U-Pb detrital-zircon geochronology of northern Salinian basement and cover rocks

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ABSTRACT

Salinia is an out-of-place granitic terrane in central coastal California whose debated origin is critical to understanding the tectonic history of southwestern North America. Salinian metasedimentary and sedimentary rocks that respectively host and cover its predominant arc rocks should contribute important data about its origin and kinematic history, but pervasive intrusion, high-grade metamorphism and Cenozoic erosion of the Salinian block have inhibited their widespread characterization and correlation. To further address these problems, we report 605 U-Pb detrital-zircon geochronologic ages collected by laser-ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) from seven Salinian metasedimentary framework (Sur Series) and sedimentary cover samples. Samples collected from the Sur Series contain Late Archean (2.5–2.9 Ga), late Paleoproterozoic (1.6–1.9 Ga), Mesoproterozoic (0.9–1.5 Ga), Neoproterozoic (0.65–0.8 Ga), Paleozoic (250–450 Ma), and possibly Mesozoic U-Pb detrital-zircon ages. Samples collected from Upper Cretaceous cover units have various age-peak distributions, which collectively include late Paleoproterozoic (1.6–1.8 Ga), early Mesoproterozoic (1.35–1.55 Ga), Permo-Triassic (220–290 Ma), and Jurassic-Cretaceous (80–190 Ma) peaks. From these data, several interpretations are made. (1) Maximum depositional ages of the Sur Series and cover intervals are 280–360 Ma and 78–90 Ma, respectively. (2) The presence of Late Archean, early Paleoproterozoic, and Neoproterozoic zircons in Salinian metasedimentary rocks suggest that uplift and erosion of adjacent basins recycled sediment onto Salinia. (3) The abundant pre-Mesoproterozoic detrital-zircon ages in Sur Series and cover units preclude the possibility that Salinia originated in southern Mexico, as has been previously suggested. (4) Five of six key detrital-zircon age peaks identified in Salinian basement and cover units are nowhere more closely arranged than in the Mojave Desert–Peninsular Ranges region of Baja and southern Alta California. (5) Paleozoic and early Mesozoic detrital zircons in Sur Series and cover units match the ages of several plutonic events that occurred along the western margin of North America—however, Permian ages favor a Mojave Desert origin over other candidates. Collectively, these and other data suggest that Salinia resided in the Mojave Desert–Peninsular Ranges region from the late Paleozoic until the Late Cretaceous, after which it was rapidly exhumed, deposited upon, and then translated outboard and northward to its current position.

Keywords: tectonics, Cordillera, California, provenance, Sur Series, depositional age.

INTRODUCTION

Salinia is an enigmatic granitic terrane that interrupts the classic juxtaposition of arc, forearc, and accretionary wedge tectonostratigraphic domains that are otherwise typical of the Mesozoic Cordilleran subduction system in California (Dickinson, 1981). In its current location adjacent to outcrops of the low-temperature, high-pressure Franciscan complex and strata of the Great Valley Group (Fig. 1), Salinia is not contiguous with the associated metamorphic and igneous terranes characteristic of arc volcanism. Some of this anomalous juxtaposition can be attributed to 300–350 km of dextral offset that occurred along the San Andreas transform system during the late Cenozoic (Matthews, 1976; Graham et al., 1989; Powell, 1993; Dickinson and Wernicke, 1997). However, restoration of this deformation does not return Salinia to an intra-arc position, and as a result, its origin and pre-Neogene transport history have been widely debated.

In general, three models compete to explain the origin of Salinia. (1) Continental strontium-isotope signatures (Kistler, 1978; Kistler and Champion, 2001) and geologic relationships (Page, 1970; Page, 1981; Hall, 1991; Saleeby, 2003; Barth et al., 2003) suggest that top-to-the-west thrusting of eastern California arc rocks over forearc and accretionary wedge tectonostratigraphic domains may have brought Salinia into its anomalous outboard position. (2) Paleomagnetic data collected from coastal and Baja California have been interpreted to indicate long-distance northward translation of terranes exotic to the Farallon-Pacific margin of the United States and suggest that Salinia may have originated near southern Mexico (Champion et al., 1984; Hagstrum et al., 1985; Debiche et al., 1987). However, this model has been largely undermined by studies that suggest pluton-tilt and sedimentary compaction-shallowing of remnant magnetizations may be responsible for the interpreted discordance between coastal

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and Baja California paleolatitudes and the North American apparent polar wander path (Butler et al., 1991; Dickinson and Butler, 1998; Whidden et al., 1998; Kodama and Ward, 2001). (3) Moderate distance (<3° latitude) lateral-translation models (e.g., Dickinson, 1983) are consistent with the reevaluated paleomagnetic data and are bolstered by geometric and geologic arguments that tie Salinia to portions of the Mojave Desert and eastern Peninsular Ranges regions (Ross, 1984; Silver and Mattinson, 1986; Hall, 1991). Enduring interest and research into the possibility of long-distance transport of Salinia and other Pacific-Farallon margin terranes (Umhoefer and Schiarizza, 1996; Cowan et al., 1997; Housen and Beck, 1999; Hollister and Andronicos, 1997; Mahoney et al., 1999; Butler et al., 2001; Trop et al., 2002; Cowan, 2003), however, indicate that this debate is not yet resolved.

Metasedimentary and sedimentary rocks that respectively host and cover Salinia's predominant arc rocks should contribute important data about its origin and kinematic history. However, several factors inhibit the widespread characterization and correlation of these framework and cover rocks. Pervasive intrusion of Cretaceous granitoids throughout Salinia has left few and discontinuous exposures of host rocks. Of the sedimentary septa, pendants, and rafts that remain, high-grade metamorphism has largely obscured faunal assemblages and stratigraphic and crosscutting relationships. Further, Cenozoic erosion of the Salinian block has removed original depositional and stratigraphic relationships in the Upper Cretaceous–Quaternary cover. This is exacerbated by the poorly dated nature of sparse but important Upper Cretaceous strata. The high closure temperature of zircon, however, provides an opportunity to circumvent these impediments through U-Pb geochronology.

To further address the debated origin of Salinia and to better characterize the enigmatic Salinian basement and cover rocks, we report U-Pb detrital-zircon age data acquired by laser-ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) from seven sandstone and quartzite samples collected in the western, central, and eastern blocks of northern Salinia (Fig. 2; Table 1). Comparison of detrital-zircon age spectra from Salinian basement and cover units with possible sources and other North American detrital-zircon age spectra allows us to assess the Mojave Desert, eastern Peninsular Ranges, and southern Mexico origins proposed for Salinia. Moreover, this study contributes to the growing body of zircon age data collected from California tectonostratigraphic domains and places maximum depositional ages on Salinian framework and cover rocks.

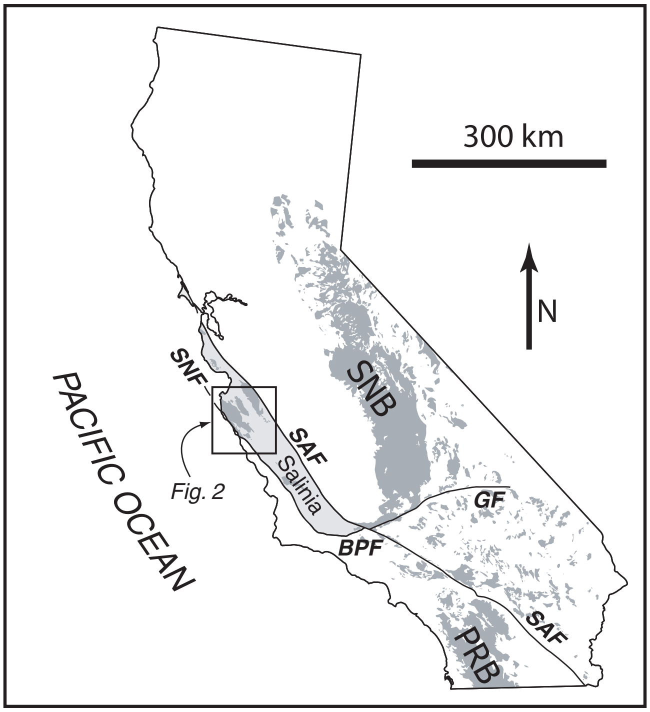

Figure 1. Location map for Salinia and study area. Salinia is bounded to the east by the San Andreas fault (SAF), to the west by the Sur-Nacimiento fault (SNF) and to the south by the Big Pine fault (BPF). Cretaceous granitoids are shown in gray. PRB—Peninsular Ranges batholith. SNB—Sierra Nevada batholith. GF—Garlock fault. The location of Figure 2 (study area) is shown by box. Modified from Kidder et al. (2003).

GEOLOGIC SETTING

Salinia is a fault-bounded crustal block in the central coast of California (Figs. 1 and 2). It is bounded to the west by the Sur-Nacimiento fault, the east by the San Andreas fault, and the south by the Big Pine fault. The Palo Colorado–Coast Ridge and Reliz-Rinconada fault systems further subdivide Salinia into western, central, and eastern blocks (Fig. 2 inset). Salinia is composed of four tectonostratigraphic units, the timing and conditions of genesis of which are each constrained to varying degrees: (1) Cretaceous granitoids and associated igneous rocks, (2) the 'Sur Series' suite of metamorphosed sedimentary and igneous framework rocks into which Cretaceous magmatic rocks intruded, (3) the Upper Cretaceous schist of the Sierra de Salinas that structurally underlies the Sur Series, but likely is not intruded by Salinian granitoids (Barth et al., 2003), and (4) Upper Cretaceous to Quaternary sedimentary units that locally overlie the framework and igneous units (e.g., Page et al., 1998). A summary of the tectonic, magmatic, and sedimentary events that have been documented in the Salinian block is shown in Figure 3 and is described below.

Magmatism in Salinia occurred between ~130 and 70 Ma (James and Mattinson, 1988; Mattinson, 1990; Kistler and Champion, 2001; Barth et al., 2003) but was most intense between 93 and 81 Ma (Kidder et al., 2003), coincident with the second of two Mesozoic magmatic flare-ups common to the Sierra Nevada and Peninsular Ranges batholiths to the east and south, respectively (Coleman and Glazner, 1998; Ducea, 2001). This magmatic accumulation doubled the thickness of Salinian crust from 93 to 80 Ma (Kidder et al., 2003). The isotopic signatures of Salinian granitoids are consistent with arc magmatism that occurred along a cratonic margin and are similar to those found in the eastern (interior) parts of the California arc (Ross, 1977; Kidder et al., 2001; Kistler and Champion, 2001).

