6-2014

Geochemistry of the Great Valley Group: An Integrated Provenance Record

Kathleen D. Surpless
Trinity University, ksurples@trinity.edu

Repository Citation

Surpless, K.D. (2014). Geochemistry of the great valley group: An integrated provenance record. *International Geology Review, 57*(5-8), 747-766. doi: 10.1080/00206814.2014.923347

International Geology Review, 2014
http://dx.doi.org/10.1080/00206814.2014.923347

Taylor & Francis
Taylor & Francis Group

Geochemistry of the Great Valley Group: an integrated provenance record

Kathleen D. Surpless*

Department of Geosciences, Trinity University, San Antonio, TX 78212, USA

(*Received 13 March 2014; accepted 8 May 2014*)

Sedimentary geochemistry of fine-grained strata of the Great Valley Group (GVG) in California documents a provenance signal that may better represent unstable, mafic minerals and volcanic clasts within sediment source regions than the provenance signal documented in the petrofacies and detrital zircon analysis of coarser sedimentary fractions. Geochemistry of the GVG provides an overall provenance framework within which to interpret sandstone petrofacies and detrital zircon age signatures. The geochemical signature for all Sacramento Valley samples records an overall continental arc source, with significant variation but no clear spatial or temporal trends, indicating that the geochemical provenance signal remained relatively consistent and homogenized through deposition of Sacramento basin strata. The San Joaquin basin records a distinct geochemical provenance signature that shifted from Early to Late Cretaceous time, with Lower Cretaceous strata recording the most mafic trace element geochemical signature of any GVG samples, and Upper Cretaceous strata recording the most felsic geochemical signature. These provenance results suggest that the early San Joaquin basin received sediment from the southern Sierran foothills terranes and intruding plutons during the Early Cretaceous, with sediment sources shifting east as the southern Sierran batholith was exhumed and more deeply eroded during the Late Cretaceous. The GVG provenance record does not require sediment sources inboard of the arc at any time during GVG deposition, and even earliest Cretaceous drainage systems may not have traversed the arc to link the continental interior with the margin. Because the GVG provenance signature is entirely compatible with sediment sources within the Klamath Mountains, the northern and western Sierran foothills belt, and the main Cretaceous Sierran batholith, the Klamath-Sierran magmatic arc may have formed a high-standing topographic barrier throughout the Cretaceous period.

Keywords: Great Valley Group; sedimentary geochemistry; provenance; forearc basin; detrital zircon

Introduction

The sedimentary record preserved in forearc basins can provide remarkable insight into convergent margin processes, including arc magmatism and exhumation (e.g. Dickinson and Seeley 1979; Dickinson 1995; DeGraaff-Surpless *et al.* 2002; Barth *et al.* 2013; Sharman *et al.* in press). The Great Valley Group (GVG) of California is a well-studied ancient forearc system with accessible exposure of mudrock, sandstone, and conglomerate that preserve a record of Farallon–North American plate convergence throughout the Cretaceous period (e.g. Cowan and Bruhn 1992; Dickinson 2004; Ernst *et al.* 2008). Numerous studies focusing variously on sandstone composition and petrofacies (e.g. Ojakangas 1968; Dickinson and Rich 1972; Mansfield 1979; Ingersoll 1983), conglomerate clast compositions (e.g. Rose and Colburn 1963; Bertucci 1983; Seiders 1983), detrital zircon age distributions (e.g. DeGraaff-Surpless *et al.* 2002; Surpless *et al.* 2006; Wright and Wyld 2007; Cassel *et al.* 2012), palaeocurrent analysis (e.g. Ojakangas 1968; Ingersoll 1979; Suchecki 1984), palaeobathymetry (e.g. Ingersoll 1979; Haggart 1986; Williams 1997), and seismic stratigraphy and stratigraphic architecture (e.g. Moxon 1990; Williams 1997; Constenius *et al.* 2000; Mitchell *et al.* 2010; Williams and Graham 2013), together with the well-studied and dated sediment sources within the Klamath-Sierran magmatic arc and related terranes (e.g. Chen and Moore 1982; Bateman 1983; Hacker *et al.* 1995; Soreghan and Gehrels 2000; Irwin and Wooden 2001; and references therein; Grove *et al.* 2008), have provided a detailed view of arc–forearc development through the Cretaceous and into Cenozoic time.

Modern exposures of mid- and shallow-crustal rocks in the Klamath-Sierran arc (e.g. Ague and Brimhall 1988) mean that much of the Early Cretaceous history of this magmatic arc has been eroded or obliterated by younger magmatism and metamorphism. Reconstructing the early history of the Cretaceous arc thus requires interpreting the preserved sedimentary record in the forearc basin. However, this early forearc history remains the most elusive to reconstruct because much of the sedimentary strata deposited during this period is mudrock, and thus not amenable to petrofacies or detrital zircon analysis. Moreover, mudrock crops out poorly, and is typically exposed only along road cuts or where protected by ridge-forming sandstone or conglomerate units. As a result, provenance studies tend to focus on coarser components of the sedimentary record, even though the fine-

*Email: ksurples@trinity.edu

grained strata comprise a significant proportion of basin fill (e.g. Williams and Graham 2013).

Geochemistry of GVG strata, integrated with previous provenance studies, aids in reconstructing the Cretaceous record of the arc-forearc system in California. Mudrock tends to provide a more homogenized provenance signal than the coarser sedimentary fractions (e.g. McLennan *et al.* 1993; Mahoney 2005), and therefore records large-scale provenance shifts rather than more localized variation in provenance signals. Further, mudrock may better represent the more mafic minerals and volcanic clasts of the provenance record than either sandstone or conglomerate (e.g. McLennan *et al.* 1993). Combined with sandstone petrofacies, conglomerate clast compositions, and detrital zircon ages, geochemistry documents the development of the Great Valley forearc basin. Results presented here suggest that GVG sedimentary sources were primarily within the western margin of the developing magmatic arc prior to Late Cretaceous time, and drainage systems may not have traversed the arc from the continental interior until breaching it in latest Cretaceous and Palaeogene time. A significant provenance shift in the southern GVG strata probably documents rapid uplift and erosion of the southern Sierran batholith in Late Cretaceous time.

Geologic background

Strata of the Great Valley forearc basin crop out along the western margin of California's Central Valley, divided into the northern Sacramento Valley and the southern San Joaquin Valley (Figure 1). Upper Cretaceous GVG strata also crop out in stream valleys near the towns of Redding and Chico, CA, in the northeastern part of the basin, and near Sacramento (Figure 1; Haggart and Ward 1984; Haggart 1986). The forearc strata are underlain by the Great Valley Ophiolite, Klamath basement, and Sierran basement terranes (Harwood and Helley 1987; Godfrey *et al.* 1997; Hosford Scheirer and Magoon 2007) and covered by Cenozoic sedimentary and volcanic rocks. The GVG unconformably rests on eastern Klamath terranes to the north, Sierran arc and associated foothill terranes to the east, and is in fault contact with the Franciscan accretionary complex to the west (Ingersoll 1979; Irwin 1981). The southern San Joaquin section is further disrupted by Cenozoic faulting related to San Andreas fault motion and tectonic restructuring of the southern California margin (e.g. Dickinson 1983, 1996); displaced fragments of San Joaquin strata west of the San Andreas fault were not sampled in this study and are not shown in Figure 1.

South- and west-directed Cretaceous palaeocurrent indicators, coupled with sequence stratigraphic studies, provide evidence for both axial (N–S) and transverse (E–W) sediment transport in the basin (Ingersoll 1979; Suchecki 1984; Moxon 1988, 1990; Short and Ingersoll 1990; Williams 1997; Williams and Graham 2013). In the northern GVG, sediment dispersal directions changed from primarily S-directed in the earliest Cretaceous to S- and W-directed in the middle and Late Cretaceous, suggesting a shift from primarily Klamath to Sierran sources (Ojakangas 1968; Ingersoll 1979; Short and

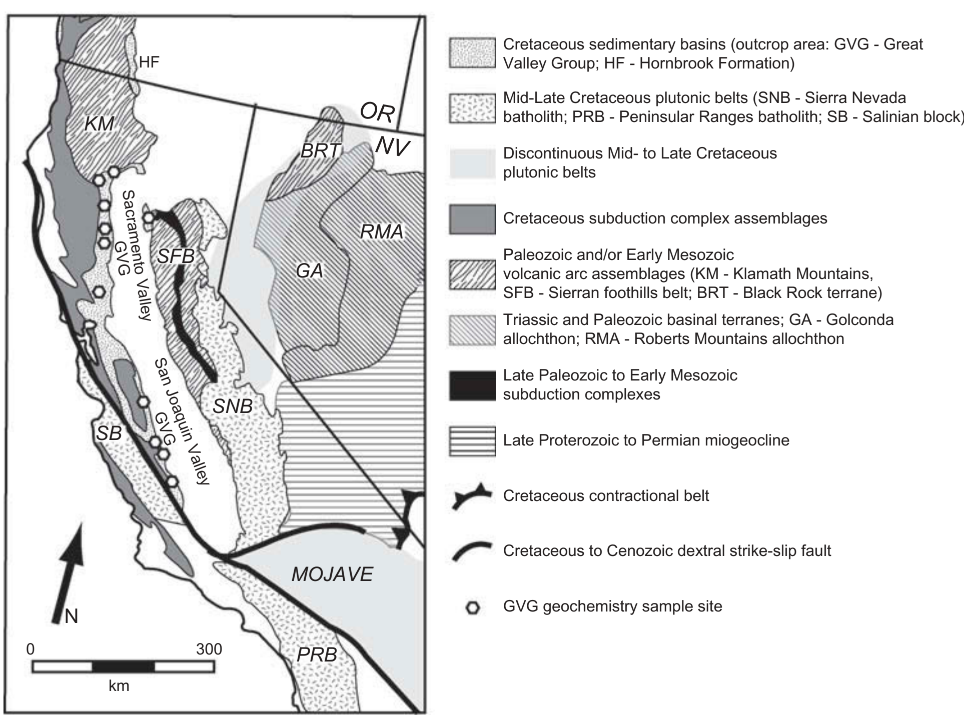

Figure 1. Map showing the general sample locations in the Sacramento and San Joaquin segments of the Great Valley forearc basin, as well as terranes of the US Cordillera (map after Wyld *et al.* (2006) and Surpless and Beverly (2013)).

Ingersoll 1990). Palaeocurrent indicators in the southern GVG are dominantly W-directed, indicating sediment derivation only from the east (Ingersoll 1979). In contrast to Sacramento Valley samples, San Joaquin Valley samples east of the San Andreas fault system represent only the eastern part of the forearc basin, with more distal, axial facies truncated and displaced by San Andreas and related fault motion (Ingersoll 1978, 1979).

Sandstone petrofacies

The stratigraphic framework for provenance analysis of the GVG is well established (e.g. Ojakangas 1968; Dickinson and Rich 1972; Ingersoll 1978, 1979; Mansfield 1979; Graham 1981, 1983; Moxon 1990; Williams and Graham 2013). Petrographic studies divide the GVG into eight major petrofacies based on the relative abundance of quartz, feldspar, phyllosilicates, and lithic grains in sandstone (Ojakangas 1968; Dickinson and Rich 1972; Ingersoll 1979, 1981; Graham and Ingersoll 1981, 1983). These petrofacies are grouped into 'super petrofacies' to document large-scale temporal (Lower and Upper GVG) and spatial (Sacramento Valley and San Joaquin Valley) changes in sandstone composition (Figure 2a; Ingersoll 1983). Comparisons of these super petrofacies reveal significant differences between the Lower and Upper Cretaceous samples. Upper Cretaceous strata are

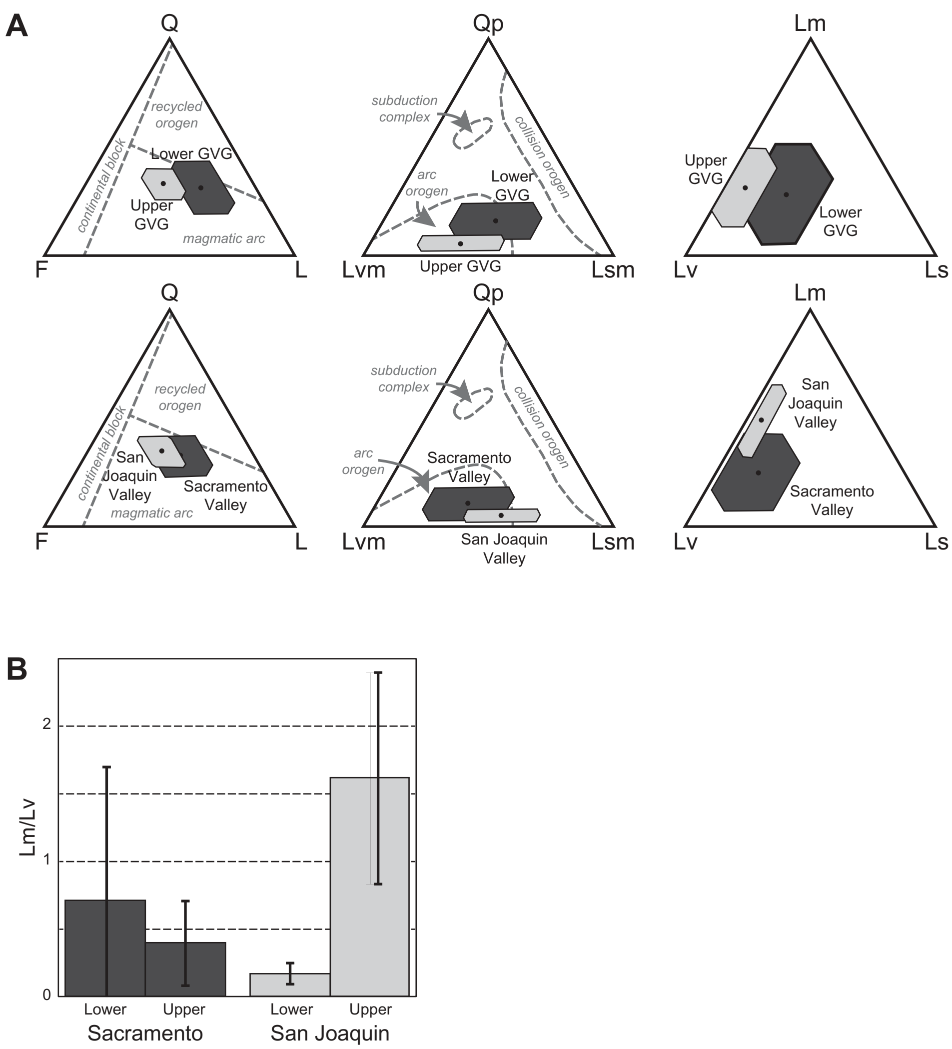

Figure 2. (a) Super petrofacies for the GVG, grouped into Upper and Lower GVG samples (top row) and Sacramento and San Joaquin Valley samples (bottom row), from Ingersoll (1983). Provenance fields are from Dickinson and Suczek (1979) and Dickinson *et al.* (1983); Q, total quartz (including chert and polycrystalline quartz); F, total feldspar; L, total lithic grains (excluding chert and polycrystalline quartz); Qm, monocrystalline quartz; Lvm, volcanic and meta-volcanic lithic grains; Lsm, sedimentary and meta-sedimentary lithic grains; Lm, metamorphic lithic grains; Lv, volcanic lithic grains; Ls, sedimentary lithic grains. (b) Lm/Lv ratios for the Lower and Upper GVG in the Sacramento and San Joaquin basins; data are from Mansfield (1979) and Ingersoll (1983).

