Structure and geochronology of the White Fork pluton, southern Sierra Nevada

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Abstract

The Sierra Nevada batholith represents an archetypal continental arc, although the style of deformation throughout the history of the arc is only poorly understood, in part due to the voluminous nature of Late Cretaceous magmatism that has overprinted earlier structures. The purpose of this study is to gain a better understanding of pre-Late Cretaceous deformation in the Sierra Nevada batholith through a structural and geochronological study of the Jurassic White Fork pluton. A Jurassic age for the White Fork pluton is indicated by its inclusion of numerous 148 Ma Independence dikes, and geochronology on the White Fork pluton is limited to discordant U–Pb zircon dates of ~156 Ma. We determined new U–Pb zircon ages using laser ablation ICPMS on two granodiorites from the White Fork pluton and one quartz monzonite correlated with the Jurassic Diamond pluton. The ages were indistinguishable within error, yielding ages of 166.4 +3.5/-3.6 and 164.8 +3.3/-3.3 Ma for the granodiorite samples, and 167.0 +3.5/-3.6 Ma for the quartz monzonite. These ages are statistically identical to the adjacent 165 Ma Woods Lake Pluton, and similar to other Jurassic plutons exposed at this latitude in the Sierra Nevada. With respect to deformation, at least three distinct sets of ductile shear zones that form cm- to tens of m- wide anastomosing shear zones were identified in a transect across the White Fork pluton and into the Woods Lake pluton: steeply NE-dipping shear zones with steeply SE-plunging lineations and E-side-up shear sense, shallowly SE-dipping shear zones with down-dip lineations and thrust shear sense, and shallowly SW-dipping shear zones with down-dip lineations and thrust shear sense. All shear zones deform the Independence dikes and are absent from adjacent Late Cretaceous plutons in the region indicating an age range of 148–92 Ma for these ductile fabrics, and shallowly SW-dipping shear zones are locally observed cutting steeply NE-dipping shear zones suggesting that they occurred later in the strain history of the pluton.

NE–SW shortening suggested by steeply NE-dipping, and shallowly SW-dipping shear zones is similar to strain observed in the nearby Sawmill Lake shear zone, and suggests that intra-arc contractional strain may have been more regional in nature in the Sierra Nevada batholith in the Early to Late Cretaceous.

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Introduction

The Cordilleran arc model is one that both answers and raises fundamental structural and geochronological questions about magmatic emplacement and tectonics as a whole. While subduction implies regional-scale subhorizontal simple shear, many features found within these granitic bodies appear to be enigmatically emplaced synkinematically within thrust faults. When considering the granitoids themselves, it is sometimes unclear as to whether they are brought to their current location mechanically along major thrust faults, or rise up buoyantly into major strike-slip faults. The Sierra Nevada Batholith, an archetypal continental arc, raises these very same questions. Three pulses of pluton emplacement have left a long record of growth along the North American plate, but each successive pulse has also obscured much of information about previous pulses. This leaves information about pre-Late Cretaceous stress fields and subsequent deformation hard to find, and even harder to decipher.

The White Fork Pluton, located within the Sierra Nevada Batholith, has the potential to be an important tool in understanding the geologic history of the Sierra Nevada Range of California due to its estimated age and deformation. Despite this, the current level of understanding regarding the timing of the emplacement and deformation events is incomplete, and is primarily based off of regional-scale mapping of the pluton's relationship with the Independence Dike Swarm (IDS) and discordant geochronological results of ~156 Ma (Chen and Moore, 1982). Based on its intimate relationship with the IDS and pervasive shear fabrics, it is speculated that the White Fork could be the oldest pluton in the Mount Pinochet Quadrangle (Moore, 1963). If this is true, the White Fork may record events predating many of the younger plutons of the region; because of this, unraveling the history of the White Fork Pluton could provide many substantial geologic insights into the early history of the Kings Canyon region, and more broadly, the entire Sierra Nevada magmatic arc.