The Sur Series (Trask, 1926) is a succession of heterolithic gneisses, schists, marbles, and quartzites that host the Cretaceous granitoids and that reached metamorphic grades in the upper amphibolite and granulite facies at ca. 81–76 Ma, although foliation development and ductile deformation occurred from 93 to 76 Ma (Kidder et al., 2003). Whereas the Sur Series protolith was originally believed to comprise

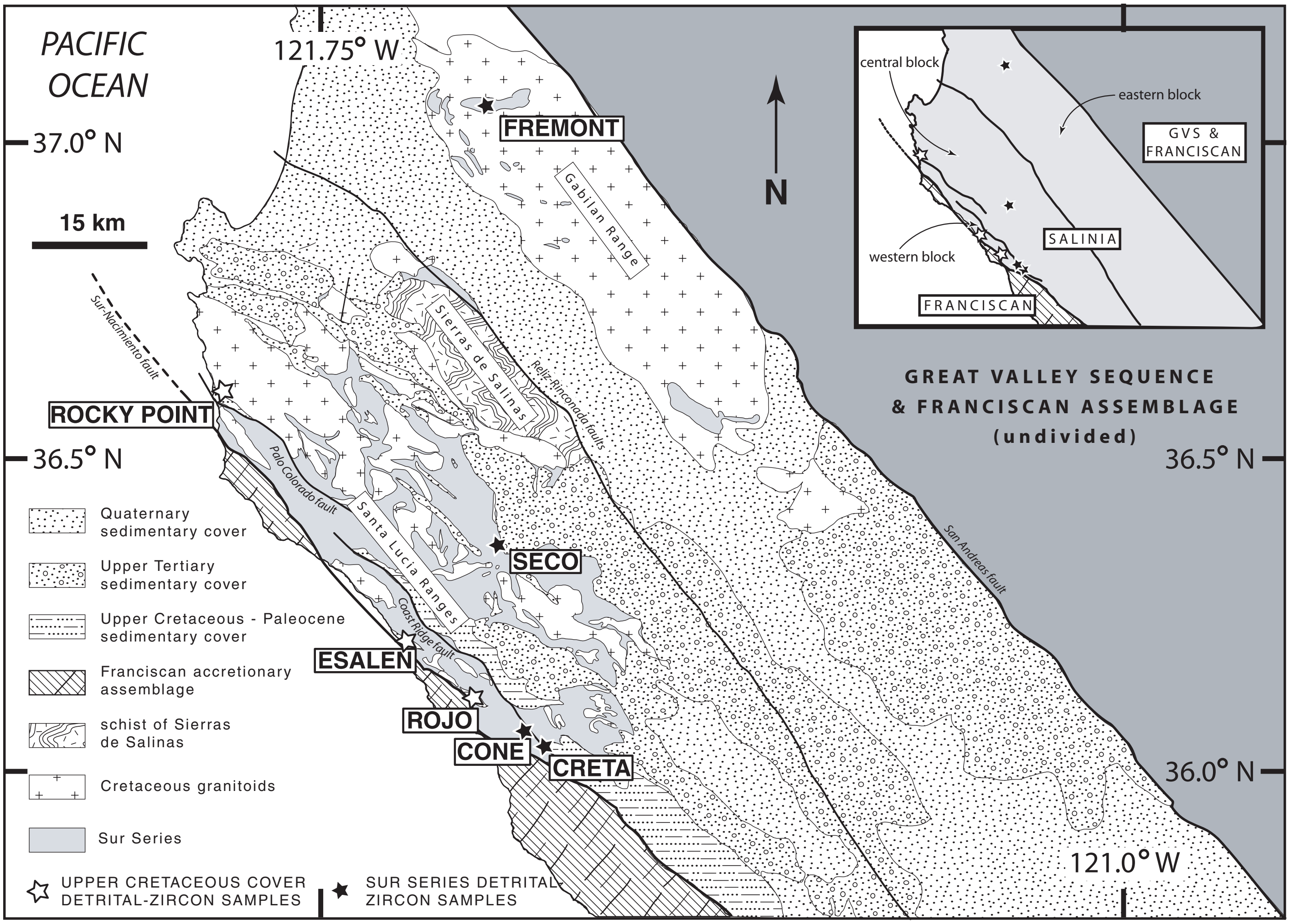

Figure 2. Map of study area in northern Salinia indicating locations of Sur Series (black stars) and Upper Cretaceous cover unit (white stars) samples relative to Franciscan complex, Cretaceous granitoids, and sedimentary units of central coastal California.

TABLE 1. SALINIA DETRITAL ZIRCON SAMPLES: FORMATIONS AND LOCATIONS UTM ZONE 10 S, NAD27 CONUS DATUM

Sample	Unit	Block	Elevation (m)	Easting	Northing	Latitude (N)	Longitude (W)
Creta	Sur Series	Western	914	0639984	3985700	36°00′20.6″	121°26′48.4″
Cone	Sur Series	Western	N/A	0638034	3987071	36°01′12.6″	121°28′05.4″
Rojo	Upper Cretaceous cover	Western	650	0629183	3991667	36°03′39.6″	121°33′56.2″
Esalen	Upper Cretaceous cover	Western	N/A	0622963	3998202	36°07′21.1″	121°38′01.1″
Seco	Sur Series	Central	630	0635458	4010973	36°14′02.9″	121°29′33.5″
Rocky point	Upper Cretaceous cover	Central	57	0597809	4029193	36°24′10.5″	121°54′33.2″
Fremont	Sur Series	Eastern	675	0634285	4069145	36°45′37.4″	121°29′44.1″

platformal Paleozoic-Mesozoic sedimentary units (Ross, 1977; Mattinson, 1990), the relative abundance of gneissic material having calcic tonalite modal compositions and isotopic signatures indistinguishable from associated intrusive rocks (Kidder et al., 2001, 2003) now suggest that much more of the Sur Series may have an igneous protolith than previously thought. The lateral discontinuity and degree of metamorphism of the Sur Series limits biostratigraphic and sequence stratigraphic constraints on the depositional age of its metasedimentary components. However, inherited and detrital zircons recovered from the Cone Peak diorite (Kidder et al., 2003) and framework metasedimentary quartzites (this study), respectively, suggest that the maximum age of parts of the Sur Series is late Paleozoic and perhaps even Mesozoic.

Upper Cretaceous–Paleocene (Gilbert, 1973; Howell and Vedder, 1978; Vedder et al., 1983; Grove, 1993), Eocene and Oligocene–Miocene (Graham, 1976; Vedder et al., 1983; Hall, 1991) marine-dominated sedimentary successions are intervened by regional unconformities and overlie the intrusive rocks and Sur Series of the Salinian block (Fig. 3). Integrated biostratigraphic, paleobathymetric (Grove, 1993), and pressure-temperature-time constraints (Ducea et al., 2003a; Kidder et al., 2003) suggest that exhumation of the Salinian arc from ~25 km depth to the surface occurred over a very short interval between the cessation of high- and mid-T metamorphism around 80 Ma and deposition of marine rocks in the Campanian (?) or Maastrichtian, ca. 75–65 Ma (Vedder et al., 1983). Calculated late Cretaceous exhumation rates of

