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Andrew P. de Wet
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Keck Geology Consortium
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PO Box 3003, Lanc. Pa, 17604

Lara Heister
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**Keck Geology Consortium: Projects 2009-2010
Short Contributions – COLORADO**

**INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK
CATCHMENT, FRONT RANGE, COLORADO**

Project Director: *DAVID P. DETHIER*: Williams College
Project Faculty: *MATTHIAS LEOPOLD*: Technical University of Munich

**FRACTURE DISTRIBUTION AND CHARACTERIZATION IN BETASSO
GULCH, CO**

ELIZABETH DENGLER
Bates College
Research advisor: Dykstra Eusden

**TALUS STRUCTURE AND EVOLUTION: A COMPARISON BETWEEN TALUS
NEAR GREEN LAKE 3 AND AT BUMMER'S ROCK, COLORADO**

EVAN RIDDLE
North Carolina State University
Research Advisor: Karl Wegmann

**THE DISTRIBUTION OF TORS IN GORDON GULCH, FRONT RANGE,
COLORADO**

JAMES TROTTA
Williams College
Research Advisor: David P. Dethier

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Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster Pa, 17603
Keckgeology.org

FRACTURE DISTRIBUTION AND CHARACTERIZATION IN BETASSO GULCH, CO

ELIZABETH DENGLER

Bates College

Research advisor: Dykstra Eusden

INTRODUCTION

The purpose of this study was to evaluate the Proterozoic rock types in Betasso Gulch, Colorado, and complete a tectonic paleostress analysis of the fracture system, which formed as a result of the Colorado (~1.8 Ga) and Laramide (80-60 Ma) orogenies that lifted the Front Range. Betasso Gulch is located in the Front Range of the Colorado Rocky Mountains, just west of Boulder (Fig. 1).

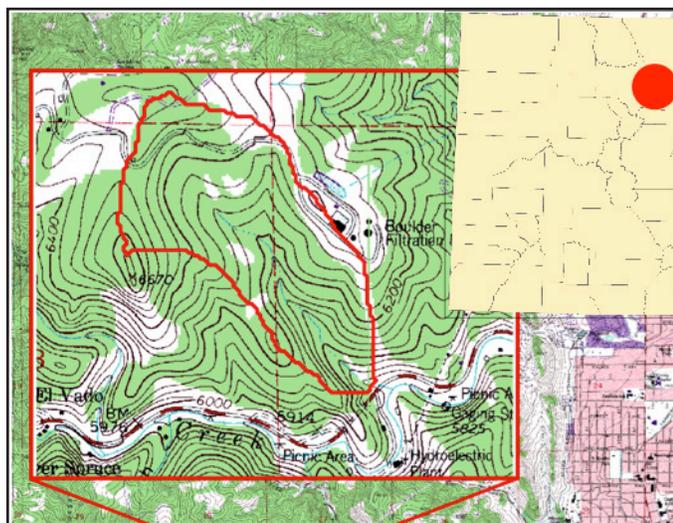


Figure 1. Insert shows the location of Boulder within Colorado. The figure shows where Betasso Gulch is in relation to Boulder. The boxes show the area containing Betasso; the gulch is represented by the polygon outlined in red. A zoomed image of the polygon reveals Betasso topography.

This study supports the interdisciplinary studies of the Boulder Creek Critical Zone Observatory, by offering new structural data that can be related to broader studies of the critical zone region.

The tectonic history of Colorado began about 1.8 Ga, with the Colorado orogeny, which involved the accretion of oceanic arcs onto the Archean Wyoming craton (Sims and Stein, 2003). Partial melting led to an influx of igneous intrusions, including the Boulder Creek Granodiorite, and deformation around 1.7 Ga. The Berthoud orogeny, a tectono-thermal event occurring between 1.45 and 1.35 Ga, further deformed the Paleoproterozoic rocks of the Colorado orogeny. NE-striking ductile shear zones formed during this orogeny, along with plutonic activity that included intrusion of Silver Plume granite (Sims and Stein, 2003), which crops out west of the study area.

