

## Two-stage contamination during crustal assimilation: isotopic evidence from volcanic rocks in eastern Nevada

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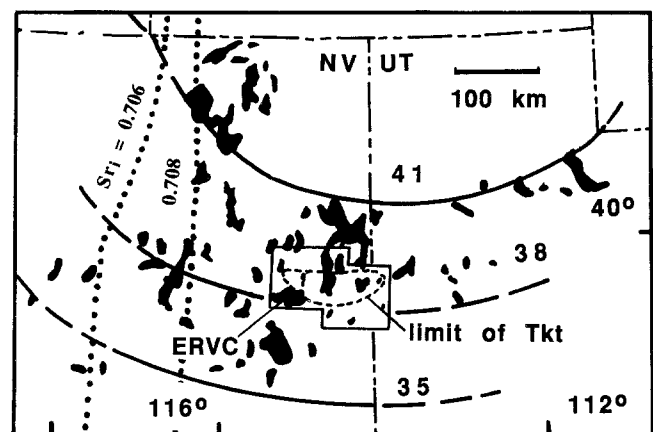
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**Abstract.** Thousands of cubic kilometers of dominantly intermediate composition, metaluminous magma erupted at approximately 35 Ma in eastern Nevada. Two stages of crustal contamination are inferred from detailed study of the earliest volcanic rocks. Fine-grained mafic rocks and rocks with mixed textures, ranging from basalt to rhyolite, were contaminated with a crustal component rich in Nd but poor in Sr. Overlying plagioclase-rich andesites and dacites have greater Sr and  $^{87}\text{Sr}/^{86}\text{Sr}$ , but less Nd and lower  $\epsilon_{\text{Nd}}$  and are interpreted to have been contaminated by a crustal component with the opposite elemental signature (i.e., poor in Nd but rich in Sr). The first contaminant represents a partial melt of the crust with plagioclase as a residual phase and the second contaminant is the residue of the partial melting event, or bulk crust. The net effect is bulk crustal assimilation, but in two “bites”. The separation of the crustal source into two elementally distinct contaminants causes divergent trends with respect to the variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $\epsilon_{\text{Nd}}$  that could be misinterpreted to indicate the existence of isotopically distinct crustal reservoirs. Comparison of the calculated contaminants to melting relationships in pelites is consistent with the two contaminants representing melt and residue at about 30% melting. The model age of the bulk crust is approximately 2.2 Ga, consistent with an early Proterozoic crustal province inferred by other workers.

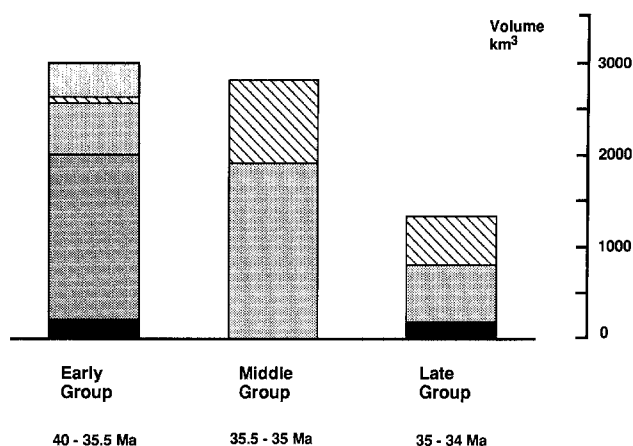
### Introduction

Assimilation of continental crust is a widely invoked process for explaining compositional and isotopic characteristics of intermediate to silicic igneous rocks. The purpose here is to examine the mechanism by which large portions of the crust are recycled by examining in detail Sr and Nd isotope variations during successive stages of voluminous intermediate to silicic volcanism in eastern Nevada. The middle Tertiary volcanic rocks there are part of widespread, “calcalkaline” Tertiary

volcanism that was characteristic of the Great Basin prior to about 17 Ma (Lipman et al. 1972). The volcanic rocks have an estimated volume of greater than 10,000 km<sup>3</sup> (Figs. 1, 2), the intrusive equivalent of which is presumably a batholith. The stratigraphic control that is possible by working on volcanic rocks has allowed construction of a temporal framework within which to examine the petrologic processes acting at different stages in the magmatic history. Feeley and Grunder (1991) demonstrated that the petrologic evolution is consistent with an early stage of magma mixing between mantle derived basalts and a rhyodacitic crustal component, followed by a stage of extensive crustal melting and equilibration of mixed magmas, which in turn was followed by a stage of differentiation dominated by crys-



**Fig. 1.** The location of the study area relative to the distribution of 43–34 Ma volcanic rocks, modified after Stewart and Carlson (1976). The distribution of the 35-Ma-old Kalamazoo Tuff is indicated by the *fine dashed line*. The Egan Range volcanic complex is marked ERVC. Isochrons for the approximate onset of Tertiary volcanism are taken from Best et al. (1989). Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  isopleths of 0.706 and 0.708 for granitoid rocks are from Kistler and Peterman (1978) and Farmer and DePaolo (1983), respectively. The study area extends from the Confusion Range in western Utah to the Butte Mountains in eastern Nevada and surrounds the metamorphic core complex in the northern Snake Range



**Fig. 2.** Estimated volume of compositional types from eastern Nevada. Estimates are corrected for 250 percent extension. (■) Basaltic andesite to andesite 52–60; (▨) Andesite to silicic andesite 60–63; (▤) Dacite to trachydacite 63–68; (▥) Silicic dacite and trachydacite to rhyolite 68–74; (▧) High-silica rhyolite >74 weight %  $\text{SiO}_2$

tal fractionation. These stages probably correlate to the onset, climax, and waning of heat input.

As part of a reconnaissance Nd and Sr isotopic study of these volcanic rocks, Gans et al. (1989) proposed two stages of crustal contamination, one with extensive contamination in the hot lower crust followed by lesser contamination at shallower crustal levels where the thermal contrast between magmas and wall rocks is greater. The evidence presented here argues that contamination of mafic magmas in the middle crust occurred in two main stages: (1) contamination with a partial melt of pelitic crust; (2) contamination with the residue of the melting event. The net effect is bulk assimilation, but the two-stage process produces Nd and Sr isotope trends that mimic contamination with multiple crustal reservoirs.

### Geologic context

The volcanic rocks of east-central Nevada are between 40 and 34 Ma old (Gans et al. 1989) and are part of an early to middle Tertiary, intermediate composition volcanic event (Fig. 1). There has been no volcanism in the area since. The volcanic section is described by Gans et al. (1989) and by Feeley and Grunder (1991). Three stratigraphic and lithologic packages have been identified: the early, middle, and late groups. The variation of composition with time in Fig. 2 results from compilation of stratigraphic data over the area outlined in Fig. 1. Volume estimates have been corrected to account for approximately 250% extension; the volcanic rocks are from a highly extended domain mapped by Gans and Miller (1983). The absolute values of the volumes differ depending on the amount of extension that is estimated, but the relative volumes of the different compositional types will be little affected. Extension was, in part, synchronous with volcanism (Gans et al. 1989); angular unconformities within the volcanic section separate units with as much as 15 degrees of discordance. The volume of the late group is least well constrained because the top of the section has been eroded and because no allowance was made for syneruptive extension.

