Implications of Franciscan Complex graywacke geochemistry for sediment transport, provenance determination, burial-exposure duration, and fluid exchange with cosubducted metabasites

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[1] Interpretation of graywacke provenance has long been used to evaluate the record of tectonic process in orogenic belts. Our geochemical data from graywackes of the Franciscan subduction complex, California, show that the connection between sedimentary record and geologic processes may be more complex than previously believed. Trace elements and Nd-Sr-Pb isotopes of Franciscan graywackes indicate two sources types. One group lacking negative Eu anomaly ($Eu/Eu^* > 0.9$), shows slightly concave-up heavy rare earth elements, arc-like trace element patterns, and western Pacific island arc-like Pb isotopes, reflecting derivation from older accreted oceanic-arc terranes in the Sierra Nevada-Klamath Mountains. The other group displays small negative Eu anomalies, with trace element patterns resembling post-Archean Australian shale and Pb isotopes similar to Jurassic-Cretaceous Sierran batholith. There is no systematic separation of these two groups by depositional ages. Thus, geochemistry of the graywackes may partly reflect variation in location of sediment delivery systems, rather than solely reflecting evolution of the neighboring arc. Variation of Nd-Sr isotopes with stratigraphic-age for the graywackes mimics the trends of the coeval Great Valley Group clastic-rocks, suggesting that (1) they share the same sediment sources, (2) there are no "exotic" sediment sources that fed the Franciscan trench, and (3) burial-exposure cycles for Franciscan clastic rocks were comparatively brief. Comparison of Franciscan graywacke and metabasite geochemistry corroborates earlier conclusions that metabasites had little or no chemical exchange with fluids from cosubducted graywacke. Detrital zircon age populations, major element chemistry, and detrital framework modes, when compared to our data suggest that the former three parameters underrepresent the mafic component of clastic sediment provenance.

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1. Introduction

[2] The provenance of clastic sedimentary rocks such as sandstones is commonly used to evaluate tectonic processes from the rock record [e.g., *Dickinson and Suczek*, 1979]. Sandstones from orogenic belts, commonly called "graywacke," although not necessarily strictly fitting sedimentologic definitions of the term, have received particular attention from researchers, for their provenance provides insight into orogenic processes [*Dickinson*, 1970; *Dickinson and Suczek*, 1979]. Graywacke provenance has been traditionally evaluated using detrital framework modes [e.g., *Dickinson and Suczek*, 1979] and, more recently with detrital zircon age population distributions [e.g., *Dickinson and Gehrels*, 2000; *DeGraaff-Surpless et al.*, 2002; *Ernst et al.*, 2009]. Geochemical studies of graywackes have been less common and tend to focus on general geochemical characteristics that can be tied to their igneous geochemical characteristics and hence provenance [e.g., *Condie and Snansieng*, 1971; *Bhatia*, 1985; *Bhatia and Crook*, 1986; *Long et al.*, 2012].

[3] Here we present trace element and radiogenic isotopic data of Nd, Sr, and Pb from graywackes of the Franciscan Complex of coastal California (Figure 1 and Table 1) to

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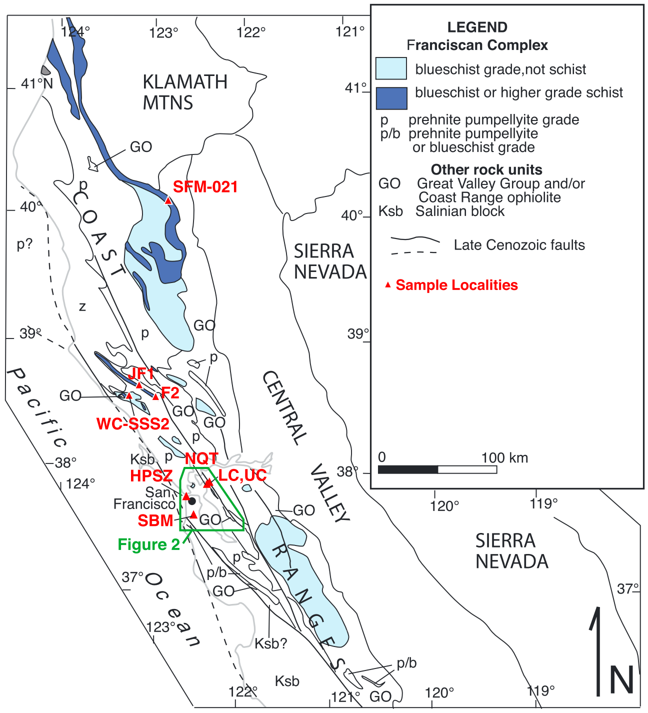

Figure 1. Geological map of the Franciscan Complex modified from *Wakabayashi* [2011] with locations of the graywacke samples of this study.

evaluate provenance, controls on trench sediment chemistry, sediment transport, tectonomagmatic evolution of the arc-fore arc system, and the fluid sources in the subduction zone metamorphism. The wealth of recently published data on ages and geochemical characteristics of potential source rocks, as well as a rapidly growing body of detrital zircon data in the graywackes, permits a more detailed evaluation of the graywacke chemistry and its connection to provenance and tectonic processes than previously possible. However, the new data also introduce complications into standard interpretations of clastic sediment provenance from detrital modes, detrital zircon age populations, and geochemistry. For example, our data suggest that mafic sources may be underrepresented by detrital mode, detrital zircon data, and

Table 1. Sample Names, Locations, Depositional Ages and Rock Type for the Nine Graywackes Analyzed for This Study

Sample	Depositional Age in Ma[a]	Location	Geologic Unit, Lithology
F-2	144z, 132a	Mill Creek Road, Sonoma County, 38.5960°N, 122.8940°W	Skaggs Springs schist; coherent glaucophane-lawsonite-quartz schist; sample NS-10 of *Snow et al.* [2010] and *Wakabayashi and Dumitru* [2007]
HPSZ	97z	Baker Beach, San Francisco, 37.8046°N, 122.4787°W	Prehnite-pumpellyitefacies greywacke from mélange; sample HPSZ of *Snow et al.* [2010]
JF-1	144z, 132a	Skaggs Springs Road, Sonoma County, 38.6630°N, 122.0272°N	Skaggs Springs schist; coherent glaucophane-lawsonite-quartz schist
LC	100z, circa 95f	El Cerrito Quarry, 37.9189°N, 122.2998°W	Coherent prehnite-pumpellyitefacies greywacke, Alcatraz nappe; sample LEC of *Snow et al.* [2010]
NQT	83z, circa 85f	Albany Hill, San Francisco Bay area, 37.8963°N, 122.3068°W	Coherent prehnite-pumpellyitefacies greywacke, Novato Quarry terrane; sample AH of *Snow et al.* [2010]
SBM	52z	San Bruno Mountain, San Francisco, 37.7046°N, 122.4603°W	Coherent prehnite-pumpellyitefacies greywacke, San Bruno Mountain terrane; sample SBM of *Snow et al.* [2010]
SFM-021 (SFM)	120z	Tom Head Mountain area, Mendocino County, 40.1291°N, 122.8362°W	Coherent mica schist, Valentine Springs Formation, Pickett Peak terrane; sample SFM-021 of *Dumitru et al.* [2010]
UC	102z	El Cerrito Quarry, 37.9207°N, 122.2998°W	Coherent jadeite-glaucophane-lawsonite greywacke, Angel Island nappe; sample UEC of *Snow et al.* [2010]
WC-SSS-2 (WC)	144, 132a	Ward Creek area near Cazadero, Sonoma County 38.5308°N, 123.1377°W	Skaggs Springs schist; coherent glaucophane-lawsonite-quartz schist

[a]z: maximum depositional age from U-Pb detrital zircon chronology [*Snow et al*., 2010; *Dumitru et al*., 2010], F-2 and WC-SSS-2 by correlation to JF-1. f: depositional age from fossils [*Blake et al*., 1984; *Elder and Miller*, 1993]. a: maximum depositional age from phengite, Ar-Ar metamorphic age [*Wakabayashi and Dumitru*, 2007].