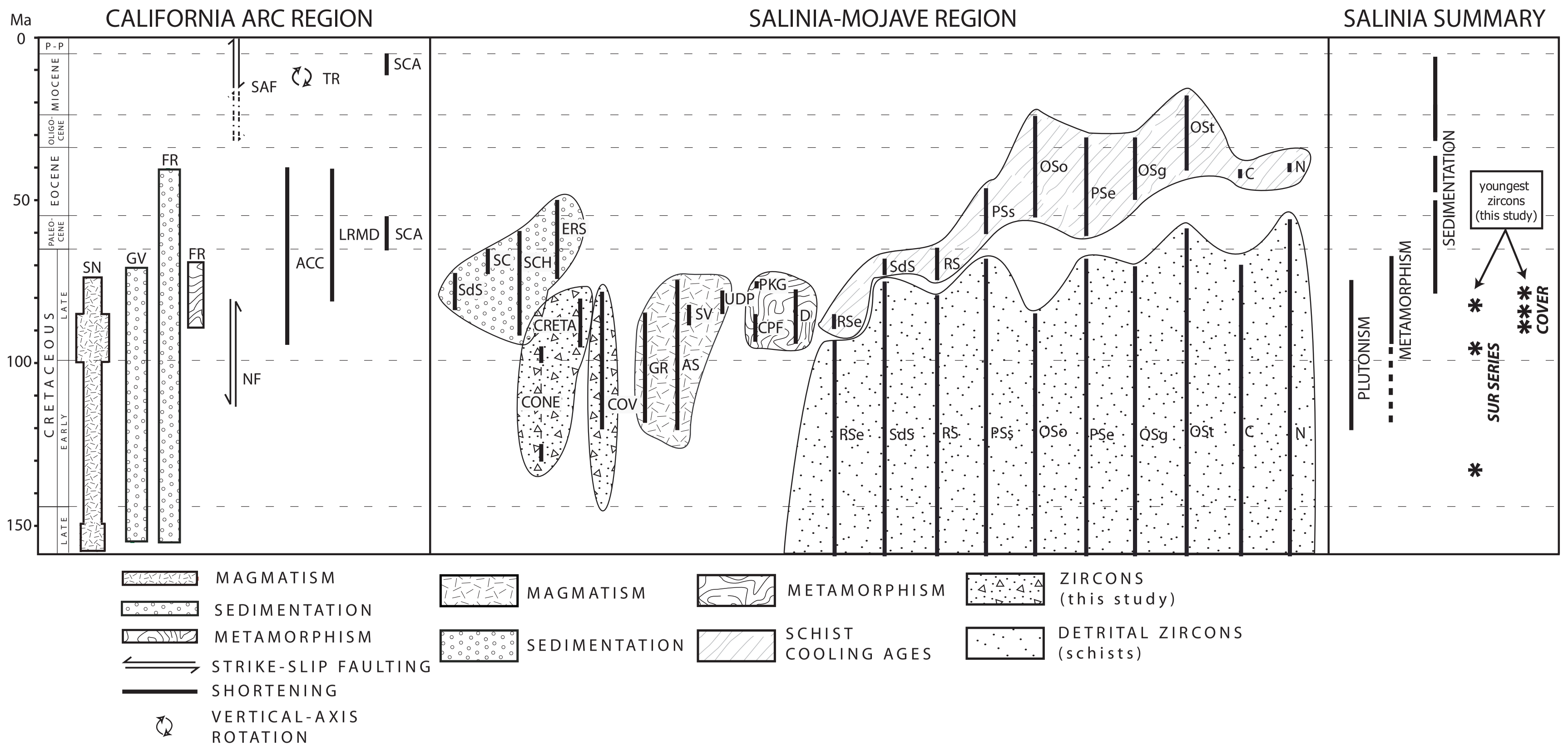

Figure 3. Chronostratigraphic and kinematic chart for Salinia and California arc regions. Left box: SN—Sierra Nevada batholith (Coleman and Glazner, 1998; Ducea, 2001); GV—Great Valley forearc basin (DeGraaff-Surpless et al., 2002); FR—Franciscan accretionary assemblage (Ernst, 1970; Gilbert, 1971, 1973; Page, 1972; Bachman, 1979); NF—Nacimiento Fault (Dickinson, 1983); ACC—underplating and accretion of lower plate schists to southwestern USA (Grove et al., 2003); LRMD—Laramide orogenesis in western interior USA (DeCelles, 2004); SCA—emplacement and movement of southern California allochthon (Gilbert, 1971, 1973; Page, 1981; Hall, 1991); SAF—San Andreas Fault (Atwater, 1970; Nicholson et al., 1994); TR—rotation of Transverse Ranges (Nicholson et al., 1994). Center box: SdS—depositional age of schist of Sierras de Salinas protolith (Barth et al., 2003). CONE—youngest zircons recovered from Sur Series sample CONE (this study); CRETA—youngest zircons recovered from Sur Series sample CRETA (this study); COV—youngest detrital zircons recovered from Upper Cretaceous Salinia cover units (this study). GR—Gabilan Range magmatism (Barth et al., 2003, and references therein); AS—Salinian magmatism (Mattinson and James, 1985); SV—Salinas Valley magmatism (Barth et al., 2003, and references therein); UDP—emplacement of Salinian plutons not deformed by Cretaceous tectonism (Mattinson and James, 1985); CPF—development of metamorphic foliation in the Cone Peak region (Kidder et al., 2003); D—Cone Peak region at 25–30 km depth (Kidder et al., 2003; Ducea et al., 2003b); PKG—growth of postkinematic garnets in Cone Peak region (Kidder et al., 2003); K/Ar and Ar/Ar cooling ages of Salinian plutons are shown by diagonally hatched polygon are from Compton (1966) and Barth et al. (2003); RSe—U-Pb detrital-zircon and Ar/Ar cooling age data from Rand Schist in San Emigdio Ranges (Grove et al., 2003); SdS—U-Pb detrital-zircon and Ar/Ar cooling age data from schist of the Sierras de Salinas (Barth et al., 2003); RS—U-Pb detrital-zircon and Ar/Ar cooling age data of Rand Schist in Portal Ridge and Rand Mts. (Grove et al., 2003); PSs—U-Pb detrital-zircon and Ar/Ar cooling age data of Pelona Schist in Sierra Pelona (Grove et al., 2003); OSo—U-Pb detrital-zircon and Ar/Ar cooling age data of Orocopia Schist in Orocopia Mts. (Grove et al., 2003); PSe—U-Pb detrital-zircon and Ar/Ar cooling age data of Pelona Schist in East Fork region (Grove et al., 2003); OSg—U-Pb detrital-zircon and Ar/Ar cooling age data of Orocopia Schist in Gavilan hills (Grove et al., 2003); OSt—U-Pb detrital-zircon and Ar/Ar cooling age data of Orocopia Schist in Trigo Mts. (Grove et al., 2003); C—U-Pb detrital-zircon and Ar/Ar cooling age data of Orocopia Schist in Castle Dome Mountains (Grove et al., 2003); N—U-Pb detrital-zircon and Ar/Ar cooling age data of Orocopia Schist along Neversweat Ridge (Grove et al., 2003). SC—depositional age of Salina cover units (Gilbert, 1971, 1973; Sutherland, 1990; Grove, 1993); SCH—depositional ages of lower plate schists (Grove et al., 2003); ERS—dissection and erosion of Salinian plutons and associated deep-sea sedimentation (Page, 1981). Right bos: Summary of plutonic, metamorphic, and sedimentary history of Salinia with respect to the ages of the youngest zircons recovered from the Sur Series and cover samples in this study.

>2–3 mm/yr (Kidder et al., 2003) require a significant component of extensional exhumation, which is congruent with Grove's (1993) model of a unified Upper Cretaceous transtensional forearc basin offshore from the Salinian arc. Discrete dextral transform motion along the western plate margin began in the middle Miocene (Fig. 3) and developed a series of disjointed transtensional marine basins along the Salinian margin (Graham, 1978; Graham et al., 1989; Hall, 1991; Grove, 1993; Page et al., 1998). A second pulse of rapid exhumation occurred at ca. 8 Ma, associated with a change in the relative plate motion vector between the Pacific and North American plates (Ducea et al., 2003a).

SAMPLES

Seven detrital-zircon samples (Table 1) were collected from the quartzites and sandstones that respectively host and cover the Cretaceous intrusive suite of which Salinia is primarily composed (Fig. 2). Four samples come from metasedimentary components of the Sur Series (CRETA, CONE, SECO, and FREMONT) and three from the Upper Cretaceous sedimentary cover units (ROJO, ESALEN, and ROCKY POINT). Four of the samples belong to the western block (CRETA, CONE, ROJO, and ESALEN), whereas two belong to the central block (ROCKY POINT and SECO), and one belongs to the eastern block (FREMONT).

Sur Series Samples

This study reports detrital-zircon age data from quartzites of the pre-Late Cretaceous Sur Series. The Sur Series' heterogeneity, amphibolite-granulite facies metamorphism, and pervasive intrusion by Cretaceous granitoids has largely inhibited its subdivision into lithostratigraphic members. As a result, little is known about the structural orientation and stratigraphic architecture of the Salinian basement and the sense of displacement on its many intraterrane faults (e.g., Fig. 2). In the southern Santa Lucia Mountains, however, the Sur Series has a predominant foliation that dips ~30° NE, as well as a northeastward decrease of regional metamorphic grade. In the context of this northeastward tilt, higher concentrations of layered granofels, amphibolites, and marbles occupy the lower part of the succession, whereas disorganized meta-igneous rocks define the upper (Kidder et al., 2003). In the southern Santa Lucia Mountains, quartzites are relatively rare and thin but are more common in the lower Sur Series (e.g., CONE and CRETA) than the upper. Quartzites sampled in the more northeastern parts of the study area (SECO and FREMONT) may represent rare preservation of sedimentary protolith in the upper Sur Series or may help define the nature of displacement between the eastern, central, and western Salinian blocks.

CONE comes from a relatively thick quartz-rich metasedimentary Sur Series unit in the southern Santa Lucia Mountains (Fig. 2). It weathers brown and displays a subtle subhorizontal metamorphic foliation. CONE is composed predominantly of quartz (96%) with subordinate plagioclase and potassium feldspars (4% total), although sparse biotite helps reveal its foliation. Minor and accessory minerals include garnet and opaque Fe-Ti oxides. Thin sections reveal grains with moderately elongated habits, sutured grain boundaries, and undulose extinction. Grain aspect ratios are ~3.3 in quartz and ~1.75 in feldspars.

CRETA was sampled from a thin metasedimentary succession in the southern Santa Lucia Mountains of the western Salinian block, not far from CONE (Fig. 2). CRETA is the southernmost sample collected in this study. In outcrop, CRETA is a white-brown quartzite with abundant microfractures, some of which are filled with quartz to form veinlets. Thin-section analysis reveals a quartz (78%), potassium-feldspar (19%), and plagioclase (~2%) composition. Sutured grain boundaries and grain elongation are prominent (aspect ratio = 3.0) and moderate (aspect ratio = 1.7) in quartz and feldspar, respectively, with the unit's mylonitic texture revealed by many of the potassium-feldspar grains.

SECO is a gray quartzite from a small mixed metasedimentary pod within abundant metagranitoids on the eastern flank of the Santa Lucia Mountains of the central Salinian block (Fig. 2). SECO is composed of quartz (80%) and plagioclase feldspar (20%), as well as trace amounts of garnet, muscovite, and biotite. SECO displays significant degrees of foliation, quartz undulose extinction, sutured grain boundaries, and grain elongation (aspect ratio = 2.1).

FREMONT was sampled from a thick metasedimentary succession near Fremont Peak in the Gabilan Range of the eastern Salinian block (Fig. 2). It is the northernmost sample collected in this study. In outcrop, Fremont is a purple medium-grained mica schist. Thin-section analysis reveals that FREMONT is composed of quartz (68%), plagioclase (19%), biotite (8%), muscovite (4%), and rare garnet. FREMONT has well-developed foliation and prominent grain elongation in quartz and feldspar (aspect ratio = 2.4–2.6).

Sedimentary Cover Samples

This study also reports detrital-zircon age data collected from Upper Cretaceous–Paleocene marine and associated sandstones exposed in the western and central Salinian blocks (Fig. 2). In the vicinity of the study area, these strata have been locally and variably named the Merle, Dip Creek, Atascadero, and Asunción Formations, although unnamed members and formations have also been described (Ross, 1977; Ruetz, 1979; Vedder et al., 1983; Grove, 1986).

The Upper Cretaceous–Paleocene strata of Salinia have generally been interpreted to result from a submarine-fan depositional system (Howell and Vedder, 1978; Ruetz, 1979; Vedder et al., 1983). Whereas this interpretation characterizes their dominant stratigraphic architecture, interbedded and laterally equivalent fluvial, fan-delta, and shallow-marine lithofacies (Grove, 1986, 1993) suggest that high-frequency base-level changes also affected the succession. In general, the Upper Cretaceous–Paleocene strata of Salinia depict an up-section deepening and retrogradation of facies (Grove, 1986), which is further supported by the recognized northeastward onlap of progressively younger strata within the Upper Cretaceous–Paleocene succession (Ruetz, 1979; Grove, 1993). Ages of the lowermost exposed Salinian strata are controversial—whereas some have reported late Campanian macrofossils (Hall et al., 1959; Vedder et al., 1983; Saul, 1983), others suggest that robust biostratigraphic markers such as foraminifera are limited to the Maastrichtian faunal zones (Almgren and Reay, 1977; Saul, 1983; Sliter, 1986). Indeed, if the lowermost Upper Cretaceous strata are Campanian, Salinian plutons that were at 25 km depth at 76 Ma (Kidder et al., 2003) would need to be exhumed at geologically unrealistic rates of >5 mm/yr.

