peak Tuff
(34 Ma [Johnson and Fridrich, 1990]), to 0.7055-0.7075
for the San Juan tuffs (29-25 Ma [Lipman et al., 1978]), to
0.7057 for the Amalia Tuff (26 Ma) that was erupted from
the Questa caldera of the Latir volcanic field [Johnson et
al., 1990]. Caution must be used in interpreting the initial
$^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the silicic, low-Sr parts of ash flow tuffs,
because their Sr isotope ratios are very susceptible to modi-
ification by late stage assimilation [e.g., Noble and Hedge,
1969; Johnson, 1989].

It is unlikely that systematic temporal changes in four
isotope systems (O, Sr, Nd, and Pb) for the tuffs in the
northern Rio Grande rift region is due to significant geo-
graphic heterogeneity of the crust. If the variation in O, Sr,
and Nd isotope ratios is due to preferential interaction with
"isotopically primitive" Proterozoic crust to the south, a
decrease in $^{206}\text{Pb}/^{204}\text{Pb}$ ratios is expected, if mafic lower
crust that has low $\delta^{18}O$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and high
present-day $\epsilon_{Nd}$ values is envisioned as the contaminant, as
the lower crust in the region has low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios [e.g.,
Johnson and Thompson, this issue]. Barker et al. [1976] note
that Rb/Sr ratios of 1700 Ma plutonic rocks increase
north to south from central Colorado to northern New
Mexico, suggesting that the Early Proterozoic crust beneath
the Latir field should have higher present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios
than under the Grizzly Peak caldera. This is opposite
to the trend observed for the ash flow tuffs, $\delta^{18}O$ and
present-day $\epsilon_{Nd}$ values are relatively high and low, respec-
tively, for 1000-1400 Ma granitic rocks in Colorado
[Barker et al., 1976b; DePaolo, 1981a] and are thought to
be the primary contaminant of the magmas that were paren-
tal to the Grizzly Peak Tuff magma [Johnson and Fridrich,
Arndt and Goldstein [1989] propose that the crust-mantle boundary represents not only an interface for transfer of fluxes which Cox [1980] and Ewart et al. [1980] propose metasomatism for generating enriched reservoirs in the mantle, as largely lies as an alternative mechanism to mantle metasomatism for proposing return of material to the mantle in the form of cumulates. Expected uplifts associated with large-scale magmatic injection in highly extended regions such as the Basin and Range province should be significantly smaller.

If basaltic magmas stagnate at the crust-mantle boundary and form crystal cumulates during assimilation, then the Sr, Nd, and especially Pb isotope compositions of the local upper mantle will be largely overprinted by crustal compositions. In their model for the Latir field, Johnson et al. [1990] calculate that the mass ratio of magma originally extracted from the mantle relative to the mass of crust returned to the mantle is approximately 5:1, indicating that despite crustal recycling, significant net crustal growth occurred on at least a local scale, in addition to significant crust formation. If the source regions for late Cenozoic mafic magmas in western North America intersected the contaminated upper mantle, the isotopic compositions would be similar to those commonly interpreted as reflecting derivation from ancient enriched mantle. Localized crustal recycling into the mantle offers an alternative explanation for the low $\Delta$Nd values of some basaltic lavas that erupted after caldera formation, which have been interpreted by some workers to reflect ancient lithospheric mantle [e.g., Leeman, 1982; Menzies et al., 1983; Fitton et al., 1988; Farmer et al., 1989; Kempton et al., this issue].

**SUMMARY AND CONCLUSIONS**

Middle to late Cenozoic ash flow tuffs and silicic lavas at large-volume volcanic fields in western North America contain a large, commonly dominant, mantle component. Detailed studies of several caldera complexes indicate that the silicic magmas fundamentally owe their origins to protracted assimilation/fractional crystallization of basaltic parental magmas. To a first order, the proportion of mantle-derived components in the ash flow tuffs discussed here is approximately the same, regardless of the tectonic setting in which the calderas formed or the extent to which voluminous high-SiO$_2$ magmas were developed. The widespread episode of Cenozoic caldera-related magmatism in western North America represents a major period of rapid crust formation that may rival crustal growth rates in the Proterozoic [e.g., Nelson and DePaolo, 1985].

Addition of mantle-derived basaltic magmas to the crust results in a shift toward more mafic bulk composition and an increase in crustal density (Figure 14), particularly in the

**Mass Transfer in the Lithosphere**

Following the ideas of Cox [1980] and Ewart et al. [1980] regarding crustal growth by magmatic underplating, Arndt and Goldstein [1989] propose that the crust-mantle boundary represents not only an interface for transfer of mantle components to the crust but also return of crustal material to the mantle, if mantle-derived magmas stagnate near the crust-mantle boundary. The Arndt and Goldstein model envisions crustal recycling to largely occur by fountaining of the crust, and the motivation for this model largely lies as an alternative mechanism to mantle metasomatism for generating enriched reservoirs in the mantle, as well as recognition of the fact that the large basaltic magma fluxes which Cox [1980] and Ewart et al. [1980] propose should result in large-scale uplift that is not generally observed.