Currently, the most reliable age for the White Fork Pluton is >148 Ma (Chen and Moore, 1982). We propose a Middle Jurassic age of approximately 165 Ma for the White Fork Pluton based on measurements and observations in the field, as well as observations of thin sections and zircon geochronology. Strain observed in the White Fork pluton (Kwf) is recorded by steeply NE-dipping shear zones with down-dip lineations. The age of these shear zones is bracketed between 148 Ma – 92 Ma due to their presence within the IDS and their absence from late Cretaceous plutons.

Geologic History

Magmatism

The Sierra Nevada is a complex mountain chain located in California that owes its current configuration to the geologically dynamic western boundary of the North American plate. The Sierra Nevada Mountains are built on a primarily intrusive string of granitic plutons that form the Sierra Nevada batholith (SNB) (Moore, 2000). Starting approximately 250 Ma ago, a subduction zone formed on the western boundary of the North American plate that was coincident with, and most likely a result of, the break-up of the Pangaea supercontinent (Bateman, 1988; Hill, 2006). Three pulses of magmatism followed the formation of this subduction zone: one in the Triassic (ca. 210 Ma), one in the Late Jurassic (ca. 170-150 Ma), and one in the Late Cretaceous (ca. 100-85 Ma) (Stern, 1981; Ducea, 2001). The Late Jurassic pulse of magmatic intrusions ended approximately 150 Ma ago, which was followed by a period lasting 30 Myr of virtually no intrusive activity (Stern, 1981). This pause of intrusion roughly correlates with the occurrence of a mountain-building event triggered by the subduction of the Farallon Plate beneath North America (Moore, 2000).

After the Farallon plate began to subduct beneath the North American plate, the presence of a new magmatic fuel source allowed for emplacement of a voluminous generation of plutons to begin, starting approximately 125 Ma ago (Stern, 1981). This final pulse of intrusions, which forms the backbone of the present-day SNB, is distinctly zoned from west to east in both age and composition (Moore, 2000). Much more is currently known about this Late Cretaceous pulse than earlier intrusive events due to the fact that Triassic and Jurassic plutons outcrop much less than Cretaceous plutons, which form the bulk of the SNB (Bateman, 1992). Jurassic outcrops occurring both east and west of Cretaceous plutons indicate a crosscutting relationship of the Late Jurassic suite by the Late Cretaceous plutons (Bateman, 1992). Bateman (1988) determined that there was only one locus of pluton formation at any one time, and that this locus changed position through time. It was later theorized that the eastward decrease of pluton age was due to the subducting plate rising up underneath the continental plate, steadily moving the locus of pluton formation eastward (Tobisch et. al, 1995). This eastward migration of the locus occurred at a rate of 2.7 mm/year (Chen and Moore, 1982).

Prior to this, subduction fueled intrusion into the western margin of the new North American continent starting with an initial flare-up around 210 Ma ago and reignited approximately 40 Myr later in the Middle Jurassic (Stern et al, 1981). Much less is known about these intrusive events due to a relative lack of Triassic and Jurassic plutons. During this time, the locus of pluton formation shifted over time, although it is unclear as to whether there was a single locus or multiple loci at any given time (Bateman, 1988). It is within this intrusion suite that the White Fork Pluton is suspected to have formed, despite its label of “late Cretaceous” in the relative ages of Moore (1963).

The zoning of compositions in the Late Cretaceous plutons is due to a related zoning of materials that the plutons melted through before emplacement (Moore, 2000). A large amount of juvenille material had accreted onto the western margin of the North American Plate, and as the locus moved eastward, the material each pluton was melting through and incorporating into its structure moved from this juvenille material to the more felsic Jurassic intrusions and continental crust farther east (Moore, 2000). As the Cretaceous magma intruded into the Jurassic plutons, they melted and recrystallized the original structures, obliterating much of their original record (Moore, 2000). This is the reason why the survival of the White Fork Pluton is very valuable in terms of geochronology; it provides a record of the deformational history that occurred before the main intrusive suite that now forms the SNB was emplaced.

Cretaceous intrusion comes to a sudden stop approximately 80 Ma ago, most likely due to an increase in the rate of convergence between the two plates, as well as an almost horizontal flattening of the subducting plate (Chen and Moore, 1982). The cessation of pluton emplacement could also be due to the slab fuel source becoming melt-drained (Ducea, 2001).

