ABSTRACT

Title of Thesis:	ROCK FABRIC ANALYSIS OF THE SIERRA CREST SHEAR ZONE SYSTEM, CALIFORNIA: IMPLICATIONS FOR CRUSTAL-SCALE TRANSPRESSIONAL SHEAR ZONES
	Callan Bentley, Master of Science, 2004
Thesis Directed By:	Dazhi Jiang, Assistant Professor, Geology Department

Crustal-scale tabular shear zones are common features of transpressional orogens and arcs. Though foliation development in shear zones is well understood, the development of another rock fabric element, lineation, is not. Computer modeling shows that monoclinic solutions for lineations are unstable; triclinic models better explain the variation of lineation in natural transpressional zones. This thesis investigates an example of natural lineation variation in three segments of the Sierra Crest shear zone system, Sierra Nevada, California. Field data collected during large-scale mapping indicate an early (Paleozoic?) generation of deformation overprinted by a Cretaceous, dextral, reverse (west-over east), steeply-dipping shear zone active for ~20 Ma. A third generation of deformation overprints previous fabrics. Estimates of shear zone volume reduction are correlated with volumetrically-complementary emplacement of the Sierra Nevada batholith across strike. Disagreement between single-domain model predictions and field observations is interpreted as being due to heterogeneous strain localization on many scales.

ROCK FABRIC ANALYSIS OF THE SIERRA CREST SHEAR ZONE SYSTEM, CALIFORNIA: IMPLICATIONS FOR CRUSTAL-SCALE TRANSPRESSIONAL SHEAR ZONES

By

Callan Bentley

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Advisory Committee:
Assistant Professor Dazhi Jiang, Chair
Professor Philip A. Candela
Adjunct Professor E-an Zen

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Callan Bentley

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Chapter 1: Transpression and tabular shear zones

1.1 Transpression

Transpressional shear zones are a common feature in many orogens and magmatic arcs. The rock fabrics that develop in these zones contain important information about the tectonic history of the area. Though these shear zones have been studied for many years, the interpretation of their rock fabrics is still being refined. Various models have been developed to provide an understanding of rock fabric in transpressional zones, a goal they achieve with varying degrees of sophistication and success.

Harland (1971) was the first to define transpression as a tectonic regime of oblique convergence and transtension as a tectonic regime of oblique divergence. As Figure 1 shows, the transpressional regime occurs between pure convergent and pure transform (strike-slip) boundary conditions. Harland mainly used the concept of transpression to better explain the rotation of Caledonian fold axes in Spitsbergen, Norway. It was conceived of as a boundary condition. Within regions of transpressional boundaries, deformation on smaller scales may be accommodated by different deformation paths, including ones occurring in transtensional boundary conditions (Harland, 1971).

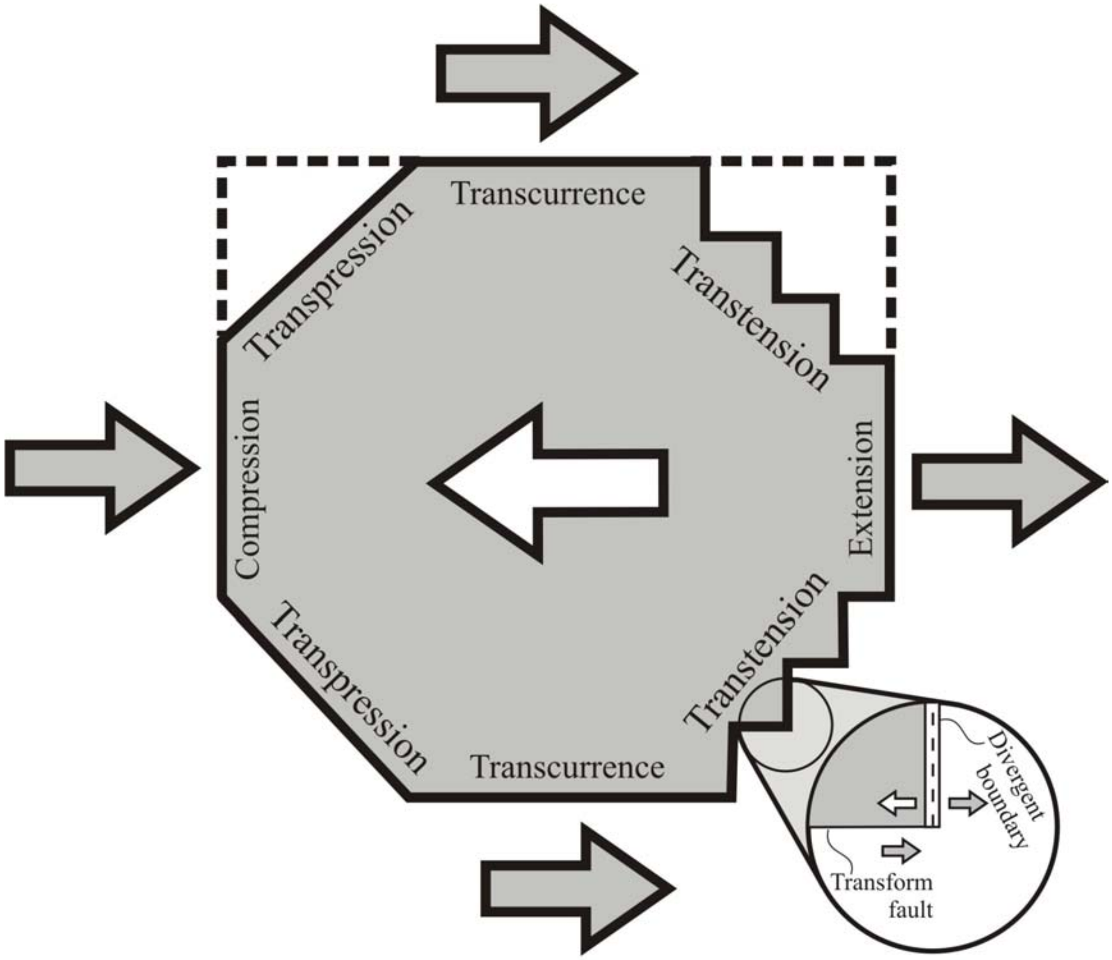


Figure 1: Transpression and transtension as tectonic boundary conditions. Two hypothetical plates move with respect to each other: an octagonal one completely enclosed in another. Along different sides of the octagon, different tectonic regimes exist. Transpression exhibits qualities of both convergence and transcurrence. Transtension exhibits qualities of both extension and transcurrence (inset). Redrawn from Harland (1971).

Sanderson and Marchini (1984) applied the concept of transpression to deformation in shear zones, extending the simple shear model described in a landmark paper by Ramsay and Graham (1970) as "shear belts" (two dimensional cross-sections of tabular shear zones). Sanderson and Marchini modeled transpressional deformation of a central tabular shear zone (what Ramsay and Graham alluded to as a "ductile fault") bounded by the oblique convergence of two blocks (Figure 2).

Accommodated by this vertical tabular zone, Sanderson and Marchini-style transpression includes components of both pure shear and simple shear. This is superficially similar to Harland's tectonic transpression, but at least an order of magnitude smaller in size, and just one specific type of deformation that satisfies Harland's boundary condition.

Their modeling assumes homogenous deformation. Rheological homogeneity is an assumption that is regularly made in transpressional modeling that is rarely matched in reality. Their model predicts that, because of homogeneity of deformation, the central block rises straight-edged as the shear zone is subjected to transpression, a condition that is impossible in geological reality. However, the key concept in Sanderson and Marchini's (1984) model was the need to maintain constant volume and homogenous strain, resulting in vertical extrusion of material in the shear zone. This approach is a purely finite strain approach: only the initial and final states of deformation are considered, with no consideration of the progressive deformation leading to the final state.

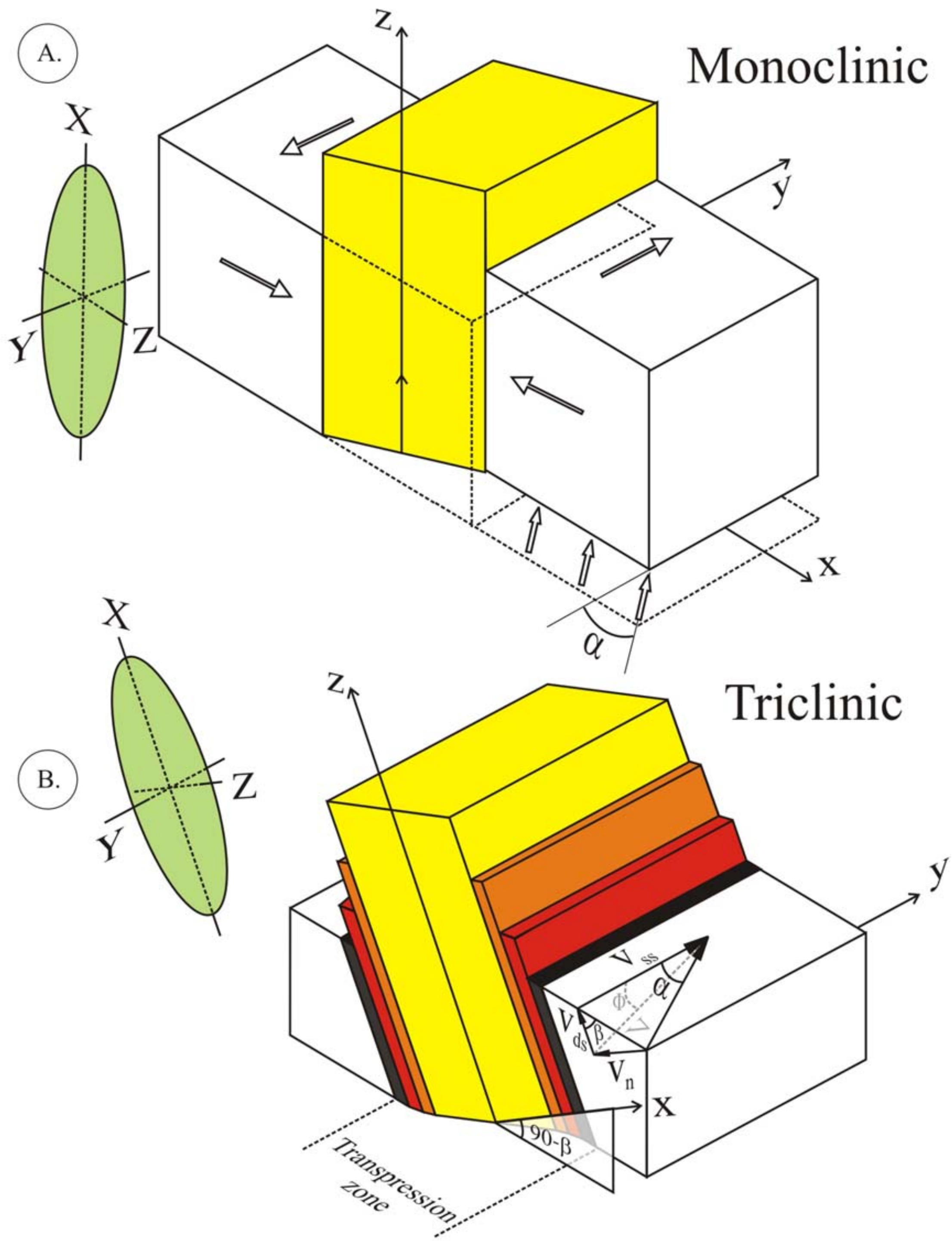


Figure 2: Transpression as deformation in tabular zones. A) The Sanderson and Marchini (1984) model of transpression. B) Triclinic widening model. Two unit cubes transpress a third central cube, which is then deformed by shortening parallel to the Y-axis and simple shear parallel to the X-axis. Extension in the *z* direction in accordance with conservation of volume. See text for discussion. (A) Redrawn from Sanderson and Marchini (1984). (B) Modified from Jiang (in review).

1.2 Kinematics

1.2.1 Pure- and simple-shear-dominated transpression

Fossen and Tikoff (1998) recognized the Sanderson and Marchini model as being but one specific scenario in a broader spectrum. They detailed the horizontal angle of transpressional convergence (α in Figure 2A), kinematic vorticity (= cos α in Figure 2A), principal strain axes (X, Y, and Z in Figure 2A), a finite strain coordinate system (x, y, and z in Figure 2A), and rotational aspects of five transpressional regimes and five transtensional regimes (Fossen and Tikoff, 1998). β is the dip angle of the zone (only denoted in Figure 2B, since it is 90° in Figure 2A). Their model is monoclinic, with shear zone boundaries being vertical and shear direction horizontal (Figure 2A). This means that the Φ component (as denoted in Figure 2B) is equal to 0. Each of these regimes is in fact simply one point along a spectrum of possible combinations of pure shear, simple shear, and vertical extension. Sanderson and Marchini's (1984) model corresponds only to one point along Fossen and Tikoff's (1998) transpression. In differentiating patterns of strain, consideration must be given to the two broadest regimes of transpression: pure-shear-dominated and simple-shear-dominated transpression.

Simple shear may be thought of as the "trans-" component of transpression (i.e. strike-slip), while pure shear is the "press-" component (i.e. convergent). For monoclinic cases, the ratio of simple shear to pure shear determines whether the shear zone's deformation is pure-shear-dominated or simple-shear-dominated. A simple / pure shear ratio of 1, for instance, means that the deformation is pure-shear-dominated. On the other hand, a simple / pure shear ratio of 5 causes simple-shear-dominated deformation. For monoclinic transpression, this ratio is related to the horizontal convergence angle (α) of the blocks bounding the shear zone. When α is greater than 19.5º, the deformation is called pure-shear-dominated; when α is less than 19.5º yields a deformation called simple-shear-dominated. If α is greater than 19.5º, then the maximum axis of the strain ellipsoid (X) will be vertical throughout deformation. There will be a difference if α is less than 19.5º, in which case the maximum axis of the strain ellipsoid (X) will start horizontal. At 19.5º, the critical value of the ratio of simple shear to pure shear is 2.824. Of course, tectonic boundaries are not perfectly planar. At the initiation of transpressional deformation, the presence of salients and recesses in the shear zone bounding blocks will alter these values for the rock between them at various points along strike. With progressive deformation over time, those irregularities will be burnished away.

1.2.2 Triclinic transpression and variation along and across the shear zone

Figure 2B shows a more complex situation, where relative motion between the two bounding blocks must be expressed in three components, not just two, as in the monoclinic case (V_{ds}, V_n, and V_{ss} in Figure 2B). Lin et al. (1998, 1999) and Jiang et al. (1999) extended the model to include shear zones with triclinic deformation expected in inclined ($\beta \neq 90°$ in Figure 2B) zones and / or zones with shear direction not parallel to the strike of the zone ($\Phi \neq 0°$ in Figure 2B). Φ is defined as angular deviation of transpression direction from the horizontal. (i.e. $\Phi = 0$ for perfectly monoclinic transpression). In comparing fabric geometries between model predictions and the actual rock record, Lin et al. (1998) argued that pure shear is widely distributed through a shear zone, while simple shear is localized in discrete areas.

Jiang and Williams (1998) added to the triclinic model by including consideration of along-strike variation in strain and volume change.

1.3 Fabric development in shear zones

1.3.1 Foliation and lineation in shear zones

In the interpretation of rock fabrics, the assumption is often made that the lineation is parallel to the long axis (X axis) of the finite strain ellipsoid, and the foliation plane is assumed to be the XY plane. Foliation and lineation are the two most important observable fabric elements in transpressional zones, and are often used for kinematic analysis of transpressional zones. Foliation is a planar arrangement of structural, mineralogical, or textural features in a rock. Similarly, lineation is a linear arrangement of such features. Where both are present, lineation commonly lies within the plane of foliation; however lineation may exist without foliation being present, and vice versa. However foliations in shear zones include the S, C, and C' surfaces of mylonites (Berthe, 1979, Lister and Snoke, 1984) of which only the S-foliation (shape fabric) can be regarded as the XY plane. Specific lineations include mineral lineations and lineations defined by stretched markers, such as pebbles in a conglomerate or volcanic lapilli. The trend and plunge of lineation, and the strike and dip of foliation can be measured in the field. The arrangement of the lineation and foliation determine the strain geometry of the zone in question. In addition, the components of a rock, once deformed, may serve as kinematic indicators, relaying a sense of the relative motions of the sides of the shear zone in question (normal, reverse, dextral strike-slip, sinistral strike-slip, or some mixed displacement). Figure 3 gives some examples of these fabric elements.

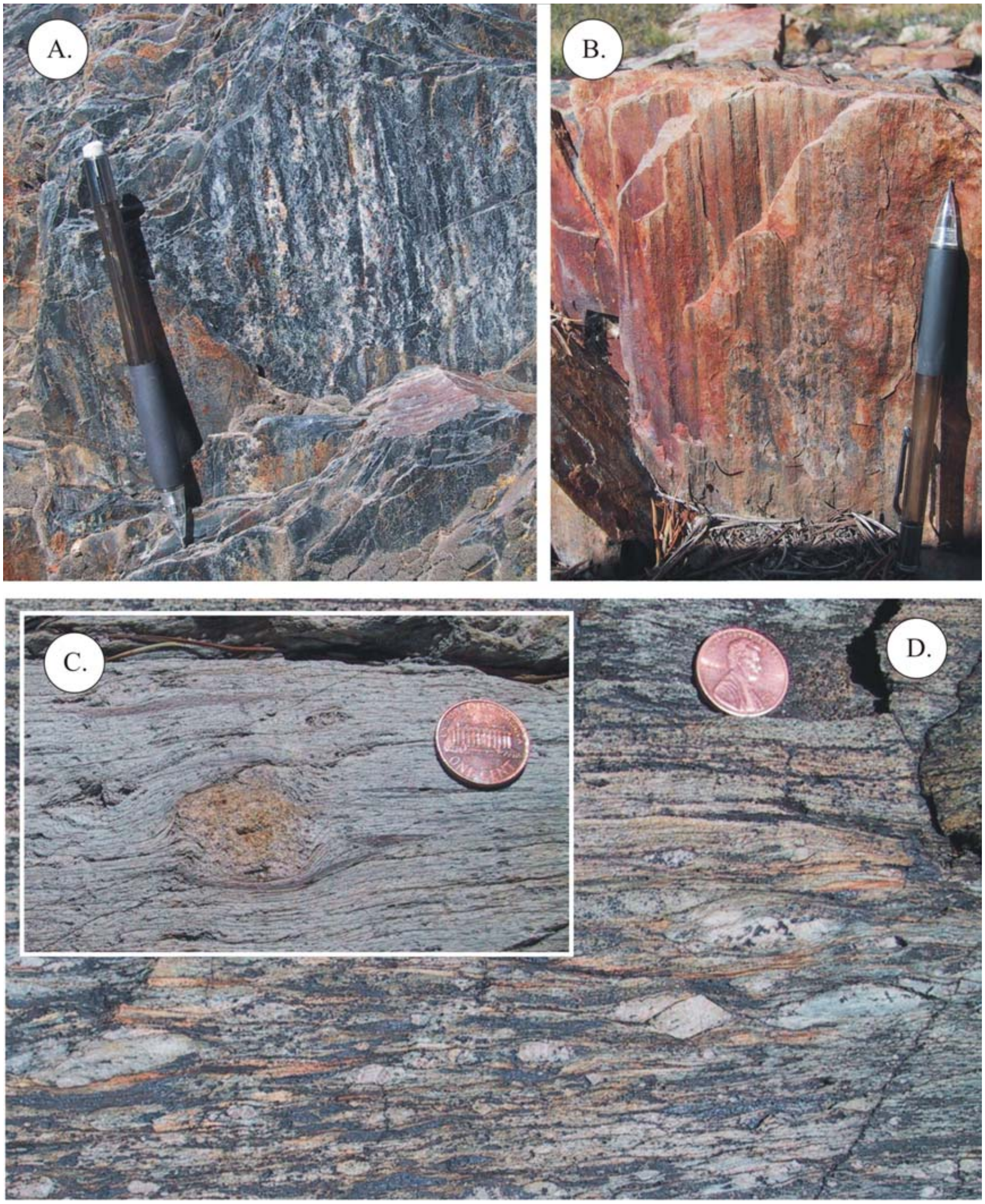


Figure 3: Lineations and foliations (A and B) and kinematic indicators (C and D) are common elements of rock fabric in shear zones. A and B) Photographs are taken on a vertical section, perpendicular to foliation and parallel to stretching lineations. Left, stretching lineation plunging 66º towards 290º, Gem Lake segment. Right, downdip stretching lineation plunging 87º towards 254º, Mono Pass segment. C and D) Both Gem Lake segment. Photographs taken on the horizontal section, perpendicular to both foliation and lineation. Sigma clast (C) and imbricated feldspars (D) indicate a dextral sense of shear.

1.3.2 Transition from horizontal to vertical lineation

Both the monoclinic and triclinic models predict foliation to develop parallel to the shear zone boundary, successfully explaining foliation within natural transpressional zones. However, they make different predictions for lineation, and the variation of lineation remains to be accounted for. As deformation proceeds in a transpressional shear zone, the lineation changes, while the foliation remains relatively constant.

In the context of monoclinic transpression, pure-shear-dominated and simple-shear-dominated transpression theoretically yield different deformation paths, which may be expressed as different rock fabrics. As Figure 4 shows, in pure-shear-dominated transpression, the fabric will have vertical foliation and vertical lineation. In simple-shear-dominated transpression, initially vertical foliation and horizontal lineation would develop. As deformation proceeds, however, simple-shear-dominated transpression will also attain a vertical lineation. The mechanism by which simple-shear-dominated transpression makes this transition depends on whether the transpressional zone is triclinic or monoclinic. However, because triclinic transpression may be broken down into three components (V_{ss}, V_{ds}, and V_n in Figure 2B) and cannot be characterized by a pure to simple shear ratio alone, “pure-shear-dominated” and “simple-shear-dominated” transpression do not apply to triclinic transpression.

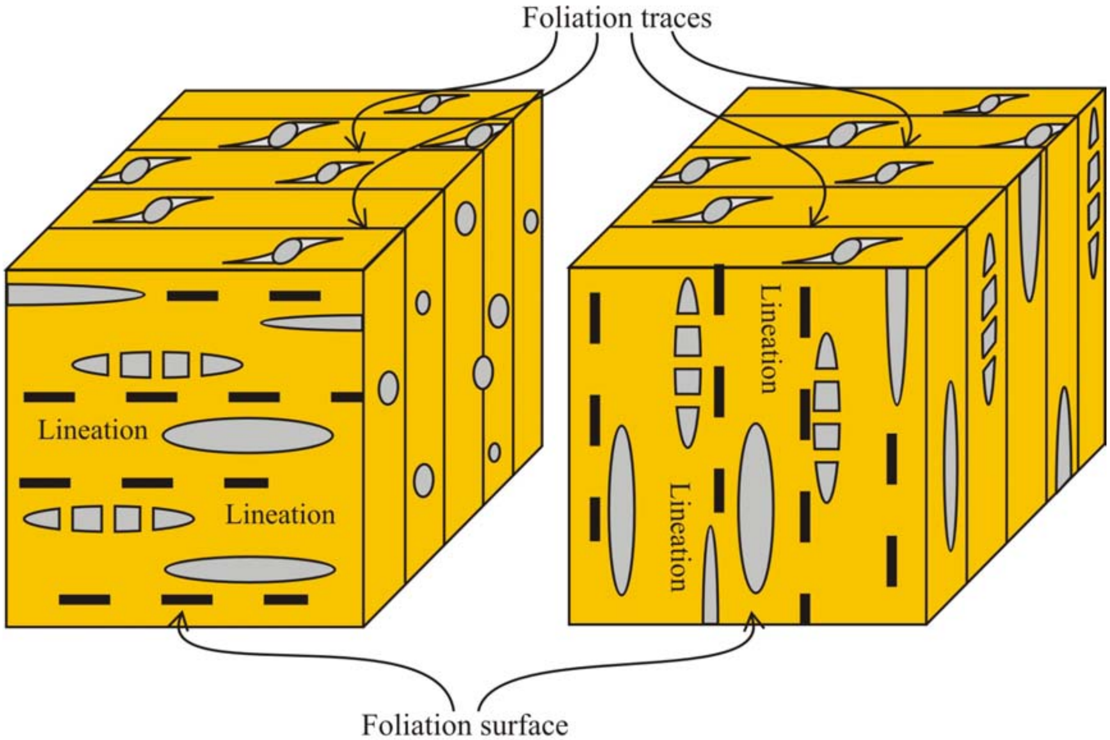


Figure 4: A comparison of the idealized rock fabrics interpreted by Tikoff and Greene (1997) in the Sierra Crest shear zone system. Purely monoclinic deformation is assumed. Left block: foliation is vertical but lineation is horizontal, indicating simple-shear-dominated transpression. Right block: foliation and lineation are both vertical, indicating pure-shear-dominated transpression. Note the boudinaged lithic clasts.

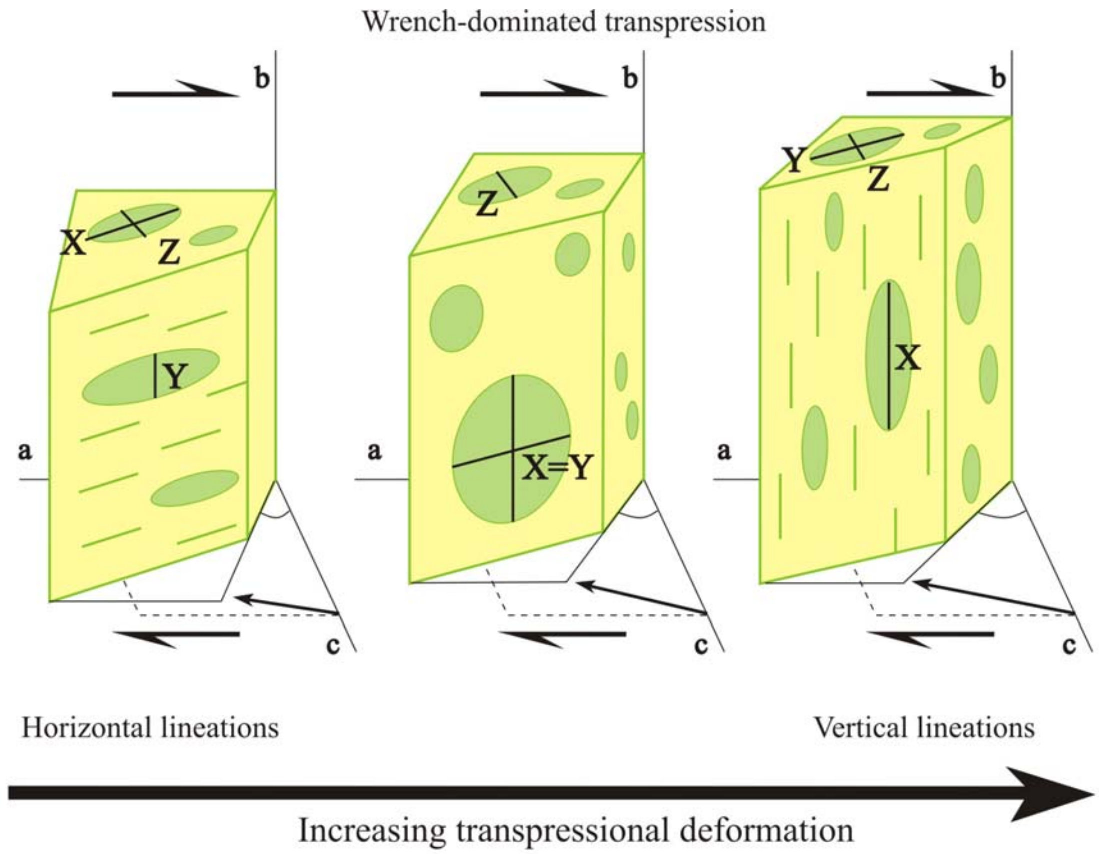


Figure 5: The development of lineation in a steady-state dextral simple-shear-dominated transpressive shear zone and the concept of "lineation switch" in perfectly monoclinic wrench-dominated or "simple-shear-dominated" transpression. Initially the horizontal axis is the X-axis of the strain ellipsoid. Lineation is horizontal. However, there comes a time when the increased growth rate of the vertical axis catches up to the horizontal axis, and X =Y. After that point, the vertical axis is longest, and hence the new X. Lineation is vertical from then on as deformation proceeds. An initial cube of constant volume becomes taller and flatter as deformation proceeds. Redrawn after Tikoff and Greene (1997).

The monoclinic models of Tikoff and Greene (1997) and Fossen and Tikoff (1998) predict the monoclinic scenario pictured in Figure 5. In a steady-state dextral simple-shear-dominated shear zone, lineation evolves in the following fashion: Initially, lineation is horizontal, and the Y-axis (medium axis of the strain ellipsoid) is vertical (Figure 5, left). However, vertical extrusion of matter from the shear zone causes the Y-axis to grow at a faster rate than the X-axis. At some point, the vertical Y-axis catches up to the X-axis, (i.e. X=Y ; Figure 5, middle). At this point, the vertical and horizontal axes switch 'rank' (i.e. their relative magnitude and therefore designation). Thereafter, the vertical axis (which is now the X-axis) continues to grow at a rate exceeding the horizontal axis (which is now the Y-axis) (Figure 5, right). Thus, a monoclinic model like this predicts *only* horizontal or vertical lineations, but nothing in between (Figure 6A).

The triclinic models of Lin et al. (1998) and Jiang and Williams (1998) predict stretching lineations that plot between horizontal and downdip, forming a half-girdle (Figure 6B). These types of lineation patterns are common in natural transpressional zones, (e.g. Xu et al., 2003; Czeck and Hudleston, 2003; Lin et al., 1998) but are unexplained by the Fossen and Tikoff (1998) model (Figure 6C).

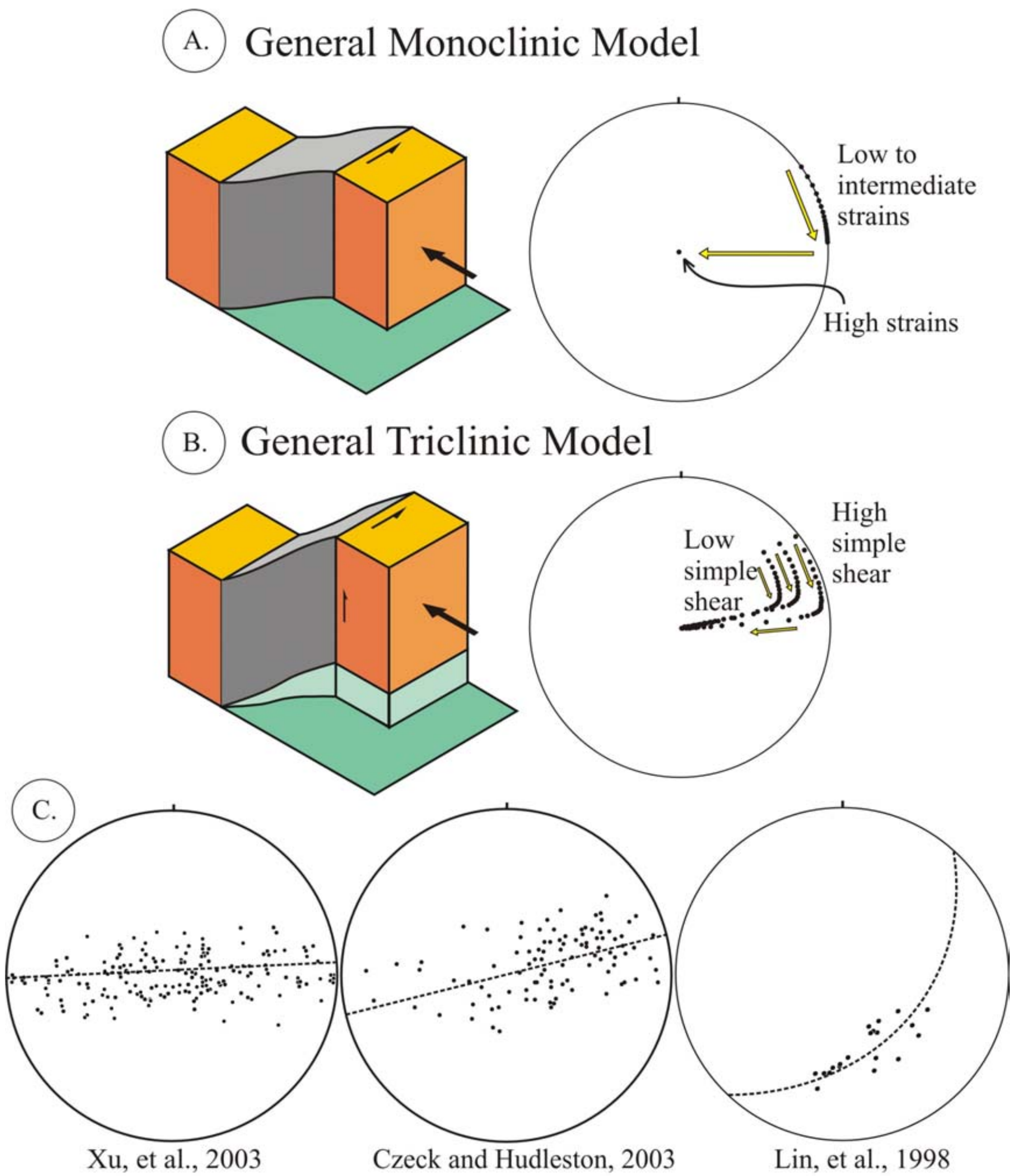


Figure 6: A comparison between the predictions of strain geometry from forward numerical modeling and the patterns of strain geometry as seen in field examples. A) Monoclinic and B) triclinic transpressional zone models [Monoclinic after Ramsay and Graham (1970), Sanderson and Marchini (1984), and Fossen and Tikoff (1998). Triclinic after Lin et al. (1998, 1999), and Jiang and Williams (1998).] Lineation is plotted on equal-area lower-hemisphere stereographic projections as black dots. Polar foliation data is represented as open squares. Overall trend of shear zone (average foliation) is shown by dotted lines. C) Natural transpressional zones display strain patterns that plot as full girdles (Xu et al., 2003 and Czeck and Hudleston, 2003) or half-girdles (Lin et al., 1998).

1.4 Aims of this study

1.4.1 Unresolved issues in the study of transpressional zones

The two unresolved issues in the study of transpressional zones are 1) the variability of lineations (strain geometries varying between point maxima and full circle girdles), and 2) the stability of the lineation switch solution for monoclinic transpression. The lineation switch mechanism's sensitivity to slight deviations from a perfectly monoclinic zone renders it theoretically unstable. In addition, it makes predictions that are not borne out by field investigations (i.e. *only* vertical and horizontal lineations, with an intervening zone of X=Y, no lineation at all).

1.4.2 Field study of variation in a natural transpressional zone

This study has applied field mapping of a natural transpressional shear zone to address the issue of lineation variability and forward numerical modeling to address the monoclinic solution stability issue. Because a detailed history of the rocks' deformation history (i.e. its "path") is not obtainable from structural analysis, we must address fabric evolution through a forward modeling approach. That is, we test likely deformation paths by modeling and compare model predictions with field observations. But, because models are simplified versions of complex natural phenomena, it is essential to build the model on observations of real rock as exposed in a real shear zone. Field work and modeling approaches offer different strengths; by employing a joint approach, we hope to (a) see which model predications are matched by real rock deformation, (b) decide which predictions are not met, (c) infer reasons that the model failed to describe the actual shear zone, and (d) contribute to the tectonic history of the field area by offering insights from the model and systematic fieldwork.

Chapter 2: Stability of monoclinic solutions

2.1 Lineation evolution mechanism in monoclinic and triclinic transpression

Whether the transpressional zone is monoclinic or triclinic has a profound influence on the means by which the lineation evolves and in turn how the lineation is kinematically interpreted. Figure 6 shows the difference between the predictions of monoclinic and triclinic transpressional models for simple-shear-dominated transpression. In the monoclinic model, lineation evolves towards parallelism with the shear zone boundary and then instantaneously switches to vertical (indicated as the larger open arrow). There are no lineations between horizontal and vertical. However, when the relative motion of the sides of the shear zone is made triclinic, even by a very small amount, the long axis, instead of an instantaneous swapping of the horizontal and vertical axes, rotates progressively first towards parallelism with the strike of the shear zone boundaries (quasi-horizontal) and then towards parallelism with the dip line (quasi-vertical). This implies that the monoclinic solution is theoretically unstable. In triclinic transpression, as orientation develops, it follows a J-shaped pattern on the stereographic projection (Figure 6B). In cases where not all of the lineation has evolved at the same rate, a half-girdle pattern would be present.

The monoclinic and triclinic models mark the transition from horizontal to vertical lineation in simple-shear-dominated transpression by different mechanisms, and they have different predictions for field measurements in natural transpressional zones. In monoclinic transpression, this mechanism is known as the “lineation switch”.

2.2 Stability test of monoclinic solutions

The monoclinic solution is unsupported by field evidence. If the lineation switch explanation were valid, one would expect to see either horizontal or vertical lineations in the field, but nothing in between. In cases where not all of the lineation has evolved at the same rate, both horizontal and vertical lineations would be present (two point maxima). One would also expect to see a zone of no lineation between the zones of horizontal lineation and vertical lineation where X=Y (pure flattening strain) and the finite strain ellipsoid is perfectly oblate (Figure 5, middle stage). The monoclinic model predicts that natural transpressional shear zones would contain horizontal lineations towards their outer boundaries, vertical lineations in their centers, and a zone of no lineation (X = Y) separating these. However, natural transpressional zones (Figure 6C) do not display such a pattern.

Flinn Diagrams plot the axial ratios of strain ellipsoid. The ellipsoid’s X/Y axial ratio is on vertical axis of plot and the Y/Z ratio is on horizontal axis. A perfect sphere would plot at the origin; a cylinder-like prolate form on the vertical axis; a circle-like oblate form on the horizontal axis. In Figure 7, the development of the strain ellipsoid in a monoclinic transpressional zone is shown. From the origin to the point where the trend touches the horizontal axis, the lineation is horizontal. At the point where the trend “bounces off” the horizontal axis, the strain ellipsoid’s X=Y, and a perfectly oblate ellipsoid is achieved. After that point, lineation is vertical.

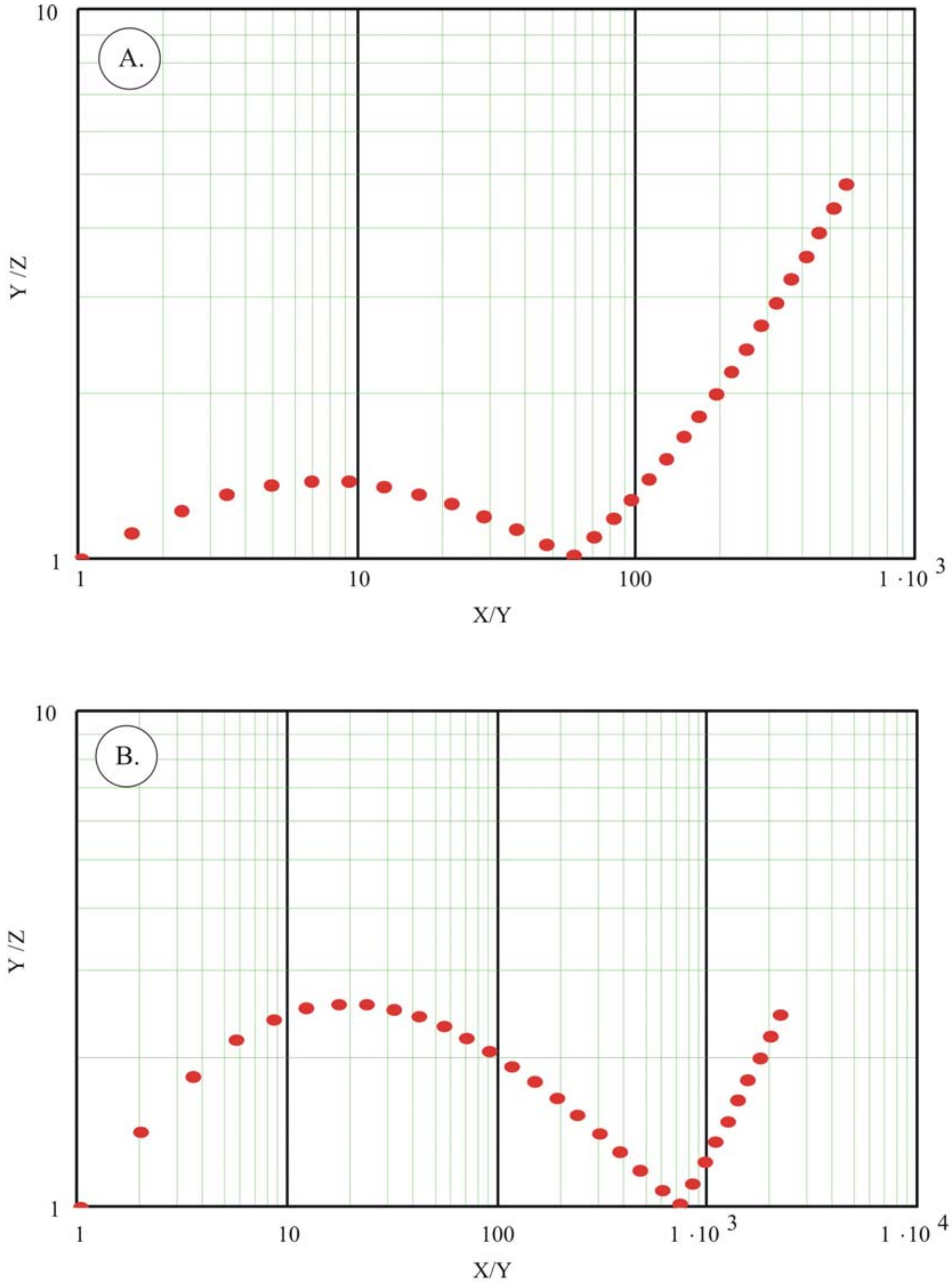


Figure 7: Flinn diagrams showing evolution of the strain ellipsoid for perfect monoclinic transpression (Φ = 0º). A) a simple shear / pure shear ratio of 5, B) a simple shear / pure shear ratio of 10. Strain ellipsoid X/Y axial ratio on vertical axis of plot; Y/Z ratio on horizontal axis of plot. For discussion, see text.

In contrast, Figure 8 illustrates the difference in mechanism for lineation's transition between horizontal and vertical in triclinic and monoclinic shear zones. In monoclinic transpression (8A), the lineation "switch" mechanism supplies the transition. In triclinic transpression (8B), the lineation evolves by rotating progressively from horizontal towards vertical.

Figure 9 shows the evolution of the finite strain ellipsoid for differing degrees of triclinicity. With increasing Φ, the transpressional zone becomes more and more triclinic. With any $\Phi \neq 0$, the trend does not "touch down" on the plot's horizontal axis, indicating that a perfectly oblate (X=Y) ellipsoid is never achieved.

The orientation of the ellipsoid's X-axis is plotted in Figure 10. For even slightly triclinic situations, a drastic difference in lineation is predicted. Instead of going through a "lineation switch" (e.g. Figure 8A), the X-axis progressively rotates from horizontal to vertical, following a J-shaped path. From its starting position, the long axis of the strain ellipsoid rotates first into parallelism with the strike of the shear zone boundary, then progressively downwards along the shear plane to a more vertical orientation (e.g. Figure 8B).

The predictions made by the two models allow us to address their validity. As Figures 9 and 10 show, the lineation switch mechanism's dependence on a perfectly monoclinic zone renders it theoretically unstable. Even a tiny deviation from perfect monoclinicity causes the strain ellipsoid to rotate gradually from the horizontal to the vertical rather than an instantaneous "switch" from horizontal to vertical.

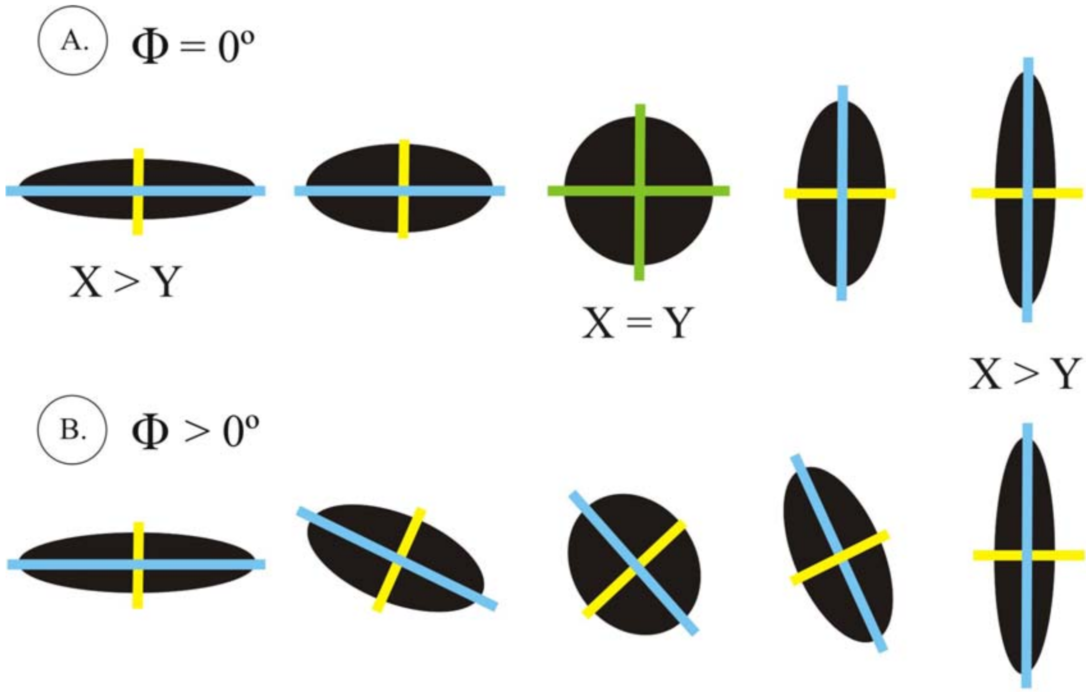


Figure 8: Difference in mechanisms for converting the initial horizontal long axis of the strain ellipsoid of simple-shear-dominated transpression to the final vertical long axis of the strain ellipsoid. X axes are denoted in blue. Y axes are denoted in yellow. Green signifies the instantaneous state when X =Y. A) Perfect monoclinic transpression invokes a switch between the vertical and horizontal axes. In the middle ellipse, X = Y. B) A slight triclinic component in the vector between the opposite sides of the shear zone results in a progressive rotation of the strain ellipsoid's long axis from horizontal to vertical; X never equals Y. See text for further discussion.

The triclinic model makes different predictions than the monoclinic model. In cases where not all of the lineation has evolved at the same rate, a full suite of lineation would be expected, ranging between horizontal and vertical, and including a spectrum of plunges in between (a half girdle).