more feldspathic than lithic-rich Lower Cretaceous samples; lithic populations in Upper Cretaceous strata are volcanic and metamorphic-rich, but are dominated by polycrystalline quartz (mostly chert) and sedimentary and meta-sedimentary grains in Lower Cretaceous strata (Ingersoll 1983). Spatial variation in sandstone composition within the GVG is less pronounced, with significant overlap between the Sacramento and San Joaquin Valley samples. The Sacramento Valley samples are more variable in sandstone composition, have slightly higher lithic content, and lithic populations include more volcanic grains and more chert; the San Joaquin samples contain very little chert or other sedimentary lithic grains (Ingersoll 1983).

The ratio of metamorphic to volcanic lithic grains (Lm/Lv) in the GVG sandstone remains consistently low throughout the section in the Sacramento Valley, although the variability of this ratio is much greater in the Lower Cretaceous samples (0.7 ± 1.0) than in the Upper Cretaceous samples (0.4 ± 0.3; Figure 2b). The very low Lm/Lv ratio in the Lower Cretaceous San Joaquin section (0.2 ± 0.1) contrasts dramatically with the Upper Cretaceous (1.6 ± 0.8), marking a distinct relative drop in volcanic lithic grains in the strata. Only the Upper Cretaceous San Joaquin section has an Lm/Lv ratio > 1.

Conglomerate composition

Conglomerate represents a small proportion of the GVG, particularly in Lower Cretaceous strata. Unlike mudrock, which likely represents homogenized third-order systems sourced by large areas, conglomerate tends to result from first-order systems sourced from a limited region (e.g. Ingersoll 1990; Doebbert *et al.* 2012) and not well mixed with sediment from other areas. As a result, conglomerate clast compositions can be quite variable (Figure 3). San Joaquin conglomerate typically includes more granite and diorite clasts (up to 47%) than Sacramento Valley conglomerate, which is richer in sedimentary and meta-sedimentary clasts (Figure 3; data from Rose and Colburn (1963), Bertucci (1983), and Seiders (1983)). The majority of sedimentary clasts in Sacramento Valley Lower Cretaceous conglomerate are chert; the Bidwell Point conglomerate lens within the Lower Cretaceous Sacramento Valley section contains the most volcanic and meta-volcanic clasts (Bertucci 1983).

Detrital zircon ages

Extensive detrital zircon analyses of GVG sandstone document the evolution of the basin and its magmatic arc source region through Mesozoic time (e.g. DeGraaff-Surpless *et al.* 2002; Surpless *et al.* 2006; Wright and Wyld 2007; Cassel *et al.* 2012; Clemens-Knott *et al.* 2013, and unpublished data; Sharman *et al.* in press). Previously published and new detrital zircon data are combined here into five sections: Lower and Upper Cretaceous strata from the Sacramento and San Joaquin Valleys, as well as the Platina section in the northernmost Sacramento Valley (Figure 4; see online supplemental material DR1 for data and data sources and DR2 for sample locations at http://dx.doi.org/10.1080/00206814.2014.923347). All GVG sections are characterized by Mesozoic arc sources, with the greatest proportion of Palaeozoic and Precambrian detrital zircon in the Lower Cretaceous sections (Figure 4).

Within the Mesozoic detrital zircon age distributions, a nearly unimodal age population of 155–130 Ma

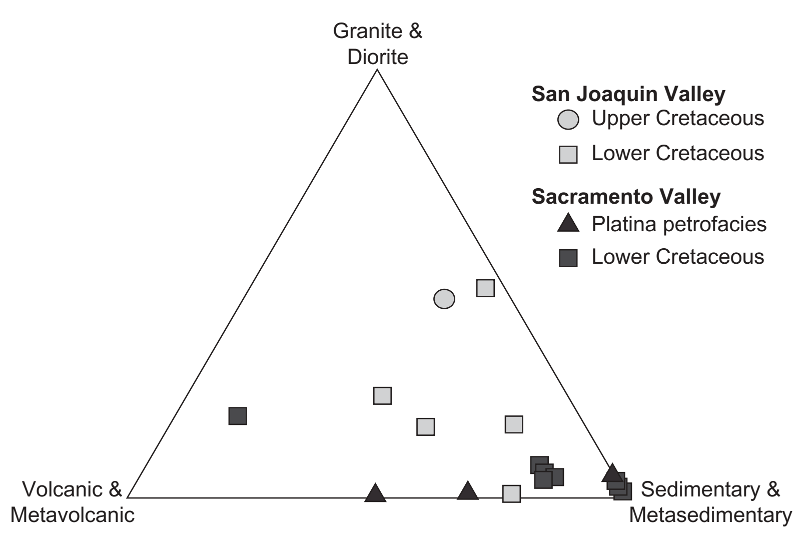

Figure 3. Ternary diagram showing conglomerate clast compositions for Sacramento and San Joaquin Valley conglomerate units (data from Rose and Colburn (1963), Bertucci (1983), and Seiders (1983)).

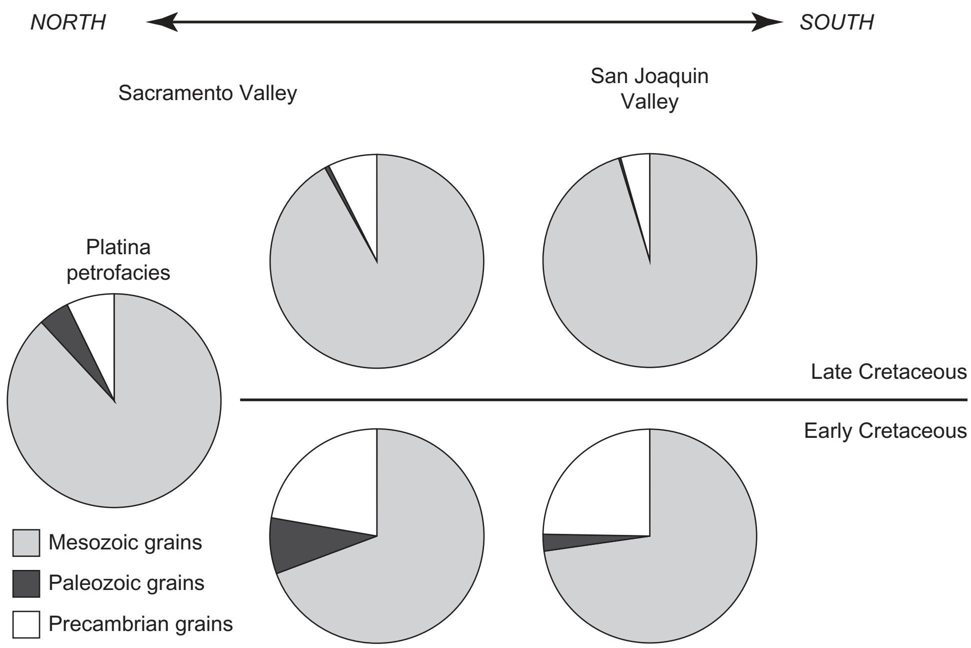

Figure 4. Pie graphs showing the distribution of detrital zircon ages within the GVG strata; Sacramento Valley data are from DeGraaff-Surpless *et al.* (2002), Surpless *et al.* (2006), Wright and Wyld (2007), Surpless and Augsburger (2009), and previously unpublished; Late Cretaceous San Joaquin data are from DeGraaff-Surpless *et al.* (2002); Early Cretaceous San Joaquin data are unpublished data provided by D. Clemens-Knott (personal communication, 2013); Platina petrofacies data are previously unpublished.

characterizes the Platina petrofacies, which is distinct from the broader Middle Jurassic through Early Cretaceous (170–130 Ma) age range present in the entire Sacramento Valley section (Figure 5). Zircon grains younger than 125 Ma are essentially absent from the Platina and Lower Cretaceous Sacramento Valley sections, and form only a minor component of the Upper Cretaceous Sacramento Valley section. In contrast, middle and Late Cretaceous zircon grains (130–90 Ma) constitute the dominant populations in the Upper Cretaceous San Joaquin section, which also includes a latest Jurassic peak at 148 Ma. The Lower Cretaceous San Joaquin section is characterized by a large 162 Ma peak and a few Early Cretaceous grains, and lacks the Late Jurassic–Early

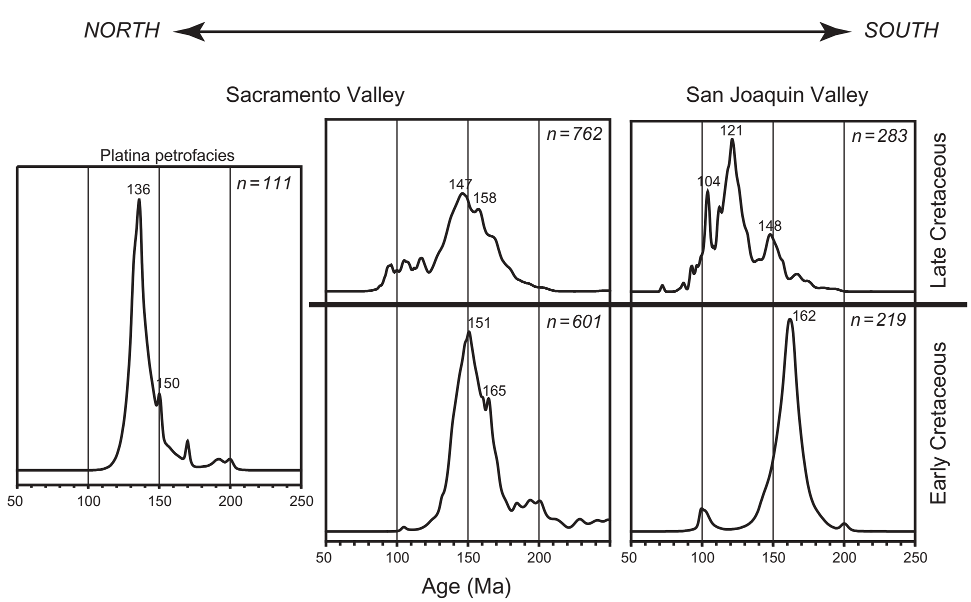

Figure 5. Probability density plots of the Mesozoic detrital zircon age signatures from the Sacramento and San Joaquin Valleys (see Figure 4 for data sources).

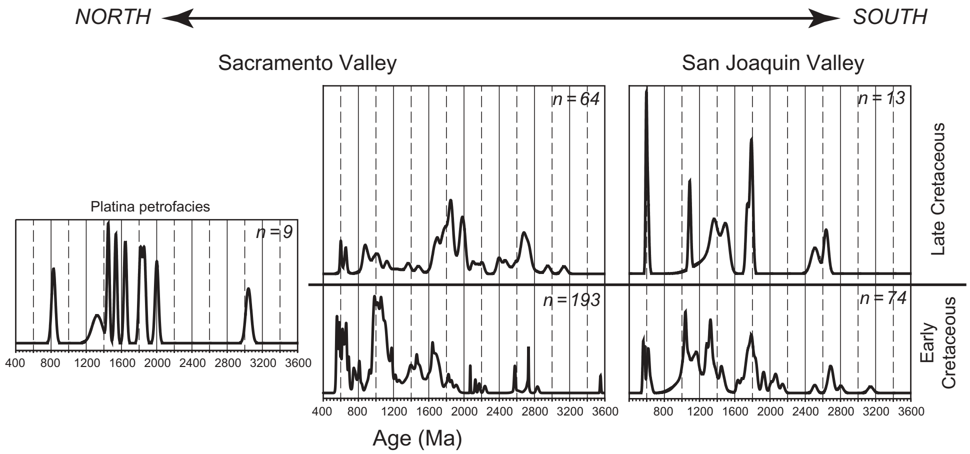

Figure 6. Probability density plots showing Precambrian detrital zircon age signatures from the Sacramento and San Joaquin Valleys (see Figure 4 for data sources). Shaded regions highlight age ranges characteristic of a southern Laurentian or northern Laurentian signature (after Grove *et al.* 2008).