The Laramide orogeny occurred between 80 and 55 Ma, creating the fold and thrust belt of the Rocky Mountains as well as exposing Precambrian rocks formed during the Colorado orogeny (English et al. 2003). It is hypothesized that the Laramide orogeny occurred due to flat-slab subduction of the Farallon Plate, supported by the presence of extensive magmatism inland from the trench (English et al. 2003). The Colorado Mineral Belt formed during the Laramide orogeny, resulting in the emplacement of ores (Tweto et al. 1963).

Front Range uplift occurred during the Laramide orogeny around 70-65 Ma. The range trends north-northwest and deformation was controlled by preexisting faults and shear zones that formed in the Proterozoic. In the late Cretaceous, the Laramide orogeny not only uplifted the Front Range, but in the process exposed Proterozoic basement rocks (Sonnenberg and Bolyard 1997). The faults found in the region suggest basement compression as well as arching and thrust faulting as the major sources of uplift (Sonnenberg and Bolyard, 1997). Betasso

Gulch lies within a highly faulted region and is adjacent to the Colorado Mineral Belt, both of which have influenced on the bedrock geology of the region.

Hypotheses for the formation of fractures in Betasso Gulch are few but some insight comes from a recent study by Erslev (2009). Erslev (2009) suggests that fractures in the Rocky Mountains most likely formed as regional compression and extension during the Laramide reactivated older structures. Several of the fractures formed post-Laramide due to regional extension or the back-sliding of thrust faults.

METHODS

Bedrock properties and fracture geometry were mapped in Betasso using the 7.5-minute topographic Boulder Quadrangle map as a base. Outcrops larger than 1 square meter were mapped and the fractures were recorded. The orientation of each prominent fracture in the mapped outcrops was measured by taking the strike and dip with a Brunton compass. Over 500 fracture orientations were measured in this fashion between the 284 GPS waypoints that were collected using a WAAS-enabled Garmin Etrex.

The strike and dip fracture data were initially compiled by rock type and plotted using the great circle function in Stereonet v.6.3.3 (Allmendinger, 2006) in order to show the primary fracture sets. Fracture data were compiled onto one stereonet to determine primary orientations. Rock samples were collected in order to capture a representative suite of each rock type, and made into thin sections. Rock types were then classified based on observational analysis, which included estimated modes of each thin section, and SEM/EDS analysis. Fracture orientations and cross-cutting relationships of fractures were analyzed using aerial imagery, field photos, and fracture maps. A fracture map was created by placing several stereonets showing the most prominent fracture orientations in red. This map was then used to analyze the relationship between the various fractures and rock types. A 0.32 meter resolution aerial

image and several field digital images were used to trace fracture orientations then determine cross-cutting relationships.

Using the data from the field, as well as data from previous maps (Kellogg et al., 2008), a detailed map of the Betasso Gulch region was created using ArcGIS 9.3. Color-coding by rock type was used when drawing in rock boundaries. Several faults and foliations were added based on data from pre-existing maps (Kellogg et al., 2008).

RESULTS

Seven thin sections were made for EDS analysis; the samples were labeled ED005, ED094, ED147, ED147a, ED022, ED139a and ED082 based on their waypoint number. The two main rock types are the Boulder Creek Granodiorite and quartz monzonite, with the critical differences being the concentrations of plagioclase, potassium feldspar, and quartz. Plagioclase and potassium feldspar in many of these samples are intermixed and the EDS spectra often returned with combinations of elemental data. Estimated modes of each thin section can be seen on Table 1. Using these estimated modes the samples were classified using a QAPF diagram.

Based on the estimated modes sample ED005 is a medium to coarse-grained black and white granodiorite. Its constituents are potassium feldspar, plagioclase, quartz, small lenses of biotite and hematite and traces of hornblende and apatite. ED094 is a medium-grained quartz monzonite that appears darker than ED005 in hand sample. It contains potassium feldspar, plagioclase, quartz, biotite, hornblende, and traces of hematite and apatite. ED147 and ED147a are both alkali feldspar syenites; even though they are from the same rock sample, they vary in their concentrations of minerals. The rock itself is pink with lenses of mafic minerals. ED147 is abundant in potassium feldspar and contains some hornblende, while ED147a has almost equal concentrations of potassium feldspar and hornblende. ED022 is a medium-grained quartz monzonite that is pink in hand sample and contains potassium feldspar, plagioclase, hornblende, quartz, large grains of

