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The Creede, Colorado Ore-Forming System: A Summary Model

by

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This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards and stratigraphic nomenclature

This report includes the transcript and figures of a talk presented at the Symposium entitled: San Juan Volcanic Field: Volcanology, Petrology, Geophysics and Ore Deposits: A Symposium in honor of Thomas A Steven held as part of the Annual Meeting of the Rocky Mountain Section of the Geological Society of America Meeting, Boulder, May 2-4, 1987. Abstracts of the 42 papers presented are published in: Abstracts with Programs, 1987, v.19, no. 5, Geological Society of America.

Color slides presented in the talk are reproduced here in black and white, and the text has been modified in places to reflect this difference. One copy of the report containing color prints is available for inspection at USGS libraries at Reston, Denver and Menlo Park. No attempt has been made at full documentation. The list of references at the end of the report includes only those studies to which specific reference is made in the text.

ABSTRACT

(As published in Abstracts with Programs, 1987,
v.19, no. 5, Geological Society of America, p. 260-261)

This paper summarizes the results of detailed and comprehensive studies of the ore-petrology, fluid-inclusions, stable isotopes, gas chemistry, Pb isotopes, geochronology, and wallrock alteration in the Creede mining district, Colorado and of studies of the evolution of the central San Juan caldera cluster. Most of these results are presented as individual contributions to the symposium. These individual studies provide multiple evidences that converge to document a synoptic, but still qualitative and still evolving, model of the Creede hydrothermal system.

Ores were deposited from a single hydrothermal system over a strike length of nearly 8 km, including the recently discovered mineralization in the northern end of the district. The system was dominated by two fortuitously distinctive meteoric fluids: 1) brines that entered the system from the south, and 2) nearly fresh waters that entered from the north. The southern brines achieved their high salinity and isotopic composition by processes of evaporation in a playa lake in the moat of the Creede caldera and later diagenesis. Much of the ore lead was derived from deep Precambrian sources. The heat-source which drove the system was located near the triple junction of the LaGarita, Bachelor and San Luis calderas, as was the upwelling portion of the hydrothermal plume. Boiling, which occurred in the upwelling part of the plume, contributed to mineral deposition and promoted intense sericitic wall-rock alteration by condensation of acid volatiles in the overlying ground water. Mixing of the brine with overlying ground water was the primary cause of mineral deposition south of the upwelling plume. The ore fluids were buffered by the assemblage Fe-chlorite + pyrite + hematite + quartz, and solution-crystal equilibrium was closely approached most of the time. In contrast, aqueous sulfide and sulfate did not equilibrate in the ore zone.

This model has evolved over a period of 25 yrs, and continuing modifications are expected. The convergence of evidences suggests, however, that the main structure of the model is fundamentally sound.

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INTRODUCTION

During the remainder of the afternoon we'll finish our discussion of the central San Juan caldera complex with a look at the epithermal base- and precious-metal mineralization that has been the focus of extensive - and intensive - study for more than 30 years - beginning with the District study by our honoree, Tom Steven and his cohort, Jim Ratte (Steven and Ratte, 1965).

Much has been published - and many talks given - about the Creede mineralization during that time, but over the past several years, access to materials from the newly discovered mineralization several kilometers north of the main district, the application of new techniques, and the re-interpretation of several aspects of the evolution of the caldera complex have changed our viewpoints on some important aspects of the Creede hydrothermal system. Several lines of evidence have come together to support a much more comprehensive conceptual model of the Creede mineralization than we could previously attempt. It has been a tremendously exciting time, and I hope the talks to be presented during the rest of this afternoon will impart some of that excitement to you.

The results to be presented in the following papers are many and complex, and each speaker's time is short. For those reasons, I'll describe some of the important aspects of the Creede mineralization to set the stage for their talks, and present, without documentation, a conceptual model of the Creede hydrothermal system to which each of the speakers refer. They will present the meat of this afternoon's session - except, of course, for Paul Barton who will serve up dessert (Barton, 1987).

BACKGROUND

SLIDE 1: (*Map of central San Juan caldera cluster*)

Previous talks today have set the Creede district in the framework of the central San Juan caldera cluster. The Creede ores are principally open-space fillings along fractures which are part of a graben radial to the Creede caldera and running between it and the San Luis caldera - the Creede Graben.

