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PRELIMINARY SCIENTIFIC RESULTS OF THE CREEDE CALDERA CONTINENTAL SCIENTIFIC DRILLING PROGRAM

P.M. Bethke, Editor

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OVERVIEW OF THE CREEDE CALDERA CONTINENTAL SCIENTIFIC DRILLING PROGRAM

By

P.M. Bethke
U.S. Geological Survey, Reston, VA
W.R. Campbell
U.S. Geological Survey, Reston, VA[1]
J.B. Hulen
University of Utah Research Institute, Salt Lake City, UT[2]
T.H. Moses, Jr.
U.S. Geological Survey, Menlo Park, CA

Present Addresses:
[1] 11 Manzanita, Littleton, CO 80127
[2]Energy & Geoscience Institute, University of Utah,
Salt Lake City, UT, 84112
[3]1050 Larrabee Avenue, Suite 104, PMB 358, Bellingham, WA 98225

INTRODUCTION

In the fall of 1991, the U.S. Geological Survey (USGS), in cooperation with the National Science Foundation and U.S. Department of Energy, drilled two continuously cored holes through the Creede Formation, a dominantly lacustrine volcaniclastic unit that accumulated in the moat of the 26 Ma Creede caldera. The drilling was part of the U.S. Continental Scientific Drilling Program coordinated by DOSECC (Deep Observation and Sampling of the Earth's Continental Crust). It was the initial phase of a program originally designed to test the roots and margins of the hydrothermal system responsible for the deposition of the epithermal Ag and base-metal ores of the Creede mining district (Bethke and Lipman, 1987)

The principal objective of the initial phase of the program was to test the hypothesis that lake or pore waters, whose salinity and isotopic composition evolved by processes of evaporation and diagenesis, were an essential part of the hydrothermal system that deposited the ores of the Creede mining district, as originally proposed by Bethke and Rye, (1979) and expanded by Rye et al., (1988). Such a test requires a broad understanding of the evolution of Ancient Lake Creede including its physical, chemical and isotopic evolution and of processes of sedimentation and diagenesis operating in the lake and its sediments. In addition, the drilling program offered opportunities for topical and characterization studies and for the refinement and evaluation of down-hole geophysical logging techniques in a volcaniclastic environment. It now appears that the second phase of the program, drilling one or more 3-5 Km-deep holes into the roots of the hydrothermal system, will not be initiated for many years, if ever.

A consortium of Investigators from nine university, government, and private laboratories began core studies in March 1992. This Open-File Report describes the results of their investigations, in most cases preliminary results. A later publication will update the materials presented here and will integrate them to present a more comprehensive description of the characteristics and evolution of ancient Lake Creede and an interpretation of its relationship to ore deposition.

This chapter summarizes the geologic setting of the Creede caldera and the Creede mining district, the general nature of Ancient Lake Creede, and the conceptual model for ore formation. It further describes pertinent aspects of the operation of the drilling program, the on-site science activities, and the protocols governing handling, sampling, and archiving of the core.

GEOLOGIC SETTING

Volcano-Tectonic Evolution of the San Juan Mountains

The evolution of the San Juan volcanic field has been summarized by Steven and Lipman (1976) and Lipman (1989) from which most of the following material on the volcanic history of the Creede area is taken. The Creede caldera lies in the central part of the San Juan volcanic field. The San

Juans are the erosional remnant of a high constructional plateau comprising a composite volcanic field that covered much of the southern Rocky Mountains in middle Tertiary time (Steven, 1968). The field consists mainly of intermediate composition lavas and volcaniclastic rocks erupted about 35-30 Ma from numerous scattered central volcanoes, overlain by voluminous silicic ash-flow sheets erupted 30-26 Ma from mainly clustered caldera sources. Gravity data by Plough and Pakiser (1972) suggest that the area containing most of the calderas is underlain by a major silicic batholith. A change in volcanic style at about 25 m.y. ago to a bimodal basalt - high silica rhyolite sequence (greatly dominated by basalts) corresponds to the initiation of Basin-and-Range normal faulting in the Rio Grande graben in the San Luis Valley to the east. The bimodal volcanism continued intermittently until 5 m.y. ago; basaltic lavas that erupted during this period capped most of the high volcanic plateau.

The Central San Juan Caldera Cluster and the Creede Caldera

The Creede caldera is part of the central San Juan caldera cluster, a set of overlapping calderas that erupted over a remarkably brief period, about 28 Ma to 26 Ma (Figure 1). Ash flows erupted from these calderas range from quartz dacite to low silica rhyolite. Four of the calderas are resurgent, the Creede caldera strongly so. The Creede caldera collapsed in response to the eruption of the Snowshoe Mountain Tuff, a quartz dacitic unit that accumulated to a depth of greater than 1.5 km inside the caldera. Outflow Snowshoe Mountain Tuff is recognized at only a few locations as unconsolidated to poorly consolidated tuff; presumably the bulk of the outflow unit has been lost to erosion. Current K/Ar and $^{40}Ar/^{39}Ar$ geochronologic data and stratigraphic observations on the relative ages of the Creede and San Luis Peak calderas are conflicting. Geochronology indicates that the San Luis Peak caldera is younger than the Creede (Lanphere, 1988), whereas stratigraphic observations suggest the opposite (P. Lipman written comm., 1994). Integrated field, petrologic, geochronologic, and rock- and paleo-magnetic studies are currently underway in an attempt to resolve this problem (Lipman, et al., 1994). Stable isotope data (Rye, et al., Chapter G, this volume) are most readily interpreted under the assumption that the Creede caldera is the youngest in the cluster.

