Trace Element Evidence for Hydrous Metasomatism at the Base of the North American Lithosphere and Possible Association with Laramide Low-Angle Subduction

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ABSTRACT

Trace element signatures of mantle xenoliths along an east-west transect extending from the Sierra Nevada to the Colorado Plateau were investigated in this study. Those beneath the Sierra Nevada are highly enriched in fluid-mobile elements (Cs, Pb, U, and Sr) and, in particular, are characterized by low U/Pb and high Sr/Nd. These signatures imply that aqueous fluids derived by dehydration of seawater-altered lithologies have been introduced into the Sierran xenoliths. Peridotite xenoliths from beneath the Colorado Plateau, lying ~1000 km inboard, are also enriched in fluid-mobile elements, but the extent is lower, the U/Pb ratios are high, the Sr/Nd ratios are low, and there is a strong enrichment in the light rare earth elements but negligible enrichment in the heavy rare earths. These features require the introduction of an aqueous component and a silicate melt component into the plateau xenoliths, with the latter, in particular, derived from a garnet-rich source such as an eclogite that has already been stripped of Pb and Sr relative to U and Nd by earlier dehydration. This hypothesized eclogite source may represent subducted Farallon oceanic crust or preexisting Proterozoic oceanic crust. In both cases, a source of aqueous fluids from greater depths is required to explain the enrichment in fluid-mobile elements and to sufficiently depress the eclogite solidus for melting to take place. Such fluids are suggested here to come from dehydration of serpentinite, whose most probable origin is the colder core of the shallowly subducting Farallon plate. The distinctive signatures of the Sierran xenoliths, by contrast, probably derive from dehydration of seawater-altered oceanic crust earlier in the subduction sequence. These observations corroborate suggestions that low-angle subduction during the Laramide orogeny may have hydrated a laterally extensive region of western North America. However, the vertical extent of hydration remains an open question.

Introduction

The North American Cordillera is a ~1500-km-wide region of intraplate deformation and volcanism, characterized by anomalously high elevations and topographic relief (Dickinson 1981). The origin of wide intracontinental orogenic and magmatic belts has long been debated, particularly because such features do not fit the classic theory of plate tectonics, which describes the relative motions of plates and volcanic activity as being confined to narrow plate boundaries (Molnar 1988). It is generally believed that the broad Cordilleran orogenic belt and associated magmatism are manifestations of the peculiar nature of subduction of the Farallon plate beneath the North American plate since the Mesozoic. For example, the cessation of Mesozoic arc magmatism in the Sierra Nevada at ~74 Ma and subsequent migration of the locus of arc magmatism several hundred kilometers inboard of the trench are often attributed to a period of shallow subduction (74–40 Ma; Lipman 1992). This eastward migration of arc magmatism was accompanied by the Laramide orogeny, a period of broad internal deformation of the North American continent (Dickinson and Snyder 1978) and hypothesized to be a consequence of mechanical coupling between the flat-subducting Farallon plate and the overriding North American lithosphere (Bird 1988).

A number of investigators have suggested that flat subduction of the Farallon plate hydrated much of the North American lithosphere, perhaps as far east as the Rocky Mountains (Smith et al. 1999;

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Humphreys et al. 2003; Smith et al. 2004; Hyndman et al. 2005; Smith and Griffin 2005). This hypothesis is referred to from here on as the "Farallon hydration" hypothesis. If correct, it has far-reaching ramifications. First, the rheologic properties of the Cordilleran lithospheric mantle would have been affected by hydration. Addition of water to nominally anhydrous minerals (e.g., olivines and pyroxenes) is known to substantially decrease their viscosities (Hirth and Kohlstedt 1996; Mei and Kohlstedt 2000*a*, 2000*b*); hence, hydration of the lithosphere, depending on the extent, could have had profound impacts on the distribution of intracontinental deformation in the Cordillera (Dixon et al. 2004; Lee et al. 2005). Second, hydration of the lithospheric mantle would also depress the solidus, promoting melting of the lithospheric mantle after the slab rolled back ~40 m.yr. ago (Dickinson and Snyder 1978; Lipman 1992; Humphreys 1995; Humphreys et al. 2003) or during the Basin and Range extension (Leeman and Harry 1993). In fact, important questions still remain regarding the origin of Eocene magmatic flare-ups within the Basin and Range Province (Lipman 1992; Leeman and Harry 1993).

The goal here was thus to test whether the metasomatic signature of the deep North American lithosphere along an east-west transect is consistent with fluids originating from dehydration of the flat-subducting Farallon plate during Laramide times. If it is not consistent, then alternative models must be considered or developed. An implicit prediction of the Farallon hydration hypothesis is that the eastward variation in the composition of slab-derived fluids/melts should be consistent with prograde metamorphism of seawater-altered oceanic crust and lithospheric mantle. In particular, different parts of the subducting oceanic lithosphere will thermally equilibrate at different times with the ambient mantle; that is, heating up of the interior of the slab lags that of the slab surface such that dehydration reactions will be protracted in time and hence in distance from the trench (Peacock 1990, 1996). Near the trench, the slab surface has just warmed but the slab's interior (the serpentinized mantle) remains cold; hence, the resulting metasomatizing fluids should be dominated by an aqueous component and enriched in aqueous fluid-mobile elements (mainly the large ion lithophile elements Cs, Rb, Li, K, Sr, Ba; cf. Leeman 1996) originating primarily in seawater-altered oceanic crust. Progressing farther inboard of the trench, the oceanic crust will eventually become dehydrated, but because the increase in temperature of the slab interior lags that of the slab surface, the serpentinized slab interior may have only begun to dehydrate. Serpentinized oceanic mantle may not have the same trace element characteristics as seawater-altered oceanic crust (it should be less enriched), which means that one might expect a change in the composition of the aqueous component with distance from the trench. It may also be possible that fluids derived from breakdown of antigorite might help to cause flux melting of overlying oceanic crust that has already been dehydrated. If so, a mixture of silicate melts and aqueous fluids would be expected. In this case, one might expect to see a mixture of aqueous fluids derived from the serpentinized slab interior and silicate melts derived from the dehydrated oceanic crust. Such a mixture will be enriched not only in those elements typically thought of as only fluid-mobile (e.g., large ion lithophiles) but also in those elements (rare earth elements, high field strength elements, etc.) that are typically thought of as mobile only in silicate melts (Mungall 2002). Thus, the hydration hypothesis predicts that the composition of metasomatizing agents should change in a prograde sense with distance away from the trench. This is the prediction that we wish to test here.