Cretaceous grains that are typical of the Sacramento Valley section and also occur in the Upper Cretaceous San Joaquin section.

Within the Sacramento Valley, 22% of zircon grains in the Lower Cretaceous section and 8% in the Upper Cretaceous section are Precambrian. Lower Cretaceous Sacramento Valley strata include more Grenville-age zircon (1200–1000 Ma), whereas the Upper Cretaceous strata include more grains >1800 Ma (Figure 6). An even more dramatic decrease in the percentage of Precambrian grains occurs in the San Joaquin Valley, from 25% of the Lower Cretaceous section to only 4% of the Upper Cretaceous section, but similar Precambrian ages occur throughout the San Joaquin section (Figure 6). Palaeozoic detrital zircon grains occur in all sections, but do not form robust age peaks (>3 grains form a peak) and are not considered further here.

Because not all rocks in a tectonically active source region yield significant detrital zircon, zircon age signatures cannot provide a complete picture of a source area. Detrital zircon is typically derived from felsic to intermediate sources (Poldervaart 1956; Watson and Harrison 1983), and rarely occurs in samples lacking detrital quartz (Gehrels *et al.* 2006). Thus, prevalent sources of detrital zircon in the GVG are the felsic plutonic arc rocks and supracrustal metamorphic components of the country rock and adjacent terranes, with minor input from intermediate volcanic cover rocks and more mafic components. Moreover, zircon is most abundant in medium- to coarse-grained sandstone, effectively eliminating from age analysis the finer-grained sediment that comprises a significant part of the GVG.

Whole-rock major- and trace element geochemistry results

Geochemical analysis can help characterize provenance composition and delimit the effects of weathering and sedimentary sorting (e.g. McLennan 1989; McLennan *et al.* 1993), providing a useful complement to petrographic information and detrital zircon age signatures. Sedimentary geochemistry also permits identification of minor minerals not readily apparent in petrographic analysis, and can better characterize mafic components (McLennan *et al.* 1993; Fralick 2003). Mudstone, siltstone, and sandstone samples from the Sacramento Valley were analysed by XRF at the University of Wisconsin–Eau Claire; San Joaquin Valley samples were analysed by ICP-MS and XRF at Washington State University, following the procedures of Knaack *et al.* (1994) and Johnson *et al.* (1999; data presented in Tables 1 and 2).

Major-element geochemistry

Because major elements are susceptible to post-depositional mobility resulting from chemical weathering and diagenesis, the degree of weathering can be estimated using the chemical index of alteration (CIA; Nesbitt and Young 1982). The CIA is a ratio of the mole proportions of Al_2O_3 over the sum of Al_2O_3, K_2O, Na_2O, and CaO*, where CaO* is calculated by correcting for apatite using values of P_2O_5, following the method of McLennan *et al.* (1993). The ratio is multiplied by 100, such that fresh igneous and metamorphic rocks have CIA values of about 50, shale has CIA values of 70–75, and pure aluminosilicate weathering products, such as kaolinite, have a CIA value of 100 (Taylor and McLennan 1985; McLennan *et al.* 1993). The index of compositional variability (ICV) is the ratio of the mole proportions of the sum of CaO, K_2O, Na_2O, Fe_2O_3, MgO, MnO, and TiO_2 over Al_2O_3; it provides a measure of the source rock type (Cox *et al.* 1995; Potter *et al.* 2005). Rocks rich in non-clay silicate minerals or unweathered rocks have high ICV values, and

Table 1. Major-element geochemical data.

Sample	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	Total (%)
Sacramento Valley Early Cretaceous											
10GVG14	54.85	0.75	12.69	7.12	0.239	4.42	6.55	0.76	2.09	0.233	89.702
10GVG15	54.22	0.93	14.8	11.78	0.159	6.23	1.58	1.35	2.05	0.15	93.249
10GVG16	41.89	0.53	8.91	6.78	0.198	5.6	18.15	1.14	1.09	0.294	84.582
10GVG17	56.33	0.88	14.8	9.94	0.289	5.97	3.32	1.09	2.02	0.156	94.795
10GVG18	54.5	0.84	13.38	8.63	0.188	5.9	2.37	0.92	1.98	0.19	88.898
10GVG19	56	0.88	13.78	9.43	0.073	5.68	1.27	0.94	2.08	0.16	90.293
10GVG07	52.78	1.01	18.11	10.66	0.096	3.9	1.19	0.85	1.87	0.078	90.544
10GVG10	51.05	0.86	14.77	10.37	0.175	5.12	4.37	0.64	1.52	0.08	88.955
10GVG11	52.18	0.95	15.64	11.95	0.051	6.02	1.55	0.59	1.76	0.089	90.780
10GVG12	53.4	0.87	16.38	9.96	0.073	4.12	2.01	0.64	0.99	0.061	88.504
10GVG13	50.79	0.86	14.44	11.27	0.079	9.25	2.1	0.65	1.49	0.062	90.991
Sacramento Valley Upper Cretaceous											
10GVG01	51.96	0.85	15.87	12.64	0.192	5.29	2.2	0.66	1.62	0.066	91.348
10GVG02	51.04	0.81	15.8	11.01	0.161	8.53	4.9	1.23	1.69	0.13	95.301
10GVG03	49.86	0.93	15.31	11.74	0.14	7.39	3.37	1.09	1.43	0.106	91.366
10GVG04	55.1	0.94	15.96	10.36	0.055	4.13	1.72	0.81	2.43	0.114	91.619
10GVG05	53.72	0.88	15.7	10.92	0.066	5.04	1.85	0.83	2.33	0.092	91.428
10GVG06	54.67	0.83	13.85	9.59	0.051	5.49	2.11	1	1.95	0.114	89.655
10GVG08	52.15	0.84	16.62	11.07	0.143	5	2.27	0.98	1.67	0.083	90.826
10GVG09	50.49	1.01	13.07	12.34	0.121	6.57	3.13	0.99	1.6	0.148	89.469
10GVG29	40.18	0.42	7.76	3.79	0.325	2.29	28.21	0.43	1.53	0.281	85.216
10GVG30	52.17	0.88	11.88	7.94	0.065	5.12	2.46	0.72	1.95	0.125	83.310
Platina Petrofacies											
10GVG20	54.29	0.92	15.89	11.47	0.088	4.81	2.06	0.97	2.03	0.103	92.631
10GVG22	55.54	0.95	16.56	9.75	0.075	4.26	1.08	1.04	2.13	0.089	91.474
10GVG23	54.09	0.82	15.09	9.76	0.14	4.75	2.6	1.28	2.02	0.144	90.694
10GVG24	54.73	0.88	14.92	10.38	0.102	4.61	1.09	0.94	2.05	0.135	89.837
10GVG25	53.61	0.54	12.29	6.43	0.08	4.39	2.41	1.33	1.26	0.041	82.381
10GVG26	53.64	0.85	16.35	9.93	0.09	4.55	1.17	0.93	2.04	0.076	89.626
10GVG27	57.42	0.87	15.98	10.01	0.081	4.56	0.93	1.41	2.23	0.111	93.602
San Joaquin Early Cretaceous											
12GVG01	72.98	0.587	10.96	5.81	0.051	2.25	1.55	3.02	0.40	0.045	97.665
12GVG02	53.66	0.724	16.55	8.72	0.092	2.70	3.28	2.73	1.63	0.098	90.179
12GVG03	73.69	0.499	10.03	5.68	0.039	1.89	1.54	2.92	0.29	0.042	96.616
12GVG04	57.64	0.750	16.73	7.03	0.043	2.29	1.28	3.01	1.80	0.074	90.640
12GVG05	23.64	0.161	3.69	3.22	0.484	0.95	35.63	0.99	0.13	0.552	69.444
12GVG06	55.25	0.631	13.28	6.97	0.112	2.16	6.73	2.39	1.10	0.097	88.723
12GVG07	59.75	0.662	14.96	7.60	0.083	2.44	2.10	2.59	1.34	0.148	91.674
12GVG08	55.14	0.834	16.39	7.89	0.082	2.59	1.59	2.28	1.28	0.090	88.154
12GVG09	55.21	0.793	16.97	8.16	0.077	2.96	1.86	2.20	1.51	0.084	89.823
12GVG10	69.01	0.654	11.81	6.61	0.082	2.34	2.14	2.97	0.37	0.049	96.037
12GVG11	53.24	0.667	9.93	3.83	0.517	1.50	13.99	2.60	0.47	0.046	86.799
12GVG12	55.38	0.851	17.81	7.04	0.058	2.69	1.65	2.25	1.84	0.085	89.652
San Joaquin Late Cretaceous											
12GVG13	72.51	0.456	12.79	2.86	0.043	1.15	1.69	2.63	3.39	0.070	97.595
12GVG14	65.16	0.631	15.14	3.70	0.024	1.03	1.56	2.00	2.61	0.060	91.922
12GVG15	59.89	0.821	18.85	4.40	0.016	1.09	1.18	1.06	2.26	0.068	89.638
12GVG16	58.28	0.752	16.45	6.94	0.099	2.85	1.60	1.72	2.18	0.174	91.051
12GVG17	57.09	0.754	16.32	6.83	0.055	2.95	1.78	1.57	2.37	0.145	89.851
12GVG18	55.72	0.644	12.23	3.82	0.334	1.65	10.33	2.16	1.69	0.121	88.690
12GVG19	54.31	0.435	10.47	2.61	0.526	1.45	14.57	2.06	1.53	0.082	88.047
12GVG20	54.96	0.751	16.39	7.03	0.054	4.02	1.58	1.97	2.16	0.121	89.030
12GVG21	55.88	0.745	15.07	6.50	0.053	3.71	1.81	1.92	2.01	0.125	87.833
12GVG22	58.52	0.770	15.18	6.46	0.056	3.35	1.45	1.89	2.29	0.125	90.101
12GVG23	68.95	0.645	12.97	4.19	0.046	2.13	2.61	2.58	1.76	0.097	95.979
12GVG24	62.57	0.661	15.30	5.74	0.043	2.56	1.81	2.32	2.17	0.105	93.273
12GVG25	68.64	0.574	13.70	3.73	0.031	1.73	2.14	2.64	1.86	0.085	95.131
12GVG26	59.46	0.705	16.76	5.46	0.048	2.46	2.29	1.82	1.89	0.119	91.015
12GVG27	70.66	0.500	13.13	3.35	0.046	1.48	2.72	2.57	1.74	0.075	96.264
12GVG28	57.23	0.683	16.80	5.34	0.060	2.59	1.73	1.44	2.06	0.149	88.102

Table 2. Trace element geochemical data.

Sample	Ba (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Hf (ppm)	La (ppm)	Nb (ppm)	Nd (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sc (ppm)	Sr (ppm)	Th (ppm)	V (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
Sacramento Valley Early Cretaceous																			
10GVG14	370	37.9	59	245	69	4.5	12.5	8.8	22	126	16.8	58	21	182	6.3	179.7	27.6	147	144
10GVG15	572	30.4	67	287	99	4.3	14.3	6.2	19.4	137	8.2	53	25	141	3.4	261.3	20.5	139	130
10GVG16	359	24.4	74	305	48	3.2	7.5	4.3	16.6	177	3.3	28	27	212	1.9	157.6	15.5	78	95
10GVG17	742	39.6	63	258	83	5	13.6	7.3	22.1	117	13.8	59	23	165	5.4	228.6	21.8	157	140
10GVG18	882	34.1	64	384	63	5.6	14.2	8.8	18.1	193	10.8	56	19	111	5.9	203	23.2	152	155
10GVG19	731	39.1	63	290	76	5.1	17	8	20.2	164	11.6	63	20	146	7.8	216.6	23.5	153	146
10GVG07	621	36.4	70	243	114	4.5	9.9	6.4	17.5	69	13.4	63	33	160	6.4	263.3	20.8	143	133
10GVG10	569	27.6	76	398	85	3.5	14.2	5.1	14.7	191	9.3	48	30	111	4.4	225.8	24	126	108
10GVG11	652	29.2	70	405	107	4.4	17.3	6.5	12.2	234	8.4	59	33	88	4.3	264.4	18.5	132	115
10GVG12	259	21.9	63	352	63	3.9	9.3	3.6	15.1	52	5.3	33	29	116	2.9	230.1	18.4	127	101
10GVG13	535	25.4	85	536	88	4.3	9.9	5.2	20.6	279	9.7	46	31	133	4.6	285.2	21.3	128	110
Sacramento Valley Upper Cretaceous																			
10GVG01	727	15.7	23	347	84	3.4	14.7	4.9	9.6	84	11.1	58	26	152	4.4	221.3	17.5	130	103
10GVG02	430	24.3	33	246	100	3.2	11	4.2	16.4	123	6.5	61	32	263	2.8	211.6	23.4	119	104
10GVG03	397	20.4	37	365	96	3.2	12.2	4.4	16.9	115	6.3	52	33	286	3.5	227.1	19.9	121	112
10GVG04	756	44.1	51	181	90	4.8	15.8	8.3	24.2	88	21.8	90	23	221	9.5	223.8	21.5	160	144
10GVG05	781	49.1	56	206	90	4.7	15.1	7.2	22.2	88	17.1	87	25	242	7.2	210.3	21.1	154	137
10GVG06	581	43.7	58	233	49	4.5	13.5	6.9	17.9	86	18.5	64	18	245	7.8	180	22.5	121	145
10GVG08	486	28.5	69	230	98	4.1	8.7	4.5	15.8	70	9	59	30	200	3.5	219.8	18.9	126	112
10GVG09	563	40.1	73	467	92	3.8	18.6	6.1	20.9	127	8.1	44	30	243	3.2	264	21.7	105	128
10GVG29	272	30.2	63	310	11	4.1	4.8	5.2	13.5	43	9.5	39	23	224	3.6	89.5	14.2	59	127
10GVG30	1054	38.5	62	561	27	5.4	13.5	8.6	20.9	97	9.9	64	21	509	7.8	202	19.3	94	190
Platina Petrofacies																			
10GVG20	666	31.2	71	257	100	4.1	11.9	6.9	15.1	131	13.9	72	27	199	6.3	231.2	18.8	150	124
10GVG22	629	40.7	63	240	83	4.9	17.4	7.8	24.8	81	13.5	62	25	139	5.9	252.4	22.2	156	145
10GVG23	650	37.9	75	257	80	4.4	12.3	6.4	24.8	115	20.7	56	25	194	5.5	239.8	28.8	198	132
10GVG24	767	40.3	63	226	89	4.3	15.5	7.3	20.3	86	11.5	63	25	124	6.1	264.6	23.8	154	128
10GVG25	651	30.9	53	626	21	3.3	14.9	3.9	17.4	33	7	29	19	205	7.1	149.2	19.3	82	113
10GVG26	935	30.2	67	245	87	4.2	14.2	6.4	18	73	11.4	59	27	107	4.1	236	22.9	136	124
10GVG27	650	40.3	58	152	88	4.7	11.8	6	21.1	57	11.8	63	25	158	5.9	242.1	24.2	173	142
San Joaquin Early Cretaceous																			
12GVG01	268	13.24		140	12	1.81	6.55	1.66	8.49	21	2.94	11.2	17.8	117	0.63	146	12.63	50	64
12GVG02	715	16.00		109	81	2.33	7.74	3.35	10.87	54	8.95	53.1	27.2	110	2.44	194	23.32	125	83
12GVG03	219	8.10		119	15	1.64	4.30	1.39	5.37	16	2.14	8.8	16.1	90	0.54	130	10.33	54	56
12GVG04	894	9.58		112	100	2.58	5.02	3.72	7.20	42	5.15	60.7	32.3	139	2.97	215	17.58	126	89
12GVG05	231	10.24		26	21	0.60	8.92	0.82	5.50	9	1.43	4.8	7.1	294	0.65	51	13.12	28	25

