

Rock Geochemistry and Mineralogy from Fault Zones and Polymetallic Fault Veins of the Central Front Range, Colorado



Data Series 492

FRONT AND BACK COVER—Rock sample of a fault vein from the Denver Water fault located at Gross Reservoir, Boulder County, Colorado. Photograph taken in August 2005.

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By Jonathan Saul Caine and Dana J. Bove

Data Series Report 492

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Conversion Factors and Datums

Multiply	By	To obtain
Length		
inch (in.)	25,400	micrometer (μm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
ounce, fluid (fl. oz)	29.57	milliliter (mL)
gallon (gal)	3.785	liter (L)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, "North American Datum of 1927 (NAD 27)."

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Introduction

During the 2004 to 2008 field seasons, approximately 200 hand samples of fault and polymetallic vein-related rocks were collected for geochemical and mineralogical analyses. The samples were collected by the U.S. Geological Survey as part of the Evolution of Brittle Structures Task under the Central Colorado Assessment Project (CCAP) of the Mineral Resources Program (http://minerals.cr.usgs.gov/projects/colorado_assessment/index.html). The purpose of this work has been to characterize the relation between epithermal, polymetallic mineral deposits, paleostress, and the geological structures that hosted fluid flow and localization of the deposits. The data in this report will be used to document and better understand the processes that control epithermal mineral-deposit formation by attempting to relate the geochemistry of the primary structures that hosted hydrothermal fluid flow to their heat and fluid sources. This includes processes from the scale of the structures themselves to the far field scale, inclusive of the intrusive bodies that have been thought to be the sources for the hydrothermal fluid flow.

The data presented in this report are part of a larger assessment effort on public lands. The larger study area spans the region of the southern Rocky Mountains in Colorado from the Wyoming to New Mexico borders and from the eastern boundary of the Front Range to approximately the longitude of Vail and Leadville, Colo. (fig. 1). Although the study area has had an extensive history of geological mapping (for example, Lovering and Goddard, 1950; Sims, 1964; Moench and Drake, 1966; Taylor, 1976; Gable, 1980), the mapping has resulted in a number of hypotheses that are still in their infancy of being tested. For example, the proximity of polymetallic veins to intrusive bodies has been thought to reflect a genetic relation between the two features; however, this idea has not been well tested with geochemical indicators. Recent knowledge regarding the coupled nature of stress, strain, fluid flow, and geochemistry warrant new investigations and approaches to test a variety of ideas regarding the genetic processes associated with ore-deposit formation (for example, Caine and others, 2006). The central

part of the eastern Front Range has excellent exposures of fault zones and polymetallic fault veins, subsequently resulting in some of the most detailed mapping and associated data sets in the region. Thus, the area was chosen for detailed data compilation, new sample and data collection, and a variety of structural and geochemical analyses (fig. 2). The data presented in this report come from samples of fault-related exposures in the Front Range and include elemental chemistry and mineralogy from the outcrop-scale study localities within the larger CCAP study area (figs. 1 and 2).

Methodology

Sampling Methods

Viable exposures for detailed study were identified using existing 1:24,000-scale geological maps and mine maps at a variety of scales. Reconnaissance fieldwork revealed a number of excellent exposures of fault zones and fault veins in natural outcrops, roadcuts, and quarries. The fault-zone architectural conceptual model of Caine and others (1996) was used as a guide to sampling the components of each structure. Fault-related architectural components include a fault core where most of the strain is accommodated and where fault rocks such as clay-rich gouge and fault breccias are common (Caine and others, 1996). Fault cores are commonly surrounded by damage zones where networks of small faults, fractures, and veins form in response to growth of the fault. In the Colorado Front Range, many of the major fault zones have damage zones affected by argillic hydrothermal alteration. Surrounding the damage zone is the protolith or host rocks that have a variety of structures that are primarily related to regional-scale deformation such as joints. Fault veins are commonly quartz veins that have evidence of slip along or adjacent to them and are commonly surrounded by an argillic and (or) sericitic alteration halo. Samples from each component of the model were collected at each study site to assess the nature of these structures and identify evidence of paleofluid flow within and around them. Multiple samples were collected where large along-strike exposures were evident.