The Creede caldera is remarkable for its physiographic expression. The strong resurgence of the core of the caldera created a deep moat between the resurgent core and the topographic wall. The soft sediments filling the moat were easily eroded by the headwaters of the Rio Grande leaving a broad, arcuate basin 2-3 km wide, whose floor is 1 km lower than the caldera rim. The top of the resurgent dome stands nearly 1.5 km above the valley floor.

Calderas are common containment basins for lakes. In the central San Juan caldera complex, small patches of lacustrine sediments are exposed in the La Garita and San Luis Peak calderas and lake sediments of the Bachelor caldera were encountered in drill holes. Only in the Creede caldera is a sizeable volume of lacustrine sediments known to be preserved (Figure 2). There, lake sediments accumulated in all but the southern quadrant of the moat of the resurgent caldera. These lacustrine rocks have been mapped and described as the Creede Formation

The Creede Formation and Coeval Fisher Volcanics

Creede Formation was first described and named by Emmons and Larsen (1923), and was described in greater detail by Steven and Ratte (1965) in their report on the Creede mining district. A number of subsequent studies have added to our knowledge, the most comprehensive of which are those of Heiken and Krier (1987) and Larsen (1994a,b).

As previously noted, the Creede caldera is strongly resurgent. The collapse and subsequent resurgence formed a steep-sided moat between the resurgent core and topographic wall of the Creede caldera. Relief between the deepest part of the moat and the surrounding volcanic plateau was as much as 1.8 km. The Creede Formation accumulated to a probable maximum thickness of over a kilometer in the moat. Drilling sampled the lower one-third to one-half of the Creede Formation. Post-Miocene erosion has removed most of the upper part, leaving portions as relatively thin veneers on the topographic wall of the moat.

Concurrently with sedimentation, volcanoes erupted along the ring fracture of the caldera. Their lavas (Fisher Quartz Dacite) fill the southern quadrant of the moat (Figure 2). The chemical compositions of the Fisher lavas are similar to those of the Snowshoe Mountain Tuff suggesting both were derived from the same magma chamber (Ratté and Steven, 1967).

Volcanic ash and phenocryst fragments, erupted from the Fisher volcanoes and weathered from unconsolidated Snowshoe Mountain Tuff, were the major original components of the lacustrine sediments of the Creede Formation. Some of this volcaniclastic material entered the lake directly as air-fall tuff from the Fisher volcanoes. Sedimentation in Lake Creede was punctuated by numerous air-falls as demonstrated by graded tuff units ranging in thickness from centimeters to tens of meters. Much of the volcaniclastic material in the lacustrine sediments between tuff units washed into the lake by erosion of unconsolidated Fisher air-fall deposits and Snowshoe Mountain Tuff in the watershed. The relatively steep walls of the moat, and probable tectonic "jiggling" led to numerous graded turbidite deposits of such material ranging in thickness up to 30 meters (Larsen, 1994a).

Carbonate is abundant in the Creede Formation. Numerous travertine mounds occur along the inner and outer margins of the Creede Formation and interfinger with the lake sediments. Micritic and peloidal limestone lamellae are interlayered with the tuffaceous sediments throughout most of the drill core (Hulen et al., 1992). Calcite pseudomorphs interpreted to be after ikaite ($CaCO_3 \cdot 6H_2O$) occur associated with travertine mounds and as rice-grain-shaped structures in laminated siltstones, demonstrating at least seasonally low (< 6°C) lake temperatures (Larsen, 1994b). Small-aperture veinlets of calcite occur throughout the drill core. Calcite is a common cement and calcite concretions occur sporadically throughout the core.

Although plant fragment fossils are relatively abundant (Axelrod, 1987), the lake apparently did not support animals having hard parts, for no such fossils have been found. Diatoms occur in banded silica-travertine deposits. Rod-shaped structures in peloidal limestones are interpreted as brine shrimp fecal pellets, and thin, discontinuous algal masses are common in the fine-grained laminated siltstones. (R. Forrester, oral comm., 1994). Finely laminated siltstones, absent of worm burrows and containing up to several percent pyrite (some of which appears to have precipitated in the water column) indicate that the lake bottom was euxinic, at least at times.

SCIENTIFIC RATIONALE FOR THE CREEDE DRILLING PROGRAM

Conceptual model of mineralization in the Creede mining district

The epithermal Ag-Pb-Zn-Cu deposits of the Creede mining district lie just to the north of the Creede caldera (Figure 2). They formed 25 million years ago -- approximately a million years after the last known volcanism in the district (Bethke et al., 1976). More than 30 years of interdisciplinary studies of the district have developed a conceptual model for the mineralization (Steven and Eaton, 1975, Barton et al, 1977, Bethke and Rye, 1979, Rye et al. 1988, Hayba, 1993). The model is illustrated in the schematic North-South cross section in Figure 3.

This conceptual model proposes that lake waters or Creede Formation pore fluids entered the hydrothermal system in the south -- probably along ring fractures. The fluids acquired moderate salinity and unusual hydrogen and oxygen isotopic compositions through processes of evaporation and diagenesis. These fluids traveled north, were heated by a small pluton, rose buoyantly in the north end of the district and, on nearing the surface, mixed with surrounding and overlying ground waters. Some boiling occurred in the uprising plume and along the top of the system. The fluids traveled southward along the top of the hydrothermal system, eventually returning to the region of the moat. Along most of their southward path, the hydrothermal fluids mixed with fresh meteoric waters along the top of the system. However, at the south end of the district -- in the region indicated by the barite-rhodochrosite zone -- they mixed with lake or pore waters.

This model was based entirely on studies of the ore district itself and the principal objective of the drilling program was to test the model and extend or modify it, if found generally valid. Testing the model is of more than academic interest because models such as this are used to guide both mineral exploration and development, and mineral resource assessment. In this case, it is particularly important to know whether or not Ancient Lake Creede was a critical element in ore formation.