While we have this slide, I'll point out that the Creede caldera is outlined by sediments filling its moat over an arc of 270 degrees - the Creede Formation. The Creede formation sediments interfinger with coeval ring-fracture volcanics (identified as postcaldera lavas on this slide), particularly in the southern quadrant. In contrast, the moat of the San Luis caldera is filled mainly by volcanic flows and domes, although some lake sediments are known. Intrusives, most of which were volcanic feeders, are abundant in the San Luis caldera, particularly around its southern margin.

We'll take a closer look at the Creede graben in this next slide, which covers a somewhat larger area than that indicated by the box.

SLIDE 2: (*Map of the Creede mining district*)

Almost all production from the Creede district to date has come from the

Amethyst-OH-P vein system and the Bulldog Mtn. system. The Solomon-Holy-Moses system bounding the graben on the east, and the Alpha-Corsair system bounding it on the west, are mineralized, but have not contributed significantly to production to date. A clastic tongue of the Creede Formation, which fills a paleostream channel incised into the wall of the Creede caldera north of the town of Creede, has been mineralized by fluids leaking up from the vein system, and contains a sizable, but low grade, potential silver resource.

I've indicated the general area of historic production by the lower shaded circle. We will refer to it as the "Main Mining District" (MMD) in order to distinguish it from mineralization several kilometers to the north recently discovered by the Homestake Mining Company in an exploration program orchestrated by Stan Caddey, Craig Byington, and David Vardiman. We refer to that area as the "Northern Exploration Area" (NEA). I will return to the relationship between the two mineralized areas shortly, but first I want to discuss some of the characteristics of the Creede mineralization, most of which have been worked out in the Main Mining District. The next slide will be a very generalized, and interpretive, longitudinal section, along the Amethyst vein system, from the San Luis caldera to the Creede caldera.

SLIDE 3: (*N - S crosssection from the San Luis to the Creede caldera*)

In both mineralized areas, the mineralization is confined to a vertical interval of less than a kilometer, but in the Main Mining district the ores have been mined for a strike-length of more than 3 kilometers. The dimensions of the mineralization in the NEA are not known - at least to me - but what information we have indicates that the mineralized zone preserves the same, horizontally dominated, aspect ratio.

In the Main Mining district, the host rock for the veins is the intercaldera fill of the Bachelor caldera (except for the disseminated mineralization in the Creede Formation). In the Northern Exploration Area, however, the mineralization is hosted by the intracaldera fill of both the Bachelor and San Luis calderas.

SLIDE 4: (*Coarse sphalerite, galena and chalcopyrite; OH vein*)

In the Main Mining district the ores are zoned. In the deeper and northern parts of the area they consist of sphalerite, galena and chalcopyrite often occurring in beautiful encrustations such as this. This specimen is 6 inches across. The silver occurs almost exclusively in the early part of the paragenesis, as fine-grained tetrahedrite and less important sulfosalts in sphalerite, galena or chalcopyrite.

The gangue is quartz with abundant chlorite, pyrite, and hematite. Because this assemblage is so well developed on the OH vein, we call it the "OH assemblage". I want to emphasize, however, that it occurs in the deeper, northern portions of all the veins in the Main Mining District.

SLIDE 5: (*Rhodochrosite filling brecciated wallrock; Bulldog Mtn. vein system*)

In the southern portion of the Main Mining District the assemblage

consists of abundant early rhodochrosite which is cut by banded barite - sulfide ores and quartz, as shown in the next slide.

SLIDE 6: (*Banded barite + sulfide; Bulldog Mtn. vein system*)

The fact that rhodochrosite was the first mineral to have been deposited is very unusual for epithermal systems - usually it is among the last.

The sulfides interbanded with the barite consist of sphalerite and galena with minor chalcopyrite. Chlorite is notably absent and hematite is rare in this part of the MMD. The silver occurs both as blebs of tetrahedrite, ruby silver and other sulfosalts in sphalerite and galena, and as abundant native silver as in the specimen in the next slide:

SLIDE 7: (*Native Ag in banded barite-sulfide; Bulldog Mtn. vein system*)

Because this assemblage is so well developed on the Bulldog Mtn. vein system - where Geoff Plumlee and Penny Heald have studied it intensively - we call it the "Bulldog assemblage"; but, again, note that it is characteristic of the southern parts of each of the vein systems in the MMD.