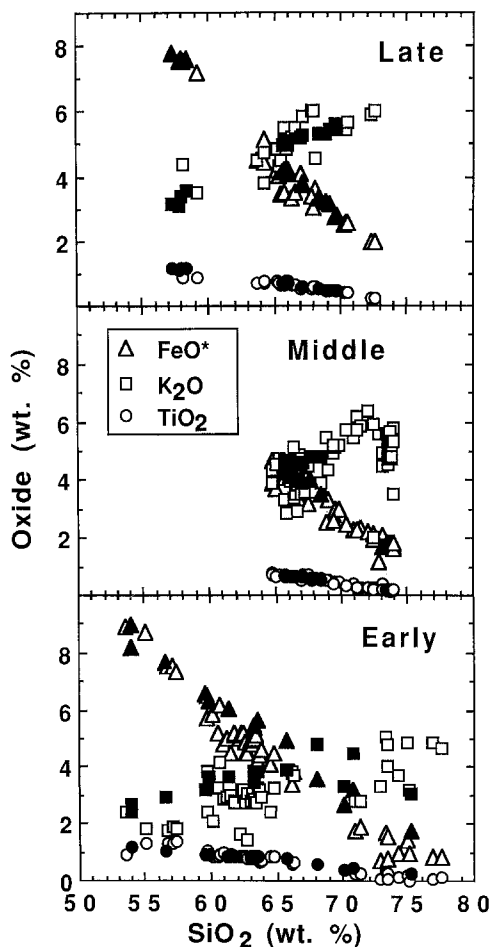
The volcanic section overlies mainly the Permian Arcturus Formation and the Permian to Pennsylvanian Ely Limestone with little angular unconformity (Gans and Miller 1983). The carbonate-

dominated Paleozoic section is principally in the upper plate of the Snake Range metamorphic core complex and overlies Precambrian (McCoy Creek Group) to Cambrian silstones, shales, and quartzites (Hose and Blake 1976) that occur in the upper and lower plate. The relative volumes of Tertiary intrusions and volcanic rocks is 1:1.8 at the present level of exposure in the upper plate, assuming that intrusions and volcanic rocks were tilted the same amount.

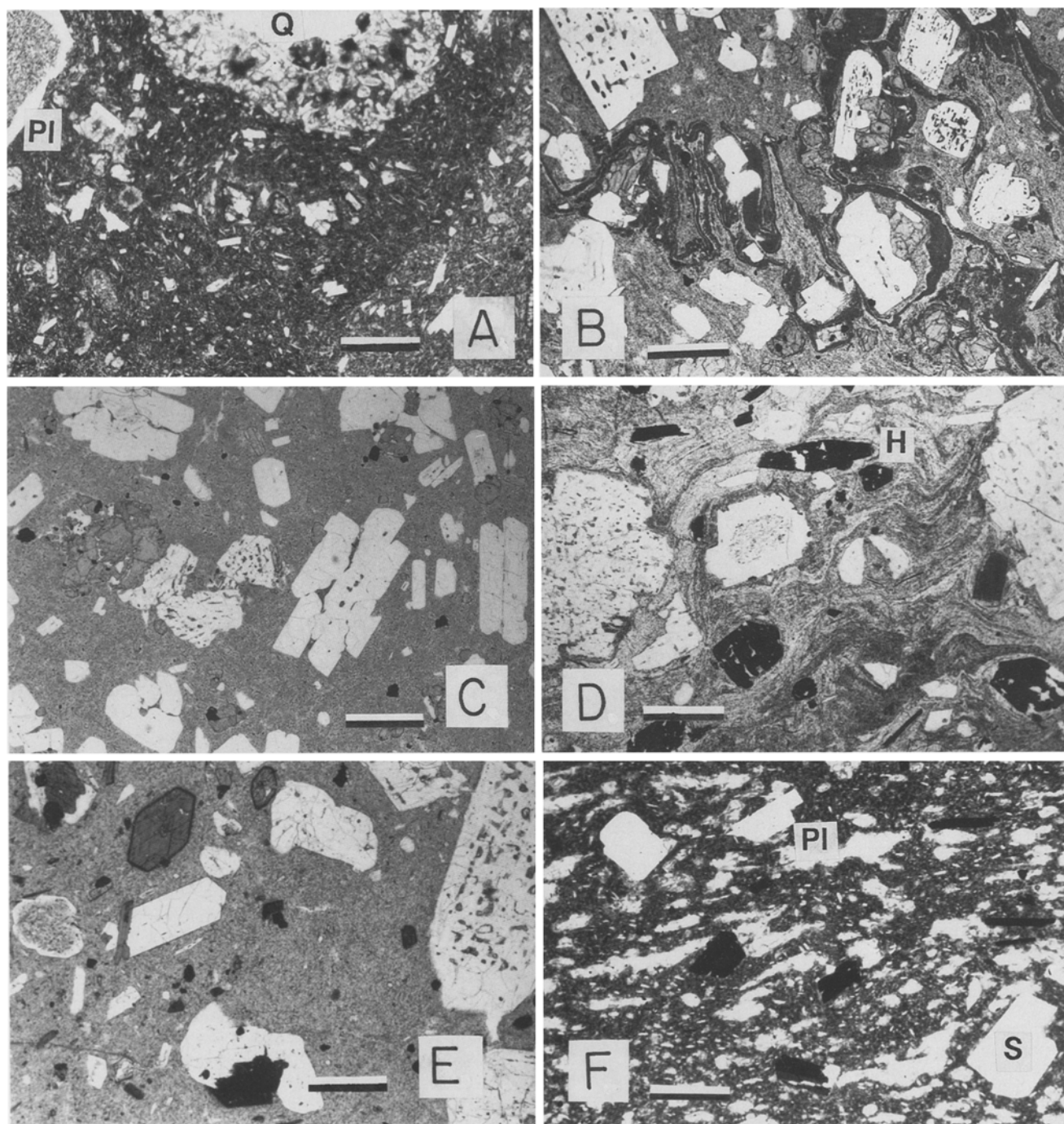
### Summary of petrology and textures

The principal petrologic trends for the early, middle, and late groups have been documented by Feeley and Grunder (1991) for the Egan Range volcanic complex (Fig. 1). The chemical trends established there are largely representative of the regional suite in east-central Nevada (Figs. 3, 5, and 6), but the proportion of the early group is greater, and that of the late group is less on a regional basis.