Evidences from the district study for lake involvement.

The conceptual model was built on several lines of evidence, discussed only briefly below.

1- The presence of large volumes of preserved lacustrine strata of the Creede Formation cut by the roughly coeval ($\Delta t = \sim 1$m.y.) mineralized vein system.

2- The δD and $\delta^{18}O$ values of inclusion fluids and fluid values calculated from alteration minerals are not consistent with either magmatic or unevolved meteoric water and cannot be derived from either by simple mixing processes, rock-water interaction, or boiling. They are, however, the values predicted from evaporation of surface waters (Bethke and Rye, 1979, Rye et al. 1988).

3- The salinities of the ore fluids, as determined by thermometric studies of fluid inclusions, are as high as 13 wt. % NaCl equivalent -- whereas most Adularia-Sericite epithermal deposits were deposited from low salinity fluids (Heald et al., 1987).

4- Detailed time-space studies of fluid inclusions from the OH vein demonstrate mixing of deeper, high temperature, high salinity fluids with cooler, low salinity fluids along the top of the hydrothermal system (Hayba, 1993).

5- The sulfur and oxygen isotopic compositions of barites -- which occur nearly exclusively in the south end of the system -- are both extremely variable, unusual for hydrothermal barites, and are mainly inconsistent with the sulfur isotopic compositions of sulfides from the ore bodies and the oxygen isotopic composition of ore fluids. They are interpreted to require bacteriogenic reduction of sulfate in an anoxic sedimentary environment (Rye et al., 1988).

6- The presence and character of hydrocarbons in fluid inclusion gases requires a sedimentary component in the ore fluid (Landis and Rye, 1989, Sweetkind, 1994).

DRILLING PROGRAM

Evidences sought by drilling

The drilling program was designed to evaluate the assumptions about the lake and its associated pore fluids implicit in the model for the mineralization in the Creede mining district presented above. Primary among these were: 1) that the Creede caldera was the youngest of the central San Juan caldera cluster; 2) that a lake existed in a closed basin in the moat of the caldera; 3) that the lake underwent sufficient evaporation to evolve the oxygen and hydrogen isotopic composition of the lake waters to values similar to those determined for the ore fluids; and 4) that the sulfur and oxygen isotopic composition of the lake and pore water sulfate evolved, through biogenic sulfate reduction, to the exceptionally heavy values recorded in barite accompanying mineralization.

To evaluate these assumptions, studies were undertaken to: (1) determine the source(s) of the volcaniclastic material comprising the bulk of the lake sediments; (2) develop geochronologic and paleomagnetic evidences as to the age of the lake and duration of sedimentation; (3) characterize the physical limnology of the lake; (4) determine the oxygen, hydrogen, carbon and sulfur isotopic composition of authigenic zeolite, calcite and pyrite in the lacustrine sediments, and veinlet pyrite and calcite in the sediments and underlying Snowshoe Mountain Tuff; (5) determine the amount, nature and maturity of organic matter; (6) search for evidences of aquatic life that might serve as salinity indicators; and (7) estimate the chemical composition of the lake and pore waters from the authigenic mineral assemblage.

Program Design

The design of the Creede Moat Drilling Program evolved through a number of stages beginning in April of 1985 at a DOSECC-sponsored open workshop in Alamosa, Colorado, attended by representatives of 8 universities, two mining companies, the Geological Survey of Colorado, The Los Alamos National Laboratory, and the U.S. Geological Survey. The results of the Alamosa workshop formed the principal basis for the Science Plan. However, the recommendations from that workshop were extended and modified at a later workshop held in May of 1987 in Boulder, Colorado, and through a Peer Review Panel evaluation of proposals for scientific studies received in response to a call for proposals issued by DOSECC in 1990.

The drilling plan included two continuously cored diamond drill holes through the Creede Formation and into the floor of the moat (Figure 2). One hole (CCM-2, also known as Airport 1-6) was sited in the deepest part of the moat (as indicated by geophysical studies), and along the strike of the major vein systems of the Creede mining district. The expected depth of penetration was approximately 1 km. The second hole (CCM-1, also known as Hosselkus 1-10) was sited approximately 4 km. to the west in order to avoid possible overprinting of the sediments by the Creede hydrothermal system. The expected depth of penetration was approximately 500 m.

Drilling and Down-Hole Logging Operations

Thomas H. Moses of the USGS designed the drilling plan for the Creede Moat Hole Drilling Project to meet the scientific objectives of the program. Moses was on site for the duration of the drilling project and served as Project Manager. The USGS contracted the drilling to Tonto Drilling Company, Wayne Beaupre, Drilling Supervisor. Core drilling was conducted using a Universal 1500 drill rig and diamond core bits. Core recovery was by a wire line system using 10-foot core barrels. Columbine Logging, Inc. provided mud logging services. The U.S. Geological Survey conducted down-hole geophysical logging under the direction of Philip Nelson (see Nelson and Kibler, Chapter P, this Open-File Report). Edward Decker of the University of Maine ran temperature logs (see Decker, Chapter O this Open-File Report). Location, elevation and drilling depth data for both holes are given in Table 1.