(*Continued*)

Table 2. (Continued).

Sample	Ba (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Hf (ppm)	La (ppm)	Nb (ppm)	Nd (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sc (ppm)	Sr (ppm)	Th (ppm)	V (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
12GVG06	490	13.97		92	68	2.33	7.24	3.07	9.62	32	5.91	38.0	23.6	163	2.79	159	19.19	113	78
12GVG07	538	21.10		90	96	2.41	10.77	3.51	16.29	41	6.70	45.8	27.3	142	2.99	179	24.81	110	84
12GVG08	287	17.56		97	83	2.57	8.11	3.79	10.77	37	5.80	45.6	29.4	106	2.90	196	20.25	116	90
12GVG09	320	18.39		97	78	2.75	8.14	3.88	10.43	38	5.80	52.5	28.7	95	3.12	195	19.81	114	93
12GVG10	179	13.88		84	25	2.04	6.28	1.62	8.10	22	3.77	11.3	20.2	115	0.72	153	14.65	64	70
12GVG11	148	15.28		93	17	2.11	7.00	1.61	10.04	11	2.17	13.7	20.8	145	0.66	168	26.54	55	73
12GVG12	359	15.63		102	87	3.03	6.96	4.18	9.63	33	5.20	62.6	33.1	101	3.62	208	18.63	117	104
San Joaquin Late Cretaceous																			
12GVG13	853	51.13		27	11	3.91	27.34	9.96	20.57	8	15.94	115.6	7.7	224	11.50	67	15.77	55	142
12GVG14	596	24.87		48	11	3.05	12.41	9.21	11.39	11	12.36	120.1	8.8	164	7.60	87	10.20	82	105
12GVG15	634	31.67		105	48	3.66	16.44	12.19	19.86	25	32.52	78.0	15.5	105	13.78	152	17.31	106	127
12GVG16	630	48.11		118	71	3.45	22.89	8.93	23.89	77	14.76	94.0	19.4	148	8.58	158	26.59	116	123
12GVG17	661	40.21		115	66	3.76	20.81	9.56	20.06	61	14.92	95.0	20.1	136	9.09	161	22.93	122	132
12GVG18	513	40.27		84	27	4.95	20.66	7.67	18.32	43	9.73	58.2	12.4	240	7.60	98	22.06	63	184
12GVG19	479	26.70		62	15	2.95	13.43	4.97	12.50	22	6.60	49.9	10.4	246	4.82	81	14.40	44	107
12GVG20	578	47.97		124	37	3.62	23.72	8.80	23.96	32	16.53	90.7	20.4	155	8.67	165	26.71	121	131
12GVG21	544	46.97		108	37	3.74	23.40	8.89	23.28	29	16.43	84.9	18.3	166	8.03	146	26.70	107	135
12GVG22	616	56.14		102	54	4.25	27.67	9.93	27.13	54	14.73	93.6	19.2	176	9.33	154	27.53	104	154
12GVG23	524	38.32		107	18	4.92	19.15	6.60	17.57	33	8.15	55.5	16.3	213	7.02	125	17.53	63	177
12GVG24	572	42.69		97	38	4.35	21.16	8.35	19.73	55	14.93	81.0	17.3	178	10.03	124	20.27	95	150
12GVG25	519	35.14		79	19	4.04	17.74	6.91	16.08	30	8.26	61.7	13.2	201	7.28	98	15.95	57	144
12GVG26	515	44.88		79	52	3.47	27.96	7.99	26.86	28	12.43	78.9	17.2	202	7.81	141	23.91	99	125
12GVG27	504	39.13		41	10	5.76	16.41	5.67	15.59	13	8.04	56.4	13.2	251	10.19	78	13.70	51	204
12GVG28	602	46.26		102	51	3.55	23.23	9.24	24.43	37	14.18	91.1	19.3	198	9.65	144	27.81	102	123

mature sedimentary rocks or weathered rocks have low values.

A plot of CIA *versus* ICV can help assess the relationship between the extent of weathering and source rock type (Cox *et al.* 1995; Potter *et al.* 2005; LaMaskin *et al.* 2008). CIA values for all GVG samples are similar, but samples from the Sacramento Valley (mean ICV of 1.5 ± 0.2) plot above the weathering trend of fresh basalt (Figure 7a) and are distinctly more immature than samples from the San Joaquin Valley (mean ICV of 1.0 ± 0.2). The more immature ICV values for Sacramento Valley samples suggest a high proportion of non-clay silicates and/or abundant montmorillinite and sericite clay minerals, which is typical of tectonically active settings receiving first-cycle detritus (Cox *et al.* 1995). Within the San Joaquin samples, the most mature ICV values occur in the Upper Cretaceous samples (mean ICV of 0.9 ± 0.1), with the Lower Cretaceous San Joaquin samples (mean ICV of 1.2 ± 0.2) plotting closer to the Sacramento Valley samples (Figure 7a). The more mature ICV record from the San Joaquin Valley suggests the presence of more kaolinite group clays and fewer non-clay silicates, which is typical of sedimentary recycling (Cox *et al.* 1995). The weathering trends for all San Joaquin samples indicate original source rock composition between basalt and andesite.

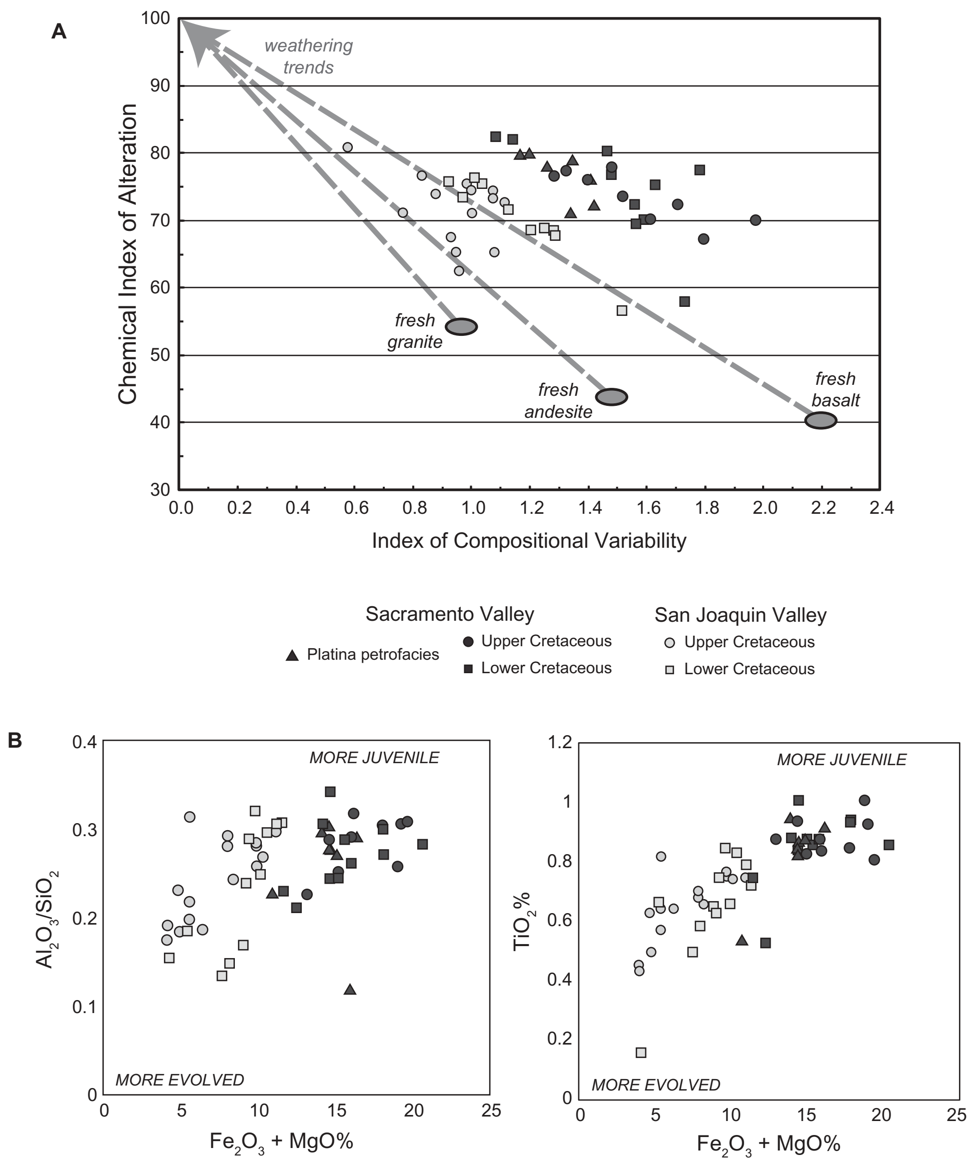

Figure 7. (a) Plot of chemical index of alteration (CIA) *versus* index of chemical variability (ICV) showing the relationship between the degree of source-area weathering and the original detrital mineralogy (after Potter *et al.* (2005) and LaMaskin *et al.* (2008)). ICV values for basalt and granite from Li (2000) and for andesite from Ewart (1982). (b) Major-element provenance diagrams after Bhatia and Crook (1986), showing more evolved provenance for San Joaquin Valley samples and more juvenile provenance for Sacramento Valley samples.

Although post-depositional mobility limits the use of major elements for provenance determination (Armstrong-Altrin and Verma 2005), Ti and Al are considered immobile up to greenschist-grade metamorphic conditions (MacLean 1990; Jenner 1996). Thus, mafic *versus* felsic sources may be distinguished on plots of wt% TiO_2 and Al_2O_3/SiO_2 *versus* FeO* + MgO (Bhatia and Crook 1986; Ryan and Williams 2007; LaMaskin *et al.* 2008). Again, the Sacramento and San Joaquin samples plot in two distinct fields, with Sacramento samples showing a consistently more mafic, juvenile provenance signature than San Joaquin samples in both plots (Figure 7b). Overlap among samples within each of these fields precludes further subdivision based on age or location.

Trace element geochemistry

Trace elements (large-ion lithophile elements [LILEs], high-field-strength elements [HFSEs], and rare earth elements [REEs]) generally have low post-depositional mobility and are strongly excluded from seawater, making them extremely useful provenance indicators (McLennan *et al.* 1993). These immobile trace elements, such as Th, Sc, and La, can effectively highlight differences between samples (Ryan and Williams 2007), revealing lateral and vertical changes within basin stratigraphy and between basins, even if they are not reliable indicators of specific tectonic settings (e.g. Armstrong-Altrin and Verma 2005).

Comparing incompatible elements Th and Zr to the compatible element Sc provides a measure of the relative importance of magmatic *versus* sedimentary processes within the source region, as well as differentiates among contributions of source compositions (e.g. Fralick 2003). Magmatic differentiation tends to increase the Th/Sc ratio, whereas sedimentary recycling tends to concentrate zircon and thereby increase the Zr/Sc ratio (McLennan *et al.* 1990). A plot of Zr/Sc *versus* Th/Sc shows all Sacramento Valley samples plotting near andesite values (values from Taylor and McLennan (1985)), with a spread towards granodiorite (Figure 8a; values from Taylor and McLennan (1985)). In contrast, San Joaquin Valley samples plot in two distinct fields: Lower Cretaceous samples plot close to andesite values, but extend towards MORB (value from Sun and McDonough (1989)) along a vertical trend indicative of magmatic differentiation; Upper Cretaceous samples plot close to granodiorite, along a trend suggestive of increased sedimentary recycling (Figure 8a).

