relation between terrestrial C and atmospheric CO_2. Assessment of modern terrestrial inventories alone will not provide sufficient information to predict potential future sinks and sources for atmospheric CO_2. One must also base such predictions on time-series data and process studies to determine the effects of landscape alterations, including those caused by human activities (*2*).

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Evidence from the Lamarck Granodiorite for Rapid Late Cretaceous Crust Formation in California

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Strontium and neodymium isotopic data for rocks from the voluminous 90-million-year-old Lamarck intrusive suite in the Sierra Nevada batholith, California, show little variation across a compositional range from gabbro to granite. Data for three different gabbro intrusions within the suite are identical within analytical error and are consistent with derivation from an enriched mantle source. Recognition of local involvement of enriched mantle during generation of the Sierran batholith modifies estimates of crustal growth rates in the United States. These data indicate that parts of the Sierra Nevada batholith may consist almost entirely of juvenile crust added during Cretaceous magmatism.

Present models for the origin of the Sierra Nevada batholith developed from the strontium isotope studies of Kistler and Peterman (*1*) and indicate that the isotope systematics of the batholith can be reproduced through mixing between depleted mantle and Proterozoic upper crust (*2–5*), or by mixing of crustally contaminated mafic magmas and siliceous melts of Proterozoic lower crust (*6*). These models assume that the regular east/west change in the isotopic composition of granitic rocks in the batholith reflects an eastward increase in the contribution of old continental crust. In particular, the $^{87}Sr/^{86}Sr = 0.706$ isopleth (*1*), or the $^{87}Sr/^{86}Sr = 0.708$, $\varepsilon_{Nd} = -7$ isopleths (*3, 7*), commonly are interpreted to reveal the approximate western limit of the continental crust under the United States. DePaolo *et al.* (*8*) reached similar conclusions regarding the origin of the batholith using Nd model ages for granitic rocks.

All of these models assume a depleted composition for the mantle end member. However, isotope studies in the Basin and Range province of the western United States suggest that parts of eastern California, Nevada, and Utah were underlain by enriched lithospheric mantle during Cenozoic (*9–13*) and Mesozoic (*14*) magmatism. Limited data from mantle xenoliths and alkalic lavas also suggest the presence of an enriched mantle component as far west as the central Sierra Nevada [Fig. 1 (*15, 16*)]. If an enriched mantle was involved in Sierra Nevada batholith formation, estimates of crust for-

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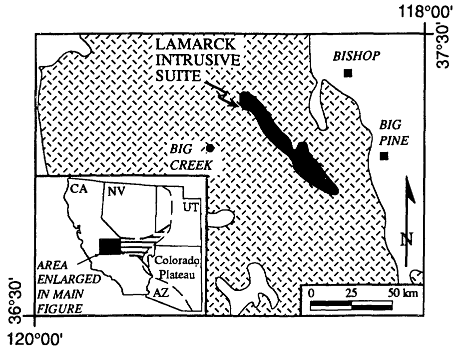

Fig. 1. Location of the Lamarck intrusive suite. Inset shows location of main figure. Ruled area on inset outlines the approximate limit of the area characterized by Cenozoic igneous rocks with enriched Sr isotopic compositions [modified from the Sierran Province of Menzies *et al.* (*11*)]. Patterned area on the main figure is the outline of the Sierra Nevada batholith.

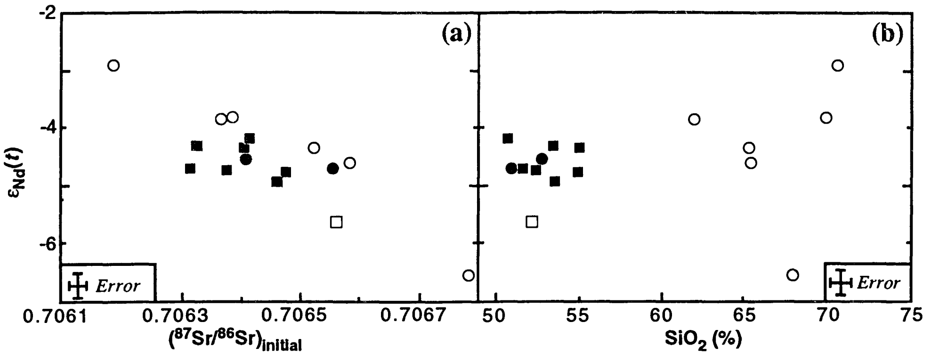

Fig. 2. (**a**) Initial Nd versus Sr for the Lamarck intrusive suite. The isotopic compositions of the mafic rocks are interpreted to be representative of their mantle source whereas the granodiorites are interpreted to reflect derivation from the mafic rocks with variable and apparently minor contamination by older crustal rocks. (**b**) Nd versus silica concentration. The gabbros and diorites show a tight cluster of Nd isotopic compositions despite a variation of almost 5% SiO_2 by weight. With the exception of one sample, the rocks show a weak positive relation between Nd isotopic composition and SiO_2 concentration. This trend is opposite that predicted by simple mixing of depleted mantle and Proterozoic crust. Solid squares, gabbros and diorites; open circles, granodiorites and granites; solid circles, hybrid inclusions; open squares, cumulus schliere. Error bars are discussed in (*17*).