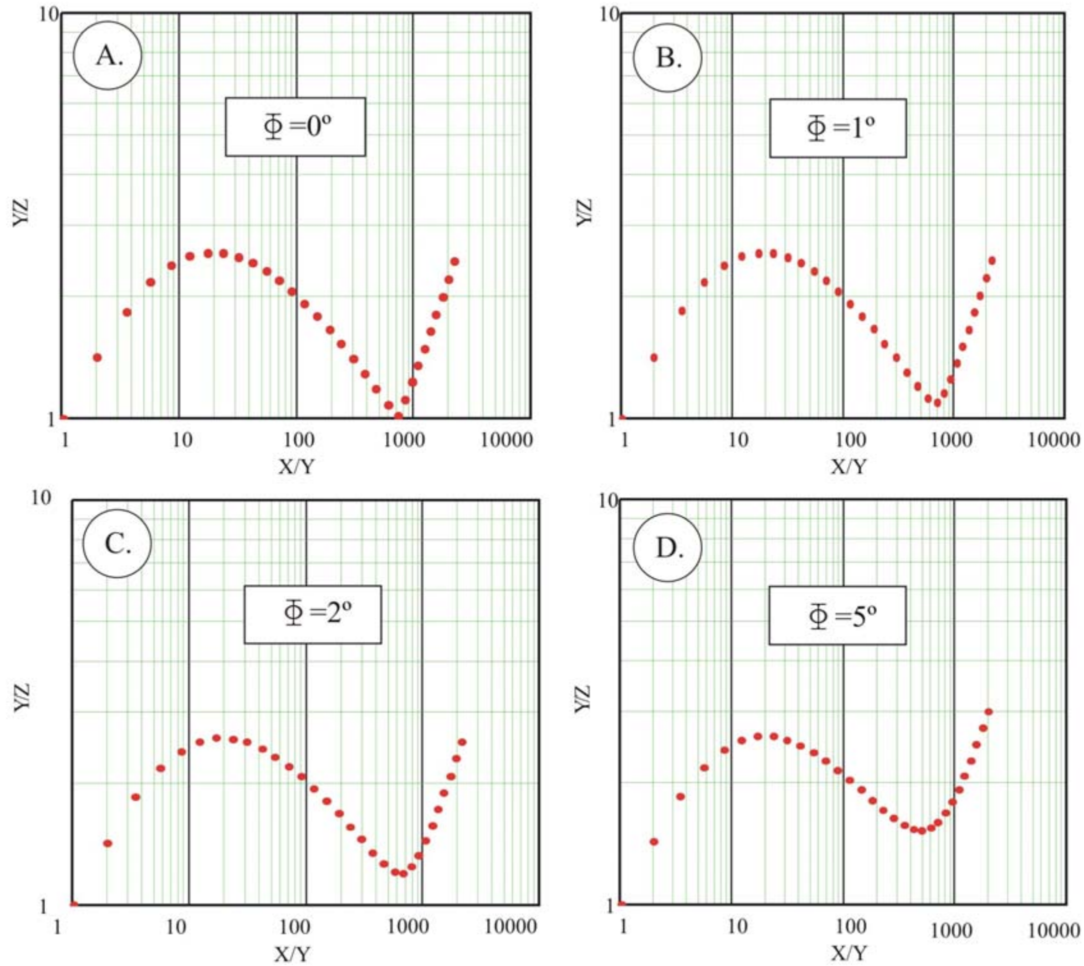


Figure 9: Stability test of monoclinic solutions. Flinn plots for simple / pure shear ratio of 10 and various degrees of deviation from perfectly monoclinic transpression. Strain ellipsoid X/Y axial ratio on vertical axis of plot; Y/Z ratio on horizontal axis of plot. Φ = angular deviation of transpression direction from the horizontal. A) Φ = 0º; B) Φ =1º; C) Φ =2º; D) Φ=5º. See text for discussion.

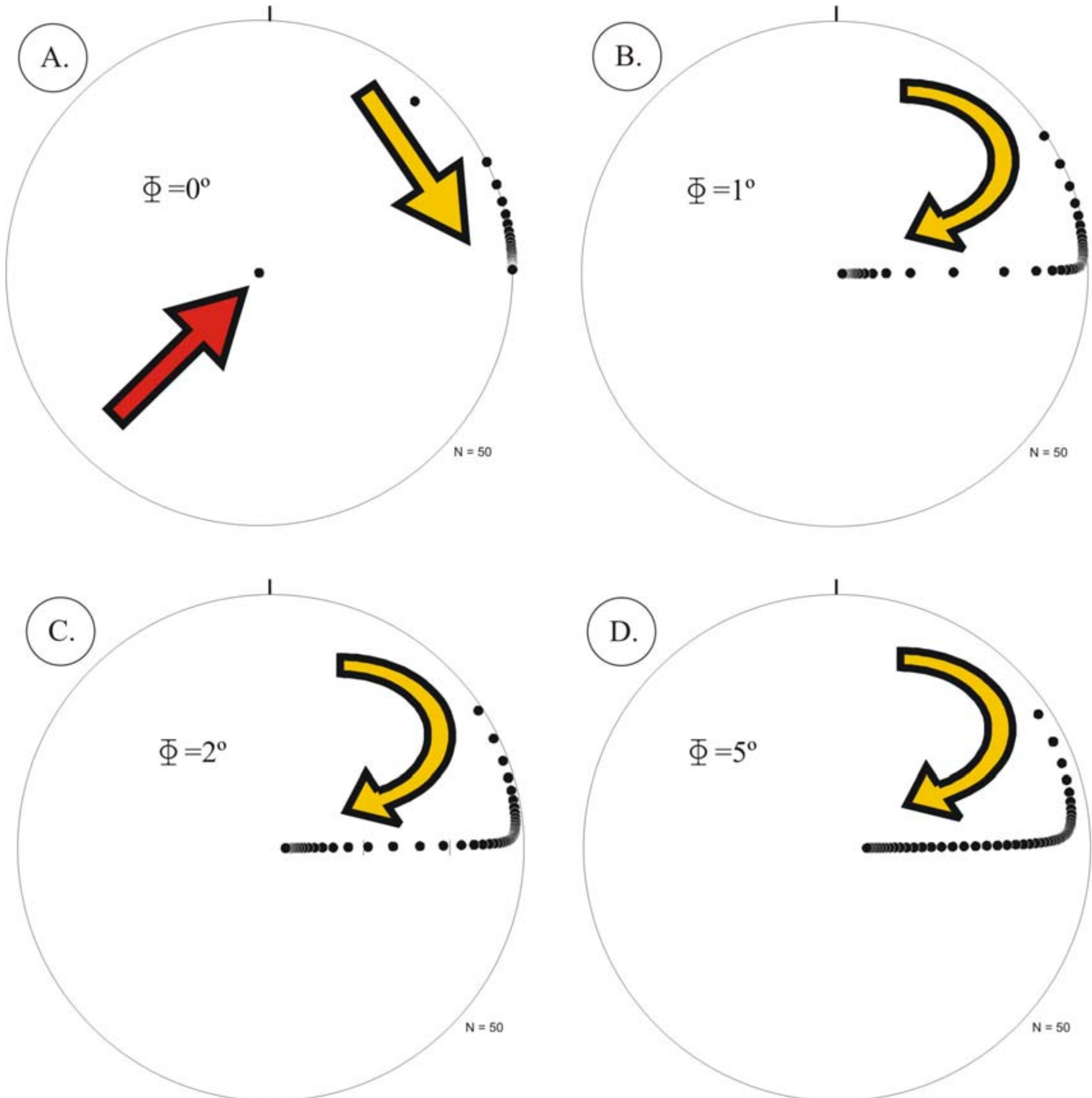


Figure 10: Orientation of the long axis of the strain ellipsoid with various degrees of deviation from perfectly monoclinic transpression. Equal-area stereonets. A) The perfectly monoclinic case, $\Phi = 0^{\circ}$. In perfectly monoclinic transpression, the long axis of the strain ellipsoid rotates into parallelism with the shear plane, but then (via a change in shape) switches the intermediate vertical Y axis with the long horizontal X axis of the strain ellipsoid as the intermediate axis grows at a faster rate and surpasses the horizontal axis to become the new X axis (vertical). No orientations exist between the horizontal and the vertical. In remaining three stereonets, the long axis of the strain ellipsoid progressively rotates first into parallelism with the shear zone, then downward along the shear plane to a more vertical orientation, with data intermediate between horizontal and vertical. B) $\Phi = 1^{\circ}$; C) $\Phi = 2^{\circ}$; D) $\Phi = 5^{\circ}$. See text for further discussion.

2.3 Widening model zones and observations in natural transpressional zones

As shown above and in Figure 6B, lineations from domains with high simple / pure shear ratios plot nearest the edge of the stereonet, and those with lower simple / pure ratios shear plot closer to the center of the stereonet. However, as Figure 6C illustrates, the strain geometries of natural transpressional zones are not restricted to point maxima and half-circle girdles. While some do display these strain geometries, other field examples display a full girdle and are still unexplained, as Czeck and Hudleston (2003) pointed out (Figure 6C, center).

An attempt to address these different regional strain geometries is underway. Recent work by Jiang (in review) has extended modeling to include inclined shear zones that maintain constant width over time by widening into the surrounding wall-rock to compensate for the zone-normal flattening. Figure 11 shows this model both conceptually (top left) and in terms of its predictions of strain geometry (right). With varying values of α and β, four lineation patterns are predicted. In domain I, lineations are grouped in a point maximum close to the simple shear direction. In domain II, lineations are grouped in a great circle girdle pattern. In domain III, strain data is transitional between point maxima and a girdle. In domain IV, lineations define a point maximum close to the dip line of the shear zone. Note that domain IV is simply the pattern of domain I rotated 90º. The model potentially offers the ability to predict the full range of strain patterns: girdles, half-girdles, and point maxima.

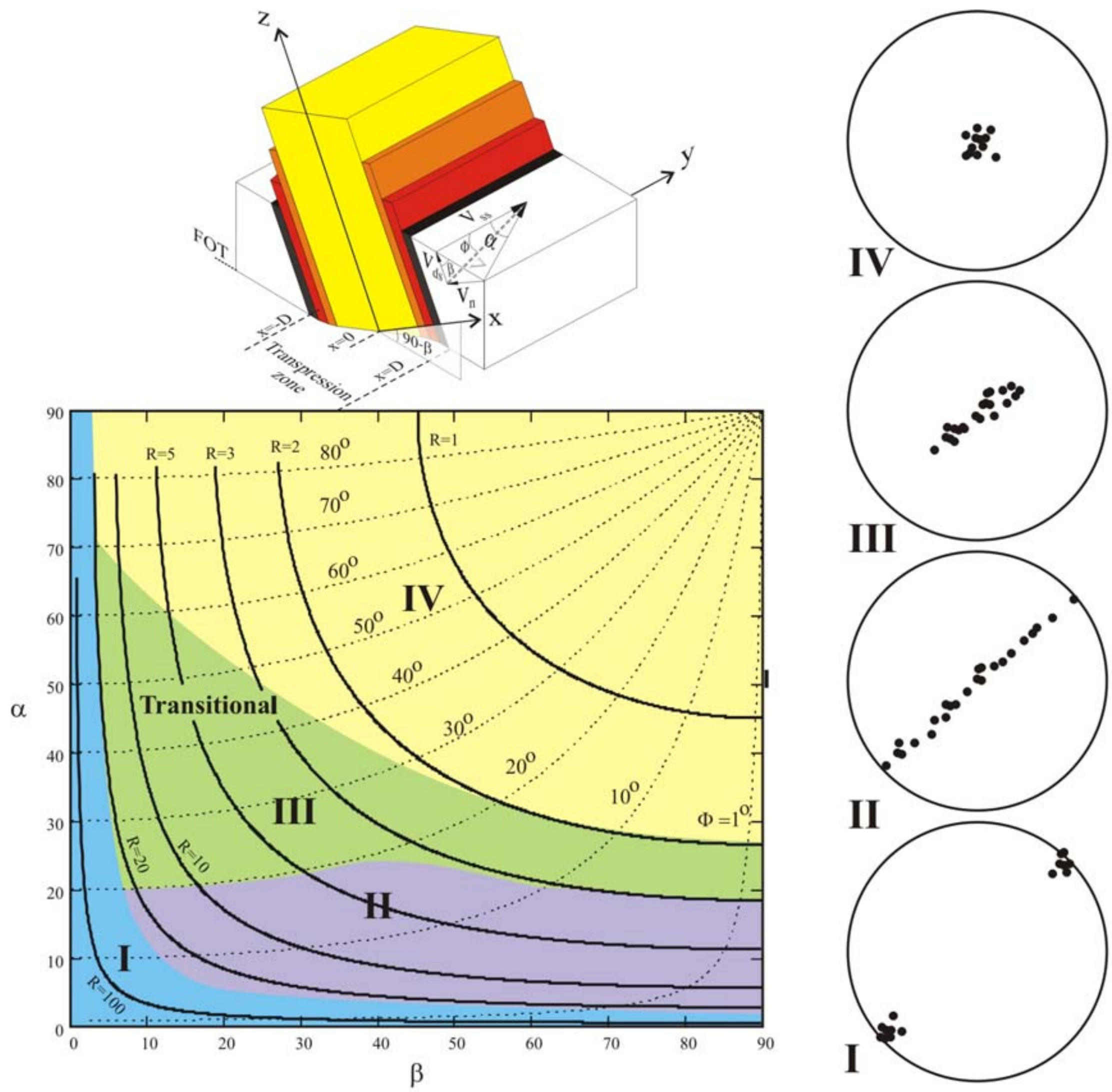


Figure 11: Lineation patterns expected for different values of α (angle of convergence) and β (dip of the shear zone). Left top: reference shear zone. V is overall velocity of the shear-zone-bounding block on the right, and may be broken down into three components: V_n is boundary-normal velocity, V_{ss} is the strike-slip velocity, and V_{ds} is dip-slip velocity. α is the angle between V_{ss} and V on the horizontal surface. β is the angle between V_{ds} and the horizontal. a is the angle between V_{ss} and V_{ds}. FOT is "floor of transpression," horizontal plane below which material moves downward, and above which material moves upward. D is the half-width of the shear zone. Left bottom: Solid lines are isopleths of the simple shear to pure shear ratio. Dotted lines are isopleths of the pitch of the shear direction (ϕ). R is the ratio of simple shear to pure shear. Right: Four lineation pattern domains are designated on the right, plotted for a hypothetical shear zone that strikes 045º. Domain I; lineations are grouped in a point maximum close to the shear direction. Domain II; lineations are grouped in a great circle girdle pattern. Domain III, transitional between point maxima and a girdle. Domain IV: lineations define a point maximum close to the dip line of the shear zone. Note that pattern IV is simply Pattern I rotated 90º.

Chapter 3: Background of the Sierra Crest shear zone system

3.1 California and the Sierra Nevada: general background

3.1.1 Geologic history of the west coast: convergent margin to transform boundary

The western margin of the North American Plate has long been dominated by transpressional tectonics, with profound geological consequences. The geologic story of the Sierra Nevada mountain range is intrinsically linked to the rest of the area, and may be viewed broadly as the story of the western margin of the North American continent. The Sierra Nevada is one of the most physiographically distinct features of the North American continent (Figure 12). The entire Sierra Nevada block is sometimes regarded as a microplate (e.g. Gordon and Argus, 1993), recognizing its status as a large and discrete block encompassing the Sierra Nevada mountain range and its extension as the basement bedrock of the Great Central Valley far to the west of the mountains themselves. The Sierra Nevada microplate is bounded on the west by the San Andreas Fault system, the Coast Ranges and Pacific plate. On the east, it is defined by the normal-faulted eastern escarpment dropping steeply to the Owens Valley and the Long Valley; the westernmost extent of the Basin and Range province. Topography only tells half the story here: The Sierras are the tallest range of mountains in the lower 48 United States, and the block / microplate extends to a correspondingly impressive depth at 6 to 10 km under the surface of the Great Central Valley to the west (Page, 1986).

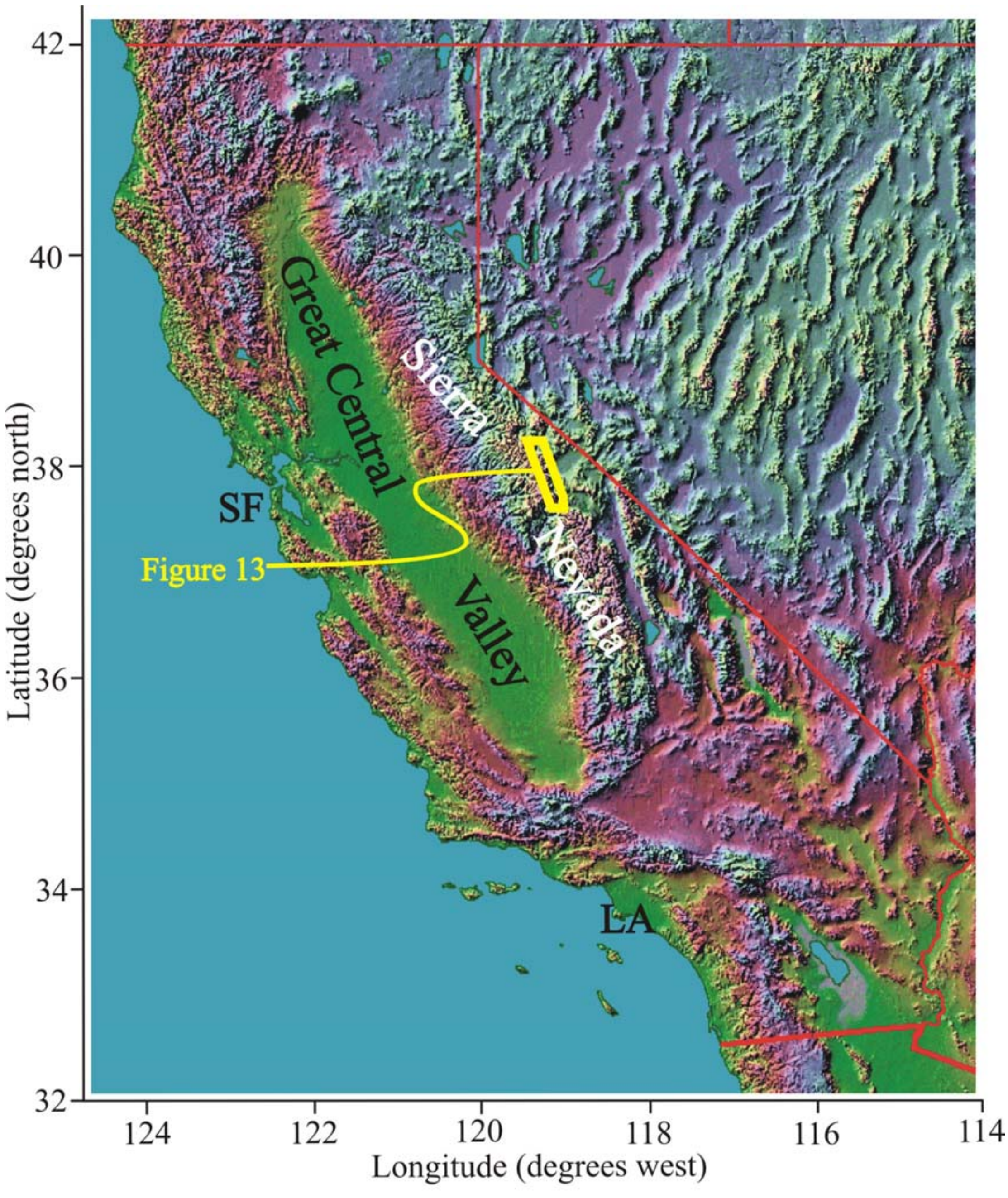


Figure 12: Physiographic map of California. The Sierra Nevada block / microplate is a physiographically distinct NW-SE trending feature in the center of the image: the mountain range in the east, and the filled basin of the Great Central Valley (underlain by the block / microplate) to the west. SF = San Francisco. LA = Los Angeles. Area of Figure 13 indicated in yellow. Modified from Ray Sterner, Johns Hopkins University Applied Physics Laboratory, 1995, http://www.wcei.org/california/jh-ca-radar.html

On the whole, the Sierra Nevada block is a granitic batholith (Bateman, 1992), but portions of the northern range consist of accreted terranes and intercalated serpentinite and ophiolite sequences (Schweickert, 1981; Saleeby, 1981). In addition, there are a few small remnants of the metamorphic rocks that were underlain by the now-uplifted granite plutons. Where they survive, these metamorphic suites have bedding, cleavage, and fold axes generally trending N30ºW to N35˚W (Bateman, 1992).

The seismic Moho is at a maximum depth of 52 km beneath the Eastern Sierra crest, and slopes upwards to the west (Bateman, 1981).

Of the many continental margins known in the world today, four main "types" may be distinguished (Dickinson, 1981). The western margin of the North American continent has experienced all of them in the past 600 Ma. In chronological order, they are: rifted Atlantic-type margin (Precambrian to early Paleozoic), transpressional Japan-type margin characterized by off-shore island arcs (Devonian to Triassic), obliquely-convergent Andean-type margin with a trench just off-shore (Triassic to mid-Tertiary), and finally the strike-slip dominated transpressional regime that is termed California-type and has typified the region from the mid-Tertiary (late Miocene/early Pliocene) until today (Dickinson, 1981). The deformation examined in this thesis occurred during the Andean-type period (though it was not orthogonal). Perhaps a modern analogue better representing oblique convergence in the Mesozoic Sierra Nevada may be found in the Sunda arc (west of Sumatra and the Malay Peninsula). There, transpressive subduction is producing many similar features, albeit at a much quicker rate (Saleeby, 1981).

The convergent tectonic regime was initiated during the late Paleozoic Antler Orogeny, after the breakup of Pangea. During the Mesozoic there was extensive volcanism and numerous terranes were emplaced along the west coast of North America. The Klamath Mountains of northwestern California and the northern Sierra Nevada together comprise one such terrane (Schweickert and Snyder, 1981).

Uplift of the Sierra Nevada microplate began 130 Ma. A large mountain range resembling the modern Andes (the “proto-Sierra”) was raised and eroded, while at its roots, granitic plutons were being emplaced that would provide the material for the modern Sierra Nevada.

The transition from oblique subduction of the Mesozoic to the transpressive strike-slip of the Cenozoic occurred with the subduction of the spreading ridge between the Farallon Plate and the Pacific Plate. Once one corner of the spreading center was consumed, two tectonic triple-points were established. These propagated to the north and south; between them lay a strike-slip boundary. North of the Mendocino triple point are the Gorda and Juan de Fuca plates. They are remnants of the former Farallon that remain in subduction beneath northern California, Oregon, and Washington. Likewise, south of the Rivera triple point, the Cocos Plate persists as a Farallon fragment continuing in subduction beneath Mexico (Dickinson, 1981). In the zone where the North American Plate and the Pacific Plate are now in contact, the lack of an active spreading center has diminished the convergent aspect of the margin, and increased the relative importance of the transform component of inter-plate motion: hence, a dextral strike-slip boundary was established and maintained.

3.1.2 Plutonism and the emplacement of the Sierra Nevada batholith

The Sierra Nevada Batholith is a composite body comprising hundreds of individual plutons. Exposed at the surface are approximately 25,000 mi^2 of granitoid rocks (Norris and Webb, 1990). All plutons are Mesozoic in age (Bateman, 1992). In general, from the west to the east the plutons become younger, spanning 50 Ma (Saleeby, 1981), more felsic (Philip Piccoli, University of Maryland, personal communication) and more shallowly emplaced (Ague and Brimhall, 1988). For unknown reasons, there were two distinct episodes of emplacement: one at 180-150 Ma, and a second at 120-80 Ma (Ducea, 2001; Schweickert and Snyder, 1981). It was during this second episode of pluton emplacement that the Sierra Crest shear zone was active. This early Jurassic to late Cretaceous time-frame saw a near-constant stream of volcano-plutonic arc activity as the Farallon Plate was obliquely subducted under the North American Plate (Saleeby, 1981). Hornblende geobarometry data indicate granitoid emplacement at 1.2-2.4 kbar, corresponding to 4.5-9.0 km depth, at temperatures of 665º-730º C (Ague, 1997; Ague and Brimhall, 1998).

3.1.3 Cenozoic modifications

Renewed uplift at 10 Ma was coincident with extension in the central Basin and Range, which initiated at ~16 to 14 Ma (Sonder and Jones, 1999). It is at this time that the West Coast switched tectonic regimes from oblique subduction to transform, giving rise to the San Andreas Fault. The subduction of the Farallon Plate beneath North America ended with the consumption of the spreading ridge between the Farallon Plate and the Pacific Plate, and the switch to a transcurrent regime. The total scale of the uplift is obscured by sedimentary infill to the east of the Sierras in the Long/Owens Valley basin.

At ~3.5 Ma, uplift of the Basin and Range province propagated extension to the west, resulting in staggered parallel normal faulting along the Eastern side of the range. While the mountains rise 2,745 to 3,355 m above the valley floor, the corresponding graben-block is a further 3,050 m below, implying a total displacement of ~6.4 km (Norris and Webb, 1990).

Glaciation facilitated the removal of rock in the Sierra Nevada, possibly contributing via orographic isostacy to further uplift. There have been three major periods of glaciation in the Sierra in the last 10,000 years. The landscape of the high Sierra bears the glacial signature of U-shaped valleys, cirques, horns, tarns, and glacial striations (Huber, 1987).

3.2 Lithology of roof pendants and wall rocks

The bedrock of the Sierra Nevada range consists dominantly of the granitoid plutons that comprise the Sierra Nevada batholith. However, the metasedimentary and metavolcanic rocks into which those plutons intruded are preserved in several places in the central Sierra, especially along the eastern margins of the batholith. Where these rocks occur with no further plutons east of them, they are referred to as wall rocks. Where they exist with plutons both east and west of them, they are referred to as roof pendants. Even though true roof pendants, which are downward projections of country rock into an igneous intrusion, may be rare since the batholith is not a single intrusion (Bateman 1992; Saleeby, 1981). Metavolcanic and metasedimentary host rocks in the study area are described in the literature as being part of the Ritter Range roof pendant and the Saddlebag Lake roof pendant.

These rocks lie along the eastern boundary to the batholith proper, with the exception of some isolated plutons. In the central Sierra, on either side of the contact, the rocks are highly sheared. Several names have been applied to these sheared rocks in the literature (Greene and Schweickert, 1995; Tikoff and Greene, 1997; Tikoff and Saint Blanquat, 1997). Described in greater detail in Section 3.4, these zones of sheared rocks have been described in the literature as the ‘Sierra Crest shear zone system’ (Greene and Schweickert, 1995; Tikoff and Greene, 1997).

The Sierra Crest shear zone system is the field area surveyed in this study (Figure 13). For the purposes of examining along-strike variation, three areas along the shear zone were studied as samples of the entire shear zone system. The three specific areas of field mapping will be referred to as the Gem Lake segment (southernmost), the Mono Pass segment (central), and the Cascade Lake segment (northernmost).

The metasedimentary and metavolcanic rocks vary across the shear zone in a parallel fashion. The metavolcanic and metasedimentary sequences found in each segment are thick, and all three segments are bounded on the west by mid-Cretaceous granodioritic plutons (from south to north, the Rush Creek, the Kuna Crest, and the Half Dome and the Cathedral Peak granodiorites).

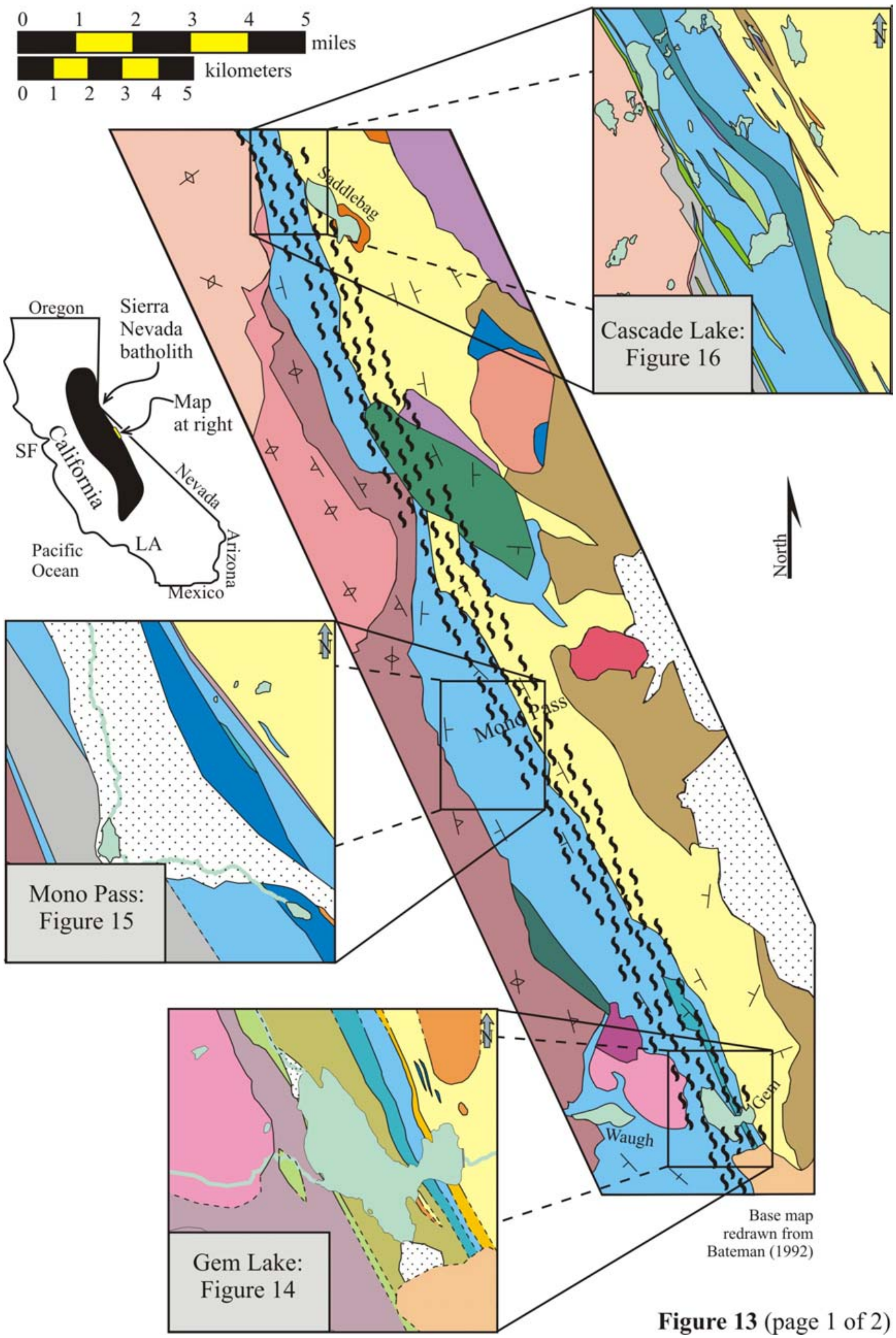


Figure 13 (page 1 of 2)

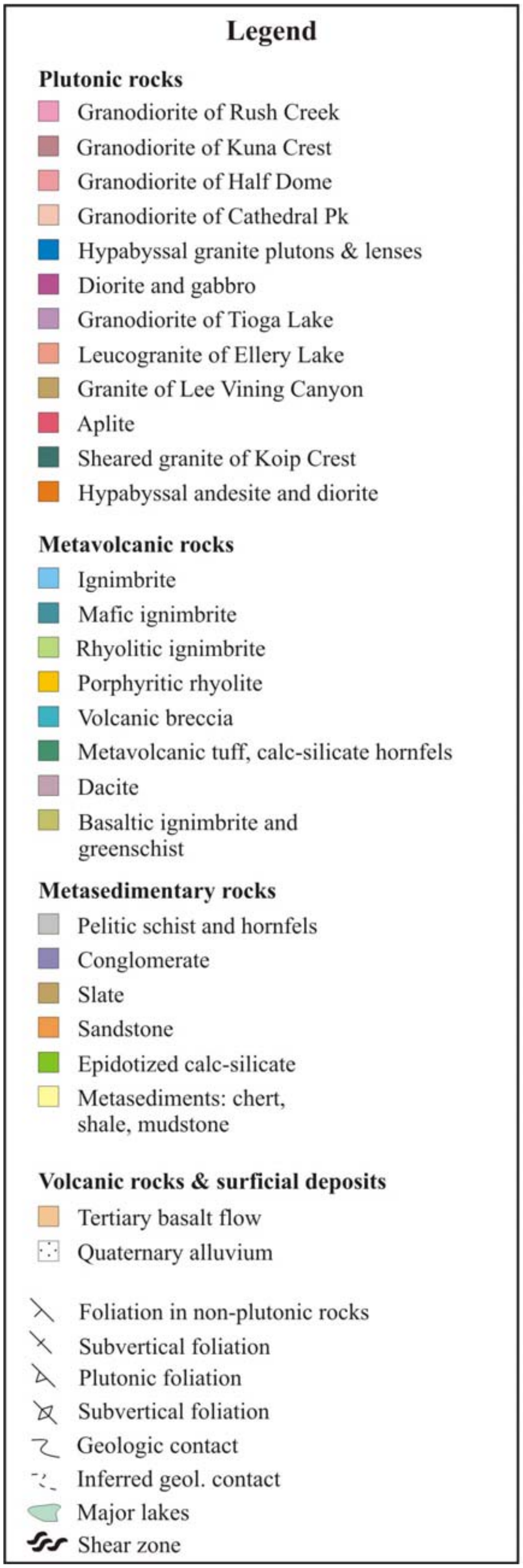


Figure 13 (page 2 of 2): Regional map of the Sierra Crest shear zone system and surrounding rocks. Insets denote positions of Figures 14, 15, and 16. Base map redrawn from Bateman (1992).

3.2.1 Lewis sequence

In the study area (Figure 13), the shear zone is bounded in the east by a metamorphosed sedimentary sequence of chert, shale, carbonates, and sandstone. Kistler (1966) interpreted this sequence as Paleozoic (Mississippian to Permian) and referred to it as the Lewis sequence. Primary sedimentary structures such as graded bedding are locally recognizable. The “up” (or “younging”) direction is predominantly to the west, though locally it is to the east, as on eastward-dipping fold limbs. In the Gem Lake and Mono Pass segments of the shear zone, several lenses or lenticular pods of granite are present in this domain also (blue lenses in Figures 14 and 15).

In the eastern portion of the Mono Pass segment (Figure 15) is a thick package of metasedimentary rocks, mainly comprised of cherts and siltstones, with epidotized nodules, again interpreted as being the Paleozoic (Mississippian to Permian) Lewis sequence by Kistler (1966). Brook et al. (1979) found crinoid, brachiopod, and pelecypod fossils in cherts of the Saddlebag Lake pendant which they interpreted as Mississippian in age.

In the eastern portion of the Cascade Lake segment (Figure 16), shales and mudstones dominate the metasedimentary sequence. Some conglomerates are present as well, including at least one complete turbidite sequence (Figure 17). In the area adjacent to Hummingbird Lake, virtually undeformed metasediments may be found, with primary sedimentary structures such as ripple marks, mud cracks, and flame structures observable (Figure 18). The sedimentary “younging” direction is to the west. As in the more southerly segments, the sediments become completely

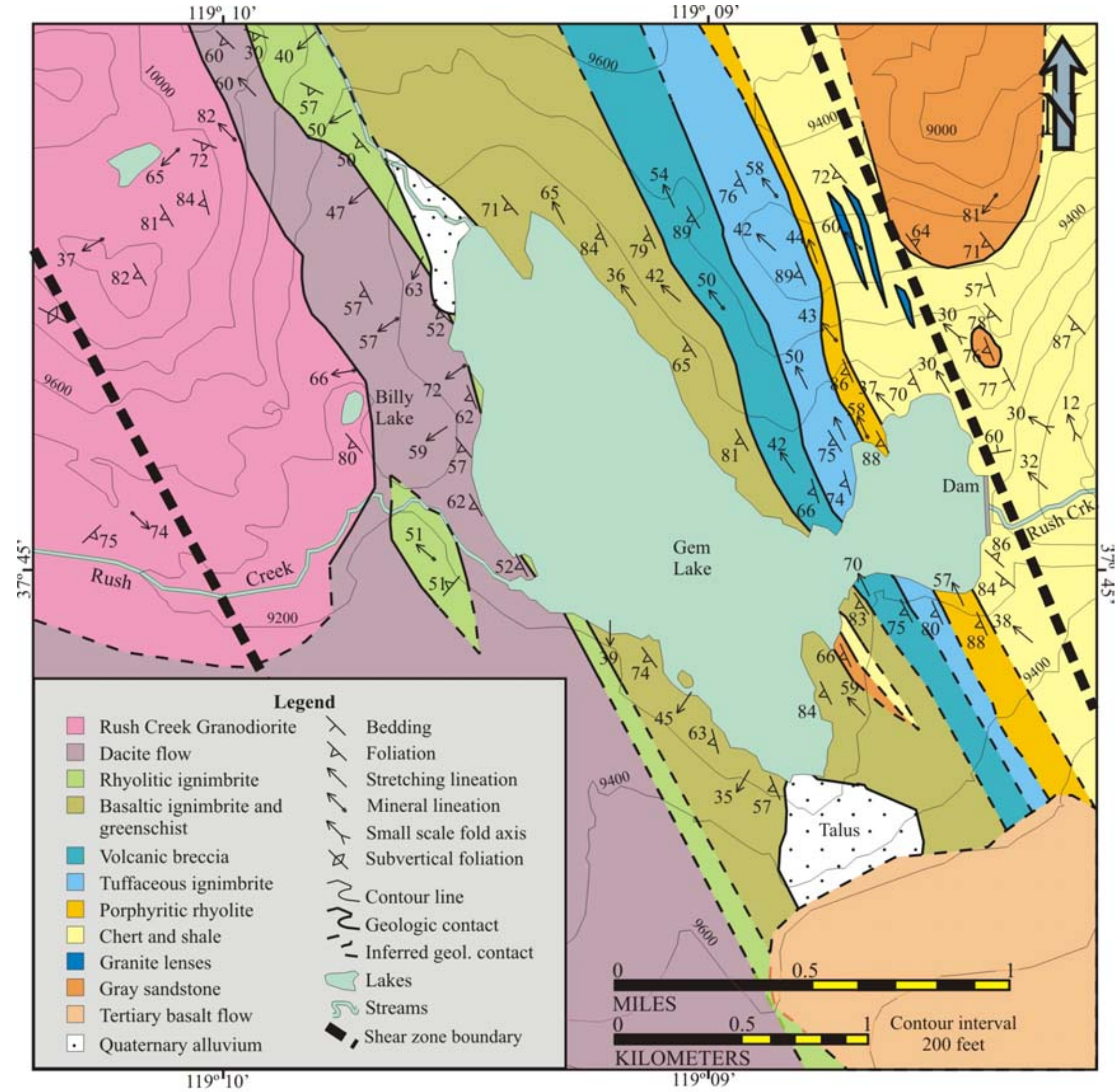


Figure 14: Geologic map of the Gem Lake segment of the Sierra Crest shear zone system.

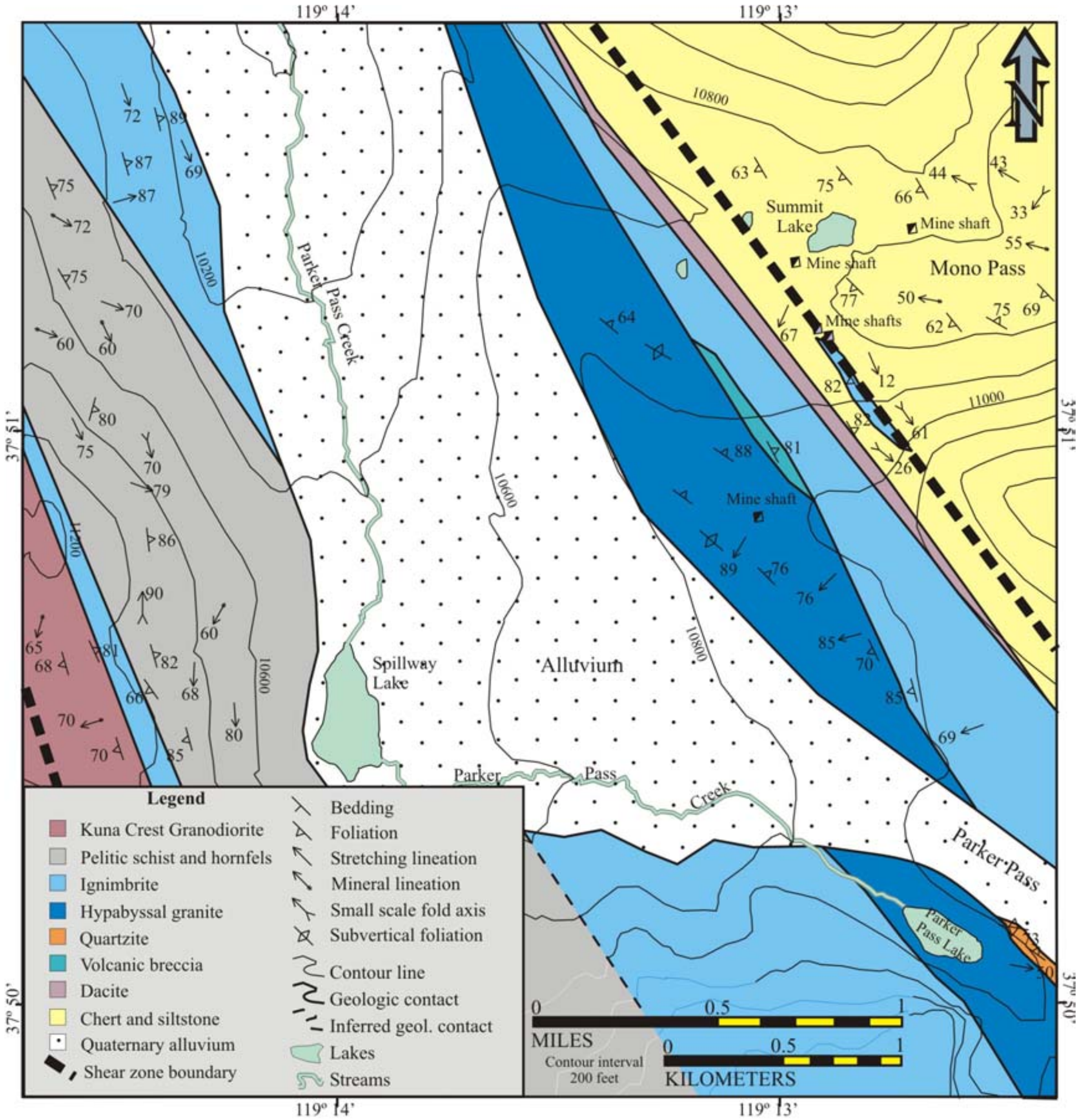


Figure 15: Geologic map of the Mono Pass segment of the Sierra Crest shear zone system.

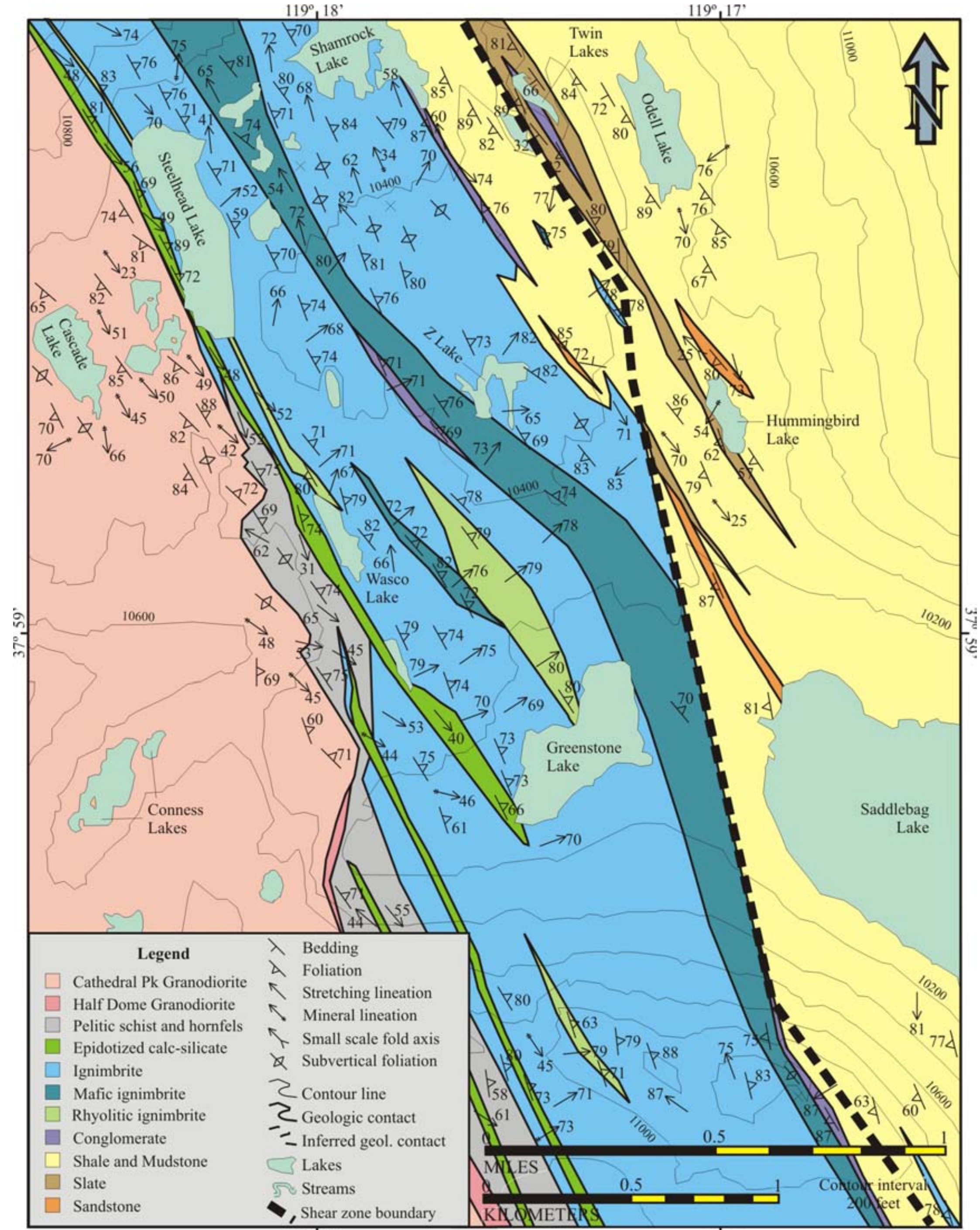


Figure 16: Geologic map of the Cascade Lake segment of the Sierra Crest shear zone system.

Figure 17: Graded bedding in a lens of conglomerate, Cascade Lake segment of the Sierra Crest shear zone system, representing a possible turbidite sequence. A) The entire sequence. Outcrop face strikes 064° and dips 84°, towards the camera. Brunton compass for scale. View is towards 235°. B) Pebbles pressed into the mud at the bottom of the sequence. Outcrop face as in (A). Pencil for scale. Same view as (A).