A ternary plot of incompatible elements La and Th and compatible element Sc is also a good discriminator of juvenile and evolved crust (Bhatia and Crook 1986; McLennan *et al.* 1990, 1993). GVG samples have diverse compositions overall, but only the Upper Cretaceous San Joaquin samples plot near the North American Shale Composite (NASC; values from Gromet *et al.* (1984)) and Upper Continental Crust (Figure 8b). All Sacramento Valley samples plot near continental arc values, with scatter trending towards MORB; only Lower Cretaceous San Joaquin samples plot close to MORB values (Figure 8b).

Where Cr and Ni concentrations are anomalously high, a Cr/Ni ratio between 1.2 and 1.6 suggests an ultramafic source (Garver and Royce 1993; Garver *et al.* 1994). None of the GVG samples show anomalously high Cr or Ni concentrations, suggesting limited or diluted contribution from ultramafic sources. Cr concentrations in the Sacramento Valley range widely from 152 to 626 ppm, with a mean of 316 ± 117. Cr concentrations are both lower and less variable in the San Joaquin Valley, ranging from 26 to 140 ppm, with a mean of 91 ± 28. Ni concentrations show similar variation, with lower concentration and variability in San Joaquin samples, such that Cr/Ni mean ratios from the Sacramento Valley and San Joaquin

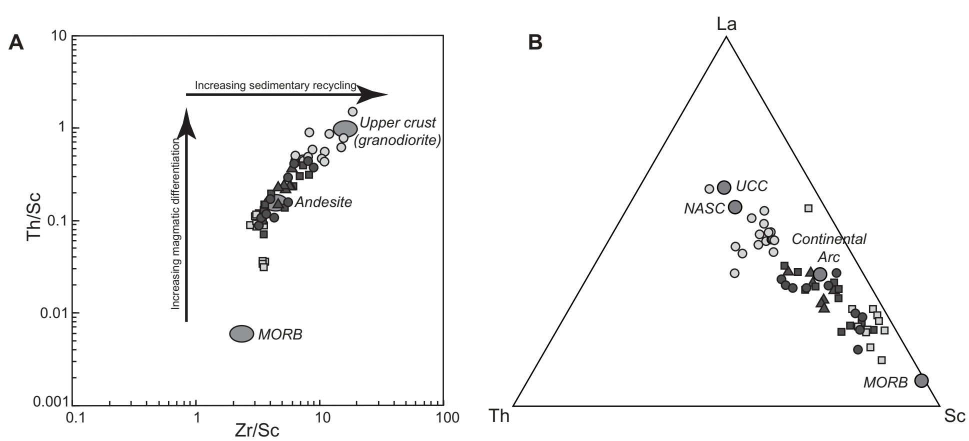

Figure 8. (a) La/Sc *versus* Zr/Sc plot, after McLennan *et al.* (1990); values for andesite and upper crust granodiorite from Taylor and McLennan (1985), MORB value from Sun and McDonough (1989). (b) Ternary plot of La-Th-Sc; values of potential source rocks are from Taylor and McLennan (1985) and McLennan *et al.* (1993).

Valley are similar (3.5 ± 3.4 and 3.3 ± 1.7, respectively), although the greater spread within the Sacramento Valley results in the larger standard deviation around the mean.

V, Ni, and Th*10 can be used as proxies for relative contributions of mafic, ultramafic, and felsic sources, respectively (Figure 9a; Bracciali *et al.* 2007). No GVG samples record dominantly ultramafic or felsic sources, but the San Joaquin samples again split into two distinct fields, with Lower Cretaceous samples plotting closest to the mafic pole (V), and Upper Cretaceous samples plotting closest to the felsic pole (Th*10). Platina samples plot between these end members and contain no evidence of ultramafic source contribution, whereas Lower Cretaceous Sacramento samples show the most ultramafic influence (Figure 9a).

Increasing V and Sc concentrations suggest an increasing volcanic component in the sediment (Ryan and Williams 2007). In general, Sacramento Valley and Lower Cretaceous San Joaquin Valley samples all show elevated V and Sc relative to Upper Cretaceous San Joaquin samples, suggesting relatively reduced volcanic contribution to the Upper Cretaceous San Joaquin basin (Figure 9b).

Discussion

Sacramento Valley provenance record

The Sacramento Valley provenance signature is consistent with sediment sources in the Klamath Mountains and northern Sierran foothills terranes. Middle to Late Jurassic and earliest Cretaceous magmatic zircon from the developing Jurassic-Cretaceous magmatic arc dominates the detrital record (e.g. DeGraaff-Surpless *et al.* 2002; Sharman *et al.* in press). Lower Cretaceous conglomerate and sandstone lithic populations are consistent with sources in the accreted terranes that comprise the northern Sierran foothills and the Klamath Mountains (e.g. Bertucci 1983; Ingersoll 1983; Short and Ingersoll 1990). Precambrian detrital zircon in these Lower Cretaceous strata was probably recycled through quartz-rich meta-sedimentary units within the Klamath Mountains and/or the northern Sierran foothills terranes. For example, detrital zircon from the Duzel Phyllite and Moffett Creek Formation within the Yreka subterrane in the Klamath Mountains includes similar abundant Grenville-age zircon (950–1200 Ma), as well as peaks at 1400 and 1600–1700 Ma, considered characteristic of southern Laurentia basement rocks (Figure 10; Grove *et al.* 2008). Early Cretaceous exhumation of Klamath terranes (Cashman and Elder 2002; Batt *et al.* 2010) may have followed proposed 140–136 Ma Pacificward offset of the Klamath Mountains (Ernst 2012), and resulted in abundant Klamath-derived sediment shed southward into the Sacramento Valley during the Early Cretaceous.

Upper Cretaceous sandstone recorded more sediment contribution from the magmatic arc rocks that intruded the accreted terranes, and the more volcanic- and metamorphic-rich lithic compositions were probably derived from eroded roof pendants and the volcanic carapace of the arc (Ingersoll 1983). Similarly, reduction in the percentage of Precambrian grains in Upper Cretaceous strata may reflect dilution of the Precambrian signal by the increasingly abundant zircon eroded from the zircon-rich magmatic arc. Furthermore, the shift in the Precambrian age signature from abundant Grenville-age zircon in Lower Cretaceous strata to a larger proportion of >1800 Ma zircon in Upper Cretaceous strata may reflect derivation of zircon from different meta-sedimentary terranes in the Sierran foothills (Figure 10), such as the Shoo Fly Complex (Harding *et al.* 2000) and overlap sequence (Spurlin *et al.* 2000), rather than from Klamath Mountains sources. This shift to Sierran sources for the Upper Cretaceous GVG is consistent with a change from south- to west-directed palaeocurrent indicators and may be related to Late Cretaceous subsidence of the eastern Klamath Mountains and deposition of the middle to

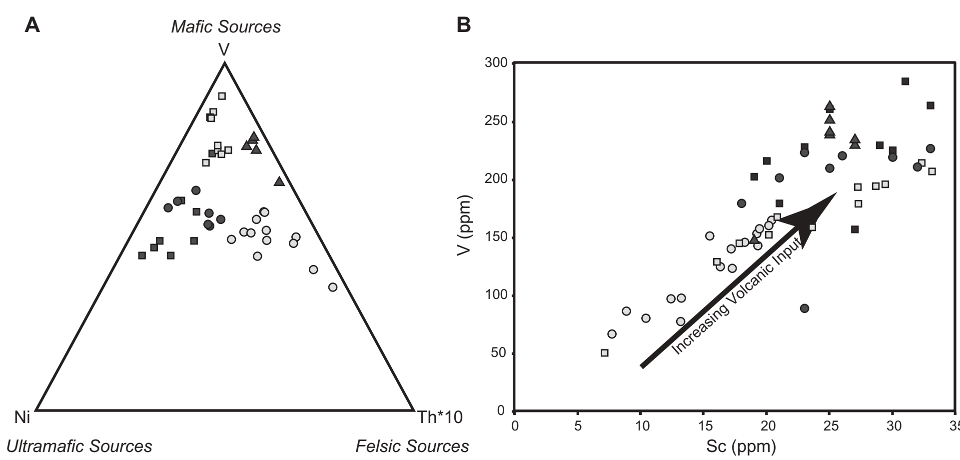

Figure 9. (a) Ternary plot of V-Ni-Th*10 to represent relative contributions of mafic, ultramfic, and felsic sources, respectively (after Bracciali *et al.* (2007)). (b) Plot of Sc *versus* V concentrations; Upper Cretaceous San Joaquin Valley samples have the lowest Sc and V concentrations, indicative of reduced volcanic input (after Ryan and Williams (2007)).

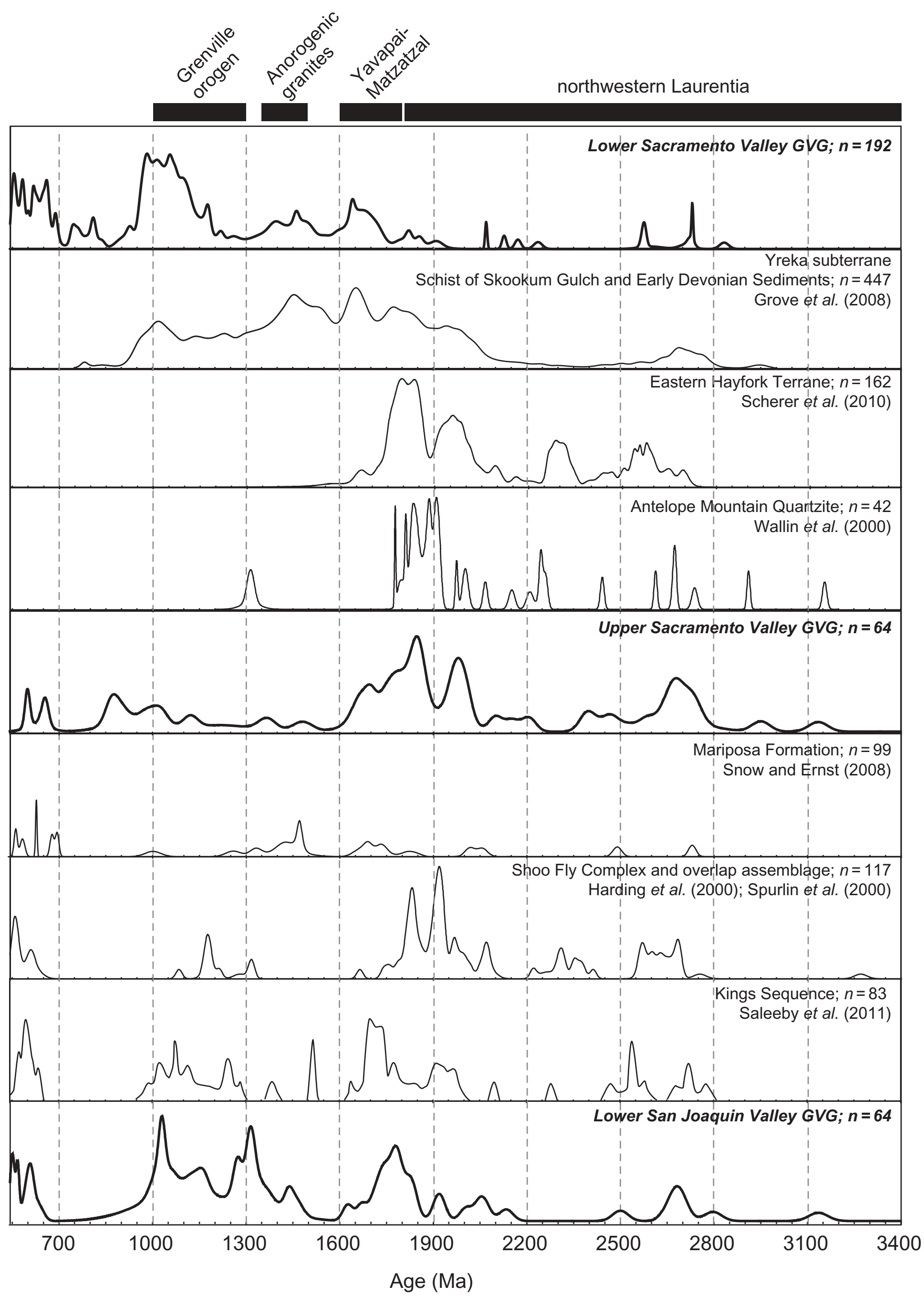

Figure 10. Precambrian detrital zircon age spectra for the Lower and Upper Cretaceous Sacramento Valley and the Lower Cretaceous San Joaquin Valley GVG, plotted with reference detrital zircon age spectra for Palaeozoic and Triassic terranes of the Cordillera. Black bars at the top represent crystallization ages characteristic of northwestern Laurentia (abundant 1800–2000 Ma and older zircon) and southwestern Laurentia (abundant zircon younger than 1800 Ma; Grove *et al.* 2008).

Upper Cretaceous Hornbrook Formation on eastern Klamath terranes (Haggart 1986; Nilsen 1993; Surpless and Beverly 2013). The Platina detrital zircon signature is consistent with sediment sources wholly in the Klamath Mountains, dominated by latest Jurassic and earliest Cretaceous plutons that intruded the southern Klamath Mountains, including the Shasta Bally batholith (136 Ma; Lanphere and Jones 1978).