TABLE 1. PRINCIPAL DATA FOR CORE HOLES CCM-1 AND CCM-2

	CCM-1	CCM-2
USGS Quadrangle	Creede 7.5 minute	
Township	41N	41N
Range	1W	1W
Section	10	12
Longitude	37°49'2.02"N	37°49'32.1"N
Latitude	106°58'17.98"W	106°55'7.07"W
Depth	418 meters	708 meters
Collar Elevation	2652 meters	2627 meters
Bottom Elevation	2234 meters	1919 meters

Hole CCM-1 was drilled first in order to provide experience for the deeper and more expensive hole CCM-2. CCM-1 was collared on October 7, 1991. Rio Grande river gravel and conglomerate "overburden" was drilled with an $8^3/_4$ inch rock bit to a depth of 7.3 m (24 ft). The hole was reamed to a depth of 6.3m ($20^3/_4$ ft). Coring of the Creede Formation began at a depth of 7.3 m using HQ (3.83 inch) wireline coring, and continued to a total depth of 417.9 meters (1371 ft). During the coring operation, circulation was lost at 35.4 m (116 ft) and the hole was reamed to a depth of m 73.2 m (240 ft) with an $8^3/_4$ inch rock bit, and $6^5/_8$ inch casing set and cemented before resumption of drilling. Prior to casing, a suite of geophysical down-hole logs was run by the USGS logging team. At a depth of 367 m (1204 ft) the drill bit exited the volcaniclastic sediments of the Creede Formation and entered a monomictic angular breccia with Willow Creek Rhyolite clasts, presumed to be a collapse breccia from the wall of the Creede caldera. Coring was terminated in that unit at a depth of 418 m (1371.5 ft) on October 19. Core recovery at CCM-1 was 100%. A suite of geophysical logs was run from 73.2 m (240 ft) to total depth by the USGS logging team. Following completion of geophysical logging, $2^7/_8$ inch casing was set and cemented to a depth of 416.4 m (1366 ft). The cement slurry "flash set" across a minor lost circulation zone, making it impossible to push the cement plug and slurry out of the casing, leaving the casing filled with cement. The cement plug and cement slurry were later (November 17-22) cored to a depth of 411.5 m (1350 ft) using a BQ (2.18 inch) bit in order to insure access for heat-flow measurements and possible fluid sampling.

Hole CCM-2 was collared on October 22, 1991. Spencer Drilling Company of Monte Vista, Colorado, air-drilled and drove casing through 36.6 m (120 ft) of Rio Grande river gravel and conglomerate "overburden" and an additional 5.3 m (17.5 ft) of Creede Formation (from which only cuttings were recovered). Coring of the Creede Formation began on October 30, again using a HQ (3.83 inch) bit. At a depth of 76.2 m (250 ft), coring was stopped and the hole reamed to $8^3/_4$ inches and cased with $6^5/_8$ inch casing. As at CCM-1, prior to casing, a suite of geophysical down-hole logs was run by the USGS. Coring resumed on November 2 and continued until November 13 when the coring was terminated in Snowshoe Mountain Tuff at a depth of 708 m (2323 ft). Core recovery for CCM-2 was 99.6%. The deepest clearly lacustrine strata were encountered at a depth of 475.2 m (1559 ft). The Snowshoe Mountain Tuff was entered at a depth of 653.5 m (2144 ft). The intervening 178 m are dominated by intervals of monomictic or polymictic volcanic breccia separated by intervals of sandy to conglomeratic units with occasional silicic tuff units, some of them reworked. A warm aquifer was encountered at a depth of approximately 518 m (1700 ft). Matt Powell, of Columbine Logging, Inc., measured the temperature of the outflow as 67.5 °F and its resistivity as 16.03μΩ. A crudely estimated flow rate of 40 gallons per minute was made by the driller, Justin Samidini. Following completion of coring, the USGS ran a suite of down-hole geophysical logs from 76.2 - 708 m (250 - 2323 ft). Subsequent to geophysical logging, $4^1/_2$ inch casing was set to a depth of 701 m (2300 ft). Attempts to cement the casing failed due to cement loss at the 518 m (1700 foot) level.

Core Handling, Sampling and Curation Protocol and Operations

In order to preserve the integrity of the core and to provide continuing availability of samples to the scientific community, a comprehensive sample handling and curation protocol was developed specifically for the Creede Moat Drilling program by Wayne R. Campbell of the USGS (Campbell, 1992).

On-site core handling was conducted by the On-site Science Team lead by Jeffrey Hulen of the University of Utah Research Institute, assisted by Wayne R. Campbell of the USGS (Table 2).

TABLE 2 ON-SITE SCIENCE TEAM CREEDE DRILLING PROGRAM

Philip M. Bethke, Chief Scientist	U. S. Geological Survey
Jeffrey B. Hulen, Scientist in Charge	University of Utah Research Institute
Wayne R. Campbell	U. S. Geological Survey
Daniel O. Hayba	U. S. Geological Survey
Daniel Larsen	University of New Mexico
Timothy Muzik	U. S. Geological Survey
Randy Streufert	Colorado Geological Survey
Nora K. Foley	U. S. Geological Survey
Frances E. Gay	U. S. Geological Survey
Andrew J. Hopkins	U. S. Geological Survey
William c. Whitus	U. S. Geological Survey
William Linenberger	U. S. Geological Survey

Upon the completion of each core run, the Science Team, assisted by the drillers, transferred the core from the liner into a PVC trough and washed it to remove the drilling mud. The core was then pieced together as necessary, marked, boxed in core boxes, and transferred to the core handling trailers supplied by the USGS. Reconnaissance logging of the core was conducted by the Science Team, recording lithology, sedimentary structures, diagenetic and vein mineralogy, organic content and wallrock alteration. In addition, magnetic susceptibility logs were run for both holes, and gamma ray logs were run for CCM-1 core. The gamma ray logs for CCM-1 core showed little variation, and, therefore, were not run on core from CCM-2. Samples with potential ephemeral properties required special handling. A summary lithologic log for each hole was prepared at a scale of 1 inch = 12 feet (Hulen, 1992).

A number of whole-core samples appearing to contain organic material were selected and wrapped in aluminum foil by Joel Leventhal for organic analysis. Similarly, whole-core samples of various lithologies were coated with wax and sent to Edward Decker for thermal conductivity studies. Color photographs were taken of each box of core prior to transfer of the core to the USGS Core Research Center in Denver.