SLIDE 8: (*Mineral zoning on combined OH - Amethyst longitudinal section*)

The relationship between the two assemblages is generalized on this longitudinal projection of the Amethyst-OH vein systems. The zoning records very well our interpretation of the dominant direction of fluid movement in the ore zone - laterally from North to South.

SLIDE 9: (*Ag/Pb ratio zoning and alteration cap; OH vein*)

The metal zoning also parallels that of the metal zoning on the OH vein - the Ag/Pb ratio is illustrated on this slide.

This slide also serves to introduce the subject of wallrock alteration. As shown, a zone of intense sericitic alteration marks the top of mining on the OH vein. Along the Amethyst and Bulldog Mountain vein systems, the bottom of the alteration fluctuates over vertical distances of several hundred feet, but the alteration always forms a cap to the ore body. The clays are mixed-layer illite-smectites. They have been studied by both Duane Horton (Horton, 1987) and Norma Vergo (Vergo, 1984), and their compositional variations may provide important constraints on the thermal history of the Creede system as Norma will discuss later (Vergo, 1987).

SLIDE 10: (*Sulfides on fresh rock; OH vein*)

The vertical transition between the intensely altered and unaltered wallrock is surprisingly sharp along the OH vein, and throughout almost all of the ore body the veins are hosted by fresh (that is - feldspar stable) wallrock as shown in this slide.

SLIDE 11: (*Coarse sphalerite, galena and chalcopyrite; OH vein*)

This is the same 6 inch specimen I showed earlier - but in a different orientation. The large size of the crystals lining the OH vein in places was one of the principal reasons for choosing the OH as a natural laboratory. Its so much easier to work with large crystals, and the superposition of crystals provides incontrovertible evidence of sequence of deposition.

SLIDE 12: (*Doubly polished section of banded sphalerite; P vein*)

When we slice and polish such crystals we see that the sphalerite is spectacularly banded, reflecting, in most cases, variations in iron content. The banding records a wealth of information about crystal growth and dissolution. Even more importantly, the growth zones can be correlated along the OH vein, and even, in part, between the OH and other veins. Such correlation has been critical in tracing the evolution of the ore fluid in time and space, allowing us to develop, for the Main Mining District, the systematics of chemical, isotopic and thermal variations in the ore zone - as Bob Rye, Dan Hayba, Geoff Plumlee and Gary Landis will discuss shortly (Rye et al., 1987, Hayba, 1987, Plumlee et al., 1987, and Landis and Rye, 1987). The development of such systematics for the Main Mining District has enabled us to make at least a preliminary interpretation of the fluid inclusion and isotopic data from the Northern Exploration Area where paragenetic control is, as yet, lacking.

SLIDE 13: (*Sphalerite stratigraphy column*)

Using the banding in sphalerite and the superposition of minerals, we have been able to develop a "stratigraphic column" for the OH vein as shown in this slide. Note that the sphalerite sits on either wallrock or an early quartz stage, and is, itself, divisible into 2 major units - an early "fine" stage and a later coarse stage. A period of intense leaching separates the two, and on that leached surface a quartz-fluorite-siderite stage is found; but it is not shown in this column. The sequence is capped by a late "gel pyrite" stage which is locally very strongly developed in the upper parts of all the veins in the MMD.

SLIDE 14: (*Comparison, Paragenetic sequence: OH vs. Bulldog Mtn. vein systems*)

The mineralogy of the major stages on the OH Vein - that is, the "OH assemblage" - is shown on the left in this slide. Penny Heald and Geoff Plumlee (Heald-Wetlaufer and Plumlee, 1984), working on the Bulldog ores, have been able to define 5 comparable stages in the Bulldog Assemblage which they consider to be Southern facies of each of the OH stages, as shown on the right half of the slide. The principal differences in mineralogy are the abundant rhodochrosite in the first stage of the Bulldog sequence and the abundant barite in the second.

SLIDE 15: (*logfS₂ - logfO₂ diagram; OH mineral assemblage*)

The OH mineral assemblage has been interpreted by Paul Barton to have buffered the ore fluid in oxygen and sulfur fugacity near the pyrite-chlorite-

hematite triple point, although excursions from this point occurred periodically (Barton et al., 1977).

SLIDE 16: (*Aqueous sulfide-sulfate stability fields; logfS₂ - logfO₂ diagram*)

This slide shows the same mineral fields on the same coordinates as on the last slide, and I use it to show that during almost all of the deposition of the OH sphalerite the ore fluid was oxidized enough that sulfate was the thermodynamically dominant aqueous sulfur species - if those species were in equilibrium - which Bob Rye will show they were not (Rye et al., 1987).