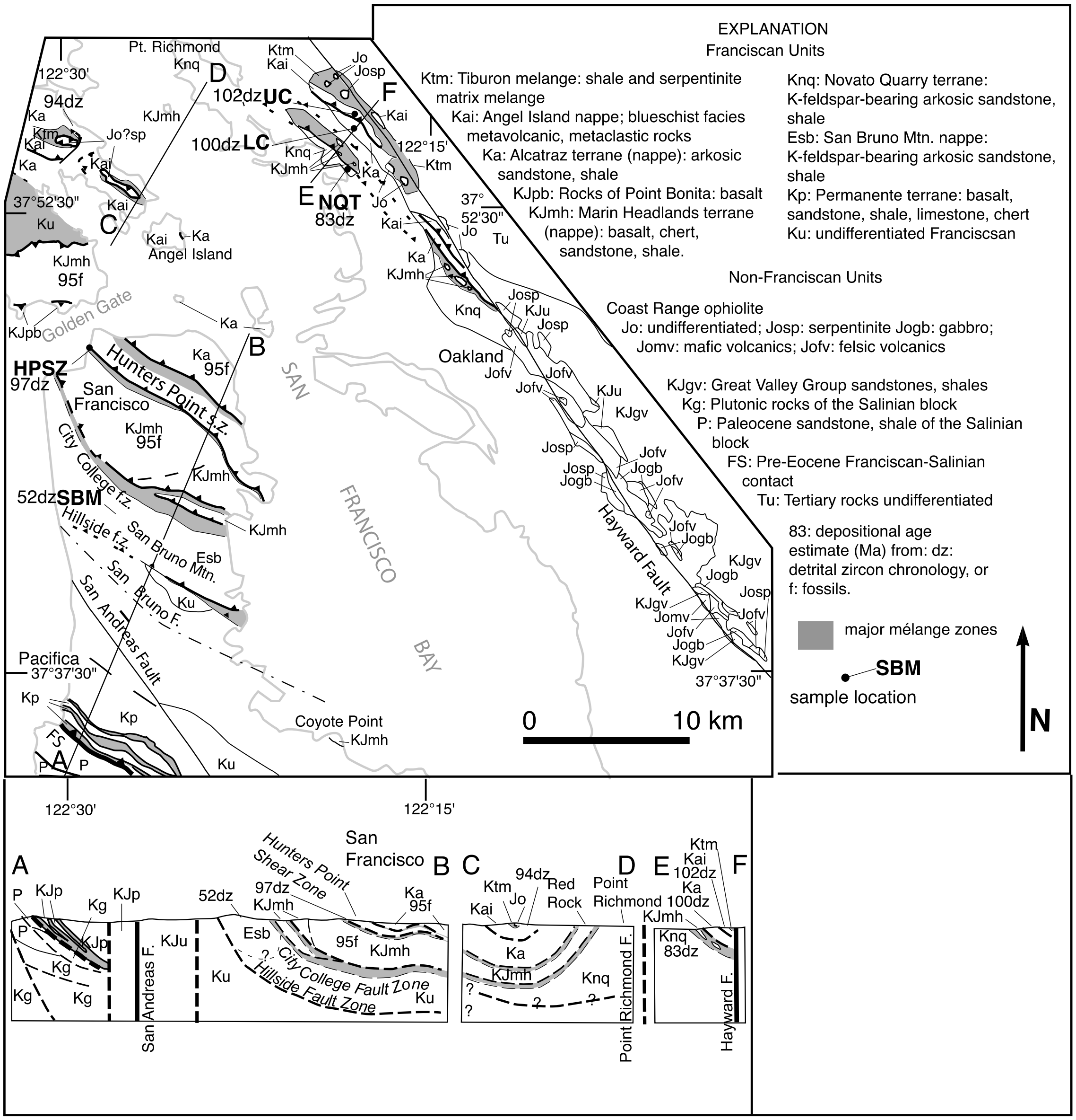

Figure 2. Franciscan Complex geology of the San Francisco Bay area with locations of five of the samples shown. Modified from *Wakabayashi* [2012]. Detrital zircon maximum depositional ages from *Snow et al*. [2010] and fossil ages from *Blake et al*. [1984] and *Elder and Miller* [1993].

major element data compared to trace element data. The differences between the various types of data may provide insight into source-to-sink processes, such as weathering and diagenesis. Analysis of trace element and radiogenic isotope data alone, however, cannot give the specific source data given by detrital zircon age populations, or petrographic analysis of detrital modes.

2. Geological Setting

[4] The Franciscan subduction complex is well known as part of a paleo arc-trench system that includes the Sierra Nevada batholith as the roots of a continental margin magmatic arc, and the Great Valley Group (GVG) as the fore-arc sedimentary basin fill [*Hamilton*, 1969; *Dickinson*, 1970]. The Franciscan Complex comprises graywackes, shales, and conglomerates, representing trench sediments that were shed from the continental margin. Lesser amounts of pelagic sediments, chert and limestone, and mafic-ultramafic rocks are also present. The Franciscan was episodically scraped off and accreted from the eastward subducting oceanic plate following initiation of subduction at 160–170 Ma to less than 35 Ma [*Ernst*, 1984; *Blake et al*., 1988; *Wakabayashi and Dumitru*, 2007; *Snow et al*., 2010; *Dumitru et al*., 2010, 2013]. The subduction event continued resulting in younger offscraped rocks that are largely offshore [e.g., *Atwater*, 1970; *Atwater and Stock*, 1998]. The GVG clastic sediments young upward in a normal stratigraphic sequence [e.g., *Ojakangas*, 1968; *Ingersoll*, 1983; *Moxon*, 1988], in contrast to their coeval Franciscan equivalents that young structurally downward in a series of nappe sheets, reflecting tectonic offscraping and underplating of trench sediments during the extended subduction episode [*Wakabayashi*, 1992, 1999a; *Snow et al*., 2010; *Dumitru et al*., 2010].

Table 3. Sm-Nd, Rb-Sr, and U-Th-Pb Systematics and Nd, Sr, Pb Isotopic Data of All the Graywackes of This Study Age Corrected to Individual Depositional Ages[a]

