Timing of plutonism and deformation in the White Mountains of eastern California

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ABSTRACT

New mapping and U-Pb zircon geochronology help establish the timing of contractional deformation and magmatism in the White Mountains of California. In the Redding Canyon area of the west-central White Mountains, Mesozoic deformation characterized by east-directed movement along reverse faults as well as recumbent folding was followed by development of upright folds with axes that plunge moderately to the north. This later folding event produced penetrative, vertical, north-striking axial-planar cleavage that is present along much of the western flank of the range. Deformed units include folded and/or boudinaged diorite dikes (ca. 165 Ma; U-Pb zircon) that contain the later penetrative cleavage. The cleavage is clearly cut by the Redding Canyon pluton (ca. 164 Ma; U-Pb zircon), demonstrating that at least some of the intense deformation preserved in the area is Middle Jurassic and correlative with the East Sierran thrust system identified elsewhere in California. Dates for the Beer Creek pluton (ca. 179 Ma; U-Pb zircon) and the Sage Hen Flat pluton (ca. 175 Ma; U-Pb zircon), which cut deformation in their wall rocks, suggest that East Sierran thrust deformation did not propagate as far eastward as these plutons at the present level of exposure. The new dates also cast doubt on the presence of any Late Jurassic–Early Cretaceous plutonism in the White Mountains. Throughout the east-central Sierra Nevada and White Mountains, high-precision U-Pb zircon geochronology is resolving significant plutonism into two short-lived events that occurred at ca. 180–165 Ma and 102–86 Ma.

Keywords: geochronology, deformation, Mesozoic, White Mountains, California.

INTRODUCTION

Neoproterozoic through early Paleozoic passive-margin sediments deposited along the western margin of North America were deformed by numerous episodes of contractional deformation that began with the Devonian–Mississippian Antler orogeny and culminated with intrusion of the Mesozoic arc exposed in the Sierra Nevada of California (Burchfiel and Davis, 1975; Stevens et al., 1997). Understanding the nature, extent, and timing of these events is important to unraveling the history of plate motions along western North America, to understanding the correlations between deformation and magmatism during subduction, and to clarifying how strain is distributed and partitioned in an intra-arc and backarc setting on continental lithosphere. Debate persists, however, regarding the regional correlation and significance of individual contractional events and structures, in large part because the timing of deformation is poorly known (e.g., Stone and Stevens, 1993; Snow and Wernicke, 1993). Additional difficulties in regional correlation result from (1) pervasive intrusion of the structures by the Mesozoic batholith in the west, and (2) dissection of the area by Cenozoic Basin and Range extension.

The White Mountains are located on the western edge of the Basin and Range province and expose deformed Late Proterozoic to Paleozoic strata intruded by several Mesozoic plutons (Fig. 1; Nelson, 1966; Stevens et al., 1997). Although many reports describe the nature of deformation throughout the White Mountains (e.g., Dunne et al., 1978; Nelson et al., 1991; Morgan and Law, 1998), little is known about the timing of deformation in the range, making correlation with well-dated events in surrounding areas difficult.

Here we describe field relationships and present new geochronologic data from five samples that tightly delimit the timing of deformation in the range: three undeformed plutons from the White Mountains and northern Inyo Mountains (Beer Creek, Sage Hen Flat, and Redding Canyon) and two deformed mafic dikes near the Redding Canyon pluton in the southwestern White Mountains (Fig. 1). New U-Pb zircon analyses of intrusive rocks in the White-Inyo Mountains are significant for two reasons. First, the plutons represent early magmatic activity of the easternmost part of the greater Sierra Nevada batholith, and new ages will lead to a better understanding of early activity in the batholith. Second, these data are critical to interpretations of tectonic studies centered in the White-Inyo Mountains (e.g., Sylvester et al., 1978; Stone and Stevens, 1984; Corbett et al., 1988; Morgan et al., 2000).

GEOLOGIC SETTING

The geology of the White and Inyo Mountains reflects four distinct episodes: passive-

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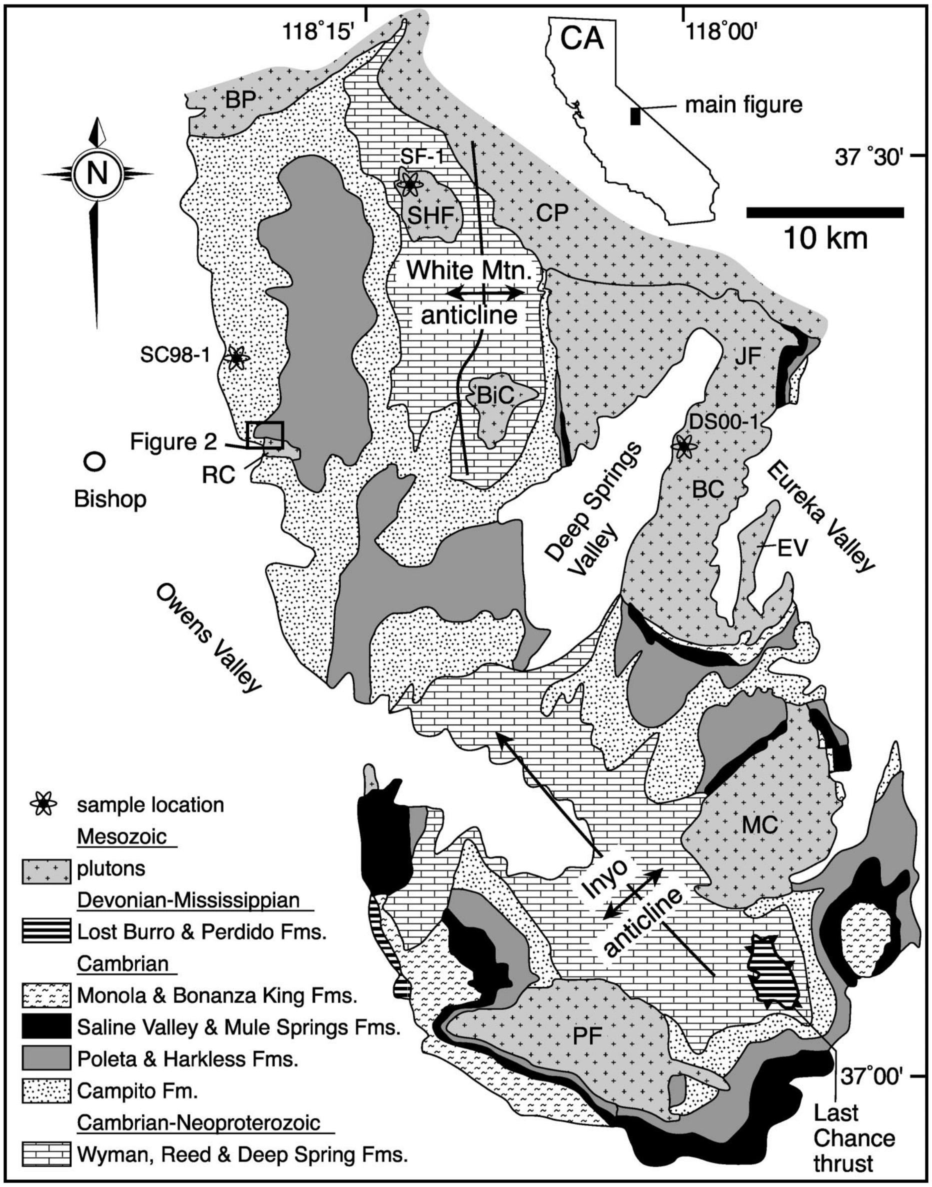