Deformation

Deformation of Wall Rocks

Intrusion of the SNB produced deformation in the country rock that almost entirely obscures any pre-Cenozoic structure (Moore, 1963). The sedimentary and volcanic country rock deformed into vertically-oriented, highly metamorphosed septa between plutons (Moore, 1963). This wall rock has steeply dipping lineations, and any recognizable original bedding is oriented parallel to schistosity. (Moore, 1963). Most of the wall rocks are not folded, and are present as homoclinal masses (Moore, 1963).

Deformation of Plutons

The granitoids of the SNB record a large amount of deformation in the form of foliations, lineations, faults, joints, and intrusive relationships (such as the IDS). The few remaining Jurassic and Triassic plutons in particular are useful for their extended record of deformation within the SNB. In general, the plutons in the Mount Pinchot quadrangle have a steeply dipping foliation that follows the walls of the pluton (Moore, 1963). Many of the plutons and granitic masses surrounding the Kwf have strong lineations, including the Dragon pluton, the Arrow pluton, and the Tinemaha granodiorite (Moore, 1963). In the two plutons, the lineations are near horizontal and are parallel to the long axis of the pluton; this is evidence for the bulbous, expanding emplacement model rather than a dike-like intrusion model (Moore, 1963). However, these foliations and lineations are most likely magmatic in origin and do not record deformation from forces outside the plume itself.

Throughout the Mount Pinchot quadrangle, steeply dipping conjugate joints cut across contacts between plutons and are therefore younger than and unrelated to pluton emplacement (Moore, 1963). The Arrow pluton contains many small east-trending sinistral strike-slip faults that show evidence of plastic deformation, indicating the faulting was deep-seated and occurred soon after emplacement (Moore, 1963). Moore (1963) correlated these faults with three larger, map-scale left-lateral faults that cut the Cotter, Bullfrog, Dragon, and Diamond plutons. The McDoogle pluton (Kmd) is a Cretaceous pluton that does not contain the IDS, and is separated from the Kwf by the Tinemaha granodiorite. Its fabric parallels the overall trend of the pluton, and the lineation plunges steeply to the southeast (Mahan et al., 2003). It contains deformed wall rock that represents Jurassic granodiorite that is referred to as the granodiorite of Sawmill Lake (Mahan et al., 2003). This wall rock contains a solid-state penetrative northeast-side up simple shear fabric with boudinage that indicates northeast-southwest shortening (Mahan et al., 2003). The Kmd records a southwest-to-northeast strain profile, with centimeter-scale mylontic shear zones in weakly deformed rocks found in the Woods Lake/Twin Lakes area to the southwest and the Mule Lake pluton to the northeast (Mahan et al., 2003). Between these two locations, the granodiorite of Sawmill Lake found within Kmd shows the strain increasing to ultramylonite closer to the center of Kmd (Mahan et al., 2003). Mahan (2003) suggests this shear zone is not related to the Sierra Crest Shear System due to discordance between the types of strain (horizontal shortening in Kmd vs predominately transform in the Sierra Crest system) and the fact that it is older than 90 Ma. Instead, they propose that it is related to the East Sierran Thrust System and isostatic sinking due to its proximity to the thrust system, overlapping age constraints, and similar kinematics (Mahan et al., 2003).

Approximately 20 Ma ago, extension associated with the formation of the Basin and Range Province of Nevada formed Cenozoic volcanoes within the Sierra Nevada, and 10 Ma ago this extension began to tilt the Sierran block westward (Moore, 2000). This uplift, along with glaciation that has occurred in cycles starting 2.5 Ma ago and denudation by water, has eroded away almost all of the layers of volcanic, metamorphic, and sedimentary rocks overlying the SNB, particularly in the south; this process is still going on today (Moore, 2000).