CURRENT CONCEPTUAL MODEL OF THE CREEDE HYDROTHERMAL SYSTEM

So much for background; now let me go on to outline our current concepts of the structure and dynamics of the Creede ore-forming system.

SLIDE 17: (*Map of the Creede mining district*)

In order to do so we need to address the question of the relation of the mineralization in the Northern Exploration Area to that in the Main Mining District.

Just over 2 years ago we held a workshop in Alamosa to begin the development of a proposal for a program of research drilling in the Creede district. The program considered at that workshop focused on the Main Mining District because we considered that the hydrothermal system was driven by a buried pluton beneath the center of the district. That focus concerned Stan Caddey and Craig Byington because Homestake's exploration program, based on a heat source north of the Main Mining district, had discovered mineralization in the Northern Exploration Area which they considered to have been deposited by the same hydrothermal system that formed the ores in the Main Mining District. Frankly, we were skeptical and thought it likely that the mineralization in the Northern Exploration Area was produced by an older system. However, petrographic, fluid inclusion, stable isotope, Pb isotope, gas analysis, and geochronological studies (Rye et al 1987, Bazrafshan and Norman, 1987, Hayba, 1987, Foley et al, 1987, Landis and Rye, 1987, Lanphere, 1987) samples made available to us by Homestake, and by Pioneer Nuclear and its successor, Mesa Limited Partnership, together with information provided by both companies (particularly a magnificent set of fluid inclusion data provided by Pioneer) have changed our minds. The fluid inclusion data provided by Pioneer were measured by Khosrow Bazrafshan in David Norman's laboratory at the New Mexico Institute of Mining and Technology, under contract to Pioneer. They were scheduled to present the data, and their interpretation of it, at this symposium (Bazrafshan and Norman, 1987) but had to withdraw their paper at the last minute. Both Dan Hayba and I will present and use their data, but we want to make it clear that it is their data.

SLIDE 18: (*Comparison NEA vs. MMD*)

The identical ages, the fact that galenas in the Northern Exploration Area have Pb-isotopic compositions essentially identical to the unusually radiogenic and homogeneous values that characterize the Main Mining district,

and the similar ore, gangue, and alteration mineralogy strongly suggest that the two areas are part of the same system. If this is true, the differences noted, then, must result from differences in the hydrothermal system in the two areas.

SLIDE 19: (*Schematic section; Wairakei geothermal field*)

Let's look now at some of the characteristics of a modern geothermal system in a silicic volcanic terrain. I borrowed this slide and the next from Dick Henley. This slide is a longitudinal section of the Wairakei geothermal field in New Zealand based on sampling during exploration and development drilling. The lightest shading represents the plume of heated, near neutral, chloride waters which displaces the fresh ground water shown, surrounding it, in intermediate shading. Mixing is shown to occur along the top and sides of the plume resulting in dilute chloride waters, and boiling near the top of the plume is indicated by circles. Note that the isotherms are displaced to the right by the gravity-driven lateral flow along the top of the system due to the topographic gradient, and that boiling occurs in the upper 400 meters of the chloride water plume. Let's move a little closer and examine the detail along the top of the plume.

SLIDE 20: (*Blow-up of top of Wairakei schematic section*)

Boiling in the upper parts of the plume fractionates volatiles such as H₂O and CO₂ into the vapor phase. The steam so generated rises in the system and begins to condense in the cooler, overlying waters. Hydrolysis reactions of H₂S and CO₂ on condensation, slightly acidify the waters and lead to a zone of argillic alteration - usually sericite or mixed-layer clays. If the volatiles rise to the water table, the oxidation of H₂S produces sulfuric acid which produces intense acid-sulfate alteration in the near surface environment shown by the darkest pattern. The condensation of the steam in the overlying cooler waters raises their temperature, and they are called steam-heated waters. Note that these waters may be weakly acid due to hydrolysis reactions of H₂S and CO₂, or, at and above the water table, strongly acid due to the oxidation of H₂S. Steam-heated waters occur along the top of all such geothermal systems, but only if the H₂S reaches the water table do they become acid enough to produce acid-sulfate alteration.