mation rates during Mesozoic arc magmatism in the western United States could increase significantly over earlier estimates (8) because the isotopic composition of enriched mantle (EM) may be variable and significantly different from that of depleted mantle (DM) [for example, ε_{Nd}(EM) 0 to −11 (*11, 12*); ε_{Nd}(DM) +8.5 (8)]. No isotopic data have been available for mafic plutonic rocks from the eastern Sierra Nevada batholith to test this possibility.

Here we report Sr and Nd isotope data (*17*) from the voluminous, compositionally heterogeneous, 90-million-year-old Lamarck intrusive suite in the central Sierra Nevada batholith (Fig. 1). The Lamarck lies at the western limit of the Sierran enriched mantle province of Menzies *et al.* (*11*), between the Cenozoic Big Pine volcanic field, which contains lavas with an enriched mantle signature (9), and the Big Creek pipe, where Domenick *et al.* (*16*) collected a mantle xenolith with enriched mantle characteristics. This area also lies in a gap in the existing Nd data base for the Sierra Nevada batholith between 36°30′ and 37°00′N latitude. Field relations and geochemistry of the Lamarck intrusive suite were reported by Frost (*18*) and Frost and Mahood (*19*), who concluded that much of the chemical variation among rocks with silica contents between 49 and 64% by weight could be explained by mixing between mafic and felsic end members coupled with concomitant fractional crystallization of both end-member magmas.

Field, petrographic, and chemical data indicate that many mafic schlieren in the Lamarck suite represent cognate accumulations of mafic minerals from the host granodiorite magma similar to those described elsewhere in the Sierra Nevada batholith (*20*). However, the gabbro and diorite intrusions and inclusions in the suite are not cumulates, but were intruded as magmas that interacted with the felsic magmas of the Lamarck (*19*). Only one sample (76c) that we analyzed is considered to be a cumulate on the basis of field and petrographic data, and it is clearly chemically distinct from those samples considered to represent magmatic or hybrid compositions [(*18, 19*) Table 1].

Isotope data for rocks from the Lamarck intrusive suite show little variation despite a wide variation in bulk chemistry, and variation among the mafic rocks is considerably smaller even though analyses were obtained from four different intrusions separated by a total distance of 40 km (Table 1 and Fig. 2). The variation among samples probably reflects open-system interaction of silicic magmas with their wall rocks. Interestingly, there is a general trend (with the exception of one sample) toward decreasing $^{87}Sr/^{86}Sr$ ratio and increasing ε_{Nd} with increasing silica (Fig. 2).

Table 1. Sr and Nd isotopic compositions of rocks from the Lamarck intrusive suite. Sample names, unit designations and oxide concentrations are from Frost (*18*) and Frost and Mahood (*19*). Trace element concentrations were determined by isotope dilution techniques except for starred (*) samples which have Rb and Sr data from Frost (*18*). Analytical procedures are described in (*17*).

Sample	Unit	SiO_2 (%)	MgO (%)	K_2O (%)	Rb (ppm)	Sr (ppm)	$(^{87}Sr/^{86}Sr)_I$	Sm (ppm)	Nd (ppm)	$\varepsilon_{Nd}(t)$
80fG	Mount Gilbert gabbro	50.67	5.69	1.75	66.30	735.98	0.70641	4.98	25.75	−4.20
20b*	Mafic inclusion in 20a	50.97	4.66	2.36	190	400	0.70656	5.36	25.17	−4.70
80c*	Mount Gilbert gabbro	51.63	5.51	1.63	48	850	0.70631	4.66	21.70	−4.72
6c	Mafic inclusion in 6a	52.15	4.87	2.13	110.35	756.71	0.70656	5.89	29.99	−5.63
SAB-1b	Lake Sabrina diorite	52.45	4.68	2.00	100.13	712.04	0.70638	6.79	37.71	−4.75
76c	Schliere in 76a	52.78	7.19	2.35	109.43	251.25	0.70641	17.30	86.68	−4.54
87a	Piute Creek diorite	53.39	5.38	1.93	101.86	582.33	0.70633	4.01	20.27	−4.33
UB-1b*	Upper Basin gabbro	53.55	4.73	1.73	74	630	0.70646	4.13	18.57	−4.94
UB-5	Upper Basin gabbro	54.94	3.12	2.03	55.17	847.46	0.70648	5.20	26.72	−4.79
83c	Mount Gilbert diorite	55.03	3.66	1.96	76.53	809.13	0.70640	7.70	40.64	−4.34
80fL	Lamarck granodiorite	61.99	2.86	1.58	65.17	698.80	0.70636	5.47	32.68	−3.87
76a	Lamarck granodiorite	65.34	2.23	3.70	114.25	466.81	0.70652	4.03	21.37	−4.35
20a*	Lamarck granodiorite	65.39	2.01	3.47	130	445	0.70658	3.67	18.78	−4.62
15a	Lamarck granodiorite	67.95	1.54	3.82	141.45	463.26	0.70679	3.28	19.87	−6.55
6a	Lamarck granodiorite	69.82	1.11	4.50	130.48	379.66	0.70639	3.26	19.98	−3.84
UB-1a	Lamarck granodiorite	70.53	0.91	3.55	102.81	391.05	0.70619	4.08	24.09	−2.91