Although deposition continued throughout the Late Cretaceous, relatively few Late Cretaceous zircon grains from the main Cretaceous Sierran batholith (125–85 Ma) reached the Sacramento Valley until the latest Cretaceous

(DeGraaff-Surpless *et al.* 2002; Sharman *et al.* in press). These results suggest that sediment sources may have remained largely limited to western Sierran terranes until Maastrichtian time (DeGraaff-Surpless *et al.* 2002; Sharman *et al.* in press), or that the volcanic carapace to the <100 Ma arc intrusions did not include abundant zircon (Sharman *et al.* in press). Maastrichtian and younger GVG detrital zircon signatures are characterized by abundant mid-Cretaceous zircon and fewer Early Cretaceous and Jurassic grains, suggesting either that GVG drainage systems reached eastward into the <100 Ma arc rocks by latest Cretaceous time (DeGraaff-Surpless *et al.* 2002; Sharman *et al.* in press) or that removal of the zircon-poor volcanic carapace finally exposed zircon-rich plutonic rocks of the <100 Ma arc. However, the mid-Cretaceous (ca. 98 Ma) detrital zircon peak also characterizes much of the Albian(?) and younger strata in the Ochoco basin of central Oregon (Kochelek 2009), suggesting that N-directed axial drainage within the Sierran arc transported arc-derived sediment to regions north and northwest of the arc during much of the Late Cretaceous (Kochelek 2009; Surpless and Beverly 2013). Because these Ochoco basin strata are also rich in volcanic lithic grains, both the <100 Ma volcanic carapace and its plutonic roots probably shed abundant zircon during the entire Late Cretaceous, but this central and eastern arc detritus was partitioned from the Sacramento basin to the west until eastward migration of westward-flowing drainage systems reached the arc axis during the latest Cretaceous. Abundant mid-Late Cretaceous zircon was then transported west into the GVG during Maastrichtian and Palaeocene time (DeGraaff-Surpless *et al.* 2002; Sharman *et al.* in press), reflecting the high-standing topography of the Late Cretaceous Sierra Nevada arc (Cecil *et al.* 2010; Cassel *et al.* 2012; Sharman *et al.* in press).

Geochemical results from the Sacramento Valley complement the provenance record contained in the sandstone; these samples record a mafic geochemical signature, with immature compositions suggesting significant compositional variability in source rocks typical of first-cycle detritus and consistent with derivation from the accreted terranes of the Klamath Mountains and northern Sierran foothills terranes. Elevated V and Sc abundance in Sacramento Valley samples suggests significant volcanic input, consistent with the high volcanic lithic component in the sandstone, and any signal from ultramafic sources, if present, is minor compared with the more abundant mafic to intermediate compositions in source areas. Similarly, Linn *et al.*'s (1992) isotopic study of GVG strata shows that Sacramento Valley sandstones are characterized by mainly positive ε_{Nd} values ranging from −1.6 to +7, and that significant variation in ε_{Nd} correlates with lithic composition; samples with abundant volcanic lithic grains have more positive ε_{Nd} values, whereas sandstone with sedimentary and meta-sedimentary lithic grains have more negative ε_{Nd} values.

The geochemical signal from Sacramento Valley samples remains relatively consistent through time, even as detrital zircon and sandstone petrofacies record a Late Cretaceous shift to more feldspathic, arc-derived sediment. These results are consistent with sediment sources in the Klamath Mountains, northern Sierran foothills terranes, and the northern Sierra Nevada batholith, all of which have positive ε_{Nd} values (0 to more than +6; DePaolo 1981), and are north and west of the $^{87}Sr/^{86}Sr$ 0.706 line denoting the edge of North American Precambrian basement (Kistler and Peterman 1973; Linn *et al.* 1992).

San Joaquin Valley provenance record

The San Joaquin basin provenance record shares many similarities with the Sacramento Valley provenance signal and is consistent with sediment sources in the southern Sierra Nevada (e.g. Dickinson and Rich 1972; Ingersoll 1979; Mansfield 1979). Both basins are characterized by first-cycle arc-derived sandstone that shifted to more feldspathic compositions in Late Cretaceous time. However, the San Joaquin basin samples record greater exhumation and erosion of the volcanic carapace of the southern Sierra Nevada during the Early Cretaceous. Chert-rich sources in the Klamath Mountains and northern Sierran Foothills terranes apparently did not supply sediment to the San Joaquin basin. Instead, volcanic rocks of the western Sierran magmatic arc shed abundant sediment west into the San Joaquin basin during the Early Cretaceous, and sources shifted eastward into the more deeply eroded magmatic arc and its metamorphic roof pendants by Late Cretaceous time.

Detrital zircon ages from Lower Cretaceous samples are characterized by a prominent Late Jurassic peak, whereas Upper Cretaceous San Joaquin samples include abundant Late Cretaceous zircon, as well as latest Jurassic-earliest Cretaceous zircon (Figure 5). San Joaquin samples also record a significant decrease in Precambrian detrital zircon in the Late Cretaceous, and the few Precambrian grains in Upper Cretaceous San Joaquin strata are similar in age to those abundant in Lower Cretaceous strata (Figure 6), suggesting a consistent source of Precambrian zircon that was diluted by the abundant Mesozoic magmatic zircon as the arc was further exhumed and more deeply eroded.

Lower Cretaceous San Joaquin strata have the most mafic trace element geochemical signature of any GVG samples (Figures 8 and 9), and may show evidence of significant magmatic differentiation processes controlling geochemical character (Figure 8). In contrast, Upper Cretaceous San Joaquin samples record the most felsic geochemical signatures (Figures 8 and 9) and contain the lowest abundance of Sc and

V, indicative of reduced volcanic input and consistent with the very high Lm/Lv ratio of Upper Cretaceous sandstone. ε_{Nd} values from Upper Cretaceous San Joaquin Valley samples are also more evolved and less variable than Sacramento Valley samples, with ε_{Nd} ranging from −0.7 in the lowermost Upper Cretaceous samples to −5 in the uppermost (Linn *et al.* 1992).

The southwestern Sierra Nevada foothills provide an excellent match for the provenance record of the Lower Cretaceous San Joaquin strata. The southwestern Sierran foothills belt includes Early Cretaceous meta-volcanic rocks, including ring dike complexes that may have fed Early Cretaceous arc volcanoes (Clemens-Knott and Saleeby 1999), as well as Upper Triassic to Jurassic meta-siliciclastic turbidites (Saleeby 2011). The Precambrian detrital zircon age signature from the Kings Sequence (Saleeby 2011) is typical of a southern Laurentian signature with a few >1800 Ma grains (after Grove *et al.* 2008), and is similar to Precambrian ages in Lower Cretaceous San Joaquin Valley samples (Figure 10; Clemens-Knott *et al.* 2013). Although much of the Precambrian zircon can ultimately be traced to crystalline basement rocks in northern or southern Laurentia (cf. Grove *et al.* 2008), the likelihood of recycling Precambrian grains through Palaeozoic and younger deposits prior to deposition in the Cretaceous forearc basin (Dickinson and Gehrels 2009; LaMaskin *et al.* 2011; LaMaskin 2012) precludes direct connection between the GVG basin and crystalline basement rocks in the continental interior.

The volcanic carapace fed by ring dikes in the Stokes Mountain region within the southwestern Sierran foothills (Clemens-Knott and Saleeby 1999) may have provided abundant volcanic lithic grains to Lower Cretaceous San Joaquin strata without supplying much Early Cretaceous detrital zircon, as these volcanic compositions likely did not produce much zircon. Moreover, the ring dike complexes were emplaced 123–117 Ma, and have a MORB geochemical signature (Clemens-Knott and Saleeby 1999). Although depositional age control on Lower Cretaceous San Joaquin strata is limited (e.g. Rose and Colburn 1963; Linn *et al.* 1992), the youngest detrital zircon grains within these samples suggest deposition in the late Early Cretaceous, following development of Early Cretaceous stratovolcanoes and emplacement of associated ring dikes.

By Late Cretaceous time, the volcanic carapace of the southwestern Sierran foothills and western magmatic arc was eroded, and emplacement and rapid uplift of younger plutons to the east resulted in a dramatic shift in sediment character. Upper Cretaceous San Joaquin strata were derived from the rapidly denuding magmatic arc east of the initial $^{87}Sr/^{86}Sr$ 0.706 line (Mansfield 1979; Ingersoll 1983), and the increase in felsic plutonic sources greatly diluted the Precambrian detrital zircon contribution; detrital zircon was mainly derived from the Late Cretaceous arc. Major- and trace element geochemistry effectively documents this shift as well, with only Upper Cretaceous San Joaquin samples showing the most evolved and felsic geochemical signatures.

Translational forearc basin?

Alternatively, changes in GVG provenance signatures may result from translation of much of the GVG forearc from a more southerly location during its earliest history to its current position by middle Early Cretaceous time (Wright and Wyld 2007). Based on Precambrian detrital zircon ages, differences in deformation and metamorphic histories, and discontinuities within the Lower Cretaceous GVG, Wright and Wyld (2007) proposed at least 500 km offset along a dextral strike-slip fault located within the forearc basin, placing basal GVG strata adjacent to the Mojave–Arizona–Sonora segment of the Mesozoic continental arc and far removed from the Platina strata that form a Lower to Upper Cretaceous overlap sequence on the Klamath Mountains. Wright and Wyld (2007) proposed that translation occurred during Early Cretaceous time and suggest that Cenomanian GVG strata may form an overlap assemblage linking their northern 'Klamath Mountains' GVG basin with their 'Coast Ranges' GVG basin. According to the Wright and Wyld (2007) model, sediment sources of basal GVG strata would be within the Cordilleran Mesozoic arc that intruded southwestern Laurentia, Early Cretaceous strata may record a translational history, and middle and Upper Cretaceous strata would have sediment sources in the Klamath-Sierran arc.

Geochemical results presented here suggest that the Platina, Lower, and Upper Cretaceous strata within the Sacramento Valley record similar sediment sources throughout deposition, and these sources include not only significant compositional variability but also a consistently mafic to intermediate arc source, with possible contribution from ultramafic rocks. These results, combined with abundant volcanic and chert lithic grains in sandstone, detrital zircon ages consistent with Klamath Mountains and northern Sierran sources, and previously published positive ε_{Nd} values, are not consistent with large-scale translation and more southerly sediment sources for the older, non-Platina Sacramento Valley samples. The overlap among Sacramento basin samples indicates that sediment sources remained largely consistent and west of the initial $^{87}Sr/^{86}Sr$ 0.706 line. Variability within the provenance signal that is reflected in sandstone petrofacies and detrital zircon ages could have resulted from changing drainage systems as the Cretaceous arc was uplifted and eroded, but does not reflect a trend to more mafic and juvenile sources of the Klamath Mountains and Sierran foothills terranes from the more evolved sources that would characterize a southwestern Laurentian source region.

Lower Cretaceous San Joaquin basin samples may postdate proposed Early Cretaceous translation, but geochemical results from the San Joaquin basin effectively illustrate that even the homogenized provenance signal recorded by geochemistry can reveal significant changes in provenance. The shift from mafic and MORB-like signals with abundant volcanic lithic grains in sandstone, to the most felsic and upper-continental crustal geochemical signal with abundant metamorphic lithic grains in sandstone is consistent with sediment sources shifting from the volcanic-rich western foothills belt during the Early Cretaceous to the deeply eroded plutons of the Cretaceous batholith during the Late Cretaceous. San Joaquin basin Precambrian detrital zircon ages remain consistent through the Cretaceous, even as these older grains were swamped by abundant arc zircon in Late Cretaceous time. Although the ultimate source of much of Precambrian detrital zircon within forearc strata may include basement terranes in southwestern Laurentia, the recycling of these grains through younger Palaeozoic and Mesozoic strata has been documented within terranes of the Sierran foothills belt (e.g. Grove *et al.* 2008; Saleeby 2011; LaMaskin 2012), and thus their presence within the GVG forearc basin does not require that drainage systems transported zircon directly from southwestern Laurentian sources.

Conclusions

The robust GVG provenance signatures compiled here document primarily magmatic arc sources throughout GVG deposition. The GVG provenance record does not require sediment sources inboard of the arc at any time during GVG deposition, and even earliest Cretaceous drainage systems may not have traversed the arc to link the continental interior with the margin. The GVG provenance signature is compatible with sediment sources within the Klamath Mountains, the northern and western Sierran foothills, and the main Cretaceous Sierran batholith, suggesting that the Klamath–Sierran magmatic arc may have formed a high-standing topographic barrier throughout the Cretaceous Period.

The southern Sierran batholith was uplifted and shedding sediment into the San Joaquin basin to the west by early Late Cretaceous time, but abundant sediment derived from the Cretaceous batholith in the north did not find its way into the Sacramento basin until latest Cretaceous time. The marked change in the geochemical provenance signature of San Joaquin samples from Early to Late Cretaceous probably reflects a shift from sources in the now-eroded western arc volcanoes of the Sierran foothills largely west of the margin of Precambrian continental crust, to more eastern plutonic rocks and metamorphic roof pendants of the main Cretaceous batholith that intruded into evolved basement close to and east of the Precambrian continental margin. Farther north, the Precambrian continental margin is east of the main Cretaceous batholith. As a result, Upper Cretaceous strata in the Sacramento and San Joaquin basins have distinct geochemical signatures, while Lower Cretaceous strata share a common geochemical signature derived from more juvenile volcanic arc rocks and intruded terranes of the Klamath Mountains and the northern and western Sierran foothills terranes.

The GVG geochemistry documents the presence of significant sediment sources in mafic and non-zircon-bearing terranes of the Klamath Mountains and Sierran foothills terranes, providing a more robust provenance signature than either sandstone petrofacies or detrital zircon analysis alone. Because fine-grained GVG strata comprise a significant part of GVG sediment, geochemistry provides an overall provenance framework within which to interpret sandstone petrofacies and detrital zircon ages. The integrated provenance signature for the GVG throughout the Cretaceous may help constrain proposed links between the main GVG outcrop belt and faulted GVG exposures west of the San Andreas fault system, and strengthen existing links between the forearc and the accreted Franciscan Complex (e.g. Ghatak *et al.* 2013).