	HPSZ	LC	JF-1	NQT	SBM	UC	WC-SSS-2	SFM-021	F-2
$^{147}Sm/^{144}Nd$	0.13	0.15	0.13	0.13	0.12	0.14	0.14	0.14	0.14
$^{143}Nd/^{144}Nd_{(0)}$	0.51252	0.51260	0.51233	0.51225	0.51235		0.51234	0.51276	0.51270
$^{143}Nd/^{144}Nd_{(I)}$	0.51244	0.51250	0.51220	0.51212	0.51230		0.51222	0.51265	0.51259
$\varepsilon_{Nd(I)}$	−1.5	−0.2	−4.9	−6.8	−5.2		−4.7	3.2	2.1
TDM (Ma)	1164	1269	1577	1712	1357		1667	803	987
$^{87}Rb/^{86}Sr$	2.18	1.59	2.11	0.68	0.39	3.23	0.83	9.88	0.27
$^{87}Sr/^{86}Sr_{(0)}$	0.70912	0.70671	0.70952	0.71009	0.70671	0.70979	0.70754	0.70754	0.70484
$^{87}Sr/^{86}Sr_{(I)}$	0.70612	0.70445	0.70519	0.70928	0.70643	0.70511	0.70585	0.69840	0.70428
$^{206}Pb/^{204}Pb_{(0)}$	18.94	18.90	19.25	19.74	19.02	19.29	19.30	19.00	19.14
$^{207}Pb/^{204}Pb_{(0)}$	15.64	15.59	15.64	15.67	15.63	15.71	15.68	15.61	15.62
$^{208}Pb/^{204}Pb_{(0)}$	38.69	38.48	39.05	39.45	38.60	39.03	39.15	38.68	38.87
$^{238}U/^{204}Pb$	9.98	5.68	13.15	6.28	4.57	11.12	17.24	13.89	15.55
$^{235}U/^{204}Pb$	0.07	0.04	0.10	0.05	0.03	0.08	0.13	0.10	0.11
$^{232}Th/^{204}Pb$	34.6	14.8	56.7	27.2	20.7	38.8	69.9	38.6	45.3
$^{206}Pb/^{204}Pb_{(I)}$	18.79	18.81	18.95	19.66	18.98	19.11	18.91	18.74	18.79
$^{207}Pb/^{204}Pb_{(I)}$	15.64	15.58	15.63	15.67	15.63	15.70	15.66	15.59	15.60
$^{208}Pb/^{204}Pb_{(I)}$	38.52	38.41	38.65	39.34	38.55	38.83	38.65	38.45	38.54

[a] $^{143}Nd/^{144}Nd_{(0)}$, $^{87}Sr/^{86}Sr_{(0)}$, $^{206}Pb/^{204}Pb_{(0)}$, $^{207}Pb/^{204}Pb_{(0)}$, and $^{208}Pb/^{204}Pb_{(0)}$ are measured ratios. $^{143}Nd/^{144}Nd_{(0)}$, $^{87}Sr/^{86}Sr_{(0)}$, $^{206}Pb/^{204}Pb_{(0)}$, $^{207}Pb/^{204}Pb_{(0)}$, and $^{208}Pb/^{204}Pb_{(0)}$are age-corrected initial ratios as per the depositional ages given in Table 1.

[5] Detrital zircon chronology and sedimentary petrology indicate that much of what makes up the Franciscan graywackes were derived from the coeval Klamath and Sierran continental margin magmatic arcs to the east [*Ernst et al.*, 2009] (Figure 1), consistent with earlier conclusions based on petrography [*Jacobson*, 1978; *Dickinson and Suzcek*, 1982]. These researchers suggested that Franciscan trench sediments and GVG fore-arc basin strata have the same source. Based partly on the lower lithic fraction of many Franciscan versus coeval GVG graywackes, other authors proposed that some Franciscan graywackes had an exotic source such an island arc, west of the California margin, with a clastic flux that fed the Franciscan trench but not the GVG fore-arc basin [*Blake and Jones*, 1981; *Jayko and Blake*, 1984]. However, *Dickinson and Suzcek* [1982] argued that the lower lithic fraction in Franciscan versus coeval GVG sandstones resulted from metamorphism of the former that reduced the proportion of the labile lithic clasts. The systematic reduction in lithic components and plagioclase with increasing metamorphic grade, noted by *Ernst and McLaughlin* [2012], is consistent with the conclusions of *Dickinson and Suzcek* [1982]. Although GVG and Franciscan deposition was coeval with Late Jurassic-Cretaceous magmatic arc activity inboard (to the east), the potential sediment source regions, including the Klamath and Sierran regions, also feature abundant mafic-ultramafic rocks, island arc fragments, and pelagic and clastic sedimentary rocks that predate the Late Mesozoic arc [e.g., *Saleeby*, 1990].

3. Graywacke Samples

[6] All but two of our samples were collected from same outcrops (Figures 1 and 2 and Table 3) where maximum depositional ages have been determined by U-Pb detrital zircon chronology based on the younger zircon age populations in each sample [*Snow et al.*, 2010; *Dumitru et al.*, 2010]; detailed petrographic information is also presented in those papers. Maximum depositional ages are commonly younger than ages previously estimated from sparse, probably recycled, macrofossils and closely approximate true depositional ages for many samples, based on continuity of inboard magmatism during depositional history, small differences between metamorphic and maximum depositional ages for some metagraywackes, and regional correlations [*Ernst et al.*, 2009; *Snow et al.*, 2010; *Dumitru et al.*, 2010]. These samples span a range of depositional ages from about 144 to 52 Ma, so they encompass most of the depositional age range of Franciscan graywackes [e.g., *Ernst et al.*, 2009; *Snow et al.*, 2010; *Dumitru et al.*, 2010; *Dumitru et al.*, 2013]. In addition to the samples from the *Snow et al.* [2010] study (HPSZ, JF-1, LC, NQT, SBM, UC) and one sample from the *Dumitru et al.* [2010] study (SFM-021), two additional samples of the Skaggs Springs schist, the oldest metaclastic unit in the Franciscan [*Wakabayashi and Dumitru*, 2007; *Snow et al.*, 2010], were collected and analyzed (F-2, WC-SSS-2; Figures 1 and 2 and Table 3).

[7] The Skaggs Spring schist (F-2, JF-1, WC-SSS-2) appears as a gray phyllite or schist in outcrop, whereas petrographically it is a quartz-rich schist with glaucophane, lawsonite, and phengite. Metamorphic minerals range up to 1 mm in long dimension and this is the coarsest grained (in terms of metamorphic grain size) and most completely recrystallized of Franciscan metaclastic units [*Wakabayashi*, 1992; *Wakabayashi and Dumitru*, 2007; *Snow et al.*, 2010]. Relics of original clastic texture are only locally preserved, primarily as quartz porphyroclasts. The original detrital modes cannot be determined. Owing to the fact that two of the Skaggs Springs schist samples were not colocated with geochronologic samples, additional justification for correlation of outcrops and similar ages for different parts of this unit need to be presented. The correlation of various outcrop belts of Skaggs Spring schist has been corroborated by the identical post-Franciscan strike-slip fault offsets of the Skaggs Springs schist and spatially limited Late Cenozoic volcanic rocks [*Wakabayashi*, 1999b]. In addition, samples from outcrops 60 km apart in the largest belt of Skaggs Spring schist yielded nearly identical phengite Ar-Ar ages of circa 132 Ma [*Wakabayashi and Dumitru*, 2007]. Two of our samples come from this belt of Skaggs Springs schist: F-2, colocated with the detrital zircon sample of *Snow et al.* [2010] and one of the

Table 2. Trace Element Concentrations for All the Greywacke Samples of This Study[a]