Sample Number	Potassium Feldspar	Plagioclase	Quartz	Hematite	Hornblende	Biotite	Chlorite	Allanite	Epidote	Apatite	Rock Name
5	10	65	20	1	>1	3	0	0	0	>1	Granodiorite
94	45	30	15	>1	2	7	0	0	0	>1	Quartz Monzonite
147	97	0	0	>1	3	>1	0	0	0	0	Alkali Feldspar Syenite
147a	50	0	0	>1	50	0	0	>1	0	0	Alkali Feldspar Syenite
22	60	24	10	>1	0	>1	4	1	0	0	Quartz Monzonite
139a	40	40	17	>2	0	0	0	0	1	0	Quartz Monzonite
82	10	40	30	20	0	0	>1	0	0	0	Granodiorite

Table 1: Estimated modes for Betasso rock samples and corresponding rock type.

allanite and traces of hematite. ED139a is classified as quartz monzonite; it is finer-grained and has large grains of hematite and bands of epidote. It contains almost equal portions of potassium feldspar and plagioclase, quartz, and traces of hematite and epidote. ED082 is identified as granodiorite and is a medium to coarse-grained pinkish rock with a prominent vein of hematite; it contains mostly plagioclase, some potassium feldspar, quartz and traces of hornblende. The hematite vein also contains traces of pyrite. A geologic map was created using these classifications as well as data from previous maps (Kellogg et al., 2008).

Most of Betasso Gulch is considered to be granodiorite with lenses of quartz monzonite in the southeast and northwest (Fig. 2). These lenses are oriented northwest parallel to foliation. There is also a small lens of alkali feldspar syenite, located in the central part of the study area. The main faults strike parallel to the foliation in a northwest direction. Hematite-rich veining strikes the length of one of the northwest oriented faults. The pegmatites generally strike east-northeast, at high angles to the foliation. A map showing the fractures, grouped by waypoints as depicted on stereonet, was added to the geologic map (Fig. 2). This map shows no clear relationship between rock types and fracture orientations in the gulch. The fractures appear to be uniform throughout the Betasso Gulch study area.

The fracture data were then compiled into a single stereonet, revealing four main fracture orientations in Betasso Gulch: (1) 10°, 40°E; (2) 336°, 67° E; (3) 41°, 81°E; and (4) 252°, 74°N (Fig. 3). The fracture data have sets that are parallel to the mapped faults, foliations and pegmatites. Cross-cutting relationships, established using aerial and field imagery,

are ambiguous and have led to two hypotheses for fracture formation and relative timing.

DISCUSSION

According to Gable (1980), there are two main rock types in the batholith, granodiorite and quartz monzonite, with several smaller lenses of mafic plutonic rocks, pegmatites, aplites and some metamorphic rocks. The thin section for sample 005 is representative of unaltered 1.8 Ga Boulder Creek Granodiorite. Its estimated modes revealed 65% plagioclase, 20% quartz, 10% potassium feldspar and 3-5% biotite. Thin sections for samples at waypoints 094 and 022 were classified as the 1.7 Ga quartz monzonite. Estimated modes show more potassium feldspar (45%, 60% respectively) than plagioclase (30%, 24%) and lower amounts of quartz (15%, 10%). The thin section for the sample at waypoint 094 contains 7% biotite and 2% hornblende.

Fractures are interpreted to have formed along pre-existing fabrics and anisotropies such as faults, foliations and pegmatite dikes. The northwest fractures (Set 1) strike parallel to the major fault system in the gulch, while the north fractures (Set 2) align with the echelon faults linking the main faults. The east (Set 4) and northeast (Set 3) fractures are oblique, though nearly perpendicular, to the major faults, but strike parallel or sub-parallel to the pegmatite dikes. Ages of the faults and pegmatite dikes are likely much older than the fracture sets 1 through 4.