Acknowledgements

I thank Charles Knaack, Laureen Wagoner, and Richard Conrey at the GeoAnalytical Laboratory at Washington State University, and Jill Ferguson and J. Brian Mahoney at the University of Wisconsin–Eau Clair for geochemical analyses. I am grateful to Scott Johnston for assistance in the field and numerous discussions of the GVG, and to Katie Todt and Brandon Shaw for their help with sample collection and processing, as well as discussions of Sacramento Valley geochemical results. Detrital zircon ages newly presented here were collected at the University of Arizona Laserchron Center with assistance from Nicky Geissler and Mark Pecha, and we gratefully acknowledge National Science Foundation (NSF) grant EAR-1032156 for support of the Arizona Laserchron Center. Thoughtful comments and reviews from Gary Ernst and Ray Ingersoll and Guest Editor John Wakabayashi improved this manuscript.

Funding

This work was supported by the National Science Foundation (NSF) [grant number EAR ICER 846695].

Supplemental data

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/00206814.2014.923347.

References

Ague, J.J., and Brimhall, G.H., 1988, Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization: Geological Society of America Bulletin, v. 100, p. 912–927. doi:10.1130/0016-7606(1988)100<0912:MAAADO>2.3.CO;2

Armstrong-Altrin, J.S., and Verma, S.P., 2005, Critical evaluation of six tectonic setting discrimination diagrams using geochemical data of Neogene sediments from known tectonic settings: Sedimentary Geology, v. 177, p. 115–129. doi:10.1016/j.sedgeo.2005.02.004

Barth, A.P., Wooden, J.L., Jacobson, C.E., and Economos, R.C., 2013, Detrital zircon as a proxy for tracking the magmatic arc system: The California arc example: Geology, v. 41, p. 223–226. doi:10.1130/G33619.1

Bateman, P.C., 1983, A summary of critical relations in the central part of the Sierra Nevada Batholith, California, USA, *in* Roddick, J.A., ed., Circum-Pacific plutonic terranes: Boulder, Geological Society of America, p. 241–254.

Batt, G.E., Cashman, S.M., Garver, J.I., and Bigelow, J.J., 2010, Thermotectonic evidence for two-stage extension on the Trinity Detachment Surface, Eastern Klamath Mountains, California: American Journal of Science, v. 310, p. 261–281. doi:10.2475/04.2010.02

Bertucci, P.F., 1983, Petrology and provenance of the Stony Creek Formation, northwestern Sacramento Valley, California, *in* Bertucci, P.F., and Ingersoll, R.V., eds., Guidebook to the stony creek formation, great valley group, Sacramento Valley, California: Los Angeles, Pacific Section, Society of Economic Paleontology and Mineralogy, p. 1–16.

Bhatia, M.R., and Crook, K.A.W., 1986, Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins: Contributions to Mineralogy and Petrology, v. 92, p. 181–193. doi:10.1007/BF00375292

Bracciali, L., Marroni, M., Pandolfi, L., and Rocchi, S., 2007, Geochemistry and petrography of Western Thethys Cretaceous sedimentary covers (Corsica and Northern Appennines): From source areas to configuration of margins, *in* Arribas, J., Critelli, S., and Johnsson, M.J., eds., Sedimentary provenance and petrogenesis: Perspectives from petrography and geochemistry: Geological Society of America Special Paper 420, p. 73–93.

Cashman, S.M., and Elder, D.R., 2002, Post-Nevadan detachment faulting in the Klamath Mountains, California: Geological Society of America Bulletin, v. 16, p. 839–843.

Cassel, E.J., Grove, M., and Graham, S.A., 2012, Eocene drainage evolution and erosion of the Sierra Nevada batholith across northern California and Nevada: American Journal of Science, v. 312, p. 117–144. doi:10.2475/02.2012.03

Cecil, M.R., Ducea, M.N., Reiners, P., Gehrels, G., Mulch, A., Allen, C., and Campbell, I., 2010, Provenance of Eocene river sediments from the central northern Sierra Nevada and implications for paleotopography: Tectonics, v. 29, p. TC6010. doi:10.1029/2010TC002717, 13 p.

Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotopic ages from the Sierra Nevada Batholith, California: Journal of Geophysical Research, v. 87, p. 4761–4784. doi:10.1029/JB087iB06p04761

Clemens-Knott, D., Martin, M.W., and Buchen, C., 2013, Detrital zircon evidence for linkages between Mesozoic sedimentary systems along the western flank of the Sierra Nevada arc: Geological Society of America Abstracts with Programs, v. 45, no. 6, p. 66.

Clemens-Knott, D., and Saleeby, J.B., 1999, Impinging ring dike complexes in the Sierra Nevada batholith, California: Roots of the Early Cretaceous volcanic arc: Geological Society of America Bulletin, v. 111, p. 484–496. doi:10.1130/0016-7606(1999)111<0484:IRDCIT>2.3.CO;2

Constenius, K.N., Johnson, R.A., Dickinson, W.R., and Williams, T.A., 2000, Tectonic evolution of the Jurassic-Cretaceous Great Valley forearc, California: Implications for the Franciscan thrust-wedge hypothesis: Geological Society of America Bulletin, v. 112, p. 1703–1723. doi:10.1130/0016-7606(2000)112<1703:TEOTJC>2.0.CO;2

Cowan, D.S., and Bruhn, R.L., 1992, Late Jurassic to early Late Cretaceous geology of the U.S. Cordillera, *in* Burchfiel, B. C., Lipman, P.W., and Zoback, M.L., eds., The geology of North America: The cordilleran orogen: Conterminous US Boulder, Colorado: The Geological Society of America, p. 169–189.

Cox, R., Lowe, D.R., and Culler, R.L., 1995, The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the southwestern United States: Geochimica Et Cosmochimica Acta, v. 59, p. 2919–2940. doi:10.1016/0016-7037(95)00185-9

DeGraaff-Surpless, K., Graham, S.A., Wooden, J.L., and McWilliams, M.O., 2002, Detrital zircon provenance analysis of the Great Valley Group, California: Evolution of an arc-forearc system: Geological Society of America Bulletin, v. 114, p. 1564–1580. doi:10.1130/0016-7606(2002)114<1564:DZPAOT>2.0.CO;2

DePaolo, D.J., 1981, A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, p. 10470–10488. doi:10.1029/JB086iB11p10470

Dickinson, W.R., 1983, Cretaceous sinistral strike slip along Nacimiento fault in coastal California: The American Association of Petroleum Geologists Bulletin, v. 67, p. 624–645.

Dickinson, W.R., 1995, Forearc basins, *in* Busby, C.J., and Ingersoll, R.V., eds., Tectonics of sedimentary basins: Cambridge, Massachusetts, Blackwell Science, p. 221–261.

Dickinson, W.R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system: Geological Society of America Special Paper, v. 305, p. 46.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45. doi:10.1146/annurev.earth.32.101802.120257

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222–235. doi:10.1130/0016-7606(1983)94<222:PONAPS>2.0.CO;2

Dickinson, W.R., and Gehrels, G.E., 2009, U–Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment: Geological Society of America Bulletin, v. 121, p. 408–433. doi:10.1130/B26406.1

Dickinson, W.R., and Rich, E.I., 1972, Petrologic intervals and petrofacies in the Great Valley Sequence, Sacramento Valley, California: Geological Society of America Bulletin, v. 83, p. 3007–3024. doi:10.1130/0016-7606(1972)83[3007:PIAPIT]2.0.CO;2

Dickinson, W.R., and Seeley, D.R., 1979, Structure and stratigraphy of forearc regions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2–31.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164–2182.

Doebbert, A.C., Carroll, A.R., and Johnson, C., 2012, The sandstone-derived provenance record of the Gualala Basin, Northern California, USA: Journal of Sedimentary Research, v. 82, p. 841–858. doi:10.2110/jsr.2012.72

Ernst, W.G., 2012, Earliest Cretaceous Pacificward offset of the Klamath Mountains Salient, NW California-SW Oregon: Lithosphere, v. 5, p. 151–159. doi:10.1130/L247.1

Ernst, W.G., Snow, C.A., and Scherer, H.H., 2008, Contrasting early and late Mesozoic petrotectonic evolution of northern California: Geological Society of America Bulletin, v. 120, no. 1–2, p. 179–194. doi:10.1130/B26173.1

Ewart, A., 1982, The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: With special reference to the andesitic-basaltic compositional range, *in* Thorpe, R.S., ed., Andesites: Orogenic andesites and related rocks: Chichester, United Kingdom, John Wiley & Sons, p. 25–95.

Fralick, P.W., 2003, Geochemistry of clastic sedimentary rocks: ratio techniques, *in* Lentz, D.R., ed., Geochemistry of sediments and sedimentary rocks: Evolutionary considerations to mineral deposit-forming environments: St. John's, Newfoundland, Geological Association of Canada, GeoText 4, p. 85–103.

Garver, J.I., and Royce, P.R., 1993, Chromium and nickel in shale of the foreland deposits of the Ordovician Taconic orogeny: Using shale as a provenance indicator for ultramafic rocks: Geological Society of America, Abstracts with Programs, v. 25, p. 17.

Garver, J.I., Royce, P.R., and Scott, T.J., 1994, The presence of ophiolites in tectonic highlands as determined by chromium and nickel anomalies in synorogenic shale: Two examples from North America: Geologiya I Geofizika, v. 35, p. 3–11.

Gehrels, G.E., Valencia, V., and Pullen, A., 2006, Detrital Zircon Geochronology by Laser-Ablation Multicollector ICPMS at the Arizona LaserChron Center, *in* Olszewski, T., ed., Geochronology: Emerging opportunities: Philadelphia, PA, The Paleontological Society Papers, p. 67–76.

Ghatak, A., Basu, A.R., and Wakabayashi, J., 2013, Implications of Franciscan Complex graywacke geochemistry for sediment transport, provenance determination, burial-exposure duration, and fluid exchange with cosubducted metabasites: Tectonics, v. 32, p. 1480–1492. doi:10.1002/tect.20078

Godfrey, N.J., Beaudoin, B.C., Klemperer, S.L., Levander, A.R., Luetgert, J.H., Meltzer, A.S., Mooney, W.D., and Trehu, A.M., 1997, Ophiolitic basement to the Great Valley forearc basin, California, from seismic and gravity data: Implications for crustal growth at the North American continental margin: Geological Society of America Bulletin, v. 109, p. 1526–1562. doi:10.1130/0016-7606(1997)109<1536:OBTTGV>2.3.CO;2

Graham, S.A., 1981, Field guide to the Mesozoic-Cenozoic convergent margin of northern California; objectives and geologic overview, *in* Graham, S.A., ed., Field guide to the Mesozoic–Cenozoic convergent margin of northern California: Santa Fe Springs, Pacific Section, American Association of Petroleum Geologists, p. 3–12.

Graham, S.A., and Ingersoll, R.V., 1981, Field trip road log; Great Valley Group submarine fan facies and Sacramento Valley forearc gas province; (Part I), Sacramento to Cache Creek and return, *in* Graham, S.A., ed., Field guide to the Mesozoic–Cenozoic convergent margin of northern California: Santa Fe Springs, Pacific Section, American Association of Petroleum Geologists, p. 71–78.

Gromet, L.P., Haskin, L.A., Korotev, R.L., and Dymek, R.L., 1984, The "North American shale composite": Its compilation, major and trace element characteristics: Geochimica Et Cosmochimica Acta, v. 48, p. 2469–2482. doi:10.1016/0016-7037(84)90298-9

Grove, M., Gehrels, G.E., Cotkin, S.J., Wright, J.E., and Haibo, Z., 2008, Non-Laurentian cratonal provenance of Late Ordovician eastern Klamath blueschists and a link to the Alexander terrane, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, arcs, and batholiths: A tribute to cliff Hopson: Geological Society of America Special Paper 435, p. 223–250.

Hacker, B.R., Donato, M.M., Barnes, C.G., McWilliams, M.O., and Ernst, W.G., 1995, Timescales of orogeny: Jurassic construction of the Klamath Mountains: Tectonics, v. 14, p. 677–703. doi:10.1029/94TC02454

Haggart, J.W., 1986, Stratigraphy of the Redding Formation of North-Central California and its bearing on Late Cretaceous Paleogeography: Field Trip Guidebook-Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 46, p. 161–178.

Haggart, J.W., and Ward, P.D., 1984, Late Cretaceous (Santonian-Campanian) stratigraphy of the northern Sacramento Valley, California: Geological Society of America Bulletin, v. 95, p. 618–627. doi:10.1130/0016-7606(1984)95<618:LCSSOT>2.0.CO;2

Harding, J.P., Gehrels, G.E., Harwood, D.S., and Girty, G.H., 2000, Detrital zircon geochronology of the Shoo Fly Complex, northern Sierra terrane, northeastern California, Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California: Boulder, Geological Society of America Special Paper 347, p. 43–56.

Harwood, D.S., and Helley, E.J., 1987, Late Cenozoic tectonism of the Sacramento Valley, California: Reston, US Geological Survey Professional Paper 1359, 46 p.

Hosford Scheirer, A., and Magoon, L., 2007, Age, distribution, and stratigraphic relationship of rock units in the San Joaquin Basin province, California, *in* Hosford Scheirer, A., ed., Petroleum systems and geologic assessment of oil and gas in the San Joaquin Basin Province, California: Denver, CO, US Geological Survey Professional Paper 1713, p. 2–107.