The early group is distinguished by its compositional diversity, ranging from olivine andesite to biotite rhyolite, but is mainly two-pyroxene lavas of intermediate composition (Fig. 3). Excluding the rhyolites, three textural and mineralogical types occur in the early group (Fig. 4A–C): (A) fine-grained, basaltic andesite to andesite containing mainly clinopyroxene, lesser olivine or orthopyroxene, few or no plagioclase phenocrysts, and few but conspicuous quartz xenocrysts; (B) basaltic andesites to rhyodacites with quenched

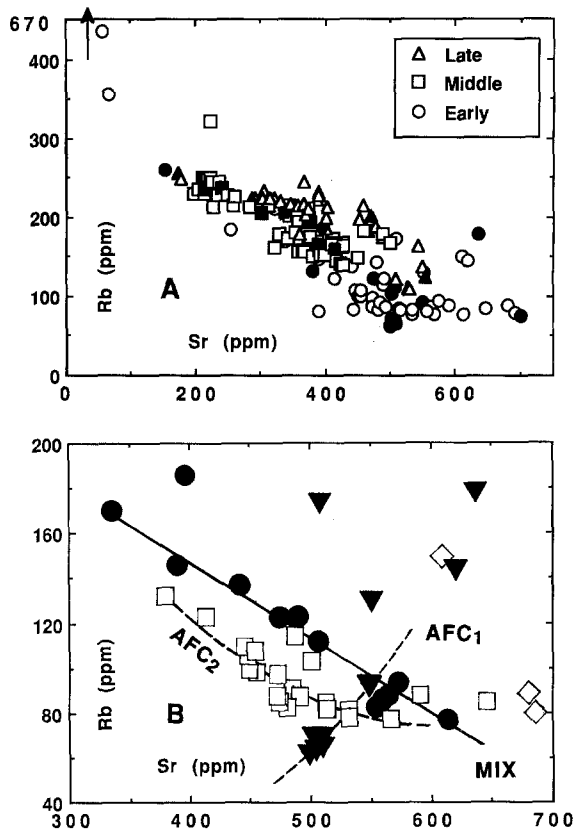


**Fig. 3.** Variation of  $\text{FeO}^*$  (Fe calculated as ferrous),  $\text{K}_2\text{O}$ , and  $\text{TiO}_2$  with  $\text{SiO}_2$  for the early, middle, and late group rocks of eastern Nevada. Samples from the Egan Range volcanic complex (Feeley and Grunder 1991) are indicated by filled symbols



**Fig. 4A–F.** Photomicrographs of the main textural types: **A** Early group – fine-grained mafic (basaltic andesite) lava including a large quartz xenocryst with a clinopyroxene corona, and finely mottled plagioclase. Clinopyroxene, olivine, and plagioclase are the groundmass microphenocrysts. **B** Early group – mixed andesite and dacite lava with glass inclusion-rich plagioclase. This textural group is in a continuum with mixed textures of the middle group (**D**). **C** Early group – plagioclase-rich, two-pyroxene andesite lava with little disequilibrium texture. Glomerocrysts are common and may have mottled plagioclase. **D** Middle group – mixed dacite

lava with glass inclusion-rich plagioclase, biotite, and amphibole. Scarce resorbed quartz can be found in outcrop. **E** Middle group – equilibrated biotite-amphibole dacite lava. Feldspars are euhedral or have euhedral overgrowths. **F** Late Group – fine-grained, crystal-poor rhyodacite lava with euhedral, glass inclusion-free plagioclase and sanidine. Glomerocrysts are rare. Light domains in the groundmass are zones of devitrification. Abbreviations: *Q*, quartz; *Pl*, plagioclase; *H*, hornblende; *S*, sanidine; *B*, biotite; *Px*, pyroxene

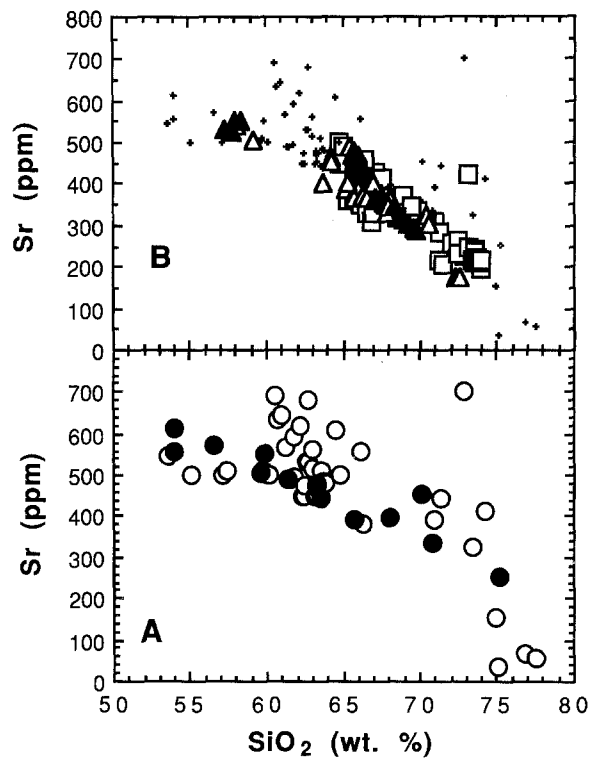


**Fig. 5.** **A** Variation of Rb with Sr for volcanic rocks in eastern Nevada according to group. Rb of sample Tht (in Table 1) of the early group is indicated with an *arrow*. **B** Variation of Rb with Sr of the early group with respect to textural type: *filled circles*, mixed type; *filled inverted triangles*, fine-grained mafic rocks; *open squares*, plagioclase-rich types; *open diamonds*, samples texturally transitional between the mafic and plagioclase-rich type in that they have fewer crystals and more disequilibrium texture in the feldspar. Rhyolites are not plotted. The petrologic mixing trend typified by the rocks of the Egan Range volcanic complex is shown by the line marked *MIX*. Combined assimilation and fractional crystallization trends *AFC<sub>1</sub>* and *AFC<sub>2</sub>* for the fine-grained mafic and plagioclase-rich textural types, respectively, are discussed with respect to isotopic variations (Table 2, Fig. 9)

mafic inclusions, xenocrysts of quartz and amphibole, and complex zoning patterns indicating they were derived by magma mixing between a basaltic andesite and a rhyodacitic crustal component, as exemplified by the rocks of the Egan Range volcanic complex (Feeley and Grunder 1991); (C) plagioclase-rich (15–25%) andesites and dacites containing ortho- and clinopyroxenes as phenocrysts and in glomerocrysts with plagioclase.

The fine-grained mafic rocks are lowest in the section and are intercalated with rhyolites. Andesites of this textural type have elevated Rb and K, and lower Sr compared to rocks of the mixed type (Figs. 5B, 6). The latter exhibit a systematic increase in grain size, abundance of crystals, and abundance of quartz with increasing silica. On a regional basis, the plagioclase-rich, two-pyroxene lavas are at least as voluminous as mixed rocks and, where the stratigraphic relationship is known, overlie the latter. They have lower Rb and K concentrations, and elevated Sr compared to simple mixtures (Figs. 3, 5B).

Rhyolites are volumetrically minor and high-silica rhyolites are restricted to the early group (Fig. 2). Rhyolite lavas are crystal poor, as are pumice and fiamme in the high-silica rhyolite ash-flow tuffs. Many of the rhyolites do not conform to the general chemical trends (Figs. 3, 5).



**Fig. 6A, B.** Variation of Sr with  $\text{SiO}_2$ : **A** in the early group; **B** in the middle and late groups. *Filled symbols* are from the Egan Range volcanic complex. *Small crosses* in B are early group compositions shown for reference. Symbols for early, middle and late groups as in Fig. 5A

Compositions of rocks of the middle group lie chiefly along the mixing trends defined by the early group, but are displaced toward more silicic compositions, indicating greater crustal contamination (Fig. 3; Feeley and Grunder 1991). Middle group samples are hornblende biotite lavas and tuffs and may have textures similar to the mixed type (Fig. 4D) or have largely equilibrated textures (Fig. 4E). The latter textural type is characteristic of samples with greater than 68%  $\text{SiO}_2$  and 200 ppm Rb, and less than 300 ppm Sr. These are transitional in character to late group rocks. Late group rocks are similar in bulk composition to the middle group rocks but are elevated in  $\text{K}_2\text{O}$  and other incompatible elements. Biotite is the principal mafic phase and may be associated with clinopyroxene, amphibole, and(or) orthopyroxene. The rocks are typically more fine grained and crystal poor than middle group rocks and lack disequilibrium textures (Fig. 4F).