Figure 1. Simplified map of the White-Inyo Range after Morgan and Law (1998). Facies within the Beer Creek intrusion: BC—Beer Creek facies; EV—Eureka Valley facies; JF—Joshua Flat facies. Other plutons: BiC—Birch Creek pluton; BP—Barcroft pluton; CP—Cottonwood pluton; MC—Marble Canyon pluton; PF—Papoose Flat pluton; RC—Redding Canyon pluton; SHF—Sage Hen Flat pluton. Approximate locations for samples collected outside the Redding Canyon area (Fig. 2) are shown.

margin sedimentation (Neoproterozoic–Devonian), orogenic contraction (Devonian–Jurassic[?]), subduction-related magmatic activity (Mesozoic), and extensional deformation and magmatism (Cenozoic). Here we concentrate on the Devonian through Cretaceous contraction and magmatism and do not discuss younger Cenozoic deformation. Rocks that were deformed and intruded during Paleozoic through Mesozoic events include passive-margin limestone, shale, dolomite, and sandstone correlative with Late Proterozoic to early Paleozoic strata in the Death Valley area (Nelson, 1978). These strata were generally thrust eastward (toward the craton) during at least three periods of contractional deformation (Morgan and Law, 1998). Although the timing of contractional events in much of eastern California and western Nevada is fairly well characterized through stratigraphic relationships, U-Pb geochronology, or both, timing of plutonism and deformation in the White Mountains is poorly defined. Consequently, correlation of deformational events within the range and from the range to surrounding areas has been based solely on sequence, orientation, and style.

Mississippian–Devonian Deformation

The oldest folding and thrusting event preserved in the White Mountains, recorded by northeast-trending folds and associated cleavage, is interpreted as the result of the Late Devonian to Early Mississippian Antler orogeny (Sylvester and Babcock, 1975; Dunne et al., 1978; Stevens et al., 1997; Morgan and Law, 1998). The main axis of this deformation is concentrated in the northern Inyo and southern White Mountains, but small, overturned northeast-trending structures also occur in the far western side of the central White Mountains in the Poleta and Silver Canyon areas (Welch, 1979; Fig. 1). Regionally, the timing of Antler deformation is well determined by stratigraphic relationships (e.g., Johnson and Pendergast, 1981). However, interpretations of Antler deformation in the White Mountains are based solely on the facts that (1) northeast-trending structures characterize the Antler elsewhere in Nevada and California, and (2) cleavage developed during northeast-trending folding in the White Mountains is cut by cleavage associated with northwest-trending structures and is, therefore, older.

Permian–Triassic Deformation

The White and Inyo ranges themselves are defined by the large-scale north- to northwest-trending White Mountain and Inyo anticlines. The anticlinoria are interpreted to be ramp anticlines associated with movement on an underlying thrust, perhaps the Permian–Triassic Last Chance thrust system (Corbett et al., 1988; Morgan and Law, 1998; Fig. 1). The timing and correlation of faults and folds related to this deformation are controversial in the White Mountains and regionally (Snow and Wernicke, 1993; Stone and Stevens, 1993). The most recent compilation of data for structures of this age in the Inyo Mountains suggests at least two episodes of contractional deformation (Early Permian through middle Permian, followed by Late Permian through Early Triassic) as well as a period of extension in the Late Permian (Stevens et al., 1997). North- to northwest-trending folds in the White Mountains have been correlated with these contractional events on the basis of similar orientation (Corbett et al., 1988).

Late Triassic–Jurassic Deformation

A later episode of east-directed contraction known as the East Sierran thrust system (Dunne et al., 1983) is recognized from the White Mountains south into the Mojave Desert (Walker et al., 1991). Timing for this event is well characterized along most of the length of its exposure. The earliest known deformation associated with East Sierran thrusting is dated between 222 and 219 Ma in the Saddlebag Lake pendant east of Yosemite National Park (Schweickert and Lahren, 1993). Structures older than 186 Ma and as young as 148 Ma from east-central California through the Mojave Desert have all been correlated with the East Sierran thrust system (Dunne et al., 1983, 1994; Walker et al., 1991; Dunne and Walker, 1993). Deformational features characteristic of the East Sierran system include (1) northeast-directed movement along reverse faults with little stratigraphic throw, and (2) folding with well-developed cleavage. Late folding and subvertical stretching commonly overprint East Sierran structures and may be as young as Cretaceous (Stevens et al., 1997).

Morgan and Law (1998) tentatively correlated localized intense deformation on the western margin of the White Mountains with the East Sierran thrust system, but Welch (2000) correlated this deformation (specifically that in the area of Fig. 2) with either Antler or Last Chance thrust deformation. As for other documented deformation in the White Mountains, there are no existing geochronologic data to test hypotheses regarding the importance of East Sierran thrusting in the range.

Mesozoic Magmatism

Early geochronologic (K-Ar) studies recognized both Jurassic and Cretaceous groups within the Sierra Nevada and White-Inyo batholiths (Curtis et al., 1958; Kistler et al., 1965). More detailed K-Ar and Rb-Sr dating led Evernden and Kistler (1970) to suggest that emplacement of the batholith occurred in five distinct intrusive events each lasting 10–15 m.y. with a 30 m.y. periodicity. With the introduction of U-Pb dating, the length of recognized intrusive events began to shrink, and some, which were apparently only cooling dates or reset dates, disappeared altogether (Stern et al., 1981; Chen and Moore, 1982).

Within the White-Inyo Mountains, plutonism began with intrusion of the Beer Creek pluton at ca. 175 Ma (McKee and Conrad, 1996) and continued episodically through the Late Cretaceous until intrusion of the Papoose Flat pluton at 83 Ma (Miller, 1996). McKee and Conrad (1996) interpreted their biotite K-Ar (91 Ma) and total fusion $^{40}Ar/^{39}Ar$ (93 Ma) dates for the Redding Canyon pluton to be the result of partial resetting; they speculated that the pluton may have been part of a regionally significant intrusive event best represented by the 165 Ma Barcroft pluton (U-Pb—Gillespie, 1979; Stern et al., 1981; SHRIMP-RG [sensitive, high-resolution ion microprobe–reverse-geometry], U-Pb—Ernst et al., 2003). Similarly, age data for the Sage Hen Flat pluton are equivocal and range from 145 Ma (U-Pb—Gillespie, 1979) to 133 Ma (K-Ar biotite—McKee and Nash, 1967).

In addition to large plutons, the White-Inyo Mountains are cut by abundant dikes that strike dominantly north. Many of these dikes may belong to the Late Jurassic (ca. 148 Ma) Independence dike swarm (Moore and Hopson, 1961; Chen and Moore, 1979), although they are undated. Ernst (1997) demonstrated that at least some dikes predate the ca. 165 Ma Barcroft pluton. The Sage Hen Flat pluton is cut by a few north- to northwest-striking dikes (Bilodeau and Nelson, 1993) that were considered to be Cretaceous on the basis of earlier estimates of the pluton's age at ca. 145 Ma. In this paper we show that the pluton is ca. 175 Ma; thus, these dikes could be part of the Independence swarm. Additionally, Ernst et al. (2003) have documented the occurrence of Tertiary mafic dikes in the range. Dikes in the White and Inyo Mountains display differing degrees of deformation (varying from intensely deformed to undeformed), whereas plutons contain little penetrative deformation.

METHODS

Field Work

We mapped the structure around the Redding Canyon pluton and determined U-Pb ages of (1) deformed dikes in the western White Mountains, (2) the Beer Creek pluton, (3) the Sage Hen Flat pluton, and (4) the Redding Canyon pluton. Mapping, which was completed in part by the 1997 University of North Carolina winter field course, concentrated on (1) establishing the relationship of deformation around the Redding Canyon pluton to regional deformation in the White Mountains, and (2) determining how much of the deformation affected mafic dikes and the Redding Canyon pluton. Samples for geochronology were chosen from plutons with clear field relationships to best determine the timing of regional deformation.