Samples and Methods

From west to east (fig. 1*A*), the samples come from the Late Miocene (8.3 Ma) Big Creek diatreme in the central Sierra Nevada (Dodge et al. 1988; Ducea and Saleeby 1996, 1998; Lee et al. 2000, 2001*a*), the Pleistocene Oak Creek lava flow in the eastern Sierra Nevada (Beard and Glazner 1995; Ducea and Saleeby 1996; Lee et al. 2000, 2001*a*), the Pliocene Cima volcanic field in the Basin and Range Province in southeastern California (Wilshire et al. 1991; Farmer et al. 1995; Mukasa and Wilshire 1997; Lee et al. 2001*b*), and a Late Oligocene to Early Miocene minette in the Colorado Plateau (the Thumb, New Mexico; Ehrenberg 1982*a*, 1982*b*; Smith and Boyd 1992; Riter and Smith 1996; Smith 2000; Lee et al. 2001*b*). The petrography of these samples has been described by investigators in the previous references. Samples are available from either the author or the Smithsonian Institution. In brief, mantle xenoliths from Big Creek, Sierra Nevada, consist of spinel harzburgites, garnet-bearing spinel lherzolites and harzburgites, and high-MgO garnet-bearing pyroxenites (lower crustal xenoliths, such as garnet clinopyroxenites, are also abundant). Oak Creek xenoliths are dominated by spinel lherzolites. Mantle xenoliths from Cima are dominated by spinel lherzolites and some spinel

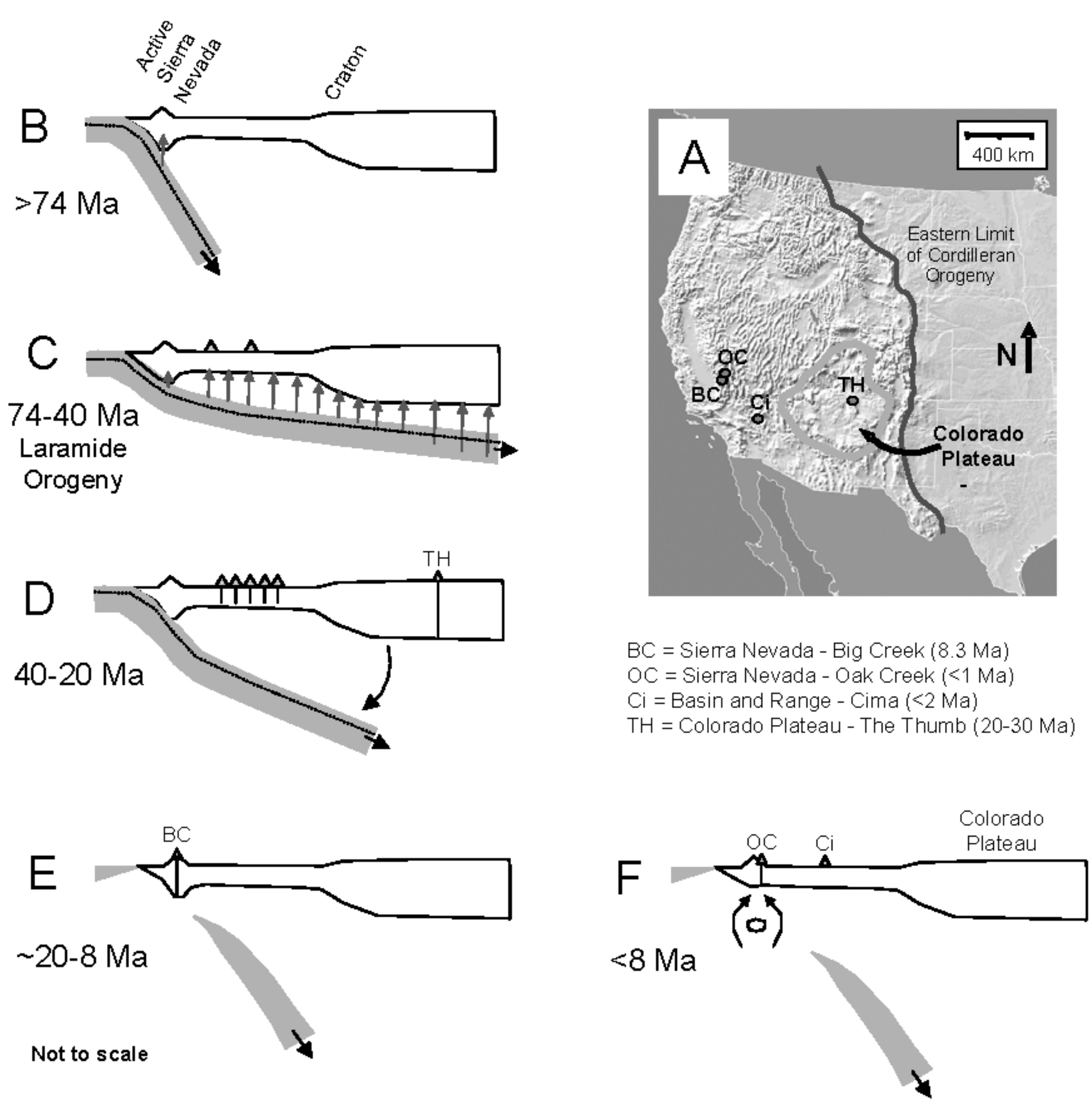

Figure 1. *A*, Shaded relief map of western United States and xenolith localities. Geologic cross-sections (*B–F*) show conceptual model for the tectonic history of the North American Cordillera as discussed in the text. *B*, Mesozoic subduction of the Farallon plate and associated Sierran arc magmatism. *C*, Shallowing of subduction angle and hydration (*arrows*) of the Cordilleran lithosphere–Laramide orogeny; fluxing of fluids from breakdown of serpentine in the oceanic lithospheric mantle causes the Farallon oceanic crust or preexisting Proterozoic oceanic crust within the plateau lithosphere to partially melt (*textured region*). *D*, Post-Laramide slab rollback exposes the base of hydrated lithosphere to hot asthenosphere; ignimbrite flare-up in the Basin and Range Province and small-volume hydrous magmatism in the Colorado Plateau; lithospheric melting beneath the Sierra Nevada shielded by the Farallon slab. *E*, Formation of the San Andreas Transform and opening of the slabless window during the Miocene; base of the hydrated Sierran lithosphere melts. *F*, Sierran mafic root delaminates, causing postdelamination magmatism in the eastern Sierra Nevada.

harzburgites, though a slight emphasis was paid here to the harzburgites previously studied for Re-Os isotopic systematics (Lee et al. 2001*b*). The Colorado Plateau xenoliths from the Thumb are dominated by garnet lherzolites and harzburgites. We analyzed five peridotites from Big Creek, three spinel lherzolites from Oak Creek, 11 spinel peridotites from Cima, and six garnet peridotites from the Thumb.

Whole-rock trace element analyses were done by magnetic-sector inductively coupled plasma mass spectrometry (Finnigan Element 2). Samples were prepared by dissolving ~80 mg of rock powder in a 1 : 1 mixture of HF : $HClO_4$ at 150°C followed by complete dry-down at 175°C. This step was repeated twice. In the third dissolution dry-down sequence, only $HClO_4$ was used. Samples were diluted by a factor of ~1500 and spiked with a known quantity of indium, which served as an internal standard. Sample concentrations were determined by external standard normalization using certified rock standards put through the same processing as the samples. Basaltic standards (BHVO-1 and BIR-1) were used for most trace elements. For Ni calibration, dunite reference standards JP-1 and/or DTS-2 were used. Most trace elements were run in low-resolution mode (maximum sensitivity). However, Al, Fe, Mn, Co, Ni, V, and Sc were run in medium-resolution mode in order to differentiate isobaric interferences. The data are presented in table 1.