These compositional and mineralogic trends have been interpreted to reflect a petrologic evolution from mixing of crust and mantle derived magmas during early stages of the magmatic system, followed by large-scale crustal melting and hybridization of mixed magmas to yield new equilibrium mineral assemblages during the middle stage (Fig. 4D, E; Feeley and Grunder 1991). During the final stages, crystal fractionation dominated, accompanied by lesser crustal assimilation.

## Isotope data

### Analytical methods

Analyses of Nd and Sr isotope (Table 1) were done at the University of Colorado at Boulder. All samples are from lavas or ash-flow tuffs except sample AG-87-45, which is from a partially molten, cordierite granite inclusion in andesite lava AG-87-46. Powdered

Table 1. Nd, Sr, and Pb isotope data for volcanic rocks from eastern Nevada

Sample	SiO <sub>2</sub> wt%	Sm (ppm)	Nd (ppm)	Rb (ppm)	Sr (ppm)	<sup>147</sup> Sm/ <sup>144</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd <sub>(m)</sub>	<sup>143</sup> Nd/ <sup>144</sup> Nd <sub>(t)</sub>	εNd <sub>t</sub>	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr <sub>(m)</sub>	<sup>87</sup> Sr/ <sup>86</sup> Sr <sub>f</sub>	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>204</sup> Pb	<sup>208</sup> Pb/ <sup>204</sup> Pb
<i>Early group</i>															
WP-1 <sup>a</sup>	53.5	5.62	29.8	84	518.8	0.11600	0.512226	0.512199	-7.4	0.46900	0.708610	0.708370	19.609	15.703	39.356
MT-87-49	54.0	7.6	34	81	556										
WP-3 <sup>a</sup>	55.0	7.05	37.7	56.6	482.9	0.11300	0.512071	0.512045	-10.4	0.33900	0.709720	0.709230	19.715	15.754	39.735
AG-88-6	57.1	7.98	44.3	71	503								19.267	15.782	40.153
MT-87-87(c)	59.6	7.1	35	114.4	517.3	0.12273	0.511878	0.511849	-14.8	0.63912	0.711808	0.711481			
HR-2 <sup>a</sup>	59.7	6.36	36.5	70.9	506.4	0.10520	0.511850	0.511820	-16.0	0.40500	0.712820	0.712610			
H-2 <sup>a</sup>	60.7	9.11	48.5	161.9	604.3	0.11310	0.511890	0.511870	-15.0	0.77600	0.711980	0.711580			
AG-87-38(f)	62.6	6.7	36	78	533	0.11260	0.511893	0.511866	-14.5	0.42293	0.713429	0.713207			
MT-87-63(c)	63.2	7.8	42	137.5	457.3	0.11236	0.511822	0.511796	-15.9	0.86896	0.712459	0.712015			
RH-86-6(cf)	64.8	7.3	53	101.5	485.9	0.08333	0.511912	0.511892	-14.2	0.60369	0.713260	0.712943			
AG-87-46(f)	66.4	6.2	37	132	381	0.10138	0.511831	0.511806	-15.7	1.00126	0.714322	0.713782	19.328	15.728	39.751
MT-87-86(c)	68.1	9.0	46	179.2	379.3	0.11837	0.511721	0.511693	-17.9	1.36538	0.713030	0.712332	19.649	15.778	39.990
AG-87-45(i)	72.9	1.7	6	75	700	0.17142	0.511745	0.511702	-17.4	0.30964	0.711189	0.711022	19.736	15.774	39.909
DC-33 <sup>a</sup>	74.9	3.67	18.6	251.8	145.6	0.11910	0.511800	0.511770	-16.9	5.01200	0.717830	0.714740	19.134	15.738	39.872
Th (tuft)	75.0	8.6	18	670	38	0.28906	0.511951	0.511883	-13.4	50.9553	0.722127	<sup>b</sup>			
<i>Middle group</i>															
Tuft of Cooper Summit															
CS3B	69.4	7.2	41	174	343								19.381	15.767	40.115
CP-3	73.2	6.6	48	142	424								19.381	15.767	40.115
Kalamazoo tuft															
4SE14A <sup>a</sup>	67.5	7.34	42.3	157.04	399.6	1.13800	0.511810	0.511780	-16.7	1.04900	0.713750	0.713200			
SK-86-6(cf)	70.4	8.1	45	240.1	271.3	0.10890	0.511736	0.511711	-17.6	2.55764	0.714006	0.712727	19.13	15.749	40.089
KC861B(f)	73.5	7.5	43	238	241	0.10552	0.511684	0.511660	-18.6	2.85402	0.714378	0.712951			
4SW23B <sup>a</sup>	73.9	10.35	65.3	239.06	193.2	0.09600	0.511750	0.511730	-17.7	3.58400	0.714680	0.712950			
NS8B(f)	74.0	7.6	49	236	217	0.09684	0.511699	0.511677	-18.3	3.14304	0.714704	0.713133			
Lavias															
AG-87-35(f)	65.7	9.1	60	195	374	0.10164	0.511640	0.511612	-19.6	1.50682	0.714813	0.714064			
4sc35(f)	65.9	7.4	41	145	416	0.10920	0.511742	0.511717	-17.5	1.00733	0.713806	0.713305	19.066	15.759	40.148
NS-3 <sup>a</sup>	67.0	7.24	41.9	165.6	377	1.04400	0.511820	0.511796	-16.5	1.27200	0.713900	0.713280			
MT-87-43(f)	67.2	8.4	50	175.7	328	0.09176	0.511633	0.511617	-19.5	1.54809	0.713692	0.712922			
AG-87-64(f)	69.9	9.3	56	207	338	0.10047	0.511668	0.511645	-18.9	1.76991	0.714282	0.713402			
<i>Late group</i>															
Lavias															
MT-87-64(c)	58.0	8.4	50	127.2	562.1	0.10164	0.511710	0.511687	-18.1	0.65399	0.713063	0.712747			
AG-87-69(f)	64.2	9.9	49	183	466	0.12223	0.511761	0.511734	-17.1	1.13491	0.711688	0.711140	19.06	15.761	40.121
MT-87-65(c)	69.5	9.3	49	229.7	276.3	0.11483	0.511606	0.511580	-20.1	2.40258	0.715681	0.714521			
AG-87-23(c)	72.6	9.3	55	259.5	172.7	0.10230	0.511643	0.511620	-19.4	4.34253	0.715793	0.713960	19.08	15.783	40.274

Elemental concentrations for MT samples are from Feeley and Grunder (1991). SiO<sub>2</sub> is by XRF analysis at Stanford University, trace elements (by isotope dilution analysis) and isotopic analyses were done at the Massachusetts Institute of Technology. Other SiO<sub>2</sub> data are from Washington State University, Pullman, all SiO<sub>2</sub> data are normalized to 100% anhydrous. Nd ( $\pm 10\%$ ) and Sm ( $\pm 5\%$ ) analyses are by instrumental neutron activation at Oregon State University. Rb and Sr analyses ( $\pm 5\%$ ) are by XRF at Washington State University, except where indicated by the (c) in which case they are isotope dilution analyses from the University of Colorado at Boulder. Isotopic analyses were done at the University of Colorado, Boulder; samples were whole-rock powders except for some feldspar separates (f). (i) = sample AG-87-45, a partially molten granitic inclusion. All other samples are lavas or tufts