**Fig. 13. Variations in $^{206}$Pb/$^{204}$Pb ratios for volcanic rocks of the northern Rio Grande rift region with time. GP, Grizzly Peak Tuff; SJ, San Juan ash flow tuffs of the central caldera cluster; AT, Amalia Tuff (Latir volcanic field-Questa caldera); ESJ, early intermediate-composition San Juan lavas (Conejos Formation); SLH, early intermedium-composition Latir lavas; SLH, early rift mafic lavas at San Luis Hills. Hybridized crust evolution curve from Johnson et al. [1990]. Data from Lipman et al. [1978], Johnson et al. [1990], Riciputi and Johnson [1990], Johnson and Fridrich [1990], Johnson and Thompson [this issue], and Colucci et al. [this issue].**
**CALDERA-RELATED MAGMATISM**

Fig. 14. Cross section through the crust and upper mantle and accompanying depth-\(V_p\)-density variations during evolution of caldera-related magmatism (generally 35-10 Ma) in western North America. Depth to Moho fixed at 40 km for simplicity, although depth to Moho will vary with the amount of magmatic underplating and extension. The crust-mantle boundary is envisioned to have been relatively sharp prior to caldera-related magmatism. Continued injection of mantle-derived magmas into the crust during evolution at large volcanic fields is envisioned to increase the density of the crust, resulting in ascent of the locus of both mafic and silicic magma chambers with time; this may be reflected in an overall increase in \(^{206}\text{Pb}^{204}\text{Pb}\) ratios of ash flow tuffs from the northern Rio Grande rift region (see Figure 13). The increase in average density of the crust will be accompanied by a decrease in the average \(^{87}\text{Sr}^{86}\text{Sr}\) ratio and increase in the average \(e_{\text{Nd}}\) value of the crust as the mantle component in the crust increases. Return of cumulate material to the mantle is envisioned (unpatterned arrow) to partially compensate for the large flux of mantle-derived basalt into the crust (solid arrow), although the difference in these fluxes will produce net crustal growth (stippled arrow). The overlapping nature of these fluxes will produce a petrologically and seismically transitional Moho (Figure 15). Basis for depth-\(V_p\)-density diagram is from Glazner and Ussler [1988].

These compositional changes can explain the anomalously high \(V_p\) of the lower crust in some areas of the Basin and Range province, as compared to those of stable cratons [e.g., Mooney and Braile, 1989]. These characteristics may be accompanied by significant increases in \(e_{\text{Nd}}\) values and decreases in \(^{87}\text{Sr}^{86}\text{Sr}\) ratios of the crust, particularly for the regions of the crust that are hybridized mixtures of original crust and new mantle-derived rocks. Precaldera mafic- and intermediate-composition magmas are envisioned to ascend into the middle crust and continue hybridization processes that began in the lower crust. Lead isotope ratios for the crust, including the hybridized crust, will be little affected, however, due to the low Pb content of mantle-derived basalts; Pb isotope ratios, therefore, provide a means to "see through" the effects of crust hybridization and retain some record of the original vertical zonations of Pb isotope ratios in the crust. Only at multicyclic caldera complexes will magmatism be sufficiently focussed so that transport of Pb from the lower crust to the upper crust occurs [e.g., Riciputi and Johnson, 1990]. Continued increases in the mean density during evolution of large volcanic fields will tend to focus the zones of silicic magma evolution to higher crustal levels. Assuming a general upward increase in U/Pb ratios of the crust, this process may explain the general increase in \(^{206}\text{Pb}^{204}\text{Pb}\) ratios that is observed for ash flow tuffs in the northern Rio Grande rift volcanic fields (Figure 13), which produced approximately 20 calderas over a 12-m.y. period.

Ponding of parental basaltic magmas in the lower crust may explain the common observation of horizontal reflectors in the lower crust [e.g., Klemperer et al., 1986; McCarthy and Thompson, 1988; Klemperer, 1989; Thompson et al., 1989]. The base of these strong reflectors probably belongs to a petrologically complex transition zone of original lower crust and young basaltic rocks and their associated cumulates, as indicated by combined geophysical and xenolith studies (Figure 15). Young cumulates are considered to lie below the Moho, because they should have relatively high seismic velocities. Although the low \(V_p\) in the upper mantle beneath the Basin and Range has been explained as a result of high heat flow [Black and Braile, 1982], silicic (crustal) material also has low velocities [e.g., Rybach and Buntebarth, 1982; Fountain and Christensen, 1989], and local recycling of crust into the upper mantle could explain the low \(V_p\) (Figure 15). The low \(V_p\) and heat
Fig. 15. Cross section through the crust and upper mantle and accompanying depth-V_p-density variations during postcaldera magmatism (generally <10 Ma) in western North America. Large fluxes of mantle-derived magmas into the crust during earlier, caldera-related magmatism (Figure 14) is thought to have produced a petrologically and seismically transitional Moho that has anomalously high lower crust V_p and low upper mantle V_p. Although the largest volumes of mafic lavas in western North America were generally erupted after caldera-related magmatism, [e.g., Christiansen and Lipman, 1972; Lipman et al., 1972], the largest fluxes of basaltic magma into the crust are thought to have occurred during earlier, caldera-related magmatism, due to the large mantle component in ash flow tuffs from western North America. Basis for depth-V_p-density diagram is from Glazner and Ussler [1988].

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