Results

Major Elements and Moderately Incompatible to Compatible Trace Elements. In order of increasing major element fertility, the peridotite xenolith suites can be arranged as follows: the Thumb, Big Creek, Cima, and Oak Creek. Here, we use "fertile" (or "infertile") to describe the amount of meltable components remaining (e.g., clinopyroxene and garnet) within a rock. In terms of major elements, fertile peridotites are characterized by lower whole-rock Mg numbers (Mg/[Mg + Fe] × 100) and higher Al contents, whereas infertile peridotites (e.g., those that have had appreciable amounts of melt extracted) have higher Mg numbers and lower Al contents. These compositional trends reflect the fact that Al-bearing phases such as garnet and clinopyroxene are progressively removed during melting and that Fe behaves slightly incompatibly (with respect to the solid residue) during partial melting, whereas Mg behaves compatibly. A comparison of olivine Mg numbers between the xenolith suites is shown in figure 2*A*. We have used olivine Mg numbers from the literature in order to amplify the database (sources given in fig. 2*A* legend), but all other geochemical measurements presented from here on refer to whole-rock measurements in table 1. It can be seen that the Colorado Plateau peridotites are the most infertile, as evidenced by their high olivine Mg numbers and low whole-rock Al contents (figs. 2*A*, 3). The Oak Creek peridotites, in contrast, are the most fertile (fig. 2*A*). These regional differences in melt fertility are also consistent with the systematics of moderately incompatible to compatible trace elements: infertile peridotites have lower whole-rock Lu and higher whole-rock Ni, while fertile peridotites have higher Lu and lower Ni (fig. 3). Importantly, the coherent positive correlations between Lu and Al and negative correlations between Ni and Al in all of the xenolith suites (fig. 3) indicate that moderately incompatible to compatible trace elements have not been disturbed by the second-stage overprints on highly incompatible trace elements discussed in the next section.

Highly Incompatible Trace Elements. The systematics of those trace elements that are highly incompatible (with respect to the solid residue) during partial melting are more complicated than those of major elements and moderately incompatible to compatible trace elements (fig. 4). Although many of the peridotites in this study have been partially melted and should be expected to be depleted in incompatible trace elements, all of the samples appear to have been reenriched in highly incompatible elements by one or more events postdating the original partial melting event. For example, although peridotites from the Thumb in the Colorado Plateau (fig. 4*D*) and Big Creek in the Sierra Nevada (fig. 4*A*) are infertile in the major element sense, they are enriched in highly incompatible elements, particularly the aqueous fluid-mobile elements Cs, Pb, U, Li, Ba, Rb, and Sr (figs. 2*B*, 4). In the Big Creek xenoliths, this enrichment in aqueous fluid-mobile elements appears to be the dominant component that has been introduced. This is evidenced by the fact that fluid-immobile incompatible elements such as Nb and Ta remain depleted relative to fertile mantle in the Big Creek xenoliths (fig. 4*A*). In contrast, in the Thumb xenoliths, Nb and Ta have clearly been enriched above typical fertile mantle concentrations (fig. 4*D*). This indicates that the Thumb xenoliths contain not only an aqueous fluid component but also a silicate melt component. This is additionally borne out by the fact that the Thumb xenoliths are also highly enriched in light rare earth elements (LREEs), which are generally considered to be only slightly fluid-mobile. The Big Creek xenoliths by contrast are only slightly enriched in LREEs. Additional differences between the Big Creek and Thumb xenoliths, which we will return to in "Laramide Enrichments Reflected by Big Creek and Thumb Xenoliths," include the following: (1) the most enriched incompatible element is Cs for Big Creek and U for the Thumb (fig. 2*B*, 2*C*); (2) Big Creek is characterized by strongly subchondritic U/Pb ratios, whereas the Thumb is strongly superchondritic (fig. 2*C*); and (3) Big Creek is strongly enriched in Sr (fluid-mobile) relative to Nd (fluid-immobile), but the Thumb