U-Pb Geochronology

Five samples of intrusive rocks were collected for geochronologic analysis. Sample processing and mineral separation followed standard crushing and density and magnetic separation techniques. All zircon fractions were handpicked by color, size, and morphology and were air abraded (Krogh, 1982), spiked with ^{205}Pb-^{233}U-^{236}U, and dissolved (Krogh, 1973). Isolation of U and Pb followed the methods of Parrish (1987). Purified U and Pb fractions were loaded on single Re filaments with silica gel and graphite, respectively. Procedural blanks during analysis were estimated to be a maximum of 5 pg Pb. Most fractions have total common Pb contents of $<$5 pg; therefore, all common Pb present was assumed to be blank Pb. For fractions with $>$5 pg common Pb, the Stacey and Kramers (1975) Pb model was used to correct the data.

RESULTS

Mapping and Field Relationships

Mapping in Poleta and Redding Canyons at a scale of 1:10,000 reveals intensely folded and faulted Cambrian strata and crosscutting diorite dikes intruded by the Redding Canyon pluton (Fig. 2). Both the Redding Canyon pluton and the adjacent strata are cut by a second set of diorite dikes. Regional stratigraphy and interpretation of some of the structure in the small map area rely on our interpretation of these structures relative to those mapped on a larger scale by Bateman (1965), Nelson (1966), and Welch (2000).

Units exposed in the map are largely Cambrian. Paleozoic miogeoclinal rocks are limited to the Cambrian Campito (Andrews Mountain Member), Poleta, and Harkless Formations. Within the map area, the Andrews Mountain Member of the Campito Formation is typically medium-bedded brown quartzite with minor brown-green shale. Despite significant deformation and imbrication, the lower, middle, and upper members of the Poleta Formation are distinguishable in the field area. In many locations, even finer details of the stratigraphy are preserved, including the well-known buff-blue-buff succession of limestone in the upper Poleta Formation, and the occurrence of brown dolomite layers near the top of the lower Poleta Formation (Nelson, 1962). Consequently, stratigraphic facing direction is known in various parts of the map area. The Poleta Formation is capped by the Harkless Formation, which includes thick sections of fissile green shale and rare, thin (10–20 cm)

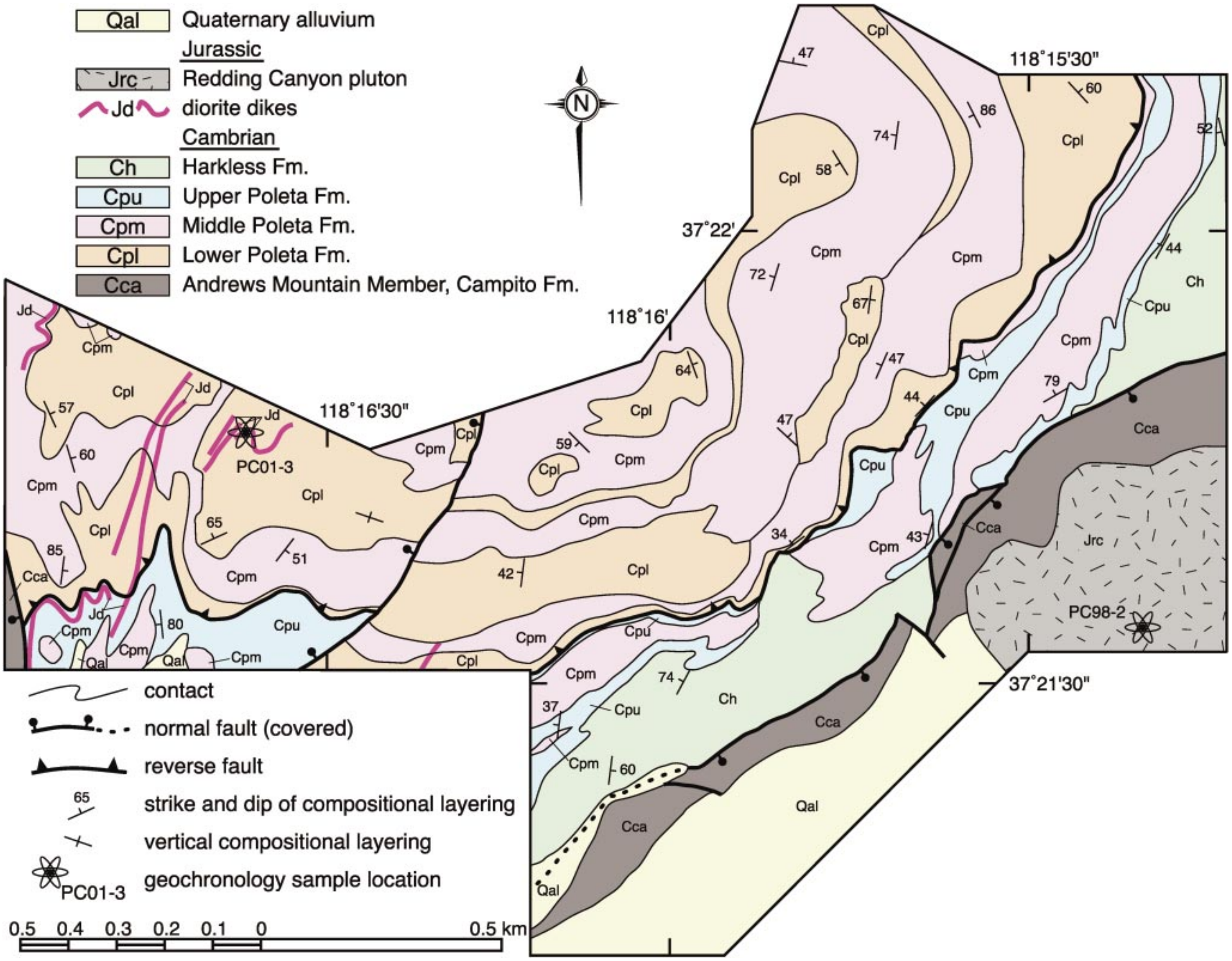

Figure 2. Geologic map of Poleta Canyon area. A large area of Redding Canyon pluton that lies to the southeast of the area in the figure was mapped, but is not shown here. Many internal contacts are reverse faults of minimal throw that, for simplicity, are not distinguished here. Key structural elements of the map area include (in age sequence) (1) southeast-directed thrusting, (2) southeast-vergent recumbent folding, (3) upright, shallowly north plunging folding and development of axial-planar cleavage, and (4) northeast-striking south-side-down normal faulting that places Campito Formation from the hanging wall of the recumbent fold against overturned Harkless Formation of the lower limb.

brown limestone layers that are also characteristic of the Harkless elsewhere in the region (Nelson, 1962).

The Cambrian sedimentary section is cut by at least three distinct intrusive rocks within the map area. The oldest intrusions are diorite dikes that were deformed with the sedimentary section. These are best represented in the western part of the map area where several dikes are parallel to folded stratigraphic contacts and structures. These dikes are possibly related to identical diorite dikes in the same small area that strike northeast and cut across stratigraphic contacts (Fig. 2). The Redding Canyon pluton is exposed in the southeastern part of the map area (only a small part of the area mapped within the pluton is shown in Fig. 2). Here the pluton is a porphyritic monzodiorite with K-feldspar phenocrysts up to 2 cm across in a matrix of plagioclase, biotite, hornblende, and quartz. The Redding Canyon pluton is distinctly chilled against the Campito Formation, clearly cuts foliation in the Campito, contains xenoliths of foliated Campito, and locally sent out thin ($<$10 cm) undeformed dikelets that cut penetrative deformation in the Campito (Fig. 3). Because there is no discernible foliation in the pluton or dikelets, we interpret intrusion of the Redding Canyon pluton to have postdated all fabric development in the area. The Redding Canyon pluton is itself cut by another set of diorite dikes that locally continue undeformed into adjacent Cambrian strata. These dikes strike north-northeast and may be related to northeast-striking dikes that cut stratigraphy in the western part of the map area.