SLIDE 21: (*N - S crosssection from the San Luis to the Creede caldera*)

Now let's turn our attention back to Creede. Here, again, is the schematic longitudinal section along the Amethyst vein system from the San Luis caldera to the Creede caldera. A 25.0 million year-old intrusion of uncertain affinity (Mi) is interpreted to lie at depth near the south margin of the San Luis Caldera and to have been the causative intrusion driving the Creede ore-forming system. Sediments filling the moats of the Creede and Bachelor calderas (Cfl, Cfc, and Bms) play an important role in our model.

A volcanic ring dome is shown on the South margin of the San Luis caldera. Its existence is demanded by fluid inclusions in quartz found on the present surface whose homogenization temperatures require a cover of at least 300 meters. The highest elevations shown on this section are in the San Luis

caldera; the lowest are in the moat of the Creede caldera.

The next slide covers the area between the dashed vertical lines, and illustrates our concept of the Creede hydrothermal system.

SLIDE 22: (*Conceptual model of the Creede hydrothermal system*)

Waters from two different sources are indicated by different types of arrows. The solid arrows indicate brines whose salinities are at least 12 wt.% NaCl - about 3 times as concentrated as sea water. They acquired their salinity by evaporation in the playa lakes in the moat of the Creede caldera and entered the hydrothermal system from the South when the fractures of the Creede Graben tapped the pore waters of the Creede moat sediments. The short-dashed arrows represent the regional ground waters which entered the system from the highlands of the San Luis caldera to the North. Both waters circulated deeply, were heated by the causative intrusion, and rose in the northern part of the district beneath the Northern Exploration Area. As in the slides of Wairakei, the 200°C isotherm serves to outline the hydrothermal plume. Note that, in addition to circulating deeply, the regional ground waters occurred along the top of the plume; again, as shown for Wairakei. Mixing of the brine and the fresh water occurred at their interfaces - particularly along the top of the system. Mixed waters are shown by the light shading and the long-dashed arrows. The heavier shading denotes the principal areas of known mineralization.

The two basic fluids - the brines and the fresh waters - were different in two important aspects prior to their entry into the system, as indicated on the next slide:

SLIDE 23: (*Comparison of salinities and isotopic characteristics; southern vs. northern waters*)

The fluids entering the system from the South were moderately strong brines enriched in salinity, ^{18}O and D by evaporation and diagenesis in the playa lake environment of the Creede caldera moat prior to recharge into the hydrothermal system. Dissolved sulfate in these brines was extremely enriched in ^{34}S and ^{18}O due to bacteriogenic reduction of sulfate in the playa lake sediments. In contrast, waters entering the system from the north had low salinities, low ^{18}O and D typical of unevolved meteoric water, and had oxygen and sulfur isotopic compositions of dissolved sulfate much lighter than that of sulfate in the brines. Those northern waters that circulated deeply and were heated by the causative intrusion became somewhat enriched in ^{18}O by exchange with wall rocks.

SLIDE 24: (*Conceptual model of the Creede hydrothermal system*)

Returning to the conceptual model we see that the areas of mineralization, shown by heavy shading, lie entirely within the zone of mixing between the brine and the overlying fresh waters - an interpretation Dan Hayba will document (Hayba, 1987). The circles indicate boiling which is most intense beneath and within the mineralized region of the Northern Exploration Area as evidenced by fluid inclusion studies. The sericitic alteration along the top of the system resulted from the condensation of the volatiles in the

cooler overlying waters. No acid-sulfate alteration resulting from the oxidation of H₂S at the water table has been found along the top of the Creede system. If areas of such alteration were produced, they have been subsequently lost to erosion.

Note that, just as at Wairakei, the plume is deflected southward, as indicated by the shading within the 200 degree isotherm, in response to the topographic gradient. The position of the 200 degree isotherm on the underside of the plume is highly speculative. Its actual position will depend on the amount of recirculation of the brine - information we do not have.

The brine is shown as flowing laterally southward and continuing to mix with the overlying fresh waters. Boiling occurs - at least sporadically - from the region of the Northern Exploration Area down to the northern part of the Main Mining District.

Let me be the first to point out that this model is highly simplistic; it is two dimensional, and permeability differences and changes with time are not considered. The indicated fluid movement is much more regular than surely existed. However, the model has one advantage in that most of its major aspects are required by observations, as will be detailed in the following talks.