The stratigraphic architecture and tectonic and geologic setting of Upper Cretaceous–Paleocene Salinian sedimentary cover rocks suggest that they were deposited within a forearc basin (Page, 1970; Graham, 1978; Grove, 1993). The presence of associated deep-water and terrestrial units within short (<10 km) lateral distances require a steep basin margin, which led Grove (1986, 1993) to suggest that these strata accumulated in an intraforearc graben that developed within rocks once part of the eastern and central parts of the California arc.

ROCKY POINT was sampled from an Upper Cretaceous sandstone in the eastern portion of the western Salinian block (Fig. 2). It is the northernmost sedimentary sample collected in this study. In outcrop, the unit from which ROCKY POINT was sampled is a succession of dark brown, lenticularly bedded sandstones and mudstones. Thin sections of ROCKY POINT display angular to subrounded, moderately sorted lower fine to upper very coarse sand grains (+3.0 to −1.0Φ. ROCKY POINT is a lithic arkose, composed of quartz (41%), feldspar (33%), and microlitic and felsitic volcanic lithic grains (26%). The feldspar population is evenly split between potassium-feldspar and plagioclase grains. The volcanolithic arkose composition of ROCKY POINT suggests it was derived from a dissected-arc terrane (Dickinson et al., 1983).

ROJO was sampled from a poorly exposed succession of coarse-grained litharenites and arkoses in the southern Santa Lucia Mountains (Fig. 2). ROJO is the southernmost sedimentary sample collected in this study. In outcrop, ROJO is a porous, friable red-brown sandstone with moderate-poor sorting of angular-subrounded lower fine to upper very coarse grains (+2.5 to –0.5Φ). In thin section, ROJO is a feldspathic litharenite, with quartz (45%), lithic (28%), and feldspar (27%) grains. The lithic fraction is dominated by volcanic clasts, with near equal modal abundances of microlitic, vitric, and felsitic textures, with subordinate lathwork volcaniclastic and shale sedimentary grains. Plagioclase grains in ROJO greatly outnumber potassium-feldspar grains, which, with the abundance of vitric and lathic textures, suggest a more mafic sediment source. However, like ROCKY POINT, ROJO falls within the dissected-arc provenance field of Dickinson et al. (1983).

ESALEN comes from an Upper Cretaceous arkose in the coastal Santa Lucia Mountains (Fig. 2). It is sampled from a well-bedded, well-sorted, gray sandstone interval associated with clast-supported conglomerates. Thin-section analysis reveals angular to subangular feldspar (55%), quartz (36%), and lithic (9%) grains, between upper middle and upper very coarse sand (+1.5 to –1.0 Φ) in size. Volcaniclastic grains with microlitic and felsitic textures dominate the lithic clast population, although some sedimentary, chlorite, muscovite, and clinopyroxene lithic grains are also present. Plagioclase-feldspar grains greatly outnumber potassium-feldspar grains, and quartz grains are entirely monocrystalline. ESALEN plots on the border of the basement-uplift continental block and dissected magmatic arc fields (Dickinson et al., 1983).

METHODS

Approximately 10–15 kg of fresh material was collected from a single ~1-m-thick succession of medium- to coarse-grained quartzite or sandstone for each of the seven samples. Special attention was paid to avoid dikelets and other small intrusive igneous bodies that are common throughout the Salinian block and would contaminate a detrital signal.

The samples were processed with standard crushing and pulverizing procedures followed by density and magnetic separations. The remaining heavy minerals were mounted in 2.5 cm epoxy mounts and were analyzed by LA-MC-ICP-MS. Each sample's analysis involves ablation of 100 randomly selected zircon grains with a New Wave DUV193 Excimer laser, operating with a wavelength of 193 nm and a spot diameter of 35–50 microns. Each grain analysis consists of a single 20-second integration on isotope peaks without laser firing to obtain on-peak background levels, 20 one-second integrations with the laser firing at the center of each grain, followed finally by a 30-second purge with no laser firing to deliver the remaining evacuated sample. Hg contributions to ^{204}Pb were removed by taking on-peak backgrounds. Each excavation pit is ~20 microns in depth.

The ablated material is carried via argon gas into a Micromass Isoprobe, which is equipped with a flight tube of sufficient width that U and Pb isotopes are measured simultaneously. The measurements are made in static mode, using Faraday detectors for ^{238}U, ^{232}Th, $^{208-206}$Pb, and an ion-counting channel for ^{204}Pb. Ion yields are ~1 millivolt per ppm. Common Pb corrections are made by using the measured ^{204}Pb and assuming initial Pb compositions from Stacey and Kramers (1975). Analyses of zircon grains of known isotopic and U-Pb composition were conducted in most cases after each set of five or ten unknown measurements to correct for elemental isotopic fractionation. In some cases, the standard analyses were sufficiently stable to measure ten unknowns between standards.

Our seven samples were analyzed during four sessions, each with separate operating conditions. The CONE and ESALEN samples were analyzed in separate sessions in hard extraction mode, which yielded higher and more variable Pb/U fractionation. The ^{206}Pb*/^{238}U values for the standards were corrected for an average of 15.3% (±2.6%) and 27.2% (±3.0%) fractionation (uncertainties at 2σ standard deviation of ~20 analyses), respectively, for these two samples. CRETA, SECO, ROJO, and ROCKY POINT were analyzed during a single session in soft extraction mode, with average fractionation factors of 10.3% ± 2.6%, 10.0% ± 2.4%, 10.5% ± 1.8%, and 11.3% ± 2.7%, respectively. FREMONT was analyzed during a separate session in soft extraction mode, with an average fractionation factor of 10.6% ± 2.2%. ^{207}Pb*/^{206}Pb* ratios for all samples were corrected for 2%–5% ± ~3% fractionation.

The analytical data are presented in an associated Data Repository (Table DR1)[1]. Unless otherwise noted, the ages used for provenance interpretation are ^{206}Pb*/^{238}U ages for grains less than 800 Ma and ^{207}Pb*/^{206}Pb* ages for grains greater than 800 Ma. Analyses that have greater than 10% uncertainty or are more than 30% discordant or 5% reverse discordant are excluded from further consideration. Concordia diagrams (Fig. 4) and age-probability diagrams (Figs. 5, 6, and 7) are presented for each sample using the plotting programs of Ludwig (2001). The age-probability diagrams depict each age and its uncertainty as a normal distribution and sum all ages in a sample or set of samples into a single curve. The curves are then divided by the number of constituent grains, such that each curve on a diagram contains the same area.

RESULTS

Sur Series Quartzites

The four Sur Series metasedimentary quartzite samples (CONE, CRETA, SECO, and FREMONT) yielded a total of 310 ages that are of sufficient concordance (Fig. 4A) and precision to provide reliable provenance information. As a whole, age spectra from the Sur Series samples reveal grains with ages from every Era between the Mesozoic and Middle Archean (Figs. 5 and 6; Table DR1). The largest peaks from Sur Series samples have Mesoproterozoic, Paleoproterozoic, Late Archean, and late Mesozoic ages. Lesser peaks have Paleozoic and Neoproterozoic ages.

CONE yielded 80 grains sufficient for provenance analysis. Dominant age groups are 96–130 Ma, scattered ages between 250 and 810 Ma, 1070–1310 Ma, 1410–1480 Ma, and 1760–1940 Ma. SECO yielded 78 grains sufficient for provenance analysis. SECO age groups include ~320–480 Ma, 670–790 Ma, 1090–1340 Ma, 1380–1450 Ma, 1700–1830 Ma, and 2520–2640 Ma. CRETA yielded 86 grains sufficient for provenance analysis. CRETA ages primarily include those between 80 and 130 Ma, with subordinate groups at 270–518 Ma, 650–805 Ma, 1030–1210 Ma, 1310–1490 Ma, 1680–1790 Ma, and 2630–2730 Ma. FREMONT yielded 66 grains sufficient for provenance analysis. FREMONT contains scattered ages between 190 and 765 Ma and significant peaks at 940–1175 Ma, 1380–1950 Ma, 2550–2750 Ma, and 3050 Ma.

Upper Cretaceous Sedimentary Cover

The three Upper Cretaceous sandstone samples (ESALEN, ROCKY POINT, ROJO) yielded a total of 295 ages that are of sufficient

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[1] GSA Data Repository item 2005xxx, Salinian basement and cover rock U-Pb detrital-zircon geochronology analyses, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