Table 1. Major and Trace Element Data

	BHVO-1 calibration	Central Sierra Nevada, CA (Big Creek)					Eastern Sierra Nevada, CA (Oak Creek)			Mojave Desert, CA (Cima volcanic field)														Colorado Plateau					
Element	values	BC77	1026V	P7	P10	BC98-2	OK98-3	OK98-9	OK98-4	Ki5-1b	Ki5-8b	Ki5-16b	Ki5-31b	Ki5-32b	Ki5-45b	Ki5-110b	CiP98-8b	CiP98-19b	CiP98-62b	CiP98-66b	CP120	CP MO77	CP713	CP105	CP126	CP104
Li	4.90	23.94	14.04	3.47	19.06	7.23	1.41	1.44	3.91	2.06	2.70	2.01	2.90	3.48	3.37	2.91	2.30	2.77	1.85	3.34	1.84	5.09	2.86	2.46	.83	142
Al_2O_3*[a]	13.80	2.29	2.96	2.98	1.67	2.63	2.79	3.27	3.62	1.65	4.13	.578	2.14	2.19	1.53	.936	1.86	1.15	1.88	3.07	.80	.51	1.90	1.37	.61	.73
P_2O_5*[a]	.273	.00529	.00138	.00835	.00631	.0175	.0219	.0305	.0371	.00335	.01474	.00122	.01896	.00567	.01423	.00776	.00438	.01369	.00576	.00911	.0122	.0248	.0264	.0170	.0102	.0543
Sc*	31.8	8.98	17.6	12.9	6.75	10.7	13.3	14.3	15.7	11.0	15.5	5.95	11.3	12.6	8.54	5.78	12.3	7.43	10.8	15.0	7.91	4.71	8.40	10.82	4.17	6.36
TiO_2*[a]	2.77	.0273	.0266	.0857	.0509	.0320	.140	.148	.154	.0389	.1428	.0130	.0439	.0502	.0792	.0264	.0390	.0348	.0504	.1153	.0116	.0886	.1004	.0250	.0174	.0209
V*	321	62.5	86.6	59.2	36.6	43.0	69.6	78.7	81.3	37.5	79.5	19.1	46.8	49.5	37.1	21.7	54.0	32.1	46.0	68.6	28.5	22.6	55.7	52.1	24.0	45.8
Mn*	1317	1073	1095	1033	1580	974	975	971	976	996	1015	899	1051	1115	1195	934	985	994	961	1271	848.3	837.7	861.9	861.8	798.4	687.7
FeOT*[a]	11.00	7.75	7.01	8.25	7.94	7.41	7.78	7.81	7.75	8.48	8.11	8.09	8.24	9.00	9.25	8.37	7.94	8.45	8.09	10.28	6.92	7.37	7.35	6.81	7.11	7.26
Co*	45.0	111	100	112	116	109	97.7	98.0	97.0	118	102	121	114	122	126	125	108	119	115	141	109	110	106	105	114	119
Ni*	120	2406	2297	2415	2490	2504	2033	2011	1977	2185	1832	2326	2175	2223	2303	2480	2038	2248	2225	2581	2531	2577	2420	2422	2767	2964
Cu*	136	1.1	43.8	24.8	1.95	1.26	2.8	12.8	17.5	.939	18.8	6.32	6.30	9.65	7.68	2.11	6.23	1.78	9.15	12.2	3.93	2.34	3.36	2.62	4.72	8.72
Zn*	105	49.6	50.2	44.4	51.2	48.6	42.9	45.7	50.0	53.4	52.8	51.1	56.8	57.5	54.1	48.6	49.7	58.4	53.8	65.0	40.3	49.0	46.2	51.7	44.6	50.5
Ga	21	2.02	2.28	2.95	1.94	2.59	2.55	3.16	3.67	1.30	3.63	.64	2.27	2.11	1.97	.96	1.58	1.29	1.53	2.29	.59	.97	1.56	1.35	.56	.842
Rb	9.31	2.02	2.58	1.20	5.89	5.05	.337	.257	1.04	.120	.731	.043	.300	.389	.171	.105	.530	.258	.332	.768	.396	1.533	.534	.476	.487	2.26
Sr	396	16.5	33.2	20.7	58.9	61.3	27.5	39.9	27.6	3.35	32.2	.752	15.9	3.73	8.94	2.74	7.73	4.21	8.16	11.2	10.5	28.9	26.1	20.9	5.72	243
Y	28	.571	2.17	2.34	.677	1.18	3.73	4.40	4.16	1.33	4.16	.218	2.13	2.49	1.33	.59	1.07	.886	1.27	1.54	.363	.789	1.436	.414	.290	.553
Zr	181	4.39	4.46	4.40	1.75	5.90	8.74	7.70	9.60	1.72	9.44	1.86	5.68	5.91	5.69	4.92	4.02	7.08	4.20	5.82	3.41	11.18	9.16	5.33	1.85	7.93
Nb	18.1	.043	.066	.061	.060	.364	.179	.0756	.294	.267	.750	.0850	.146	.432	.173	.164	.403	.457	.365	.584	.481	1.32	2.17	.773	.614	1.32
Cs	.1	1.67	2.85	1.09	5.13	2.73	.0203	.0019	.0227	.0017	.0120	.0018	.0130	.0166	.0058	.0021	.0278	.0048	.0094	.0403	.0384	.2143	.0599	.0644	.0300	.611
Ba	133	16.9	9.8	9.2	18.6	44.5	2.75	2.93	22.8	2.50	44.7	.51	1.64	2.42	2.75	2.27	2.91	2.66	3.04	4.22	11.4	35.7	16.9	26.1	5.72	75.9
La	15.5	.245	.228	.201	.384	1.14	1.82	2.14	.978	.133	.771	.065	1.10	.558	.189	.206	.490	.586	.386	.710	1.75	3.80	4.62	3.22	.532	4.19
Ce	38	.850	.877	.559	.411	2.15	4.16	3.87	2.07	.256	1.52	.157	3.54	1.09	.530	.445	1.16	.977	.837	1.68	2.82	6.46	7.90	5.32	.947	6.93
Pr	5.33	.0760	.0680	.1052	.0556	.295	.568	.481	.318	.0343	.220	.0237	.643	.140	.0926	.0723	.1809	.138	.122	.262	.414	.876	1.06	.719	.115	.979
Nd	24.8	.317	.315	.589	.254	1.21	2.31	1.95	1.49	.172	1.11	.117	3.23	.596	.492	.350	.889	.594	.549	1.29	1.63	3.36	4.09	2.68	.432	3.82
Sm	6.12	.0599	.100	.211	.0700	.234	.459	.427	.418	.0734	.367	.0315	.671	.181	.151	.0844	.211	.128	.138	.306	.274	.567	.652	.417	.070	.624
Eu	2.1	.0233	.0417	.0855	.0318	.0784	.155	.163	.161	.0340	.166	.0099	.169	.0646	.0503	.0259	.0588	.0405	.0487	.0852	.0650	.141	.152	.0971	.0198	.161
Gd	6.26	.0741	.160	.284	.0883	.216	.536	.564	.530	.113	.460	.0328	.612	.241	.173	.0877	.207	.136	.167	.300	.2082	.434	.527	.2988	.0675	.473
Tb	.954	.0121	.0323	.0531	.0151	.0324	.0924	.102	.0976	.0229	.0872	.00542	.0865	.0474	.0311	.0145	.0319	.0221	.0295	.0462	.0253	.0549	.0690	.0357	.0102	.0565
Dy	5.3	.103	.295	.367	.0918	.188	.604	.685	.659	.179	.627	.0375	.4680	.358	.217	.0958	.197	.140	.215	.285	.1061	.233	.331	.139	.0570	.215
Ho	.99	.0172	.0767	.0887	.0211	.0425	.141	.165	.161	.0508	.166	.00902	.0854	.0989	.0571	.0239	.0439	.0332	.0565	.0636	.0132	.0291	.0547	.0148	.0115	.0200
Er	2.56	.0465	.259	.275	.0631	.139	.424	.494	.495	.161	.509	.0290	.248	.314	.177	.0778	.140	.104	.176	.2030	.0311	.0639	.158	.0379	.0331	.0406
Tm	.34	.00699	.04215	.04194	.00984	.02309	.0647	.0751	.0750	.0252	.0770	.00500	.0382	.0510	.0289	.0131	.0225	.0173	.0287	.0326	.00433	.00769	.0239	.0058	.00516	.00496
Yb	2.04	.0420	.273	.260	.0679	.159	.396	.463	.461	.157	.471	.0346	.250	.322	.190	.0888	.149	.114	.184	.216	.0335	.0486	.156	.0508	.0347	.0432
Lu	.271	.00630	.0427	.0401	.0109	.0262	.0617	.0703	.0708	.0262	.0739	.00652	.0384	.0518	.0319	.0158	.0243	.0197	.0306	.0353	.00570	.0062	.0231	.0092	.00570	.00616
Hf	4.21	.110	.104	.127	.0501	.156	.231	.233	.2743	.0420	.282	.0330	.152	.146	.177	.131	.0961	.134	.119	.139	.0765	.304	.253	.126	.0449	.186
Ta	1.14	.00229	.00380	.00445	.0021	.0216	.0102	.00277	.0145	.0237	.0529	.00704	.0115	.0257	.0114	.0109	.0286	.0370	.0281	.0415	.0305	.0900	.128	.0509	.0348	.0940
Tl	.059	.0624	.129	.0794	.0595	.0857	.00202	.00084	.00557	.00172	.0122	.00046	.0043	.0041	.00481	.00109	.0045	.0017	.0934	.00657	.0164	.229	.0373	.0436	.0102	.0738
Pb	2.1	.236	.603	.227	.507	.794	.569	.387	.618	.0411	.276	.0627	.0886	.138	.0884	.0827	.210	.105	.162	.305	.413	.709	.941	.507	1.664	2.30
Th	1.26	.00773	.00873	.0337	.0410	.412	.0960	.05513	.141	.0226	.113	.0151	.0500	.279	.0415	.0424	.103	.0830	.0677	.150	.346	1.24	1.30	1.09	.077	1.42
U	.42	.0108	.00712	.0167	.0626	.211	.0555	.0744	.0923	.00770	.0368	.00737	.0207	.0764	.0797	.0253	.0318	.0326	.0253	.0461	.158	.348	1.27	.484	.158	8.80

Note. Asterisk indicates measurements made in medium-resolution mode; all other elements are in low-resolution mode.
[a] Elements are measured in percentage of weight; all other elements are measured in parts per million.