<sup>a</sup> Indicates analyses from Gans et al. (1989)

<sup>b</sup> Indicates that no Sr<sub>f</sub> value is reported because of high and uncertain Rb/Sr

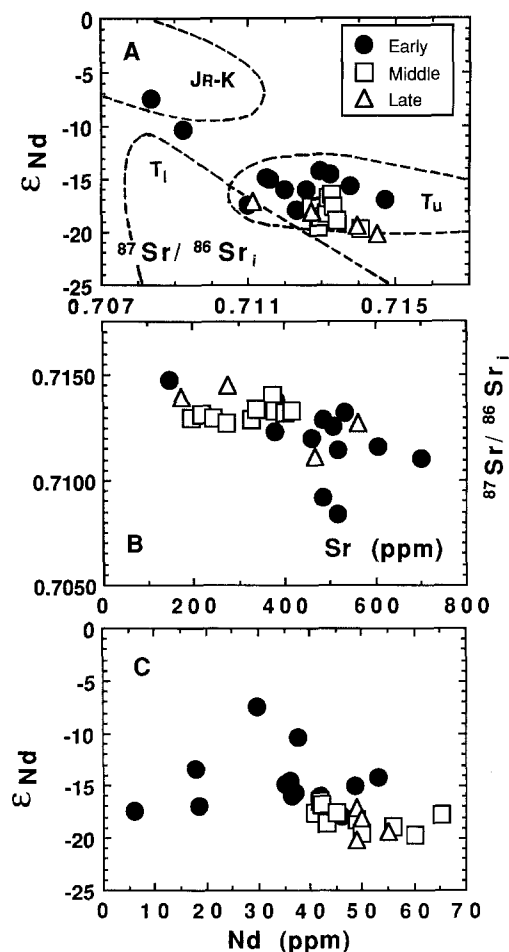


Fig. 7A–C. Sr and Nd isotopic variations of the volcanic rocks: A with respect to each other; B with respect to concentrations of Sr; C with respect to concentrations of Nd. The fields of the Jurassic to Cretaceous, *Jr-K*, granitoids and of Tertiary granitoids, *T<sub>u</sub>*, upper Tertiary, *T<sub>i</sub>*, lower Tertiary, are taken from Wright and Wooden (1991)

whole rock or feldspar separates were washed in dilute hydrochloric acid to remove any carbonate contamination. The samples were then dissolved in HF and HClO<sub>3</sub> in open containers; residues from the dissolution were dissolved in heated HF and HNO<sub>3</sub> in sealed teflon containers. Standard cation exchange techniques were used to separate Rb and Sr. The Nd and Sm were separated using high performance liquid chromatography. The rare earth element separate was injected into a silica glass column containing Bio-Rad Aminex cation exchange resin and was eluted with 0.32 N methacetic acid. The Sm and Nd separates were then cleaned by electro-deposition onto Pt cathodes from 0.002 N HCl solutions.

Concentrations of Rb, Sr, Nd, and Sm were measured by X-ray fluorescence or instrumental neutron activation analysis, as indicated in Table 1. Some samples were analyzed by isotope dilution at the University of Colorado at Boulder. Analytical precision on isotope dilution is estimated at 0.5%. Analyses of standards (AGV-1 andesite and CIT mixed Sm/Nd normal) yielded concentrations within 1% of accepted values. Average total procedural blanks for Rb, Sr, Sm, and Nd were 2 ng, 700 pg, 20 pg, and 500 pg, respectively.

The Sr and Nd isotopic analyses were performed on a Finnigan-MAT 6-collector solid source mass spectrometer. The Sr isotope analyses were done in 4-collector static mode; Nd isotope analyses were done in triple collector dynamic mode for which the external reproducibility is 0.25  $\epsilon_{Nd}$  units based on replicate analyses. Replicate analyses of standard SRM-987 yielded  $^{87}Sr/^{86}Sr$

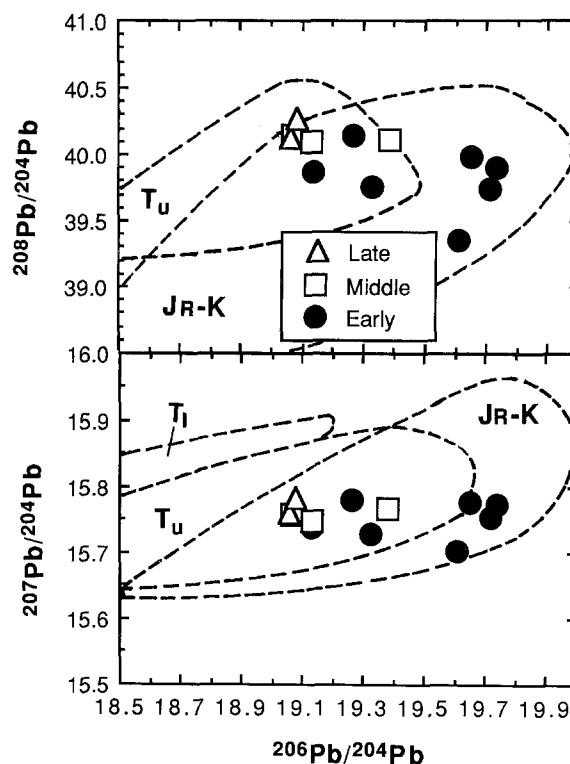


Fig. 8. Pb isotope variations. The boundaries of the fields of Jurassic and early Cretaceous, *Jr-K*, and Tertiary granitoids, *T<sub>u</sub>*, are from Wright and Wooden (1991)

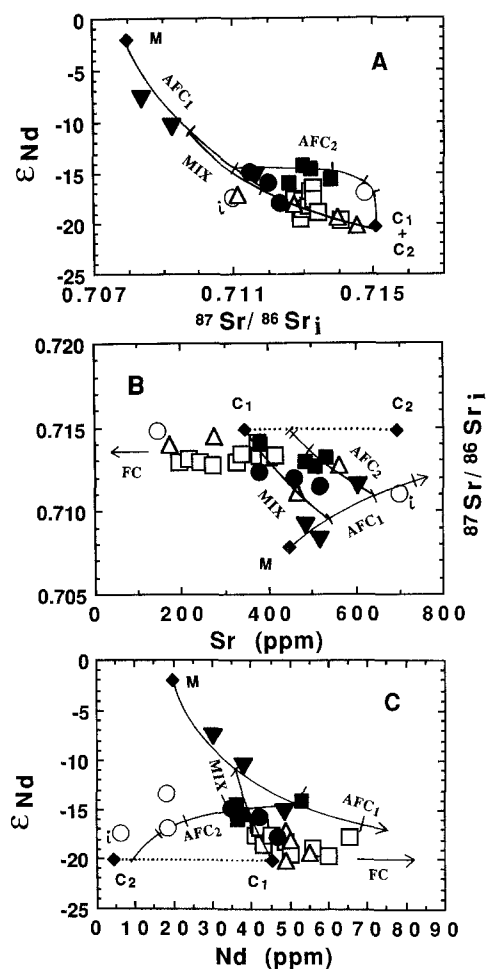
$^{86}Sr$  of  $0.71025 \pm 2(2\sigma)$  and replicate analyses of the La Jolla Nd standard yielded a mean  $^{143}Nd/^{144}Nd$  of  $0.511840 \pm 3(2\sigma)$ . Initial isotopic ratios were calculated using K–Ar and  $^{40}Ar-^{39}Ar$  ages of Gans et al. (1989) where possible. For undated samples, an age of 36 Ma was used for the early group and 35 Ma for the middle and late groups.