Using the analysis of bedrock properties, which show relatively uniform grain size throughout the gulch, as well as using principles of fracture formation, I hypothesized that there are two sets of tensile-compressive conjugate pairs. The angle of sepa-

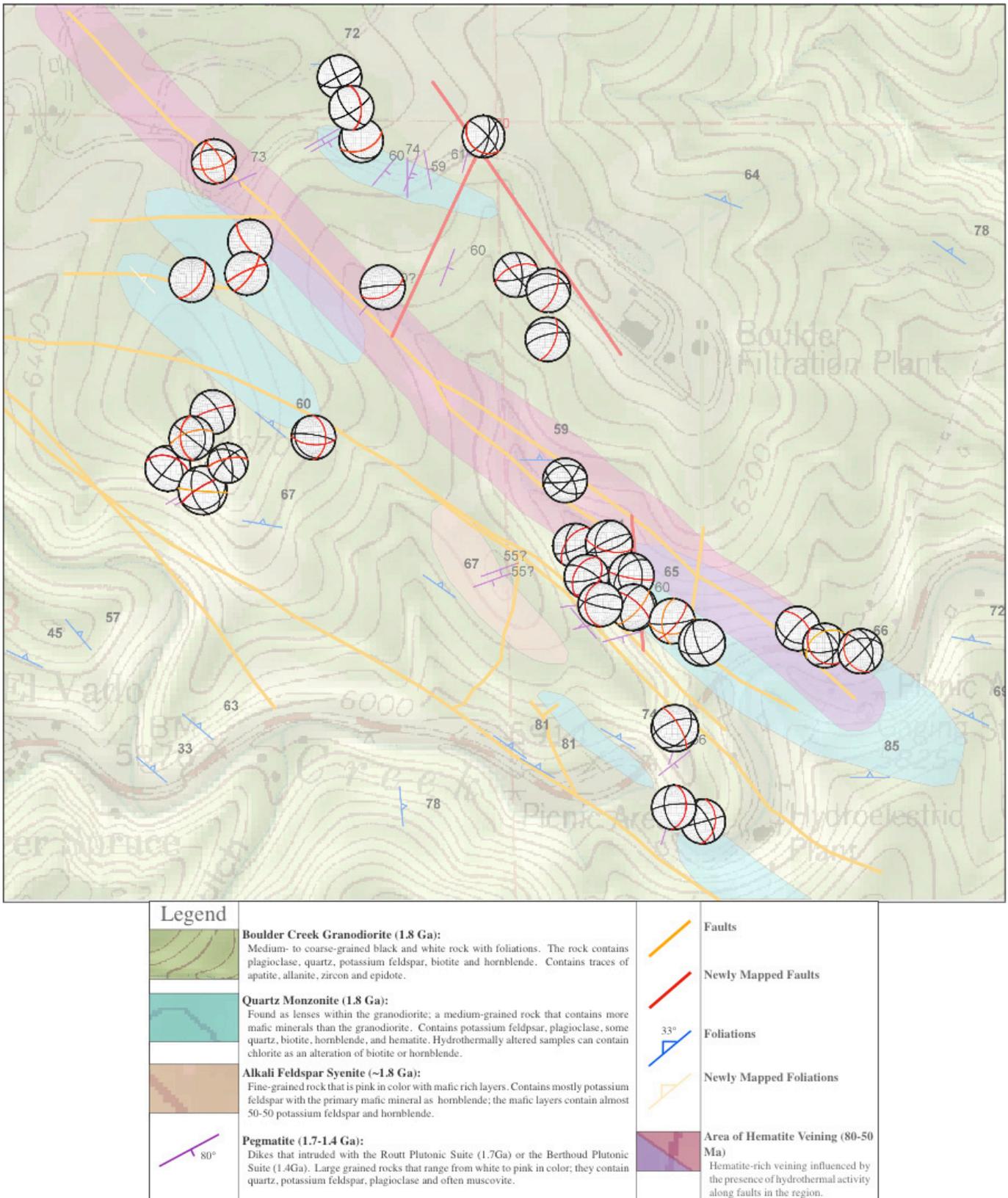


Figure 2: Map showing the geologic features of Betasso Gulch and the stereonet that relate the fractures to bedrock. Red lines on the stereonet represent the most prominent fractures seen in the gulch; black lines show less prominent orientations.