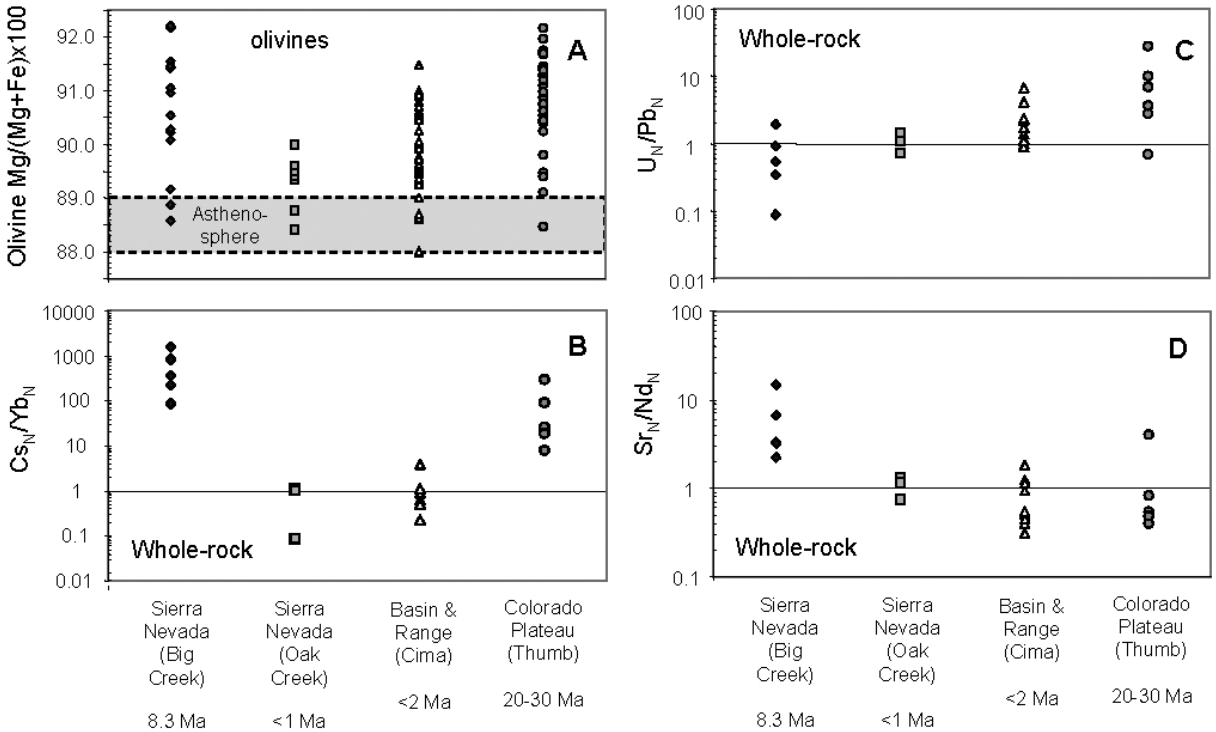

Figure 2. *A*, Mg numbers (Mg/[Mg + Fe] × 100) in olivines from Big Creek, Oak Creek, Cima, and the Colorado Plateau; data taken from various sources (Ehrenberg 1982*a*; Wilshire et al. 1988, 1991; Lee et al. 2000, 2001*a*, 2001*b*); *B*, Whole-rock Cs/Yb ratios normalized to primitive mantle Cs/Yb ratio (McDonough and Sun 1995). *C*, Primitive mantle–normalized U/Pb ratios for whole rocks. *D*, Primitive mantle–normalized Sr/Nd ratios for whole rocks. Shaded region bounded by dashed lines in *A* represents range for fertile asthenospheric mantle. Horizontal lines in *B*–*D* represent nominal primitive mantle estimates.

ranges from depleted to only slightly enriched (fig. 2*D*). Importantly, the mantle xenolith trace element signatures are roughly consistent with the trace element signatures of primitive lavas in the Sierra Nevada and Colorado Plateau regions (Van Kooten 1981; Menzies et al. 1983; Alibert et al. 1986; Ormerod et al. 1988; Roden et al. 1990; Feldstein and Lange 1999), which confirms that the enriched signatures seen in these lavas are unlikely to be related to crustal contamination.

Oak Creek (fig. 4*B*) and Cima peridotites (fig. 4*C*) differ from Big Creek and the Thumb xenoliths in that they are less enriched in highly incompatible elements, as can be seen from their roughly flat, primitive mantle–normalized (McDonough and Sun 1995) rare earth element abundances (fig. 4*B*, 4*C*). These observations are consistent with previously published rare earth element abundances of whole rocks and clinopyroxenes from both localities (Beard and Glazner 1995; Mukasa and Wilshire 1997). The role of aqueous fluid introduction also appears to be much smaller in the Oak Creek and Cima peridotites than in Big Creek and the Thumb. In the case of Cima, the slightly subchondritic Nb/La ratios indicate that aqueous fluid components must have been very small. In the case of Oak Creek, the low Nb/La ratios may hint at a larger aqueous fluid component, but the enrichments in fluid-mobile elements are still lower than those seen in Big Creek and the Thumb.

Metasomatism versus Contamination from the Host Lava. A complication that can arise in whole-rock measurements is the possibility of contamination from the host lava during or shortly before eruption. One approach in determining the "uncontaminated" composition is to reconstruct the whole-rock composition from the compositions of mineral cores determined by in situ techniques under the assumption that recently introduced highly incompatible trace elements will be present in interstitial metasomatic phases (Eggins et al. 1998; Condie et al. 2004). Another way to assess contamination is to compare mantle xenolith compositions to host lava compositions.