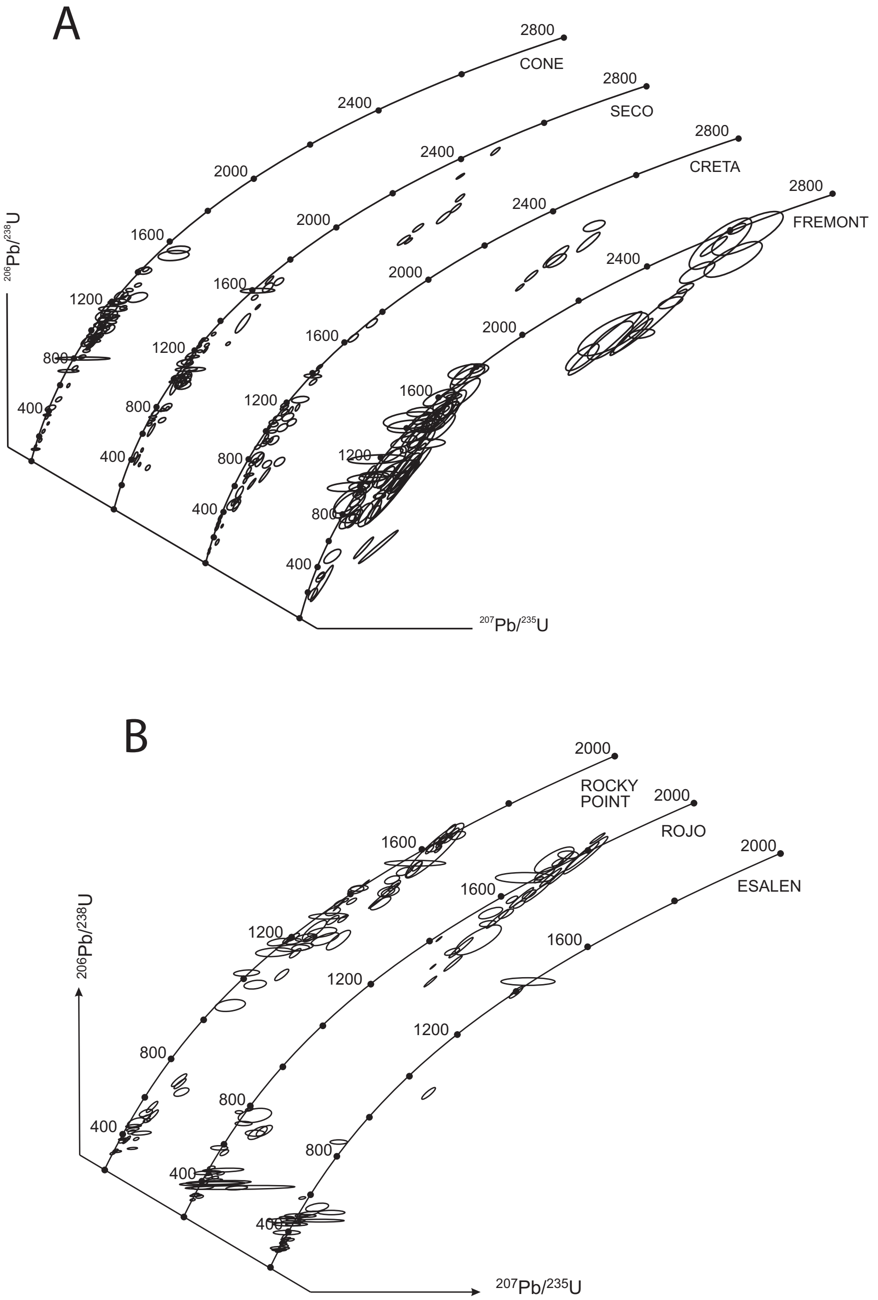


Figure 4. A. U/Pb concordia plots for Salinian basement (Sur Series) samples. B. U/Pb concordia plots for Salinian cover samples. Ellipses depict 2σ error margins.

concordance (Fig. 4B) and precision to provide reliable provenance information. Age spectra from the Upper Cretaceous samples reveal a dramatic variation between the different stratigraphic units, and all are different from the Sur Series samples (Figs. 5, 6 and 7; Table DR1).

ESALEN yielded 104 grains sufficient for provenance analysis. ESALEN is dominated by Mesozoic ages, with main clusters between 85 and 165 Ma (age-probability peaks at 95 and 135 Ma) and between 230 and 295 Ma (age-probability peak at 265 Ma). ESALEN also contains two grains with ages of ~1430 Ma. ROCKY POINT yielded 89 grains sufficient for provenance analysis. ROCKY POINT has subequal proportions of Mesozoic and Proterozoic ages, with main clusters at 90–125 (peak at ~100 Ma), 155–200 Ma (peak at ~177 Ma), 220–350 Ma (peak at ~235 Ma), 1355–1470 Ma (peak at 1435 Ma), and 1635–1700 Ma (peaks at 1655 and 1675 Ma). ROJO yielded 79 grains sufficient for provenance analysis. ROJO contains a distribution similar to that seen in ROCKY POINT, with main age groups of 80–110 Ma (peak at ~100 Ma), 135–250 Ma (peak at 145 Ma), and 1625–1810 Ma (peak at 1740 Ma).

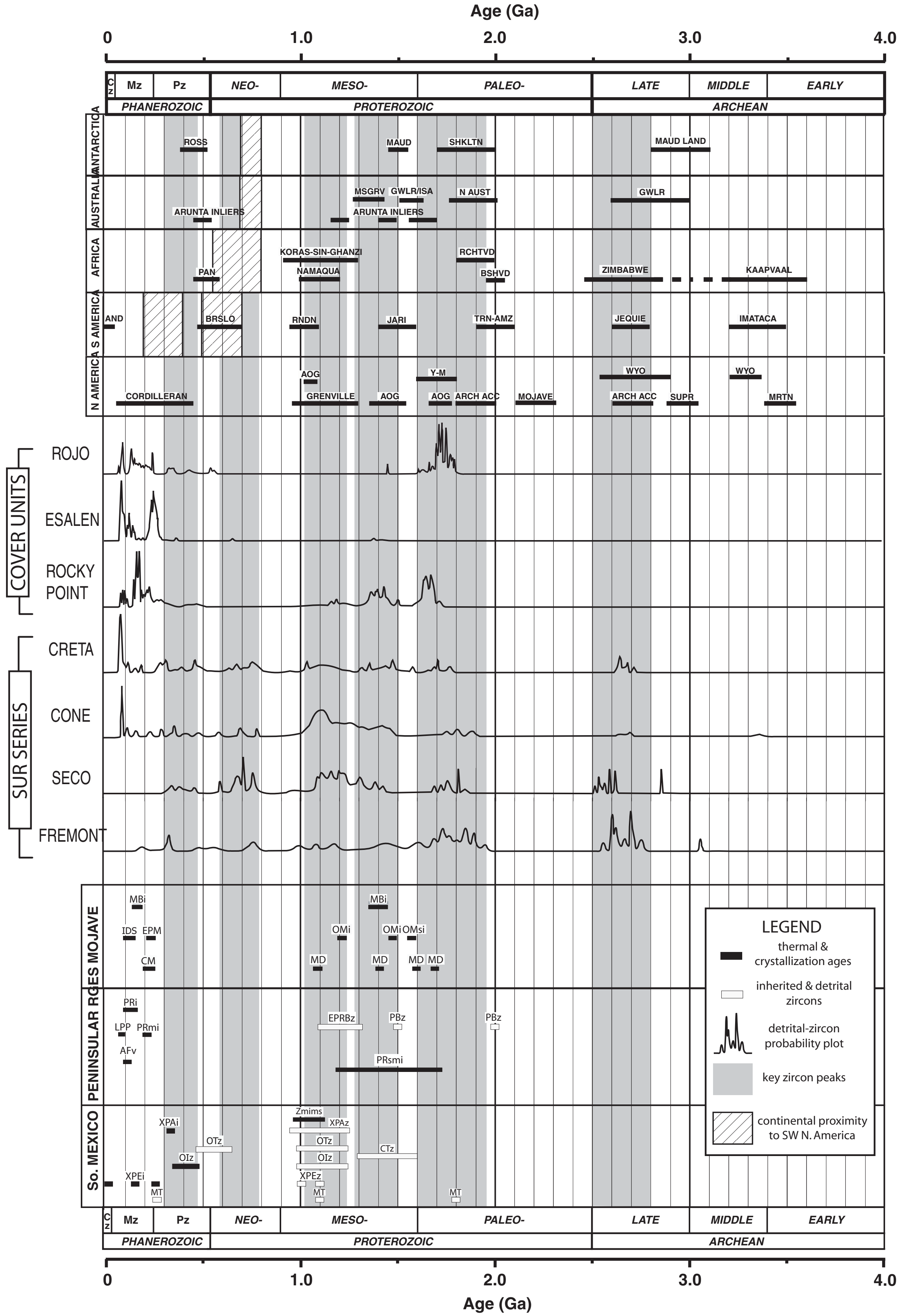
INTERPRETATIONS AND DISCUSSION

Constraints on Depositional Ages and Sediment Pathways

Detrital-zircon geochronology studies are a useful means to provide maximum depositional ages on stratigraphic units that are deformed and recrystallized by metamorphism or are otherwise poorly dated, because primary components of a stratigraphic unit cannot be younger than the strata themselves. However, two important caveats to consider when using zircon geochronology to bracket depositional ages in metasedimentary units and/or units that predate proximal intrusives are: (a) the growth of primary zircon during metamorphism, and (b) dikelet contamination. Both of these possibilities are concerns for Sur Series zircon geochronology.

Thin-section and hand-sample analysis reveals quartz-rich veinlets of unknown origin in CRETA and none in CONE or SECO, suggesting that some Sur Series samples may be contaminated by microscale intrusives not visible in the outcrop scale. This suspicion is confirmed by detrital-zircon data recovered from CONE and CRETA, which both contain several zircons with ages <100 Ma and as young as 81 Ma. Paleobarometric data (Kidder et al., 2003) from tonalites and host rocks of the Cone Peak region (where CONE and CRETA were collected) suggest that the western block of Salinia was at 25–30 km depth from 93 to 77 Ma, which with widespread evidence of magmatism from 120 to 75 Ma throughout Salinia (Mattinson and James, 1985; Kistler and Champion, 2001; Kidder et al., 2003; Barth et al., 2003), precludes post-Neocomian Sur Series zircons from being detrital. Whereas the U/Th ratios of the youngest zircons recovered from Sur Series samples CONE and CRETA are generally greater than those of the samples' older zircons, these values are typically too low to have been formed as a result of regional metamorphism associated with Salinian plutonism (Williams, 2001). Therefore, it is most likely that Late Cretaceous zircons recovered from Sur Series samples result from igneous contamination by dikelets.