Independence Dike Swarm

The Independence Dike Swarm is a regional-scale group of mafic dikes found along the eastern side of the Sierra Nevada and Mojave Desert that spans an area about 600 km long by 30 km wide and trends about 330° (Carl et al., 1998; Chen and Moore, 1982). Overall, the dikes strike consistently northwest, although Carl et al. (1998) notes that this is a generalization, with some dikes diverging from the trend by 10-20° counterclockwise, and others striking northeast, completely breaking the trend. The dikes have been dated at 148±2 Ma old (Chen and Moore, 1979).

According to the Chen and Moore (1982) interpretation of the IDS, the stresses associated with Farallon subduction beneath the North American Plate created regional NE−SW-directed extension on the eastern side of the proto-SNB during the 30 Ma hiatus between the two major intrusive events. This extension formed a system of fractures greater than 350 km in length in the newly formed Jurassic intrusions (Chen and Moore, 1982). These fractures allowed dominantly mafic, calc-alkalic magma to rise from the upper mantle and form a series of dikes (Chen and Moore, 1982). The dikes were emplaced over a short amount of time (Moore and Hopson, 1961).

However, a second interpretation by Carl et al. (1998) relates the en echelon pattern of the dikes to intrusion of magma along oblique fractures caused by a crustal-scale left-lateral shear zone. They argue that the 10-20° difference between the orientation of the dikes north of the Garlock Fault and the overall trend of the swarm weakens the argument that they were formed by extension (Carl et al., 1998). They also argue that temporal relationships linking the Nevadan Orogeny and the IDS by papers including Chen and Moore (1982) are weakened by recent studies that extend the time period of the orogeny to >20 Ma (Carl et al., 1998). They propose that a change in motion of the North American Plate caused the formation of the IDS due to sudden strain partitioning. (Carl et al., 1998). Fractures oriented north to northeast accommodated left-lateral shearing, whereas fractures oriented toward the west acted as regional-scale en echelon dikes (Carl et al., 1998).

In both cases, the same stresses that caused the fracturing of the proto-batholith may be related to a counterclockwise rotation of the North American Plate in relation to the source of plutonic activity (Bateman, 1988). This would account for the slight difference in orogenic strike between the Jurassic and Cretaceous intrusive suites (N 40° W and N 20° W, respectively) (Stern, 1981).

Methods and Materials

Two weeklong fieldwork trips were taken in the summers of 2014 and 2015. In 2014, 63 foliation and lineation measurements were taken at 27 locations within and around the White Fork Pluton (Kwf) using a Brunton compass, and fourteen samples were collected. Thin sections from all fourteen samples were made for further petrographic observations. Three samples were also chosen for zircon U−Pb geochronologic analysis. Samples J140904N and J140904H were Kwf granodiorites from the northern end of the pluton, and sample J140905L was quartz monzonite from the Jurassic Diamond Pluton (Kdi) intruding into the southern end of Kwf (Fig. 1). These samples were ground to a fine pounder using a disc mill rock pulverizer. This powder was then subjected to hand panning, lithium metatungstate heavy liquid separation, magnetic separation with a Frantz Magnet, and hand picking to extract a total of 71 zircons from the samples. These samples were taken to the University of California at Santa Barbara, where their U-Pb ratios and heavy metal composition were analyzed using laser ablation split stream inductively coupled plasma mass spectrometry (LA-ICP-MS).

In 2015, three samples were taken from the Woods Lake Basin. The first was a mylonzied Tinemaha granodiorite (Kta) on the western side of the pluton between High Heel Lake and Cliff Lake. The second sample came from a mafic dike that cross cut a felsic dike, which was the source of the third sample. Both dikes intruded into the western side of Kta near the contact with Kwf. The mafic sample was sent to a laboratory to be mounted as a thin section. Future work will use LA-ICP-MS to determine the age of the dike, and potentially constrain the age of deformation further. 81 foliation measurements and 69 lineation measurements were also taken using a Brunton compass and the iOS application “Field Clino.”

Foliation and lineation data from both fieldwork trips was organized using Microsoft Excel and plotted onto stereonets using Stereonet 9, created by Rick Allmendinger. Extraction of ages from raw U-Pb data was done using the TuffZirc algorithm of Ludwig and Mundil (2002) in the program Isoplot (Ludwig, 2000).