The structure of the map area is dominated by three features. The first is west-northwest–dipping reverse fault or ductile shear zone (the Poleta Canyon thrust fault) that places an upper plate of lower and middle Poleta Formation over a lower plate of middle through upper Poleta and Harkless Formations. The Poleta Canyon fault itself is characterized by

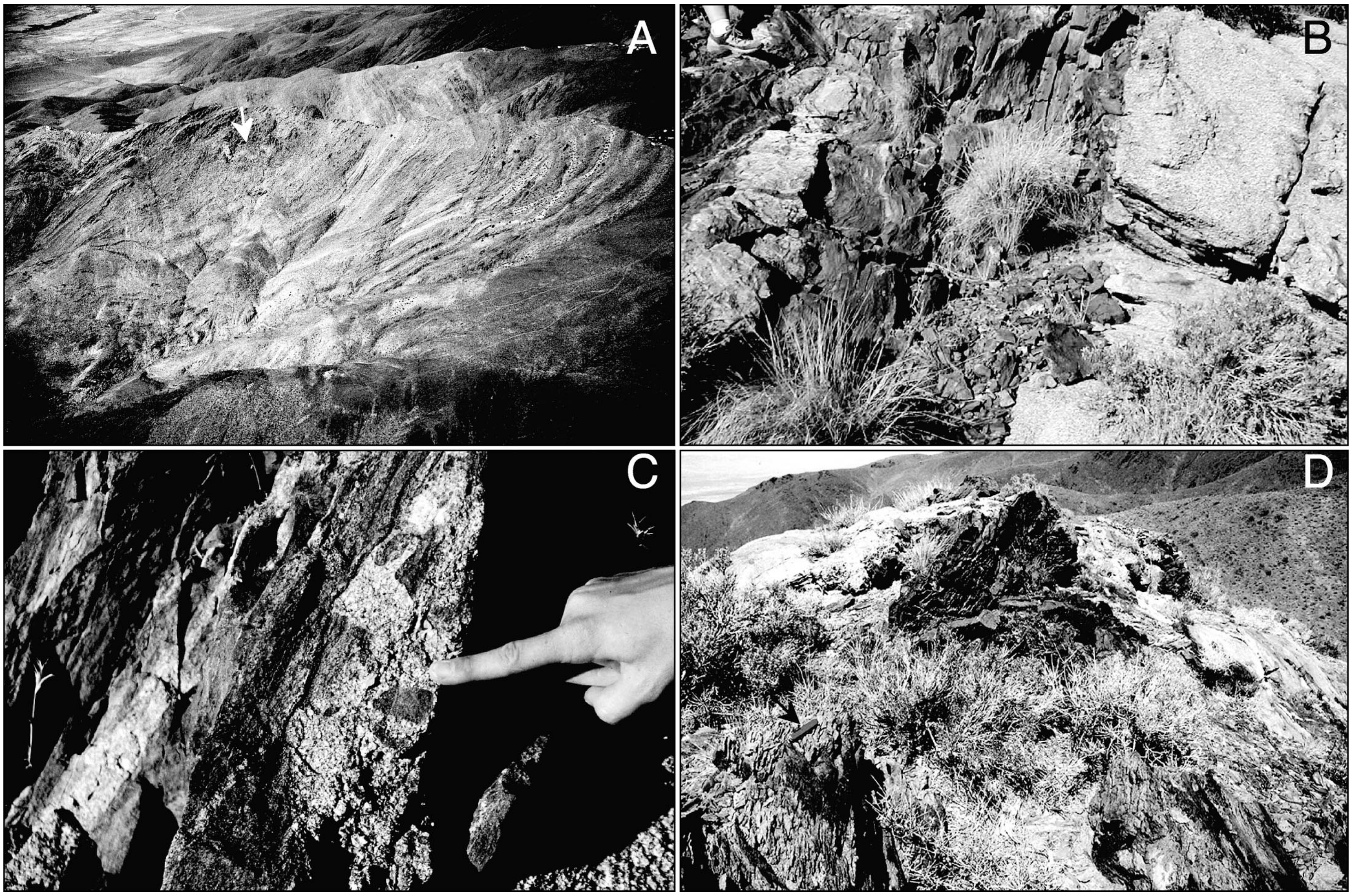

Figure 3. Field photographs from Poleta Canyon. (A) A view from the air, to the north across the eastern part of the map area. The overturned limb of a recumbent fold dominates the field of view. Small upright folds related to the second folding event and development of axial-planar cleavage are visible in the white dolomite layer indicated by the white arrow. (B) Undeformed dikes (light color) of the Redding Canyon pluton cutting foliated Campito Formation. (C) Inclusions of foliated Campito Formation in undeformed Redding Canyon pluton. (D) View along the axis of north-plunging upright fold. Dark rocks in the foreground are porphyritic diorite dike with well-developed axial-planar cleavage. Pocket knife (~10 cm long, indicated by black arrow) for scale. This photograph shows the site where sample PC01–3 was collected.

intensely ductilely deformed and attenuated strata. Within both the upper and lower plates of the fault, the Cambrian section has been repeated by numerous internal reverse faults with less stratigraphic throw (typically lower on middle Poleta and middle on upper Poleta) that are not distinguished in Figure 2 for simplicity.

The second dominant set of structures within Poleta and Redding Canyons constitutes folds that include an east-southeast–vergent, recumbent fold that plunges gently to the north and folds the older reverse faults. Most of the map area lies within the lower limb of the recumbent fold and, consequently, the stratigraphic section is upside down. To the north, however, the units pass through the closure of the fold and continue as the upright limb (e.g., Bateman, 1965), only a small part of which is exposed at the far northern end of the map area. This recumbent fold was refolded by north-northwest–trending, open to tight, upright folds. The later upright folding is associated with a regionally significant north-northwest–striking axial-planar cleavage that is well developed in all mapped Cambrian units and in the diorite dikes exposed in the western part of the map area (Figs. 2–4). In outcrop, the penetrative cleavage can be followed continuously from the folded sedimentary rocks across the margins of diorite dikes and into the core of the dikes with only local minor refraction of the cleavage adjacent to the margin. Dikes with orientations close to the bulk finite stretching direction (parallel to the cleavage) exhibit boudinage within the less competent sedimentary rocks; other dikes oriented at a relatively high angle to the cleavage have been shortened and folded.