At the Core Research Center, the core was split into Sample and Archive sets, marked for run and footage, and the Archive set photographed in color. Upon completion of splitting, marking and photographing, the Principal Investigators gathered at the Core Research Center in March of 1992 to collect samples for study and analysis. Additional samples were taken at later dates by several Principal Investigators.

Sample Storage, Distribution and Availability for Further Study

Both Sample and Archive sets of core, along with original reconnaissance lithologic logs, downhole geophysical logs, mud logs, magnetic susceptibility and gamma-ray logs, and Archive photographs remain in storage at the USGS Core Research Center and are available for further study by interested scientists. Samples taken by Principal Investigators remain in their possession, but will be returned to the Core Research Center following completion of studies.

SUMMARY OF SCIENTIFIC RESULTS TO DATE

The chapters in this report present the results of study by the Principal Investigators to date. It is anticipated that a special publication will be prepared at a later date that presents the final scientific results of the program. The following is a brief, and not necessarily complete, summary of results presented in the various chapters of this report.

Sedimentologic studies indicate that ancient Lake Creede was a perennial, closed-basin lake with alternating low-stands and high-stands (Larsen and Crossey, Chapter E, this report). Geochronologic results indicate that sedimentation continued for a maximum of 0.6 m.y. (Lanphere, Chapter C, this report). Both holes sampled basinal facies dominated by laminated tuffaceous siltstone and graded tuffaceous sandstone (debris flows). Micritic and peloidal limestones are interlaminated with the tuffaceous siltstones

(Larsen and Crossey, Chapter E, this report; Finkelstein et al, Chapter F, this report). The basinal section is punctuated by fine-ash tuff from episodic, mainly hydrovolcanic, eruptions (Heiken et al., Chapter D, this report). Phenocryst compositions from the lacustrine tuffs are similar to those for phenocrysts from the Snowshoe Mountain Tuff, whereas those from boulders in a paleostream channel incised into the north wall of the Creede caldera are similar to those in ashflows erupted from the San Luis Peak caldera suggesting that the Creede caldera is indeed the youngest in the complex (Lipman and Weston, Chapter B, this report).

Disseminated and stratiform pyrite occurs throughout the section as framboids, euhedral crystallites and aggregates as well as matrix replacements (Rye et al., Chapter G, this report; McKibben and Eldridge, Chapter H, this report; Ilchik and Rumble, Chapter I, this report). The presence of pyrite and the lack of bioturbation indicates anoxic bottom conditions. Rock magnetism and paleomagnetism studies yield a complex record that is yet not completely interpreted Reynolds et al., Chapter L, this report). Diagenetic pyritization of magnetite and Ti-magnetite has greatly lowered the magnetic susceptibility and obscured the detrital remnant magnetism in most lacustrine rocks. In addition, chemical remnant magnetism apparently overprinted the weak residual detrital remnant magnetism producing a complex polarity stratigraphy that is inconsistent between the two holes. Samples with low sulfidization and relatively high susceptibility are expected to produce a consistent polarity stratigraphy.

Silicic volcanic glass was converted to clinoptilolite, smectite, opal CT, K-feldspar, and lesser amounts of rectorite, analcime, quartz, and erionite during diagenesis (Larsen and Crossey, Chapter E, this report; Finkelstein, et al., Chapter D, this report). Biotite and plagioclase phenocrysts are remarkably fresh although some plagioclase is partially replaced by calcite. Rock-Eval and mass spectrometry of biomarkers indicate that the sediments were immature relative to petroleum generation, but show a trend to higher maturity with depth. Vitrinite reflectance of plant remains does not show the same increase, suggesting accumulation under a decaying, elevated thermal gradient. Low carbon/sulfur ratios and a high degree of pyritization suggest addition of sulfide sulfur from extraneous sources (Leventhal et al., Chapter J, this report, Leventhal, Chapter K, this report; and Lillis, Chapter L, this report). Vertical zoning of the diagenetic mineralogy with higher temperature assemblages at depth supports deposition and diagenesis under an elevated thermal gradient. The presence of minor discrete illite in the upper part of the CCM-2 core suggests a possible local hydrothermal overprinting. The diagenetic record does not provide direct mineralogical evidence that the lake waters underwent extensive evaporation during that early part of the lake history represented by the drill core.

Hydraulic conductivity measurements on samples of various lithologies show a range of values from 10^{-12} to 10^{-7}cm/s (10^{-9} to 10^{-4} darcy) which do not correlate with physical properties including porosity or bulk mineralogy (J. Conca, Chapter N, this report). Instead, plugging of pore space by clay minerals as shown by SEM studies appears to be a major control on permeability. Thermal data from downhole measurements (in part cooperative with P. Nelson, USGS) and from previous downhole measurements in exploration drill holes north of the moat area yield near-surface heat-flow values of 78-92 mW/m^2 for the moat area and 95-105 mW/m^2 for the mining district to the north. Bulk densities of core samples range from 1.87 to 2.41 g/cm^3, and average 2.13±.03 g/cm^3, and thermal conductivities range from 1.06-2.05 W/mK, averaging 1.39±.05 W/mK. (E. Decker, Chapter O, this report).