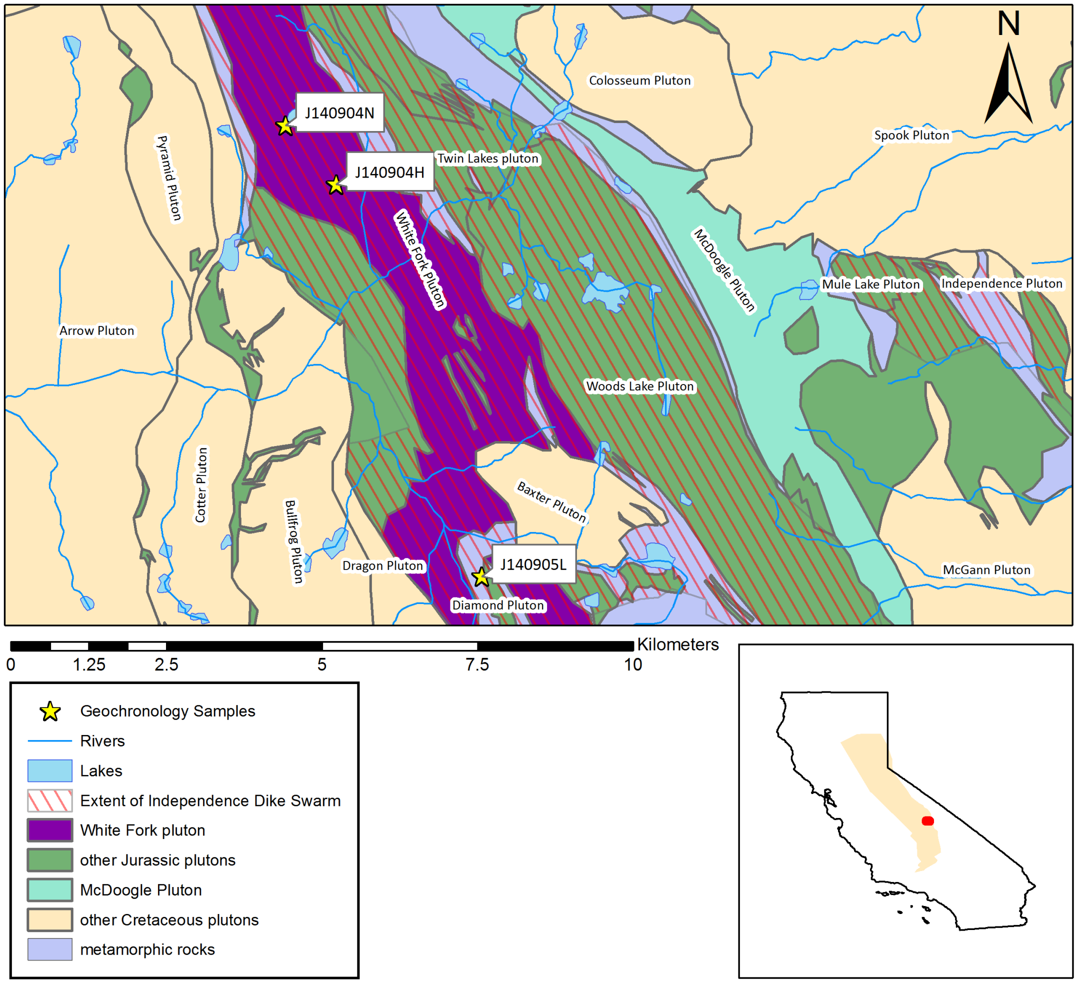

Figure 1. Simplified geologic map of the White Fork Pluton (Kwf), the Tinemaha granodiorite (Kta), and locations of 3 samples taken in 2014.