Plots of poles to compositional layering and axial-planar cleavage within Poleta and Redding Canyons (Fig. 4) compare well to compilations of regional data (e.g., Bateman [1965], as summarized in Fig. 4B, and area 1 of Morgan and Law, 1998). These data are consistent with shallowly north-plunging, north-northwest–trending fold axes throughout the White-Inyo Mountains. Axial-planar cleavage measured in Cambrian strata within the map area is indistinguishable from that measured in diorite dikes. The dispersion of northwest-trending fold axes measured in this study along a great circle is consistent with either (1) the geometric interaction of the northwest-trending and earlier northeast-trending recumbent folds, or (2) overprinting of the

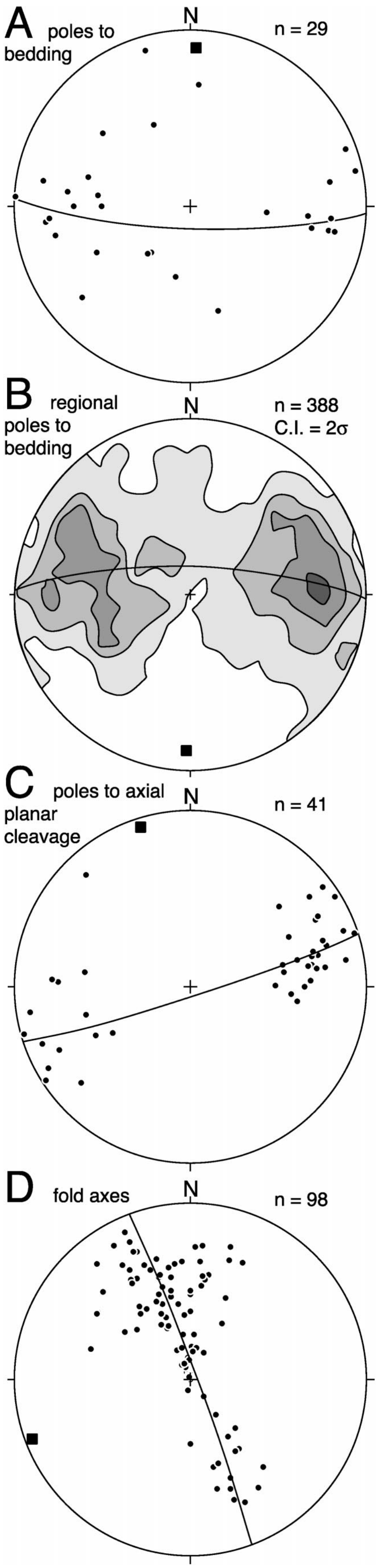

Figure 4. Stereonet plots of structural data. All data plotted by using Stereonet version 6 by R. Allmendinger. Best-fit plane and pole (solid square) are shown on each plot. (A) Poles to bedding in area shown in Figure 2. Data lie on a poorly defined great circle, suggesting a shallow, north-plunging fold axis. (B) Poles to regional bedding taken from Bateman (1965). Contours are at 2 (darkest), 4, 6, and 8 (lightest) standard deviations greater than a uniform distribution of points on the projection (method of Kamb, 1959). (C) Poles to axial-planar cleavage in map area. (D) Fold axes from the map area are generally consistent with a shallow north-plunging fold, but also are distributed along a great circle, suggesting that they may have been refolded by cryptic shallow west-plunging folds.

northwest folds by a cryptic younger generation of northeast-trending folds that have not yet been recognized.

The last major structural feature preserved within the map area is a northeast-striking, down-to-the-south normal fault, which we informally name the Corvair fault. The Corvair fault places upright Campito Formation on the south against overturned Harkless and Poleta Formations on the north. The fault has variably been interpreted as a normal fault (Bateman, 1965; Nelson, 1966; Welch, 1979) and a Mesozoic thrust with later reactivation as a normal fault (Welch, 2000; T.C. Welch, 2002, personal commun.). Unlike other Mesozoic faults in the area, however, the Corvair fault is brittle and brecciated, and the Campito Formation is silicified along much of its length (Bateman, 1965). A north-striking, west-side-down, range-bounding normal fault also drops upright Campito Formation on the west against overturned Poleta Formation on the east at the western edge of the map area and has a displacement and style very similar to that of the Corvair fault.

Redding and Poleta Canyons appear to cut into the lower limb of an east-vergent recumbent fold that may underlie much of the western flank of the White Mountains. In the hanging wall of the Corvair fault, the structure is dominated by the upper limb of the fold; here a relatively simple, upright, Precambrian through Cambrian stratigraphy is exposed. In the footwall of the fault, the overturned limb of the recumbent fold is exposed. However, because the fold plunges gently to the north, the overturned limb is buried, and the exposed west flank of the White Mountains returns to an upright Cambrian section.

Geochronology

Sample DS00–1 is from the Beer Creek pluton, an equigranular granodiorite that makes up part of the composite Eureka Valley–Joshua Flat–Beer Creek pluton of Morgan et al. (2000). The phase collected for dating predates the Joshua Flat facies of the pluton (Crowder et al., 1973). Ten zircon fractions from this sample lie on a well-defined Pb-loss trajectory with a lower-intercept age within error of zero and an upper-intercept age of 179 ± 3.4 Ma (mean square of weighted deviates [MSWD] = 1.06; GSA Data Repository Table DR1[1]; Fig. 5A). Four additional fractions show variable amounts of inheritance and are not included in the regression.

The Sage Hen Flat pluton (Bilodeau and Nelson, 1993) is a felsic fine-grained biotite-hornblende quartz monzonite residing in the western limb of the White Mountain anticline. It is noted for its strain-free contact with wall rocks and has been described as a ''cookie-cutter'' pluton (Morgan et al., 2000), because strata terminate at the pluton-wall rock boundary without deflection or deformation. Sample SF-1 from the Sage Hen Flat pluton yielded four concordant fractions that give weighted mean $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 175.4 ± 0.3 Ma (MSWD = 0.12) and 175.7 ± 0.4 Ma (MSWD = 0.14), respectively (Table DR1; Fig. 4B). Three additional discordant fractions are interpreted to reflect variable Pb loss and inheritance and are not included in the regression. We accept the weighted mean $^{206}Pb/^{238}U$ age for this sample as the crystallization age because it is the least sensitive to corrections for common Pb and inheritance.

The Redding Canyon pluton was sampled between Poleta and Redding Canyons in the northwest corner of the pluton (Fig. 2). Zircon from this sample is dominated by inherited grains, consistent with the fact that the pluton contains numerous small xenoliths of its sedimentary wall rock (Fig 3C). Two concordant zircon fractions from the Redding Canyon pluton give weighted mean $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 163.8 ± 0.5 Ma (MSWD = 0.15) and 163.9 ± 0.7 Ma (MSWD = 0.08), respectively (Table DR1; Fig. 4C). A poorly defined discordia array through all points gives an age of 162 ± 2 Ma (MSWD = 9.7) that overlaps (and is anchored by) the concordant points (Fig. 4D). Given that the inheritance in this sample is probably derived

[1]GSA Data Repository item 2003007, Table DR1, U-Pb data for plutonic rocks from the White Mountains, is available on the Web at http://www.geosociety.org/pubs/ft2003.htm. Requests may also be sent to editing@geosociety.org.