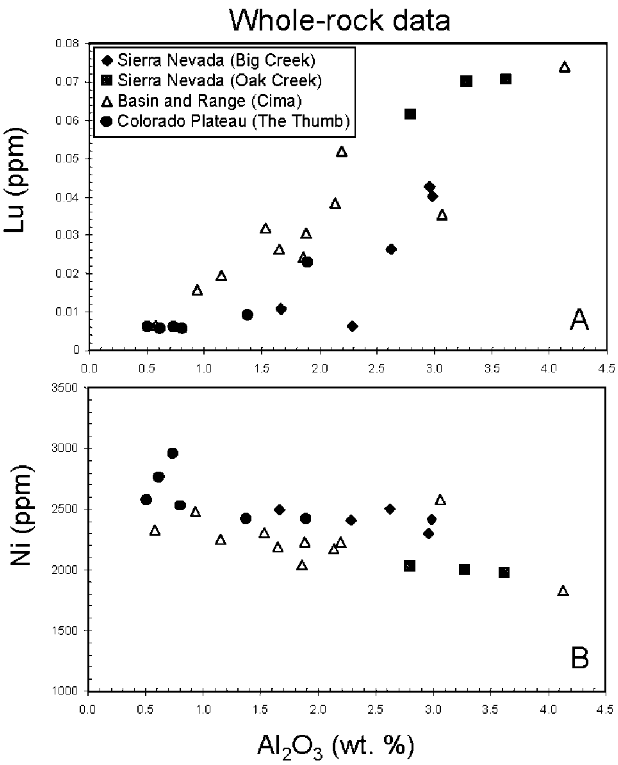

Figure 3. *A*, Whole-rock Lu (ppm); *B*, Ni (ppm) versus Al_2O_3 (wt%).

In figure 4*A*, we compare trace element compositions of ultrapotassic lavas in the central Sierra Nevada (Feldstein and Lange 1999) with the Big Creek peridotite xenoliths. There is a rough similarity in trace element abundance patterns, but the Big Creek peridotites have Rb/La and Sr/Nd ratios much higher than the lavas as a consequence of the high aqueous component in the trace element compositions of the Big Creek peridotites. We have also plotted the average of five garnet websterites (Lee 2005) from Big Creek to show that they do not exhibit the same highly incompatible element signatures as the peridotites, as one might expect if both xenolith types were contaminated by the same magma. These observations indicate that the trace element signatures do not reflect simple contamination by the host lava during eruption. What is more probable is that the trace element enrichment was associated with the same event that generated the enriched source regions of the ultrapotassic lavas. A similar argument can be made for the Cima peridotites based on rough similarities yet subtle differences between the trace element patterns of the Cima peridotites and host lavas (Farmer et al. 1989). For example, Cima basalts have only slightly LREE-enriched signatures like those of the Cima peridotites, but they appear to be enriched in Ba, whereas the Cima peridotites are not (fig. 4*C*).

Peridotite xenoliths from the Thumb also have whole-rock trace element abundance patterns very similar to those of the Thumb minette (Ehrenberg 1982*b*) and other coeval minettes in the region (Roden et al. 1990). In addition, Ehrenberg (1982*b*) showed that reconstructed whole-rock rare earth elements based on cleaned mineral separates yield roughly flat abundance patterns, indicating that much of the LREE-enriched character of the measured whole rock is situated on grain boundaries and hence is likely to represent a recent feature. This is also suggested by the fact that clinopyroxenes from the Thumb peridotites have radiogenic $^{143}Nd/^{144}Nd$ (Roden et al. 1990), which indicates long-term (e.g., since the mid-Proterozoic) LREE depletion, in apparent contradiction to the present LREE-enriched signature of the whole rocks and the clinopyroxenes. It is thus probable that the Thumb peridotites have recently been modified by the addition of small amounts of melts and fluids from the host lava during eruption or from the magmatic precursor to the host lava before eruption.

Regardless of when these fluids and melts were introduced, the very fact that all of these mantle xenoliths have been reenriched attests to the existence of an enriched metasomatized source for these fluids/melts at depths greater than those from which the xenoliths derive (~150 km; Riter and Smith 1996; Smith 2000; Lee et al. 2001*b*). Thus, these enriched source zones must lie either at the base of the lithosphere or within the asthenosphere itself. It is the origin of these distinct enriched sources that is of interest here.

Post-Laramide Processes Reflected by Oak Creek and Cima Peridotites

Oak Creek and Cima peridotites appear to have been sampled in host lavas that erupted after commencement of the Basin and Range Province extension (e.g., post-Laramide times) within their respective regions. Because the Basin and Range extension was associated with pervasive decompressional melting of the asthenosphere and lithospheric mantle, it is probable that any subduction-related trace element signatures of the lithospheric mantle would have been overprinted by these later processes. For example, any previous enrichments of the lithospheric mantle in fluid-mobile elements such as Cs, Rb, Ba, U, and Pb would probably be stripped away if such mantle were partially melted. This is because these elements are highly incom-