Analyses of Pb isotopes were done by J.E. Wright on whole-rock powders by standard HBr–HCl anion chemistry at the U.S. Geological Survey laboratories of J.L. Wooden. The Pb isotopic compositions are corrected for a mass fraction of 0.11% per a.m.u.

## Results

The principal trend of the isotopic data is a change from a wide range of values in the early group to more restricted values in the middle and late groups (Figs. 7, 8), paralleling the change from diverse to more restricted bulk compositions in time. On the whole, initial  $^{87}Sr/^{86}Sr$  ratios correlate negatively with Sr concentration and with initial  $\epsilon_{Nd}$ , and positively with increasing SiO<sub>2</sub> (cf., Fig. 6). The high proportions of radiogenic Sr and Pb and low  $\epsilon_{Nd}$  values, particularly in the rocks of intermediate to silicic composition, indicate a large continental crustal contribution to magmatism.

Based on textural and petrologic distinctions, the isotopic trends of the early group can be subdivided into three: (1) the fine-grained mafic type, which includes the least isotopically evolved samples; (2) rocks of the mixed type, which trend to increasing  $^{87}Sr/^{86}Sr$  with more negative  $\epsilon_{Nd}$ ; and (3) the plagioclase-rich type,



**Fig. 9** A–C. Isotopic and elemental variations with respect to calculated petrologic models discussed in the text and outlined in Table 2. Calculations are according to combined assimilation and fractional crystallization equations of DePaolo (1981). Middle and late group rocks are represented by *open squares* and *triangles*, respectively. Samples of the early group are plotted according to textural type: *inverted triangles*, fine-grained mafic lavas; *filled squares*, plagioclase-rich type; *filled circles*, mixed type; and *open circles*, rhyolites and a granitic inclusion, subscript “i”. C<sub>1</sub> and C<sub>2</sub> indicate the composition of the crustal contaminants, *filled diamonds*; they are connected by a *dotted line* along which lies the composition of the bulk crust if C<sub>1</sub> and C<sub>2</sub> are partial crustal melt and residue, respectively. M indicates the parental mafic magma. FC marks the trend for fractional crystallization for an assemblage where Sr is compatible and Nd is incompatible (i.e., late stage differentiation). Tic marks on the AFC<sub>1</sub> and AFC<sub>2</sub> trends are indicated at increments of 0.9, 0.8, and 0.7 F (mass ratio of magma to magma initial). On A the trends of AFC<sub>1</sub> and Mix largely overlap; their difference has been exaggerated for clarity

which exhibits a sharper increase in  $^{87}Sr/^{86}Sr$  relative to  $\epsilon_{Nd}$  than the other two textural types (Fig. 9).

## Discussion

### The early group

The early group is the most diverse and records the early stages of development of the magma system. Therefore,

**Table 2.** Model parameters

Model	r	Nd				D
		C <sub>O</sub>	C <sub>A</sub>	$\epsilon_{Nd_0}$	$\epsilon_{Nd_A}$	
AFC <sub>1</sub>	0.8	20	45	-2.0	-20	0.4
Mix	-	36	45	-11.0	-20	-
AFC <sub>2</sub>	0.9	52	5	-14.5	-20	0.6

Model	r	Sr				D
		C <sub>O</sub>	C <sub>A</sub>	$^{87}Sr/^{86}Sr_0$	$^{87}Sr/^{86}Sr_A$	
AFC <sub>1</sub>	0.8	450	350	0.7080	0.715	0.4
Mix	-	545	350	0.7098	0.715	-
AFC <sub>2</sub>	0.9	640	700	0.7111	0.715	1.5

r, the ratio of the rates of assimilation to crystallization; C<sub>O</sub> and C<sub>A</sub>, concentrations (ppm) of the original magma and the assimilant respectively; D, bulk distribution coefficient. Models “Mix” and “AFC<sub>2</sub>” start at 0.9 and 0.8 values of F, where F is the mass ratio of magma to original magma

of the three groups it is treated in most detail. The Nd and Sr isotopic compositions of the three mineralogical and compositional types in the early group are modeled as three stages of petrologic evolution requiring a mafic parent and at least two crustal contaminants (Table 2). The mafic parent is chosen to be slightly more primitive than the mafic lava with least radiogenic Sr and most radiogenic Nd. No attempt is made to identify a specific mantle isotopic source because even the most mafic lavas are contaminated, containing xenocrysts and xenoliths of crustal material.

The isotopic composition of the crust can be constrained by the composition of crustal xenoliths and by the composition of volcanic rocks that are crustal melts or strongly contaminated by the crust, based on petrologic grounds. The rhyolites and one sample of partially molten cordierite granite (AG-87-45), found as an inclusion in an early lava (plagioclase-rich type) vary widely and nonsystematically with respect to trace element concentrations and isotopic composition. Many contain trace phases, such as allanite and garnet, that strongly affect the compatibility of Nd. These samples are important inasmuch as they are potential probes of the isotopic heterogeneity of the crust. However, except for sample DC-33 they do not represent samples on the same liquid lines of descent as the rest of the suite, from which they are separated by a compositional gap (Fig. 3). It is important to consider separately the high-silica compositions, which may represent local environments of extreme differentiation, and the dominant volume of silicic rocks, namely the dacites to rhyolites of the middle and late groups (Table 2; Fig. 9), which represent large-scale crustal magmatism.

Regardless of whether one or several crustal isotopic reservoirs are invoked, the relatively rapid increase in  $^{87}Sr/^{86}Sr$  relative to  $\epsilon_{Nd}$  for the plagioclase-rich textural type (AFC<sub>2</sub> in Fig. 9A), requires a crustal contaminant rich in Sr to counteract the compatible behavior of Sr.



The parameters and results of the calculations to model the early group rocks are laid out in Table 2 and Fig. 9. The models are chosen to be consistent with petrologic and textural information indicating simple mixing for part of the suite and combined assimilation and crystal fractionation (AFC) for the rest. Fractionation is required to account for lower compatible element concentrations (e.g., Ni, Cr, Sc) than can be modeled by mixing alone (Feeley and Grunder 1991).

Given the choice of mafic parent and the constraints on the petrologic processes, then all the Nd and Sr isotopic trends can be reconciled with contamination by two crustal contaminants: one with high Nd and low Sr concentrations and the other with the opposite elemental signature, but *identical* isotopic composition. As discussed below, partial melting of the crust will produce two compositional reservoirs of this type provided Nd is incompatible and Sr compatible (plagioclase in the residue).