Ingersoll, R.V., 1978, Petrofacies and petrologic evolution of the Late Cretaceous fore-arc basin, northern and central California: The Journal of Geology, v. 86, p. 335–352. doi:10.1086/649695

Ingersoll, R.V., 1979, Evolution of the Late Cretaceous forearc basin, northern and central California: Geological Society of America Bulletin, v. 90, p. 1813–1826. doi:10.1130/0016-7606(1979)90<813:EOTLCF>2.0.CO;2

Ingersoll, R.V., 1981, Petrofacies, lithofacies, submarine-fan facies of the Great Valley Group (Sequence), *in* Graham, S.A., ed., Field guide to the Mesozoic–Cenozoic convergent margin of northern California: Santa Fe springs, Pacific Section, American Association of Petroleum Geologists, p. 59–69.

Ingersoll, R.V., 1983, Petrofacies and provenance of late Mesozoic forearc basin, Northern and Central California: American Association of Petroleum Geologists Bulletin, v. 67, p. 1125–1142.

Ingersoll, R.V., 1990, Actualistic sandstone petrofacies: Discriminating modern and ancient source rocks: Geology, v. 18, p. 733–736. doi:10.1130/0091-7613(1990)018<0733:ASPDMA>2.3.CO;2

Irwin, W.P., 1981, Tectonic accretion of the Klamath Mountains, *in* Ernst, W.G., ed., The geotectonic evolution of California (Rubey Volume I): Englewood Cliffs, NJ, Prentice Hall, p. 29–49.

Irwin, W.P., and Wooden, J.L., 2001, Plutons and accreted terranes of the Sierra Nevada: California, US Geological Survey Open File Report 2001-229.

Jenner, G.A., 1996, Trace element geochemistry of igneous rocks: Geochemical nomenclature and analytical geochemistry, *in* Wyman, D.A., ed., Trace element geochemistry of volcanic rocks: Applications for massive sulfide exploration:

Geological Association of Canada, Short Course Notes, v. 12, p. 55–71.

Johnson, D.M., Hooper, P.R., and Conrey, R.M., 1999, XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead: Advances in X-Ray Analysis, v. 41, p. 843–867.

Kistler, R.W., and Peterman, Z.E., 1973, Variations *in* Sr, Rb, K, Na, and Initial Sr87/Sr86 in Mesozoic Granitic Rocks and Intruded Wall Rocks in Central California: Geological Society of America Bulletin, v. 84, p. 3489–3512. doi:10.1130/0016-7606(1973)84<3489:VISRKN>2.0.CO;2

Knaack, C., Cornelius, S.B., and Hooper, P.R., 1994, Trace element analyses of rocks and minerals by ICP-MS: http://www.sees.wsu.edu/Geolab/note/icpms.html (Accessed 2011).

Kochelek, E.J., 2009, Sedimentary provenance analysis of the Ochoco Basin near Mitchell, OR: Implications for Cretaceous Cordilleran paleogeography: Geological Society of America Abstracts with Programs, v. 41, no. 5, p. 7.

LaMaskin, T.A., 2012, Detrital zircon facies of Cordilleran terranes in western North America: GSA Today, v. 22, p. 4–11.

LaMaskin, T.A., Dorsey, R.J., and Vervoort, J.D., 2008, Tectonic Controls on Mudrock Geochemisry, Mesozoic Rocks of Eastern Oregon and Western Idaho, USA: Implications for Cordilleran Tectonics: Journal of Sedimentary Research, v. 78, p. 765–783. doi:10.2110/jsr.2008.087

LaMaskin, T.A., Vervoort, J.D., Dorsey, R.J., and Wright, J.E., 2011, Early Mesozoic paleogeography and tectonic evolution of the western United States: Insights from detrital zircon U–Pb geochronology, Blue Mountains Province, northeastern Oregon: Geological Society of America Bulletin, v. 123, p. 1939–1965. doi:10.1130/B30260.1

Lanphere, M.A., and Jones, D.L., 1978, Cretaceous time scale from North America, *in* Cohee, G.V., Glaessner, M.F., and Hedberg, H.D., eds., Contributions to the geologic time scale: Tulsa, OK, American Association of Petroleum Geologists, Studies in Geology, no. 6, p. 259–268.

Li, Y.H., 2000, A compendium of geochemistry: Princeton, New Jersey, Princeton University Press, p. 475.

Linn, A.M., DePaolo, D.J., and Ingersoll, R.V., 1992, Nd–Sr isotopic, geochemical, and petrographic stratigraphy and paleotectonic analysis: Mesozoic Great Valley forearc sedimentary rocks of California: Geological Society of America Bulletin, v. 104, p. 1264–1279. doi:10.1130/0016-7606(1992)104<1264:NSIGAP>2.3.CO;2

MacLean, W.H., 1990, Mass change calculations in altered rock series: Mineralium Deposita, v. 25, p. 44–49. doi:10.1007/BF03326382

Mahoney, J.B., 2005, Nd and Sr isotopic signatures of fine-grained clastic sediments: A case study of western Pacific marginal basins: Sedimentary Geology, v. 182, p. 183–199. doi:10.1016/j.sedgeo.2005.07.009

Mansfield, C.F., 1979, Upper Mesozoic subsea fan deposits in the southern Diablo Range, California: Record of the Sierra Nevada magmatic arc: Geological Society of America Bulletin, v. 90, p. I 1025–I 1046. doi:10.1130/0016-7606(1979)90<1025:UMSFDI>2.0.CO;2

McLennan, S.M., 1989, Rare earth elements in sedimentary rocks: Influence on provenance and sedimentary processes, *in* Lipin, B.R., and McKay, G.A., eds., Geochemistry and mineralogy of rare earth elements: Reviews in Mineralogy: Chantilly, VA, Mineralogical Society of America, v. 21, p. 169–200.

McLennan, S.M., Hemming, S., McDaniel, D.K., and Hanson, G.N., 1993, Geochemical approaches to sedimentation, provenance, and tectonics, in Johnson, M.J., and Basu, A., eds., Processes controlling the composition of clastic sediments: Boulder, Colorado, Geological Society of America Special Paper 284, p. 21–40.

McLennan, S.M., Taylor, S.R., McCulloch, M.T., and Maynard, J.B., 1990, Geochemical and Nd–Sr isotopic composition of deep-sea turbidites; crustal evolution and plate tectonic associations: Geochimica Et Cosmochimica Acta, v. 54, p. 2015–2050. doi:10.1016/0016-7037(90)90269-Q

Mitchell, C., Graham, S.A., and Suek, D.H., 2010, Subduction complex uplift and exhumation and its influence on Maastrichtian forearc stratigraphy in the Great Valley Basin, northern San Joaquin Valley, California: Geological Society of America Bulletin, v. 122, p. 2063–2078. doi:10.1130/B30180.1

Moxon, I.W., 1988, Sequence stratigraphy of the Great Valley basin in the context of convergent margin tectonics, *in* Graham, S.A., and Olson, H.C., eds., Studies of the geology of the San Joaquin Basin: Los Angeles, field trip guidebook – Pacific section: Society of Economic Paleontologists and Mineralogists vol. 60, p. 3–28.

Moxon, I.W., 1990, Stratigraphic and structural architecture of the San Joaquin-Sacramento Basin [Ph.D. thesis]: Stanford, CA, Stanford University, 371 p.

Nesbitt, H.W., and Young, G.M., 1982, Early Proterozoic climates and plate motions inferred from major element chemistry of lutites: Nature, v. 299, p. 715–717. doi:10.1038/299715a0

Nilsen, T.H., 1993, Stratigraphy of the Cretaceous Hornbrook Formation, Southern Oregon and Northern California: US Geological Survey Professional Paper, p. 1–89.

Ojakangas, R.W., 1968, Cretaceous sedimentation, Sacramento Valley, California: Geological Society of America Bulletin, v. 79, p. 973–1008. doi:10.1130/0016-7606(1968)79[973:CSSVC]2.0.CO;2

Poldervaart, A., 1956, Zircon in rocks; 2, Igneous rocks: American Journal of Science, v. 254, p. 521–554. doi:10.2475/ajs.254.9.521

Potter, P.E., Maynard, J.B., and Depetris, P.J., 2005, Mud and mudstones: Introduction and overview: Heidelberg, Springer-Verlag, 297 p.

Rose, R.L., and Colburn, I.P., 1963, Geology of the east-central part of the Priest Valley Quadrangle, California: American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, *in* Guidebook to the geology of the Salinas Valley and the San Andreas Fault, p. 38–45.

Ryan, K.M., and Williams, D.M., 2007, Testing the reliability of discrimination diagrams for determining the tectonic depositional environment of ancient sedimentary basins: Chemical Geology, v. 242, p. 103–125. doi:10.1016/j.chemgeo.2007.03.013

Saleeby, J.B., 2011, Geochemical mapping of the Kings-Kaweah ophiolite belt, California – Evidence for progressive mélange formation in a large offset transform-subduction initiation environment, *in* Wakabayashi, J., and Dilek, Y., eds., Mélanges: Processes of formation and societal significance: Geological Society of America Special Paper 480, p. 31–73.

Scherer, H.H., Ernst, W.G., and Wooden, J.L., 2010, Regional detrital zircon provenance of exotic metasandstone blocks, Eastern Hayfork Terrane, Western Paleozoic and Triassic Belt, Klamath Mountains, California: The Journal of Geology, v. 118, p. 641–653. doi:10.1086/656352

Seiders, V.M., 1983, Correlation and provenance of upper Mesozoic chert-rich conglomerate of California: Geological Society of America Bulletin, v. 94, p. 875–888. doi:10.1130/0016-7606(1983)94<875:CAPOUM>2.0.CO;2

Sharman, G.R., Graham, S.A., Grove, M., Kimbrough, D.L., and Wright, J.E., in press, Detrital zircon provenance of Late Cretaceous-Eocene California forearc: Influence of Laramide low-angle subduction on sediment dispersal and paleogeography, Geological Society of America Bulletin.

Short, P.F., and Ingersoll, R.V., 1990, Petrofacies and provenance of the Great Valley Group, southern Klamath Mountains and northern Sacramento Valley, *in* Ingersoll, R.V., and Nilsen, T. H., eds., Sacramento valley symposium and guidebook: Upland, CA, Pacific Section S.E.P.M., v. 65, p. 39–52.

Snow, C.A., and Ernst, W.G., 2008, Detrital zircon constraints on sediment distribution and provenance of the Mariposa Formation, central Sierra Nevada foothills, California, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, arcs, and batholiths: A tribute to Cliff Hopson: Geological Society of America Special Paper 435, p. 311–330.

Soreghan, M.J., and Gehrels, G.E., 2000, Paleozoic and Triassic paleogeography and tectonics of Western Nevada and Northern California: Boulder, Geological Society of America Special Paper 347, 252 p.

Spurlin, M.S., Gehrels, G.E., and Harwood, D.S., 2000, Detrital zircon geochronology of upper Paleozoic and lower Mesozoic strata of the northern Sierra terrane, northeastern California, in Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California: Boulder, Geological Society of America Special Paper 347, p. 89–98.

Suchecki, R.K., 1984, Facies history of the Upper Jurassic-Lower Cretaceous Great Valley Sequence; response to structural development of an outer-arc basin: Journal of Sedimentary Petrology, v. 54, p. 170–191.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematic of oceanic basalts: Implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in ocean basins: Geological Society of London Special Publication, v. 42, p. 313–345.

Surpless, K.D., and Augsburger, G.A., 2009, Provenance of the Pythian Cave conglomerate, northern California: Implications for mid-Cretaceous paleogeography of the US Cordillera: Cretaceous Research, v. 30, p. 1181–1192. doi:10.1016/j.cretres.2009.05.005

Surpless, K.D., and Beverly, E.J., 2013, Understanding a critical basinal link in Cretaceous Cordilleran paleogeography: Detailed provenance of the Hornbrook Formation, Oregon and California: Geological Society of America Bulletin, v. 125, p. 709–727. doi:10.1130/B30690.1

Surpless, K.D., Graham, S.A., Covault, J.A., and Wooden, J.L., 2006, Does the Great Valley Group contain Jurassic strata? Reevaluation of the age and early evolution of a classic forearc basin: Geology, v. 34, p. 21–24. doi:10.1130/G21940.1

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: Oxford, U.K., Blackwell, 312 p.

Wallin, E.T., Noto, R.C., and Gehrels, G.E., 2000, Provenance of the Antelope Mountain Quartzite, Yreka Terrane, California: Evidence for large-scale sinistral displacement along the North American Cordilleran margin and implications for the mid-Paleozoic fringing-arc model, in Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California: Boulder, Geological Society of America Special Paper 347, p. 119–131.

Watson, E.B., and Harrison, T.M., 1983, Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types: Earth and Planetary Science Letters, v. 64, p. 295–304. doi:10.1016/0012-821X(83)90211-X

Williams, T.A., 1997, Basin-fill architecture and forearc tectonics: Cretaceous Great Valley Group, Sacramento Basin, northern California [Ph.D. thesis]: Stanford, CA, Stanford University, 412 p.

Williams, T.A., and Graham, S.A., 2013, Controls on forearc basin architecture from seismic and sequence stratigraphy of the Upper Cretaceous Great Valley Group, central Sacramento Basin, California: International Geology Review, v. 55, p. 2030–2059. doi:10.1080/00206814.2013.817520

Wright, J.E., and Wyld, S.J., 2007, Alternative tectonic model for Late Jurassic through Early Cretaceous evolution of the Great Valley Group, California, *in* Cloos, M., Carlson, W. D., Gilbert, M.C., Liou, J.G., and Sorenson, S.S., eds., Convergent margin terranes and associated regions; a tribute to W. G. Ernst: Boulder, Geological Society of America Special Paper, v. 419, p. 81–95.

Wyld, S.J., Umhoefer, P.J., and Wright, J.E., 2006, Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implications for the Baja British Columbia hypothesis and other models, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacements: Geological Association of Canada Special Paper 46, p. 277–298.