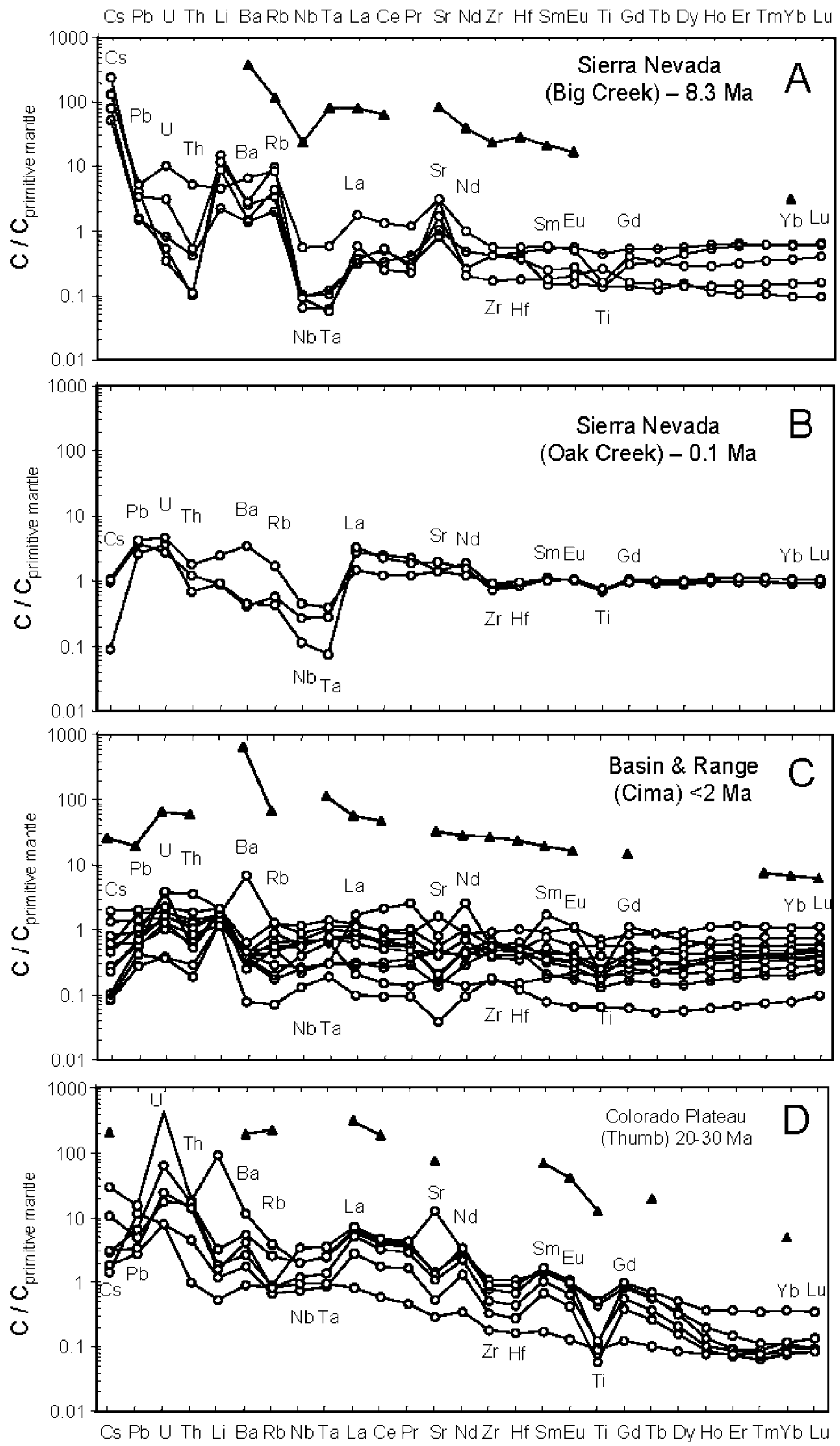

Figure 4. Whole-rock primitive mantle–normalized spidergrams for peridotite xenoliths (*open circles*) from Big Creek (*A*), Oak Creek (*B*), Cima (*C*), and the Thumb (*D*), plotted in approximate order of increasing compatibility during partial melting. Triangles represent magma compositions from Central Sierra Nevada ultrapotassic lavas (Feldstein and Lange 1999), Cima basalts (Farmer et al. 1995), and a minette from the Thumb (Ehrenberg 1982*b*; Alibert et al. 1986).

patible. Asthenosphere-derived melts could then remetasomatize the lithospheric mantle, and the resulting signature would probably have an "ocean island basalt" signature rather than a subduction signature. We thus believe that the Oak Creek and Cima peridotites have been overprinted by post-Laramide processes. Big Creek and the Thumb, however, represent pre–Basin and Range lithosphere; their trace element enrichments are discussed in the next section.

Laramide Enrichments Reflected by Big Creek and Thumb Xenoliths

Aqueous Fluid Components in the Pre-Miocene Sierra Nevada Lithosphere. The trace element signatures in the Big Creek peridotites are dominated by a large aqueous fraction, as exemplified by the pronounced enrichments in aqueous fluid-mobile elements (e.g., Cs, Sr, Rb, Pb, U) and lesser enrichments in those elements that are mobilized primarily by silicate melts (as exemplified by depletions in Nb and Ta and small enrichments in the LREEs). In particular, the Big Creek xenoliths have low U/Pb and high Sr/Nd (fig. 2*C*, 2*D*). Such elemental fractionations are consistent with the predicted relative mobilities of these elements in hydrothermal conditions: dehydration of seawater-altered crust preferentially liberates Pb over U and Sr over Nd (Brenan et al. 1995). These Big Creek trace element signatures are thus consistent with the introduction of fluids derived by dehydration of seawater-altered oceanic crust early in the subduction process.

Aqueous Fluids and Eclogite Melt Components in the Colorado Plateau Xenoliths. As discussed in "Results," the Colorado Plateau trace element signatures (enrichments in LREEs and fluid-mobile elements), as represented by the Thumb xenoliths, suggest the involvement of both an aqueous fluid and a silicate melt. Here, we expand on some of the geochemical features discussed in the "Results" section. An important feature of the plateau xenoliths is that even though they are highly enriched in LREEs, they show negligible enrichment in the heavy rare earth elements (HREEs), as exemplified by the preservation of the original melting relationships between the HREEs, major elements, and compatible trace elements (fig. 3*B*, 3*C*). This means that the Colorado Plateau enrichment agent was depleted in the HREEs, which in turn suggests an origin from a source that can hold back HREEs in the solid residue. One possibility is a garnet-bearing source, which we speculate to be eclogitized oceanic crust. Eclogitized oceanic crust might also be characterized by high U/Pb and low Sr/Nd imparted by preferential liberation of Pb and Sr during dehydration of the seawater-altered protolith early in the subduction process, as discussed in the previous paragraph (Brenan et al. 1995). Melts of eclogitized oceanic crust would then be HREE-depleted and possess high U/Pb and low Sr/Nd, as seen in the plateau xenoliths. The need for an eclogite component is also consistent with a similar suggestion based on $^{176}Hf/^{177}Hf$ and Lu/Hf ratios of the host minette lavas in the plateau region (Carlson and Nowell 2001).

If the silicate melt component in the enriched plateau xenoliths indeed originates from previously dehydrated and eclogitized oceanic crust, the question arises as to why an aqueous component also exists. Two possibilities come to mind. One hypothesis is that the aqueous metasomatic component could originate from dehydration of serpentinites preserved in the core of subducting oceanic lithosphere as a consequence of delayed thermal reequilibration with ambient mantle. In such a scenario, a hotter dehydrated slab surface (eclogitic oceanic crust) and a colder hydrated slab interior (underlying serpentinized mantle) can coexist at the same time. Although serpentinized oceanic mantle is characterized by pronounced relative enrichments in large ion lithophile elements (e.g., Cs, Sr, etc.) caused by hydrothermal seawater alteration, the absolute abundances of these highly fluid mobile elements are less than those seen in altered oceanic crust (Scambelluri et al. 2001). Fluids originating from mantle serpentinites would thus have lower large ion lithophile element abundances than those deriving from seawater-hydrated oceanic crust, possibly explaining why the plateau xenoliths are enriched in fluid-mobile elements, although not to the extent seen in the Sierran xenoliths. This hypothesis would be consistent with the eclogite and serpentinite sources deriving coevally from a subducting slab.

An alternative hypothesis is that the eclogitized source has been rehydrated sometime after its emplacement into the lithosphere. If so, this eclogite source could significantly predate metasomatic modification. For example, $^{187}Os/^{188}Os$ and $^{176}Hf/^{177}Hf$ systematics of the minettes in this region have been used to argue that the eclogite source of these minettes was probably Proterozoic and not Phanerozoic (Carlson and Nowell 2001). However, the age of the Farallon plate at the time low-angle subduction of the Farallon plate began could have been ~100 Ma (Engebretson et al. 1985), and given the range of possible Re/Os ratios in modern-day midocean ridge basalts (Shirey and Walker 1998), it is possible for sufficiently radiogenic Os isotopic signatures to have grown in. Thus, the origin of the eclogite source remains equivocal.