The internal consistency of this model is tested in Fig. 9. The calculations have limited sensitivity to the concentration of the contaminant because of uncertainties in the distribution coefficients, the rate of assimilation, and the isotopic composition of the endmembers. However, by searching for solutions that account for processes, rather than invoking a multitude of isotopic endmembers, a limited number of possibilities result. The most important constraints are that some samples must be accounted for by simple mixing, while the plagioclase-rich ones require large rates of assimilation to maintain high Sr concentrations (Fig. 5).

The distribution coefficient for Sr is dominated by plagioclase, which has Sr concentrations 1.5 to 4 times as great as intermediate composition melts (Ewart et al. 1973; Philpotts and Schnetzler 1970; Schnetzler and Philpotts 1970). Models were tested with bulk distribution coefficients between 0.2 to 0.6 for plagioclase-poor assemblages and between 1.5 and 2.5 for plagioclase-dominated assemblages (plagioclase is 80–90% of the mineral assemblage). The compatible behavior of Sr for the plagioclase-rich textural group is supported by the slight decrease in Sr with differentiation (Figs. 5, 6).

The bulk distribution coefficient for Nd is governed mainly by clinopyroxene in the absence of accessory phases, for which partition coefficients typically range from 0.1 to 0.5 (Arth 1976; Gallahan and Nielsen 1992); values between 0.2 and 0.6 were tested. Keeping these uncertainties in mind, the preferred Nd and Sr composition of the crustal contaminants are in Table 2, but for contaminant 1 values between 40 to 45 ppm Nd and 300–400 ppm Sr give satisfactory internally consistent solutions. For contaminant 2 (Nd = 5, Sr = 700 ppm), Nd concentrations as great as 10 ppm and Sr values as low as 600 ppm yield satisfactory results. Models with values outside these limits yield irreconcilable differences in the values of  $F(\text{mass}_{\text{magma}}/\text{mass}_{\text{magma original}})$  between the two isotopic systems. With respect to maintaining comparable values of  $F$ , the models are most sensitive to changes in the rate ratio of assimilation to crystallization ( $r$ ); AFC<sub>1</sub> requires  $r$  values greater than 0.5 and AFC<sub>2</sub> requires values greater than 0.8. No models with  $r$  greater

than 1 were considered because the heat available for assimilation is unlikely to be greater than that available from crystallization of mafic parental magma.

The fine-grained, mafic rocks are modeled to result from high rates of assimilation of partial melt of the crust (crustal contaminant 1) with modest crystal fractionation (10–20%), as represented by trend AFC<sub>1</sub> (Fig. 9). With respect to these mafic compositions, Sr and Nd are both incompatible (Table 2). Lesser rates of assimilation require larger distribution coefficients to fit the data. Model AFC<sub>1</sub> is selected because it provides reasonable fits with respect to isotopic *and* elemental abundances. However, the paucity of mafic lavas and their wide range in incompatible trace element compositions, such as Rb (Fig. 5), make it difficult to reconstruct the contamination history. Although their compositions are consistent with high rates of assimilation of contaminant 1, assimilation of other contaminants is probable, as reflected in the isotopic diversity of rhyolites that are intercalated with mafic magmas low in the section (Table 1).

The mixed samples are modeled as simple mixing between crustal contaminant 1 (Fig. 9, Table 2) and a mafic magma at 10% crystallization along the mafic differentiation trend (AFC<sub>1</sub>). The mafic parent was selected to be consistent with the argument of Feeley and Grunder (1991) that the bulk of the early group rocks are sub-equal mixtures of a mafic and a crustal component.

The AFC<sub>2</sub> trend that describes the plagioclase-rich samples requires a Sr-rich and Nd-poor contaminant in order to reconcile decreasing Sr and Nd concentrations and strong increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  with respect to  $\epsilon_{\text{Nd}}$ , bearing in mind that Sr is compatible and Nd is not. Substantial changes in the distribution coefficients (i.e.,  $D_{\text{Sr}} = 1.5\text{--}2$ ,  $D_{\text{Nd}} = 0.3\text{--}0.6$ ), and modest changes in the isotopic composition of the contaminant (i.e., by one  $\epsilon$  unit or  $\pm 0.001$  Sr<sub>i</sub> units) barely affect the rate of assimilation that is required; it is always greater than 0.8, and a low-Nd and high-Sr contaminant remains necessary.

Alternatively, the plagioclase-rich rocks can be interpreted to be contaminated by an isotopic reservoir in the crust with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  ( $>0.75$ ) to explain the subhorizontal trend of the plagioclase-rich lavas in Fig. 9A. Although variable isotopic reservoirs might be invoked for different parts of the evolutionary path, it is not necessary to do so.

### *The middle and late groups*

The range of isotopic ratios is more restricted in the middle and late groups, but bears out the general trend of decreasing  $\epsilon_{\text{Nd}}$  with increasing  $^{87}\text{Sr}/^{86}\text{Sr}$  (Fig. 9A). The middle group samples lie in part on the mixing trend defined by the early group, consistent with textural similarities and petrologic inferences summarized above. The remaining middle group samples and most of the late samples lie along a fractionation dominated trend, also consistent with the low values of  $r$  (0.2–0.3), inferred by Grunder and Feeley (1991). A variety of AFC models were tested for the middle and late group rocks. Choos-



ing a relatively low value of  $r$  (0.2–0.3) crustal contaminant 1 provides a more satisfactory solution than contaminant 2. Because of the lower rate of assimilation, models are not very sensitive to the composition of the assimilant. Uncertainties in the modeling are aggravated by clustering of the data and difficulties in estimating the bulk partition coefficient for Nd, because allanite, zircon, sphene, and amphibole are increasingly important in the middle and late groups. However, models for the middle and late group, using the most mafic sample within each as parent, always yield rates of assimilation less than 0.4. The andesite of the late group is texturally akin to the fine-grained mafic rocks of the early group and its composition is consistent with an origin along a path similar to  $AFC_1$ .

### The crustal contaminants

With respect to elemental concentrations, at least two crustal sources are necessary, one low in Nd and high in Sr and one high in Nd and low in Sr. A single crustal source can yield such compositionally distinct contami-

nants if it is partially molten and plagioclase, the most likely phase to retain Sr in the crust, is residual and if Nd is incompatible. The melt thus produced will be depleted in Sr and enriched in Nd relative to the residue or the bulk crust.

Based on compositional and textural evidence, Feeley and Grunder (1991) concluded that the silicic mix end-member in the early group was rhyodacitic. Bulk compositions that are reasonably close to the composition of the crustal contaminant can be produced by as little as 10 to 20 percent to as much as 40 or 50 percent melting of pelite (Vielzeuf and Holloway 1988; Patiño Douce and Johnston 1991) (Fig. 10). Pelitic metasedimentary rocks occur in the Precambrian McCoy Creek Group which crops out in structurally deep exposures in eastern Nevada and is greater than 2.7 km thick. Where exposed in the metamorphic core complexes of the Snake Range and of the Ruby Mountains (approximately 100 km to the north) it is migmatic (Miller et al. 1988; Wickham and Peters 1990). The oldest dates for the unit in the area are about 1,200 Ma (three K–Ar dates of detrital muscovite; Lee et al. 1980), but the base is not exposed.

Deep-seated granitoid rocks might also provide suitable crustal contaminants. It makes little difference whether the source is a pelite or a granitoid or, perhaps the most likely, both, as long as the lithology is fertile with respect to producing contaminant 1 and substantial plagioclase is residual.