In closing, I want to point out that the only thing unusual about the Creede hydrothermal system is the evolved brines that entered the system from the Creede moat sediment reservoir. Other than that its general structure is just like other hydrothermal systems in silicic volcanic terranes, fossil or active. But that difference makes all the difference! Because of the high contrast in salinities, fluid inclusion studies tell tales of mixing and fluid origin. Because of the isotopic contrasts, analyses of ore, gangue and alteration minerals trace the evolution of the ore fluid in both time and space - where paragenetic control exists. Because of these contrasts the Creede system offers a truly unique opportunity to study the structure, dynamics and evolution of an ore-forming system. Much has already been accomplished in that effort, as I hope the following talks will convince you. I hope they will also convince you that enormous further opportunities exist.

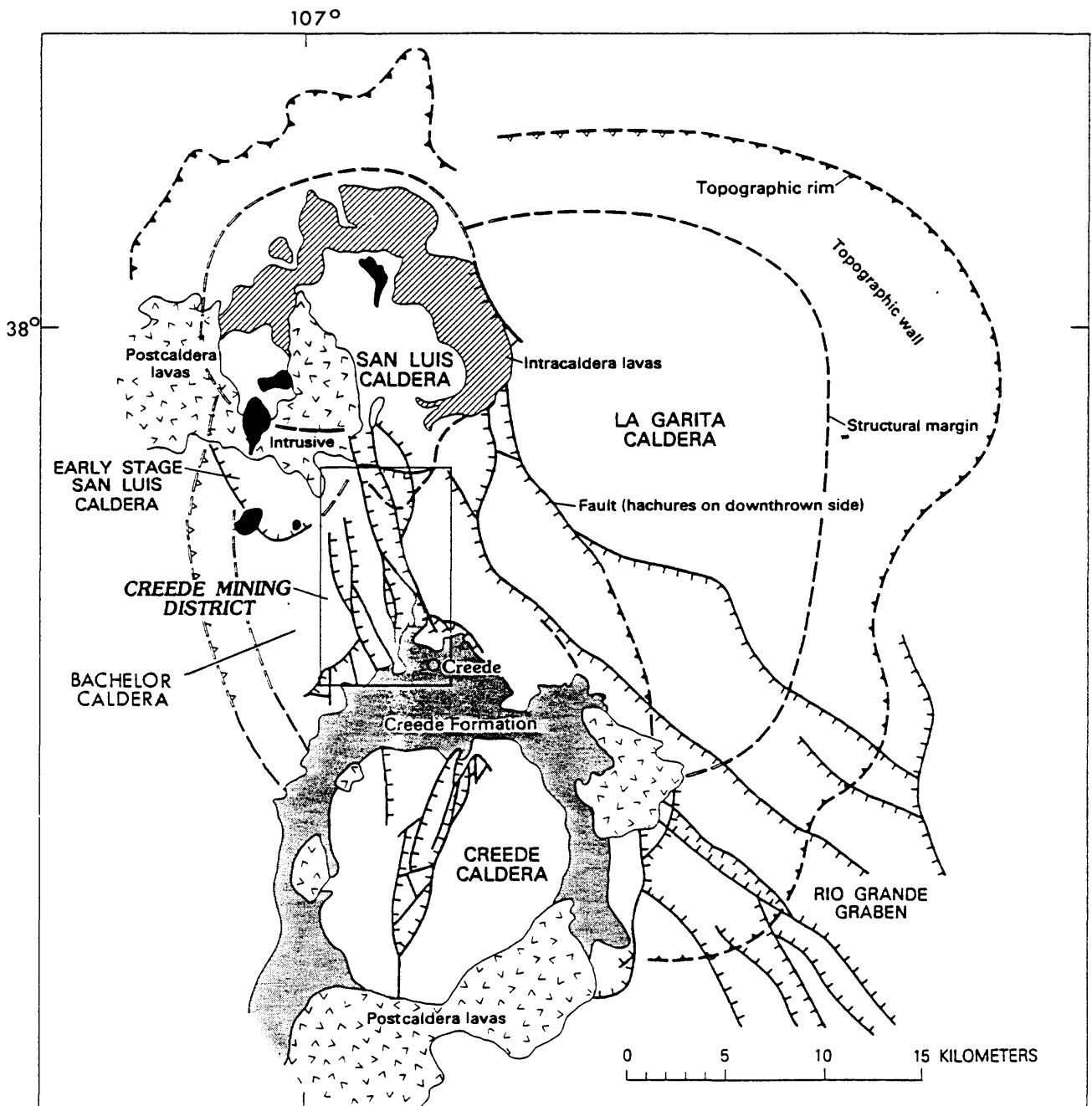
REFERENCES

Barton, P. B. Jr., 1987, The role of archetypes in understanding ore genesis: lessons from Creede, Colorado [abs]: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 259.