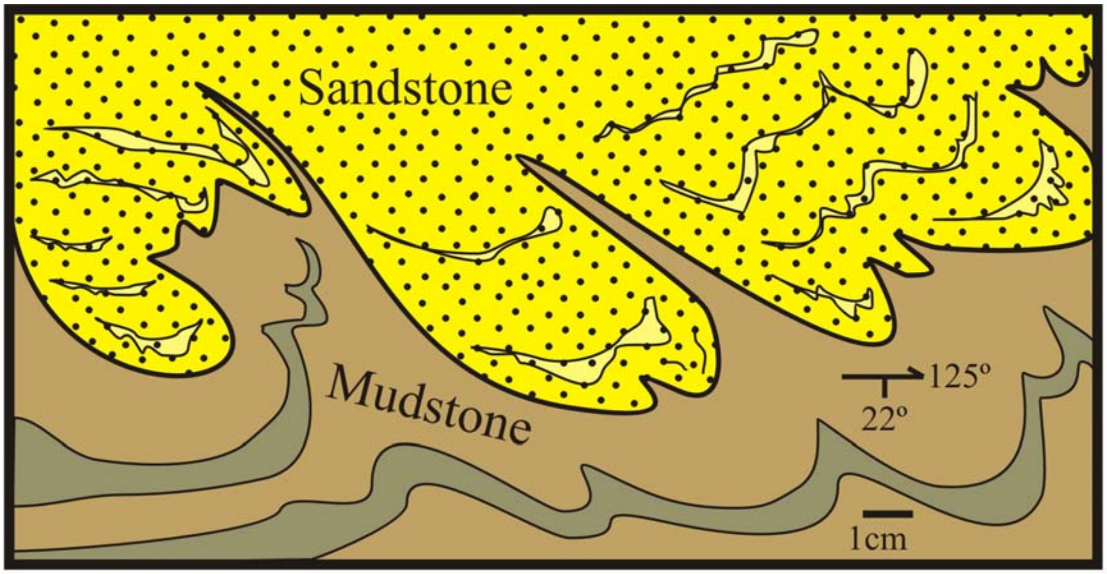


Figure 18: Primary sedimentary structures exist in the metasedimentary rocks of the easterly edge of the Cascade Lake segment of the shear zone. The preservation of mud cracks, ripple marks with a wavelength of 2-5 cm, and these flame structures indicate the relatively undeformed state of these rocks. Finer lines indicate finer lamina within the mudstone and sandstone units. Outcrop surface strikes 122º and dips 22º to the southeast. Sketch drawn looking towards ~020º.

transposed in the shear zone proper (between the two dotted lines in Figures 14, 15, and 16), obliterating all primary structures and bedding, except for isolated less deformed pods. Small (meter-scale) lenses of metavolcanic rocks are included within the sedimentary package, fully transposed, and vice versa: lenses of metasedimentary rocks are included within the ignimbrite metavolcanics that make up the bulk of the shear zone at this segment. Within the thick metavolcanic sequence, there are long lenses of greenish calc-silicate, epidotized and with extensional fractures filled with hydrothermal quartz, tourmaline, and mafic minerals. There are also a few thin lenses of conglomerate, with highly strained pebbles (Figure 19).

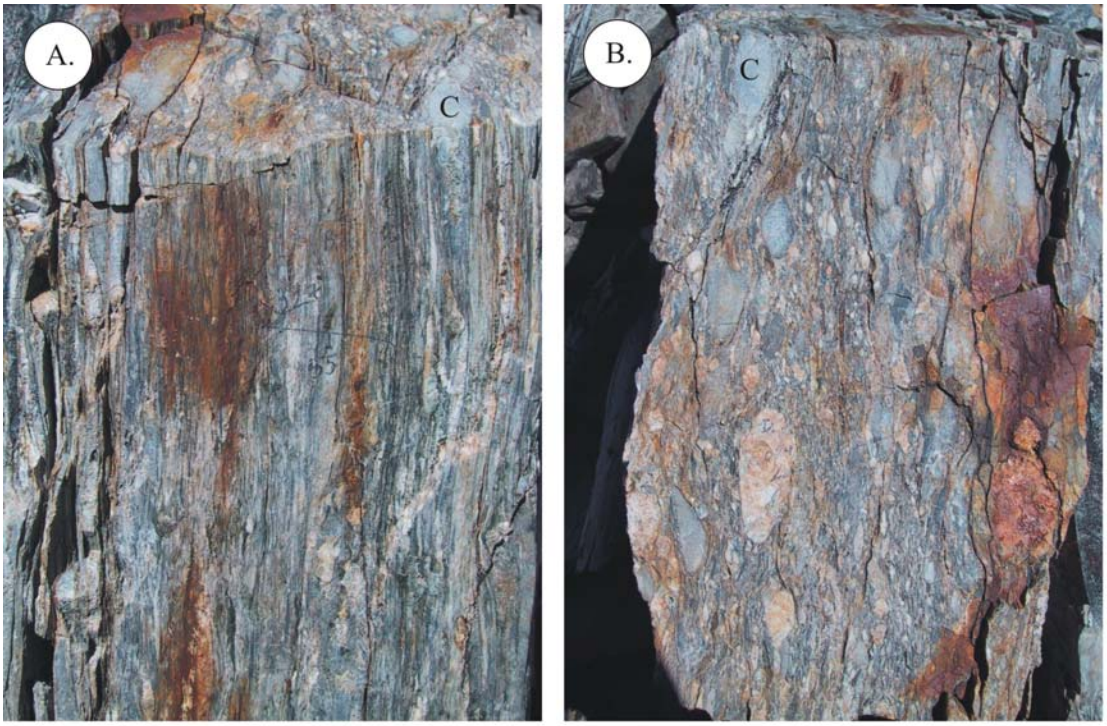


Figure 19: Conglomerates from the southeastern shore of Shamrock Lake, Cascade Lake segment of the Sierra Crest shear zone. The two sections are oriented almost at right angles to each other along the crisp edge at the top of both photographs. Stretched pebbles record lineation that was almost downdip: it plunged 75º towards 168º, on a foliation plane that struck 146º and dipped 88º. A) Outcrop surface strikes 227º and dips 55º. B) Outcrop surface strikes 024º and dips 12º (quasi-horizontal). Long axis of clast marked "C" measures approximately 3 cm on Surface (B).

3.2.2 Koip sequence

The Koip sequence is a metasedimentary and metavolcanic sequence consisting of a basal conglomerate, thin rhyodacite tuff, a thick rhyodacite tuff, hypabyssal andesitic intrusions and mafic tuffs, and an upper unit of metamorphosed volcaniclastic rocks (ignimbrites), ash-flow tuffs, and minor calc-silicate hornfels (Brook, 1977; Russell and Nokleberg, 1977). The upper unit makes up the bulk of the Gem Lake and Mono Pass segments of the shear zone as surveyed in this study. The ash-flow tuff was dated by Brook (1977) with the Rb-Sr isochron technique to be 250 Ma, which is Late Permian or Early Triassic. However, later dating by Schweikert et al. (1994) using the U-Pb geochronometer found a date of 201 Ma for the rhyolitic ignimbrite unit in the upper part of the sequence (western Gem Lake).

In the Gem Lake segment, the metasedimentary rocks of the Lewis sequence give way to the metavolcanic rocks of the Koip sequence approximately 0.3 km inside the shear zone's east boundary. From the east to the west, the Koip sequence in the Gem Lake area consists of a thin porphyritic rhyolite, a tuffaceous ignimbrite, with mafic clasts which show readily discernible foliation and stretching lineation (Figure 20), and a series of clast-rich metavolcanics, with felsic, mafic, and lithic clasts ranging in size from cm to dm. In one unit, in the center of the surveyed segment, the cobble-sized lithic clasts comprise ~50% of the rock's volume (Figure 21). Immediately west of the clast-rich metavolcanics is a unit of thinly-laminated ignimbrite, where kink bands were observed. Andesite flows make up the majority of the shear zone to the west, and are truncated by the western edge of Gem Lake with rhyolitic metavolcanics and a massive dacite flow that bears amygdules (Figure 22).

In the Mono Pass segment, the Koip sequence's easternmost presence is seen in basaltic and andesitic dikes that cut across metasedimentary strata in some locations (Figure 23 A). Isolated pods of ignimbrite appear transposed with these metasediments, as does a lenticular pod of dacite. Further west the ignimbrite is the dominant lithology, as it is in the Gem Lake segment. To the west, a volcanic breccia which resembles a pod of the larger volcanic breccia in the Gem Lake segment marks the transition to the next lithologic unit, hypabyssal granite (Figure 23 B).

Figure 20: Typical examples of rock fabric in the ignimbrite unit at Gem Lake. A) Y-Z plane (perpendicular to foliation and lineation). Quarter for scale. B) The X-Y plane (parallel to both foliation and lineation). Marker for scale.

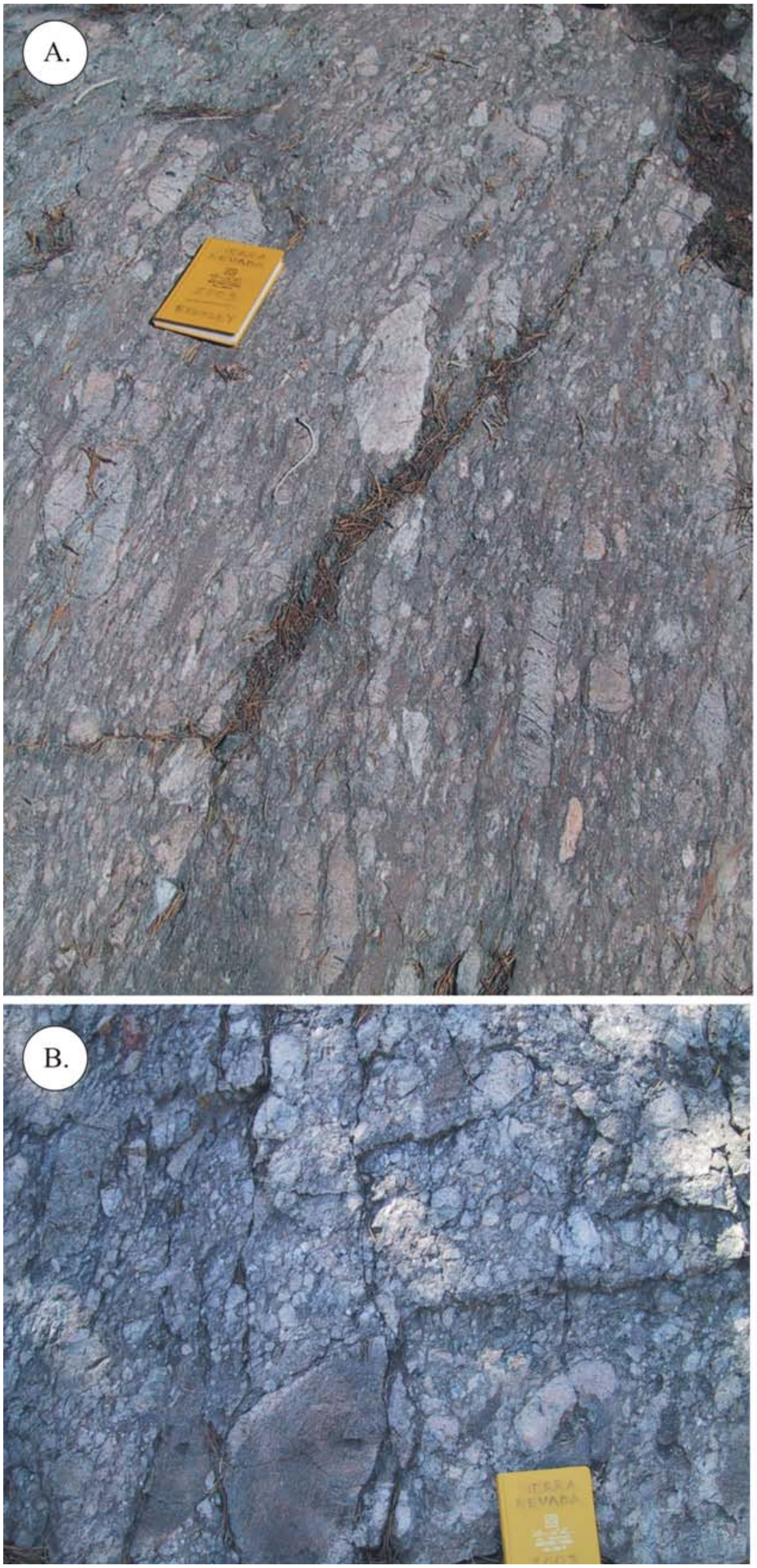


Figure 21: Clast-rich volcanic breccia, Gem Lake segment of the Sierra Crest shear zone.
A) Section is approximately parallel to both foliation and lineation. Outcrop face strikes 240° and dips ~45°. Lineation at this outcrop dips 46° towards 322°. Field notebook for scale; long axis of book is 19 cm. View is towards 250°.
B) Section is approximately perpendicular to both foliation and lineation. Outcrop face strikes 060° and dips ~45°. Field notebook for scale; long axis of book is 19 cm. View is towards 330°.

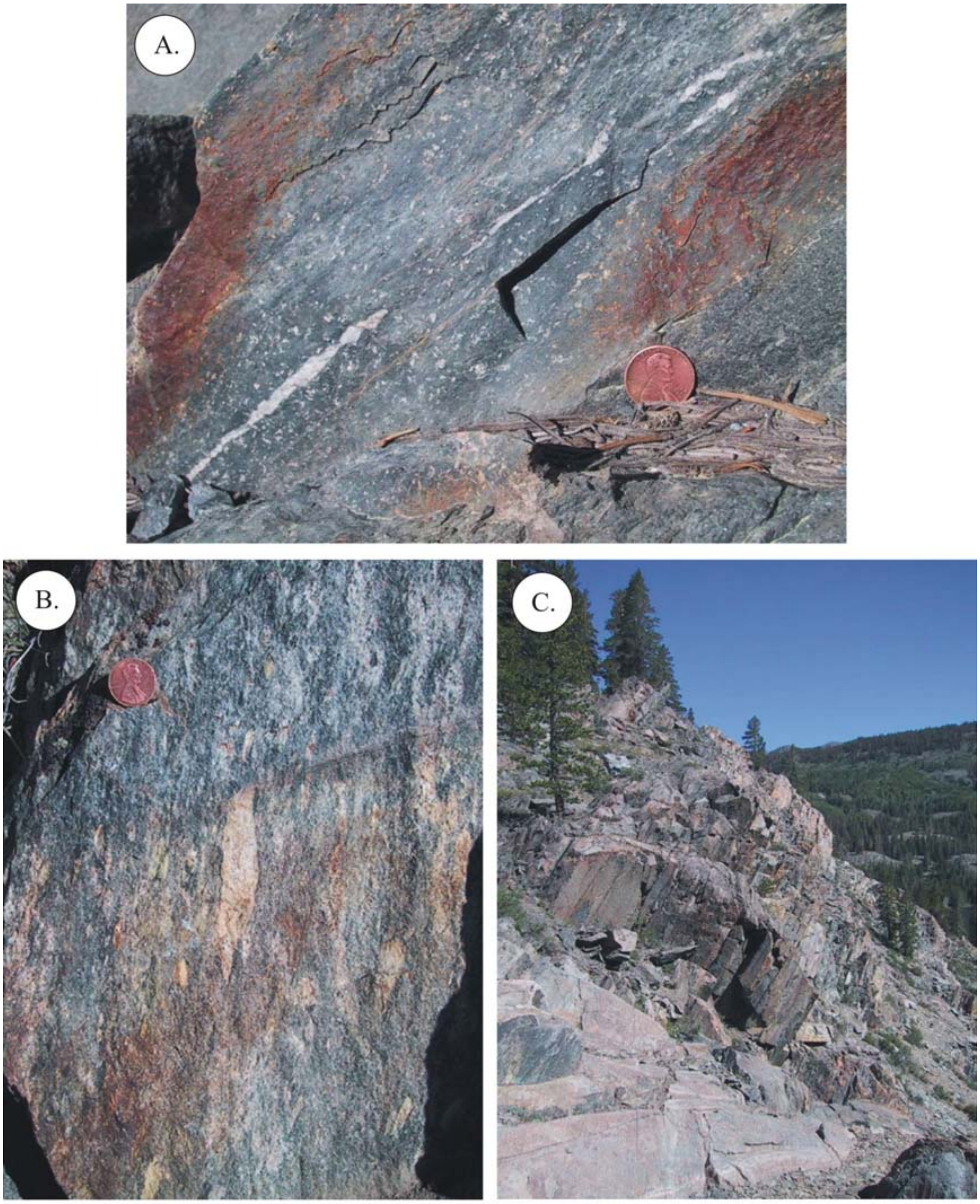


Figure 22: Lithologic units of western Gem Lake segment. A) Amygdular dacite flow. White amygdules (infilled vesicles) define fabric. Penny for scale. B) Dacitic ignimbrite with stretched felsic clasts. Outcrop is perpendicular to foliation. View is towards ~340°. Penny for scale. C) Felsic lens which approximately parallels the western shore of Gem Lake. View is towards ~north along strike. Foliation dipping steeply west, downdip lineation at this location. Trees (~6 m tall) provide a sense of scale.

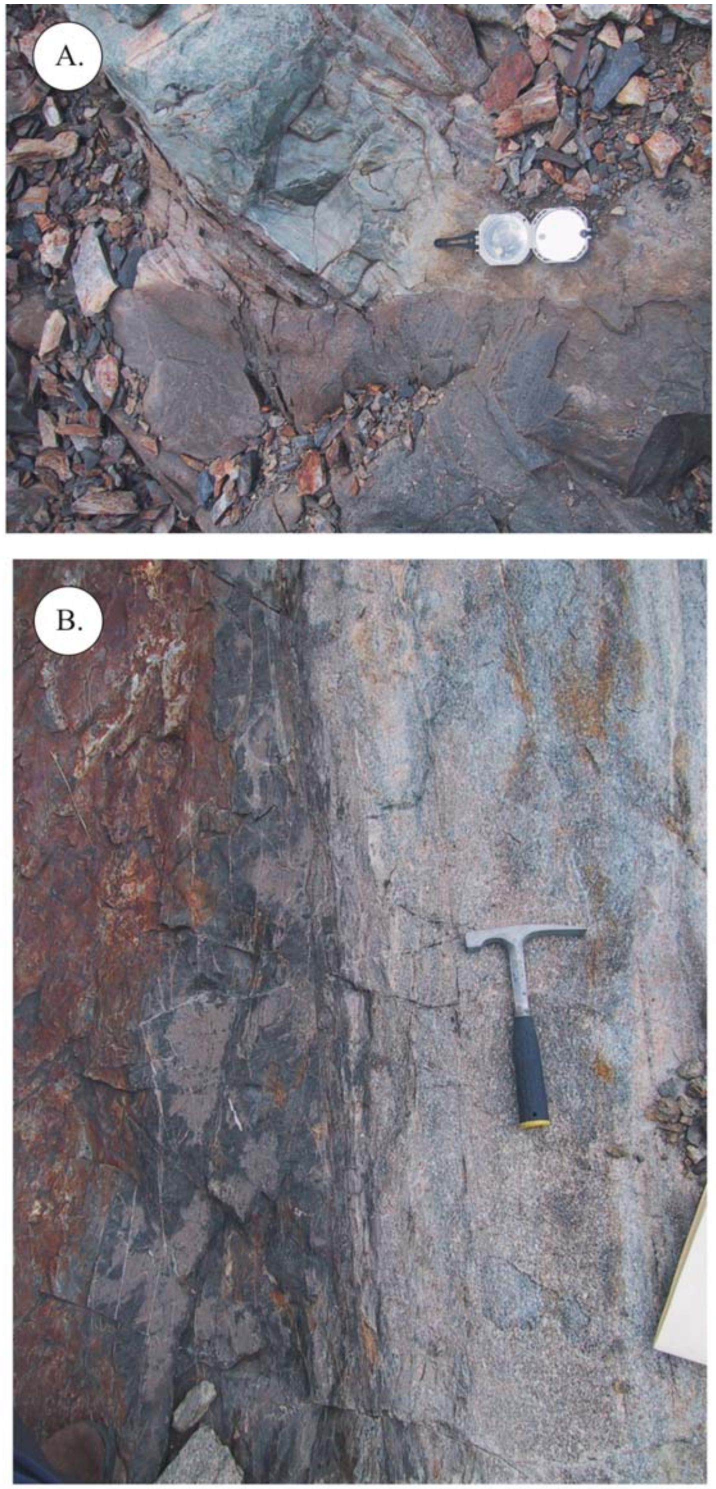


Figure 23: Igneous contacts in the Mono Pass segment of the Sierra Crest shear zone system. A) Basaltic dike cuts across chert strata east of the shear zone boundary. Contact strikes 114° and is vertical. View is towards ~190°.B) Contact between hypabyssal granite unit (right) and dark fine grained andesitic metavolcanics (left). The strike of the contact (paralleled by the handle of the hammer) strikes 110°. View is towards 110°.

Compositional layering, interpreted as primary magmatic *schlieren*, is discernible in this unit (Figure 24). A schisty, sandy unit with intercalated chert is the next unit to the west. A basalt flow is found at Parker Pass, adjacent to a small pod of quartzite. To the west, there is more ignimbrite. Original depositional strata are locally preserved in this ignimbrite, though the individual clasts have been rotated into parallelism with regional foliation (Figure 25). The ignimbrite then gives way westward to an extensive layer of metasediments: sands and cherts and pelitic units that have been metamorphosed to a quartz-rich schist (Figure 26). No such unit appears in the Gem Lake segment. In this unit, schistose texture (spacing between foliation) diminishes closer to the pluton – indicating that well-foliated schistocity was partially overprinted by contact metamorphism, and that this section of the segment did not re-develop closely-spaced foliation after pluton emplacement. Proximal to the pluton, the rock more closely resembles a quartzofeldspathic hornfels with compositional banding. This correlates with a hornfels, also increasingly massive to the west, that appears in the Cascade Lake segment. There, epidotized calc-silicate hornfels appears as repeated lenses in the more pelitic schist/hornfels. But further away from the pluton, contact metamorphic effects are lessened, and schistose, finely foliated texture is preserved. In the Mono Pass segment, the pelitic sediments that served as protolith for the schist were capped by a thin ash-flow tuff, the westernmost (and youngest) non-plutonic unit in the Mono Pass segment (Figure 27). This unit is quite thin, only ~10 m in across-strike width.

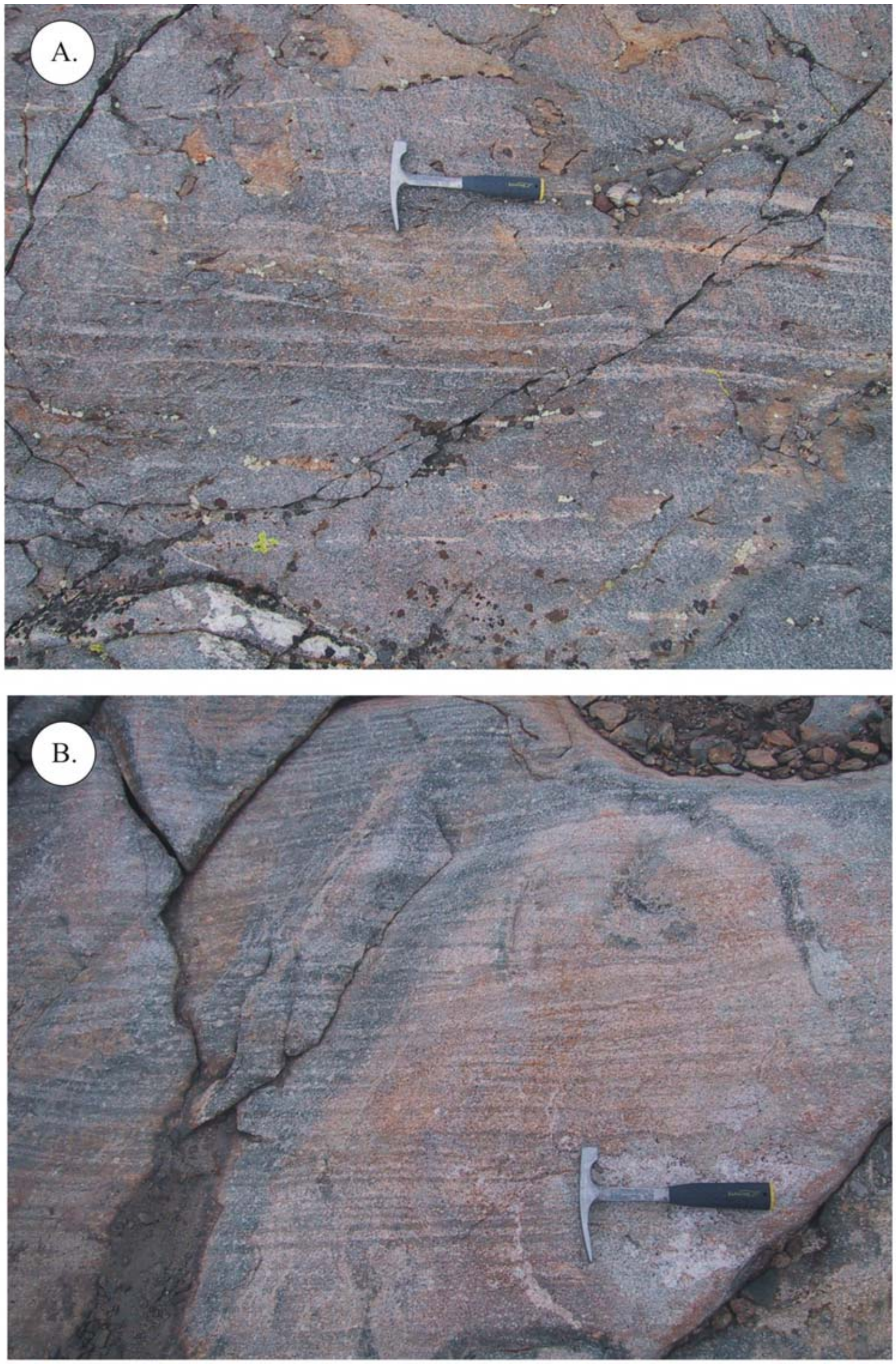


Figure 24: Magmatic *schlieren* planes in hypabyssal granite unit, Mono Pass segment of the Sierra Crest shear zone. A) Eastern portion of hypabyssal granite unit. Strike of *schlieren* is 119°, dip is unknown. B) Western portion of hypabyssal granite unit. View is towards 090°. *Schlieren* strike 350° and dip 79°. Hammer for scale.

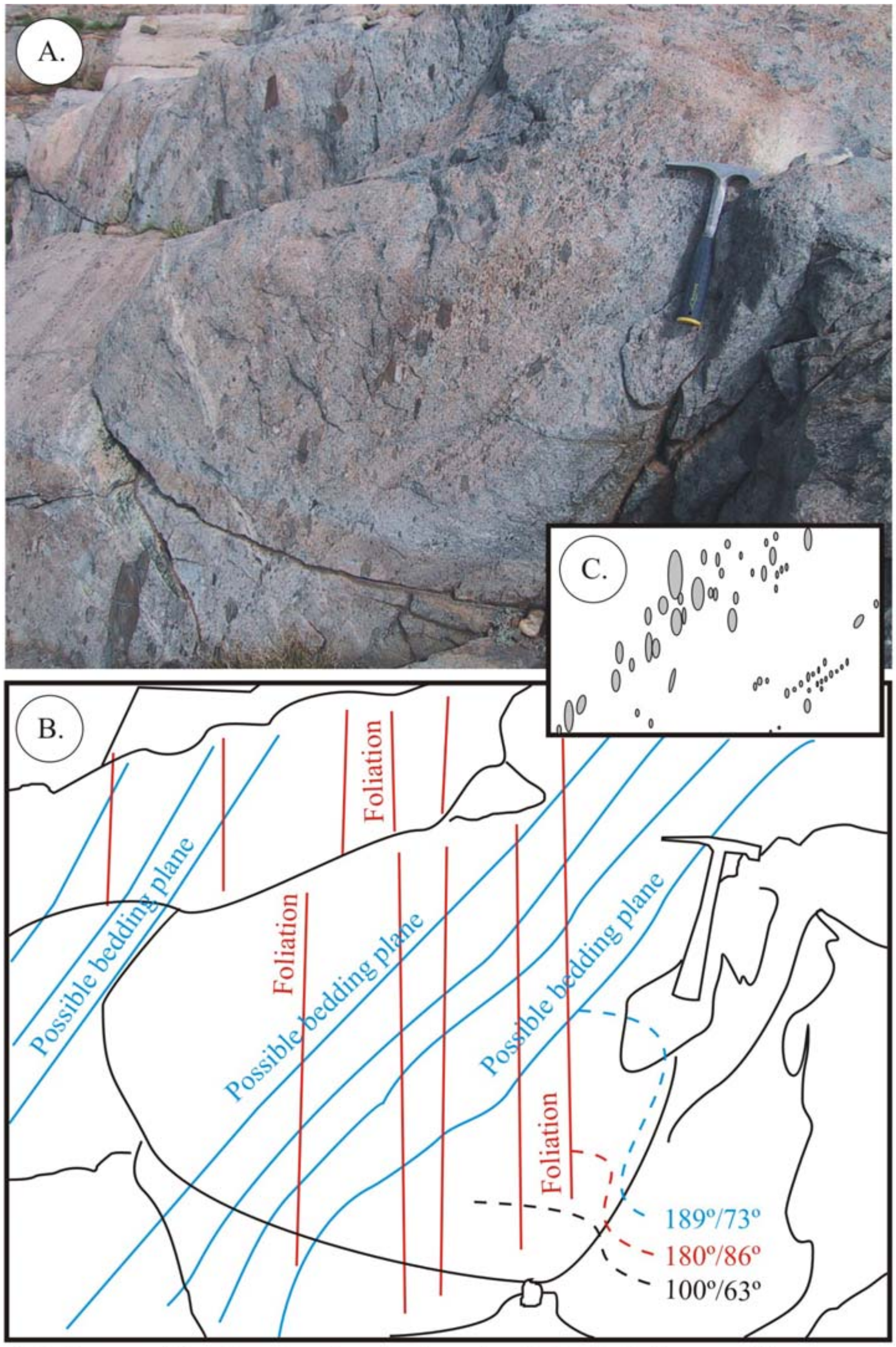


Figure 25: Compositional and grain-size layering in ignimbrite, possibly representing primary bedding, central Mono Pass segment of the Sierra Crest shear zone. A) Photograph of outcrop displaying both foliation and compositional and grain-size layering. Hammer for scale. View is towards 340°. B) Line sketch highlighting key features of the outcrop in black, foliation in red, and possible bedding planes in blue. "Bedding" strikes 189° and dips 73°, foliation strikes 180° and dips 86°, and the outcrop surface strikes 100° and dips 63° towards the camera. C) Traces of major clasts from central region of (A).

Figure 26: The dominant lithology of the western portion of the Mono Pass segment of the Sierra Crest shear zone: a well-foliated quartz-rich schist that, due to contact metamorphism, grades into a more massive hornfels closer to its contact with the Kuna Crest granodiorite. View is towards ~340°, along strike. Tioga Pass is in the distance.

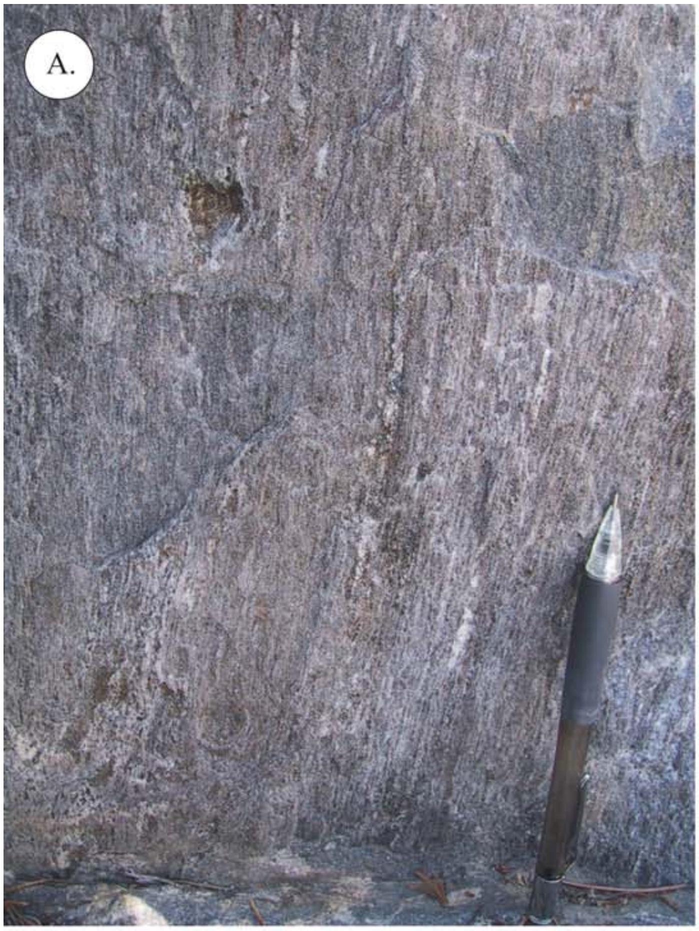


Figure 27: Westernmost non-plutonic lithologic unit in the Mono Pass segment of the Sierra Crest shear zone: an ignimbrite which locally outcrops as a thin ash-flow tuff. A) Lineation in tuff. Outcrop is plane of foliation, with fine-grained downdip stretching lineations. Pencil for scale. View is towards 254°. B) Boudinage of quartz clasts in ignimbrite. Dextral sense of shear. Pencil for scale, pencil is subparallel to strike of foliation. View is towards ~250°.

The center of the Mono Pass segment of the shear zone (Parker Pass Valley) is covered by alluvium, the only significant portion of the surveyed shear zone so obscured.

In the Cascade Lake segment (Figure 16), there is a similar arrangement of lithologic units as in the two southern segments: sediments in the east, a pluton in the west, and a thick package of metavolcanic rocks in the center, where the shear zone deformation is most intense. However, Kistler (1966) indicated that these sediments are not the Koip sequence, but instead the older Lewis sequence, as indicated by a greater number of generations of folds in the sequence. The two sedimentary sequences are separated by a large fault in the region between Tioga Pass and Mount Gibbs: The rocks of the Saddlebag Lake pendant (Cascade Lake segment) lie northeast of the fault, and the rocks of the Ritter Range pendant (Mono Pass and Gem Lake segments) lie southwest of the fault. This is cited as an additional piece of evidence for interpreting the central Cascade Lake segment's rocks as being of the Lewis sequence. However, the lithologies of the component units appear to be directly correlative with the lithologies of the segments to the south, as well as to more distant portions of the Ritter Range and possibly even the Goddard pendant further south (Brook, 1977). Though the easternmost sedimentary packages differed in the Cascade Lake segment (shale dominated) from the southerly Mono Pass and Gem Lake segments (chert dominated), the central portions of all three segments appeared correlative as Koip sequence metavolcanics. The present study did not observe multiple generations of folding in the shear zone (as reported by Kistler, 1966). I therefore follow Bateman's (1992) interpretation that they belong to the Koip sequence.

3.2.3 Dana sequence

In more westerly-reaching portions of the Ritter Range pendant, an additional sequence of metasedimentary and metavolcanic rocks called the Dana sequence forms the wall / roof rocks. However, since this sequence is unaffected by the Sierra Crest shear zone (though it does host the Bench Canyon shear zone), it will not be discussed further in this thesis.

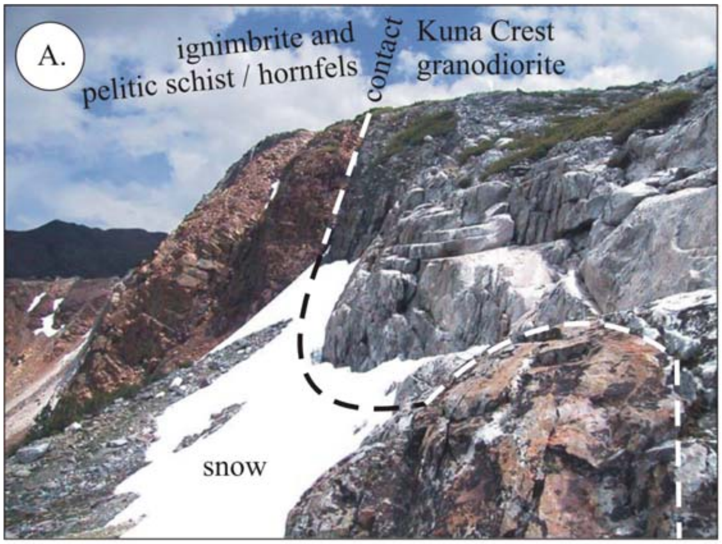
3.3 Lithology of plutons

3.3.1 Dating and ages of emplacement

The Sierra Crest shear zone traces the boundary between highly sheared metavolcanic and metasedimentary country rocks to the east-northeast and moderately sheared intrusive plutons of the Sierra Nevada batholith to the west-southwest. Each of the three surveyed segments is truncated in the west by a different pluton: Gem Lake by the Rush Creek granodiorite, Mono Pass by the Kuna Crest granodiorite, and Cascade Lake by the Cathedral Peak granodiorite (though there is also a thin veneer of the Half Dome granodiorite present in the southwestern-most portion of the surveyed segment). The Rush Creek granodiorite (U/Pb age of 100 Ma; Bateman, 1992) in the Gem Lake segment is an older pluton, emplaced in the first half of the second main episode of Sierra Nevada plutonism (Ducea, 2001; Schweickert and Snyder, 1981). The Kuna Crest, Half Dome, and Cathedral Peak granodiorites are part of the Tuolumne Intrusive Suite, emplaced in the second half of the second main episode of Sierra Nevada plutonism (Ducea, 2001; Schweickert and Snyder, 1981). The Tuolumne Intrusive Suite is a roughly-concentric series of nested plutons which from interior to exterior are progressively more equigranular, more mafic, and older (e.g. Glazner, 2004).

At Mono Pass, the shear zone finds its western boundary at the Kuna Crest granodiorite (U/Pb age 93 Ma; Glazner et al., 2004; K/Ar age 82.6, Kistler, 1966). Dikes of the Kuna Crest granodiorite intrude the adjacent schist of the wall rock, parallel to foliation (Figure 28).

At Cascade Lake, the Cathedral Peak granodiorite, with U/Pb ages of 86 Ma (Tobisch et al. 1995) to 88 Ma (Glazner et al., 2004) forms the western margin to the shear zone here (Figure 29). The Half Dome granodiorite, with U/Pb ages of 88-92 Ma (Glazner et al., 2004), forms a thin septum between the more voluminous Cathedral Peak and the wall rocks of the Saddlebag Lake pendant. The boundary between the pluton and the metavolcanics and metasediments is mainly transposed and parallel to the regional fabric, but in the center of the segment, the boundary has zigzag jogs (Figure 16): this stair-step pattern alternates between being parallel to the regional foliation and perpendicular to it. In general, it is parallel to the regional trend of foliation. The Cathedral Peak granodiorite is a distinctive unit, with large (10 cm) feldspar megacrysts (Figure 29A). The boundaries of the pluton contain at least an order of magnitude greater concentration of the megacrysts than the interior of the pluton, even within a scale of several tens of meters. Portions of the well-foliated host rock may be seen included in the margins of the pluton as xenoliths. The contact



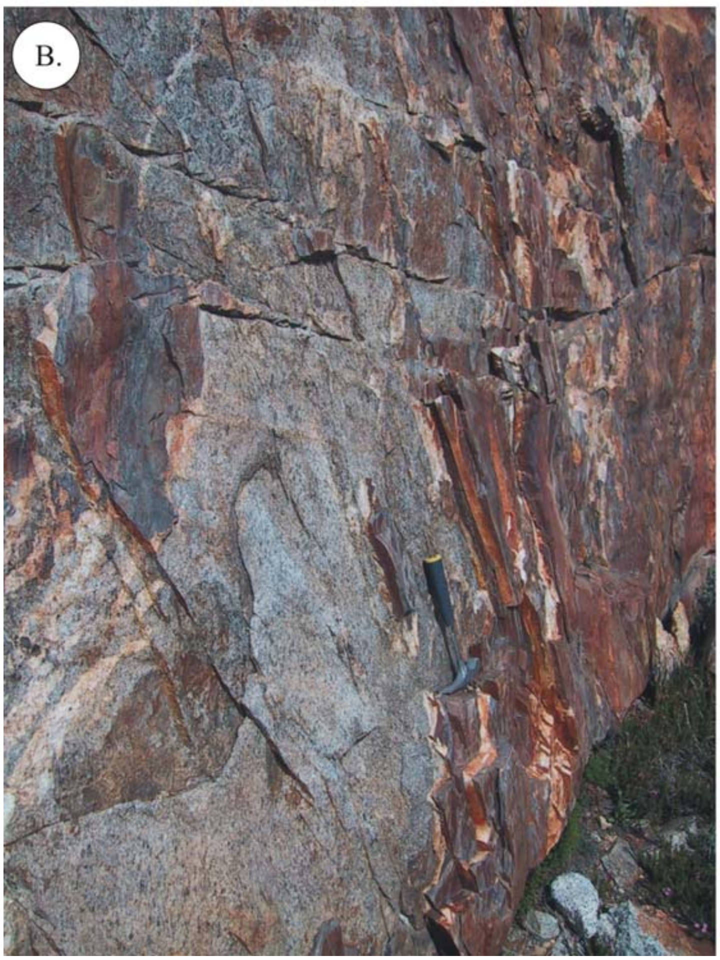


Figure 28: The Kuna Crest granodiorite, western margin of the Mono Pass segment of the Sierra Crest shear zone. A) Contact between the Kuna Crest granodiorite (west) and the thin ignimbrite cap to the pelitic schist and hornfels unit. In the photo, pluton is on the right. Camera facing towards 145°. B) Control of foliation on dike emplacement, western Mono Pass segment of the Sierra Crest shear zone. Total thickness of granodiorite dike is ~2 m. Dike intrudes hornfels component of schist/hornfels unit. Composition of the granodiorite matches the large pluton ~0.5 km west, the Kuna Crest granodiorite. A strong magmatic foliation was present in the dike. Subvertical outcrop. Hammer for scale; View is towards 300°.

between the Cathedral Peak and the wall rock exhibits a stair-step style trace in map view (Figure 16), indicating the likelihood that stoping of the well-foliated wall rock may have controlled emplacement of the pluton. Intrusion of dikes of Cathedral Peak magma along planes of foliation was observed in numerous places (Figure 29B).

3.3.2 Pluton fabrics, xenoliths and dikes

Plutonic rocks exhibit both magmatic and solid-state fabrics. Regionally, only magmatic fabrics are found (e.g. Tobisch et al., 1995), but along their contact with the strained host rocks of the shear zone, quartz ribboning indicates subsolidus deformation. Near the eastern margins of the plutons, their fabrics generally trend along with the adjacent host rock fabrics. Away from the shear zone, further west into the plutons, the fabric trends more westerly (Bateman, 1992; Scott Paterson, University of Southern California, personal communication, 2003). While shear zone fabric is more areally extensive in the host rocks, the shear zone consists of both host rocks and pluton.

The presence of well-foliated xenoliths in the margins of the plutons indicates that shear zone deformation preceded pluton emplacement. Dikes of intrusive rock also appear, emplaced preferentially along the plane of foliation. Near the margin, these dikes may have served to "wedge" off blocks of host rock, which would then be stoped into the magma chamber. So shear zone deformation must have at least partially preceded pluton emplacement. However the subsolidus deformation in the plutons indicates that shear zone deformation continued after the emplacement of the plutons as well. Late Cretaceous intrusive plutons in the Sierra Crest shear zone are

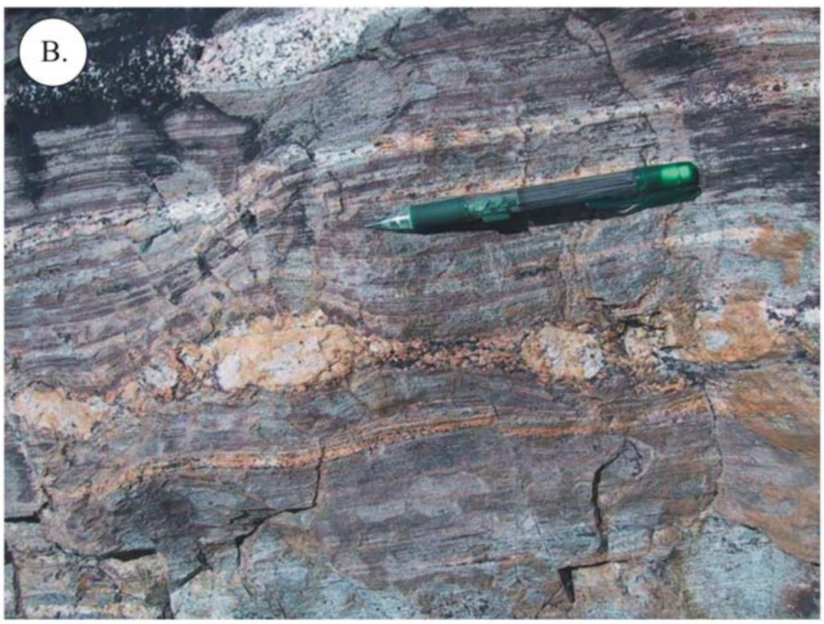


Figure 29: Cathedral Peak granodiorite, Cascade Lake segment of the Sierra Crest shear zone. A) Fabric in the margins of the pluton: Stretched quartz, alignment of mafic minerals and orthoclase feldspar megacrysts. Outcrop face strikes 325° and dips 19°. Brunton compass for scale. View is towards 242°. B) Magma from Cathedral Peak pluton intruded along the established plane of foliation of the pelitic schist and calc-silicate wall rocks, bearing the characteristic megacrysts of orthoclase feldspar. Foliation wraps around the megacrysts, indicating that they were full size, or close to it, at the time of intrusion, and that the conduit through which they were inserted has since been compressed. Note also the shear band (upper left) and brittle faulting (lower right). Section is approximately perpendicular to foliation. Outcrop face strikes 072° and dips ~70°. Pencil for scale. View is towards 330°.

therefore considered to be syntectonic. They were emplaced after deformation started and before it ended.

3.4 Previous work on the Sierra Crest shear zone

Mesozoic transpression has left its mark on the cooling plutons and their host rocks (Saleeby, 1981). Several authors have called attention to a series of shear zones that deformed plutons and wall rocks in the high Sierra.

The Sierra Crest shear zone system will serve as a field example to examine the unresolved issue of lineation variability in natural transpressional zones. The Sierra Crest shear zone system is chosen because it has already been reported on by several studies (Tikoff and Greene, 1996; Greene and Schweickert, 1995; Tobisch et al., 1995; Saint Blanquat and Tikoff, 1997; Saint Blanquat et al., 1996; Tikoff and Saint Blanquat, 1997). The Sierra Crest shear zone transects lithologic boundaries and indicates that Cretaceous deformation in the Sierra Nevada was dextrally transpressional. The shear zone trends ~N30ºW, dips subvertically and exhibits evidence of both brittle and ductile deformation and greenschist to granulite facies metamorphism (Ducea, 2001). The shear zone consists of several segments known by various names in the literature.