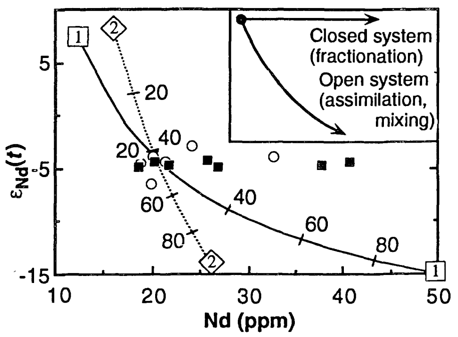

Fig. 3. Nd isotopic composition versus Nd concentration for mafic and felsic rocks of the Lamarck intrusive suite, with representative mixing models. Data symbols are the same as in Fig. 2. We consider that a mixing origin for the trend of the data is unlikely (see text for discussion). Inset shows trends generated by open and closed system effects on the main diagram. Labeled increments along model curves show weight percent crustal component in the mixture. Model 1 uses the arc tholeiite mantle source of Hill *et al.* (*4*) mixed with a crust with $\varepsilon_{Nd} = -15$ and 50 ppm Nd. The concentration of Nd chosen for this contaminant is unusually high, but an extreme value was used in order to minimize the amount of crustal component necessary to generate the gabbros (~20%). Model 2 uses the mantle and crustal parameters of DePaolo *et al.* (*8*) and requires approximately 40% recycled crustal materials in the rocks.

These trends are opposite those predicted by mixing between depleted mantle and Proterozoic crust.

The simplest interpretation of these data is that the isotopic compositions of the mafic rocks reflect the composition of their mantle source, a source that is similar in isotope and trace-element characteristics to that inferred for nearby Cenozoic basalts and xenoliths (*9, 15, 16*). If this is correct, then the more silicic members of the Lamarck series could be produced by commonly invoked petrologic processes [for example, coupled assimilation-fractional crystallization, or partial melting of the mafic members of the series (*13, 21*)]. The lack of a significant ancient crustal component in the Lamarck implied by this interpretation is supported by the apparent lack of inherited zircons in the granodiorite (*22*).

Alternatively, isotope data for the mafic rocks could be explained by cryptic contamination (*23*) of mafic magma derived from depleted mantle. Figure 3 shows two possible mixing scenarios, in which depleted mantle magmas are contaminated by mafic gneisses with variable Nd concentrations and isotope ratios. In either scenario, mixing of depleted mantle magma with 20 to 40% contaminant by weight, followed by closed system fractional crystallization, could reproduce the Nd concentration and isotope ratio data.

We view such an origin for the Lamarck suite as plausible but unlikely for the following reasons. First, for this model to explain the entire data set, a huge volume of mafic magma (enough to generate all of the rocks in the Lamarck intrusive suite) must be emplaced into the crust and experience significant and uniform contamination by a component with a very negative ε_{Nd} (*24*). The magma must then undergo almost no further crustal contamination; formation of the silicic end of the series would have to occur by closed system fractional crystallization alone (unless the contaminant fortuitously had isotopic compositions identical to those of the contaminated mafic magma). Second, for the fractional crystallization model to work requires that $D^{Nd} << 1$ in order to form the Nd-enriched mafic to intermediate magmas, followed by further closed system differentiation with $D^{Nd} \geq 1$ to form the lower Nd silicic members of the suite (*25*). This scenario is plausible but fails to account for other geochemical variations; in particular, in the gabbros and diorites, Nd concentration varies by a factor of 2, but the concentration of K_2O, which would have $D << 1$ during fractional crystallization, is essentially constant in these rocks (Table 1). Furthermore, as discussed above, field and petrographic data argue against a cumulus origin for the mafic intrusions (*19*).

If the Lamarck suite was derived from an enriched mantle with $\varepsilon_{Nd} \approx -4.5$ and an $^{87}Sr/^{86}Sr$ ratio of 0.7064, then the amount of juvenile material it represents may approach 100%. This possibility could locally double estimates of the amount of new crust generated during Mesozoic magmatism over earlier estimates (*8*). If further studies support widespread involvement of enriched mantle in generation of the Sierra Nevada batholith, then the Mesozoic (in particular, the Late Cretaceous) may have been a time of exceedingly rapid crust formation in the western United States.

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