Barton, P. B., Bethke, P. M., and Roedder, E., 1977, Environment of Ore Deposition in the Creede mining district, San Juan Mountains, Colorado: Part III. Progress toward interpretation of the chemistry of the ore-forming fluid for the OH vein: Econ. Geol., v. 72, p. 1-24.

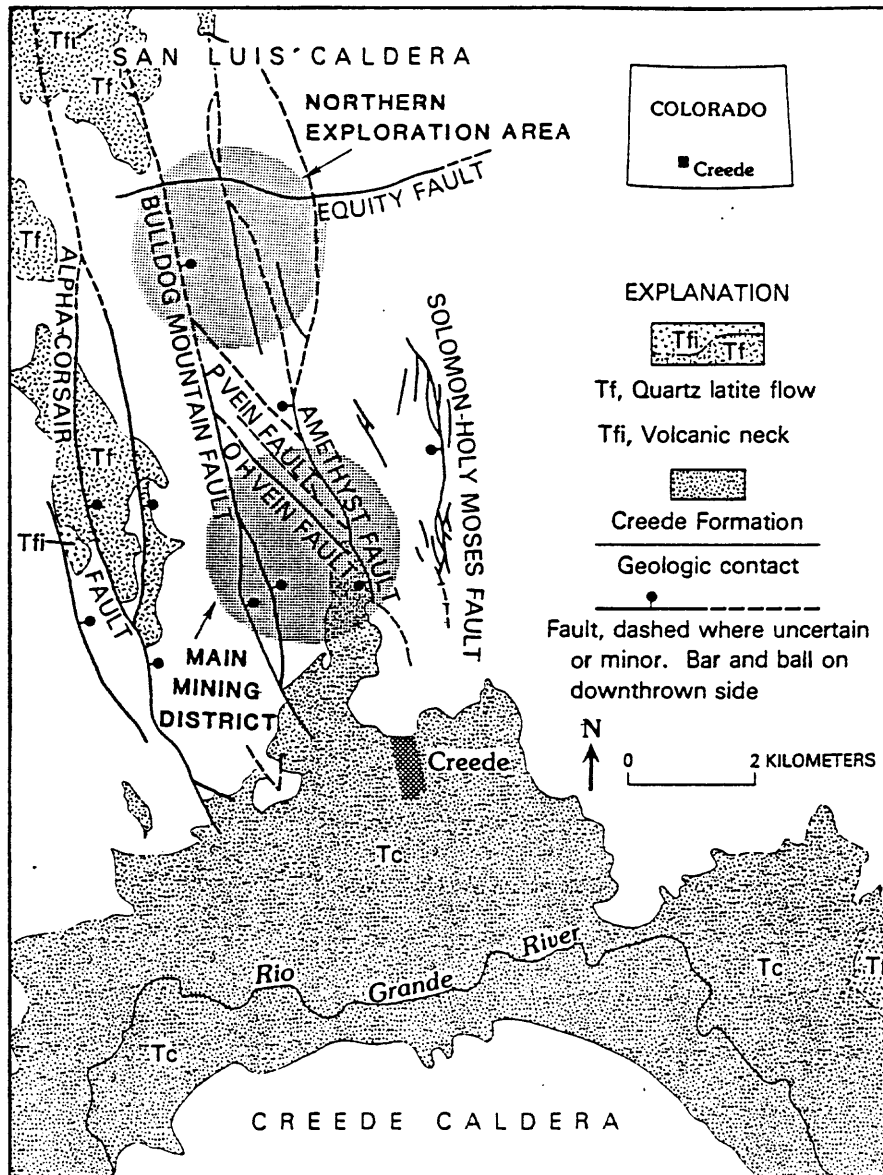
Hayba, D. O., 1987, Fluid inclusion evidence for hydrologic and hydrothermal processes in the Creede mineralizing system, Colorado [abs]: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 282.