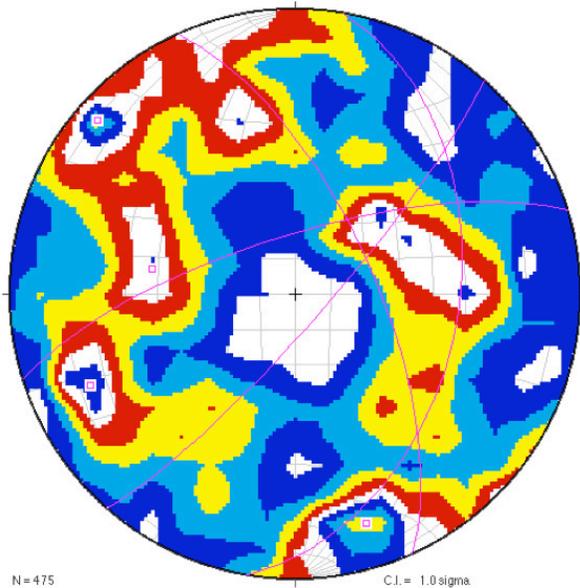


Figure 3: Three dimensional stereonet projection of primary fractures mapped in Betasso Gulch, showing the 475 fractures compiled using a Kamb contour. The regions with the highest contour intervals represent the most prominent fracture orientations. The four main fracture orientations are: 41°, 81°E; 252°, 74°N; 10°, 40°E and 336°, 67° E.

ration between fracture sets 1 and 2 is 38°, and sets 3 and 4 have an angle of separation of 40°, which places them within the parabolic failure envelope for tensile-compressive fractures (Burger and Harms, 2001-2006). The uniformity of the rock would also allow for uniform formation of tensile-compressive fractures. Sets 1 and 2 make up the first conjugate pair, A; sets 3 and 4 make up the second conjugate pair, B. Due to the ambiguity of cross-cutting relationships, I suggest two possible hypotheses for the formation of these conjugate pairs. The first hypothesis is that Pair A formed prior to Pair B and they both formed post-Laramide; the second hypothesis suggests that Pair B is actually older than Pair A, forming during the Laramide.

The stress orientations for Pair A (Fig. 4) are shown on the stereonet where σ_1 is oriented, 24°, 35° and σ_3 is 259°, 38°. The second insert (Fig. 4) shows a map view of the stresses needed to form conjugate Pair A. The σ_1 stress trajectories for this pair are shown on the map as dotted black lines. The arrows show the orientation of the shallow plunge of σ_1 to the north.

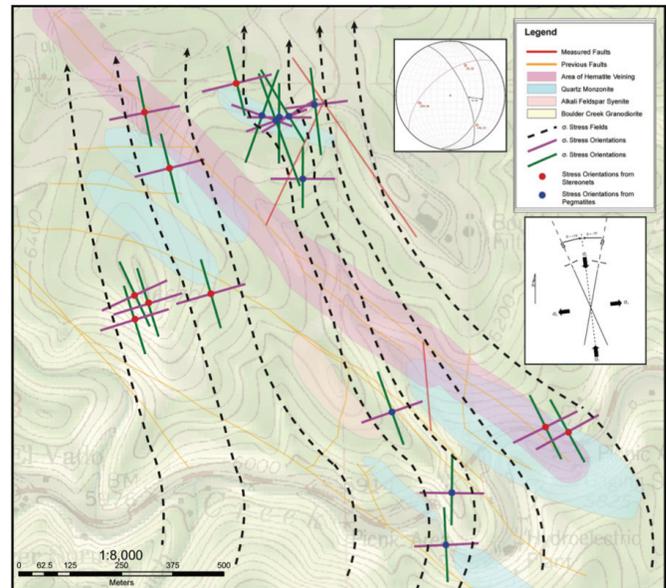


Figure 4: North-northwest fracture conjugate Pair A paleostress map showing σ_1 trajectories post-Laramide at about 50 Ma. σ_1 is oriented north-northwest while σ_3 is oriented northeast.