Such contamination may call into question the accuracy of detrital-zircon age spectra from any Sur Series sample. However, subtraction of the SECO age spectrum from the spectra


Age (Ga)
0
1.0
2.0
3.0
4.0
Cz
Mz
Pz
NEO-
MESO-
PALEO-
LATE
MIDDLE
EARLY
PHANEROZOIC
PROTEROZOIC
ARCHEAN
ANTARCTICA
ROSS
MAUD
SHKLTN
MAUD LAND
AUSTRALIA
ARUNTA INLIERS
MSGRV
GWLR/ISA
N AUST
ARUNTA INLIERS
GWLR
AFRICA
PAN
KORAS-SIN-GHANZI
NAMAQUA
RCHTVD
BSHVD
ZIMBABWE
KAAPVAAL
S AMERICA
AND
BRSLO
RNDN
JARI
TRN-AMZ
JEQUIE
IMATACA
N AMERICA
CORDILLERAN
AOG
GRENVILLE
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ARCH ACC
MOJAVE
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WYO
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COVER UNITS
ROJO
ESALEN
ROCKY POINT
SUR SERIES
CRETA
CONE
SECO
FREMONT
MOJAVE
MBi
MBi
IDS
EPM
OMi
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MD
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PENINSULAR RGES
PRi
LPP
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OTz
OTz
CTz
OIz
OIz
XPEi
XPEz
MT
MT
MT
LEGEND
thermal & crystallization ages
inherited & detrital zircons
detrital-zircon probability plot
key zircon peaks
continental proximity to SW N. America

Figure 5. Comparison of the U-Pb detrital-zircon relative probability plots of the seven samples analyzed in this study and global (upper third of figure) and North American (lower third of figure) orogenic events. Upper third: Diagonally hatched polygons indicate time periods during which the western and/or southern North American margins were adjacent to different terranes. Grey polygons highlight six key pre-Mesozoic age peaks important for determining provenance of Salinian cover and basement units. ROSS—crustal accretion and granitoid magmatism associated with Pan-African and Ross Orogenies; MAUD—Mesoproterozoic granulite facies metamorphism in Dronning Maud Land; SHKLTN—granulite facies metamorphism and isotope resetting in the Shackleton Range; MAUD LAND—Middle-Late Archean granulite facies metamorphism in Dronning Maud Land; ARUNTA INLIERS—granitoid emplacement and metamorphism associated with repeated deformation of southern margin of North Australian craton; MSGRV—felsic and mafic plutonism, granulite facies metamorphism in Mugrave Block; GWLR/ISA—voluminous felsic and bimodal volcanism in Gawler Range Volcanics and Mt. Isa Orogeny; N AUST—assembly of craton from separate fragments during Barramundi orogeny in North Australian craton; GWLR—granitoid emplacement associated with generation and accretion of Gawler craton in the Gawler Range; PAN—granitoid emplacement and juvenile crustal generation associated with amalgamation of Africa in the Pan-African Orogeny and Damaran event; KORAS-SIN-GHANZI—bimodal volcanic rocks associated with fragmentation prior to Pan-African amalgamation in Koras, Sinclair, and Ghanzi rifts; NAMAQUA—plutonism and metamorphism associated with accretion of Namaqua terrane to Kalahari craton; RCHTVD—volcano-plutonic Richtersveld domain associated with consolidation of Kalahari craton; BSHVD—mafic intrusives of Bushveld Complex; ZIMBABWE—granitoid and associated plutonism and metamorphism in Zimbabwe Craton associated with early consolidation of Kalahari craton; KAAPVAAL—tonalite and granitoid intrusions and metamorphism associated with cratonic consolidation of Kaapvaal Craton; AND—arc volcanism and metamorphism associated with B-type subduction of the Andean Orogeny; BRSLO—granitoid emplacement and juvenile crust generation associated with consolidation of South America in the Brasiliano Orogeny; JARI—granitoid plutonism and accretion to Guiana and Brazilian Shields in the Jari-Balsino Orogeny; TRN-AMZ—granitoid plutonism associated with Trans-Amazonian Orogeny; JEQUIE—granulite metamorphism associated with Archean shield consolidation in Jequie Orogeny; IMATACA—metamorphism associated with Archean shield consolidation in the Imataca Complex; CORDILLERAN—polyphase arc magmatism and accretion associated with Cordilleran Orogeny; AOG—anorogenic granitoid magmatism; GRENVILLE—arc magmatism, metamorphism, and extension associated with cratonic accretion during Grenville Orogeny; Y-M—anorogenic anorthosite and granitic batholiths associated with consolidation of Yavapai-Mazatzal Provinces; ARCH ACC—accretion of Archean blocks into composite North American craton; MOJAVE—possible crustal generation event in the Mojave Desert Region; WYO—amphibolite, migmatite, granitoid batholiths, and ultramafic complexes generated in Wyoming Province; SUPR—granitoids, metavolcanics, and migmatites generated in the Superior Province; MRTN—migmatitic tonalites of Mortonian Orogeny. Data used for this compilation shown in the upper third come largely from Goodwin (1991), Burchfiel et al. (1992), Hoffman (1989a, 1989b), Nance and Murphy (1996), and Friedl et al. (2000), and references therein. Lower third: MBi—igneous units from Maria Belt, southeast California (Boettcher et al., 2002); IDS—U-Pb zircon and sphene ages from the Independence Dike Swarm (Chen and Moore, 1979; James, 1989; Coleman et al., 2000); EPM—U-Pb zircon ages from granodiorites and gneissic quartz monzodiorites in El Paso Mts., Mojave Desert (Carr et al., 1984; Cox and Morton, 1980; Miller et al., 1995); OMi, OMsi—granitoids and amphibolite-grade metasedimentary units in Orocopia Mts., eastern Peninsular Ranges, California (Silver, 1971; Armstrong and Suppe, 1973); CM—granodiorite from Chocolate Mountains correlated to dated Lowe granodiorite (Silver, 1971); MD—metamorphic and igneous rocks from Mojave Desert (Walker et al., 2002); PRi—batholithic tonalites of Peninsular Ranges (Krummenacher et al., 1975); EPRBi—inherited zircons in Eastern Peninsular Ranges batholithic rocks (Gastil, 1993); PBz—detrital zircons in prebatholithic strata of Peninsular Ranges (Gastil, 1993); LPP—La Posta pluton (Gastil et al., 1991); PRmi, PRsmi—sedimentary, metamorphic, and igneous rocks of Peninsular Ranges (Gastil, 1993); AFv—Alisitos Formation volcanics (from Frizzell, 1984); Zmims—metamorphic, igneous, and metasedimentary units of Zapateco terrane, southern Mexico (Sedlock et al., 1993); XPAi, XPAz—primary and inherited zircons (respectively) in Xolapa complex units of Puerto Escondido (Ducea et al., 2004); XPEi, XPEz—primary and inherited zircons (respectively) in Xolapa complex units of Puerto Angel (Ducea et al., 2004); OTz—detrital zircons from Tinu Formation of Oaxaca (Gillis et al., 2001); OIz—detrital zircons from Ixtaltepec Formation of Oaxaca (Gillis et al., 2001); CTz—detrital zircons from Chatino Terrane, southern Mexico (Sedlock et al., 1993); MT—U/Pb detrital-zircon and granitoid ages from Mixteco terrane (Sedlock et al., 1993).