Results

Geochronology

Sample J140904H yielded a TuffZirc age of 167.0 Ma +3.5, -3.6 Ma with 96.5% confidence in a coherent group of 15 out of 24. Sample J140904N yielded a TuffZirc age of 166.4 Ma +3.5, -3.6 with 97.9% confidence in a coherent group of 10 out of 23. Sample J140905L yielded a TuffZirc age of 164.8 +3.3, -3.3 with 94.3% confidence in a coherent group of 14 out of 24. These ages are statistically identical to the adjacent 165 Ma Woods Lake pluton (Kta) and are similar to other Jurassic plutons found through the SNB.

Deformation

Three distinct sets of ductile shear zones that form cm- to tens of m- wide anastomosing shear zones were identified within the White Fork pluton and the Woods Lake pluton. The first set comprises steeply NE-dipping shear zones with steeply SE-plunging lineations and E-side-up shear sense (Fig. 2, 3a, 3b). These shear zones parallel the IDS. The second set contains shallowly SE-dipping shear zones with down-dip lineations and thrust shear sense (Fig. 3c). Shear zones of this orientation have been previously described by Carl (2000). These shear zones were found to crosscut IDS-parallel shear zones in Kta, with dextral displacement of the IDS indicated by a mafic enclave marker. The third set comprises shallowly SW-dipping shear zones with down-dip lineations and thrust shear sense (Fig. 3d). No crosscutting relationship could be found between these shear zones and the previous two groups of shears zones. All shear zones deform the Independence dikes and are absent from adjacent Late Cretaceous plutons in the region.