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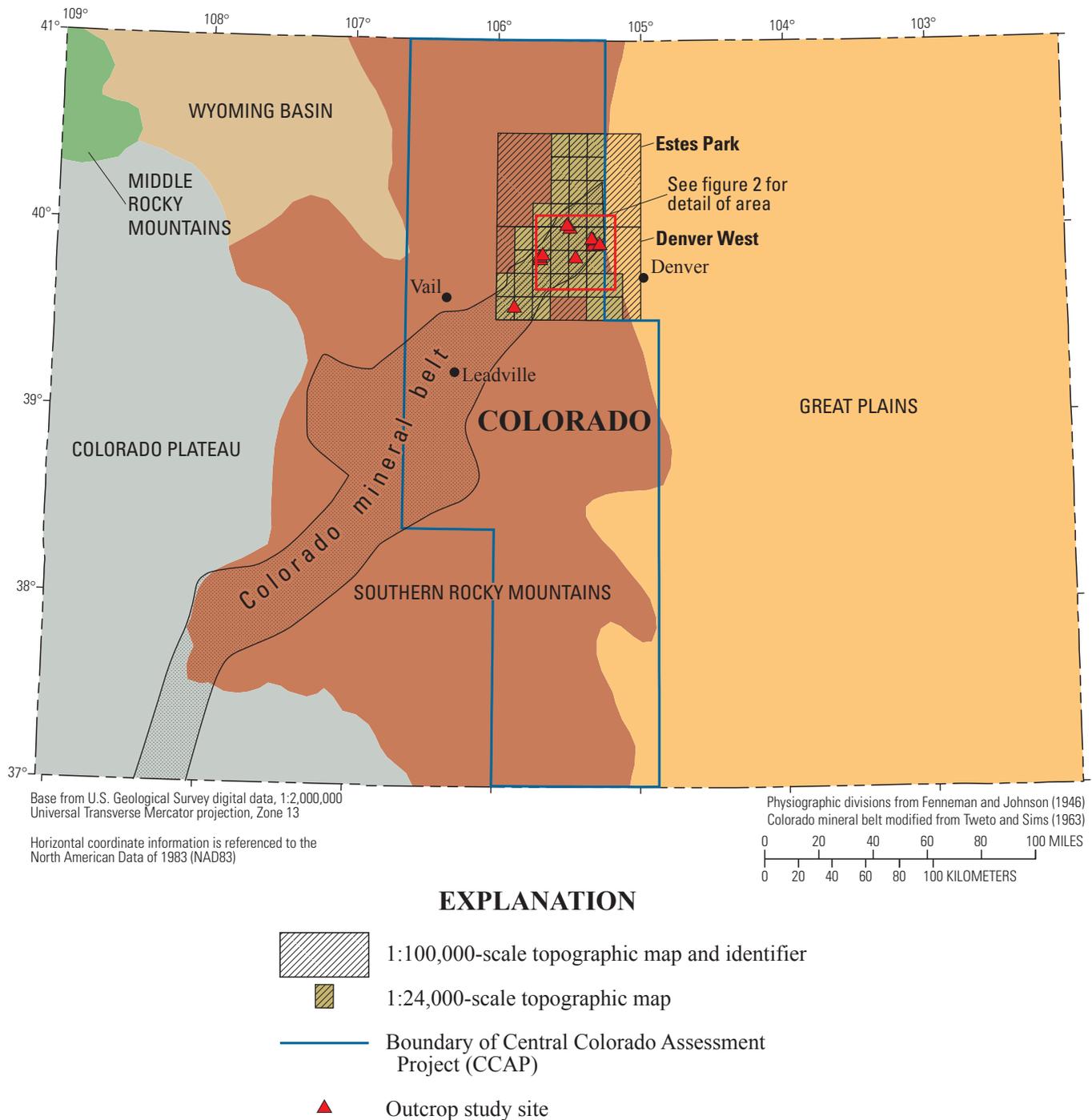
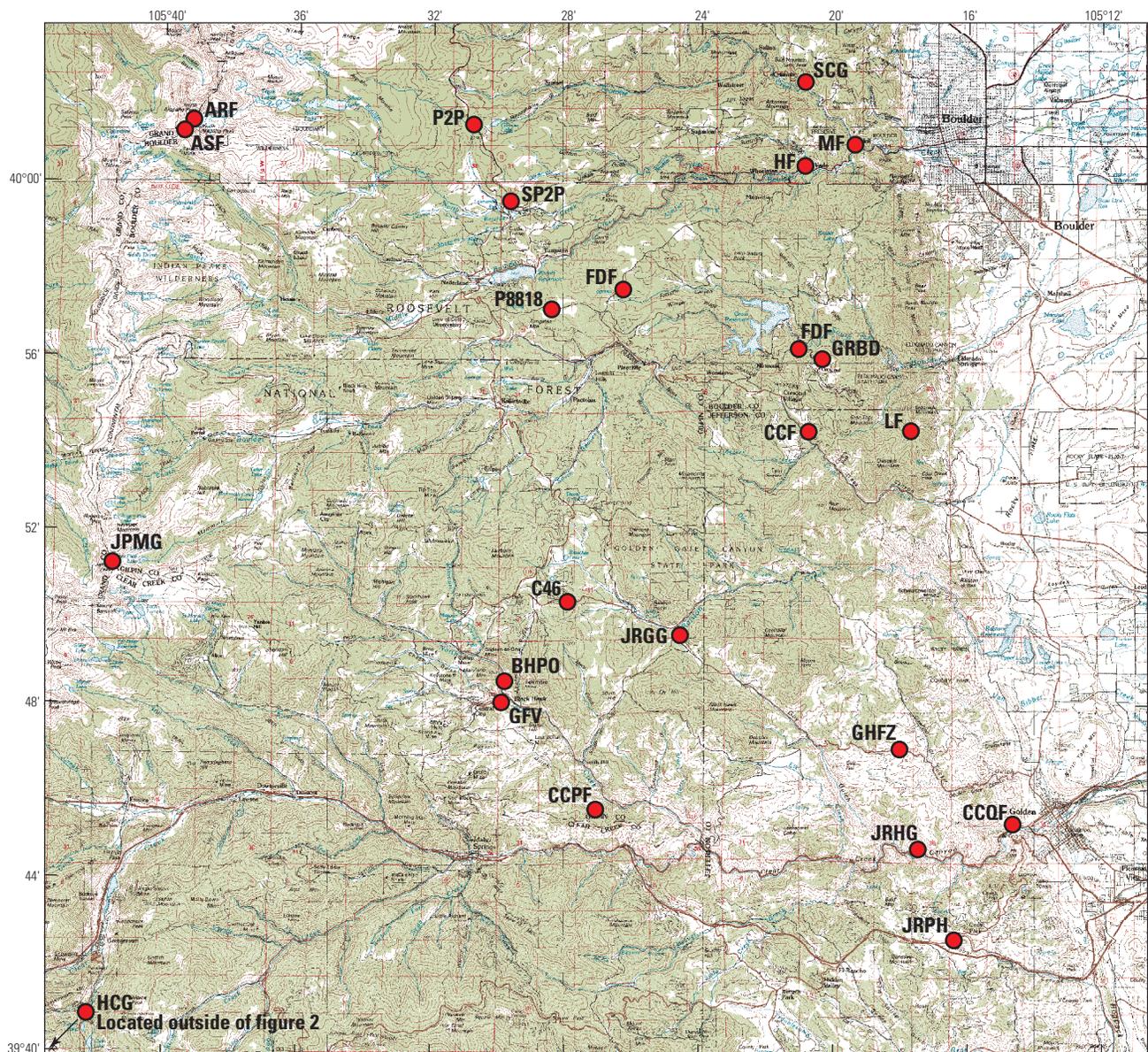