The "Gem Lake shear zone" has been investigated by Greene and Schweickert (1995) and Tikoff and Greene (1997). Description of the Gem Lake and Mono Pass segments in 1995 by Greene and Schweickert provided the first documentation that in additional to the plutons themselves, there was shear strain in the wall-rock and roof pendants of the area. The Gem Lake segment is commonly viewed today as merely the middle segment of a larger shear zone system (the "northern Sierra Crest shear zone system," (e.g. Figure 13) consisting of the Cascade Lake shear zone to the North, the Gem Lake shear zone, the Rosy Finch shear zone to the south, and potentially even the proto-Kern Canyon shear zone in the far southern Sierra Nevada (Tobisch et al., 1995; Greene and Schweickert, 1995; Tikoff and Greene, 1996; Tikoff and Saint Blanquat, 1997). This study investigated the northern portion of the "Sierra Crest shear zone system" – that is, the Gem Lake (which also includes what has been variously referred to as the Kuna Crest segment or the Mono Pass segment) and the Cascade Lake shear zones. In this thesis, "Sierra Crest shear zone" refers to this portion only.

The Cascade Lake shear zone is the northern-most segment of the Sierra Crest shear zone system (Davis et al., 1995). It is a few-hundred-meter-wide zone of sheared plutonic, metasedimentary, and metavolcanic rocks characterized by steeply-dipping foliation and shallowly-plunging lineation (Davis et al., 1995). Fabric analysis by Davis et al. (1995) shows a strain gradient that may be connected with the margin-first cooling of the pluton, a finding reinforced by the present study. In contrast, Tikoff and Saint Greene (1996) reported a pattern of subvertical foliation and subhorizontal lineation in the Cascade Lake shear zone.

The Rosy Finch shear zone is characterized as syn-magmatic, as it is predominantly contained within granitoids of 92-83 Ma age within the Mono Pass Intrusive Suite. However, it also cuts across wall rock and roof pendants (Tikoff and Saint Blanquat, 1997). Cretaceous dextral transpression is evidenced by mylonitic and cataclastic deformation with a common pattern of subvertical foliation and subhorizontal lineation (Tikoff and Saint Blanquat, 1997). The Rosy Finch has been proposed to be a southerly extension of the Sierra Crest shear zone system (Tikoff and Saint Blanquat, 1997).

Another shear zone, the Bench Canyon Shear Zone is located to the west of the Sierra Crest Shear Zone system, possibly on one of the anastomosing arms of the greater system. McNulty (1995a, 1995b, Tobisch et al.,1995) has done most of the work on this shear zone. It exposes deformation in both the brittle and ductile regimes as evidenced by the generation of two distinct forms of pseudotachylyte – one associated with cataclasite above the Brittle-Ductile Transition Zone (BDT) and one associated with mylonites below the BDT (McNulty, 1995a). McNulty interprets the Bench Canyon shear zone history during its exhumation: Starting at depth and at high temperature, and then being exhumed through lessening temperatures and pressures, the shear zone produced mylonites in the amphibolite / greenschist facies, followed by pseudotachylyte associated with mylonites, followed by pseudotachylyte generated through seismic slip, associated with cataclasite (McNulty, 1995a).

Chapter 4: Structure of the Sierra Crest shear zone system

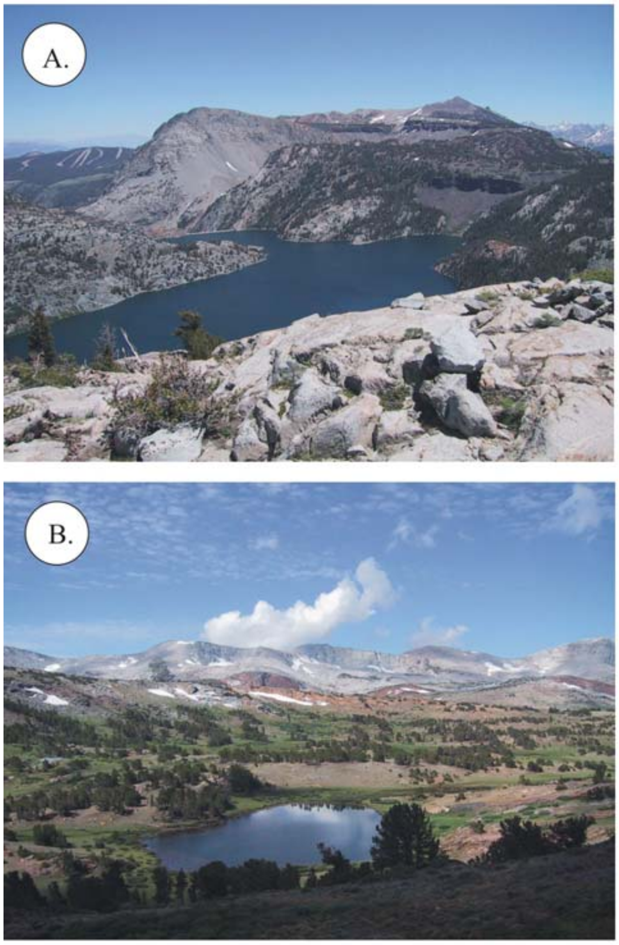
4.1 Methodology

4.1.1 Definition of field area

In summer 2003, field work was conducted in three well-exposed segments along the Sierra Crest shear zone, respectively referred to here as the Gem Lake segment, the Mono Pass segment, and the Cascade Lake segment (Figure 13). The Gem Lake segment covers the area around Gem Lake, west of Agnew Lake and east of Waugh Lake (Figure 30A). The Mono Pass segment is roughly the Parker Pass Valley, defined by the area between Parker Pass, Mono Pass, and the Kuna Crest (Figure 30B). The Cascade Lake segment is defined as the basin northwest of Saddlebag Lake, bounded by North Mountain, Sawmill Crest, Tioga Crest, and the unnamed 3,413 m peak immediately west of Saddlebag Lake (Figure 30C). All three segments are located in the Inyo National Forest, east or northeast of Yosemite National Park. Outcrop exposure is generally excellent in all three areas, except for the Mono Pass segment, where a significant portion of the shear zone in the central Parker Pass Valley is buried beneath alluvium.

4.1.2 Methodology

Large-scale structural mapping was conducted in the three areas, based on topographical and previously published geologic maps (Peck, 1980; Bateman et al.,



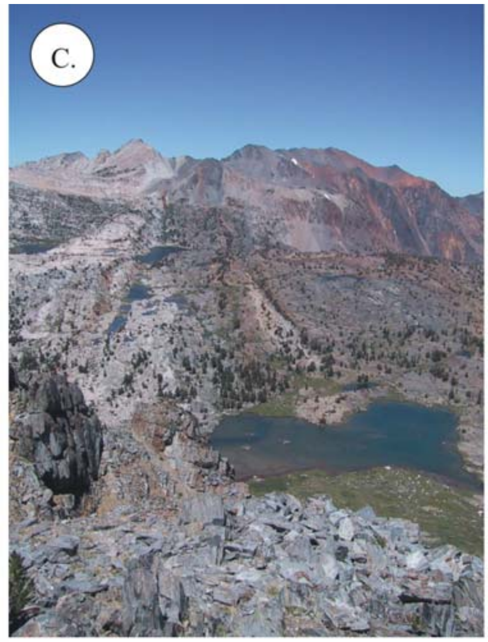


Figure 30: Surveyed segments of the Sierra Crest shear zone system: A) Gem Lake segment. Outcrop of Rush Creek granodiorite is in the foreground; Mammoth Mountain ski area is in the background, left. View is to the southeast. B) Mono Pass segment. Summit Lake is in the foreground; Kuna Crest is in the background. View is to the west-southwest. C) Cascade Lake segment. Greenstone Lake is in the middle ground; Wasco and Steelhead Lakes are arranged *pater noster* in the distance. Sawmill Crest is in the background. View is along strike to the north-northwest.

1988). Various fabric elements were observed, their overprinting and cross-cutting relationships documented, structural and lithologic samples were taken and structural analysis (measurement of foliation, lineation, kink fold axes, kink bands, and discernible bedding) was done to document along- and across- strike variation in deformation.

This mapping resulted in the segment maps: the Gem Lake segment in Figure 14; the Mono Pass segment in Figure 15; and the Cascade Lake segment in Figure 16.

Field relations indicated three generations of deformation, which for the purposes of this study may be broadly characterized as pre-shear-zone deformation, shear-zone deformation (which includes contemporaneous deformation outside the shear zone), and post-shear-zone deformation.

4.2 Pre-Shear Zone deformation

4.2.1 Folding

In the Gem Lake segment, on the north side of Agnew Lake, the bedding was folded into shallowly-plunging isoclinal folds (Figure 31). These are interpreted to be the first generation of deformation (D1) in the area. They are overprinted by steeper, NW-trending folds.

Folding in metasedimentary rocks outside the eastern shear zone boundary is common in all three segments (Figures 32, 33, and 34). In the Gem Lake segment, tight isoclinal NW- and SE-plunging folds outside the shear zone were overprinted by more-open, NW-plunging folds. The isoclinal folds (Figure 31) are interpreted to be of the first generation of folding (D1; blue in Figure 32), and the folds of the younger generation are interpreted to be D2 (red in Figure 32). All folds inside the shear zone overprinted foliation, and were thus inferred to be of the third generation of deformation (D3; green in Figure 32). In the Mono Pass segment, folds in Lewis Sequence siltstones and cherts (Figure 35) have axes trend similarly to the Gem Lake segment's second generation of folding (D2; red in Figure 33). A single fold has a subvertical axis, and is of an undetermined generation (black in Figure 33). In the Cascade Lake segment, folds occurred outside the shear zone except in one case (D3; green in Figure 34), but no overprinting relationships were observed in the folds

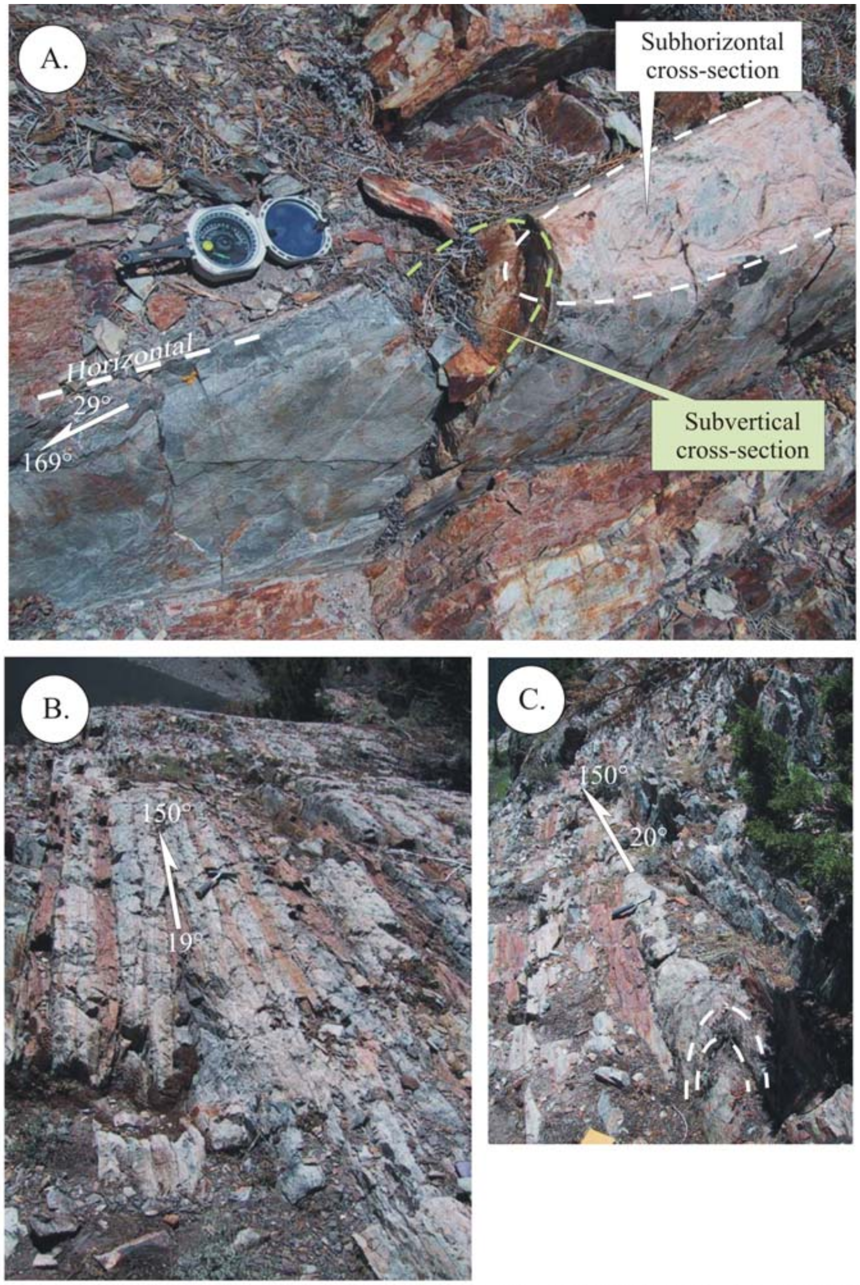


Figure 31: Isoclinal folds in chert and siltstone unit, eastern Gem Lake segment of the Sierra Crest shear zone. A) Close up of isoclinal fold hinge, metasediments north of Agnew Lake. Fold axis plunges 29° towards 169°. Natural fracturing reveals the three-dimensional shape of the hinge, with hemi-ellipsoidal cross-sections. Subhorizontal outcrop. Brunton compass for scale. View is towards 260°. B) Larger view of adjacent fold in the same area, also plunging to the southeast. Fold axis plunges 19° towards 150°. Subhorizontal outcrop. Hammer for scale. View is towards 160°. C) Looking down the axis (central rounded form) of another isoclinal fold, in the same area, also plunging to the southeast. The rounded grey chert layer is designated in cross section by the dashed lines. Fold axis plunges 20° towards 150°. Subhorizontal outcrop. Hammer for scale. View is towards 170°.

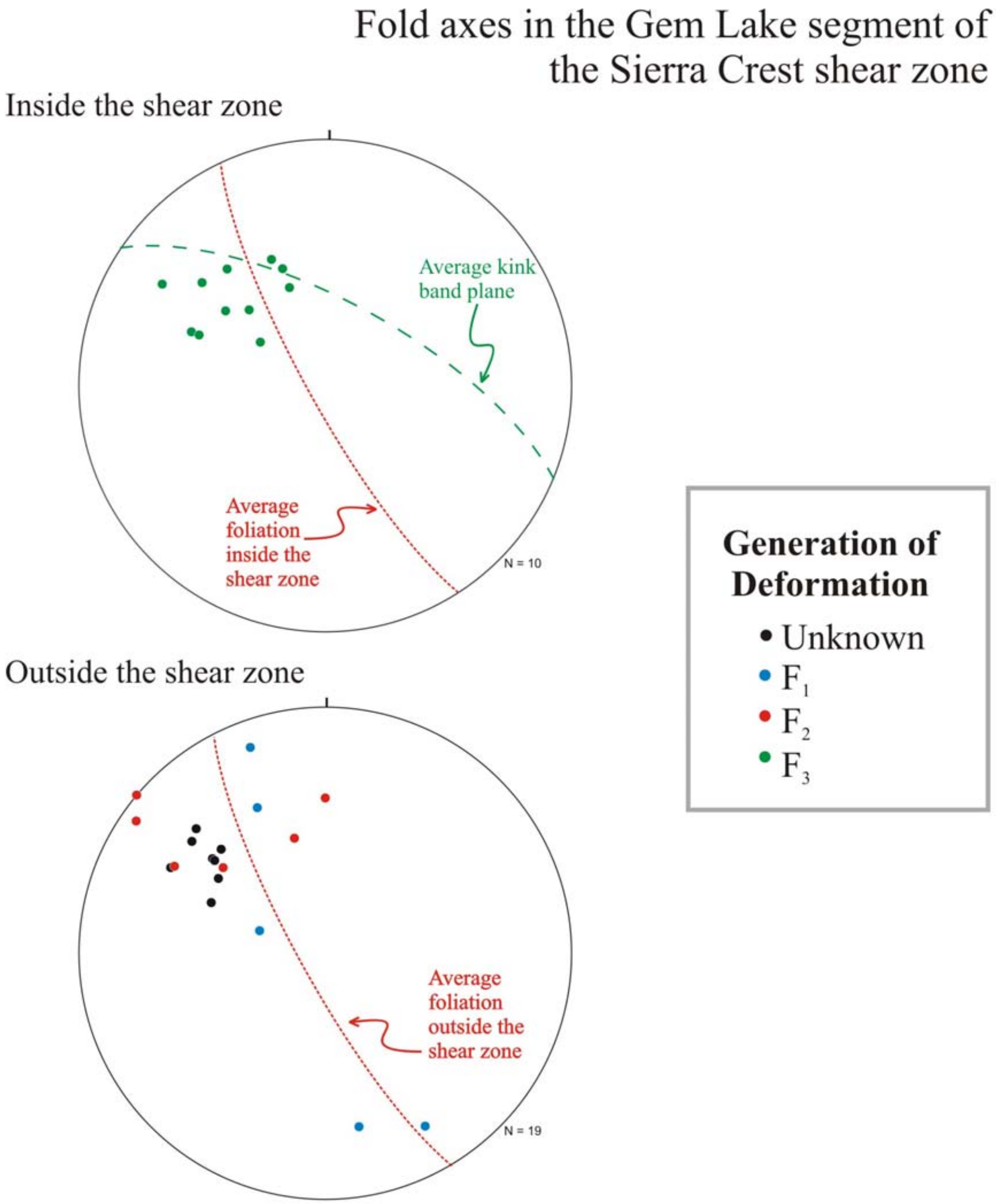


Figure 32: Stereonets of fold axes in the Gem Lake segment of the Sierra Crest shear zone. Upper net shows fold axes inside the shear zone, with average foliation and average kink band planes for reference. Lower net shows fold axes outside the shear zone (to the east). Blue dots signify isoclinal folds of the first deformational generation, pre-shear-zone (F1). Red dots signify folding concurrent with shear zone deformation. Folds which overprint foliation represent post-shear-zone deformation (F3). Folds of unknown generation are signified with black dots.

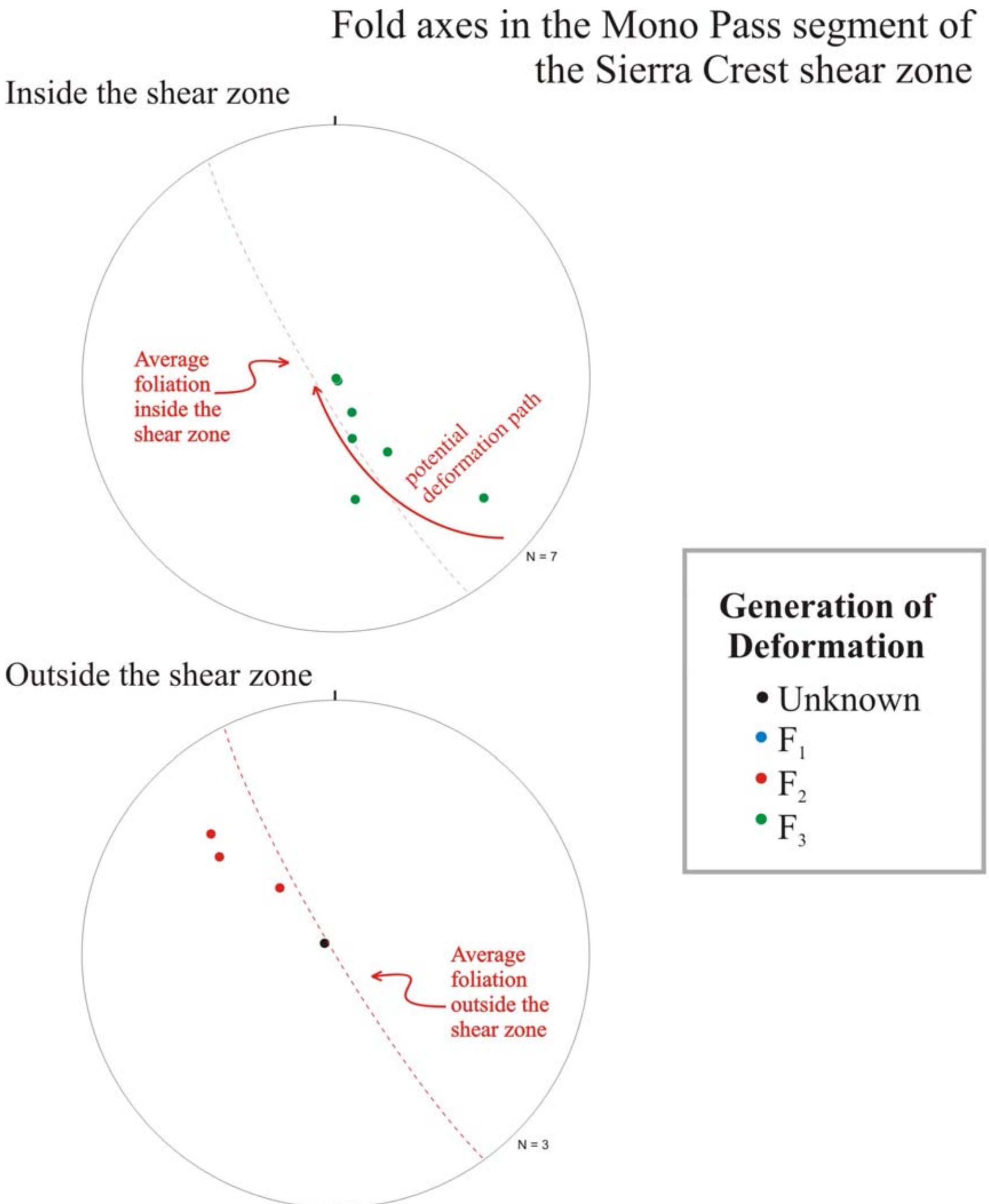


Figure 33: Stereonets of fold axes in the Mono Pass segment of the Sierra Crest shear zone. Upper net shows fold axes inside the shear zone, with average foliation and average kink band planes for reference. Lower net shows fold axes outside the shear zone (to the east). Blue dots signify isoclinal folds of the first deformational generation, pre-shear-zone (F1). Red dots signify folding concurrent with shear zone deformation. Folds which overprint foliation represent post-shear-zone deformation (F3). Folds of unknown generation are signified with black dots. In the upper stereonet, the array of axes may indicate a deformation path for drag folds: see discussion in the text.

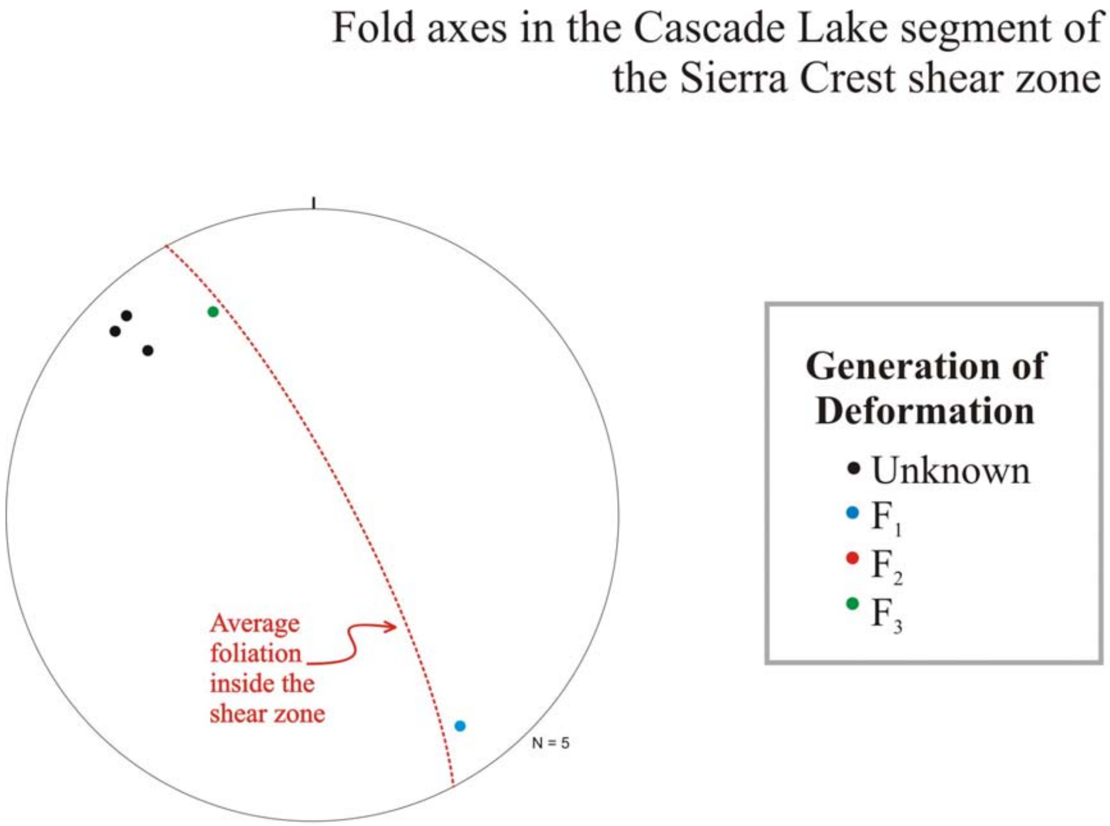


Figure 34: Stereonets of fold axes in the Cascade Lake segment of the Sierra Crest shear zone. Upper net shows fold axes inside the shear zone, with average foliation and average kink band planes for reference. Lower net shows fold axes outside the shear zone (to the east). Blue dots signify isoclinal folds of the first deformational generation, pre-shear-zone (F1). Red dots signify folding concurrent with shear zone deformation. Folds which overprint foliation represent post-shear-zone deformation (F3). Folds of unknown generation are signified with black dots, though most likely they are either F1 or F2 here.

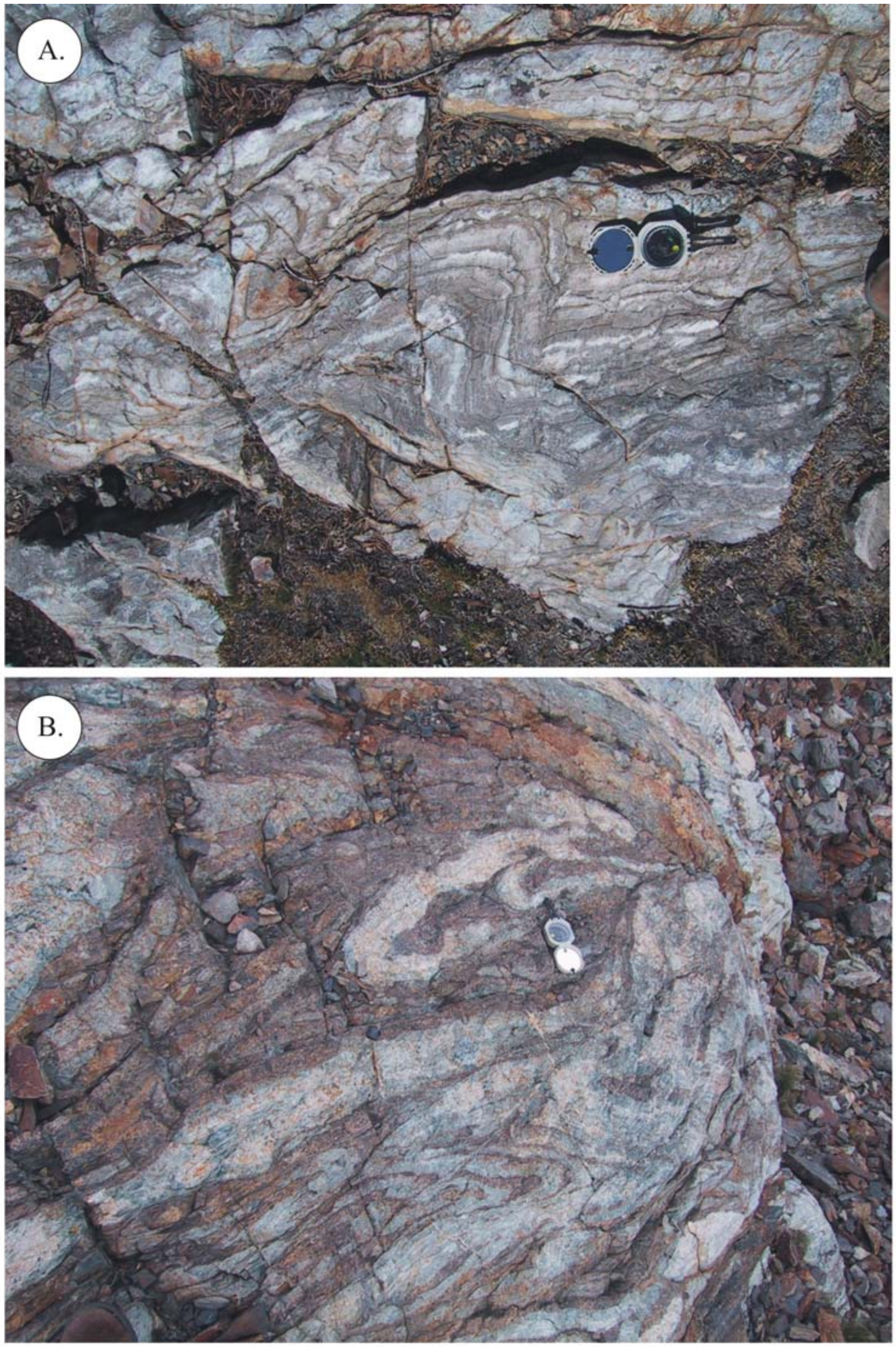


Figure 35: Folding in Lewis Sequence metasediments, eastern Mono Pass segment of the Sierra Crest shear zone. A) Z-folds in chert / siltstone strata northeast of Mono Pass. Subhorizontal outcrop. Brunton compass for scale. Fold axes at this location plunged 85° towards 315°. B) Tightly and complexly folded chert strata. Outcrop face strikes 260° and dips 33°. Brunton compass for scale. Fold axes at this location plunged 62° towards 320°.

outside the shear zone, and hence their generation cannot be determined (black in Figure 34). One Cascade Lake segment isoclinal fold resembles D1 folds in the Gem Lake segment in both its tightness and SE-plunging orientation enough to justify designating it as D1 (blue in Figure 33). The kinematic interpretation of these folds will be presented in Sections 4.2 through 4.4

4.2.2 Foliation

To the east of the shear zone (the area where first-generation structures are preserved), axial plane cleavage associated with folding trends more westerly (317° near Agnew Lake) than foliation within the shear zone. In the intrusive igneous plutons to the west, foliation is also more westerly (~300°) (Bateman, 1992). In general, foliation parallels the overall trend of the shear zone (~330° / N30 ºW). The only deviation from N30ºW is in the central third of the Cascade Lake segment, the contact between metasediments to metavolcanics swings from N30ºW to roughly N15ºW parallel to the western boundary of the shear zone (see Figure 16, southern portion).

U-Pb dating by Schweickert et al. (1994) found that a synkinematic granitic orthogneiss which intrudes metasedimentary and metavolcanic rocks in the northern Saddlebag Lake pendant (north of the area adjacent to Cascade Lake that was surveyed in this study) had an age of 233 Ma, indicating that deformation had initiated in the Early Triassic. This is the earliest date for the shear-zone-era deformation.

There is also some evidence of pre-shear-zone foliation *inside* the shear zone. Magmatic *schlieren* planes in Mono Pass's hypabyssal granite unit are preserved

(Figure 24) and do not trend parallel to shear-zone deformation features (Figure 36), such as foliation. *Schlieren* structures are generally interpreted to result from magmatic emplacement processes, and their preservation here seems to indicate that the hypabyssal granite unit, which is not as pervasively deformed as its surroundings, was either emplaced after the bulk of shear zone deformation had occurred, or that it was more competent than its surroundings, and experienced less strain than neighboring units, both to its east and west. The lack of a preserved contact aureole indicates that the latter hypothesis is more likely. While the granite has experienced solid state deformation in the shear zone, and exhibits well-defined foliation and lineation (Figure 37), microstructurally, it is the least deformed unit in this segment, exhibiting only a moderate shape fabric.

4.2.3 Lineation

Outside the shear zone, lineation is rare. Where present, mineral lineations were more common than lineations defined by stretched clasts; the latter were observed outside the transposed host rocks which define the shear zone only once per segment. In the Mono Pass and Gem Lake segments of the shear zone, lineations outside the shear zone were predominantly oriented to the northwest, but there was a wide scatter in their orientations (northeast corners of Figures 14, 15, and 16). In the Cascade Lake segment, a majority of lineations east of the shear zone boundary were oriented towards the south-southeast.

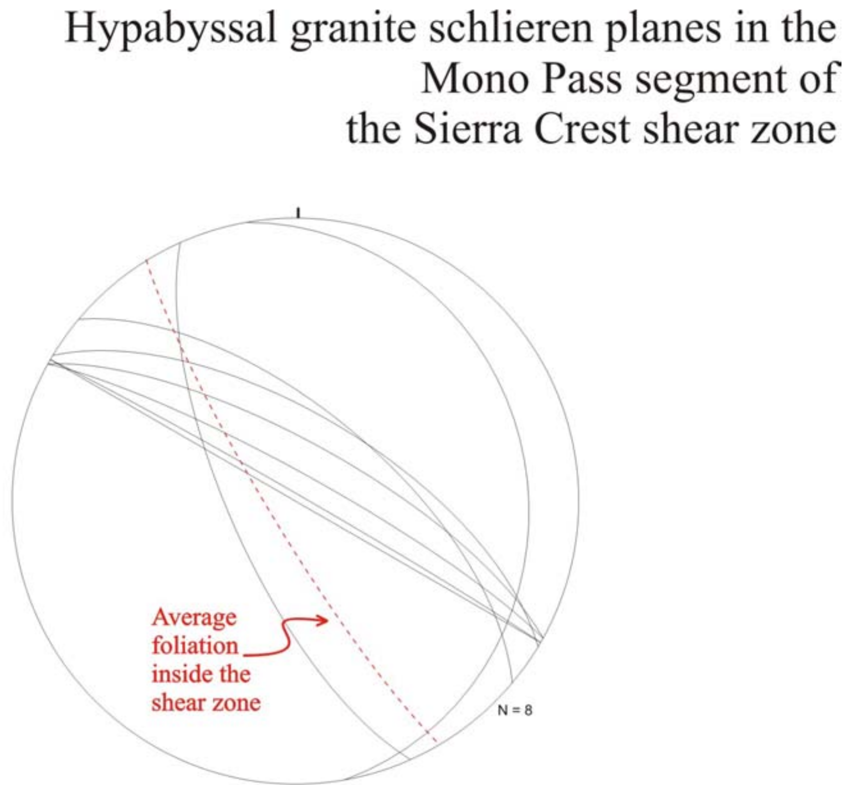


Figure 36: Magmatic *schlieren* planes, hypabyssal granite unit, Mono Pass segment of the Sierra Crest shear zone. The *schlieren* appear to be remnant structures, pre-shear-zone, that reflect pre-shear-zone emplacement of the hypabyssal pluton. See text for full discussion.

Figure 37: Strain in hypabyssal granite unit, Mono Pass segment of the Sierra Crest shear zone. Foliation and lineation as seen in outcrop. Main outcrop face is subparallel to foliation, which strikes 315° and dips 76°. Foreground outcrop is subperpendicular to foliation. Pencil for scale. View is towards 042°

4.3 Shear Zone deformation

4.3.1 Transposition foliation

Transposition foliation defines the Sierra Crest shear zone. A dominant regional foliation of ~N30˚W (Figure 38) extends from the margins of the intrusive plutons in the west 1-2 km to the first presence of coherent beds (with primary sedimentary structures) in metasedimentary rocks in the east. The foliation is uniformly steep, but dips to the west-southwest in the more southerly segments, and to the east-northeast in the northerly segment (Figure 38). The Mono Pass segment is

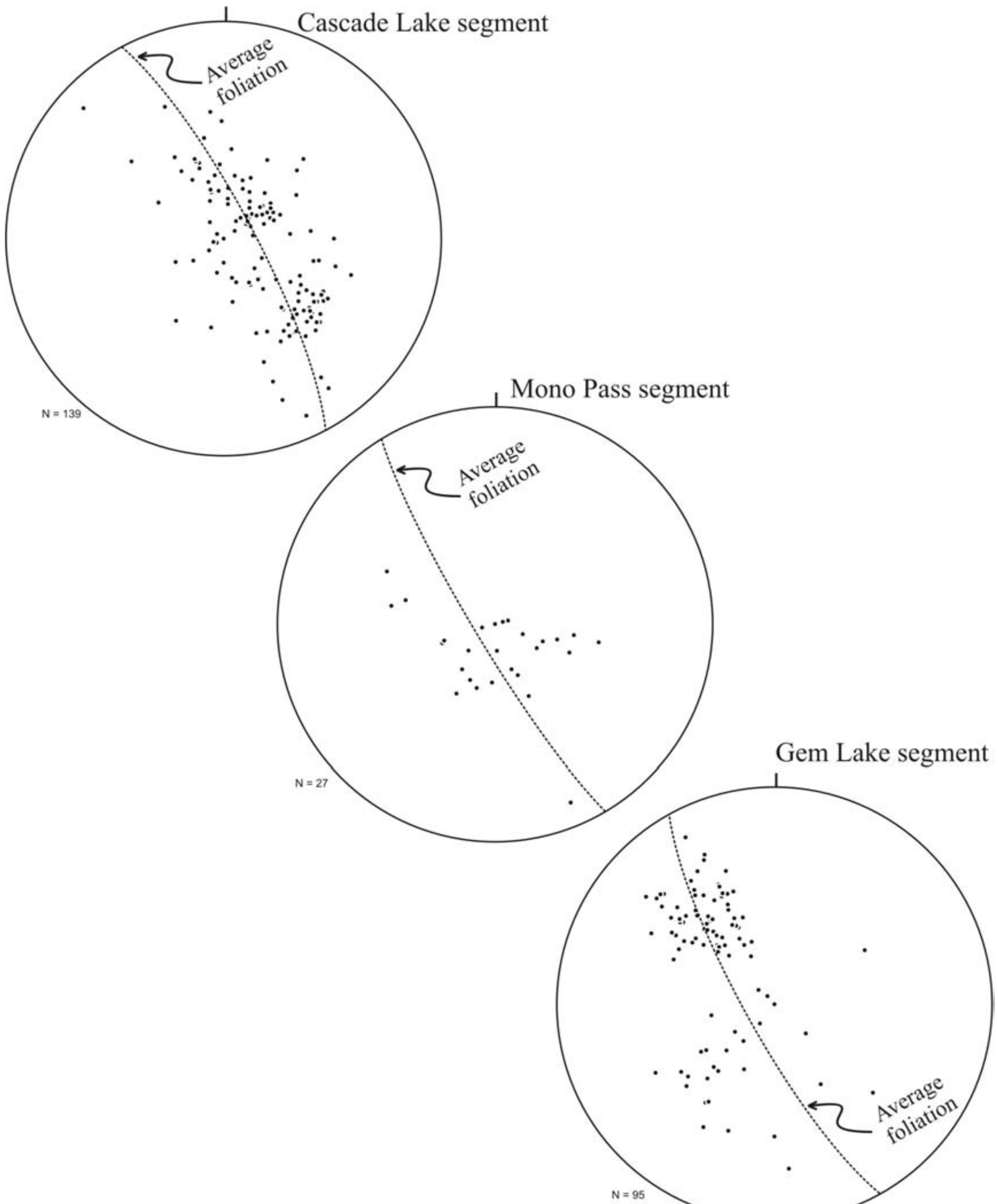


Figure 38: Stereonets showing mineral and stretching lineation and average foliation for the three surveyed segments of the Sierra Crest shear zone system. Average foliation (taken to be the trend of the shear zone itself) is plotted as a dashed great circle. All three areas display great circle girdle lineation patterns. The Gem Lake area data seems to have a bimodal distribution, with a tightly-grouped NNW-trending, ~45º dipping group of lineations and a more dispersed, quasi-vertical group of lineations. This latter group is found more commonly, though not exclusively, along the shear zone's western edge, where it is truncated by the Rush Creek pluton.

transitional (closer to vertical) between the Gem Lake segment and Cascade Lake segments' more pronounced non-vertical dips. Outside the shear zone, axial plane cleavage on F2 folds (see Section 4.4.2) is close to parallel with transposition foliation close to the shear zone's eastern boundary, and deviates further away from the shear zone. No F1 or F2 folds exist in the shear zone, indicating foliation is D2.

Strain estimates indicate strong flattening in all three segments (Figure 39). Strain measurements were performed on metavolcanic lapilli in the Gem Lake and Cascade Lake segments (as in Figure 20). Under the assumption that the clasts' axes corresponded to the axes of the strain ellipsoid, the clast lengths were measured in mm on the XY and YZ sections. 60 measurements were taken per section, and three sections were taken per shear zone segment. Figure 39 presents these measurements in X/Y and Y/Z ratios, plotted on a Flinn Diagram (e.g. Section 2.2).

All measurements display flattening strain. Typical of transpressional zones, the strain ellipsoid resembles an elongated "pancake" shape. Figure 39 presents a minimum estimate of strain, because any of the measured clasts may simply be a piece of a formerly-larger clast that was not only ductilely deformed, but also broken into multiple pieces. If clasts have been boudinaged as well as flattened and stretched, then they underestimate the total possible strain. The scatter in the data may be understood as due to the deformation of boudinaged original clasts. Breakage was certainly common among neighboring clasts. There is a pronounced competence contrast between the mafic lenses and the felsic clasts: while the mafic lenses were ductilely flattened, many of the felsic clasts were brittlely deformed (Figure 3).

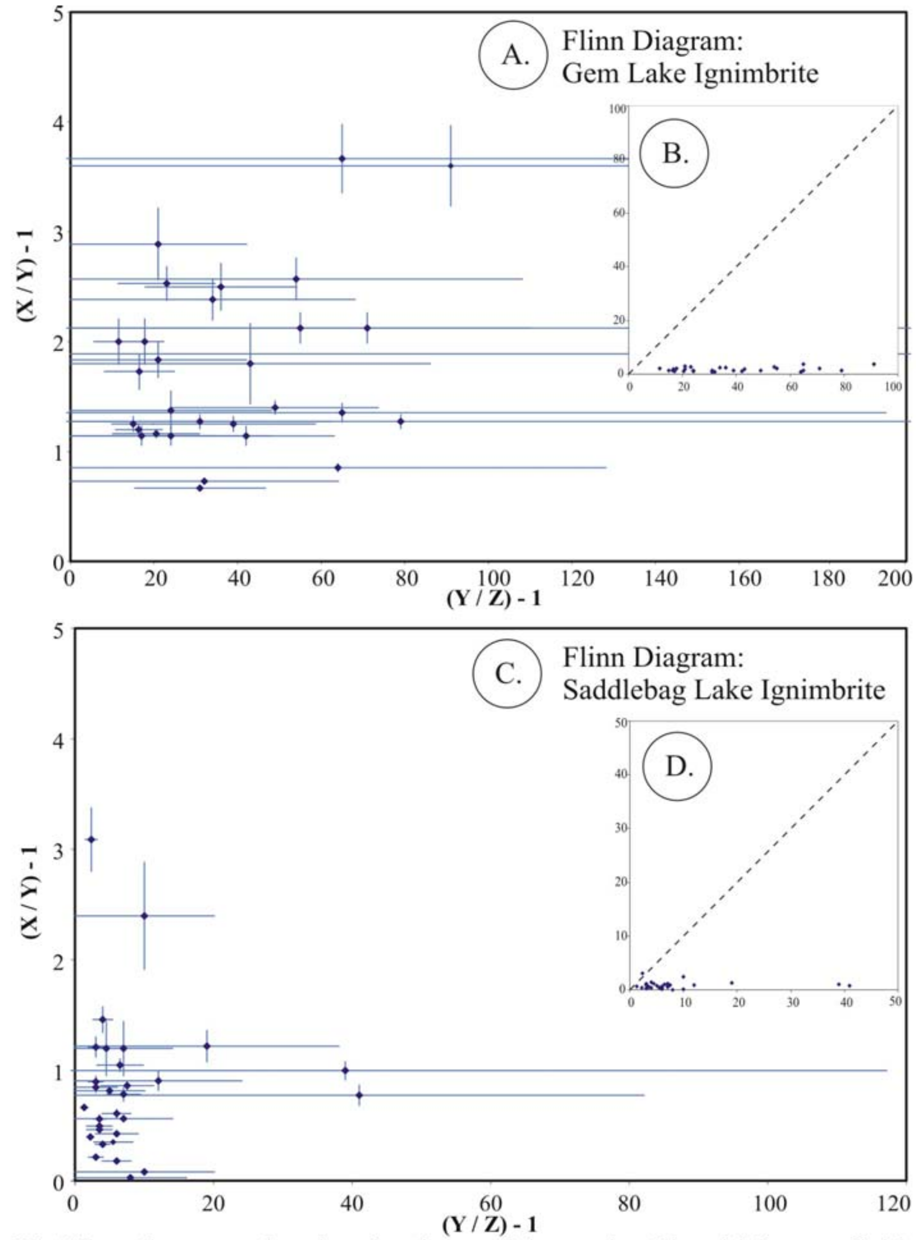


Figure 39: Flinn diagrams showing the shape of the strain ellipsoid for two field stations: (A) and (B) ignimbrite from Gem Lake segment (Foliation 152°/75° & lineation 70°→ 334°) and (C) and (D) ignimbrite from Cascade Lake segment (Foliation 345°/80° & lineation 75°→040°), Sierra Crest shear zone. Both show flattening strain, with a distinctly oblate strain ellipsoid. In both diagrams, the diagonal dashed line represents the plain strain situation, where the length of the X axis is equal to the length of the Y axis. (A) and (C) show the strain data in detail, with error bars. Error bars were calculated using a 1mm uncertainty for each measurement. (B) and (D) show the same data with an equal axial plot, where the plane strain line has a slope of 1. In (A) and (C), the plane strain line would have a slope of 20. Average ratio of long to short axes for Gem Lake segment [(A) and (B)] is 20.28.Average ratio of long to short axes for Cascade Lake segment [(B) and (D)] is 6.47.