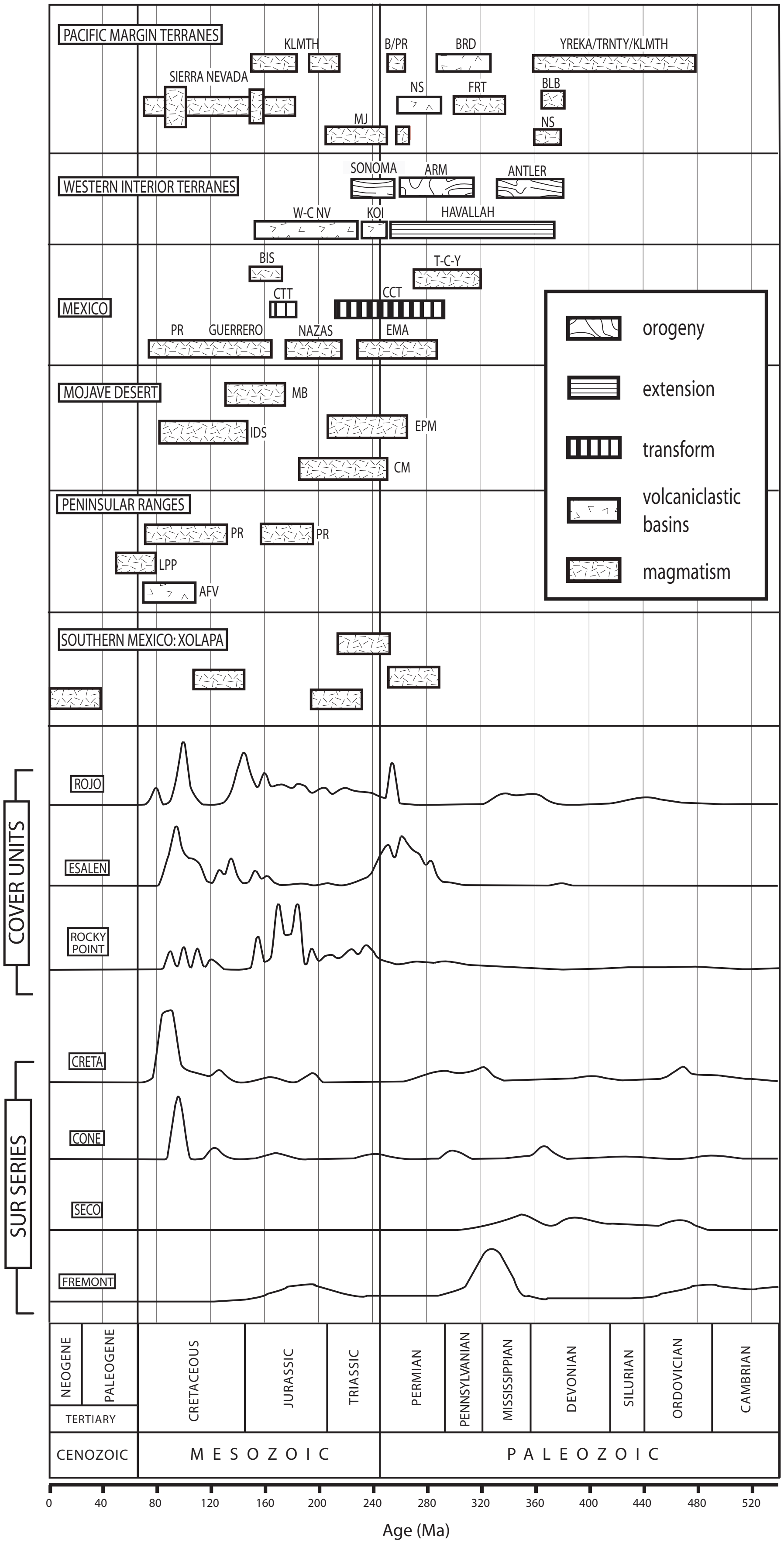

Figure 6. Comparison of the Phanerozoic U-Pb detrital-zircon relative probability plots of four samples analyzed in this study and the Phanerozoic orogenic and magmatic events of North America. SIERRA NEVADA—arc volcanism in the Sierra Nevada; KLMTH—Klamath Mountains; MJ—Mojave Desert; B/PR—Pit River Stock; NS—Northern Sierra Nevada; BRD—volcaniclastic rocks of Baird Formation; FRT—Feather River Terrane of Northern Sierra Nevada; YREKA/TRNTY/KLMTH—Yreka, Trinity Terranes, and Klamath Mountains; BLB—Bowman Lake Batholith; W-C NV—volcanism in west-central Nevada; SONOMA—emplacement of Golconda Allochthon in Sonoma Orogeny; KOI—volcaniclastic rocks of the Koipato Group; HAVALLAH—back-arc extensional Havallah Basin; ARM—intracratonic basement-involved deformation of Ancestral Rocky Mountains; ANTLER—emplacement of Roberts Mountains Allochthon during Antler Orogeny; PR—Peninsular Ranges Batholith; GUERRERO—Guerrero Superterrane; BIS—Bisbee and McCoy rift basins; CCT—California-Coahuila Transform; NAZAS—Nazas Arc; CTT—Coahuila-Tamaulipas Transform; EMA—East Mexico Arc; T-C-Y—Tamaulipas, Coahuila, Yucatan blocks; IDS—Independence Dike Swarm; MB—Maria Belt; CM—Chocolate Mountains; EPM—El Paso Mountains; LPP—La Posta Pluton; AFV—Alisitos Formation Volcaniclastics. Data for this compilation come from several sources: Southern and Eastern Belts: Rast (1989), Hatcher (1989), Hatcher et al. (1989), and Kluth (1986). Western Interior Terranes: Kluth (1986), Miller et al. (1992), Wyld and Wright (1993), and Dickinson (2000). Pacific Margin Terranes: Rubin et al. (1990), Hacker and Peacock (1990), Miller and Harwood (1990), Renne and Scott (1988), Hanson et al. (1996), Miller et al. (1992, 1995), Barth et al. (1997), Dickinson (2000), and Ducea (2001). Mexico: Sedlock et al. (1993), Dickinson and Lawton (2001), and references therein. See Figure 5 for Peninsular Ranges, Mojave, and southern Mexico references.

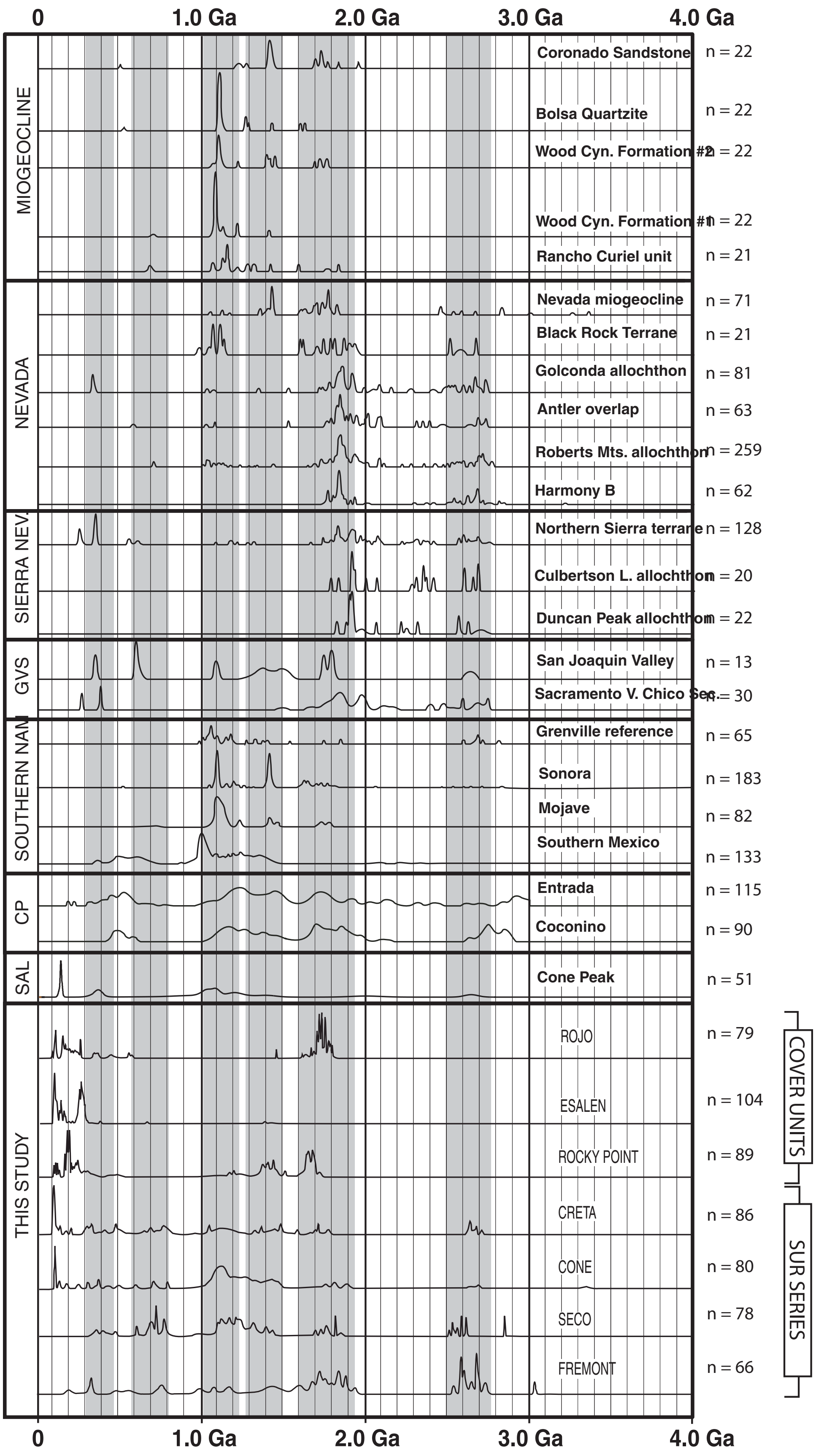

Figure 7. Comparison of the U-Pb detrital-zircon relative probability plots collected as part of this study and others compiled from the literature. Grey polygons highlight six key pre-Mesozoic age peaks important for determining provenance of Salinian cover and basement units. Data comes from various sources: MIOGEOCLINE—Neoproterozoic and Cambrian sandstones and quartzites of western United States miogeocline from Stewart et al. (2001). NEVADA—Foreland basin and overlap assemblages associated with Paleozoic and Triassic orogenic events in central and western Nevada, as well as data from Nevada miogeocline from Gehrels and Dickinson (2000), Riley et al. (2000), Darby et al. (2000), Gehrels et al. (2000a, 2000b). Sierra Nevada: sandstones and quartzites from accreted terranes and overlap assemblages in Klamath Mountains and northern Sierra Nevada from Harding et al. (2000), Wallin et al. (2000), Spurlin et al. (2000), Gehrels and Miller (2000), and Gehrels et al. (2000b). GVS—strata from Great Valley forearc assemblage of central California, from DeGraaff-Surpless et al. (2002). Southern NAM—sandstones and quartzites from various locations along the southern margin of the United States from Gillis et al. (2001), Kidder et al. (2003), Gehrels (2000), Gleason et al. (2002). CP—Jurassic and Permian eolian quartzarenites from the Colorado Plateau, from Dickinson and Gehrels (2003). SAL—inherited zircons from Cone Peak Diorite of Salinia, from Kidder et al. (2003).

of CRETA and CONE reveals that the only significant remaining peaks are Late Cretaceous in age. Because SECO comes from a lesser depth than the western block from which CONE and CRETA were sampled (Ducea et al., 2003b), and because it shows no other evidence of igneous or metamorphic contamination, we interpret all of the significant pre-Late Cretaceous Sur Series zircon age peaks as detrital and representative of the U/Pb geochronology of their source terranes.

By excluding the Late Cretaceous zircons from the interpreted detrital population, the maximum depositional ages for CRETA, CONE, FREMONT, and SECO are 115, 125, 190, and 332 Ma, respectively (Fig. 3). However, in CRETA, CONE, and FREMONT there are few Mesozoic grains that fall within 50 million years of their most proximal neighbor, which does not preclude the possibility that individual grains result from minor lead loss or the partial sampling of zoned rims. Therefore, a more conservative estimate of maximum depositional ages for CRETA, FREMONT, and CONE would be 280, 325, and 360 Ma, respectively, wherein the first multigrain peaks cluster within 50-million-year bins. We discuss the implications of these different maximum depositional ages in the context of provenance and tectonic interpretations in the following section.

The maximum depositional ages of Salinian cover units are 78–90 Ma based on the youngest detrital zircons recovered from samples ESALEN, ROCKY POINT, and ROJO (Fig. 3), and are consistent with previous biostratigraphic studies that ascribe Maastrichtian ages to similar Salinian strata (Grove, 1993).

Provenance and Tectonic Implications

Several lines of evidence have suggested that Salinia is not exotic to the North American continent (Dickinson, 1983; Butler et al., 1991; Whidden et al., 1998; Dickinson and Butler, 1998). Detrital-zircon geochronologic data reported herein also support a North American provenance and further suggest that Salinia was more likely derived from the southwestern United States and/or northwestern Mexico than southern Mexico, where others have suggested Salinia originated (Champion et al., 1984; Hagstrum et al., 1985, Debiche et al., 1987).

Whereas no single continent is known to have sources for all of the detrital zircons recovered from Sur Series and Salinian cover samples, the western United States contains primary sources for five of the six major age peaks between the Early Archean and late Paleozoic (Fig. 5). No other continent accounts for more than one-half of the six pre-Mesozoic age peaks.

Accepting above, the Wyoming Province of the northeastern quadrant of the U.S. Cordillera is the closest source for Late Archean zircons that are present in the Sur Series samples and abundant in SECO and FREMONT. However, previous to the late Mesozoic–Cenozoic Sevier and Laramide orogenies, when a large topographic front would also have inhibited westward sediment dispersal (DeCelles, 2004), post-Proterozoic exposure of the Wyoming Province was limited to a brief period and small area during the late Paleozoic Ancestral Rocky Mountain orogenic event (Sloss, 1988; Miller et al., 1992). In light of the conservative Sur Series maximum depositional ages mentioned above and the presence of a wide and disjointed late Paleozoic western margin (Dickinson, 2000), it is unlikely that Late Archean zircons recovered from the Sur Series are first-generation detrital zircons from the Wyoming Province. The presence of Late Archean detrital zircons in Cordilleran miogeoclinal and Paleozoic sediments of Nevadan terranes (Fig. 7; Gehrels and Dickinson, 2000; Riley et al., 2000; Darby et al., 2000; Gehrels et al., 2000a, 2000b; Stewart et al., 2001) suggests that those units may have been a source of second-generation Wyoming Province zircons when uplifted during the protracted history of orogenesis that has affected the western Cordillera since the mid-Paleozoic. It is also possible that Archean zircons and other detritus were transferred to western North American miogeoclinal and orogenic basins when the eastern Australian, southern African, and/or southern South American cratons (Hoffman, 1989a; Goodwin, 1991; Nance and Murphy, 1996; Friedl et al., 2000) were proximal to the western United States during the assembly and dispersal of the Rodinian, Pannotian, and Pangean supercontinents and their component pieces (Fig. 5). Subsequent uplift and erosion of these Cordilleran strata during any of several Phanerozoic orogenies in western North America may then have provided Late Archean (and other) zircons to the Sur Series.