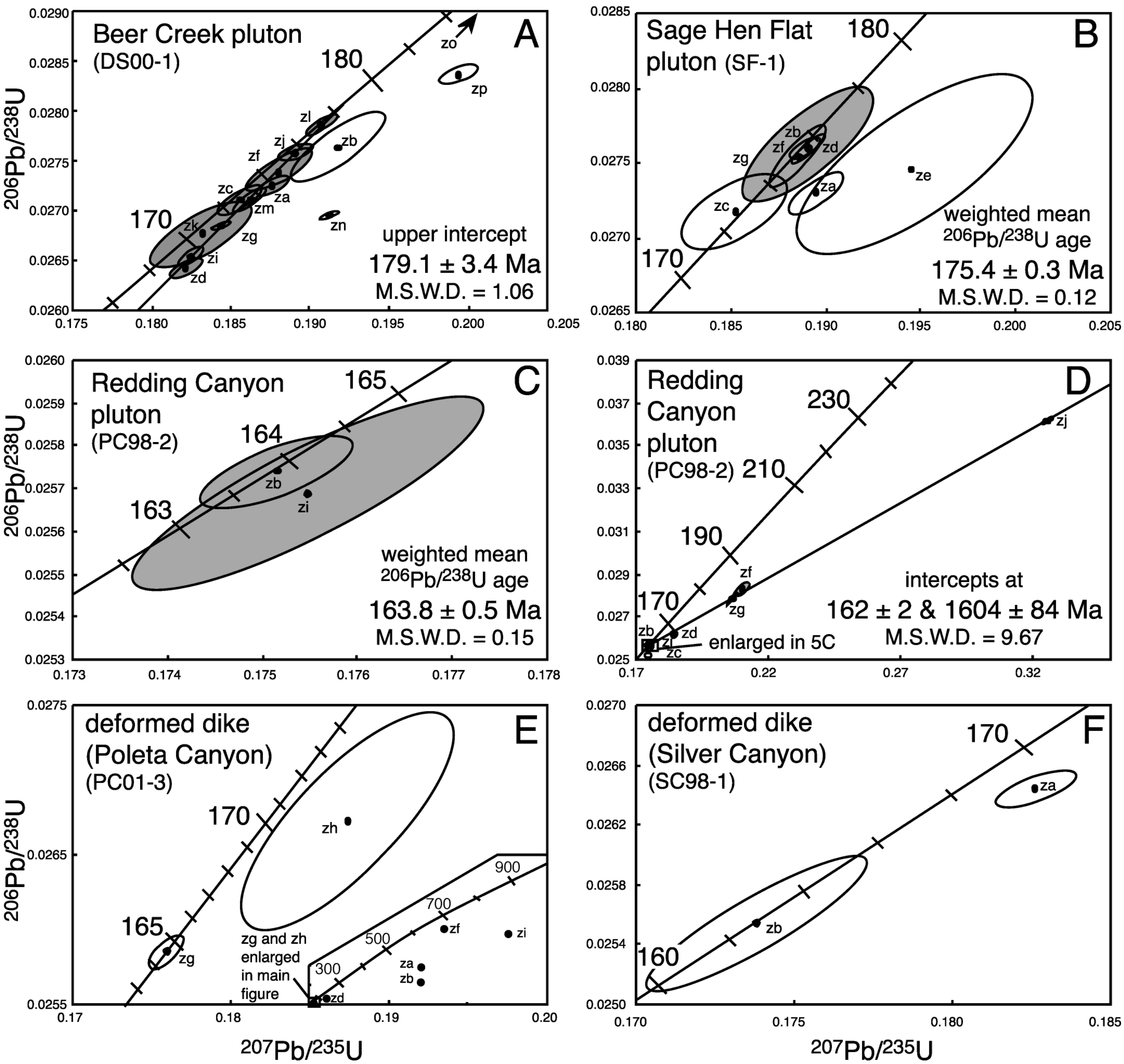

Figure 5. Zircon U-Pb concordia diagrams for samples from the White Mountains. (A) The Beer Creek pluton shows both inheritance and Pb loss. Regression of 10 analyses that appear to lie along a simple Pb-loss trajectory yielded an upper-intercept age of 179.1 ± 3.4 Ma. (B) Four concordant fractions from the Sage Hen Flat pluton yielded a weighted mean age of 175.4 ± 0.3 Ma. (C) Focused view of two concordant fractions from the Redding Canyon pluton that yielded a weighted mean age of 163.8 ± 0.5 Ma. (D) Zircon from the Redding Canyon pluton is characterized by inheritance of variable ages, consistent with assimilation of Campito Formation sedimentary rocks apparent in the field. Regression through the data yielded a poorly defined lower-intercept age of 162 ± 2 Ma that is anchored by two concordant fractions shown in C. (E) Zircon grains from a folded and foliated dike collected north of Poleta Canyon (Fig. 2) show inheritance of variable ages, which we interpret to result from assimilation of intruded sedimentary rocks. One concordant fraction with an age of 164.5 Ma is interpreted to provide the best estimate of the age of the dike. (F) A boudinaged dike from Silver Canyon yielded only four zircons that suggest an age of 162.5 Ma.

through assimilation of sedimentary wall rocks, it is not surprising that the inheritance pattern is complicated, and the significance of the discordia date is questionable. Consequently, we accept the weighted mean $^{206}Pb/^{238}U$ age of this sample as the best estimate of the time of emplacement.

The deformed mafic dike from the ridge immediately north of Poleta Canyon (Fig. 2; PC01–03) proved extremely difficult to date. Although it yielded abundant zircon, most were inherited, characteristically round, and likely derived from the sedimentary strata. Furthermore, the inherited grains appear to have been derived from diverse age groups, and no meaningful discordia array was generated (Table DR1; Fig. 4E). However, one single grain fraction is concordant at 164.6 Ma, and another slightly discordant single grain fraction is only a little older. It seems unlikely that the concordant grain could be inherited because the deformed dike must predate the undeformed 163.8 Ma Redding Canyon pluton. Therefore, we accept the age of this dike as ca. 165 Ma.

A second mafic dike from ~6 km north of Poleta Canyon, in Silver Canyon, was also sampled and yielded four zircons (SC98–2). This dike intruded parallel to (and does not contain) the regional north-northwest cleavage and is pulled apart vertically in a nearly vertical exposure, consistent with east-west shortening and vertical stretching. One two-grain fraction is concordant at 162.6 Ma and probably provides the best estimate of the dike's intrusion age (Fig. 4F). A second two-grain fraction has minor inheritance and is discordant.

DISCUSSION

The most recent compilation and assessment of geochronologic data from the White Mountains suggests that the plutons dated here would span both of the recognized Jurassic–Early Cretaceous intrusive epochs exposed in the range (ca. 180–165 Ma—Beer Creek pluton and Redding Canyon pluton[?]; ca. 150–140 Ma—Sage Hen Flat pluton and Redding Canyon pluton[?]; McKee and Conrad, 1996). Our new age for the Beer Creek pluton (179.1 ± 3.4 Ma) agrees well with previous estimates based on a discordant single-fraction U-Pb analyses (Gillespie, 1979) and on K-Ar and Ar-Ar systematics (McKee and Conrad, 1996). Our age for the Sage Hen Flat pluton (175.4 ± 0.3 Ma), however, is significantly older than McKee and Conrad's (1996) estimate of 141 Ma. The U-Pb systematics indicate that the younger date must result from partial resetting of Ar systematics. Even more dramatic resetting was recognized in the data for the Redding Canyon pluton by these authors. They suggested that the Redding Canyon pluton may be as old as 165 Ma—an estimate that the U-Pb results, which indicate an age of 163.8 ± 0.5 Ma, confirm. Dates for both of the dioritic dikes presented here demonstrate that they are not a part of the Independence dike swarm, but are part of an older swarm previously recognized in the White Mountains (Ernst, 1997). These results emphasize an earlier conclusion by Coleman et al. (2000) that caution should be exercised when using undated ''Independence-type'' dikes to determine the timing of deformational events in the Sierra-White-Inyo ranges.

Timing of Deformation in the White Mountains

The new ages presented here provide a tight bracket on the timing and spatial distribution of some of the deformation in the White Mountains. Field relationships require that a significant amount of the fabric-forming deformation in the Poleta and Redding Canyon area postdates intrusion of the deformed diorite dike (ca. 165 Ma) and predates intrusion of the Redding Canyon pluton (ca. 164 Ma). The dated dike contains the same axial-planar cleavage present in deformed Cambrian strata that is well developed along the western flank of the White Mountains; however, similarly oriented cleavage is cut by the 179 Ma Beer Creek pluton (Morgan and Law, 1998). Hence, we interpret some of the deformation along the western White Mountains to be correlative with East Sierran thrust deformation recognized and dated in the Inyo Mountains (Dunne and Walker, 1993; Dunne et al., 1994).