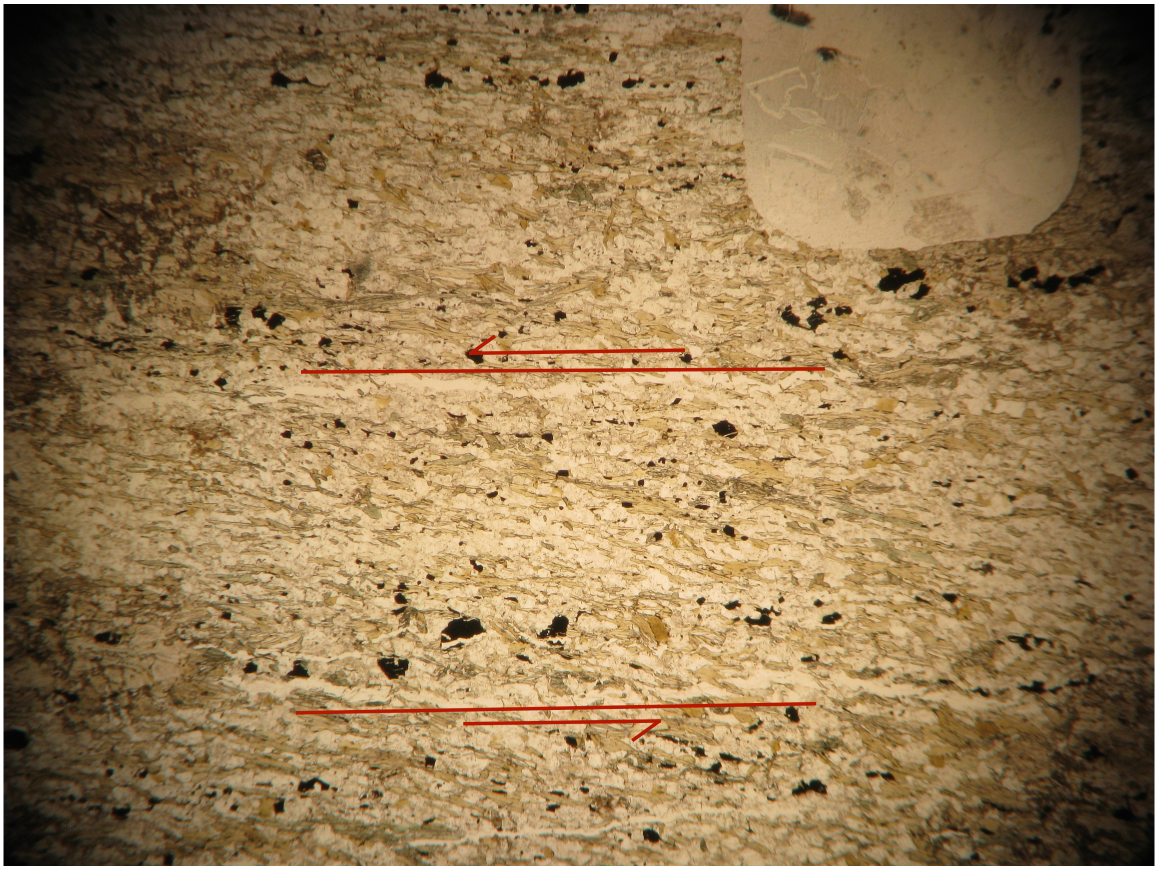

Figure 2. Oriented sample J140903C viewed in thin section with Plain Polarized Light (PPL). This granodiorite sample came from a 15m wide shear zone within Kwf and contained mafic enclaves and epidote mineralization. S_1 is oriented 067/82 (Dip Direction/Dip) and L_1 is oriented 156/46 (Trend/Plunge). S-C fabric indicates top to the left (east-side up).