The Sur Series and Salinian cover units contain three Paleo- and Mesoproterozoic age peaks that coincide with the key episodes of the billion year history (2.0–1.0 Ga) of amalgamation and anorogenic magmatism associated with the Rodinian supercontinent (Hoffman, 1989a). Whereas several modern continents were part of this supercontinent accretion event, no post-Pangean continent contains as thorough a record of the polyphase construction of Rodinia as North America (Fig. 5). Anorogenic granitoid magmatism, accretion of Archean cratons, and Yavapai-Mazatzal terrane magmatism between 1.9 and 1.6 Ga overlap with the age of Paleoproterozoic detrital zircons present in all four Sur Series samples as well as latest Paleoproterozoic zircons in cover samples ROJO and ROCKY POINT. The second phase of Rodinian anorogenic magmatism from 1.45 to 1.35 Ga roughly coincides with broad detrital-zircon age peaks in CONE, SECO, and ROCKY POINT as well as lesser peaks in CRETA, FREMONT, ESALEN, and ROJO. The 1.3–0.95 Ga Grenville orogeny was the culmination of Rodinian amalgamation and is recorded in the detrital zircons of all four Sur Series samples. In no part of North America are these terranes more closely distributed than the southwestern United States and northwestern Mexico (Hoffman, 1989a; Burchfiel et al., 1992), thereby favoring tectonic models that derive Salinia from the Mojave Desert and/or Eastern Peninsular Range regions. Moreover, Rodinia-aged zircons from plutons and sedimentary basins in southern Mexico are all younger than 1.5 Ga (Figs. 5 and 7; Gillis et al., 2001), further excluding the possibility that Salinia originated at such latitudes.

This study's only broad pre-Mesozoic detrital-zircon age peak not contemporaneous with known magmatism on the North American continent is Neoproterozoic in age and coincides with the Brasiliano orogeny (Fig. 5). These anomalous ages do not appear to result from lead loss from Grenville-aged zircons, given their relative concordance in comparison to those of other Sur Series zircons (Fig. 4A). The presence of these grains in Sur Series samples (e.g., SECO) and the absence of Neoproterozoic orogenies on other continents suggest that detritus was transferred from South American cratonic blocks to the North American miogeocline during their juxtaposition in the Neoproterozoic and Phanerozoic. The absence of such Neoproterozoic grains in other strata of western North America (Fig. 7) offers the possibility that the Sur Series were accumulated in a marginal position during the Neoproterozoic or mid-late Paleozoic when South American terranes were believed to be in proximity. Such a tectonic setting may have inhibited sediment transport to inboard depocenters, leading to the scarcity of Neoproterozoic zircons in thus sampled units further toward the craton (Fig. 7). However, it is also possible that marginal and/or miogeoclinal rocks containing Neoproterozoic peaks like those in SECO have not yet been sampled, and that both Neoproterozoic and Archean zircons may have been transferred from other continents to the western North American miogeocline for possible later recycling into Sur Series samples.

The presence of several Phanerozoic detrital-zircon age peaks supports a western North American origin for Salinia, but does little for resolving its latitude, as subduction-related processes have dominated the length of the western margin (and associated outboard terranes) of North America since at least the Carboniferous (Fig. 6; Coney, 1987; Miller et al., 1992; Sedlock et al., 1993; Coney and Evenchick, 1994; Dickinson, 2000; Dickinson and Lawton, 2001; DeCelles, 2004). The presence of early and middle Paleozoic detrital zircons in Salinian samples suggest that Salinia was more likely derived from the U.S. portion of the margin, as sources for such zircons are not well documented in Mexico (Fig. 6; Sedlock et al., 1993). However, the relative paucity of such grains and the low amplitudes of their occurrence probabilities do not preclude the possibility that lead loss or rim-sampling contributed to their inclusion in the reported age spectra.

Late Paleozoic and early Mesozoic age peaks in the Salinian cover samples eliminate neither a Mexican nor a southwestern U.S. origin, although the prominent Permo-Triassic peak in ESALEN coincides with protracted magmatism reported from the El Paso Mountains of the Mojave Desert (Figs. 5 and 6; Cox and Morton, 1980; Carr et al., 1984; Miller et al., 1995; Barth et al., 1997) and only slightly overlaps with magmatism in the eastern Peninsular Ranges and the Xolapa terrane of Oaxaca (Ducea et al., 2004). If Salinian cover units acquired their Permo-Triassic zircons from the northern Mojave Desert, these data suggest that northward translation of Salinia from that region postdated the Upper Cretaceous, as is supported by cover unit biostratigraphic data (Grove, 1993) and maximum depositional ages inferred by detrital-zircon age spectra.

Middle-late Mesozoic zircon age peaks in Salinian cover samples indicate detrital derivation from the Jurassic-Cretaceous California and/or Guerrero arcs (Fig. 6) that ran the length of the North American western margin from 18º to 40º N latitude (modern values) and from where the plutons of Salinia were likely translated to their current position outboard of the Sierra Nevada Batholith. As previously mentioned, it is possible that Jurassic and early Cretaceous zircons in Sur Series samples CRETA, CONE, and FREMONT are detrital, but paleobarometric and chronologic data from the nearby Cone Peak region (Kidder et al., 2003) require that middle-Late Cretaceous zircons are igneous or metamorphic contaminants.

In summary, detrital-zircon age peaks from Salinian basement and cover units best correlate with the age of candidate source terranes in western North America. Moreover, the presence of Late Archean and Paleoproterozoic detrital zircons in Sur Series samples precludes the possibility of a southern Mexico origin. Therefore, the proximity of several needed zircon sources in the southwestern United States and northwestern Mexico suggest that the Mojave Desert and the Eastern Peninsular Ranges are the strongest candidates for Salinia's origin. These data urge focus, evaluation, and refinement of kinematic models that derive Salinia from those regions (e.g., Dickinson, 1983; Ross, 1984; Mattinson and James, 1985; Saleeby, 2003; Barth et al., 2003).

Contributions of this study toward that goal include the recognition that: (1) Salinia was positioned in the southwestern United States or northwestern Mexico from the Late Paleozoic through the latest Cretaceous as indicated by provenance links and maximum depositional ages of Sur Series and cover units. (2) Salinia was specifically positioned in the Mojave Desert region in the Late Cretaceous, when Permian zircons from the El Paso Mountains were supplied to supracrustal Salinia. (3) The maximum depositional ages of Salinia's cover units are coeval with thrust emplacement of schist complexes beneath the California arc (Fig. 3; Barth et al., 2003; Grove et al., 2003) and the growth of post-kinematic garnets in Salinian plutons at 25–30 km depth (Kidder et al., 2003; Ducea et al., 2003b) onto which the late Cretaceous cover units were deposited. Whereas the former two contributions put constraints on the kinematic paths and history of Salinia, the latter supports interpretations that the first generation of Salinian rock uplift occurred over a very short period in the latest Cretaceous, and that sedimentation, accretion, and metamorphic events affecting the southwestern United States in the Late Cretaceous were time-transgressive (Fig. 3).

CONCLUSIONS

1. Comparison of U-Pb detrital-zircon geochronology of metasedimentary framework (Sur Series) and upper Cretaceous cover units with (a) global sources of zircons, and (b) other detrital-zircons relative probability curves, suggests that Salinia most likely originated along the southern and/or western margins of North America.

2. The abundance of Late Archean and Paleoproterozoic detrital zircons in Salinian framework units eliminates the possibility that Salinia originated in southern Mexico, as earlier models have proposed. Moreover, the collection of zircons from several different source terranes in individual and collective Sur Series and Salinian cover unit samples suggests that the Mojave Desert and Peninsular Ranges are the best candidates for Salinia's origin, given the close proximity of several diverse terranes in that region.

3. The maximum depositional ages of three Salinian framework units (Sur Series) are late Paleozoic (280–360 Ma), although low-amplitude early Mesozoic peaks do not eliminate the possibility of younger depositional ages. The maximum depositional ages of Salinian cover units are Late Cretaceous (78–90 Ma). One such cover unit contains a well-defined detrital-zircon age peak of 240–280 Ma that overlaps with plutonism in the El Paso Mountains, suggesting that Salinia did not depart the Mojave Desert until at least latest Cretaceous time, after uplift and exhumation of lower-crustal plutons.

4. The abundance of Neoproterozoic detrital zircons in Salinian framework samples suggests that detritus was transferred to North America from Brasiliano orogenic terranes when South American cratonic blocks were proximal to the southwestern North American miogeocline in the late Neoproterozoic and/or mid-Paleozoic–early Mesozoic supercontinent configurations. The presence of Late Archean and Neoproterozoic detrital zircons in Sur Series samples suggests that uplift and dissection of miogeoclinal rocks during Phanerozoic orogenic events recycled this detritus and supplied it to outboard positions of the western Cordillera.

5. The small number and narrow range of U-Pb detrital-zircon age peaks in two Salinian cover units suggest that sediment delivered to some upper Cretaceous Salinian basins was derived from small, local, zircon source terranes. However, the presence of abundant volcaniclastic detritus in one sample (ROJO) with a particularly old (1.7 Ga) and unimodal age spectrum suggests that the exposure gate of these basins' source areas may be more heterolithic than their detrital-zircon populations reveal.

6. Temporal overlap of cover unit maximum depositional ages, post-kinematic garnet growth in deep portions of Salinian plutons, and underplating, accretion, and metamorphism of outboard sedimentary terranes suggests Salinia was rapidly exhumed during the latest Cretaceous, and that tectonosedimentary processes were time-transgressive.

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