The penetrative cleavage and associated north-trending upright folds in the Poleta Canyon area deform several older generations of folds and faults that may be related to earlier orogenies, as suggested by Welch (2000), or may all be part of the same progressive deformational event (the East Sierran thrust system). The new data presented here do not permit unambiguous resolution of this issue; however, several relevant observations can be made. Although the style of faulting and folding (several generations of small-throw faults, east-vergent recumbent folds, northwest-plunging fold axes) are characteristic of the East Sierran thrust system to the south (Stevens et al., 1997), large-scale nappes such as the one exposed in Poleta Canyon are uncharacteristic of East Sierran deformation, but are similar to folds attributed to the Last Chance thrust elsewhere in the Inyo Range (Corbett et al., 1988). However, because the dated dike and several others have been rotated parallel to stratigraphic and structural contacts that owe their orientation to east-directed movement along faults as well as recumbent folding (Fig. 2), and locally the dikes have been boudinaged parallel to the faults, some late (post–165 Ma) reactivation of these structures must have occurred.

The dike sampled in Silver Canyon is boudinaged, but apparently postdates (ca. 162 Ma) the end of deformation immediately to the south in Poleta Canyon. Deformation of this dike may be related to East Sierran thrust deformation that locally continued until 148 Ma or to localized late subvertical stretching, identified elsewhere, that may be as young as Cretaceous (Stevens et al., 1997).

Dates for the Beer Creek and Sage Hen Flat plutons (ca. 179 and 175 Ma, respectively), both of which postdate penetrative deformation in their wall rocks, are important because they establish that East Sierran thrust deformation does not extend as far east as their exposures at the present level of exposure. This finding confirms an earlier assertion by Welch (1979) and Morgan and Law (1998) that the increase in intensity of deformational fabrics along the western margin of the White Mountains resulted from overprinting of older fabrics by Mesozoic deformation.

Magmatic Evolution of the Mesozoic Arc and the White Mountains

The new dates presented here demonstrate that all of the plutons investigated belong to an episode of Jurassic magmatism recognized by previous workers (Stern et al., 1981; McKee and Conrad, 1996). This observation, combined with an age for the Barcroft pluton of 165 Ma (U-Pb SHRIMP-RG; Ernst et al., 2003), reduces the potential Late Jurassic to Early Cretaceous plutons exposed in the White Mountains to the Indian Garden Creek and Cabin Creek plutons. Because age data for both of these plutons were disturbed by younger intrusive events (McKee and Conrad, 1996; much the same as dates for the Sage Hen Flat and Redding Canyon plutons), it seems likely that they, too, intruded during the 180–165 Ma event. Thus, evidence supporting the Late Jurassic–early Cretaceous intrusive episode in the White Mountains is dwindling (though it is evident south in the Inyo Mountains and Mojave Desert) and may be limited to Independence dikes. Although our dates do not confirm the occurrence of 148 Ma Independence dikes in the White Mountains, dioritic dikes that cut the Redding Canyon and Sage Hen Flat plutons and their wall rocks are plausibly part of the Independence swarm.

A reduction in the number of accepted Late Jurassic–Early Cretaceous plutons in the Sierra Nevada and White Mountains was also indicated by Stern et al. (1981). Additionally, Coleman and Glazner (1997) noted that the largest volume of Cretaceous magmatism in the region occurred during the relatively short Sierra Crest magmatic episode between ca. 98 and 86 Ma. Combined with other recently published high-precision ages (Ratajeski et al., 2001), these data suggest that the periods of most voluminous plutonism in the central Sierra–White Mountain arc are resolving into two well-defined events (ca. 180–165 Ma and ca. 102–86 Ma) with a 60 m.y. gap between them. Although a gap in plutonism has long been recognized in this part of the arc (Stern et al., 1981), it is surprising that additional dating is widening the apparent gap, rather than filling it in. Given the range of exposure levels represented between the Sierra Nevada and White Mountains, this hardly seems an accident of exposure but may be a fundamental feature of the arc.

CONCLUSIONS

New U-Pb geochronology for plutonic rocks exposed in the White Mountains indicate that the Middle Jurassic was a period of significant magmatism. The Beer Creek (ca. 179 Ma), Sage Hen Flat (ca. 175 Ma), and Redding Canyon (ca. 164 Ma) plutons all intrude variably deformed Paleozoic strata, but are themselves undeformed. In the Poleta–Redding Canyon area, mapping demonstrates that the Redding Canyon pluton cuts Cambrian strata that were folded and faulted in at least three episodes that likely persisted from late Paleozoic through Mesozoic time. The youngest preserved folding event is characterized by penetrative axial-planar cleavage that cuts a small swarm of diorite dikes north of Poleta Canyon. The age of one of these dikes (ca. 165 Ma) combined with that of the undeformed Redding Canyon pluton demonstrates that the youngest deformation occurred at ca. 165 Ma. These results indicate that the deformation is part of the East Sierran thrust system, recognized as far south as the Mojave Desert. The lack of East Sierran deformational structures in the older Beer Creek and Sage Hen Flat plutons can be attributed to localization of the Mesozoic deformation along the western flank of the White Mountains.

The rapidly expanding database of precise U-Pb dates for plutonic rocks in the White Mountains and central Sierra Nevada batholith is resolving significant emplacement of plutonic rocks in the Sierran arc into two distinct events that occurred at ca. 180–165 Ma and 102–86 Ma. Both events involved voluminous emplacement of plutonic rocks at a variety of crustal levels. Limited magmatism occurred between these events. Because the magmatic gap is widening and becoming more clearly defined as additional geochronologic data sets are acquired, it seems likely that the gap is a fundamental feature of the arc.

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REFERENCES CITED

Bateman, P.C., 1965, Geology and tungsten mineralization of the Bishop district, California: U.S. Geological Survey Professional Paper 470, 208 p.

Bilodeau, B.J., and Nelson, C.A., 1993, Geology of the Sage Hen Flat pluton, White Mountains, California: Geological Society of America Map and Chart Series, Map MCH077, 18 p.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: American Journal of Science, v. 275-A, p. 363–396.

Chen, J.H., and Moore, J.G., 1979, Late Jurassic Independence dike swarm in eastern California: Geology, v. 7, p. 129–133.

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

Coleman, D.S., and Glazner, A.F., 1997, The Sierra Crest magmatic event: Rapid formation of juvenile crust during the Late Cretaceous in California: International Geology Review, v. 39, p. 768–787.

Coleman, D.S., Carl, B.S., Glazner, A.F., and Bartley, J.M., 2000, Cretaceous dikes within the Jurassic Independence dike swarm in eastern California: Geological Society of America Bulletin, v. 112, p. 504–511.

Corbett, K.P., Wrucke, C.T., and Nelson, C.A., 1988, Structure and tectonic history of the Last Chance thrust system, Inyo Mountains and Last Chance Range, California, *in* Weide, D.L., and Faber, M.L., eds., This extended land: Geological journeys in the southern Basin and Range: Las Vegas, University of Nevada, Las Vegas, Geological Society of America Cordilleran Section Guidebook, UNLV Department of Geoscience Special Publication 2, p. 269–292.

Crowder, D.F., McKee, E.H., Ross, D.C., and Krauskopf, K.B., 1973, Granitic rocks of the White Mountains area, California–Nevada: Age and regional significance: Geological Society of America Bulletin, v. 84, p. 285–296.

Curtis, G.H., Evernden, J.F., and Lipson, J., 1958, Age determination of some granitic rocks in California by the potassium-argon method: California Division of Mines Special Report, v. 54, 16 p.