With respect to major element modeling, the  $AFC_1$  and mixing trends are consistent with modest degrees of melting of pelite; calculated linear regression fits for the major element data are best with a 25 to 35 percent melt of pelite (Fig. 10). For differentiation trend  $AFC_2$ , assimilation of the residue of the crustal melt yields somewhat better calculated results than assimilation of bulk crust, although the sum of residuals squared is always at least one even for the best models. Proportions of fractionation relative to assimilation are consistent with the high rates calculated based on isotopic data, namely close to but less than one. Although the scatter of data not on the mixing line in Fig. 10 is in the direction of bulk pelite, it must be borne in mind that fractionation of a plagioclase-rich assemblage simultaneously decreases  $Al_2O_3$  and increases  $K_2O$ , so that for  $AFC_2$  a contaminant enriched in  $Al_2O_3$  and depleted in  $K_2O$  is necessary.

These results must be considered with some caution because the experiments of Vielzeuf and Holloway (1988) were for pressures between 700 and 1,200 MPa, above the stability of cordierite, which occurs in one of the inclusions. Also, although the composition of the small degrees of melting is not affected strongly by the starting composition of the pelite, the composition of residue varies substantially (cf., Vielzeuf and Holloway 1988; and Patiño Douce and Johnston 1991). The pelite used by Patiño Douce and Johnston (1991) yields a restite too aluminous and too mafic to represent contaminant 2. Considering general major element variations and the high Sr, but low Rb concentrations of samples along  $AFC_2$  (Fig. 5), it is more likely that contaminant 2 is

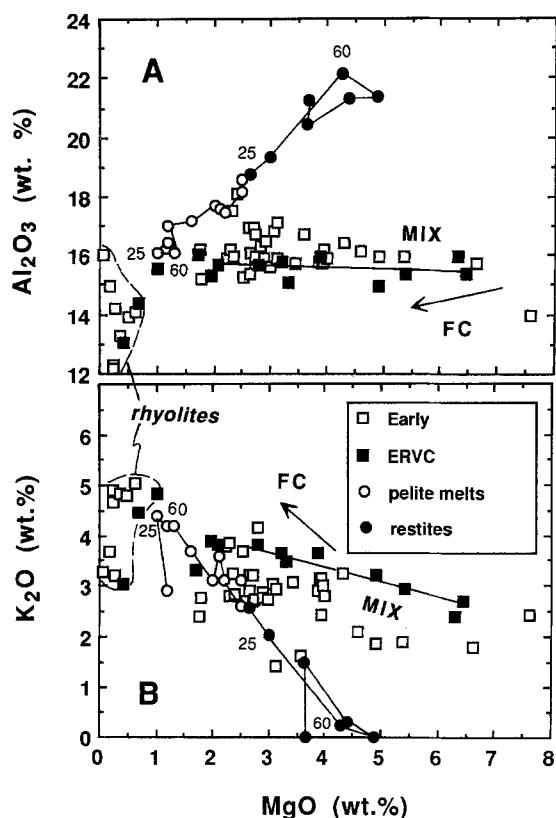


Fig. 10A, B.  $K_2O$  and  $Al_2O_3$  variations with  $MgO$  for the volcanic rocks according to group. Samples from the Egan Range volcanic complex ERVC are represented by filled symbols and, excepting rhyolites, represent the mixing trend, MIX. FC indicates the general direction of change with fractional crystallization. The composition of partial melt of a pelite and the residue are indicated by the lines along which the small symbols represent successive increments of partial melting at the intervals of 10, 25, 60, 65, 68, 70, and 75 percent melt, calculated from the data of Vielzeuf and Holloway (1988)

the residue of a partial melting event that gave rise to contaminant 1, or perhaps a second increment of melting in which plagioclase is no longer residual, rather than bulk crust. The modest increase of K and Rb with differentiation (cf., Figs. 3, 5) is the best evidence that an incompatible-element-depleted contaminant participated in AFC<sub>2</sub>. Fractionation rapidly enriches these elements. Only high rates of assimilation of an incompatible-element-poor contaminant effectively can dilute enrichment caused by fractionation.

### *Multiple contaminants model*

A conventional multiple source model can be considered to explain the fork of the isotopic trends of the early group into high and low  $\epsilon_{\text{Nd}}$  branches (AFC<sub>2</sub> and Mix, respectively, Fig. 9) instead of the two-stage single source model discussed above. The  $\epsilon_{\text{Nd}}$  branch could be attributed to contamination with a source rich in radiogenic Nd and Sr versus contamination with a source depleted in radiogenic Nd for most of the volcanic rocks (Grunder and Feeley 1989). The isotopic heterogeneity of rhyolites in the area implies the existence of a variety of crustal contaminants. The principal argument against multiple sources is the timing of volcanism. Rocks of the high  $\epsilon_{\text{Nd}}$  trend are over- and underlain by rocks contaminated along the low  $\epsilon_{\text{Nd}}$  trend (mixed and middle group rocks respectively) and all were erupted in short succession. Furthermore, limited geobarometric data from a cordierite granitoid in the plagioclase-rich suite and from rhyolites in the middle and late groups indicate midcrustal equilibration pressures (about 340–400 MPa, Grunder and Wickham 1991). A different, deeper crustal contaminant is not precluded for the most mafic rocks, as proposed by Gans et al. (1989).

### *Other source considerations*

Isotopic compositions of the intermediate to silicic rocks overlap the field for Mesozoic and Tertiary “miogeoclinal” granitoids of the northern Great Basin defined by Farmer and DePaolo (1983) and lie within the “upper array” of Cenozoic intrusions in the compiled data of Wright and Wooden (1991) (Fig. 8). The upper array includes granitoids from the study area and is interpreted by Wright and Wooden (1991) to reflect predominantly Proterozoic “undepleted” basement. Model ages of the samples with greater than 68 wt% SiO<sub>2</sub> (that is, compositions that are more nearly entirely crustal) cluster near 1.8 Ga, but range from 1.6 to 2.2 Ga. There is no systematic difference between the three groups. The model ages are consistent with an early Proterozoic crustal province in the area as inferred by Farmer and DePaolo (1983) and Wright and Wooden (1991).

### **Conclusions**

1. Only a single, middle crustal isotopic reservoir is necessary to explain the isotopic and elemental trends in

Nd and Sr of the dominant volume of the volcanic rocks. The separation of the crust into elementally distinct but isotopically identical contaminants by partial melting produces isotopic trends that simulate contamination with multiple reservoirs.

2. The earliest stage of contamination was with partial melts of the crust, by simple mixing and by assimilation accompanied by crystal fractionation. This was followed by combined assimilation and fractionation with high rates of assimilation of the residue of the partial melting event. The net effect is bulk assimilation but it occurs in two distinct steps. Late stages of magmatism were dominated by crystal fractionation.

3. The crustal contribution to magma composition in eastern Nevada increased with time, as indicated by generally increasing radiogenic Sr and Pb isotope ratios and decreasing  $\epsilon_{\text{Nd}}$  of the suite and by clustering of isotopic data for the middle and the late group rocks. Because of the large volumes of erupted material (1000s of km<sup>3</sup>), the crustal influence represents large-scale recycling of the continental crust.

4. The crustal source for the principal contaminants was probably pelitic and part of an early Proterozoic crustal province.

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