	HPSZ	LC	JF-1	NQT	SBM	UC	SSS-2	SFM-021	F-2
Rb	52	46.2	124	93	64	98	61	73	21.4
Sr	68	81	166	385	466	86	210	21.0	221
Y	11.8	10.1	25.6	12.2	14.8	20.9	17.6	15.2	14.1
Nb	8.58	5.82	10.6	10.6	6.20	9.13	47	70	53
Ba	264	415	842	1165	1018	482	477	784	224
La	16.9	7.88	22.1	14.0	17.6	15.0	16.6	15.6	12.2
Ce	33.7	17.8	42.9	28.3	32.3	30.2	33.0	29.9	25.2
Pr	4.24	2.19	5.69	3.71	4.12	4.16	4.16	3.64	3.23
Nd	16.2	8.80	21.9	14.3	15.4	16.1	16.0	13.6	12.8
Sm	3.36	2.05	4.66	3.02	3.01	3.48	3.55	2.98	2.91
Eu	0.80	0.58	1.20	0.98	0.99	0.91	0.92	1.09	0.84
Gd	3.08	1.96	4.64	2.76	2.93	3.50	3.26	2.65	2.73
Tb	0.45	0.32	0.72	0.42	0.43	0.58	0.51	0.42	0.44
Dy	2.53	1.84	4.15	2.40	2.30	3.40	3.03	2.49	2.52
Ho	0.50	0.40	0.85	0.49	0.46	0.73	0.62	0.54	0.53
Er	1.41	1.13	2.43	1.45	1.31	2.08	1.71	1.55	1.53
Tm	0.21	0.18	0.36	0.23	0.19	0.33	0.25	0.24	0.24
Yb	1.44	1.25	2.36	1.51	1.24	2.14	1.60	1.64	1.51
Lu	0.20	0.18	0.33	0.22	0.16	0.31	0.21	0.25	0.22
Hf	1.81	1.57	1.69	0.65	0.65	2.70	1.41	2.06	1.60
Ta	0.55	0.39	0.67	0.67	0.42	0.60	0.44	0.42	0.41
Pb	10.9	14.0	8.83	13.7	15.4	9.99	4.63	10.9	5.86
Th	5.70	3.15	7.48	5.50	4.80	5.78	4.78	6.31	3.98
U	1.70	1.24	1.79	1.31	1.10	1.71	1.22	2.41	1.41
Eu/Eu*	0.76	0.92	0.79	1.04	1.02	0.80	0.82	1.18	0.91

[a]Analytical errors are less than 5% for all elements and less than 2% for REEs.

phengite Ar-Ar samples of *Wakabayashi and Dumitru* [2007], and JF-1 collected 25 km northwest of F-2 along strike. The third sample, WC, comes from a separate exposure belt or slab of the Skaggs Spring schist (Figure 1).

[8] The Valentine Springs Formation sample (SFM-021) is a quartz-rich schist with primarily phengite and chlorite, as metamorphic minerals; glaucophane and lawsonite have been identified elsewhere in this unit [e.g., *Blake et al.*, 1988]. This rock is nearly completely recrystallized but exhibits relics of clastic texture in the form of quartz and albite porphyroclasts. The degree of recrystallization obscures the original detrital framework composition.

[9] The Angel Island nappe sample (UC) has the appearance of a sandstone with a pronounced cleavage, both in outcrop and petrographic view. Metamorphic minerals include jadeitic clinopyroxene, glaucophane, and lawsonite. Although the clastic texture is clearly discernible, the framework proportions have been drastically affected by deformation and metamorphic recrystallization. For example, all plagioclase has been replaced by jadeitic clinopyroxene and quartz. Volcanic, chert, and shale/siltstone clasts apparently make up the lithic fraction of the rock, and chlorite aggregates may represent replacements of serpentinite clasts as noted by *Wakabayashi* [2012].

[10] The Hunters Point shear zone (HPSZ), Alcatraz nappe (LC), Novato Quarry terrane (NQT), and San Bruno Mountain terrane (SBM) samples are sandstones that lack a penetrative fabric. Neoblastic metamorphic minerals are rare, with scattered sprays of pumpellyite being the most notable; prehnite has been found in all three of these units [*Blake et al.*, 1984]. All contain abundant quartz and plagioclase, with SBM and HPSZ having a moderate lithic fraction (approximately 30%), the Alcatraz nappe less (approximately 20%), and the Novato Quarry terrane still less (approximately 10%). The lithic grains consist of sedimentary grains (siltstone, shale), chert, and volcanic grains. The volcanic fraction comprises less than half of the total lithics, at variance with the 78–89% reported by *Jayko and Blake* [1984], but consistent with the abundance of shale chips visible in hand specimens, as well as recent petrographic examination of Franciscan graywacke by *Ernst and McLaughlin* [2012]. Small amounts of detrital feldspar are present in NQT, SBM, and to a lesser extent LC, but absent in HPSZ.

4. Analytical Methods

[11] Whole rock samples were powdered using a Spex alumina ball. All the trace element and isotopic analyses reported here were carried out at the University of Rochester. Trace element concentrations were measured using an inductively coupled plasma–mass spectrometer (ICP-MS; Thermo elemental X-7) at the University of Rochester [*Hannigan et al.*, 2001]. BCR-2 was used as a standard, and AGV-2 and BHVO-2 rock standards were run as unknowns to estimate the error. Analytical uncertainties are less than 5% for most of the trace elements and less than 2% for the rare earth elements (REEs). Trace element data are presented in Table 2.

[12] Nd-Sr-Pb isotopic ratios were measured using a multicollector thermal ionization mass spectrometer (VG-Sector) for which 100–200 mg of the powdered rock samples were dissolved in HF-HNO_3 and HCl. Nd-Sr isotopes were measured using the procedures established for our laboratory [*Basu et al.*, 1990]. Measured $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$. Uncertainties for the measured $^{87}Sr/^{86}Sr$ ratios were less than ±0.00004 (2σ of the mean). The SRM-987 Sr standard analyzed during the course of this study yielded $^{87}Sr/^{86}Sr = 0.71024 \pm 0.00002$ (2σ, n = 6). Measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$.

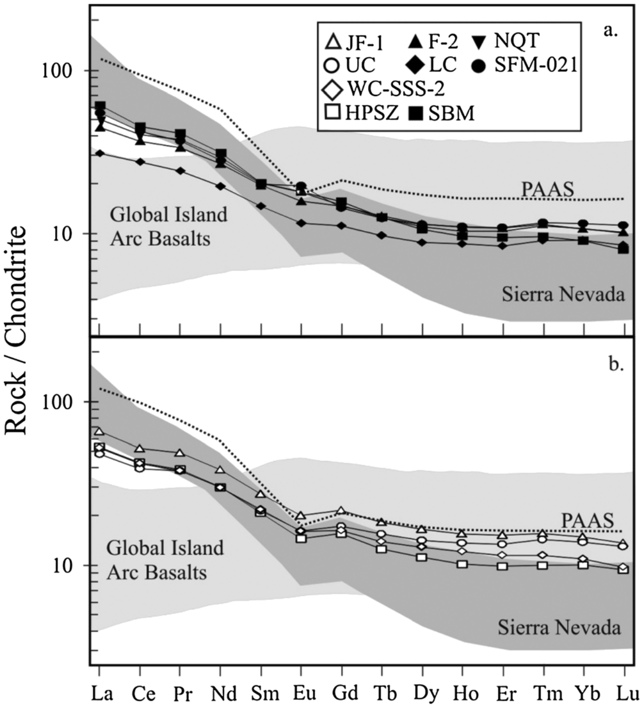

Figure 3. Chondrite-normalized REE patterns of the Franciscan graywackes (a) with no Eu anomaly and (b) with negative Eu anomaly. The shaded region is a summary of the ranges of the REE data from the literature for granodiorites from the Sierra Nevada batholith [*Bateman and Chappell*, 1979; *Burgess et al.*, 2006]. Post-Archean Australian Shale (PAAS) average data shown for comparison are from *Taylor and McLennan* [1985]. Also shown for comparison is the field of global island arc basalts [*Jakes and Gill*, 1970].

Uncertainties for the measured $^{143}Nd/^{144}Nd$ ratios were less than ±0.00003 (2σ of the mean). La Jolla Nd standard analyzed during the course of this study yielded $^{143}Nd/^{144}Nd = 0.51186 \pm 0.00003$ (2σ, n = 5). Initial ε_{Nd} values were calculated using present-day bulk Earth $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1968$ [*Jacobsen and Wasserburg*, 1984]. Pb isotopes were measured using a silica gel technique established in our laboratory [*Sharma et al.*, 1992]. Filament temperature during Pb isotope measurements was monitored; raw ratios were calculated as weighted averages of the ratios measured at 1150°C, 1200°C, and 1250°C, respectively. The reported Pb isotopic data were corrected for mass fractionation of 0.12 ± 0.03% per amu based on replicate analyses of the NBS-981 Pb standard. Estimated errors are less than 0.05% per amu. Laboratory procedural blanks are ~400 pg for Sr and ~200 pg for Nd and Pb. No blank correction was necessary for the isotope ratios reported in Table 3.