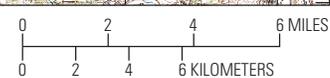
Figure 1. Map of Colorado showing major physiographic provinces, the Colorado mineral belt (modified from Tweto and Sims, 1963), the Central Colorado Assessment Project (CCAP) study area (blue), 1:100,000- and 1:24,000-scale map areas (hatched and green fill), and outcrop study localities (red triangles) within the detailed map shown in figure 2.

At each fault locality, representative samples were collected along traverses across the structure. Outcrop faces were excavated by scraping off the upper several centimeters of weathered material if the rocks were soft enough. If the rocks were competent, a sample was extracted using a chisel and

hammer to collect relatively unweathered samples. Samples were collected in a quart-size plastic bag and labeled using the date, sequential outcrop number, and a letter for the sample that is related to the architectural position of the sample in the fault zone.



Base from U.S. Geological Survey digital raster graphic data, 1:100,000
 Estes Park, Co., 1984
 Denver West, Co., 1983
 Universal Transverse Mercator projection, Zone 13



Horizontal coordinate information is referenced to the
 North American Data of 1983 (NAD83)

EXPLANATION

JRPH ● Fault zone sample site and identifier

Figure 2. Location map showing fault zones studied and sampled. The basemap is the U.S. Geological Survey, 30° × 60° Denver West topographic map. The red dots are the central locations for each sample site and the text refers to the short name for each locality as noted in the data tables (tables 1 and 2).

Sample Preparation and Analytical Methods

Whole-rock samples were washed in deionized water, and a representative portion was split for geochemical analysis. The dried rock samples were crushed to pea-sized fragments using a jaw crusher and then further reduced in

size to an approximately 100-mesh (<150µm) powder with a vertical Braun pulverizer equipped with ceramic plates. All rock geochemical analytical methods, with the exception of mineralogy by X-ray diffraction, were completed at SGS Minerals in Toronto, Ontario, Canada, under contract with the U.S. Geological Survey.

Elemental Chemistry

Major (except Si and Na), rare earth, and trace element concentrations were determined from induction coupled plasma–atomic emission spectrometry–mass spectrometry (ICP–AES–MS; Taggart, 2002). A 0.1-g sample was weighed from the powdered samples and decomposed using a sodium peroxide sinter at 450°C. The resultant cake was leached with water and acidified with nitric acid. After an addition of tartaric acid, aliquots of the digested sample were aspirated into the ICP–AES and the ICP–MS, and the concentrations of the optimal elements from the ICP–AES and ICP–MS were determined. Calibration on the ICP–AES was performed by standardizing with digested rock reference materials and a series of multielement solution standards. The ICP–MS was calibrated with aqueous standards, and internal standards were used to compensate for matrix effects and internal drifts. To monitor the quality of the data, a quality control reference standard (GSP–QC) was inserted within the samples analyzed. All detectable concentrations of the 55 elements were within two standard deviations of the expected mean, except for Fe, Mg, and Zn, which were within three standard deviations. All values fell within the acceptance criteria outlined in Arbogast (1990). Reporting limits for this method are published on the U.S. Geological Survey website (http://minerals.cr.usgs.gov/projects/analytical_chem/references.html#m22, accessed November 2009).

Ten major elements (SiO₂, Al₂O₃, CaO, MgO, Na₂O, K₂O, Fe₂O₃, MnO, P₂O₅, and TiO₂) and gravimetric loss on ignition (LOI at 925°C) were determined in rocks and minerals using wavelength dispersive X-ray fluorescence spectrometry (WDXRF; Taggart and Siems, 2002). Detection limits for all elements including LOI was 0.01 percent. Data were deemed acceptable if recovery of the major oxides was ±5 percent at the lower limit of determination (LOD), and the calculated relative standard deviation (RSD) of duplicate samples was no greater than 5 percent.

Total sulfur was determined by using an automated sulfur analyzer. Approximately 0.25 g of sample was mixed with iron chips and LECOCEL and was heated in a combustion tube in a stream of oxygen at high temperature. Sulfur was oxidized to sulfur dioxide. Moisture and dust were removed, and the sulfur dioxide gas was then measured by a CS-244 infrared detector. The reporting range for total sulfur was from 0.05 percent to about 35 percent. The data were deemed acceptable if recovery of total sulfur was ±15 percent at five times the LOD, and the calculated percent RSD of duplicate samples was no greater than 15 percent.

Essential water was determined by drying the sample for 1 h at 105±5°C to remove H₂O⁻ (hygroscopic water). Then the sample was heated to 950°C by using a tube furnace. The H₂O⁺ was absorbed by magnesium perchlorate. From its gain of weight, the amount of essential water was calculated. Non-essential water was determined by drying the sample for 2 h at 105 ±5°C; from the loss in weight, non-essential water, in percent, was calculated. The lower reporting limit was 0.05

percent for both forms of water. Data were deemed acceptable if recovery of essential and non-essential water was ±15 percent at five times the LOD, and the calculated percent RSD of duplicate samples was no greater than 15 percent.

Mineralogy by X-Ray Diffraction

Powder X-ray diffraction (XRD) analyses of whole-rock samples were completed at the U.S. Geological Survey, Boulder, Colo., XRD laboratory. The samples were prepared according to the methods described by Środon and others (2001). With a few exceptions, 3 g of sample was mixed with 0.333 g of an internal standard (zincite). The mixture was subsequently ground with 3 mL of methanol in a McCrone mill for 5 minutes, oven dried at 85°C, passed through a 4-mm sieve, and then side-loaded into an aluminum holder to optimize random orientation of the minerals. Several samples were prepared for quantitative analysis without a zincite standard (standardless and marked with an * in the table). One gram of each of these samples were also sieved and side-loaded in the same manner as the samples mixed with zincite.