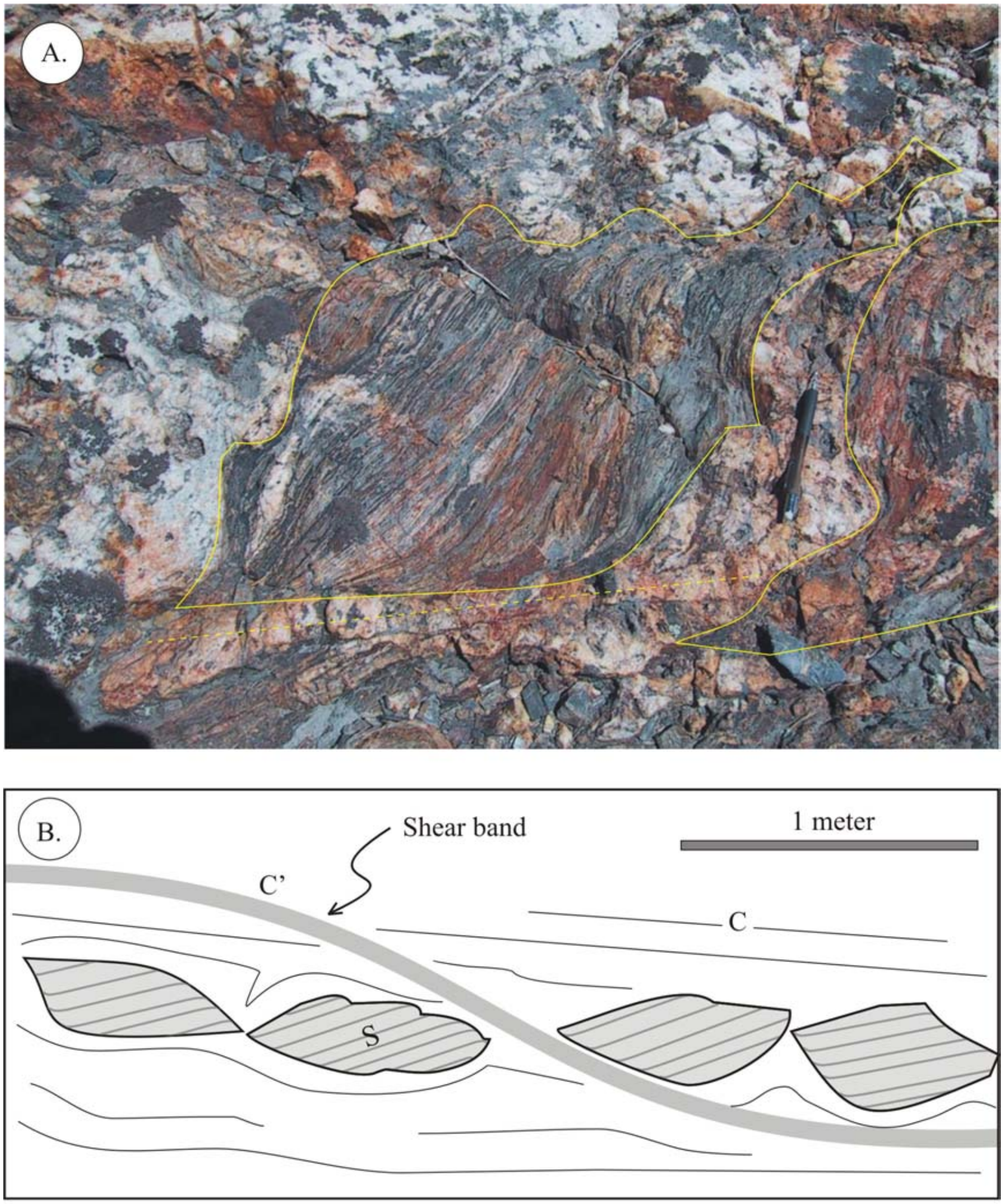


Figure 40: A) Boudins of well-foliated slate on the margin of a granite lens, northeastern Gem Lake segment of the Sierra Crest shear zone. Subhorizontal outcrop. Mechanical pencil for scale; Pencil is parallel to foliation within boudins. View is towards 130°. B) Sketch of similar boudins in the same area, but entirely within a matrix of sheared metasediments. Subhorizontal outcrop. Dominant shear band (C') strikes 162°. Matrix foliation (C) strikes 155°. Foliation within the boudins (S) strikes 140°. Scale bar is 1 m. View is towards 025°.

Xenoliths of country rock in the plutons also display well-developed foliation and lineation, indicating that deformation partially preceded pluton emplacement (Figure 40). The plutons, therefore, only record the latter part of the deformation. If their margins cooled first, then the margins have the potential to record more strain than the interiors of the plutons.

Fabrics in the plutons are similar to those of the adjacent sheared metavolcanics and metasedimentary rocks in the shear zone. In the Gem Lake segment, an S-C mylonite is well developed in the Rush Creek granodiorite atop the unnamed 3,134 m peak west of the northwest lobe of Gem Lake (Figure 41), with the C surface striking ~150º and dipping steeply to the southwest.

In the Mono Pass segment, foliation is steep, generally trending N30ºW (Figure 38). Fabric in the margin of the Kuna Crest granodiorite shows foliation parallel to the foliation in the metavolcanics and metasediments to the east, with a down-dip lineation.

The Cathedral Peak granodiorite provides the western boundary of the shear zone in the Cascade Lake segment. While not as deformed as the older and more southerly Kuna Crest and Rush Creek granodiorites, the Cathedral Peak's emplacement appears to have been significantly controlled by the shear zone. The contact zone displays clear evidence of interaction between the pluton and its wall rocks during its emplacement. Offset marker beds in Figure 42 indicate that dikes intruding the metasedimentary schist and calc-silicate have been deformed in response to accommodate dextral, reverse motion.

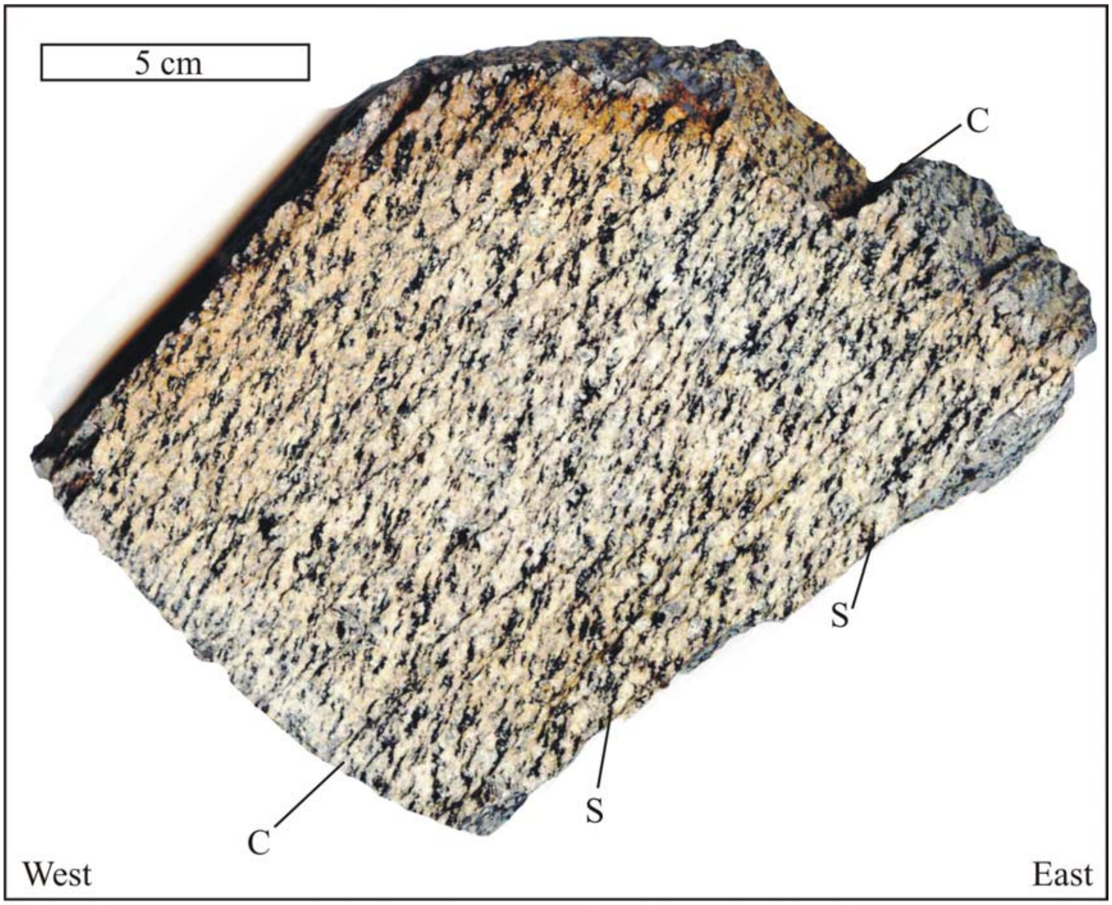


Figure 41: S-C mylonite developed in the Rush Creek granodiorite, collected on top of unnamed 3,134 m peak northwest of Gem Lake. Foliation (C-surface) is 150º / 38º at the sampling location; lineation is downdip (38º⟶254º). This section is perpendicular to foliation, but parallel to lineation. S-surface strikes the same as C-surface, and dips steeply (~75º) to the west. View of the sample is looking north along strike.

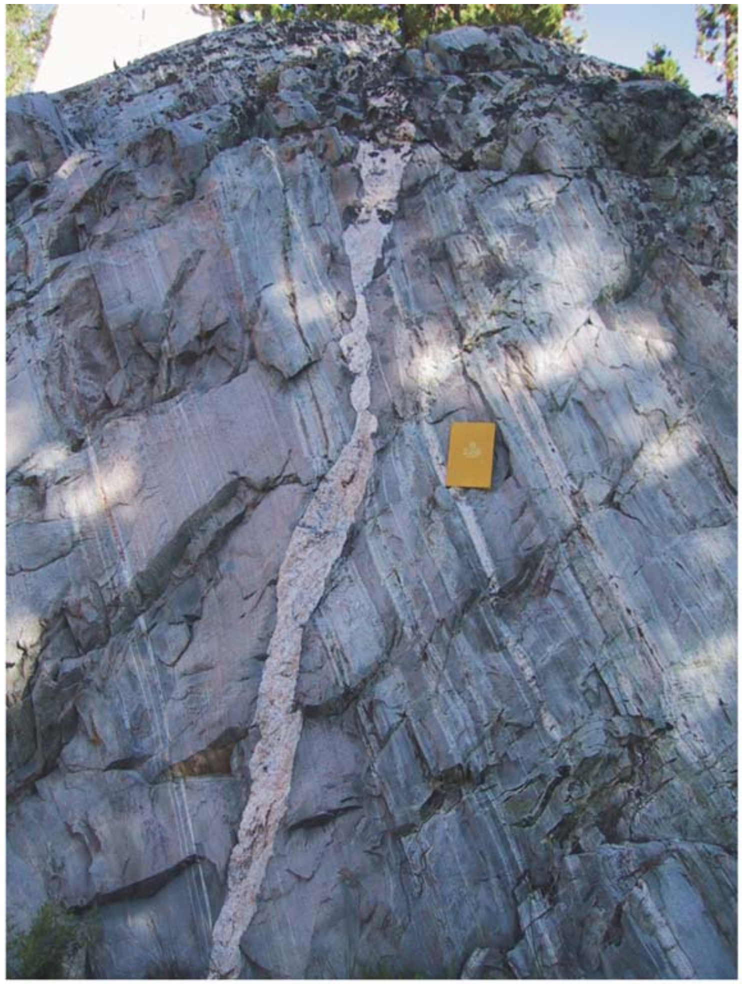


Figure 42: Stretched, dike of Cathedral Peak granodiorite which was boudinaged in response to dextral, reverse west-over-east sense of shear of pelitic schist and calc-silicate units, Cascade Lake segment of the Sierra Crest shear zone. Outcrop face strikes 068º and dips 74º, towards the camera. View is towards 331º. Field notebook for scale.

Magma from the accumulating pluton intruded along the established plane of foliation of the pelitic schist and calc-silicate wall rocks, bearing the characteristic megacrysts of orthoclase feldspar (Figure 29B). These large crystals are interpreted to have been brought in by the magma into areas between foliations of the host rock. Foliation wraps around the megacrysts, indicating (a) that they were full size, or close to it, at the time of intrusion, and (b) that the conduit through which they were inserted has since been compressed, leaving the large crystals in an incongruously thin dike. The Cathedral Peak granodiorite has in effect left its calling card with these crystals, showing clearly that foliation can influence dike emplacement. The segment map (Figure 16) shows that the same pattern is repeated on a larger scale: the contact displays a stair-step trace in map view. Stoping of blocks of well-foliated wall rock along planes of weakness (parallel to foliation) may have helped to enlarge the magma chamber (Paterson, personal communication, 2003). Bateman's (1992) map of the Mariposa 1º x 2º quadrangle describes the same stair-step pattern on a larger regional scale, and for the emplacement of not only the Cathedral Peak, but the Half Dome granodiorite as well. The stair-step pattern that we observe in two dimensions likely continues at depth (Paterson, personal communication, 2003).

The fabric in the edge of the Cathedral Peak granodiorite pluton, closest to the sheared metavolcanics strikes approximately ~130º and dips subvertically. Further into the interior of the pluton, the fabric strikes ~145º, while the dip remains approximately the same. Lineation gets steeper into the pluton (45º-66º) but is relatively shallow at the pluton edge (23º-49º). Davis et al. (1995) noted that the fabric is more intense at its margins of the pluton because it cooled first and thereby accumulated more finite strain than was imparted to the interior parts of the magma body (which were molten for longer). If the plutons were emplaced incrementally in a "nested diapir" style (e.g. Paterson and Vernon, 1995), the pattern of strain would be the same. While Tobisch et al. (1995) found that the Cathedral Peak granodiorite cooled from 700º to 500º C in 1 Ma. Glazner et al. (2004) propose that some of the plutons of the Tuolumne Intrusive Suite were emplaced piecemeal over >3 Ma (Half Dome granodiorite), and that the entire suite took 10 Ma to emplace. In contrast to the "geologically instantaneous" notion of pluton emplacement, this view would allow the outermost (oldest) portions of the plutons to be subsolidus (and therefore able to accumulate strain) for far longer than the interior portions. Quartz ribboning in the eastern margins of all three plutons indicates that transpressional deformation took place after the margin had cooled. However, evidence for subsolidus deformation is far less common in the youngest pluton, the Cathedral Peak granodiorite. Furthermore, a subsolidus S-C fabric is found in the Rush Creek granodiorite, the oldest of the shear-zone-bounding plutons, far from its contact with the host rocks.

4.3.2 Lineation

All three areas display great circle girdle lineation patterns (Figure 38). The Gem Lake segment data seem to have a bimodal distribution, with a tightly-grouped NNW-trending, ~45º dipping group of lineations and a more dispersed, subvertical group of lineations. While distributed across the whole segment, this latter group is found most concentrated along the shear zone's western edge, where it is truncated by the Rush Creek pluton.

The ignimbritic metavolcanic units in the bulk of the shear zone serve as excellent recorders of strain. Ductile deformation of felsic and mafic lenses (deformed lapilli) record a flattening strain that plots in the flattening field of the Flinn diagram (Figure 39). Axial measurement data from these deformed lapilli serve to estimate strain in the shear zone (Sections 4.3.1 and 5.5.2).

A possible bedding plane was observed oblique to foliation in the ignimbrite unit of the Mono Pass segment (Figure 25). Though clasts of different size and composition appear grouped together in planar arrangement ("bedding"), each individual clast is oriented with respect to the shear zone foliation (Figure 25C). This would appear to be a relatively less deformed section of the ignimbrite unit. This presents a challenge to any homogenous-model-based interpretation of the shear zone as a whole, because if any discernible bedding were to be preserved then local displacement would have been very minor indeed: on the scale of less than a meter! A more likely explanation is that strain was taken up heterogeneously by the shear zone's rock, and the area where this "bedding" was found was less deformed than neighboring lithologic units (perhaps it was in the pressure shadow of the only-moderately-deformed hypabyssal granite unit, which was immediately along strike to the northwest).

Conglomerates appear intercalated with the ignimbrite unit particularly in the Cascade Lake segment, frequently appearing at the demarcation between different sub-units. The conglomerates' component clasts serve as excellent strain markers, showing significant stretching which defines a steep lineation (Figure 19). Distinctly bedded sequences of chert and siltstone do not offer such clear strain markers, but they do exhibit boudinage in areas close to the edge of the shear zone (Figure 43).

Data from the Cascade Lake segment contradicts Tikoff and Greene's (1997) reported "shallowly dipping" lineations for that shear zone, used as field evidence supporting the lineation switch hypothesis. Paterson and Albertz have mapped in the same area and have also reported steep lineations for the Cascade Lake shear zone (Paterson, personal communication, 2003).

An additional complicating factor for considering the fabrics in this shear zone is raised by Albertz and Paterson (2002): the pluton edges could have a significant influence on the shear zone lineation. Their data indicate that stretching lineations in the Cascade Lake area host rock (i.e. not the pluton) are sub-vertical, but are significantly shallower towards the contact with the pluton. “Chocolate-tablet” (mutually perpendicular bi-directional) boudinage indicates orthogonal bi-directional stretching (Figure 43). They conclude that regional-scale simple-shear-dominated transpression is modified by flattening strain that resulted from pluton emplacement.

4.3.3 Kinematic indicators

Sigma- and delta- type tailed porphyroclasts, S-C fabric, *en echelon* fractures, imbricated feldspars and “chocolate tablet” boudinage indicate a sense of dextral, reverse (west-over-east) motion for the Gem Lake segment during shear zone deformation (Figure 44; Figure 45A) consistent with the interpretation of the area as a transpressional zone, though rare examples of sinistral indicators were also noted (Figure 45B).

4.3.4 Microstructure

Thin sections made from oriented field samples were examined under the microscope to precisely identify lithologies and microstructures of the various rock units mapped. Units identified in the field as similar were distinguished on the basis of their mineralogy. Microscopy also allowed investigation of microstructures on both the YZ (perpendicular to both foliation and lineation) and XZ (perpendicular to foliation but parallel to lineation) planes. The ignimbrite unit, common to all three surveyed segments of the shear zone, generally provided the best kinematic indicators

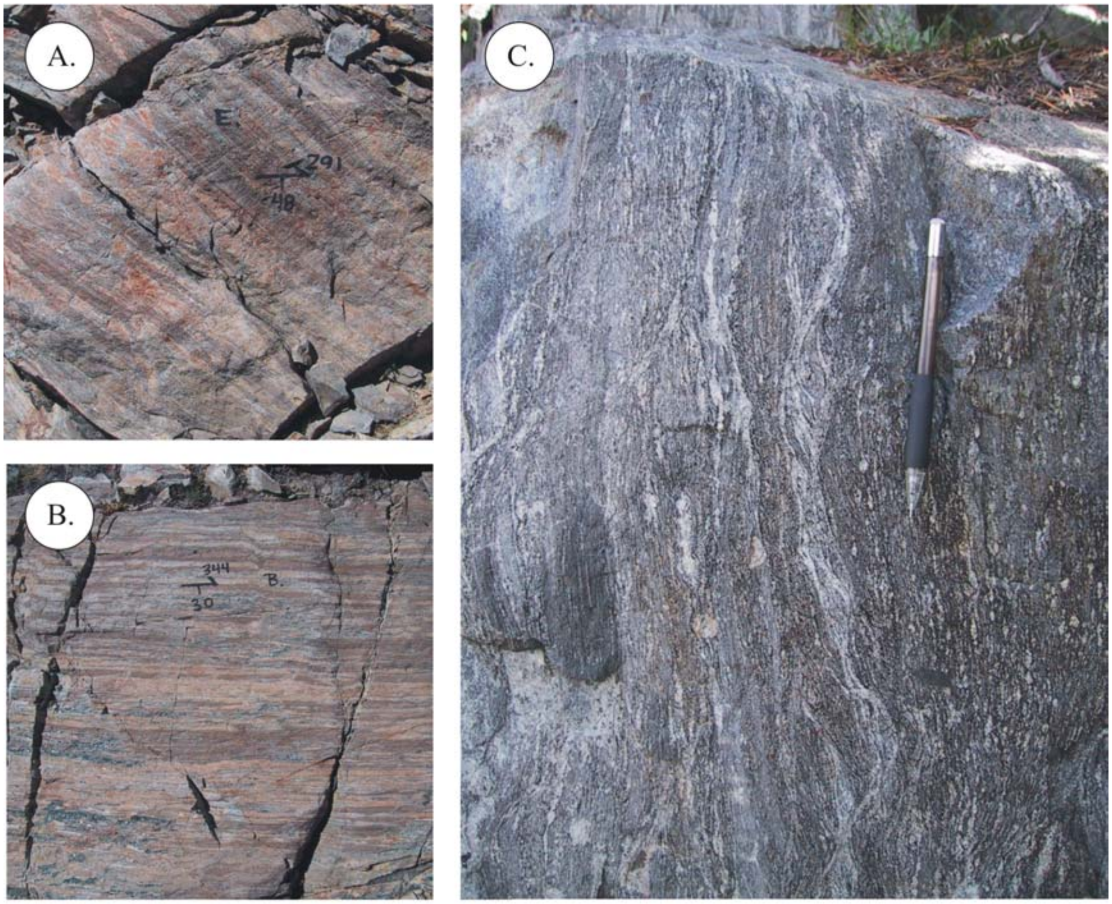


Figure 43: Chocolate-tablet boudinage. A) and B) Mudstone and sandstone exhibiting chocolate tablet boudinage in southeastern Cascade Lake segment of the Sierra Crest shear zone. Mudstone is boudinaged within sandy matrix. C) Fine-grained ignimbrite, western Mono Pass segment of the Sierra Crest shear zone. Outcrop is a subvertical face perpendicular to foliation. View is to the south.

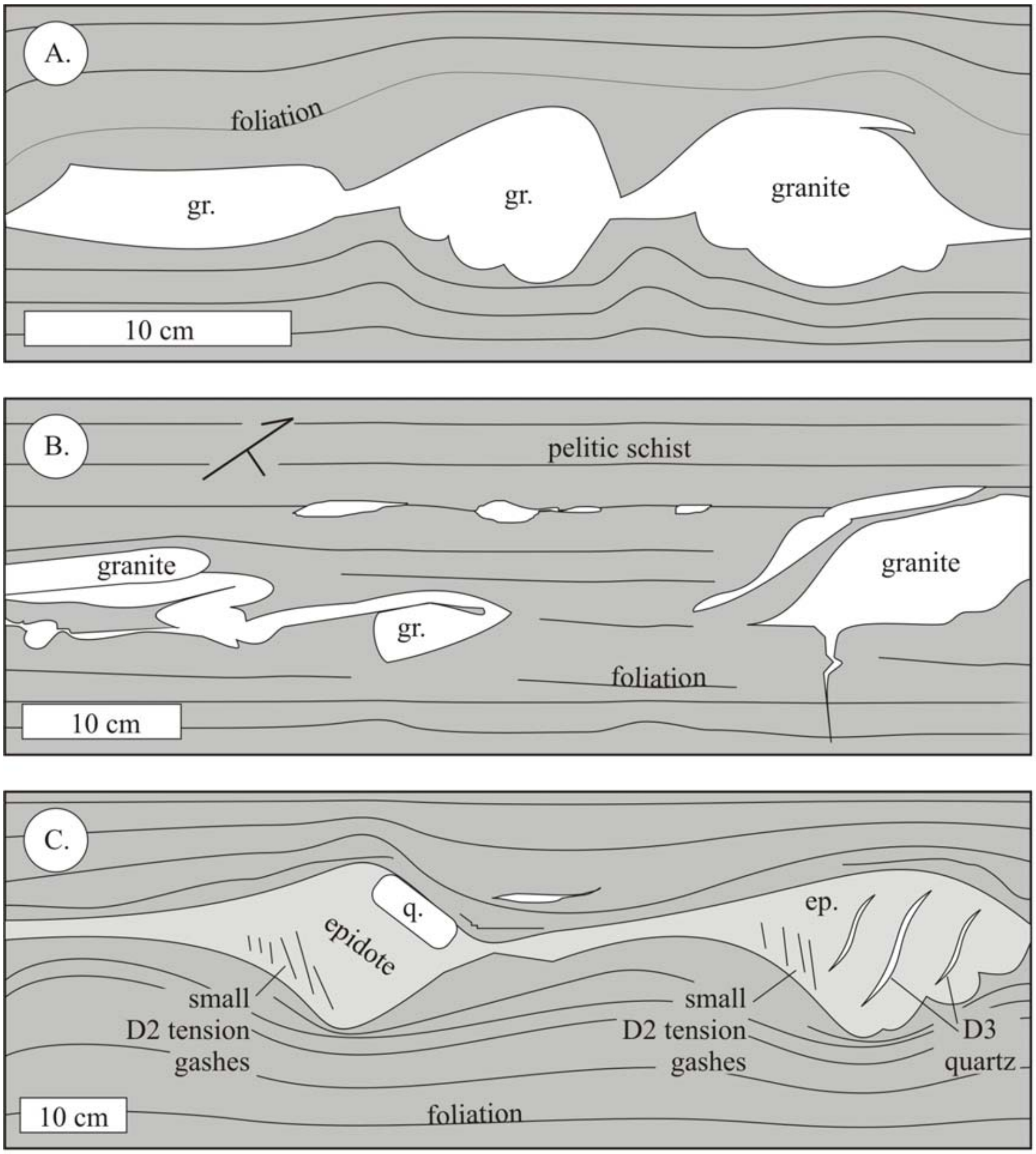


Figure 44: Evidence for (D2) dextral transpression; field sketches from the Cascade Lake segment of the Sierra Crest shear zone. A) Boudinaged granite dike in pelitic schist. Dike is overtly felsic, and likely an offshoot of the Cathedral Peak granodiorite. The boudins show asymmetry indicating dextral sense of shear. Subhorizontal outcrop. Foliation strikes 334°. Scale bar is 10cm. View is towards 065°. B) Ptygmatic fold of granite dike in pelitic schist, with asymmetry indicating a dextral sense of shear. Outcrop face 080°/55° (see symbol). Foliation strikes 328°. Scale bar is 10 cm. View is towards 040°. C) Boudinaged epidote pods with two generations of tension gashes: smaller set is filled with indeterminate mafic minerals and consistent with dextral transpression (D2); larger set with quartz infill is consistent with sinsitral sense of shear, and therefore D3. Subhorizontal outcrop. Foliation strikes 325°. Scale bar is 10cm. View is towards 078°.

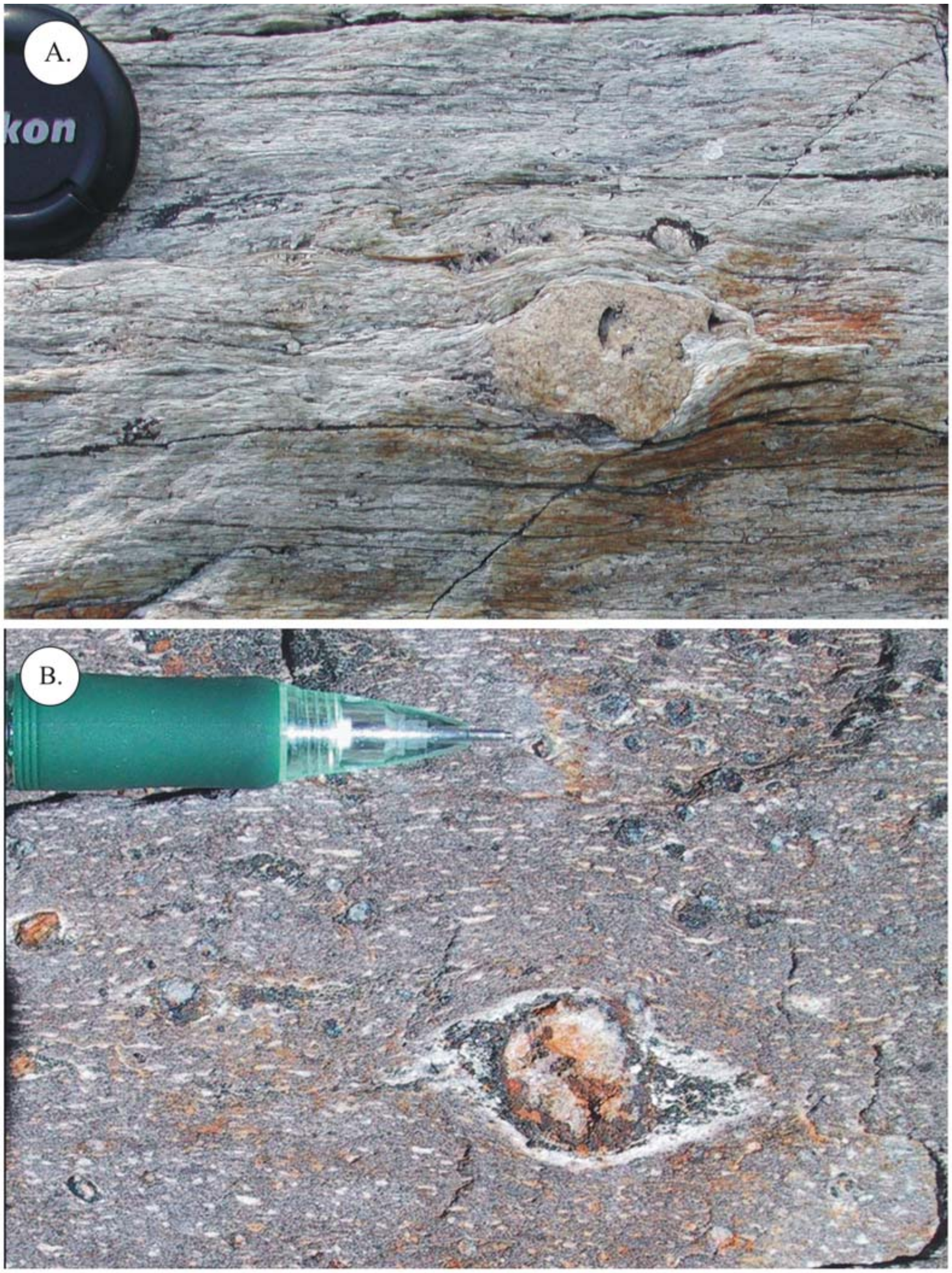


Figure 45: Porphyroclasts that serve as kinematic indicators, Sierra Crest shear zone. A) Dextral delta porphyroclast, Gem Lake segment. Section is approximately perpendicular to both foliation and lineation. Outcrop face strikes 240° and dips ~45°. Lineation at this outcrop plunges 46° towards 322°. Lens cap (3 cm diameter) for scale. B) Sinistral sigma porphyroclast, Cascade Lake segment. Section is approximately perpendicular to both foliation and lineation. Outcrop face strikes 024° and dips 14°. Pencil tip for scale. Lineation at this outcrop plunges 72° towards 354°. View is towards 077°.

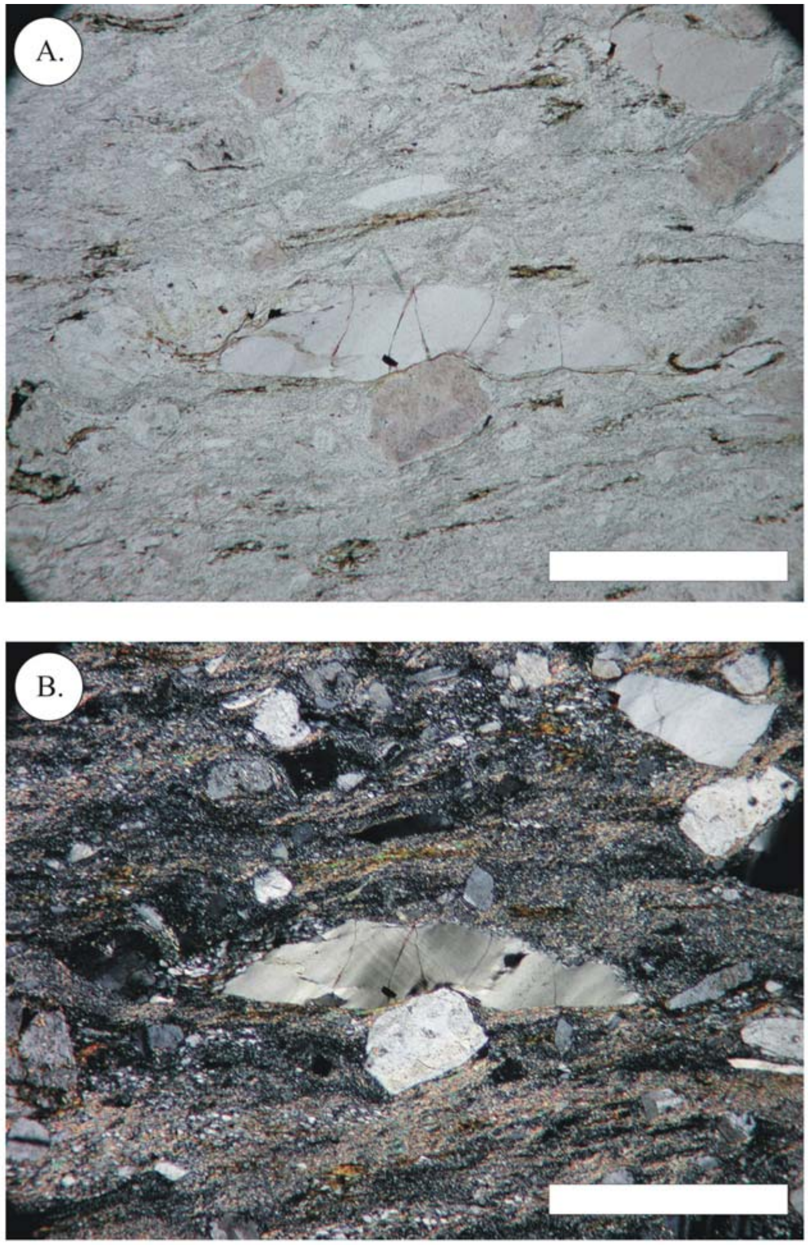


Figure 46: Quartz lattice deformation due to flattening normal to foliation, ignimbrite unit, Mono Pass segment of the Sierra Crest shear zone. Large central elongate quartz is impinged upon by rigid orthoclase feldspar clast. From the point where the feldspar is touching the quartz, undulose extinction indicating lattice deformation emanates into the less deformed portions of the quartz clast. Plane of section is perpendicular to foliation and parallel to lineation. Matrix is mainly quartz, muscovite, and biotite. A) Plane polarized light; B) Cross polarized light. Scale bar is 1 mm.

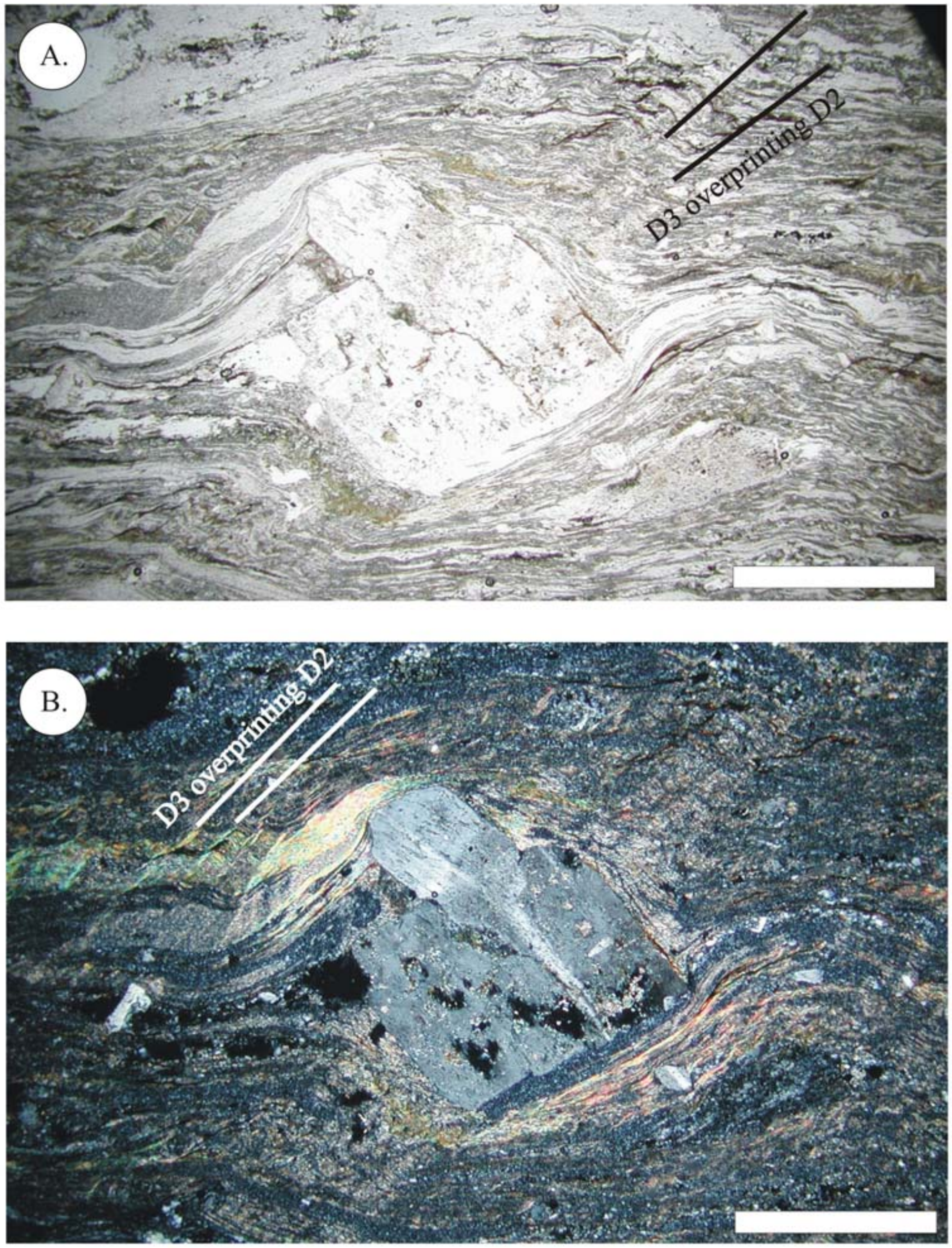


Figure 47: Dextral delta porphyroclast, ignimbrite unit, Gem Lake segment of the Sierra Crest shear zone. Plane of thin section is the YZ plane (perpendicular to both lineation and foliation). Large central porphyroclast is orthoclase feldspar; delta tails are mainly of muscovite mica and quartz; matrix is mainly quartz and muscovite mica. Note D3 kink bands overprinting D2 foliation in the matrix. A) Plane polarized light; B) Cross polarized light. Scale bar is 1 mm.

and most distinct microstructures. Figure 46 shows the flattening component of transpressional deformation well. In the polymictic ignimbrite, a rigid orthoclase feldspar is impinging upon an elongated quartz porphyroclast. At the site of impact, the quartz shows undulose extinction emanating through the quartz from the corner of the feldspar. These cross-hatched extinction lamellae indicate lattice deformation due to the flattening component of transpression. Figure 47 shows a winged porphyroclast indicating dextral shear of the shear zone. Small kink bands are also visible in the upper portion of the photographs, overprinting foliation. More distinct kink banding is shown in the muscovite and chlorite micas of Figure 48, where foliation overprinted by the kinks indicates oblique shortening of foliation with a dextral sense of shear. Figure 49 shows the development of a pronounced S-C microstructural fabric. The S-C fabric wraps around rigid porphyroclasts, and is defined by biotite alignment. As with the other samples, a dextral sense of shear is indicated.

4.3.5 Folding

The shear zone boundary is the plane beyond which bedding is fully transposed and all original bedding, folds, and structures have been obliterated by the shear strain. East of this plane, and therefore outside of the shear zone, the metasediments' second generation (D2) of folding overprints the first (D1; Figure 50). The Gem Lake segment is also the only area to show this fold-overprinting-fold relationship, though the other two segments show examples of folds overprinting foliation, and all three segments show isoclinal folding in their eastern metasedimentary domains. The second generation of folds (D2) is parallel to

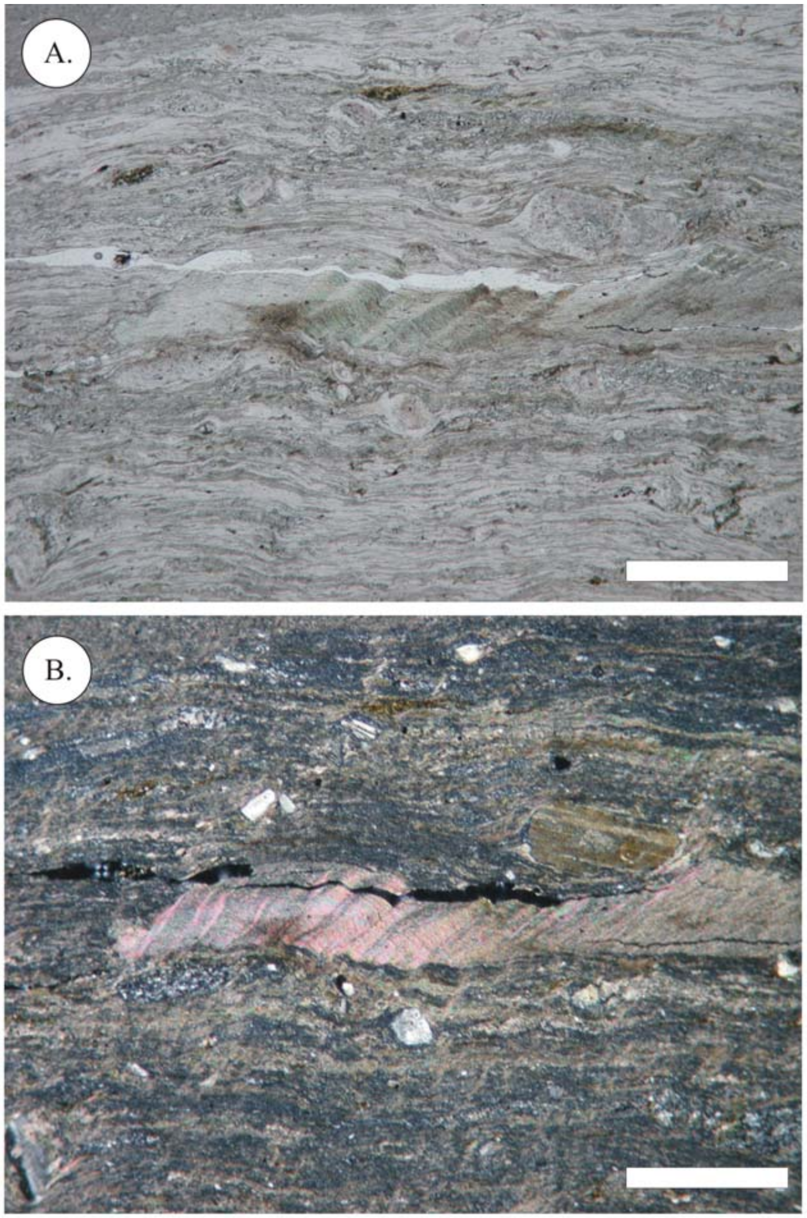


Figure 48: Kink bands in muscovite and chlorite, ignimbrite unit, Gem Lake segment of the Sierra Crest shear zone. Kinks overprint foliation; foliation was shortened by oblique shortening with a dextral sense of shear. Matrix is mainly quartz, muscovite, and biotite. A) Plane polarized light; B) Cross polarized light. Scale bar is 1 mm.

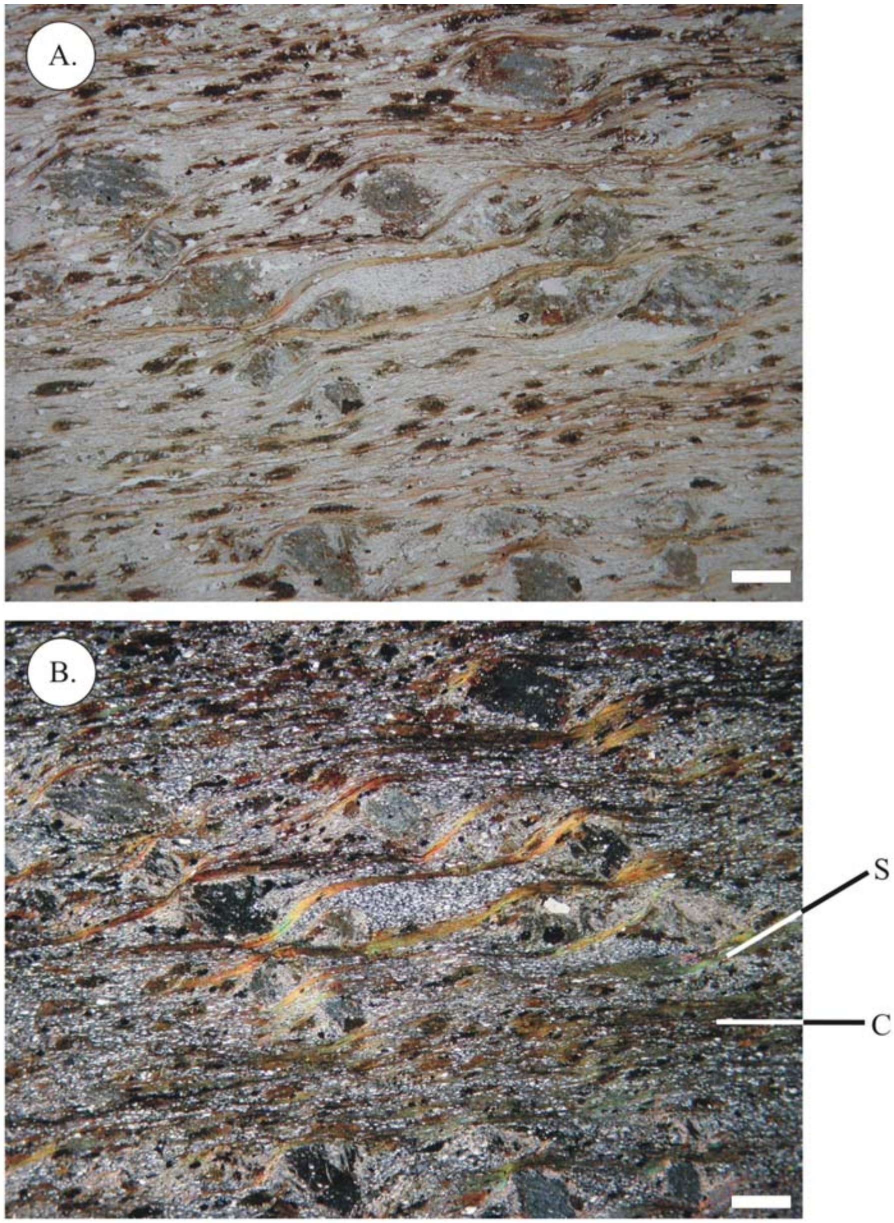


Figure 49: S-C fabric in ignimbrite unit, Cascade Lake segment of the Sierra Crest shear zone. S-C foliation is definted by biotite alignment; fabric wraps around clasts of orthoclase feldspar and quartz. Matrix is mainly quartz, muscovite, and biotite. A) Plane polarized light; B) Cross polarized light. Scale bar is 1 mm.