Pair B yields a σ_1 of 240°, 40° and σ_3 , of 146°, 4° (Fig. 5). The stereonet insert and second insert show the fracture orientations relative to stresses needed to form them. This second insert relates to the σ_1 stress trajectories on the map in Figure 5, which shows a northeast trending σ_1 stress field with a dotted black line and arrows representing a southwest plunge.

Several images show north and northwest oriented fractures that cut each other, clearly showing a conjugate pair that formed with tensile-compressive stresses with some shear movement as determined by slicken lines on fracture faces seen in the field. Ambiguous cross cutting relationships identified in field and other images made establishing relative fracture ages problematic. However the east and northeast fractures appear to terminate against the north and northwest fractures, suggesting that the north trending set is youngest. If Pair A is older, the fracture set may result from formation of the northwest trending foliations, faults and north trending echelon faults in Betasso Gulch during the Laramide orogeny. After the Laramide, regional extension or back-sliding of Laramide thrusts (Erslev, 2009) would have allowed Pair A to form along the pre-existing planes of weakness. The principle tensile stress,

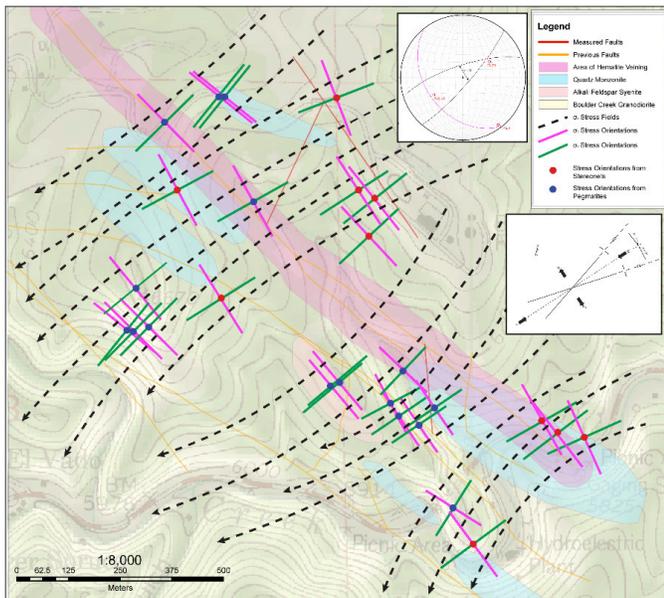


Figure 5: East-northeast fracture conjugate Pair B paleostress map showing σ_1 trajectories post-Laramide at about 50 to 35 Ma. σ_1 is oriented northeast while σ_3 is oriented northwest.

σ_3 , is oriented east-northeast while the maximum compressional stress, σ_1 , is oriented north-northwest (Fig. 3). These stresses correspond with regional extension oriented southwest to northeast, which would have occurred just after the Laramide (Erslev, 2009). Pair B formed along the pre-existing weaknesses generated by the pegmatites in the region and likely formed due to un-roofing of the batholith post Laramide. The extensional stress, σ_3 , of Pair B is oriented northwest, while σ_1 , the principal compressional stress, is oriented northeast. These stresses may have developed during unroofing of the batholith during erosion of the Front Range 50-35 Ma (Livaccari, 1991). This hypothesis is compelling given the stresses needed to form both pairs of conjugate fractures.

CONCLUSIONS

The bedrock of Betasso Gulch is primarily granodiorite with lenses of quartz monzonite, alkali feldspar syenite and pegmatite dikes, all of which are older than 1.4 Ga. The Laramide orogeny, which occurred around 80 to 50 Ma, resulted in the formation of two conjugate pairs of fracture sets measured in Betasso Gulch. The northeast-oriented subduction

of the Farallon plate formed northwest trending foliations and faults. These features, as well as the northeast-trending pegmatites, created weaknesses in the batholith, allowing for the development of fracture planes once new stresses were generated in the region. Evidence in Betasso Gulch suggests that fracture Pair A formed first, post-Laramide, due to regional extension and/or back-sliding of Laramide age northwest trending faults. Fracture Pair B formed second during regional unroofing of the batholith. The timing and spatial patterns of fracture formation is important in studying weathering patterns as fractures are the planes along which weathering first occurs. This analysis of fractures thus contributes to the Boulder Creek Critical Zone Observatory's research.

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