Dunne, G.C., and Walker, J.D., 1993, Age of Jurassic volcanism and tectonism, southern Owens Valley region, east-central California: Geological Society of America Bulletin, v. 105, p. 1223–1230.

Dunne, G.C., Gulliver, R.M., and Sylvester, A.G., 1978, Mesozoic evolution of rocks of the White, Inyo, Argus and Slate ranges, eastern California, *in* Howell, D.G., and McDougall, K., eds., Mesozoic paleogeography of the western United States: Pacific Coast Paleogeography Symposium: Los Angeles, Society of Economic Paleontologists and Mineralogists, v. 2, p. 189–207.

Dunne, G.C., Moore, S.C., Gulliver, R.M., and Fowler, J., 1983, East Sierran thrust system, eastern California: Geological Society of America Abstracts with Programs, v. 15, p. 322.

Dunne, G.C., Walker, J.D., Stern, S.M., and Linn, J.K., 1994, New U-Pb age constraints on Late Jurassic magmatism and contractile deformation in east-central California: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. 386.

Ernst, W.G., 1997, Metamorphism of mafic dikes from the central White-Inyo Range, eastern California: Contributions to Mineralogy and Petrology, v. 128, p. 30–44.

Ernst, W.G., Coleman, D.S., and Van de Ven, C.M., 2003, Petrochemistry of granitic rocks in the Mount Barcroft area—Implications for arc evolution, central White Mountains, easternmost California: Geological Society of America Bulletin, v. 115 (in press).

Evernden, J.F., and Kistler, R.W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.

Gillespie, J.G., Jr., 1979, U-Pb and Pb-Pb ages on primary and detrital zircons from the White Mountains, eastern California: Geological Society of America Abstracts with Programs, v. 11, p. 79.

Johnson, J.G., and Pendergast, A., 1981, Timing and mode of emplacement of the Roberts Mountains allochthon, Antler orogeny: Geological Society of America Bulletin, v. 92, p. 648–658.

Kamb, W.B., 1959, Ice petrofabric obervations from Blue Glacier, Washington, in relation to theory and experiment: Journal of Geophysical Research, v. 64, p. 1891–1909.

Kistler, R.W., Bateman, P.C., and Brannock, W.W., 1965, Isotopic ages of minerals from granitic rocks of the central Sierra Nevada and Inyo Mountains, California: Geological Society of America Bulletin, v. 76, p. 155–164.

Krogh, T.E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494.

Krogh, T.E., 1982, Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649.

McKee, E.H., and Conrad, J.E., 1996, A tale of 10 plutons—Revisited: Age of granitic rocks in the White Mountains, California and Nevada: Geological Society of America Bulletin, v. 108, p. 1515.

McKee, E.H., and Nash, D.B., 1967, Potassium-argon ages of granitic rocks in the Inyo batholith, east-central California: Geological Society of America Bulletin, v. 78, p. 669–680.

Miller, J.S., 1996, Pb/U crystallization age of the Papoose Flat pluton, White-Inyo Mountains, California: Geological Society of America Abstracts with Programs, v. 28, no. 5, p. 91.

Moore, J.G., and Hopson, C.A., 1961, The Independence dike swarm in eastern California: American Journal of Science, v. 259, p. 241–259.

Morgan, S.S., and Law, R.D., 1998, An overview of Paleozoic–Mesozoic structures developed in the central White-Inyo Range, eastern California: International Geology Review, v. 40, p. 245–256.

Morgan, S.S., Law, R.D., and Saint Blanquat, M. de, 2000, Papoose Flat, Eureka Valley, Joshua Flat–Beer Creek, and Sage Hen Flat plutons: Examples of rising, sinking, and cookie-cutter plutons in the central White-Inyo Range, eastern California: GSA Field Guide 2, p. 189–204.

Nelson, C.A., 1962, Lower Precambrian–Cambrian succession, White-Inyo Mountains, California: Geological Society of America Bulletin, v. 73, p. 139–144.

Nelson, C.A., 1966, Geologic map of the Blanco Mountain quadrangle, Inyo County, California: U.S. Geological Survey Geologic Quadrangle Map GQ-529, scale 1: 62,500.

Nelson, C.A., 1978, Late Precambrian–Early Cambrian stratigraphic and faunal succession of eastern California and the Precambrian–Cambrian boundary: Geological Magazine, v. 115, p. 121–126.

Nelson, C.A., Hall, C.A., and Ernst, W.G., 1991, Geologic history of the White-Inyo Range, *in* Hall, C.A., ed., Natural history of the White-Inyo Range, eastern California: Berkeley, University of California Press, p. 42–74.

Parrish, R.R., 1987, An improved microcapsule for zircon dissolution in U-Pb geochronology: Chemical Geology, v. 66, p. 99–102.

Ratajeski, K., Glazner, A.F., and Miller, B.V., 2001, Geology and geochemistry of mafic to felsic plutonic rocks in the Cretaceous intrusive suite of Yosemite Valley, California: Geological Society of America Bulletin, v. 113, p. 1486–1502.

Schweickert, R.A., and Lahren, M.M., 1993, Tectonics of the east-central Sierra Nevada: Saddlebag Lake and northern Ritter Range pendants, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds., Crustal evolution of the Great Basin and the Sierra Nevada: Geological Society of America Annual Meeting, Cordillera and Rocky Mountain Sections, Field Trip Guidebook: Reno, University of Nevada at Reno Department of Geological Sciences, p. 313–351.

Snow, J.K., and Wernicke, B., 1993, Large-magnitude Permian shortening and continental margin tectonics in the southern Cordillera: Reply: Geological Society of America Bulletin, v. 105, p. 280–283.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221.

Stern, T.W., Bateman, P.C., Morgan, B.A., Newell, M.F., and Peck, D.L., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California: U.S. Geological Survey Professional Paper 1185, 17 p.

Stevens, C.H., Stone, P., Dunne, G.C., Greene, D.C., Walker, J.D., and Swanson, B.J., 1997, Paleozoic and Mesozoic evolution of east-central California: International Geology Review, v. 39, p. 788–829.

Stone, P., and Stevens, C.H., 1984, Stratigraphy and depositional history of Pennsylvanian and Permian rocks in the Owens Valley–Death Valley region, eastern California, *in* Lintz, J., Jr., ed., Western geological excursions: Reno, Nevada, Geological Society of America National Meeting: Reno, McKay School of Mines, p. 94–119.

Stone, P., and Stevens, C.H., 1993, Large-magnitude Permian shortening and continental margin tectonics in the southern Cordillera: Discussion: Geological Society of America Bulletin, v. 105, p. 279–280.

Sylvester, A.G., and Babcock, J.W., 1975, Regional significance of multiphase folding in the White-Inyo Range, eastern California: Geological Society of America Abstracts with Programs, v. 7, p. 1289.

Sylvester, A.G., Oertel, G., Nelson, C.A., and Christie, J.M., 1978, Papoose Flat pluton: A granitic blister in the Inyo Mountains, California: Geological Society of America Bulletin, v. 89, p. 1205–1219.

Walker, J.D., Martin, M.W., Bartley, J.M., and Coleman, D.S., 1991, Timing and kinematics of deformation in the Cronese Hills, California, and implications for Mesozoic structure of the southwest Cordillera: Geology, v. 18, p. 554–557.

Welch, T.C., 1979, Superposed Mesozoic deformations in the southern White Mountains, eastern California: Geological Society of America Abstracts with Programs, v. 11, p. 134–135.

Welch, T.C., 2000, The structural setting and significance of the Poleta Canyon thrust in the White Mtns., Inyo Co., eastern California: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-232.

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