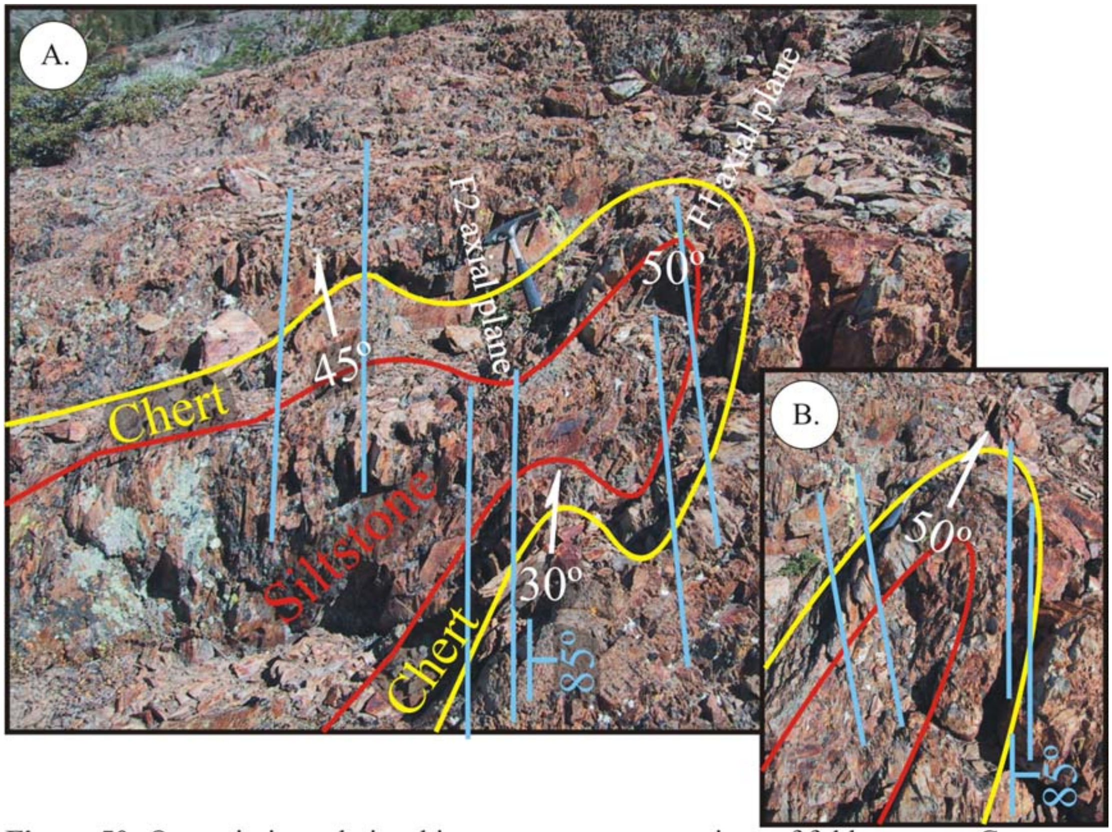


Figure 50: Overprinting relationships among two generations of folds, eastern Gem Lake segment. First (F1) generation of deformation creates recumbent near-isoclinal fold of siltstone and chert layers (younging outwards). F1 fold plunges at 50º towards 315º. Second (F2) generation refolds the fold with F2 fold axis plunging 30º to 45º towards 310º to 314º. Transposed foliation strikes parallel to F2 (~310º) and dips 85º to the northeast. A) Both generations. Hammer for scale. Camera is pointed towards ~315º. B) Hinge of F1 fold. Hammer for scale.

transposition foliation at the shear zone's eastern boundary. As noted above, the transposition foliation strikes ~N30ºW, parallel to the trend of the shear zone boundary, and dips steeply to the northwest (Figure 38). Away from the shear zone to the east, foliation is far less common. Where present, it trends more westerly (317° near Agnew Lake, for instance).

In Mono Pass, fold axes may be differentiated into different patterns inside and outside the shear zone (Figure 33). A series of folds in the pelitic schist unit in the western shear zone may represent post-shear zone deformation because they do overprint foliation. However, they may also represent drag folds that formed syn-tectonically with foliation, even though they overprint foliation. If so, this would offer an explanation for the grouping of these folds (D2 inside the shear zone) in the southeast quadrant of the stereonet (Figure 33): they would show a deformation path, as fold axes follow a progressive path towards parallelism with lineation, rotating from initial positions towards the vertical. Because they develop during shear, they are of the same generation of deformation that gave rise to the shear zone foliation, and therefore D2. However, if these folds were drag folds formed during shear-zone deformation, we would expect the more steeply-dipping folds to be more tight than the more shallowly-dipping folds, which should be relatively more open (Jiang and Williams 1999). Such a pattern was not observed in the field. This doesn't negate the possibility of the fold data representing a deformation path (the green arrow in Figure 33), but it does make it less likely.

4.3.6 Tension gashes

The extensional tension gashes that opened inside the shear zone, overprinting foliation, most likely denote post-shear-zone deformation. However, a large tension gash was observed in the northern Gem Lake segment, shown in Figure 51. This one was folded back on itself and had its main axis rotated in dextral reverse motion, indicating that although it overprints foliation, dextral transpressive deformation overprints it, and therefore it represents evidence of shear-zone (D2) deformation.

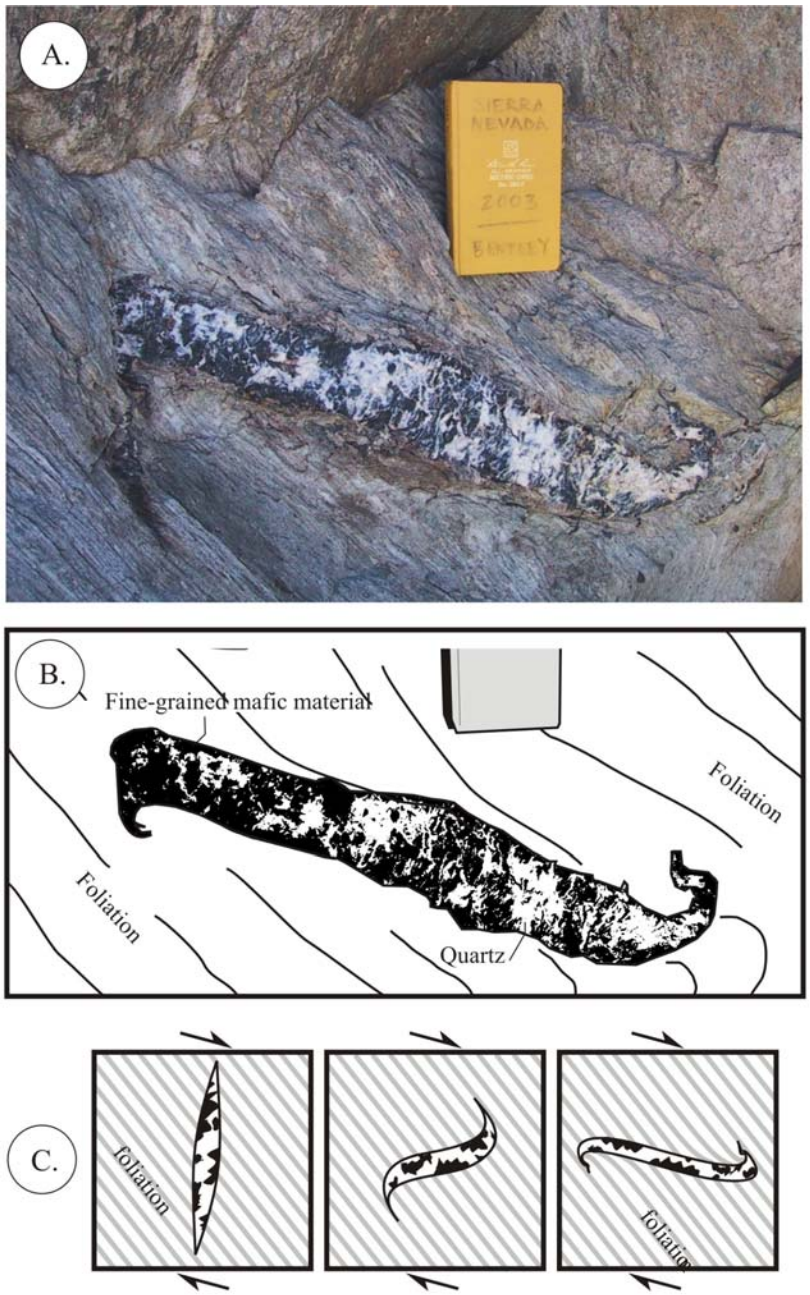


Figure 51: Sigmoidally deformed tension gash in foliated ignimbrite, Gem Lake segment of the Sierra Crest shear zone. A) Photograph showing large tension gash of quartz and fine-grained mafic material cutting across foliation. Distal-most "tails" of the structure curve back into parallelism with foliation. Field notebook for scale; long axis of field notebook is 19 cm. Outcrop surface strikes 135° and dips 56°. Foliation strikes 151° and dips 71°. View is towards 150°. B) Sketch showing major features of (A). C) Proposed mechanism by which this structure evolved: first, dextral transpressional shear opened a tension gash oblique to foliation, which was infilled by quartz and fine-grained mafic minerals, then the same dextral motion folded the gash back on itself, stretching its long axis out opposite to its original orientation.

4.4 Post-Shear Zone deformation

4.4.1 Kink banding

Kink bands were observed in large concentrations in the Gem Lake segment of the shear zone (Figure 52A, B). Because they overprint shear zone foliation, the kink bands indicate a later episode of deformation, D3, which is post-shear zone deformation. Kink axes plunge towards the northwest (Figure 53). The kink band planes themselves strike ~N60°W and dip moderately (~45°) to the northeast. My kinematic interpretation of these kink bands is presented in Figure 52C. Jiang et al. (2003) demonstrated that the direction of principal stress (σ_1) encourages the development of a conjugate set of kink bands in anisotropic materials. However, as Figure 53 shows, only one set of kink bands is developed in the Gem Lake segment of the Sierra Crest shear zone. The second of the conjugate set never develops because its orientation is subparallel to transposition foliation. Slip was likely accommodated on these pre-existing foliations, and the second set of kink bands never developed. The kink bands themselves are dextral, but their orientation demonstrates that the overall system is sinistral (Figure 52C). The overall system is also slightly transtensional; and the kink bands allow a slight widening of the overall shear zone – a finding indicating that D3 deformation was not only sinistral but also east-west extensional.

4.4.2 Folding

In the Gem Lake segment, similar to the kink bands, small-scale folds in the shear zone overprint foliation and plunge moderately to the northwest (Figure 54). These fold axes are parallel to those of the second generation outside the shear zone,

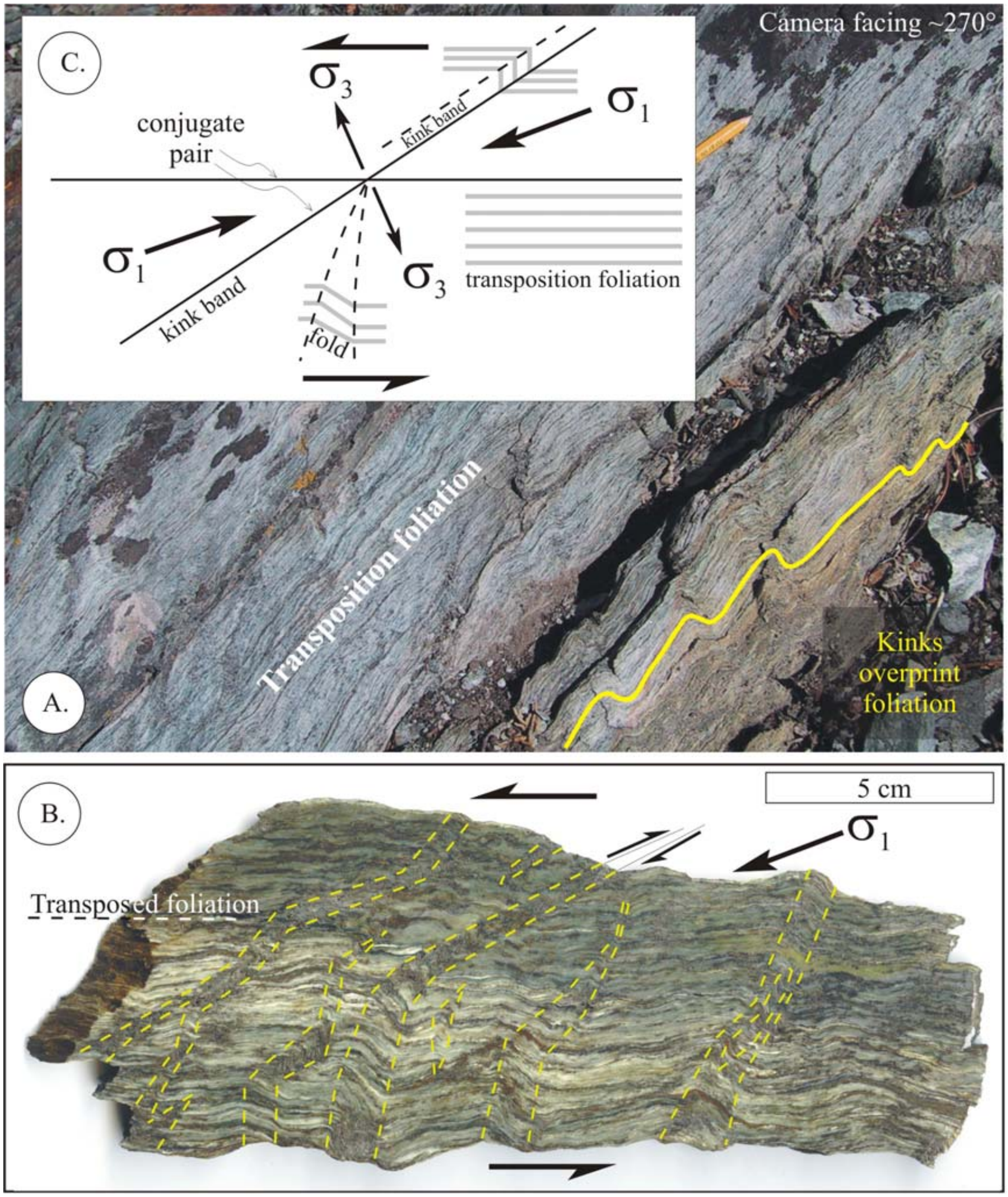


Figure 52: Kink bands in well-foliated ignimbrite, Gem Lake segment of the Sierra Crest shear zone. A) Photograph of kinked foliation *in situ*, tuffaceous ignimbrite unit. Trend of kinks highlighted in yellow. Outcrop surface strikes 040° and dips 40°. Foliation strikes 151°. Pencil for scale. View is towards 270°. B) Kink bands in sample GL08, from the same field station as (A). Hand sample was sawn perpendicular to foliation along strike, polished, and scanned. Scale bar is 5cm. Trends of kink bands highlighted in yellow. C) Kinematic interpretation of kink banding: sinistral, with principal stress (σ_1) oblique to foliation. A conjugate set of kinks is favored, but one is ~parallel to foliation, and so slip on pre-existing foliations serves as another slip system, conjugate with the kink bands.

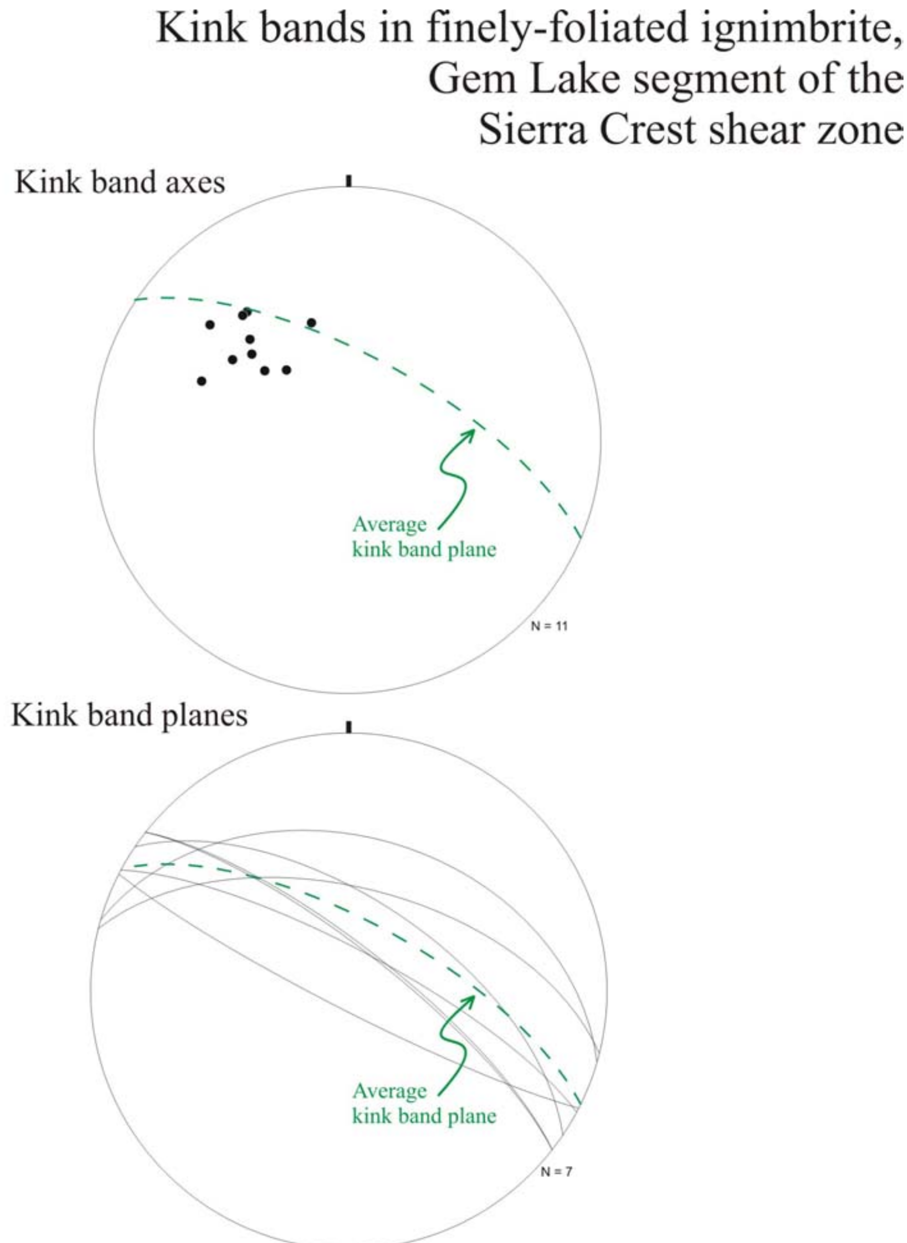


Figure 53: Orientation of kink bands in finely-foliated ignimbrite, Gem Lake segment of the Sierra Crest shear zone system. Upper stereonet shows relationship in the orientation of kink band axes with the average kink band plane. Lower stereonet shows variation in kink band planes.

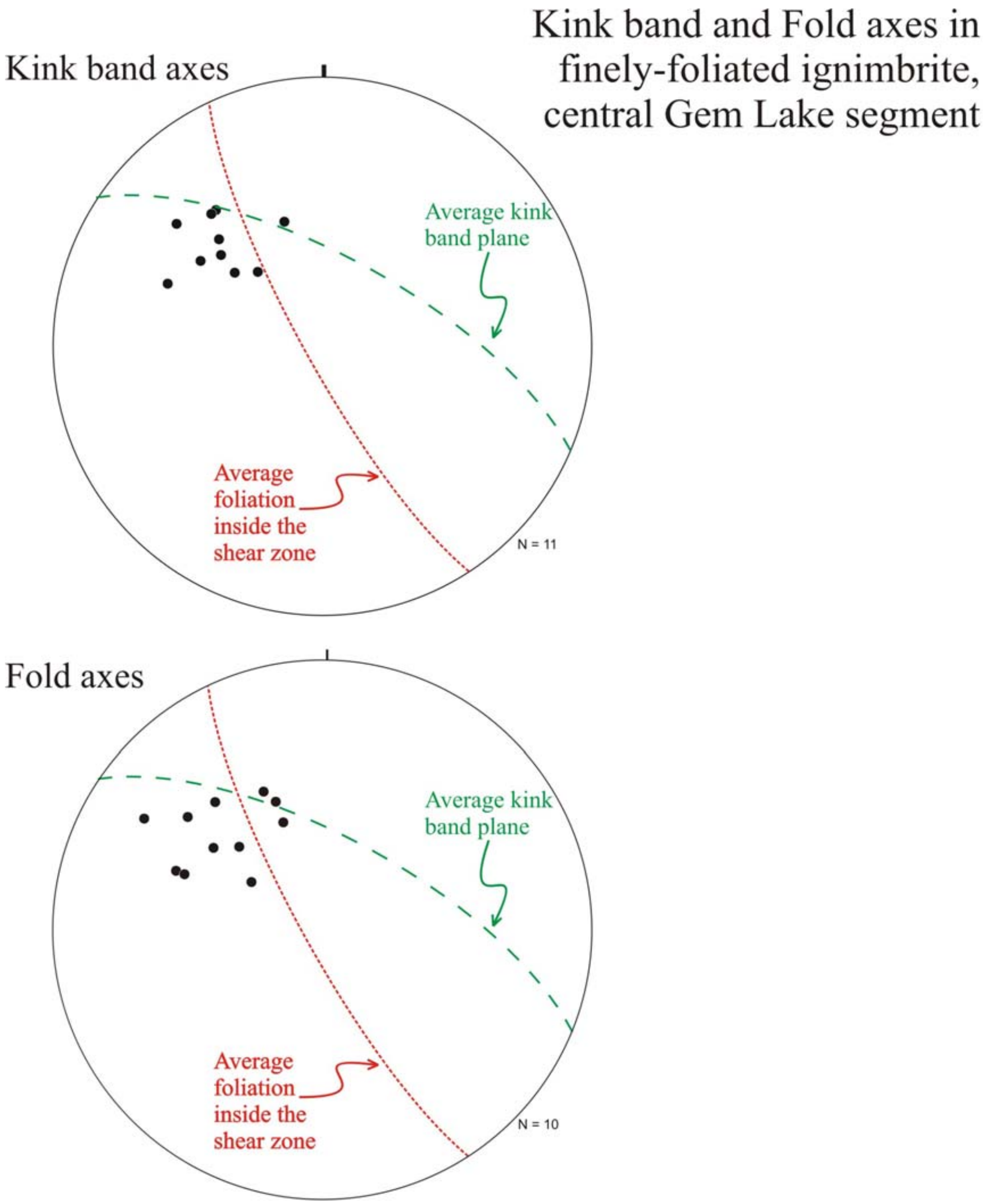


Figure 54: Orientation of kink band axes and fold axes in finely-foliated ignimbrite, Gem Lake segment of the Sierra Crest shear zone. Upper stereonet shows orientation data for kink band axes. Lower stereonet shows orientation data for third generation folds (overprinting foliation) in the shear zone. Fold axes and kink bands occurred in the same area of the shear zone. Not surprisingly, both groups of measurements cluster around the intersection of the average foliation inside the shear zone and the average kink band plane.

but must be of a later generation of deformation because they overprint foliation. These folds are by far the least common in the surveyed segments of the shear zone, a finding also noted by Russell and Nokleberg (1977).

Figure 29 compares fold axes inside and outside the Gem Lake segment. Axes of isoclinal folds of the first generation (D1) are noted in blue, indicating the first generation of deformation. Second generation folds that overprinted first generation folds (D2) are denoted in red, and their axes parallel the trend of regional foliation. Inside the shear zone, folds that overprint foliation (D3) are shown in green. Folds which meet none of these criteria are of an unknown generation, and shown in black. Based on trend and plunge alone, these folds of unknown generation are most likely shear-zone or post-shear-zone (D2 or D3).

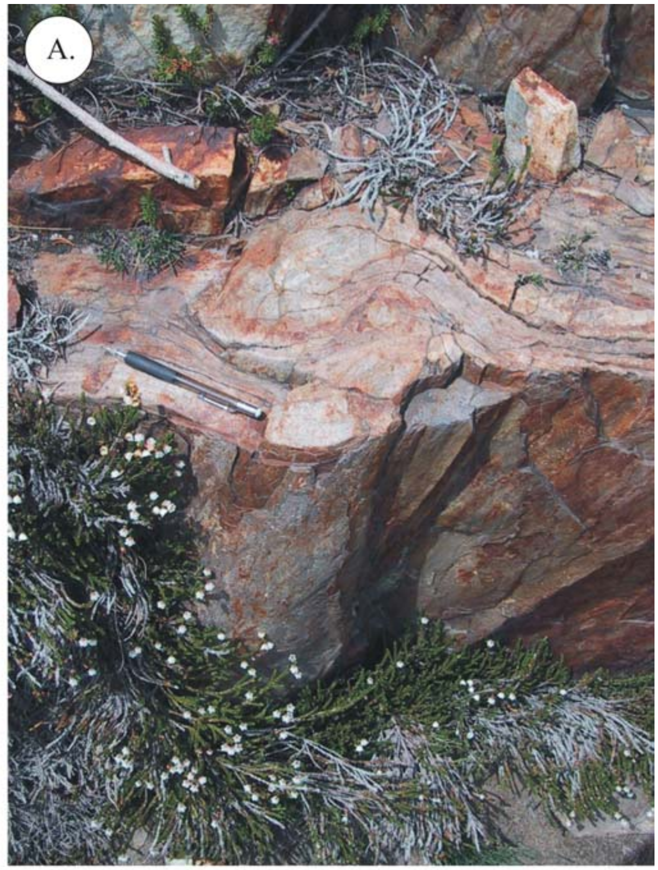
Similar folding of foliation appears inside the shear zone in both Mono Pass and Cascade Lake (Figure 55).

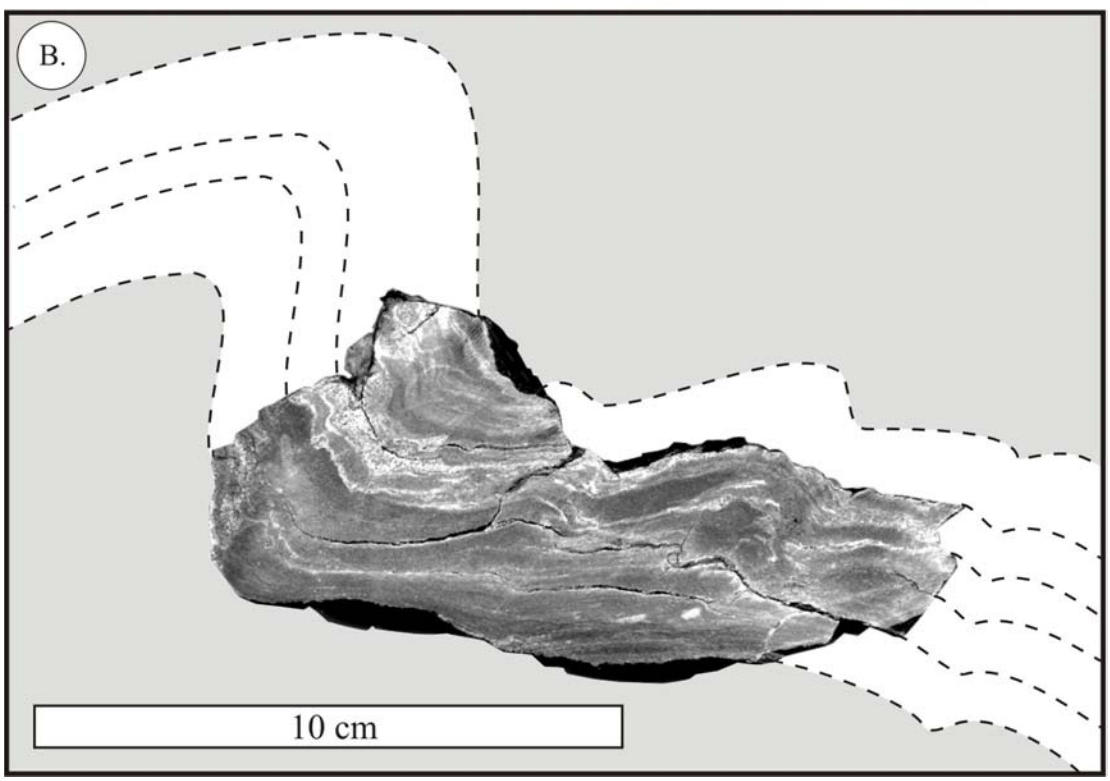
4.4.3 Fracture and reactivation of kink bands

Some kink bands were reactivated during yet-later deformation with a sinistral sense of motion, resulting in the opening of tension gashes along the kink band plane, and infilling with hydrothermal quartz (Figure 56). This may be correlated with the initiation of sinistral, east-side-up motion with the extensional regional regime that gave rise to the Basin and Range province, 14~16 Ma (Sonder and Jones, 1999).

Outside the shear zone, not all deformation in the wall rocks was ductile. Fracturing with an east-side-up, sinistral sense of shear occurred (Figure 57) in many areas. These fractures and brittle reactivation of the kink bands indicate that the rocks may have begun to be uplifted; they would have only stopped behaving in a ductile

Figure 55: Folding in shear zone, overprinting foliation in pelitic schist unit, Mono Pass and Cascade Lake segments of the Gem Lake shear zone. A) S-fold with subvertical axis, western Mono Pass segment. Pencil for scale. View is towards 260°. B) Z-folds in pelitic quartz schist, southwestern Cascade Lake segment. Section is perpendicular to fold axis, which plunges at 27° towards 334°. Dotted lines describe the trace of the folded foliation in the outcrop from which the sample was taken. Scale bar is 10 cm.





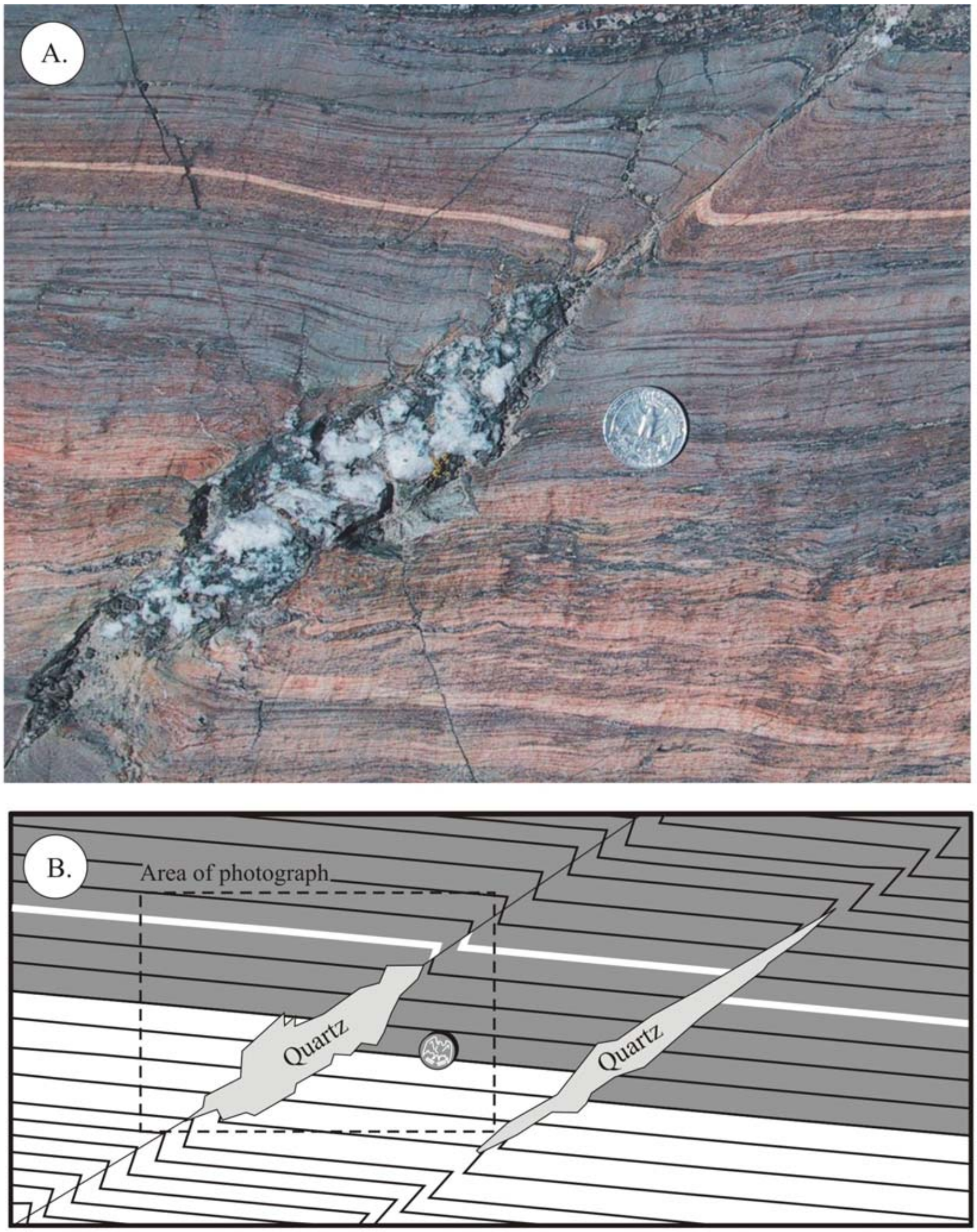


Figure 56: Evidence for reactivation of kink bands as tension gashes in foliated ignimbrite, Gem Lake segment of the Sierra Crest shear zone. A) Photograph showing a quartz vein overprinting a kink band plane. Light-colored marker band shows how foliation was kinked, then fractured along the plane of the kink band, with a sinistral sense of shear. Quarter for scale. Foliation strikes 155° and dips 75°. Kink band fold axis is 44° 305°. View is towards 245°. B) Sketch of larger area. Dashed box shows area of (A). Another quartz vein overprints another kink band plane. Orientations as in (A).

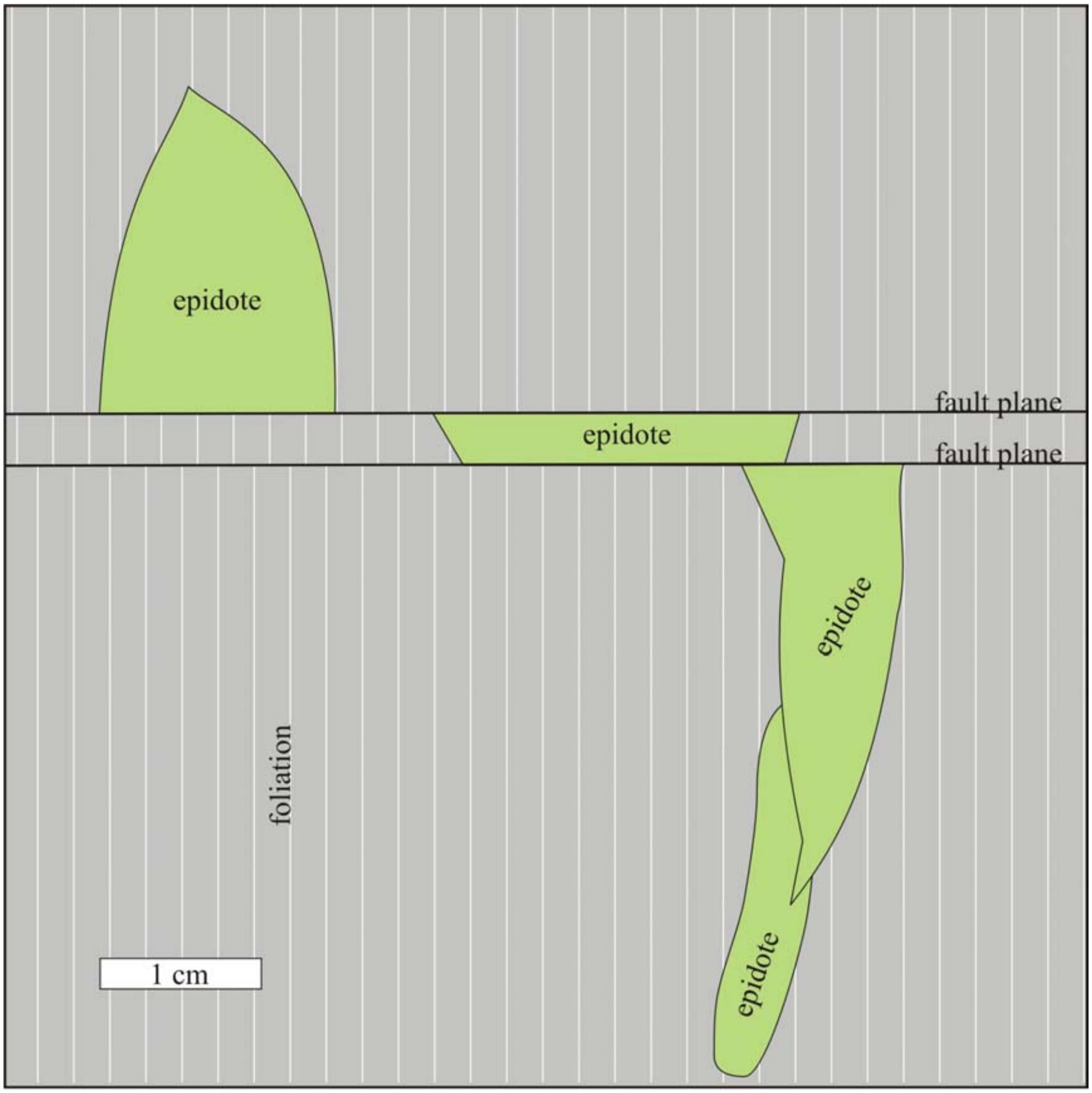


Figure 57: Field sketch of an epidote pod offset by faulting, foliated ignimbrite unit, Cascade Lake segment of the Sierra Crest shear zone. Total displacement is ~4 cm. Foliation laminae are also offset by the two small faults. Subhorizontal outcrop. Foliation strikes 305°. Scale bar is 1 cm. View is towards 305°.

fashion and begun to behave in a brittle fashion once they had been uplifted to or past the brittle-ductile transition. In the Gem Lake and Mono Pass segments, there was a competence contrast between strata of different lithologies, as evidenced by boudinage of more competent layers (Figure 58). In this case, sinistral, brittle D3 deformation overprints the D1 isoclinal fold.

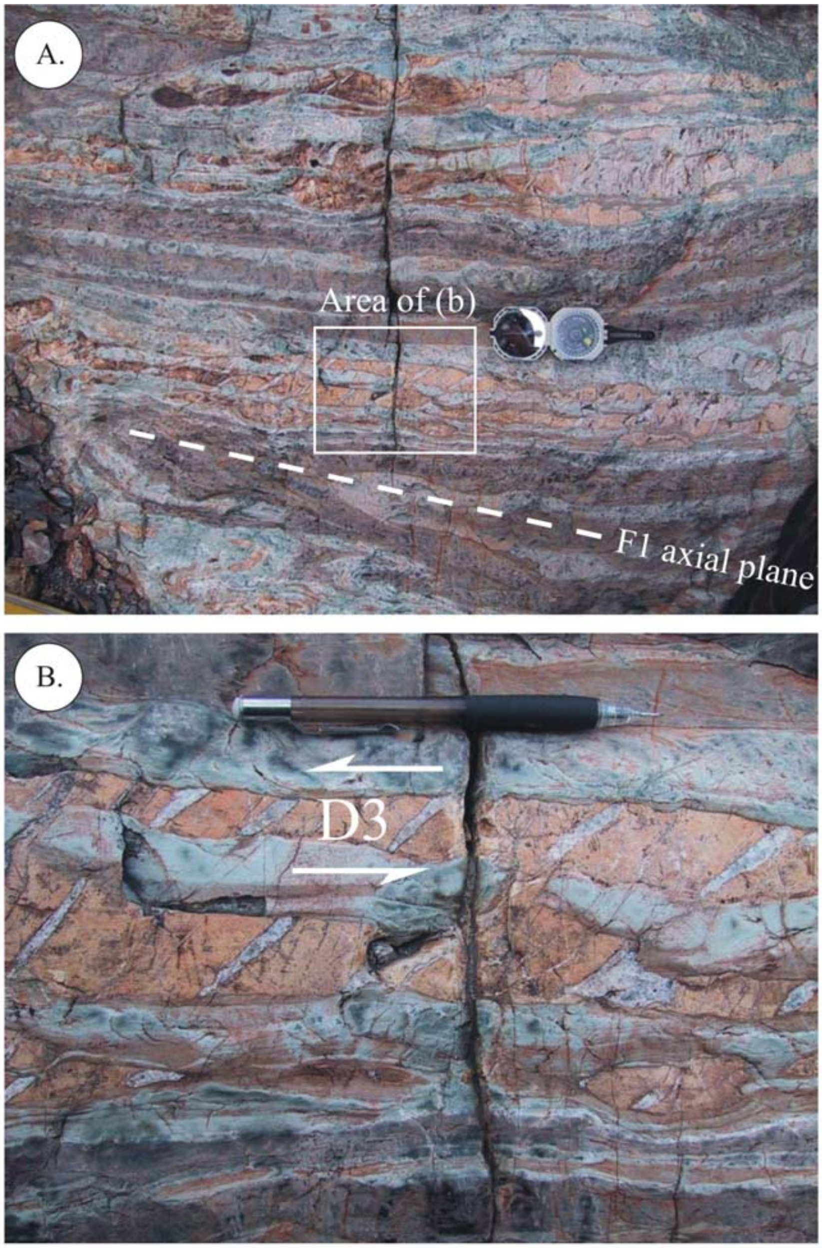


Figure 58: Boudinage and competence contrasts in chert and siltstone strata, Lewis Sequence metasediments, eastern Mono Pass segment of the Sierra Crest shear zone. D3 overprints D1. A) Siltstone layer is boudinaged within a more ductile chert matrix; tension gashes are filled in with quartz. Note the isoclinal fold in the lower portion of the picture. Fold axis plunged 40° towards 310°. Outcrop face strikes 332° and dips 26° towards the camera. Brunton compass for scale. View is towards 240°. B) Close-up of the boxed area in (A). Brittle, sinistral deformation is typical of D3 kinematic style. Pencil for scale.

4.5 Variations

4.5.1 Across strike variation

Each segment of the shear zone has steeply southwesterly dipping foliation on both its eastern metasedimentary margin and its western plutonic margin. In between, however, each segment varies. In the Gem Lake segment, for instance, foliation is steepest on the eastern boundary of the shear zone, and on its truncated western boundary in the Rush Creek granodiorite. In the center of this southerly segment of the shear zone, however, foliation dips moderately steeply to the west (Figure 59). At Gem Lake, the eastern edge of the shear zone bears moderately plunging (30˚~60˚) lineations, which continue across strike to the west to the rhyolite ignimbrite unit that corresponds roughly with the western shore of Gem Lake itself. From the rhyolite ignimbrite west into the dacite flow, lineation is much steeper relative to foliation, and approaches downdip in most locations. In the Rush Creek granodiorite, foliations parallel the regional trend of the shear zone in the eastern margin of the pluton, but diverge into a wider variety of attitudes beyond a 0.3 km from the eastern contact, approximately at the location of the thick dotted line ("Shear zone boundary") in Figure 14.

In the central segment, variation across strike is more moderate. In the Mono Pass segment of the shear zone, foliation is generally steeply–dipping, with a more southwesterly dipping pattern in the eastern part of the shear zone segment, and more northeasterly dipping in the western half of the segment. At several locations in the hypabyssal granite unit, foliation was vertical, perhaps marking a transition between these two dip-directions. At the margins of the Kuna Crest granodiorite, foliation

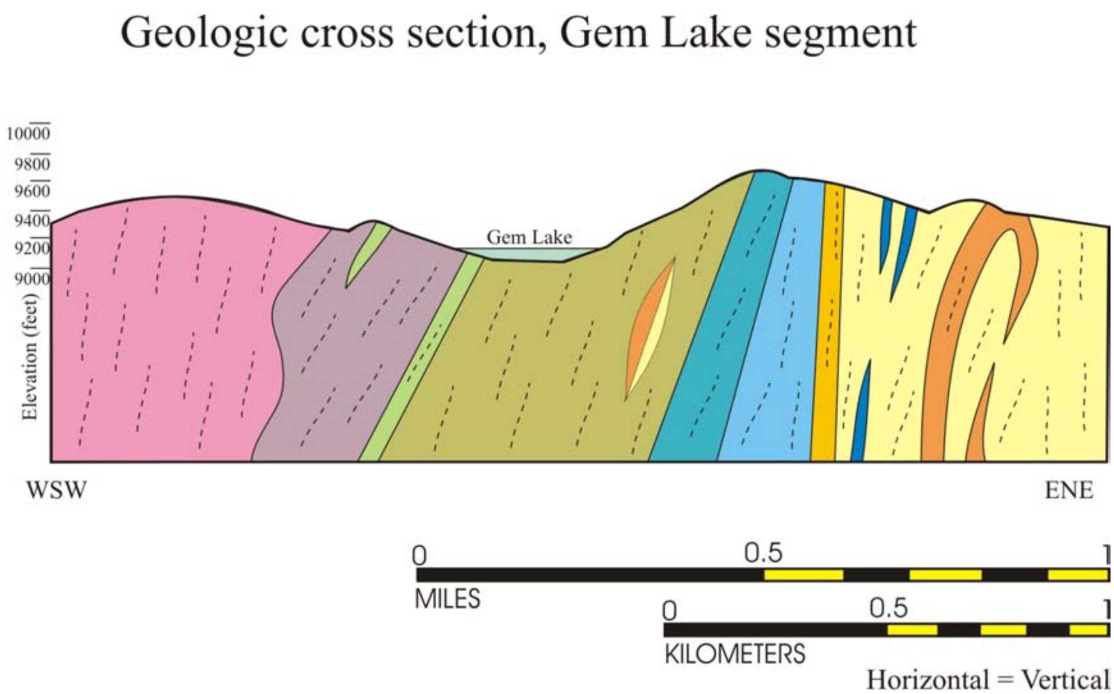


Figure 59: Schematic cross section, Gem Lake segment of the Sierra Crest shear zone system. No vertical exaggeration. Dotted lines represent traces of foliation. Legend as in Figure 14.

again dips to the southwest, a pattern that is shared by the fabric in the pluton itself (Figure 60). Lineation is steep in the eastern half of the segment, with downdip lineations observed in the hypabyssal granite unit and portions of the surrounding ignimbrite. In the very easternmost portion of the shear zone proper, however, the lineation is moderately plunging and not quite down-dip. In the western half of the segment, lineations trend steeply to the southeast. Lineations on both sides of the contact with the Kuna Crest granodiorite remained steep but trended to the southwest (Figure 15).