5. Analytical Results

5.1. Presentation of Geochemical Data of the Graywackes

[13] We analyzed the trace element concentrations and Sr, Nd, and Pb isotopic ratios of nine Franciscan graywacke samples (Figure 1). The chondrite-normalized [*Evensen et al.*, 1978] rare earth element (REE) patterns for the graywackes of this study are shown in Figure 3 and compared with post-Archean average Australian sediments (PAAS) [*McLennan*, 1989]. The nine samples of this study have been divided into those that have a negative Eu anomaly [$Eu/Eu^* < 0.9$] (Figure 3b) and those that do not show this anomaly (Figure 3a).

[14] Twenty-five compatible and incompatible trace element concentration patterns for each of the nine graywacke samples are shown normalized to Normal Mid-Ocean Ridge Basalt (N-MORB) and compared with Sierran granodiorites as shown in Figures 4a and 4b. Graywackes lacking negative Eu anomalies in Figure 3a show high Ba and Pb concentrations and high Ba/Rb, Ba/Th, U/Th, U/Nb, and La/Nb ratios (Figure 4a). A strong negative Nb anomaly is observed along with low Ce/Pb ratios. The graywackes displaying negative Eu anomalies (Figure 3b) only mildly exhibit some of the typical arc-like trace element patterns and display a slightly different set of trace element concentrations and ratios (Figure 4b).

[15] The correlated initial ε_{Nd} and $^{87}Sr/^{86}Sr$ values (Table 3) for the depositional ages of these rocks are plotted in Figure 5. Sample 93-SFM-021 has a high $^{87}Rb/^{86}Sr$ value of 9.9 and is likely overcorrected for its initial $^{87}Sr/^{86}Sr$ value. Initial ε_{Nd} ranges from +2.2 to −6.2, while the initial $^{87}Sr/^{86}Sr$ values range from 0.69840 to 0.70845 for all the graywackes of this study. The initial Nd-Sr isotopic ratios of the eight graywackes are compared to literature data on MORB, Pacific chert [*Shimizu et al.*, 1991; *Shimizu et al.*, 2001] arc tholeiites

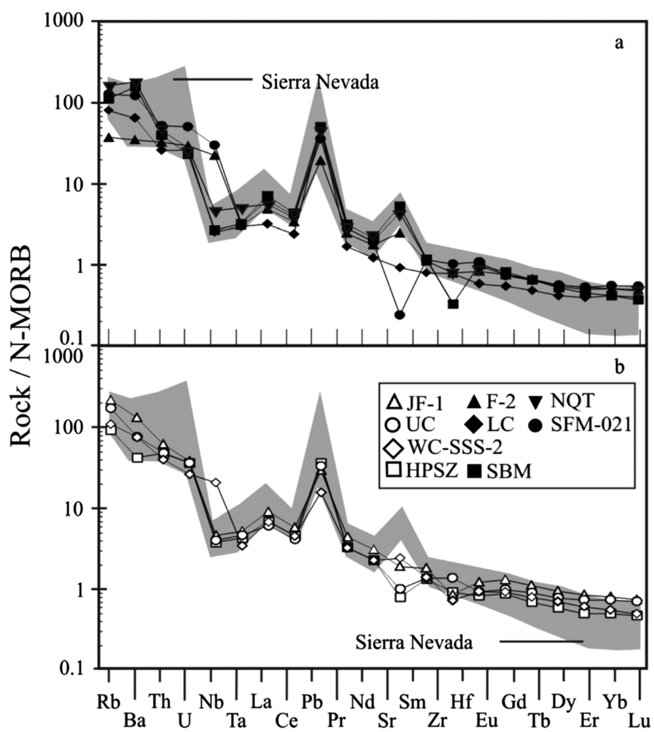

Figure 4. Multiple trace element concentrations are plotted normalized over N-MORB for the Franciscan graywackes, (a) with no Eu anomaly and (b) with negative Eu anomaly of Figure 3. The shaded region is a summary of the ranges in trace element concentrations, normalized similarly, for the granodiorites from the Sierra Nevada batholith [*Bateman and Chappell*, 1979; *Burgess et al.*, 2006]. Symbols are as in Figure 3.

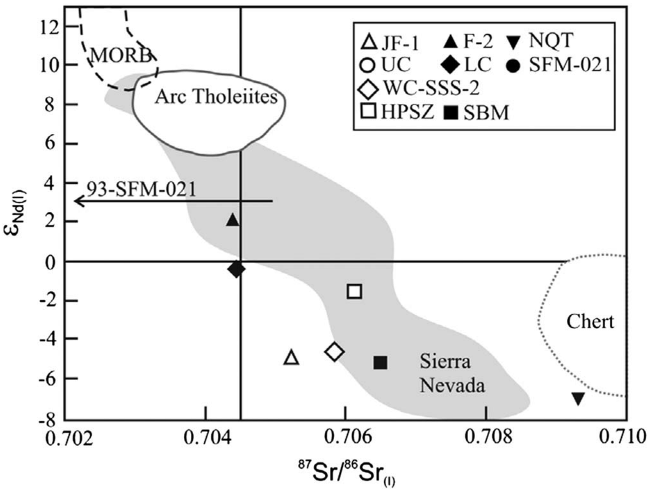

Figure 5. Initial ε_{Nd} versus initial $^{87}Sr/^{86}Sr_{(I)}$ of all the graywacke samples of this study, compared with similar data from the literature of the Sierra Nevada batholith [*Farmer et al*., 2002]. Shown also are the fields of chert [*Shimizu et al*., 1991; *Shimizu et al*., 2001], MORB, and arc tholeiites as in *Saha et al*. [2005]. Sample UC is not shown in this because Nd isotopic data for this sample were not available.

[*Tatsumi and Eggins*, 1995], and the Sierra Nevada batholith [*Farmer et al*., 2002] for comparison in Figure 5.

[16] Initial $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ of the Franciscan graywackes corrected for depositional ages (Figure 6) show ranges of 18.65–19.58, 15.58–15.70, and 38.08–38.43, respectively (Table 3). The initial Pb isotopic ratios of the graywackes are compared with initial Pb isotopic ratios of the Sierra Nevada batholith [*Farmer et al*., 2002], three intraoceanic arcs of the western Pacific, i.e., the Mariana, Kurile, and Izu-Bonin arcs, the Pacific MORB (Geochemistry of Rocks of the Oceans and Continents), various mantle reservoirs, and Northern Hemisphere Reference Line (NHRL).

[17] Variation in Nd and Sr isotopic composition of the graywackes and GVG fore-arc sedimentary rocks [*Linn et al*., 1992] with respect to the depositional ages for both these groups is shown in Figures 7a–c. Note that the Nd isotopic ratios of the GVG rocks were corrected to an initial 100 Ma (Figure 7a) whereas Sr isotopic ratios are present-day values (Figure 7b) in *Linn et al*. [1992]. For ease of comparison with Nd isotopic data, we have also plotted the GVG rocks corrected to an initial 100 Ma age of deposition (Figure 7c). Our graywackes samples are age corrected for their individual depositional ages in Figure 7b and are corrected for 100 Ma average depositional age in Figures 7a and 7c. In addition, we show present-day Sr isotopic ratios in Figure 7b to facilitate comparison with the published GVG data of *Linn et al*. [1992].