Both the lacustrine sediments and the underlying ash-flow tuffs are cut by relatively sparse veinlets as wide as 2 cm. Veinlets are much more abundant, and generally wider, in the underlying tuffs. The principal vein-filling mineral is calcite, but pyrite, analcime, and other probable zeolite minerals are present locally, particularly in the deeper parts of CCM-2. Pyrite framboids, apparently gravity-settled, and framboid-bearing pyrite stalactites are early phases in pyrite-calcite veinlets in the ash flow tuffs. Stable isotope studies of both sedimentary and veinlet pyrite and carbonate provide important data for the interpretation of the isotopic evolution of the lake and lake sediments. $\delta^{34}S$ values gathered by conventional analyses of sedimentary pyrite (Rye et al., Chapter G, this volume) show a remarkable range from -20 to 35‰ interpreted to be due to derivation of H_2S by bacteriogenic reduction of sulfate as predicted by Rye et al. (1988). SHRIMP microprobe analyses (McKibben and Eldridge, Chapter H, this volume) of some samples of disseminated pyrite exhibit outward zonation from light to heavy $\delta^{34}S$ values consistent with local closed-system bacteriogenic sulfate reduction. Laser microprobe analyses give a similar range (Ilchik and Rumble, 1993), but those investigators prefer mixed sources to bacteriogenic reduction to explain the large range in $\delta^{34}S$ values. SHRIMP and laser probe analyses of vein pyrites from the underlying tuffs show even larger ranges, indicating they also formed as part of the diagenetic process, and implying substantial fluid movement during, or perhaps, shortly following, diagenesis.

The $\delta^{13}C$ and $\delta^{18}O$ values of micritic and peloidal limestones record an as yet incompletely understood history of deposition and diagenesis. Low-Mg calcite occurs as micrites, peloids and rice-grain shaped pseudomorphs. The peloids are interpreted as brine shrimp fecal pellets (see Eardley, 1938). Larsen (1994b) interprets the pseudomorphs to be after ikaite ($CaCO_3 \cdot 6H_2O$), indicating that the lake waters reached temperatures near 0°C during the cold season. The isotope data indicate that the sedimentary carbonates precipitated from an alkaline lake water that was high in dissolved atmospheric CO_2 and rich in organic matter (a possible paradox because the cores are low in organic matter). An increase in $\delta^{18}O$ with height in the sedimentary section suggests increasing degrees of evaporation during the evolution of the lake (Rye et al., Chapter G, this report). In contrast to lacustrine carbonates worldwide, $\delta^{18}O$

and $\delta^{13}C$ values for primary micrites show a negative correlation. A similar negative trend, offset to smaller $\delta^{18}O$ values, has been found for veinlet calcite (Ilchik and Rumble, Chapter I, this report). Some peloids have $\delta^{13}C$ and $\delta^{18}O$ values overlapping those of the micrites, whereas others have much larger $\delta^{18}O$ values similar to those for calcite pseudomorphs after ikaite, These large values suggest that these peloids are fecal pellets of brine shrimp that ingested suspended fine calcite derived from the breakdown of ikaite. The field for $\delta^{13}C$ and $\delta^{18}O$ values for the sedimentary carbonates overlaps that for the travertines, suggesting that the latter were deposited along the lake margins by the mixing of deeply circulating pore fluids with lake waters. The isotope data for Creede Formation carbonates are consistent with derivation of vein carbonates in the Creede mining district from lake or pore waters as predicted by Rye et al. (1988).

Concluding Remarks

Although some evidences appear to conflict, and not all PIs agree on all points, the present authors interpret the combined studies to indicate that the Creede Formation accumulated to a maximum thickness of about 1 km in a moderately deep, relatively steep-sided lake over a period of approximately 0.5 my. Most of the time during the first one-half to two-thirds of its history, the lake bottom, where sampled by drilling, was below wave base (perhaps 50 m), but several periods of shallower water are indicated in the later record. Diagenetic alteration of the glassy tuff, which dominated the sedimentary fill, produced lake waters of high alkalinity. Bottom waters were anoxic. The lake became more evaporative as the moat filled and its surface area increased. The weight of evidence to date is consistent with the ore genesis model wherein the ore fluids originated, in part, as lake and/or pore waters in the moat of the Creede caldera. However, that conclusion must be supported by quantitative modeling of the chemical and isotopic evolution of the lake and pore waters before it can be accepted.