In the Cascade Lake segment, southwesterly-dipping foliation dominates the metasediments in the eastern portion of the shear zone. Isolated lenses of material (such as the slate unit) dip to the northeast even amid this general pattern. Foliation transitions to vertical or northeasterly dipping in the metavolcanic center of the

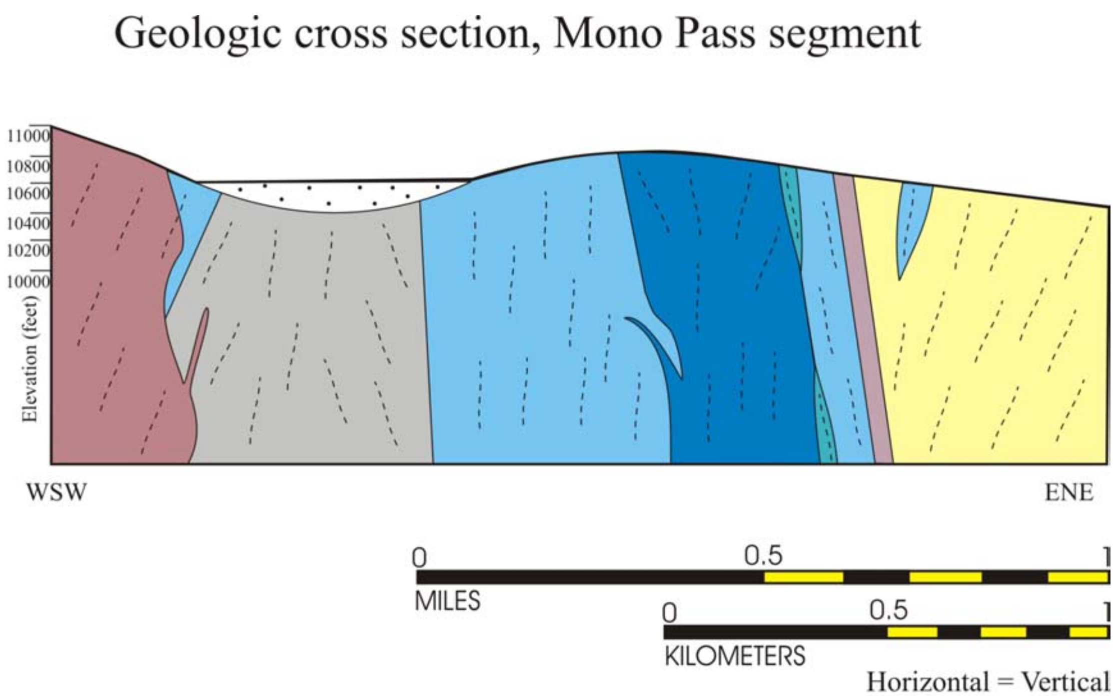


Figure 60: Schematic cross section, Mono Pass segment of the Sierra Crest shear zone system. No vertical exaggeration. Dotted lines represent traces of foliation. Legend as in Figure 15.

segment, a pattern that continues across the rest of this segment of the shear zone. In the Cathedral Peak granodiorite, foliation dips steeply northeast at the margins of the pluton, but steeply southwest further away from the contact (Figure 61). Lineation in this most northerly segment is steep to downdip in the eastern portion of the shear zone (in the shale/mudstone and easternmost ignimbrite units, as well as in portions of the central mafic ignimbrite unit). In the western portion of the segment, lineations are more moderately dipping (60˚~30˚), particularly in the pelitic quartz schist and calc-silicate units west of the metavolcanic sequence. In the margins of the Cathedral Peak granodiorite, lineation remains moderate (60˚~30˚) to the southeast, though approximately half a kilometer into the pluton, lineation swings around and trends of the south or southwest (Figure 16).

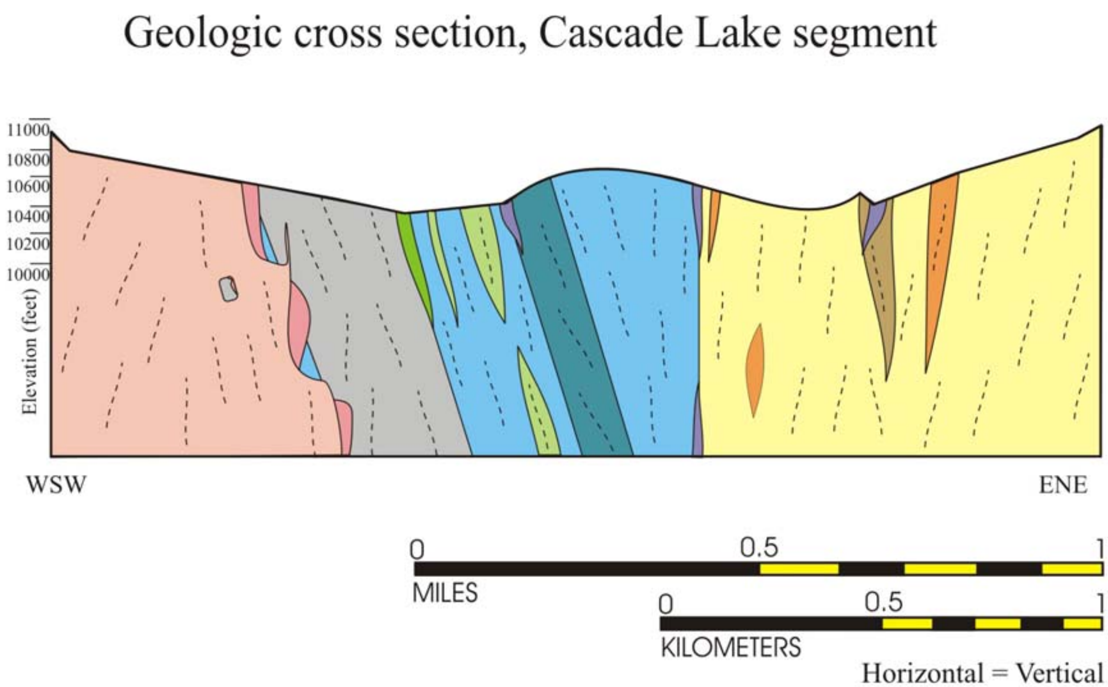


Figure 61: Schematic cross section, Cascade Lake segment of the Sierra Crest shear zone system. No vertical exaggeration. Dotted lines represent traces of foliation. Legend as in Figure 16.

4.5.2 Along strike variation

Surveying the shear zone in three segments along its length allows comparison of strain pattern between southerly, central, and northerly segments. All three segments share the characteristics of having steeply southwest-dipping foliation in the metasedimentary units at their eastern boundaries and steeply southwest-dipping foliation in the igneous plutons at their western boundaries. In the shear zone itself, foliation is most southwesterly dipping in the southernmost Gem Lake segment, and most northeasterly dipping in the northernmost Cascade Lake segment. The central Mono Pass segment is transitional between these two, with a dominantly vertical foliation, with separate zones of “splayed” foliation, narrowing upward in the pelitic schist unit (Figure 60).

Each segment can be broadly divided into a more moderately dipping (30˚~60˚) domain and a more steeply (downdip or quasi-downdip) dipping domain. In the southern portion of the shear zone (Gem Lake segment), the downdip portion is in the western "half" of the segment, while the moderately dipping portion is in the east. The reverse pattern is true in the northerly portion of the shear zone (both Mono Pass and Cascade Lake segments), which both have an eastern downdip / steeply dipping portion, and their moderately dipping portions on the west, adjacent to their plutons. However, the Mono Pass segment has its 'downdip' portion more centrally located, with a small moderately-dipping zone along the eastern edge of the shear zone. Furthermore, the directions of the moderately dipping zones of lineation vary between the different segments. The Gem Lake segment's moderately-dipping lineations predominantly trend to the northwest, while moderately dipping lineations in the Mono Pass segment trend to the south (on both sides), and in the Cascade Lake segment, to the southeast.

The overall shear zone appears to be a ribbon-like shape, dipping to the southwest in the south and to the northeast in the north, the location of the highest-strained portions of the zone vary systematically, from the eastern half in the south, to the center of the shear zone (across strike) in the center of the shear zone (along strike), to the western half in the north.

Chapter 5: Kinematic interpretation of the study area

5.1 Conditions at the time of deformation

5.1.1 Temperature and Pressure

Hornblende geobarometry data indicate granitoid emplacement at 1.2-2.4 kbar, corresponding to 4.5-9.0 km depth, at temperatures of 665º-730º C (Ague, 1997; Ague and Brimhall, 1998). This corresponds with Bateman's (1992) estimate of 4-8 km of erosion since 100 Ma.

5.1.2 Brittle-ductile transition

Shear zones may be thought of as "ductile faults" (e.g. Ramsay and Graham, 1970), and the majority of deformation that defines an area as a shear zone is therefore ductile in nature. However brittle deformation is not absent from the Sierra Crest shear zone: "bookshelfed" porphyroclasts, kink bands, and small-scale faulting all indicate brittle behavior at various scales. Based on overprinting relationships, however, the kink banding and small-scale faulting occurred after the bulk of ductile shear zone deformation, and only the brittle behavior of feldspars and other porphyroclasts can be justifiably considered part of the shear zone deformation.

5.1.3 Pluton emplacement

Field evidence indicates that pluton emplacement was syntectonic. As noted in Section 3.5.2, foliated xenoliths and the preferential intrusion of magmatic dikes along planes of foliation indicate that shear zone deformation was already well underway when the plutons were emplaced. While magmatic fabrics trend N60˚W, solid-state fabrics that trend N30˚W in the plutons (parallel to neighboring host rocks) indicate that shear zone deformation continued to occur after crystallization of the plutons.

5.2 Pre-shear zone deformation

Schematic block diagrams have been prepared for each segment of the shear zone, showing key kinematic data as well as foliation and lineation (Figures 62, 63, and 64).

5.2.1 Preservation of primary structures

The magmatic *schlieren* planes present in the hypabyssal granite unit in the Mono Pass segment (Figure 63) are interpreted to be related to magma-emplacement processes. Their orientations (Figure 53) correspond to regional trends in other plutons beyond the shear zone (Bateman, 1992).

5.2.2 First generation isoclinal folds

First generation folding is isoclinal in nature. Both the Gem Lake segment and the Cascade Lake segment displayed F1 folds (Figures 62 and 64). In the Gem Lake segment, these isoclinal folds were overprinted by second generation (F2) folds. In the Cascade Lake segment, no such folds were noted (Figure 64). However in the Mono Pass segment (Figure 63), no distinctive F1 folds were noted, which may be because the fold axes were too shallowly dipping to be noted in mapping surveys. Because the Mono Pass segment lies between the Gem Lake and Cascade Lake segments, it is inferred that F1 folds may be present there, and might be detected in future surveys.

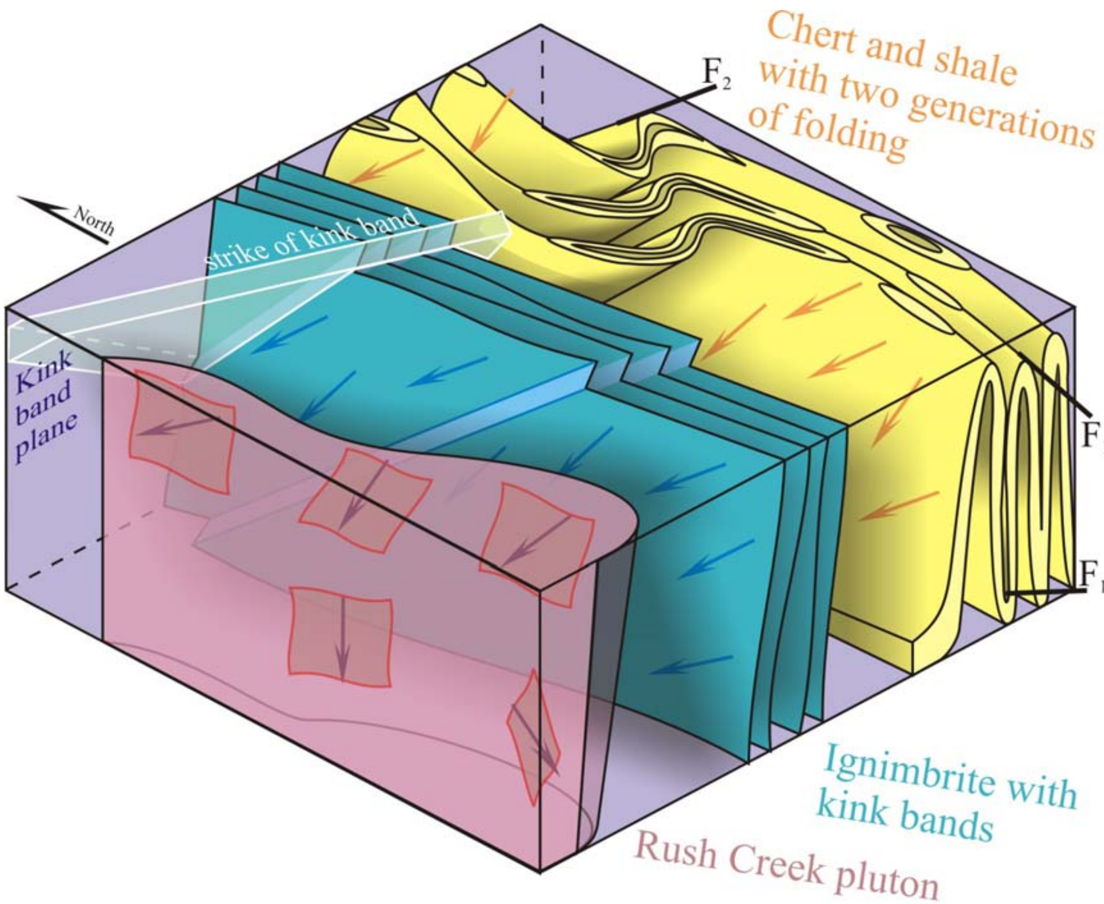


Figure 62: Schematic geologic block diagrams of the Gem Lake segment of the Sierra Crest shear zone system, emphasizing key elements of structural geometry. F1 and F2 folds noted, as well as orientation of kink bands, lineation, and foliation in select units.

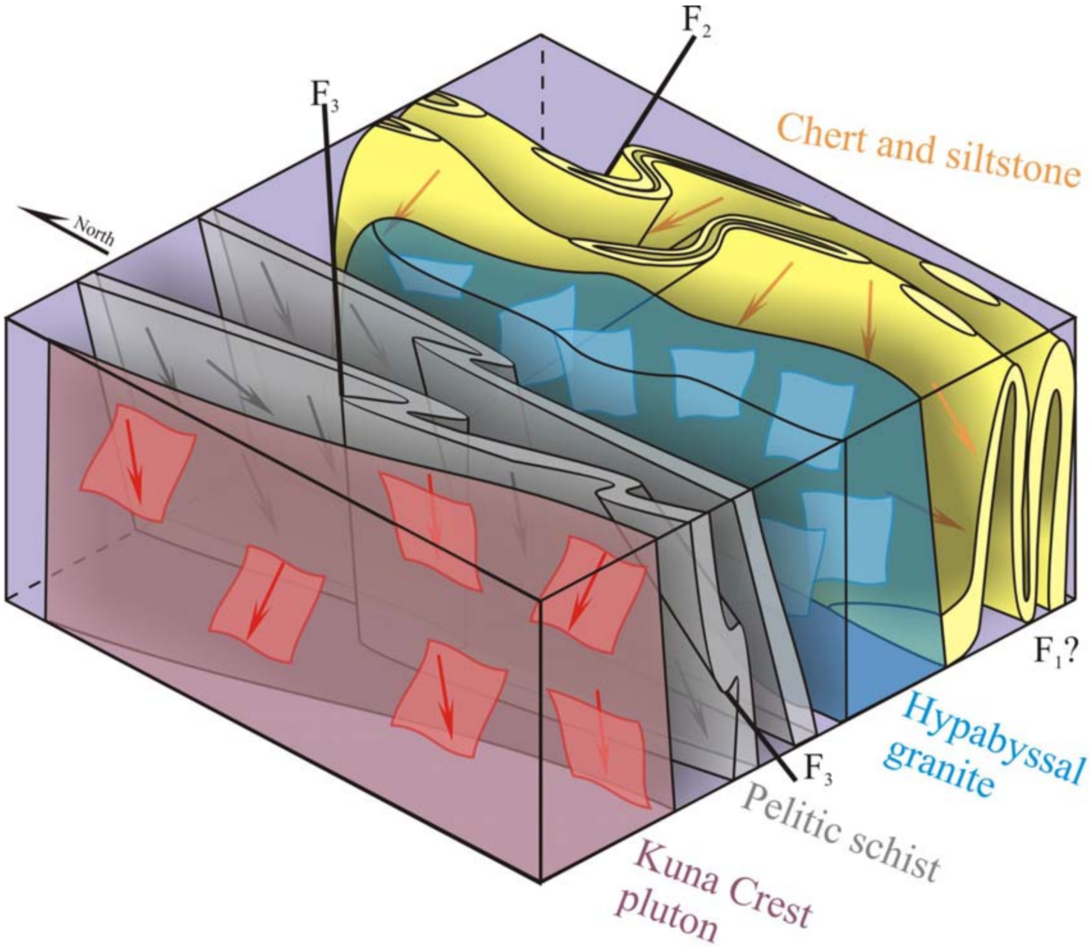


Figure 63: Schematic geologic block diagrams of the Mono Pass segment of the Sierra Crest shear zone system, emphasizing key elements of structural geometry. F1 and F2 folds noted, as well as orientation of kink bands, lineation, and foliation in select units.

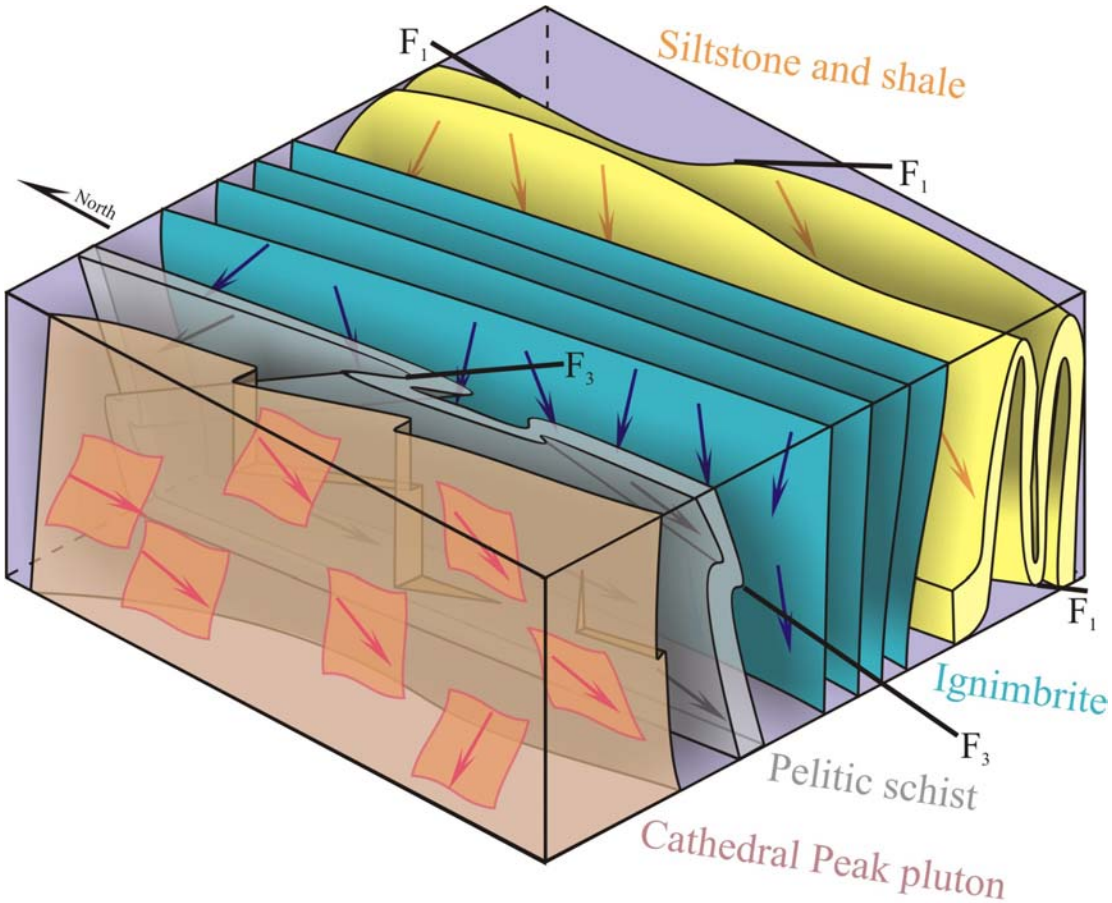


Figure 64: Schematic geologic block diagrams of the Cascade Lake segment of the Sierra Crest shear zone system, emphasizing key elements of structural geometry. F1 and F2 folds noted, as well as orientation of kink bands, lineation, and foliation in select units.

5.3 Shear zone deformation

5.3.1 Development of transposition foliation

The foliation observed in the Sierra Crest shear zone parallels the overall N30˚W trend of the shear zone, and indeed defines the shear zone itself. The line beyond which primary structures were obliterated was defined as the shear zone boundary. Thereafter, transposition foliation was pervasive, and only in isolated pods of less deformed material (see Section 5.3.3) were primary structures preserved.

Transposition of foliation in the shear zone created vast tabular zones of a dozen lithologies, which varied across strike in parallel bands or elongated lenticular pods.

5.3.2 Lineation

Overall, model predictions of a coherent, steady-state homogenous shear zone would have lineation varying in a systematic way across strike. Figure 65 shows model predictions using the forward numerical model used to test the stability of monoclinic solutions in Chapter 1. Figure 65 plots the pitch of lineation against distance from the eastern edge of the shear zone. Pitch is used because plunge is determined by the orientation of the plane of foliation in which the lineation rests; only pitch varies independently of foliation's angle; a 90° pitch is therefore downdip, regardless of what the dip itself may be. The eastern edge only is used in these plots because the shear zone is of unknown total width (an unknown portion of sheared rock was consumed by the intrusion of the westerly bounding plutons). These model results predict shallowly-plunging lineation along the outer edges of the shear zone, and steeply-plunging lineations in the center of the shear zone. The mechanism by which the transition between shallow (subhorizontal) and steep (subvertical) lineation is made depends on Φ: if the shear zone model is monoclinic, it is an instantaneous switch (as in Figure 65A). With increasing degrees of triclinicity (Figure 65B-D), the lineation evolves more and more progressively.

However, as the segment maps (Figures 14, 15, and 16) have indicated, and Figure 66 shows decisively, there is no such pattern evident in the Sierra Crest shear zone. The pitch of lineation varies widely from the edge of the shear zone to its center. There is no systematic variation of lineation across strike.

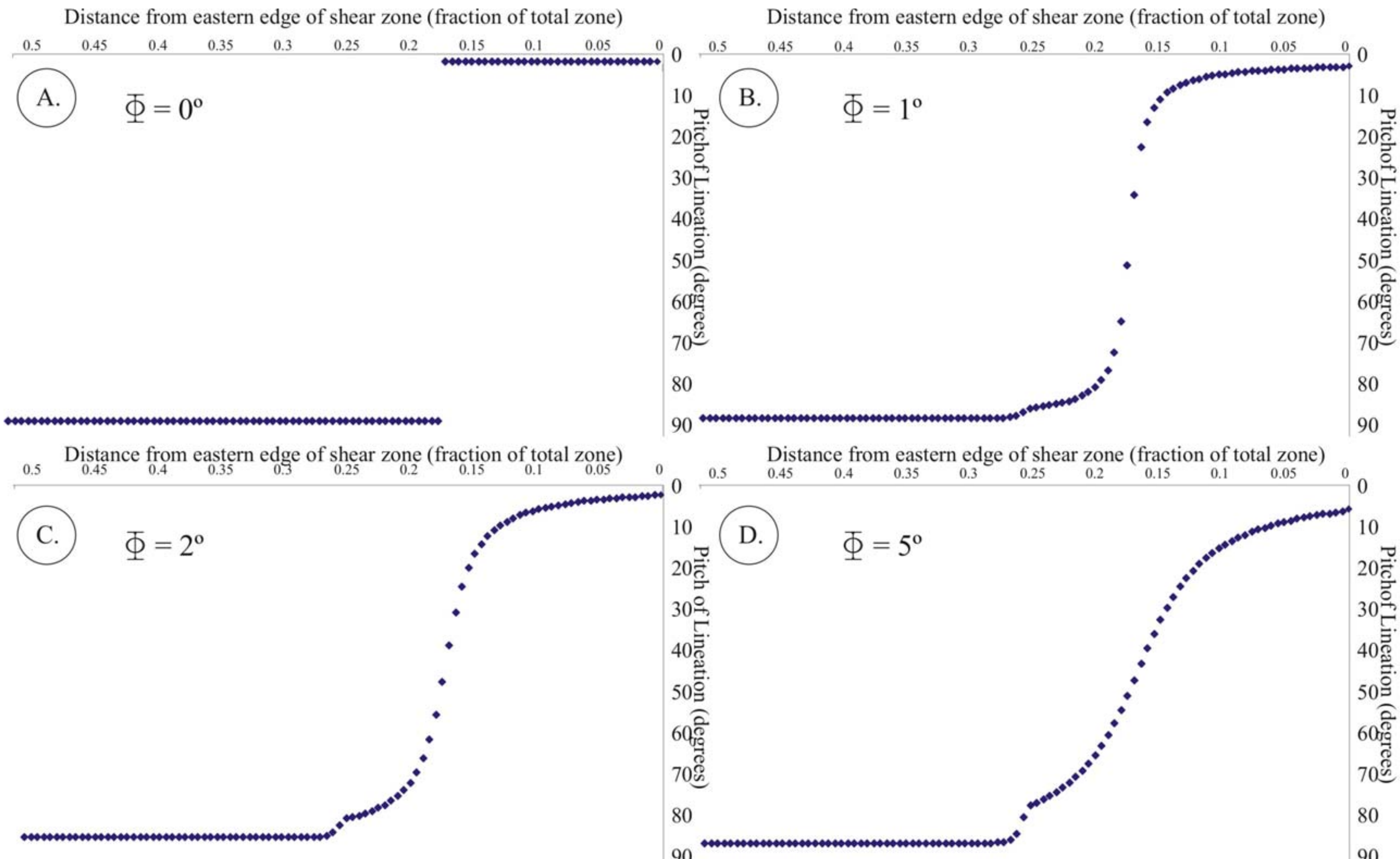


Figure 65: Model predictions for pitch of lineation (in degrees) plotted against distance across strike of shear zone (in fraction of total zone width) for different values of Φ. Model conditions as in Figures 9 and 10. A) Monoclinic $\Phi = 0^{o}$. Lineation switches instantly from horizontal to vertical. B), C), and D) Triclinic. $\Phi = 1^{o}$, 2^{o}, and 5^{o}, respectively. Lineation evolves progressively.

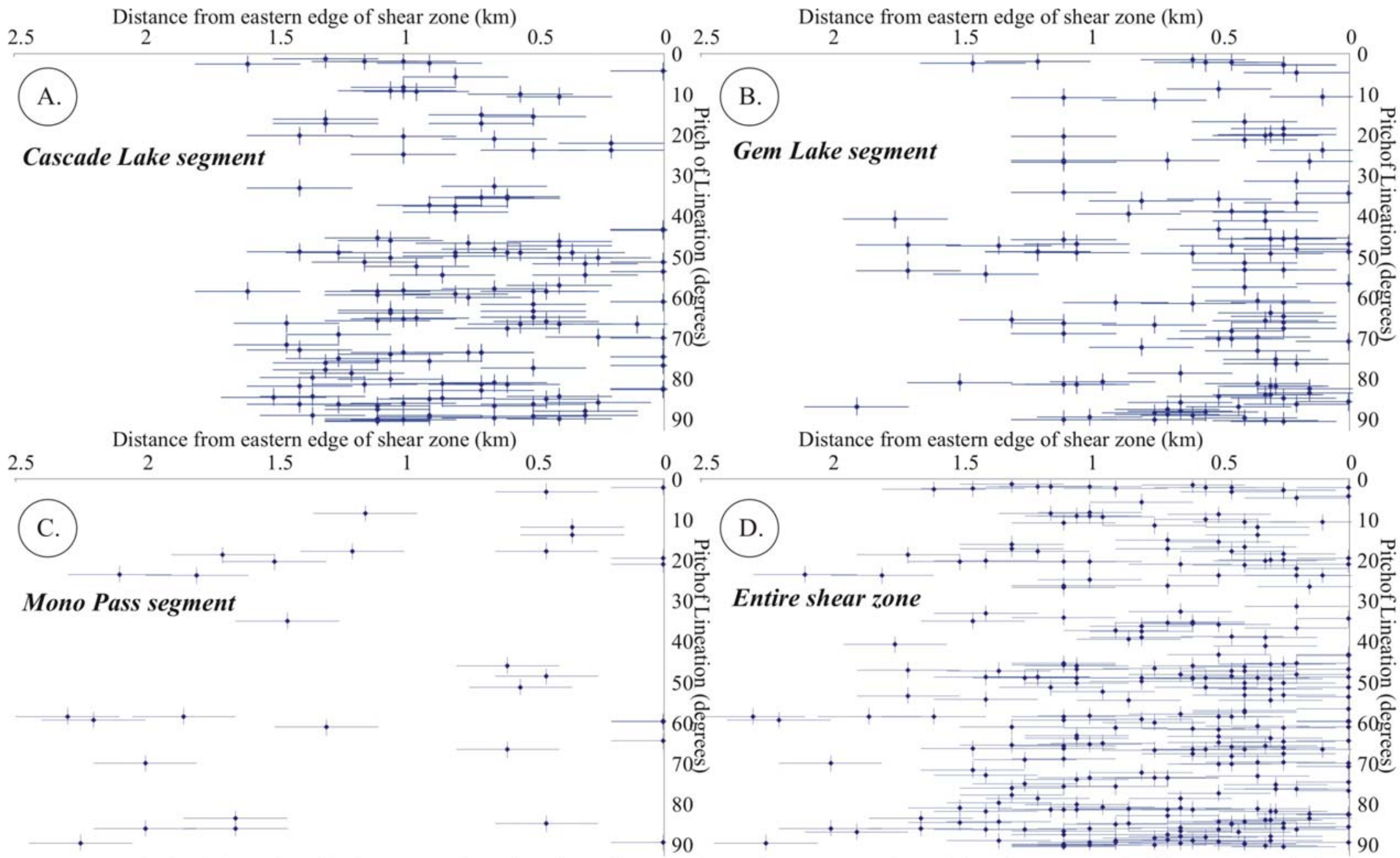


Figure 66: Pitch of lineation (in degrees) plotted against distance from the eastern edge of the shear zone (in kilometers). Pitch was calculated using the equation tan(pitch) = [tan (plunge)] / [sin(dip)]. A) Cascade Lake segment. B) Gem Lake segment. C) Mono Pass segment. D) Entire shear zone (all three segments plotted together). There is no discernible pattern that emerges from this comparison.

The lack of agreement between model predictions of lineation pitch (Figure 65) and measured lineation pitch in the Sierra Crest shear zone (Figure 66) may be reconciled by recognizing that strain has not been partitioned evenly across the shear zone. The simplistic model's basic assumptions (of homogeneity, steady-state deformation, parallel-sidedness) are unmatched by reality, where strain is localized rather than evenly accommodated. A full discussion of this lack of agreement between models and actual natural transpressional zones is provided in Section 6.3.

However, in terms of their overall orientation, the lineations observed in all three segments of the Sierra Crest shear zone do match the predictions of the (more robust) inclined model incorporating widening boundaries (Jiang, in review). Stereonet plots of lineation data from all three segments display great circle girdle patterns (Figure 38). Full circle girdles are expected due to natural strain partitioning in the system. Great circle girdles are found in Domain II of Figure 11. Domain II is characterized by having moderate simple-to-pure shear ratios ($2 < R < 20$), a high β (dip angle of the zone), moderate α (in general, between 5 and 20) and a Φ of not more than 20˚. The α corresponds with Tobisch et al.'s (1995) estimation of the angle of obliquity between the convergence of the Farallon and North American plates to be ~20˚ at 100 Ma. These values all seem to agree with field evidence in the Sierra Crest shear zone. The main distinguishing characteristic of the area defining Domain II is the high β value, which corresponds to a more high-angle (subvertical) shear zone, which the Sierra Crest most demonstrably is.

5.3.3 Lenses of less deformed material

Several lenses of less-deformed rock are present throughout the Sierra Crest shear zone. The presence of magmatic *schlieren* in the hypabyssal granite in the eastern Mono Pass segment (Figure 24), for instance, indicates that the granite was not sheared pervasively enough to obliterate those primary features. Nearby, the curious possibility of a preserved volcanic bedding plane oblique to foliation (Figure 25) offers the same interpretation: some areas were strained more than others. Most notably, the volcanic breccia of the Gem Lake and Mono Pass segments displayed only moderate deformation (e.g. Figure 21). Because of rheological differences between lithologies (or due to the presence of elevated temperatures or fluids), or because of local variations in the stress field (due to salients and recesses in the imperfectly parallel shear zone boundary walls), certain rocks accumulated less strain than their neighbors. Implications of this heterogeneous strain accommodation are discussed in detail in Section 6.3.4.

5.3.4 Dextral, reverse (west side up) motion

The vast majority of kinematic indicators in all three segments of the Sierra Crest shear zone indicate that, during shear-zone-deformation, the area experienced dextral, west-side-up reverse motion. Chocolate tablet boudinage in all three segments reinforce this interpretation (e.g. Figure 43), as do countless dextral winged porphyroclasts (e.g. Figure 45A), bookshelfed feldspars, and examples of S-C fabric (e.g. Figure 41). The dextral aspect of this transpressional tectonic regime matches the accepted dextral oblique convergence hypothesized for the North American / Farallon plate boundary in the late Cretaceous in California (Dickinson, 1981). The west-over-east reverse aspect to the kinematics may be explained by the strain incurred as a result of pluton emplacement processes to the west.

5.3.5 Folding

Second generation fold axes parallel to lineation are found in the Gem Lake and Mono Pass segments of the shear zone (Figure 62 and 65). These fold axes plunge intermediately to the northwest, and are interpreted as being of the same generation as shear zone deformation.

5.3.6 Pluton emplacement

Because of the field relations between intrusive plutons and well-foliated host-rocks detailed in Section 3.5.2, and then the subsequent subsolidus deformation of the plutons themselves, the emplacement of the plutons bounding the Sierra Crest shear zone to the west are considered to be syntectonic. The oldest pluton, the Rush Creek granodiorite (100 Ma; Bateman, 1992), is the most deformed of the intrusive igneous rocks (e.g. Figure 41), and not only just in its margins but also substantially into its interior. Likewise, the youngest of the affected plutons, the Cathedral Peak granodiorite (88 Ma; Glazner, 2004) is the least deformed, with the least amount of subsolidus quartz ribboning, and the dominance of magmatic N60˚W fabric becoming dominant a short distance into the pluton, away from the N30˚W-trending fabric in its eastern margin.

5.4 Post-shear zone deformation

5.4.1 Kink banding

Kink banding of finely-foliated ignimbrite (Figure 52) in the central Gem Lake segment indicates a third generation of deformation followed shear-zone-deformation. Kink band axes plot at the intersection of the average kink band plane and the average foliation plane in the shear zone (Figure 54, upper stereonet). Kink bands are Z-style, and are geographically associated with larger m-scale Z-folds, as well as having the same orientation (Figure 54, lower stereonet). Using the kinematics of the kink banding model developed by Jiang et al. (2003), the Gem Lake kink bands are interpreted in Figure 52C. If the orientation of maximum D3 stress were as illustrated by σ_1, then a conjugate pair of kink bands would develop, one in the orientation of kink bands measured, and a conjugate set subparallel to foliation. On that plane, strain was accommodated by slip along the plane of foliation. Though individual kink bands were dextral, overall the kinematics of the system were sinistral (Figure 52C) and slightly transtensional in the east-west direction. Where kink bands strayed from either of these preferred orientations, the band widens, and can no longer be properly called a kink; it is more accurately a small fold.

5.4.2 Small scale folding

Locally common small scale Z- and S-folds overprint foliation in all three surveyed segments of the Sierra Crest shear zone. Because they overprint foliation, these folds are interpreted to be of the third generation of deformation to affect the area. Z-folding indicates dextral convergence; S-folds indicate sinistral convergence.

Z-folding is predominant in the Mono Pass segment and Gem Lake segment, though some S-folds were locally common. Both styles of folding were equally predominant in the Cascade Lake segment.

5.4.3 Sinistral, east side up motion

Sinistral deformation is not uniformly brittle in the Sierra Crest shear zone (e.g. Figure 45B), but all brittle deformation is sinistral (e.g. Figures 56, 57, and 58). Likewise, brittle faulting is correlated with east-side-up motion, as opposed to the dominant dextral, west-side-up motion that is indicated by the bulk of the shear zone's kinematics. I interpret this as an indication that (east-side-up) uplift of the Sierra Nevada block brought the deformed rocks of the Sierra Crest shear zone above the brittle-ductile transition, overprinting foliation and kinking with brittle strain.

With further uplift coincident with Basin and Range extension, and therefore further cooling, and further release of pressure, the rocks were lofted to their present elevations.

5.5 Regional kinematics

5.5.1 Estimates of total time of shear zone activity

Based on a variety of geochronometers, McNulty (1995a) estimated that the Bench Canyon shear zone, which is parallel to and southwest of the Sierra Crest shear zone system, was active for approximately 17 Ma. Because these dates (95 to 78 Ma) overlap the period of pluton emplacement of the Tuolumne Intrusive Suite (Tobish et al. 1995, Glazner, 2004), and assuming that both shear zones are products of the same overall tectonic regime, it is inferred that the Sierra Crest shear zone may have been active for a similar duration of time, and perhaps contemporaneously with the Bench Canyon shear zone. However, it may also be that the Sierra Crest shear zone was active after the Bench Canyon shear zone – i.e. once movement ceased on the Bench Canyon shear zone, the need to accommodate tectonic stresses caused strain to be accumulated in a parallel shear zone to the east, beyond the ‘advancing front’ of intrusive magmatic bodies.

Unfortunately, estimates of along-strike movement (strike-slip component of transpression) are difficult in the Sierra Crest shear zone. Unlike the Alpine Fault in New Zealand, which has an ophiolite belt displaced 450 km, in the Sierra Nevada no geologic marker could serve to estimate regional strike-slip displacement. It is perhaps significant that this is the case: the Sierra Crest shear zone serves (a) as a ‘ductile fault’ (e.g. Ramsay and Graham, 1970), but more importantly, (b) as the boundary between the Sierra Nevada batholith and the older country rocks. It may be that this second ‘function’ is in fact the more important one (see Section 6.2 for further discussion).

To gauge the total time of deformation of the shear zone’s activity, I rely on overprinting relationships observed in the field and published radiometric dates on the shear zone’s metamorphic minerals. Three generations of deformation were observed in this study. Russell and Nokleberg (1977) also noted three generations of folding in the Mount Morrison pendant, a block of metasedimentary and metavolcanic rocks bounding the batholith along strike to the south-southeast. They concluded that that these three generations of folding respectively represent the effects of the Antler, Sonoma, and Nevadan Orogenies. Their second generation fold axes have a similar trend (~N23°W in the Mount Morrison pendant; ~N30°W in the Ritter Range pendant) to those observed as F2 fold axes in the Sierra Crest shear zone. Their third generation fold axes are more westerly in orientation (~N61°W in the Mount Morrison pendant; ~N50°W in the Ritter Range pendant), as are the F3 folds in the Gem Lake segment, where they are most discernible. If Russell and Nokleberg's (1977) interpretation is correct, then it follows that the Sierra Crest shear zone is a feature of the Nevadan Orogeny.

However, the Nevadan Orogeny is far too early an event, at ~163 Ma (Shervais et al., 2002), to be responsible for the deformation that we see associated with the Sierra Crest shear zone. Tobisch and Fiske (1982) concluded this on the basis of well-developed foliation in a ~100 Ma dike. Geochronological studies have pushed the date even later: in this study, fabric development must have occurred until at least 88 Ma (the U/Pb date by Glazner et al., 2004, for the cooling of the Cathedral Peak granodiorite). For this reason, I suggest that the deformation of the Sierra Crest shear zone must have been a later event than the Nevadan Orogeny – an event that initiated before 100 Ma (and the intrusion of the Rush Creek granodiorite) and concluded after 88 Ma (with the cooling of the Cathedral Peak granodiorite). Ar^{40}/Ar^{39} cooling ages of metamorphic hornblende, muscovite, and biotite in wall rocks by Sharp et al. (2000) indicate that "transpressional cleavage" (i.e. foliation) developed from ~89 Ma to a conclusion near ~80 Ma. Estimating the onset of metamorphism is more difficult because later peaks in temperature will overprint geochronometers' earlier dates. Because of the appearance of foliated xenoliths in the Rush Creek granodiorite and contemporaneous plutons, the earliest onset of deformation must be pushed back to prior to 100 Ma, with conclusion at ~80 Ma on the basis of Sharp et al.'s (2000) cooling ages for metamorphic minerals. By this logic, the Sierra Crest shear zone appears to have been active for ~20 Ma.

5.5.2 Strain estimates

As described in Section 4.3.1, an estimated strain ellipsoid was calculated for the Sierra Crest shear zone from measurements of strained mafic clasts in porphyroclastic ignimbrite. However, it is likely that at least some of the clasts have been boudinaged (especially in the direction of maximum stretching, corresponding to the X-axis), resulting in two or more separate sub-clasts whose axial measurements are a minimum measure of those of their parent clasts.

To reach a conservative estimate of strain for the area, the highest X/Y and Y/Z ratios were used to calculate a strain ellipsoid based on the assumption of conservation of volume. That is, the clasts are assumed to have been initially spheres of volume 1, and after deformation, ellipsoids of volume 1. The axes multiplied by each other should have the same product in both cases (i.e., $X \cdot Y \cdot Z = 1$). For the Gem Lake sampling area, these ratios were Y/Z ~80 and X/Y ~3.5, yielding a strain ellipsoid ratio of 9.93 : 2.83 : 0.03 (X : Y : Z). For the Cascade Lake sampling area, these ratios were Y/Z ~40 and X/Y ~3, yielding a strain ellipsoid ratio of 7.11 : 2.37 : 0.06.

5.5.3 Estimates of shear zone width prior to pluton emplacement

Assuming that the Sierra Crest shear zone is a transpressional zone with migrating boundaries, and assuming that the measured strains represent the strain

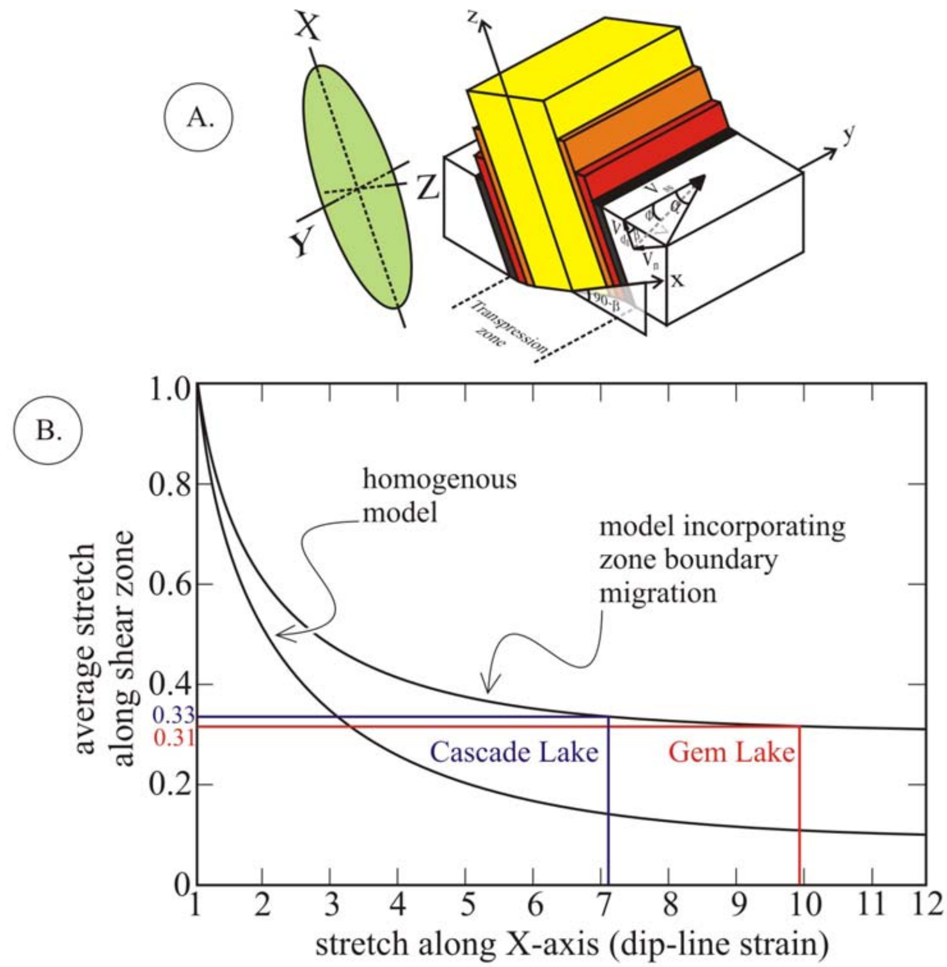


Figure 67: A) Transpressional zone with migrating boundaries, from Jiang (in review). B) Approximating across-strike shortening of the shear zone. Stretch along the X-axis was calculated for a high-strain portion of the shear zone bearing many markers (mafic clasts in metavolcanic ignimbrite). Lineation was approximately down-dip at each sampling site, and a sample size of 60 ratios was obtained for each segment. The maximum stretch was taken as the minimum estimate of stretch, since boudinage of marker clasts was likely (and the axial ratios of boudinaged clasts would have conveyed an underestimate of total stretching). The axial ratios of the strain ellipsoid were then calculated, using the assumption that there was no volume loss of the marker clasts throughout deformation (i.e. $X \cdot Y \cdot Z = 1$). The Gem Lake segment's strain ellipsoid axial ratios were 9.93 : 2.84 : 0.03. The Cascade Lake segment's strain ellipsoid axial ratios were 7.11 : 2.37 : 0.06. Curves in the diagram show the relationship between shortening across the shear zone and strain along the dip line direction in the center of the zone. The upper curve is the triclinic widening-zone model of Jiang (in review). The lower curve is that based on a homogenous transpressional zone, which likely overestimates shortening. Taking the stretch along the x-axis as determined above (9.93 and 7.11, respectively), the corresponding position along the y-axis is determined (0.31 and 0.33, respectively) for the Gem Lake and Cascade Lake segments of the Sierra Crest shear zone system. With the shear zone ~0.32 of its initial size, a volume loss of ~0.68 may be inferred across strike. Redrawn from Jiang (in review).

incurred by the entire shear zone, the estimated maximum principal strain along the dip-line direction (X-axis of the strain ellipsoid; Figure 67A) has a simple relationship with the average shortening strain across the zone (Jiang, in revision). As Figure 67B shows, the shape of this curve starts at an initial shear zone width of 1, and decreases in a style reminiscent of "exponential decay": it rapidly thins at first, and then thins more slowly later on. This is because initially strain is taken up efficiently by the shear zone and a small amount of across-strike strain leads to a large amount of vertical extrusion. Eventually, though, strain accommodation across strike (shortening) becomes less efficient ("strain hardening"), and a large amount of across-strike strain leads to only a small amount of vertical extrusion.