5.2. Geochemical Results

[18] The REE patterns of the graywackes lacking negative Eu anomalies (Figure 3a) resemble global island arc basalts [*Hawkesworth et al*., 1977; *Tatsumi and Eggins*, 1995]. They differ from PAAS by lack of negative Eu anomaly, lower light rare earth elements (LREE), and slightly U-shaped heavy rare earth element (HREE) patterns. These rocks differ from depleted MORB and may have either enriched MORB (E-MORB) or arc tholeiites as primary source material. In contrast, graywackes with negative Eu anomalies have REE patterns very similar to PAAS (Figure 3b) likely reflecting a greater proportion of continental source material.

[19] N-MORB normalized multiple trace elements patterns of arcs typically show Nb depletion, high concentrations of Ba and Pb, high Ba/Pb, Ba/Th, U/Th, U/Nb, and La/Nb ratios, and low Ce/Pb ratios [*Tatsumi and Eggins*, 1995]. Graywackes without the negative Eu anomaly show characteristic island arc signatures (Figure 4a), whereas this typical island arc signature is only partially present in the graywackes with the negative Eu anomaly (Figure 4b), implying a different, perhaps a more continental provenance for them. We note that graywackes without the negative Eu anomalies are no more chert rich than those without. These two groups of graywackes display both positive and negative Sr anomalies, due possibly to different amounts of modal plagioclase and differential weathering, consistent with their REE patterns (Figure 4).

[20] In Nd-Sr isotopic space (Figure 5), most of the graywackes fall within the field of the Sierra Nevada batholith, including those samples in Figure 3a lacking the Eu anomaly. Since the latter group show strong correspondence

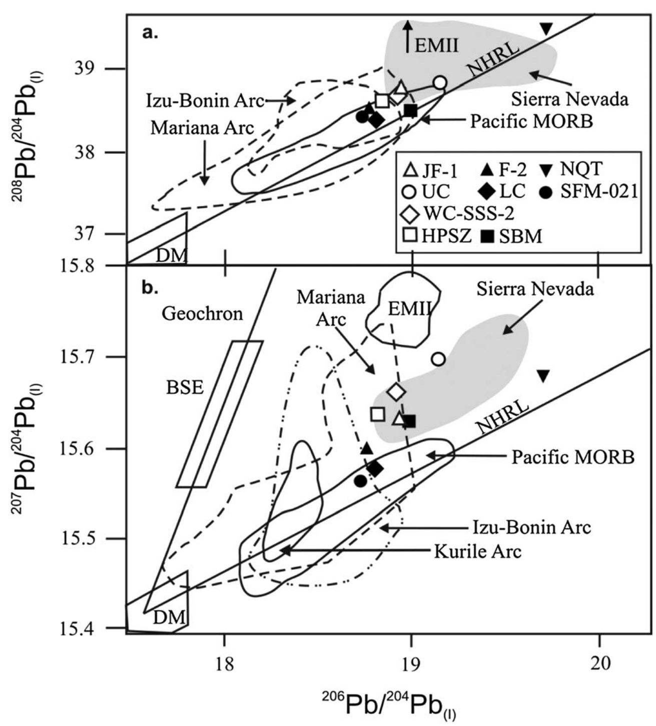

Figure 6. (a) Initial $^{208}Pb/^{204}Pb$ and (b) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ of the Franciscan graywackes compared with literature data of present-day Pb isotope ratios of three intraoceanic arcs of the western Pacific (Geochemistry of Rocks of the Oceans and Continents (GEOROC), http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp, Max Planck Institute, Mainz, Germany) and the Sierra Nevada batholith [*Farmer et al*., 2002]. The Pb isotope ratios of the graywackes are age corrected based on the U-Pb age distribution data of zircons, after *Snow et al*. [2010].

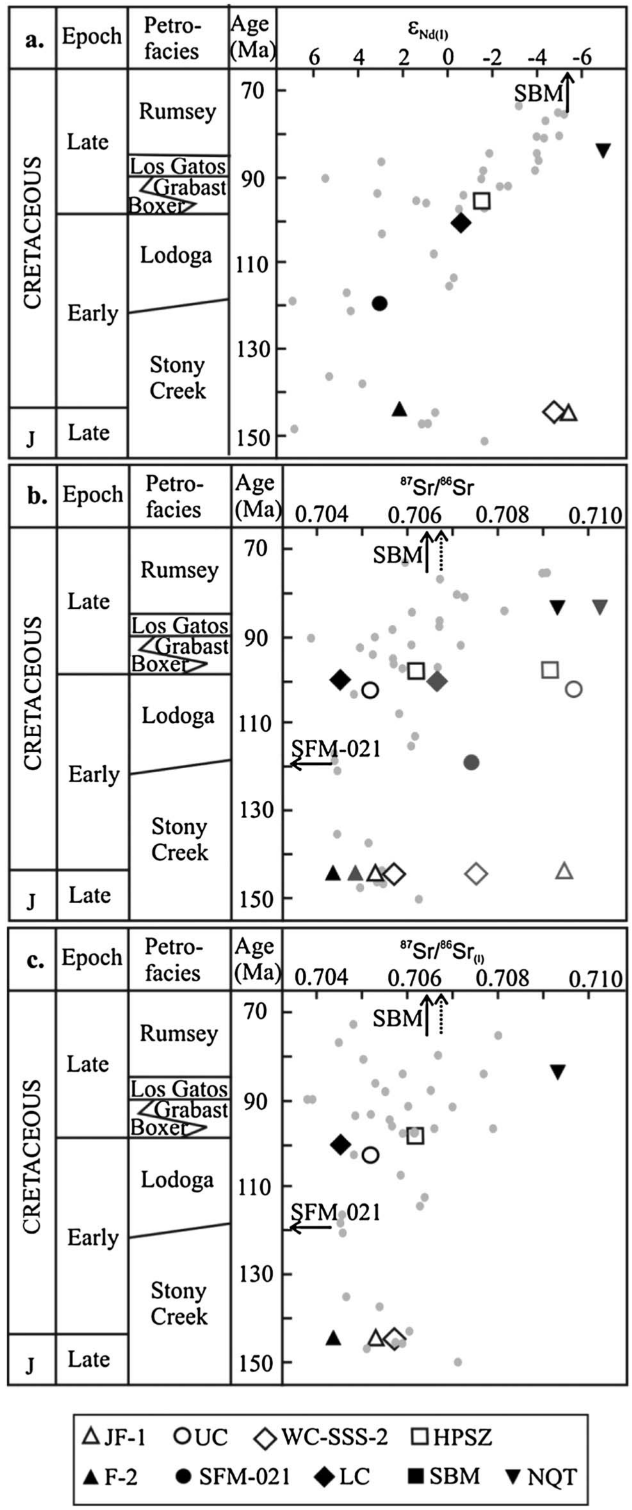

Figure 7. (a) Comparison of initial ε_{Nd} isotopic compositions of graywackes of this study and GVG sediments [*Linn et al.*, 1992] with respect to 100 Ma time of deposition. (b) Comparison of present-day Sr isotopic compositions the GVG sediments [*Linn et al.*, 1992] with the graywackes of this study. Sr isotopic ratios of the Franciscan graywacke samples are plotted as present-day values as well as for their individual ages (Table 1) of deposition as inferred from U-Pb ages of zircon distribution [*Snow et al.*, 2010]. The gray symbols and dotted arrow for sample (SBM) represent the present-day Sr isotope ratios of the Franciscan graywackes, with the corresponding black symbols and the solid line (SBM) indicating age-corrected data for the graywackes based on their zircon age distribution data. (c) Initial Sr isotopic compositions of the Franciscan graywackes of this study and GVG sediments [*Linn et al.*, 1992] plotted with respect to 100 Ma time of deposition.

to an island arc source in their trace element patterns (Figures 3a and 4a), their $\varepsilon_{Nd(I)}$ and $^{87}Sr/^{86}Sr_{(I)}$ are possibly influenced by the presence of nonbasaltic lithologic components such as radiolarian chert as indicated by the ubiquitous presence of chert clasts in these rocks. In contrast, the graywackes with negative Eu anomalies and PAAS-like REE patterns (samples in Figure 3b) may contain a higher proportion of detritus from the Sierra Nevada batholith as they fall within this field (Figure 3b).