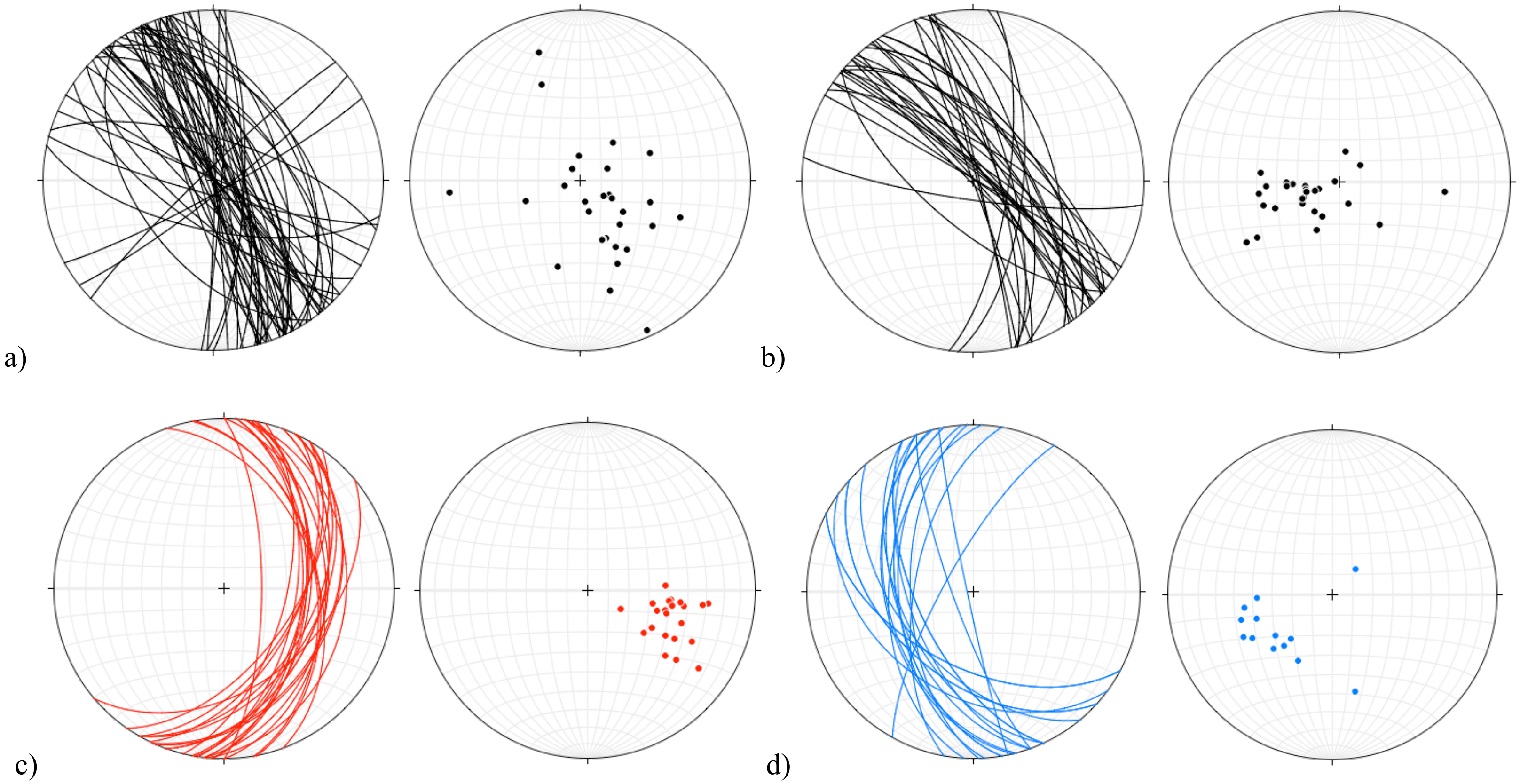

Figure 3. Stereonet diagrams of foliation planes and lineations from the White Fork pluton (Kwf) and the Woods Lake mass of the Tinemaha granodiorite (Kta), Sierra Nevada, California. a) Steeply NE-dipping shear zones with steeply SE-plunging lineations and E-side-up shear sense found in Kwf and generally parallel to IDS. b) Measurements taken from Kta similar to those taken in Kwf (steeply NE-dipping shear zones with steeply SE-plunging lineations and E-side-up shear sense). c) Shallowly SE-dipping shear zones with down-dip lineations and thrust shear sense found in Kta that are correlated with shear zones described in Carl (2000). d) Shallowly SW-dipping shear zones with down-dip lineations and thrust shear sense found near the northern end of the contact between Kwf and Kt

Figure 4. S_1 is oriented 080/72 and is representative of shear zones from Figure 3a and 3b. Mechanical pencil in center of picture included for scale.

Figure 5. S_1 is oriented 228/47 and L_1 is oriented 245/40. This outcrop is representative of shear zones from Figure 3d. Marker in bottom of picture included for scale.

Figure 6. Shear zones (parallel to pencil; Fig. 3c) offsetting shear zones oriented to the IDS (Fig. 3a, 3b). North is pointed toward the top left corner of the picture.

Conclusions

All three shear zones identified in this study are present within the IDS but absent from late Cretaceous plutons. Therefore, an age range of 148-92 Ma has been assigned to these fabrics. Based on crosscutting relationships, it has also been determined that the shallowly SE-dipping shear zones are younger relative to the steeply NE-dipping shear zones. Since no crosscutting relationships exist between the SW-dipping shear zones and the steeply NE-dipping shear zones or the SE-dipping shear zones, the age of the SW-dipping shear zones relative to these two fabrics is still unknown.

The steeply NE-dipping shear zones parallel shear zones identified by Mahan et al. (2003) and are consistent with the NE-SW contractional strain profile identified by Mahan et al. (2003) in the Sawmill Lake area. This shear zone, called the Sawmill Lake shear zone by Mahan et al. (2003) is also bracketed between 148-92 Ma using the same timing constraints used for the shear zones found in the Woods Lake and White Fork plutons, namely their presence in the IDS and absence from Late Cretaceous plutons. It is possible that the SE-dipping faults caused the left-lateral shear strain on the steeply NE-dipping faults, because they are oriented obliquely to the NE-dipping faults and came after the NE-dipping faults had formed. SW-dipping and SE-dipping shear zones are approximately conjugate with average lineations that are 51° apart, although average foliation surfaces that are 87° apart. If the SW-dipping and SE dipping shear zones are conjugate planes and formed at the same time, this would suggest a component of N−S directed shortening without a component of left-lateral shear. No significant relationship between the SW-dipping and the NE-dipping shear zones is yet apparent.

The Sawmill Lake shear zone could represent backthrusting on the western edge of the East Sierran Thrust system because the Sawmill Lake shear zone dips opposite of the East Sierran Thrust System (Mahan et al., 2003). If the NE-dipping shear zones found in the Woods Lake Pluton and the White Fork Pluton are related to the Sawmill Lake shear zone, it would suggest that intra-arc contractional strain may have been more regional in extent throughout the Cretaceous.

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