Figure 67 shows the relationship between shortening strain across a model shear zone and stretching of the strain ellipsoid along the X-axis. The X-axes of the strain ellipsoids calculated above from Gem and Cascade Lake segments are correlated with the average stretch across the shear zone. For the Cascade Lake segment, the shear zone is inferred to have been shortened to 0.33 of the original width of the rocks it then strained. For the Gem Lake segment the shear zone is inferred to have been shortened to 0.31 of this original rock width. The shear zone itself was likely never wider in total extent than it is now – but widened over time to include more rock as it thinned. These estimates represent substantial volume removed for the Sierra Crest shear zone: 69% and 67% across-strike shortening has profound implications for the emplacement of the Sierra Nevada batholith (see Section 6.2.3 for a discussion of these implications). This estimate exceeds that of Tobisch and Fiske (1982), who concluded that 30-50% shortening of the metasedimentary and metavolcanic host rocks had taken place. However, shortening of 69% to 67% is undoubtedly an overestimate across the entire shear zone, while it may remain accurate for the ignimbrite unit (which provided the lapilli whose measured axes provide the basis for these estimates), for the reasons of heterogeneous strain localization, discussed in detail in Section 6.3.3.

5.5.4 Estimates of total amount of material extruded

Given that the shear zone's current width of ~3 km in the Gem Lake area and ~1.5 km in the area of Cascade Lake, a crude estimate of volume removal (i.e. material extruded) may be made. If the assumption is made that strain is homogenously distributed (see caveat above), this implies that the shear zone has modified (strained) ~4.4 km for the Gem Lake segment and ~2.25 km for the Cascade Lake segment. A one-km wide, one-km deep volume of rock across strike of each segment would imply original country rock volume of 4.4 and 2.25 cubic km, respectively. When this is reduced to the current 3.0 and 1.5 cubic km for the same across-strike section, it implies a volume removal of 1.4 and 0.75 cubic km of rock, respectively, from these two segments of the shear zone. Extrapolated to the ~32 km section of the Sierra Crest shear zone along which these three segments were surveyed, this implies between 24 and 45 cubic km of material removed adjacent to the intruding Sierra Nevada batholith. It is worth recalling here that this does not imply that the shear zone was ever fully 4.4 km wide, but that it widened its boundaries over time to compensate for strain hardening due to thinning/volume removal.

Again, this undoubtedly an overestimate of volume removal for the reasons of strain localization denoted above and explored in detail in Section 6.3, but if volume removal for the shear zone were even half of this estimate, that is still a significant amount of rock volume removed from the area adjacent to pluton emplacement, an incompletely-understood process whose need for volume is characterized by the "room problem" (e.g. Hutton, 1990; Tikoff and Teyssier, 1992). Section 6.2.3 suggests the possible tectonic implications of this volume removal.

5.6 Kinematic evolution of the Sierra Crest shear zone

The overall chronological evolution of the Sierra Nevada shear zone is then:

Deposition of strata

Deposition of the cherts, shales, mudstones, and sandstones of the Lewis Sequence occurred in an off-shore marine environment during the late Paleozoic. Deposition of Koip Sequence volcanics occurred next, beginning 240-250 Ma(?) (Brook et al., 1979) and possibly concluding as late as 201 Ma (the U/Pb date for its upper rhyolite stratum by Schweikert et al., 1994).

Pre-shear zone folding

Folding of Lewis Sequence metasedimentary strata occurred prior to shear zone deformation itself. These folds, which are dominantly isoclinal in nature, trend roughly parallel to later-generation folds which overprint them. However, unlike second generation folds, their fold axes dip to both the north-northwest *and* south-southeast (e.g. Figure 32).

Shear zone deformation; second generation folding; transposition

The Sierra Crest shear zone system was activated by oblique convergence between the Farallon plate and the North American plate, sometime prior to 100 Ma. Shear zone deformation caused the development of transposition foliation inside the shear zone (which is defined by its transposition foliation), and caused a second generation of folding, D2, in adjacent wall rocks outside the shear zone boundary. D2 is syn-kinematic with shear zone deformation because its axial plane cleavages outside the shear zone are parallel to and transitional to the shear zone transposition foliation. Shear zone deformation dominantly had a dextral, west-over-east sense of shear.

Pluton emplacement at ~100 to ~80 Ma

The second half of the second major episode of emplacement of the Sierra Nevada batholith coincided with the activity of the Sierra Crest shear zone. The Sierra Crest shear zone was active prior to the emplacement of the Rush Creek granodiorite (100 Ma), and concluded sometime after the emplacement of the Cathedral Peak granodiorite (88 Ma).

Kink banding and third generation folding

After the cessation of shear-zone deformation, which perhaps was coincident with the cooling of the youngest plutons of the Sierra Nevada batholith (see Section 6.2 for further discussion of this possibility), a third generation of deformation left its mark on the rocks of the Sierra Crest shear zone. While the rocks were still hot and deep enough to behave ductilely, the foliation was folded and kinked with a dominantly sinistral sense of shear.

Reactivation of kink band planes, tension gashes

Cooling of shear zone rocks, perhaps coincident with uplift and exhumation, caused brittle behavior. Kink band planes appear to have served as planes of weakness that were re-activated in post-shear zone deformation (Figure 56). The initial kinking implied a sinistral sense of shear (Section 4.4.1). Later, their reactivation offset opposite sides of the kink band plane with a sinistral, east-over-west sense of shear. Tension perpendicular to the new stress directions opened tension gashes, which were infilled by quartz.

Uplift, tilting, and exposure

All of the features described in the Sierra Crest shear zone are rotated during exhumation; in fact, the mechanism of their uplift has been partially due to the tilting of the entire Sierra Nevada block about a hinge line which lies somewhere west of the present day margin between the Great Valley and the Sierra Nevada foothills (Unruh, 1991). However, the total tilting in the central Sierra Nevada is around 1.4˚ on average (Unruh, 1991), so significant reorientations of the shear zone fabrics are unlikely to be wrought by this mechanism alone. It is probably enough to remember that each of the features we observe is dipping a degree or two more northeasterly than its original position. In terms of the chronological interpretation of the shear zone, however, this uplift of the eastern portion of the block and dropping of the western portion (beneath the Great Valley) was initiated by Eocene time (45-50 Ma) as evidenced by the establishment at that time of large rivers draining the Sierra and flowing to the west (Bateman and Wahrhaftig, 1966).

Chapter 6: Tectonic significance of the Sierra Crest shear zone system and implications for crustal-scale transpressional shear zones

6.1 Background geology of west coast

6.1.1 Setting changes: Atlantic, Japan, California type margins

As mentioned in Section 3.1.1, the west coast of the North American plate has undergone each of Dickinson's (1981) four types of continental margins during its long history. During deformation on the Sierra Crest shear zone, the area was a magmatic arc akin to the modern Andes mountains, with surface volcanism and pluton emplacement at depth. The Sierra Crest shear zone accommodated strain that resulted from the oblique convergence of the Farallon and North American Plates. The general flattening strain, ("elongate pancake" strain ellipsoid; Figure 39; Section 5.5.2) are indicative of the transpressional tectonic regime. Kinematics of the shear zone were dextral and west-over-east, as indicated by winged porphyroclasts, S-C fabric, and Z-folds. Although less common sinistral porphyroclasts and S-folds were also observed, these likely represent localized strain partitioning around resistant pods (see Section 6.3.1 for a full discussion of this phenomenon), and the overall kinematics of the entire transpressional zone fit well with the dextrally transpressive tectonics of Cretaceous California.

6.1.2 Pluton emplacement problem

A shear zone which was active for ~20 Ma (Section 5.5.1) may have had some significant effects on the contemporaneous, relatively rapid process of pluton emplacement. If there is interplay between the processes of shear zone deformation and the process of pluton emplacement, it would be of fundamental importance in understanding the mechanism by which magmatic arcs emplace individual plutons. It may also bear on the batholithic "room problem": the seeming paradox that voluminous intrusions are emplaced in a tectonic regime that is overall transpressional.

In terms of providing a mechanism aiding emplacement, Brown and Solar (1998, 1999) found in another transpressional orogen (central Maine belt), crustal-scale shear zone systems provided a physical and geochemical focusing mechanism enabling the transfer of granitic melt, and that the form of the conduits through which magma ascended were deformation-controlled. Tobisch and Cruden (1995) also found that crustal-scale deformation explained north-south orientation of magma-ascent conduits in two eastern-central Sierra Nevada nested plutons. Working in Spain, Gumiel and Quesada (2003) found that lithospheric scale strike-slip structures enhanced magma ascent, pluton emplacement, and ore depositing hydrothermal circulation.

Bateman (1988) originally proposed what has since become a widely accepted hypothesis: that the plutons of the Tuolumne Intrusive Suite were emplaced as a series of magmatic surges, each inside its predecessors. The result is a concentrically arranged suite of intrusions, with the oldest, isotopically most primitive, more mafic, more equigranular units on the outer margins, and the younger, isotopically more evolved, felsic, porphyritic units on the interior. Chronologically, then, the sequence of emplacement of the members of the Tuolumne Intrusive Suite was: (1) the Kuna

Crest granodiorite, (2) the Half Dome granodiorite's outer equigranular unit, (3) the Half Dome granodiorite's inner porphyritic unit, (4) the Cathedral Peak granodiorite, and finally (5) the Johnson granite porphyry. Isotopic ages for the individual plutons reinforce this sequence (Tobisch et al., 1995; Glazner et al., 2004).

Similar nested patterns have been observed in other intrusive suites in the eastern Sierra: both the John Muir Intrusive Suite and the Mount Whitney Intrusive Suite display the same concentric zonation in mafic mineral content, porphyritic texture, and age (Tikoff and Teyssier, 1992). Noting the key structural relation – that the shear zones bound the largest elongate plutons and nested intrusive suites – Saleeby (1991) has suggested that the Sierra Crest and its contemporaries represent strike-slip shear zones which link en echelon batholithic spreading centers.

Tikoff and Teyssier (1992) correlated the common patterns of all three intrusive suites to a transpressional regional setting. The John Muir, Tuolumne, and Mount Whitney Intrusive Suites not only share the characteristics listed above; they also have a common NW-SE orientation (Tikoff and Teyssier, 1992; Schweickert, 1981). Tikoff and Teyssier (1992) interpret these plutons as being emplaced preferentially in pull-apart zones created by several-kilometer-scale transtensional releasing bends bounded by P-fractures (15º angle to the overall slip direction) within the larger 1000-kilometer scale transpressional regime. They were not the first to suggest such a mechanism; Bateman (1981) noted that co-magmatic granitoid sequences are elongated in a NW-SE trend, parallel to the greater batholith, and Dickinson (1981) mentioned the possible role of *en echelon* pull-apart basins in the tectonics of the region, but he did not link it to the emplacement of plutons.

Schweickert (1981) hypothesized a similar mechanism of magma chambers preferentially occupying extensional zones to explain *en echelon* arrangement of plutons in the Kern Canyon area. Tobisch and Cruden (1995) noted yet another series of nested plutons (not among the the John Muir, Tuolumne, and Mount Whitney Intrusive Suites) was emplaced in part via a common planar conduit, though the pulses of magma came 2-10 Ma apart. The authors interpret these north-trending conduits as representing "tension fractures" associated with transpression. However, Tobisch and Cruden invoke an overall trend of N40˚W for the magmatic arc, in support of their tension fractures' north-south orientation, whereas Tikoff and Teyssier (1992) invoke an overall batholith orientation of N25˚W to explain the orientation of their P-shear bridges. This study focused on only the eastern boundary of the batholith, but found a N30˚W orientation, a finding that undermines these interpretations by 5˚ and 10˚, respectively.

6.2 Tectonic significance of the Sierra Crest shear zone system

As noted in Section 5.1.4, there is a variety of evidence indicating that the plutons were emplaced syn-tectonically with shear zone deformation. In addition, as noted in Section 5.5.4, the deformation of the Sierra Crest shear zone system may have removed significant volumes of host rock from the area: estimates for volume removal range between 24 and 45 cubic km of rock along the shear zone's ~32 km length. This enormous volume of material extruded from the YZ plane of the shear zone would have substantial implications for the adjacent intrusion across strike of high-volume igneous plutons.

6.2.1 Bench Canyon: a parallel shear zone

The Bench Canyon shear zone (McNulty 1995a, 1995b) is inferred to have been active for ~17Ma. It too bears evidence that pluton emplacement was syn-tectonic with shear zone deformation: foliated xenoliths in pluton margins in a variety of orientations, an increase in magmatic structures away from the shear zone, sills of plutons with fabrics parallel to the shear zone fabric, and the parallelism of magmatic and solid-state fabrics in the intrusive rocks (unpublished field data; McNulty 1995a). The Bench Canyon shear zone has discrete boundaries along strike: in the north, it is truncated by first the Red Devil Lake pluton, which bears magmatic and solid state foliation, and then by the Half Dome granodiorite (92-88Ma; Glazner 2004), which shows no evidence of having been deformed by the shear zone (McNulty 1995a, Figure 2). In the south, the shear zone is truncated by the Mount Givens pluton (90 Ma; McNulty 1995a) that, except for a sill that projects into the shear zone, also bears no shear zone fabric.

McNulty concluded that (1) deformation was aided by the magmatic and contact metamorphic processes related to pluton emplacement, and (2) that "forceful" emplacement of the Jackass Lakes pluton (west of the shear zone) did not initiate dip-slip thrusting in the Bench Canyon shear zone. While McNulty makes a convincing argument from geometry that the Jackass Lakes pluton could not possibly be the sole driver of deformation, the possibility that pluton emplacement augmented the simple-shear component of regional transpression remains. It is also possible that the shear zone made room for the pluton.

6.2.2 A proposed hypothesis linking shear zones and pluton emplacement

It is clear that there is an intimate connection between the emplacement of the plutons of the Sierra Nevada batholith, and the deformation of tabular shear zones like the Sierra Crest shear zone system. A main feature of transpressional shear zones as defined by Sanderson and Marchini (1984) is that in order for the deformation to be volume constant, material must be extruded across strike (i.e. in the X-direction of the strain ellipsoid). Like a jelly sandwich being squeezed too hard, this extruded material could go up or down, but regardless of direction, it leaves the system. If deformation is constant-volume, then across-strike shortening must be compensated by vertical extrusion. Extruded material above is removed by erosion. Jiang (in review) termed the plane above which extruded material travels up and below which material travels down as “the floor of transpression.” The effect of this extrusion of material (shown schematically in Figure 68B) is to reduce the volume of the shear zone across strike. Were a pluton to be intruding adjacent to the shear zone, this reduction in volume across strike would allow the pluton to expand laterally. Potentially, this has significant implications for the batholithic room problem.

Further, a regional system of parallel-trending transpressional shear zones would provide for material removal, and thus volume reduction, across strike with shear zones more distal to the plutons able to continue operating as volume reducers even as the expanding plutons consumed (through assimilation, stoping, and related processes) more proximal shear zones. Figure 69 demonstrates the proposed relationship.

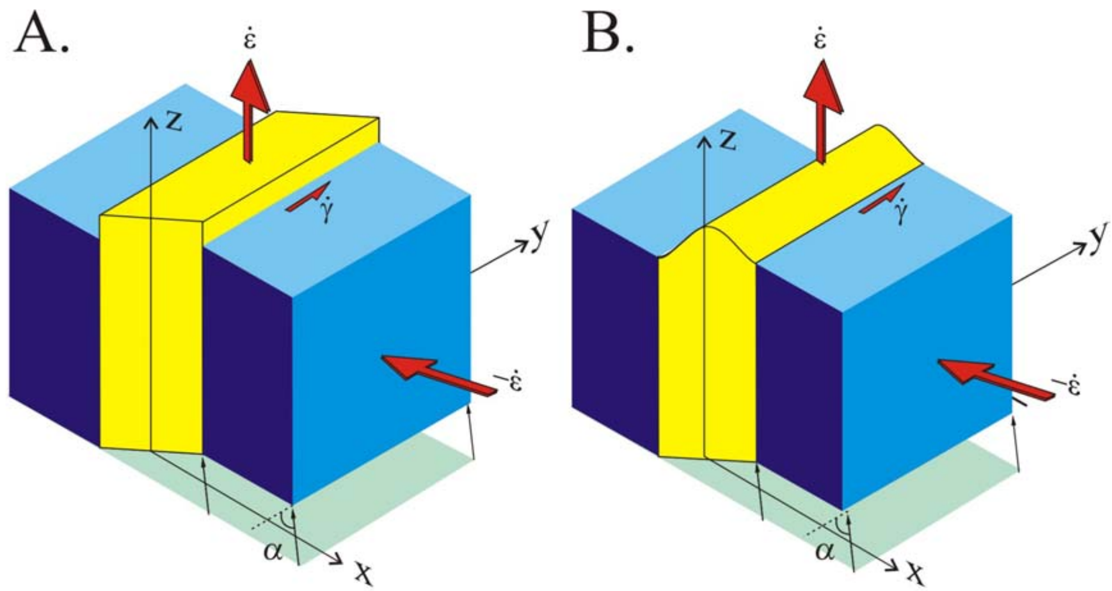


Figure 68: Homogeneous versus heterogeneous monoclinic shear zone deformation. A) Homogenous shear zone deformation, of the type envisioned by Sanderson and Marchini (1984). B) Heterogeneous shear zone deformation, where deformation is most intense in the center of the zone, and grades out to zero deformation at the margins of the shear zone. α is the angle of convergence between the two blocks. $\dot{\gamma}$ is the simple shear component of relative motion between the two blocks. $\dot{\varepsilon}$ is the pure shear component of relative motion between the two blocks.

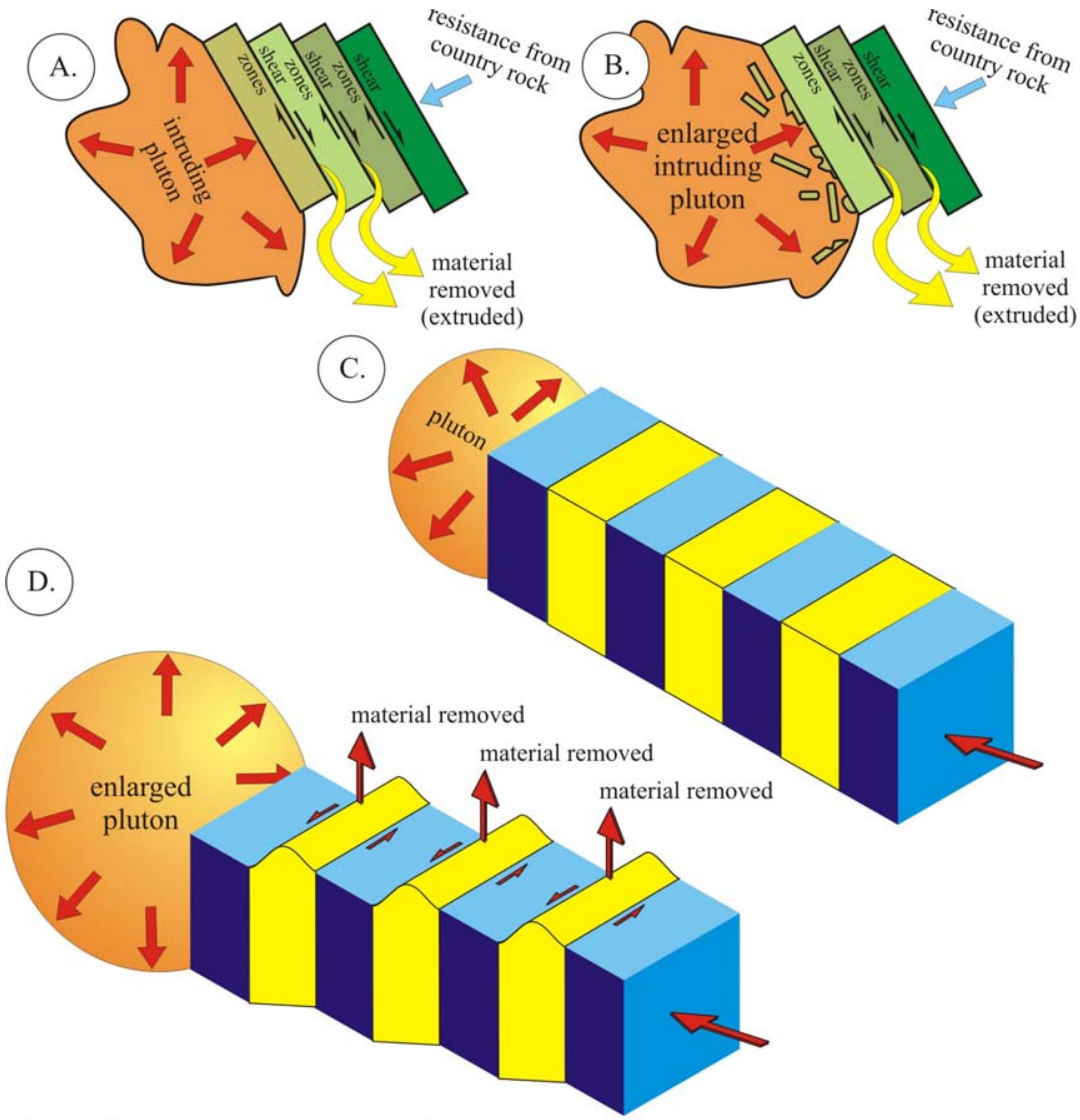


Figure 69: Possible relationship between crustal scale transpressional shear zones and pluton emplacement. (A) and (B) are map view, (C) and (D) are drawn from a three-dimensional perspective. A) Incipient pluton begins intruding area. Outward directed force (pure shear) from pluton inflation pushes against country rock. A series of parallel anastamosing shear zones are activated, either by the force of the intrusion, or more likely by regional tectonic forces (imparting the simple shear component), augmented by pluton inflation. Transpressional shear zone deformation removes material (out of the plane of the drawing), reducing the volume of country rock adjacent to the pluton. B) The pluton then expands in size, exerting more pressure on the country rock, which causes further transpressional deformation to occur. Shear zones proximal to the pluton may be consumed and incorporated into the pluton as melt, stoped blocks, and xenoliths. C) and D) The same relationship, rendered to better show the volume of country rock displaced by transpressional deformation (yellow blocks). Such a mechanism could link the Sierra Crest shear zone system, adjacent parallel-trending shear zones, and the emplacement of the plutons constituting the Sierra Nevada batholith.

The Bench Canyon shear zone serves as a key piece of evidence in support of this hypothesis. In this scenario, the deformation of the area would have taken place in the following fashion: a series of transpressional shear zones were active across the region with magma (generated by subduction and melting of the Farallon Plate beneath the North American plate) intruded as discrete plutons. First, shear zones in the west were more active, taking up strain and removing volume across strike (i.e. from the shear zone coordinate system's *xy* plane), because (a) they were closer to the heat source of the magma, and (b) they were subjected to compression due to pluton emplacement, which augmented the pure shear component of regional transpression. Then, as the westerly shear zones removed rock volume, the plutons in the west grew larger and consumed the shear zones. When the westerly shear zones were truncated so that they could no longer accommodate enough regional tectonic strain, more easterly shear zones became active, allowing new plutons to intrude to their west, overlapping pre-existing plutons and remnant shear zones preserved in roof pendants. Saleeby (1991) noted the overall progressive eastern movement of the batholith's locus of magmatism (actually a line or "front"), as did Sharp et al. (2000), who calculated its rate of movement to be 2.7mm/year.

The Bench Canyon shear zone is one of the preserved remnant shear zones, according to this story, a fraction of its former size along strike. Further along strike to both the north and south, the Bench Canyon shear zone was destroyed by intruding magma, including the Mount Givens and Half Dome plutons (but not the Red Devil Lakes pluton, since the shear zone was still evidently active enough to deform it with a transpressional fabric). With the Bench Canyon shear zone "out of commission," the need to accommodate strain propagated to the east, to the next available shear zone that could remove material from the system, the Sierra Crest shear zone. With a dextral, reverse sense of shear, the Sierra Crest shear zone system removed material across its width, allowing the emplacement of plutons such as the Rush Creek, Kuna Crest, Half Dome, Cathedral Peak, and Johnson porphyry adjacent, across strike. It is worth reiterating here that all the plutons of the Tuolumne Intrusive Suite have a N30°W axis. At this point, magma production ceased, probably coincident with the subduction of the spreading center separating the Farallon and Pacific plates beneath the North American plate, a tectonic event that effected the California's transition from a convergent to transform tectonic boundary (Dickinson, 1981). The Sierra Crest shear zone was the last shear zone east of the batholith to be activated, and is therefore preserved in greater continuity than its predecessors to the west because there was no more incoming magma to destroy evidence of its existence. The engine of magma emplacement consumed all but a shred of the Bench Canyon shear zone, and presumably many others where the batholith now exists, whereas when the engine shut off, only the most recent and most easterly shear zone was preserved: the Sierra Crest.

My suggestion here implies neither that the shear zone initially created room for the pluton, nor that the pluton caused the shear zone through forceful emplacement, merely that the two are complementary through a feedback mechanism. One process (pluton emplacement) calls for expansion in volume across strike, while the complementary process (transpressional shear zone deformation's material extrusion) calls for reduction in volume across strike. In terms of a regional strain field, it would be surprising if the two processes did not play complementary roles. Each may have influenced the other, but as with most “chicken and egg” problems, it may easily be the case that neither was in “control.”

Since transpressional shear zones are a common feature of many orogens, it will be instructive to determine whether in other magmatic arcs similar relationships between the shear zones and plutons may be discerned.

Another variation on this hypothesis would be the consumption of shear zones by widening and merging with adjacent parallel shear zone systems. Instead of proximal shear zones being consumed by plutons as is shown in the diagram, the shear zones themselves might (1) extrude material from the *xy* plane (of the coordinate system), (2) widen in the direction of maximum pure shear (*x*-direction) (e.g. Jiang, in revision), and (3) as a parallel shear zone undergoes the same process, the two widening zones approach and merge into one another, consuming the intervening wall rock: Two shear zones become one. In this scenario, the batholith might preserve a perpetual edge of volume-alleviating shear zone deformation on its margins for the duration of its emplacement.

The undeformed blocks (blue in Figure 69 C and D) would not necessarily have to be moving all in the same direction. (See Section 6.3.3 for a discussion of how anastomosing shear zones might flow around many large blocks of undeformed country rock.)

6.3 Implications for crustal-scale transpressional shear zones

The data collected along the three segments of the Sierra Crest shear zone do not correlate directly with the predictions from any model. Lack of correlation between crustal-scale transpressional shear zones such as the Sierra Crest shear zone system and model predictions such as even the most sophisticated triclinic models (Jiang, in review) must be addressed if we are to reconcile theoretical understanding of transpressional zones with observations of natural deformation.

6.3.1 Explanations of lack of agreement with model predictions

How do we explain the variation we see in rock fabric from a natural transpressional zone, when it strays so widely from what is predicted by homogenous tabular shear zone modeling? Several possibilities are raised by forward numerical modeling: (1) variation in Φ along strike and/or across strike, (2) widening the shear zone over time, or (3) both. Variation in Φ can occur if, as is almost certainly the case, strain is localized in the transpressional zone, and lenticular pods of less deformed material are moving in relation to one another independent of the movement of the shear-zone-bounding wall rock. Variation in Φ can also occur if the orientation of a single-domain shear zone were to vary along strike. The Sierra Crest shear zone shows a “twist” in its overall orientation along strike, dipping steeply southwest in the Gem Lake segment, and dipping steeply northeast in the Cascade Lake segment. Secondly, as the shear zone widens over time (Means, 1995) to balance thinning due to transpressional deformation, new material is introduced which then evolves from a different starting time. With a constant input of new material which then evolves its own fabric through progressive deformation, only the oldest lineations have the opportunity to fully develop. New lineations will be forming at shallow inclinations to the overall shear zone boundaries, and partially-developed lineations will plunge at intermediate angles between these two. Like an age distribution in a population of organisms, the full circle girdle shows 'juvenile,' 'adolescent,' and 'mature' lineations, all of which continue to evolve as deformation continues and new material is added to the system.

6.3.2 Matters of scale

There is also a discrepancy in scale. Unfortunately, the idea of a "transpressional shear zone" means many things to many workers. In 1970, Ramsay and Graham made a classic and enduring description of "shear belts."

While this landmark paper is truly the predecessor to the current study, and all kinematic interpretations of high strain zones, it is instructive to re-examine it. Each of the field examples used to illustrate the phenomenon is so small they can be captured in a single photograph, with a coin for scale (Figure 70). None of the examples measures even a meter across strike. Forward numerical models would doubtless be capable of the task of predicting the strain geometry of such a shear zone within an acceptable margin of uncertainty. However, we must question how appropriate it is to apply knowledge of such small structures to crustal-scale transpressional zones.

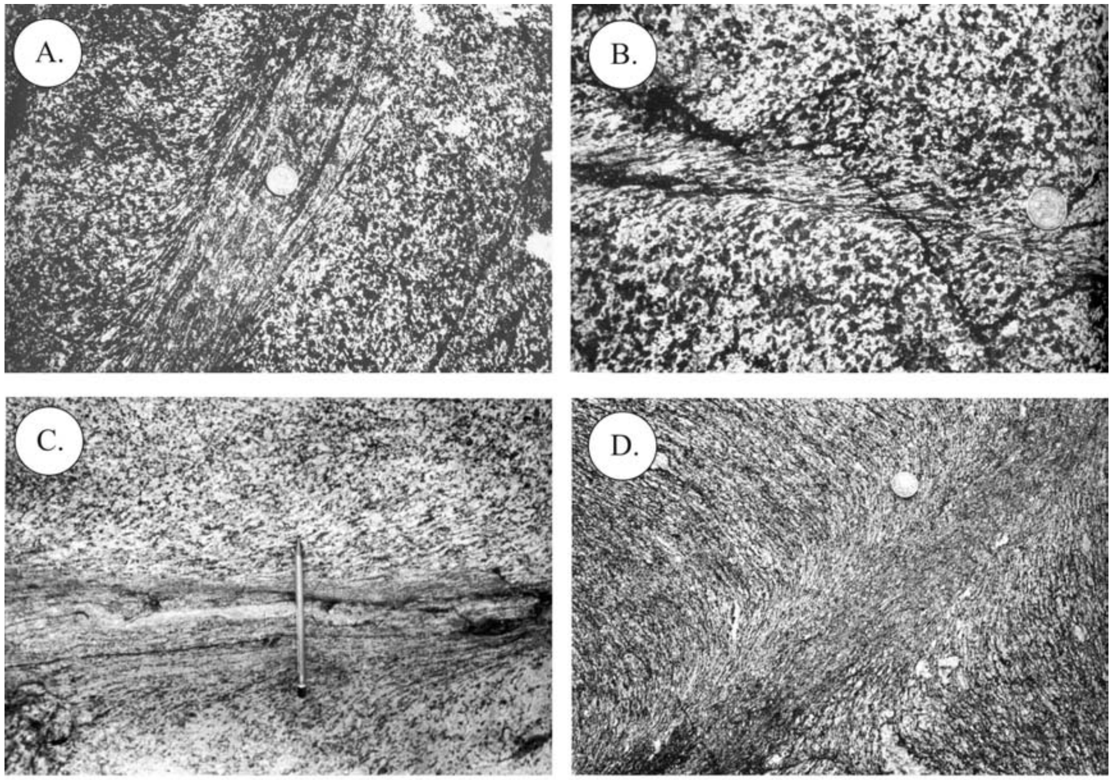


Figure 70: Shear zone photographs used as examples in Ramsay and Graham's (1970) seminal paper on shear zones. These shear zones only range in size from ~2.5 cm to 25 cm across strike. (A) Figure 14 from Ramsay and Graham (1970). Shear zone in metagabbro, Castell Odair, North Uist, Outer Hebrides, Scotland. Coin for scale. (B) Figure 13 from Ramsay and Graham (1970). "Small" shear zone in metagabbro, Castell Odair, North Uist, Outer Hebrides, Scotland. Coin for scale. (C) Figure 21 from Ramsay and Graham (1970). Shear zone in granite, Pennine dei Laghetti, Ticino, Switzerland. Pencil for scale. (D) Figure 25 from Ramsay and Graham (1970). "Complex" shear zone in granitic rocks, Cristallina, Ticino, Switzerland. Coin for scale.

6.3.3 Reconciling homogenous modeling & heterogeneous crustal-scale shear zones.

Perhaps the most obvious discrepancy between forward numerical modeling of tabular transpressional zones and the strain we observe in natural transpressional zones is that natural zones may contain multiple kinds of rock, each with distinctive rheological properties. Ramsay and Graham's (1970) shear belts were at least mono-lithologic (granites and gabbros) even if their component minerals were not necessarily rheologically homogenous. But how correlative can a natural transpressional zone of a dozen rock types be when compared to a model which assumes a homogenous generic rock? Certainly no published data from any natural zone match model predictions exactly (e.g. Figure 6) [though Lin (personal communication, 2004) may have found one in Canada].

A current study by Nadin and Saleeby (2004) on the Proto-Kern Canyon Fault indicates that lithologic boundaries may serve to localize strain, so the issue is quite pertinent. Nadin and Saleeby found that in the southern portion of the batholith, the shear zone is best preserved (and thus was most recently active) at the contact between the early (100 Ma) and later, easterly (85-80 Ma) plutons, a discrete lithologic boundary rather than the hotter area to the east, where the more recent plutons would have raised temperatures to higher levels.

6.3.4 Strain localization and anastomosing shear zones

Another issue that may contribute to the lack of agreement between the Sierra Crest shear zone system and modeling predictions is that models distribute strain systematically across a shear zone, whereas it is instead localized in natural systems. The shear zone is itself a localization of strain, of course. The question is, 'how local?' In other words, at which scale(s) is strain being accommodated? Possible triggers for strain localization are many: rheological contrasts between lithologies (Nadin and Saleeby, 2004), variations in temperature or fluid flux (due perhaps to proximity to an intruding magma body) (McCaig, 1984; O'Hara, 1988; Tobisch et al., 1991), variations in stress (due perhaps to salients of wall rock which project into the shear zone or the presence of resistant blocks inside the shear zone), presence of fluids, and / or pre-existing structural heterogeneities. For whatever reason, certain areas within a shear zone may accommodate more strain than neighboring areas.

Shear localization may occur on many scales. Figure 71 shows cm-scale localization of strain as small pebbles in a metaconglomerate wrap around a larger, central, less deformed clast. Pebbles immediately across strike from the large clast are more deformed than pebbles along strike from the large clast (i.e. those in the rigid clast's 'pressure shadow'). As a result, the orientations of the long axes of the surrounding pebbles (i.e. lineation) occur in a variety of orientations, a condition also seen in traces of the foliation.

Figure 72 demonstrates this on the outcrop (m) scale. The white marker band (b) and other foliation traces (a) converge at the right-center portion (c) of the photograph. "c" is therefore an area of strain localization, where material (including the traces of foliation which are absent there) are interpreted to have been extruded from the plane of the outcrop.

On a shear-zone-segment (km) scale, strain localization may be noted in the appearance of pods of relatively undeformed rock surrounded by well-foliated and lineated rock more typical of the shear zone. In the Gem Lake and Mono Pass segments, for instance, lozenge-shaped pods of clast-rich volcanic breccia (Figure 21; Figures 14 and 15) were far less deformed than neighboring rock. The implication is that the deforming portions of the shear zone "flowed" around these pods of more resistant material.

Figure 71: Strained pebbles in multiple orientations as a result of being deformed around a resistant clast, Cascade Lake segment of the Sierra Crest shear zone. A) Photograph of stretched pebbles in metaconglomerate. Outcrop surface strikes 214° and dips 13°. Foliation strikes 146° and dips 88°. Long axis of large pebble is ~6 cm; photograph is approximately actual size. View is towards 124°. B) Line drawing emphasizing key pebble orientations (ellipses) and how foiliation wraps around the large central clast. Drawing is 80% scale of the original photograph.

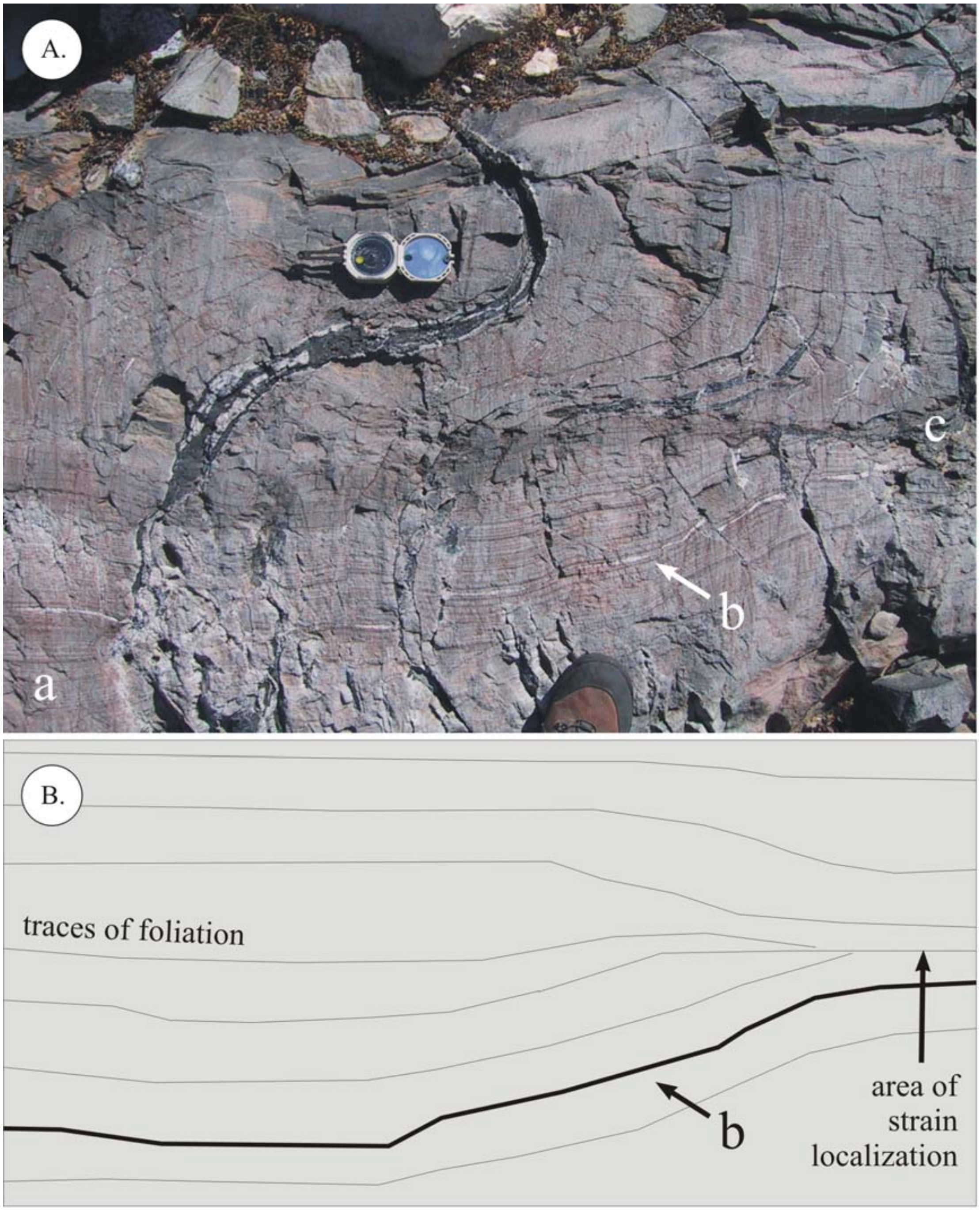


Figure 72: Deformed cracks in pelitic schist unit, Cascade Lake segment of the Sierra Crest shear zone. A) Photograph of deformed cracks, some infilled with quartz and fine-grained mafic minerals. Subhorizontal outcrop. Foliation strikes 342°. Brunton compass for scale. View is towards 075°. Notations: a is foliation trace typical of the surrounding area, b is white quartz marker band, c is area of strain localization, where foliation traces, including b, converge. B) Line drawing emphasizing how many foliation traces, including b, converge at area c, where material (including the vanished foliation traces) is interpreted to have been extruded out of the plane of the outcrop.

On a regional (10s of km) scale, the Sierra Crest shear zone system is but one of many parallel-trending shear zones in the eastern Sierra roof pendant and wall rocks (see Tobisch, et al, 1995a, Figure 1). The Bench Canyon, Rosy Finch, Courtright-Wishon, Quartz Mountain, and Kaiser Peak shear zones, and the proto-Kern Canyon fault all share the same northwest-trending orientation. Regionally, then, the same patterns that can be observed at smaller scales are repeated: areas of less deformed rock are surrounded by anastomosing shear zones which together accommodate regional tectonic deformation.

Hudleston (1999) examined the issue of strain localization in tabular shear zones. By building a model network of undeformed lozenges surrounded by interconnected ductile shear zones, Hudleston found multiple deformation paths within a single network: transpressional flattening, transtensional constriction, and plane strain simple shear. As Hudleston points out, “isolated, straight, parallel-sided shear zones may be the exception in nature.” This realization is likely applicable to the eastern Sierra Nevada.

Even on a gross map view, the Bench Canyon shear zone narrows from south to north (McNulty, 1995a Figure 1). Because it is not parallel-sided, it would not be comparable with the predictions of any extant model. Similarly, the Cascade Lake segment of the Sierra Crest shear zone has a mappable ‘jog’ in its trend: the shear zone bends for a short distance from its typical N30°W trend and for ~1.5 km trends N15°W. While it may not be perfectly parallel-sided, the Sierra Crest shear zone seems to be of reasonably constant width (though narrowest in the Cascade Lake segment), but it is impossible to tell for sure, since the original western margin of the shear zone is consumed by pluton intrusion.

In theory, one could estimate how much of the shear zone is missing based on rock fabric, but this would require that the shear zone be isolated, straight, and parallel-sided. And as the stereonets of Figure 38 and the lineation pitch data (as compared in Figures 62 and 63) show us, the Sierra Crest shear zone does not conform to model predictions in some critical respects. In Figure 71, opposite senses of shear would theoretically develop on either end of the central rigid clast. Echoed on a larger scale, this could explain seemingly anomalous data such as the sinistral porphyroclasts observed infrequently but regularly throughout the shear zone. Shear bands flowing in three dimensions around three-dimensional pods or lozenges would produce a wide array of fabric data far beyond the simple picture that any one of them (or any of Ramsay and Graham's (1970) shear bands) would produce by itself. The observation of Albertz et al. (2003) that the regional strain field is in various places "extensional, transtensional, neutral, transpressional, and contractional" would be reconciled, though still far from completely characterized, when interpreted as such a complex jostling of lozenges in a three-dimensional matrix of anastomosing shear zones.

What this implies, then, is that for a true understanding of a natural transpressional shear zone, an exceptional degree of observation must be employed. If anastomosing shear bands and strain localization on scales ranging from the regional to the microscopic are the way shear zones truly operate, then our methodology for understanding them must be commensurately complex. Modeling tabular shear zones will not be enough – because the resolution of a single homogenous domain is insufficient to match the whole of reality. While a tabular shear zone model will represent well a simple shear band on the scale of Ramsay and Graham (1970), it will come nowhere close to the complex reality embodied in a crustal-scale transpressional zone comprised of a dozen lithologies like the Sierra Crest shear zone system.

Jiang (in revision) discusses this idea: transpressional boundary regions (e.g. orogens, arcs) may contain multiple transpressional zones within a broader background of regional deformation. Mylonite zones, transposition shear zones, and other strain localizations may be present within the transpressional zones. Jiang shows that models that assume homogenous flow (or only a single strain localization), should only be applied to individual domains within such a regional framework, not to the regional framework itself.

Structural geologists working on field-based approaches to understanding shear zones must pay attention to less-deformed domains as well as well-deformed domains. Only by identifying areas with little or no rock fabric will rigid lozenges / pods be identified, and only when they are identified and separated from the shear zone domain(s) will the kinematics of the shear zone have a chance of making sense. Absence of discernible fabric is as much evidence of the kinematic state of the zone as measurements of fabric where it does exist. Only by recording absence of strain would one be able to identify areas like the lozenges in Hudleston (1999, Figure 6e or 7a).

6.4 Conclusions and concluding remarks

6.4.1 Main conclusions of the thesis

This thesis makes the following conclusions:

(1) Monoclinic models of transpressional shear zones are unstable. Even slight deviations from $\Phi = 0$ result in lineation evolving by a progressive rotation, rather than an instantaneous switch, from V_{ss} (horizontal) towards V_{ds} (vertical). Triclinic models ($\Phi \neq 0$) better explain the variation of lineation orientations in natural transpressional shear zones.

(2) The Sierra Crest shear zone is a ~40 km regional transpressional shear zone, the easternmost and most well-preserved of several parallel, anastomosing shear zones in the east-central Sierra Nevada, California. It was active during the mid- to late- Cretaceous, when the Sierra Nevada was a transpressional magmatic arc. Field mapping and structural analysis suggest that the area has undergone three generations of deformation: D1, pre-shear-zone, is evidenced by isoclinal folds outside the shear zone. D2 deformation was coincident with the latest emplacement of the Sierra Nevada batholith, and is evidenced by the dextral, west-over-east development of the shear zone's transposition foliation, second-generation folds outside the shear zone, and syn-tectonic pluton emplacement. D3 deformation, tentatively correlated with the initiation of Basin and Range extension, is sinistral and moderately transtensional, as evidenced by kink banding and folding overprinting transposition foliation.

(3) All three segments of the Sierra Crest shear zone display full circle girdles of lineation orientations. Lack of agreement with the half-girdle predictions of single-domain models may be explained by variations in Φ along strike, widening of the

shear zone across strike, and heterogeneous strain localization on many scales. Regional transpressional zones are better understood as complex three-dimensional arrays of multiple shear zone domains.

(4) The Sierra Crest shear zone and the array of parallel, anastomosing shear zones to its west may have served a tectonically important function in removing material volume across strike from the intruding plutons of the Sierra Nevada batholith, a hypothesis that suggests a partial solution to the batholithic room problem.

6.4.2 Concluding remarks

A year after Ramsay and Graham's initial analysis of shear bands, Harland (1971) originally invoked "transpression" to describe phenomena on the tectonic scale. Sanderson and Marchini put the two concepts together in 1984 to describe monoclinic deformation in tabular zones. Lin et al. (1998, 1999) and Jiang and Williams (1998, 1999) brought modeling closer to matching geological reality by developing a robust means to incorporate triclinic deformation conditions. Now, the next major step will be to realistically integrate rheological heterogeneity, non-parallel-sidedness of the shear zone, anastomosis, and all manner of geometrically complex initial wall configurations.

Further modeling of three-dimensional triclinic shear zone deformation incorporating these features and comprehensive studies of strain on all scales and in all increments (including no strain at all) in naturally-occurring shear zones (and arrays of shear zones) will be necessary to improve our understanding of how shear zones deform and how best to interpret the rock fabric data that we gather from them.

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