[21] The Pb isotopic compositions (Figure 6) of the graywackes (except NQT) without negative Eu anomalies show a distinct affinity with the Izu-Bonin Arc rocks, whereas those with negative Eu anomaly overlap with the field of the Sierra Nevada batholith. The latter group also has, in general, higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ compared to the arc-like graywackes (Figure 6). Higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios indicate sediment involvement in their genesis [*Meijer*, 1976; *Hawkesworth et al*., 1977]. Clearly, samples NQT and UC reflect higher time-integrated U/Pb and Th/Pb ratios in their sources. It is likely that there is some contribution from continentally derived components in the graywackes without negative Eu anomalies (samples in Figure 3a), as most of them lie within fields of intraoceanic arcs (Figure 6). Sample NQT lies outside the fields of intraoceanic arcs and Sierra Nevada, in close correspondence with the NHRL (Figure 6a) and indicates a HIMU (high U/Pb) component in its source that is mostly believed as a recycled oceanic lithospheric component.

[22] The MORB-like or mantle-derived Pb in some of the island arc-like graywackes that fall close to the NHRL line strengthens the hypothesis of arc basalts as the sources of most of the detritus for these rocks. As already discussed with the REE and Sr, Nd isotopes, an island arc protolith for these samples without Eu anomaly is a viable option. Although there is a slight overlap between the fields of intraoceanic arcs and Sierra Nevada batholith rocks (Figure 6), the graywackes with Eu anomaly trend to the EM-II field indicating a more continental source for these rocks. The data suggest that the samples with negative Eu anomalies have more continental sediment in them than those without negative Eu anomalies, rather than being derived from completely different sources (Figure 6).

[23] Comparisons of Nd-Sr isotopic compositions coupled with depositional ages of the Franciscan subduction complex graywackes and the coeval GVG fore-arc basin sandstones and shales [*Linn et al*., 1992] indicate a large degree of overlap between the Franciscan graywackes and the GVG sandstones (Figures 7a–c), especially in the Sr isotopic variations with the corresponding age plot (Figures 7b and 7c). The Rb/Sr systematic is prone to disturbance due to various sedimentary processes such as chemical weathering of feldspars, portioning of Rb into clay, solution mobilization of Sr, leaching of Rb from biotite, grain-size variability due to weathering, and sediment re-working [e.g., *Faure*, 1986; *Nelson and DePaolo*, 1988]. *Linn et al*. [1992] chose not to use the ages of the GVG data due to the above mentioned issues as well as due to the paucity of paleontological data and difficulties in establishing a radiometric time scale [*Ingersoll*, 1978]. Our graywacke data are compared to both present-day GVG data (Figure 7b) as well as GVG data corrected to 100 Ma age of deposition (Figure 7c). Nevertheless, as seen in Figures 7b and 7c, the Sr isotopic composition of the GVG rocks shows the same systematic pattern of variation. There is good correspondence of our graywacke data with both the present-day GVG data (Figure 7b) as well as the age-corrected 100 Ma GVG data (Figure 7c).

6. Discussion

6.1. Sediment Compositions, Sources, Magma-Tectonic Evolution, Alteration of Source Signals

[24] The close correspondence in age-corrected Nd-Sr isotopic compositional space (Figures 7a and 7b) between coeval sandstones of the GVG and the Franciscan Complex graywackes suggests their derivation from the same sources, as previously proposed on the basis of petrographic data [*Dickinson and Suzcek*, 1982]. These results contradict proposals for a significant sediment contribution to Franciscan graywackes from an exotic source west (outboard) of the trench, such as an island arc or a large exotic terrane [e.g., *Blake and Jones*, 1981; *Jayko and Blake*, 1984].

[25] Temporal isotopic variation in the GVG has been interpreted to record the progressive maturation of the Sierra Nevada magmatism from an island arc to a continental margin arc with progressive exhumation [*Linn et al*., 1992]. Similarly, changes in GVG chemistry have been interpreted to reflect migration of a drainage divide that resulted in the incorporation of younger magmatic arc material into GVG sediments in the Late Cretaceous [*DeGraaff-Surpless et al*., 2002]. However, the multiple isotopic and trace element data of this study suggest a more complex scenario. If graywacke compositions reflected progressive maturation and exhumation of the magmatic arc, then they should show progressively more continental character with younger ages. This is not observed for the two groups of graywackes of this study. The more primitive graywackes lacking a negative Eu anomaly and those with more continental character and a negative Eu anomaly cannot be distinguished based on age. For example, two of the oldest graywackes (WC-SSS-2 and JF-1) are grouped with the "continental group" whereas the two youngest samples (NQT and SBM) have similar geochemical affinity (Figures 3, 5, 6, and 7a).

[26] The lack of age correspondence for the two geochemical groups suggests shifting locations of the sediment transport systems, such as rivers, local geology, exhumation/erosion in drainage basins, and the tectonomagmatic evolution of the Sierra Nevada magmatic arc. This is consistent with recent findings by *Dumitru et al*. [2013] that the general pattern of sedimentation, accretion, or nonaccretion in this arc-trench system appears to have been controlled more by the position of large river systems and erosion within their corresponding drainage basins rather than changes in local trench-fore arc tectonics. Our data show that sediment sources may also vary significantly during the time span of deposition of a single (albeit regionally extensive) greywacke unit, such as the Skaggs Springs schist, from which one sample groups with the more primitive group (F-2), whereas the other two samples (JF-1 and WC-SSS-2) group with the more continental group. Samples F-2 of the primitive group and JF-1 of the continental group are taken from the same outcrop belt of the Skaggs Springs schist, sampled 60 km apart along strike.

[27] There is little or no correspondence of detrital zircon age distributions with either of the two graywacke groups for any given sample. For example, the detrital zircon age population of NQT that lacks a negative Eu anomaly is dominated by zircons similar in age to the younger part of the Sierra Nevada batholith (85–100 Ma) and has significant number of 1.4–1.8 Ga zircons in the zircon age population, [*Snow et al*., 2010], so it might be expected to exhibit a continental signature. Similarly, the age population of SBM, another sample lacking a negative Eu anomaly, is dominated by 52–75 Ma zircons that postdate the Sierran batholith [*Snow et al*., 2010], possibly derived from the Idaho batholith and neighboring regions [*Dumitru et al*., 2013]; such an age population appears to reflect a continentally dominated source for this graywacke. Zircons are more robust than any of the other components of a graywacke and these data suggest that the bulk of the graywacke source material may not necessarily reflect the age population of the zircons. In fact, mafic and ultramafic ophiolitic materials are expected to be largely free of zircon; ophiolitic material may significantly contribute to the island arc chemical signature of the greywacke owing to the island arc affinities of major ophiolites in the North American Cordillera, including the Sierran and Klamath regions [e.g., *Saleeby*, 1990; *Metcalf and Shervais*, 2008].