Inferred Metasomatic Fluids Linked to Progressive Dehydration of the Shallowly Subducting Farallon Plate

Regardless of the origin of the eclogite melt component in the plateau xenoliths, what is clear from the trace element data is that there must have been a source of aqueous fluids beneath both the pre-Miocene Sierran lithosphere and the Colorado Plateau lithosphere, as suggested by petrographic studies of peridotite and eclogite xenoliths (Roden et al. 1990; Smith et al. 1999, 2004; Smith and Griffin 2005). The origin of the fluid component in the Sierran lithosphere is undoubtedly related to Phanerozoic subduction because Os isotopic systematics of the majority of Sierran peridotites indicate recent extraction from the mantle. The origin of fluid components in the Colorado Plateau lithosphere could be associated with Phanerozoic subduction or even subduction associated with Proterozoic assembly (Karlstrom and Bowring 1993; Selverstone et al. 1999), given that Os isotopic model ages of plateau peridotites are Proterozoic in age (Lee et al. 2001*b*). However, recent U-Pb geochronology of zircons in eclogite xenoliths (which come from depths overlapping those of the peridotites and are not necessarily related to the inferred eclogite source for the silicate melt components seen in the peridotite xenoliths) from the plateau include both Proterozoic ages and younger ages ranging between ~30 and 80 Ma (Usui et al. 2003; Smith et al. 2004). The Proterozoic ages are interpreted to represent primary protolith ages, consistent with the Re-Os isotopic systematics of the peridotites. The younger U-Pb zircon ages correspond to the time interval over which the Farallon plate was believed to be undergoing shallow subduction and hence have been interpreted to represent metasomatic resetting associated with fluids released from the subducting Farallon plate (Usui et al. 2003; Smith et al. 2004). For lack of any data to suggest otherwise, we assume that the ultimate source of the aqueous fluids seen in the plateau xenoliths was likewise associated with recent subduction, that is, subduction processes significantly postdating Proterozoic assembly of the continent. If so, the combined facts that hydrous fluids existed somewhere beneath the Colorado Plateau and that the nearest trench was always far to the west imply strongly that the fluids were associated with low-angle subduction. The most probable time for low-angle subduction was during the Laramide orogeny (74–40 Ma). If our interpretations are correct, then the trace element data on peridotite xenoliths independently corroborate the suggestion that much of the North American lithosphere, at least in lateral extent, was influenced by the passage or infiltration of hydrous fluids derived from dehydration of the shallowly subducting Farallon plate (Humphreys et al. 2003; Dixon et al. 2004; Hyndman et al. 2005).

We now return to the outstanding question of whether the silicate melt component in the plateau xenoliths derived from Farallon oceanic crust or Proterozoic oceanic crust. If this question can be answered, it would have important implications for the geometry and hence thermal structure of low-angle subduction. For example, there have been a few studies of the thermal structure of low-angle subduction of the Farallon plate (Bird 1988; Spencer 1996; English et al. 2003; Smith et al. 2004; Smith and Griffin 2005). In all of these models, the temperature of the subducting Farallon plate was found to be too cold to allow for melting of oceanic crust, even if its solidus has been depressed by the addition of hydrous fluids. The reason for the cold temperatures is twofold. First, in these models, no hot asthenospheric mantle wedge is allowed to occur between the Farallon plate and the overlying continental lithosphere, and thus, the thermal evolution of the slab and overriding lithosphere involves only conduction. Second, the models assume a steady-state scenario. The effect of these collective assumptions is to retard the rate at which the slab heats up. If these model assumptions are correct, then the eclogite source for the silicate melt component in the plateau xenoliths is hard to reconcile with an origin from the shallowly subducting Farallon plate unless melting of Farallon crust occurred during slab rollback. Alternatively, the assumptions of a steady state and no asthenospheric mantle wedge may be wrong, but if so, a mechanism for generating the broad intracontinental deformation during the Laramide orogeny without direct coupling of the Farallon plate to the overriding lithosphere (Bird 1988) would have to be developed.

Conclusions and Speculations

The observations presented here are largely consistent with the hypothesis that much of the Cordilleran lithosphere, at least in lateral extent, was hydrated during Laramide times (Humphreys et al. 2003). This conclusion is similar to but independent of those arrived at by other investigators (Smith 1995; Smith et al. 1999, 2004; Smith and Griffin 2005). A natural speculation is that such hydration had important implications for the rheology of the overriding lithosphere (Dixon et al. 2004; Lee et al. 2005) and possibly even the nature and extent of post-Laramide magmatism after slab rollback. The importance of these implications, of course, depends on the vertical extent to which the North American lithosphere was hydrated, but unfortunately, this is not known precisely. What is needed is a detailed investigation of the water contents of nominally anhydrous minerals in peridotite xenoliths in conjunction with thermobarometric estimates of the xenolith derivation depths. Recent geophysical studies in the region may also help to resolve this problem (West et al. 2004; Wilson et al. 2005).

In any case, the following conceptual and admittedly speculative model is proposed to explain the spatial and temporal variation in post-Laramide magmatism (fig. 1*B*–1*F*). Low-angle subduction of the Farallon plate (beginning at about 70 Ma) resulted in hydration of the deep Cordilleran lithosphere as far inboard of the trench as the Colorado Plateau (fig. 1*C*). The nature of the hydrous fluids was controlled by prograde metamorphism of the subducting slab (fig. 1*C*). Such hydration led to depression of the solidus at the base of the lithosphere. At ~40 Ma, much of the slab and its refrigerating effects were removed, exposing the base of the lithosphere to hot asthenosphere and allowing melting of the hydrated base of the lithosphere to occur (fig. 1*D*). Post-Laramide magmatism probably first commenced beneath the Colorado Plateau because this is where slab rollback probably commenced. Magmatism probably migrated westward (for a more detailed description, see Humphreys 1995) into the Great Basin (as exemplified by the Eocene ignimbrite flare-up). Post-Laramide magmatism in the Sierra Nevada was most probably delayed until the Late Miocene because the Sierras were underlain by the Farallon plate up until probably 20 m.yr. ago, after which the Pacific-Farallon plate collided with the trench and initiated the development of a slabless window (Atwater 1970). Further magmatism in the Sierra Nevada was probably associated with the opening of the slabless window as well as the hypothesized Pliocene delamination of the Sierran lithospheric root (Ducea and Saleeby 1996; Lee et al. 2000, 2001*a*; Manley et al. 2000; Ducea 2002; Farmer et al. 2002; Zandt et al. 2004). Finally, the magnitude of magmatism was probably influenced to a certain extent by major element heterogeneities. Infertile mantle, such as that beneath the Colorado Plateau and pre-Miocene Sierran lithospheric mantle (fig. 2*A*), would have generated only small-degree melts even if hydrated; this is consistent with the low-volume magmatism characterizing these regions. More fertile mantle, such as beneath the Basin and Range Province (fig. 2*A*), could have yielded more magmatism upon hydration and subsequent heating, perhaps explaining the large Eocene ignimbrite flare-up.

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