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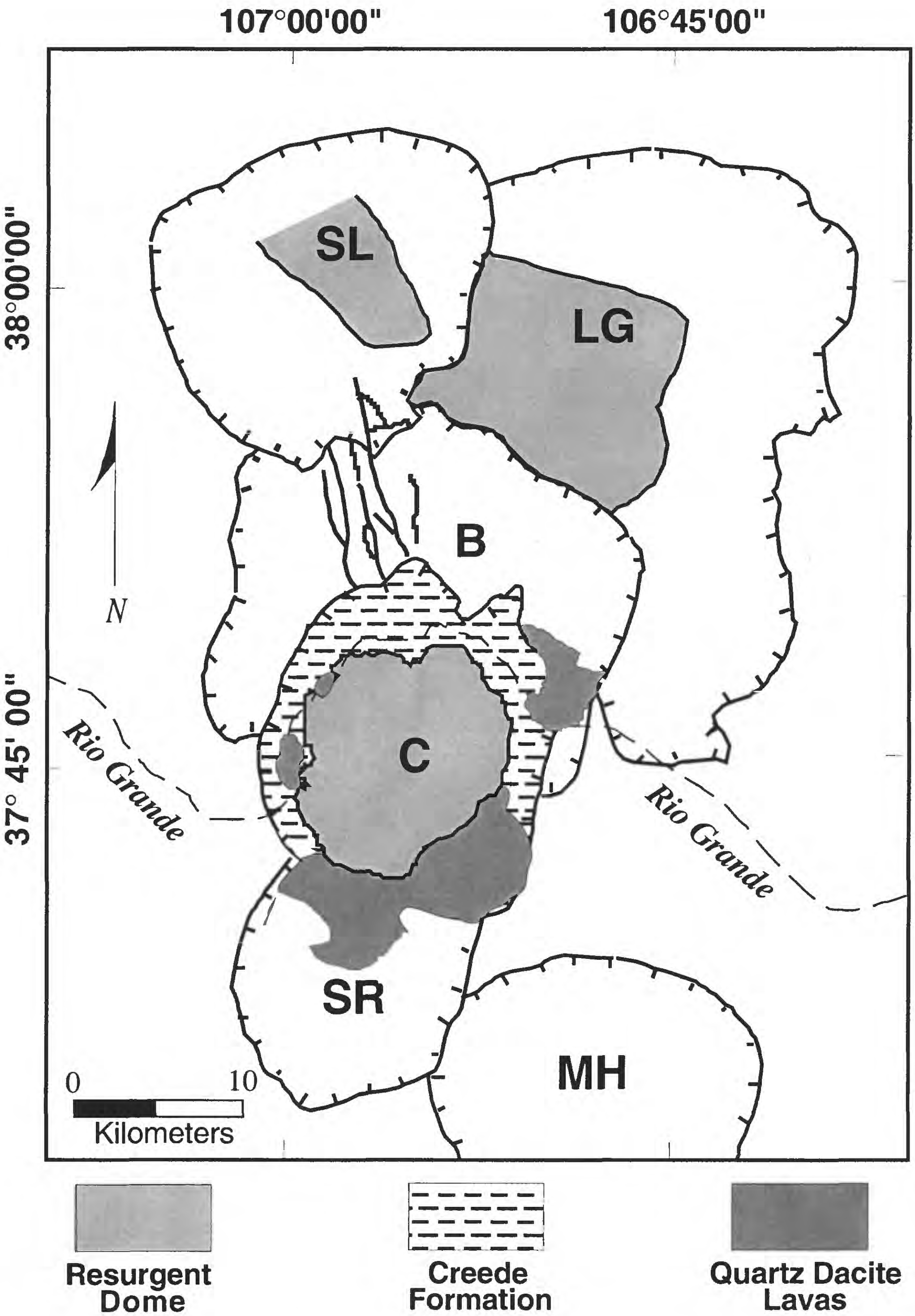
FIGURE CAPTIONS

Figure 1. Central San Juan Caldera Complex showing distribution of Creede Formation and coeval Fisher Quartz Dacite Lavas and resurgent domes of Creede, La Garita and San Luis Peak calderas. Caldera: MH, Mount Hope; LG, La Garita; B, Bachelor; SR, South River; SL, San Luis Peak; C, Creede. Modified from Bethke and Lipman, 1987.

Figure 2. Generalized geologic map of the Creede caldera showing distribution of Creede Formation, coeval Fisher quartz Dacite lavas, Snowshoe Mountain Tuff, location of the Creede mining district, and location of cross section in Figure 3.

Figure 3. Schematic N-S longitudinal cross section along the mineralized vein system of the Creede mining district illustrating the conceptual model of mineralization.



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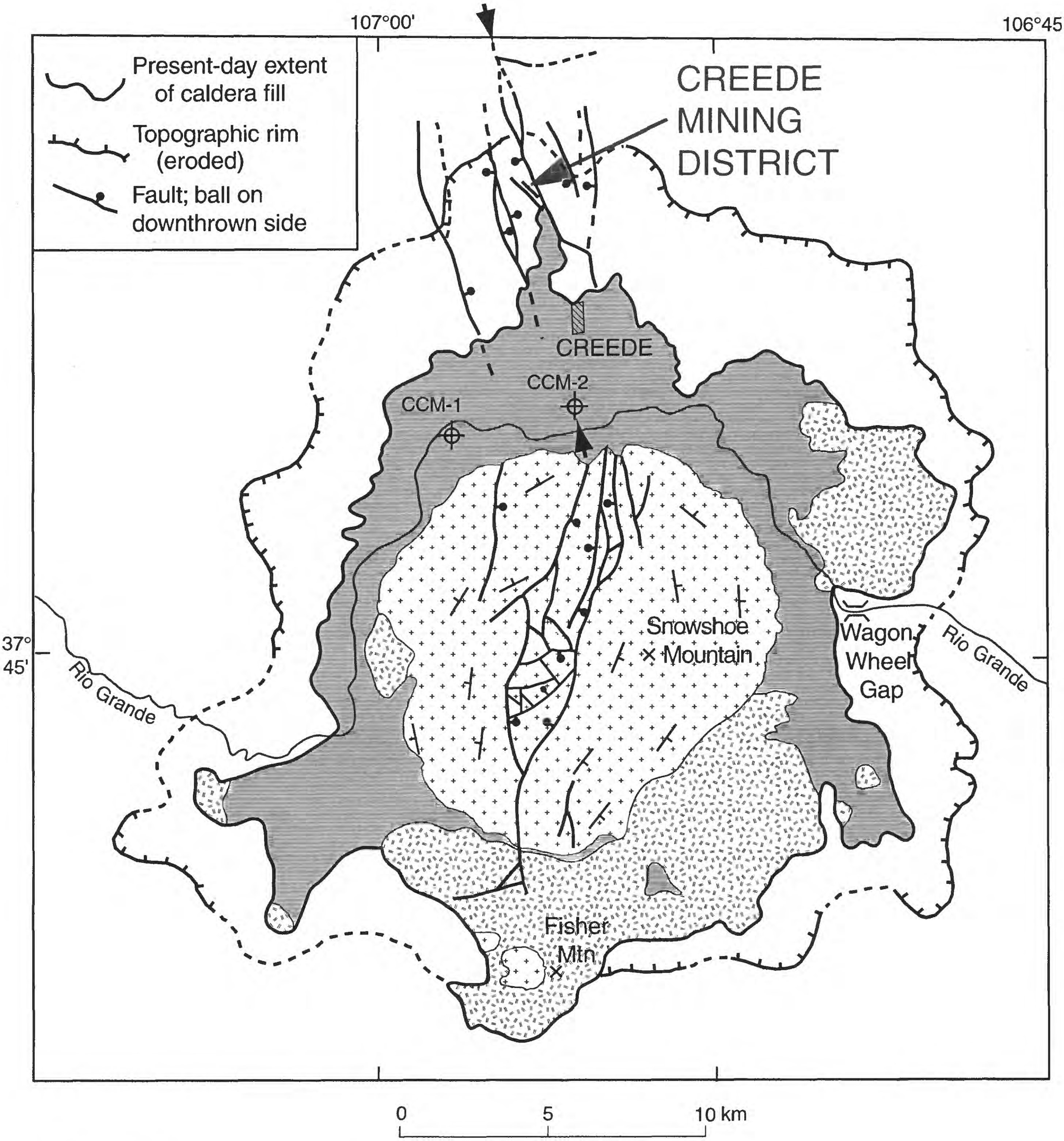