[28] Similar to the zircon age populations, the framework detrital modes of sandstones do not appear to correspond to the geochemical signature of the two graywacke groups. For example, NQT that lacks a negative Eu anomaly has average quartz-feldspar-lithic proportions of 41%, 48%, and 11%, respectively, which appears to reflect a continental or recycled type of provenance [*Jayko and Blake*, 1984]. Major element chemistry shows that graywacke samples of NQT, LC (lack negative Eu anomaly), and UC (has negative Eu anomaly), as well as high-lithic samples of the Marin Headlands terrane [*Jayko and Blake*, 1984], range in SiO_2 content from about 69% to 73% [*Bailey et al*., 1964]. Such high SiO_2 concentrations may be taken to reflect a continental source and conflict with conclusions drawn from trace element and REE data.

[29] Major and trace element data from GVG mudstones suggest a mafic provenance for the fore-arc basin from accreted island arcs and ophiolites [*Shaw et al*., 2010]. This contrasts with the interpretation of the sedimentary petrology and isotopic geochemistry of GVG graywackes (i.e., coarser clastic sedimentary rocks) [*Linn et al*., 1992] as well as the interpretation of provenance of the fore-arc basin strata from detrital zircon age populations of GVG graywackes [*DeGraaff-Surpless et al*., 2002].

[30] Collectively, our geochemical data, and detrital zircon age populations, framework modes, and geochemistry from other studies of Franciscan and GVG clastic rocks, suggest that weathering and/or diagenetic/metamorphic processes attenuate some aspects of the source signal, while concentrating others. Comparison of the mineralogy and geochemistry of stream sands to source rocks in drainage basins suggests concentration of quartz and feldspar in the sands because of preferential destruction of mafic minerals in the weathering process, resulting in elevated Si and Al compared to the source [*Cullers et al*., 1987, 1988; *Cullers*, 1994]. In contrast, the REE patterns and, particularly, ratios of the more immobile trace elements of sands, may more faithfully reflect the proportions of the source material [*Cullers et al*., 1987, 1988; *Cullers*, 1994]. Therefore, geochemistry may be a better record of the relative proportions of sediment provenance than sandstone petrography or detrital zircon age populations, although important information conveyed by the latter two types may not be revealed by the geochemical data. Whereas geochemistry may better record the mafic or noncontinental component of clastic rocks, and possibly give better insight into the proportions of source lithologies, it cannot discern ages of various source terranes, as detrital zircon data can, nor can it directly evaluate the specific lithic and mineral components as petrography can.

6.2. Recycling Within the Franciscan Subduction Complex

[31] *Wakabayashi* [2011, 2012] showed, by outcrop and petrographic examination that a significant proportion of clasts/blocks in blueschist facies Franciscan clastic rocks had undergone earlier blueschist facies metamorphism prior to deposition. Some blueschist facies sedimentary breccia units consist primarily of metagraywacke blocks (up to tens and possibly hundreds of meters in size) with internal fabrics, defined by syntectonic blueschist facies minerals, which are truncated at clast/block boundaries. From these data, he concluded that exhumed and redeposited Franciscan rocks constituted a significant component of Franciscan clastic sedimentary rocks deposited after 120 Ma. In contrast, the strata of the GVG fore-arc basin experienced a much less dynamic exhumation and deformational history [e.g., *Ingersoll*, 1982; *Moxon*, 1988; *Wakabayashi and Unruh*, 1995], indicating minimal recycling of older GVG material in GVG rocks.

[32] Comparison of the age initiation of large-scale clastic accretion in the Franciscan (circa 120 Ma) [*Dumitru et al*., 2010] and the age of the earliest metagraywacke or mélange units in the Franciscan with abundant recycled metagraywacke detritus (circa 90–110 Ma) [*Ernst et al*., 2009] suggests sedimentation/burial-exhumation-resedimentation/burial cycle times of less than 30 Ma [*Wakabayashi*, 2011, 2012]. The close correspondence between radiogenic Sr and Nd ratios of Franciscan and coeval GVG graywackes is consistent with a comparatively short recycling time for Franciscan graywackes, but the scatter of the data is too great to be definitive. For example, if samples NQT, LC, or HPSZ contained a large amount of recycled material from graywackes deposited 20 million years earlier, a higher (more positive or less negative) value of $\varepsilon_{Nd(I)}$ may be expected, but the scatter in $\varepsilon_{Nd(I)}$ for any given age of GVG graywacke makes such an assessment uncertain (Figure 7a). In spite of the widespread evidence of recycling of Franciscan graywacke material within Franciscan graywacke [*Wakabayashi*, 2011, 2012], the correspondence in Nd isotopic ratios between coeval Franciscan and GVG graywackes remains.

6.3. Implications for Chemical Mobility in Subduction Zone Metamorphism

[33] Graywackes represent the most voluminous continentally derived components of the Franciscan Complex. Widely divergent views exist on the exchange of metamorphic fluids and chemical components between subducted continental sediments and the mafic downgoing slab. Some believe that the mafic subducting slab is chemically modified by interactions with fluids from subducted continental sediments, on

the basis of difference in chemical composition of metabasites of different metamorphic grade [e.g., *Bebout and Barton*, 1993; *Nelson*, 1995; *Sorensen et al*., 1997]. In contrast, on the basis of flat to slightly depleted LREE in metabasites of prehnite-pumpellyite, blueschist, eclogite, and amphibolite grade, compared to elevated LREE of PAAS (in the absence of Franciscan graywacke data), and their Sr, Nd, isotopes, our research group concluded that the Franciscan metabasites were not modified by fluids derived from subducted continental sediments [*Saha et al*., 2005; *Wakabayashi et al*., 2010; *Ghatak et al*., 2012]. The Franciscan metabasites examined in those studies were originally accreted from circa 165 Ma to 80 Ma and include some rocks (the highest grade and oldest ones) that were accreted prior to significant accretion of clastic material in the Franciscan (pre-120 Ma) as well as those cosubducted and accreted with clastic material, Our Franciscan graywacke data show elevated LREE similar to PAAS (Figures 3 and 4), so the flat to slightly depleted LREE relative to HREE patterns of Franciscan metabasites reflect a lack of chemical exchange with fluids derived from cosubducted (or later-subducted) graywacke that should have resulted in elevated LREE in the metabasites had chemical exchange taken place. Thus, our current study supports the earlier conclusions that fluids derived from the cosubducted clastic sediment did not significantly reequilibrate with subducted oceanic crust.

7. Conclusions

[34] The combined trace element and Nd, Sr, Pb isotopic geochemical data of Franciscan graywackes illustrate complexity inherent in interpretation of sources of clastic sedimentary rocks. Our graywacke data appear to reflect variation both in the location and sources of sediment delivery systems, as well as progressive unroofing of the evolving Sierra Nevada magmatic arc. In addition, comparison of our data with those from the GVG fore-arc basin sediments suggests similar sources of sediments rather than an exotic source for the Franciscan graywackes, as suggested by several previous workers. Comparison of our data with detrital zircon age populations, major element chemistry, and detrital framework modes indicates that the latter three parameters may not adequately reflect mafic sources that may be significant for many of the graywackes. The apparent underrepresentation of mafic sources in clastic rocks by detrital zircon chronology, major element chemistry, and detrital modes may result from the scarcity of zircons in mafic rocks and preferential loss of mafic components to subaerial chemical weathering at the source. This conclusion is similar to that reached by others evaluating major and trace element geochemistry of GVG mudstones [*Shaw et al*., 2010]. Our study suggests that trace element and radiogenic isotope data may be the best recorders of the relative proportions of source lithologies in sandstones. On the other hand, geochemistry alone cannot resolve the ages of source terranes of sandstones as detrital zircon studies can, nor can geochemistry determine the details of lithic and mineral clasts as petrography can. Thus, the results of this study, when compared to other studies of clastic rocks in trench-fore arc systems, highlight the value of multidisciplinary analysis of clastic sedimentary rocks in connecting the sedimentary rock record to geologic processes.

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