All samples were X-rayed from 5° to 65° 2θ with CuKα radiation (40 Kv, 30 mA) using a Siemens D500 X-ray diffraction system using a step size of 0.02° 2θ, and a counting time of 2 s per step. After visual inspection of the raw X-ray patterns for major mineral phase characteristic peak reflections, the computer program RockJock (Eberl, 2003) was used to further analyze the X-ray patterns. For samples mixed with the zincite standard, the program compares integrated X-ray intensities for minerals present in a sample with that of an internal zincite standard in the sample, and weight percents are calculated from previously measured mineral intensity factors (MIFs). Integrated XRD intensities are determined by whole-pattern fitting (Smith and others, 1987) using a library of XRD patterns of pure minerals. Several patterns of individual minerals from the library are scaled simultaneously and summed together to create a calculated pattern that is compared to the measured sample pattern. The scaling factors are adjusted automatically until the degree-of-fit between the measured and calculated patterns is minimized. The error in the analyses is approximately ±3 weight percent (one standard deviation) at 50 weight percent of a mineral (Eberl, 2003). The Solver option minimizes the degree of fit parameter between measured and calculated patterns by varying the intensities of the stored standard patterns by multiplying each of these patterns by a separate factor. Individual mineral concentrations in each sample are normalized to 100 percent and the prenormalization totals are reported. A full-pattern degree-of-fit parameter is also reported where lower values indicate more accurate analyses with values <0.1 considered ideal. Dashed values indicate minerals that were not analyzed by RockJock, because their characteristic XRD peak reflections were not present upon visual inspection. Standardless RockJock analysis (that is, no added internal standard) is similar to the methodology utilizing an internal zincite standard; however, all analyses are

automatically normalized to 100 percent. Therefore, there is no internal check as to whether or not all minerals present are included in the analysis. Otherwise, the two types of analyses give comparable results (Eberl, 2003).

Description of Data Tables

Data are reported in the two following tables: *CCAP-FaultElementalChem.xls* (table 1) contains the elemental geochemical data, and *CCAPFaultMineralogy.xls* (table 2) contains the X-ray diffraction data. Element concentrations are reported with column headings denoting the method: ICP 55 is the 55-element ICP–AES–MS data, XRF is wavelength dispersive X-ray fluorescence spectrometry data, H₂O is essential and non-essential water data, and Tot S is total sulfur data. Elemental chemistry data are reported with the sample number, fault name, its short name as shown on the location map (fig. 2), a central location for the detailed sampling and study site using the Universal Transverse Mercator (UTM) projection, North American Datum of 1927 (NAD 27), and coordinates of meters east (mE.) and meters north (mN.), and the sample fault zone architectural position (abbreviations defined at the top of table 1). Note that the elemental chemistry sample set is not exactly the same as the mineralogy sample set, and the coordinates of the central locations may be slightly different. The data are organized by analytical type, and not all samples had the same analyses performed on them. The elemental concentrations are reported in weight percent (%) or parts per million (ppm). Values with the less-than symbol (<) or greater-than symbol (>) indicate the element concentration was less-than or greater-than the detection limit. Cells labeled ND indicate that the elemental concentration was not determined, and cells labeled NA indicate that information was not available.

All mineralogical data are reported with the fault name, its short name as shown on the location map (fig. 2), a central location for the detailed sampling and study site using the Universal Transverse Mercator (UTM) projection, North American Datum of 1927 (NAD 27), and coordinates of meters east (mE.) and meters north (mN.), the sample number, and the sample fault zone architectural position (abbreviations defined at the top of table 2). Individual minerals are organized into common rock-forming mineral groups with totals for each group reported for each sample. All mineral concentrations are reported in weight percent and are normalized to 100 percent. The full pattern degree-of-fit parameter and prenormalization totals are reported at the end of each column for each sample. Dashed values indicate minerals that were not analyzed by RockJock, because their characteristic XRD peak reflections were not present upon visual inspection. Each fault zone studied is reported in a separate, tabbed worksheet accessible at the bottom of the spreadsheet.

Acknowledgments

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