Postcaldera lava flows (Fisher Dacite)

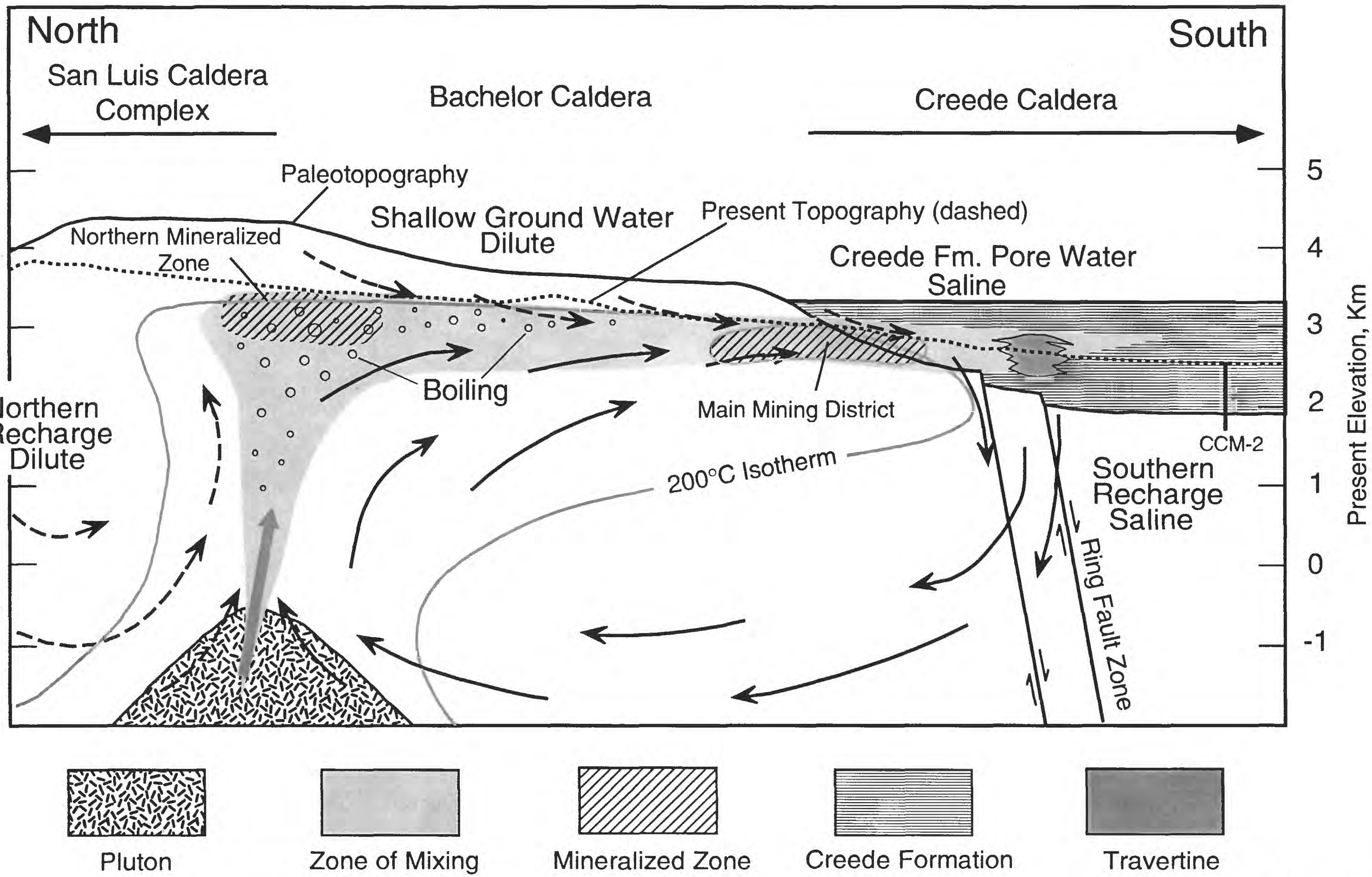
Intracaldera tuff (Snowshoe Mtn. Tuff)

Moat Sediments (Creede Formation)

Precaldra volcanic rocks

Arrows indicate line of Section on Figure 3

Figure 2



North
South
San Luis Caldera Complex
Bachelor Caldera
Creede Caldera
Paleotopography
Northern Mineralized Zone
Shallow Ground Water Dilute
Present Topography (dashed)
Creede Fm. Pore Water Saline
Boiling
Main Mining District
Northern Recharge Dilute
200°C Isotherm
CCM-2
Southern Recharge Saline
Ring Fault Zone
5
4
3
2
1
0
-1
Present Elevation, Km
Pluton
Zone of Mixing
Mineralized Zone
Creede Formation
Travertine

Figure 3