- Heald-Wetlaufer, P. and Plumlee, G. S., 1984, Significance of mineral variations in time and space along the Bulldog Mountain vein system with respect to district-wide hydrology, Creede district, Colorado [abs]: Geol. Soc. America Abstracts with Programs, v. 16, no. 6, p. 535.
- Horton, D. G., 1985, Mixed-layer Illite/Smectite as a paleotemperature indicator in the Amethyst vein system, Creede district, Colorado, USA: Contrib. Min. Pet. v 91, p 175-179.
- Landis, G. P. and Rye, R. O., 1987, Reconnaissance gas chemistry of the Creede, Colorado hydrothermal system [abs]: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 288.
- Plumlee, G. S., Barton, P. B., Jr., and Rye, R. O., 1987, Diverse chemical processes in a complex hydrothermal system [abs]: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 327.
- Rye, R. O., Plumlee, G. S., Bethke, P. M., and Barton, P. B., Jr., 1987, Stable isotope geochemistry of the Creede, Colorado hydrothermal system [abs]: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 330-331.
- Steven, T. A. and Eaton, G. P., 1975, Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: I. Geologic, hydrologic, and geophysical setting: Econ. Geol., v. 70, p 1023-1037.
- Steven, T. A. and Lipman, P. W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U. S. Geol. Survey Prof. Paper 958, 35 p.
- Steven, T. A. and Ratté, J. C., 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: U. S. Geological Survey Prof. Paper 487, 90 p.
- Vergo, N., 1984, Wallrock alteration at the Bulldog Mountain mine, Creede mining district, Colorado: MS Thesis, University of Illinois, Urbana, Illinois, 88 p.
- Vergo, N., 1987, Wallrock alteration at the Bulldog Mountain mine, Creede, Colorado: Geol. Soc. America Abstracts with Programs, v. 19, no. 5, p. 340.



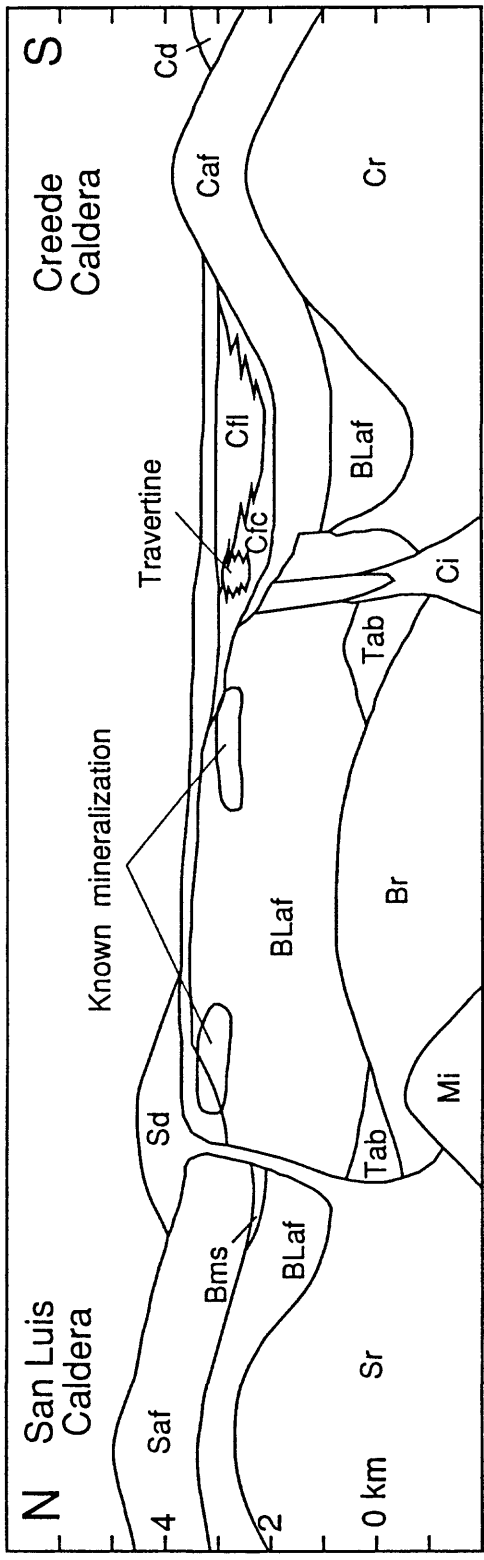
SLIDE 1:

Map of central San Juan caldera cluster (Modified from Steven and Lipman, 1976)



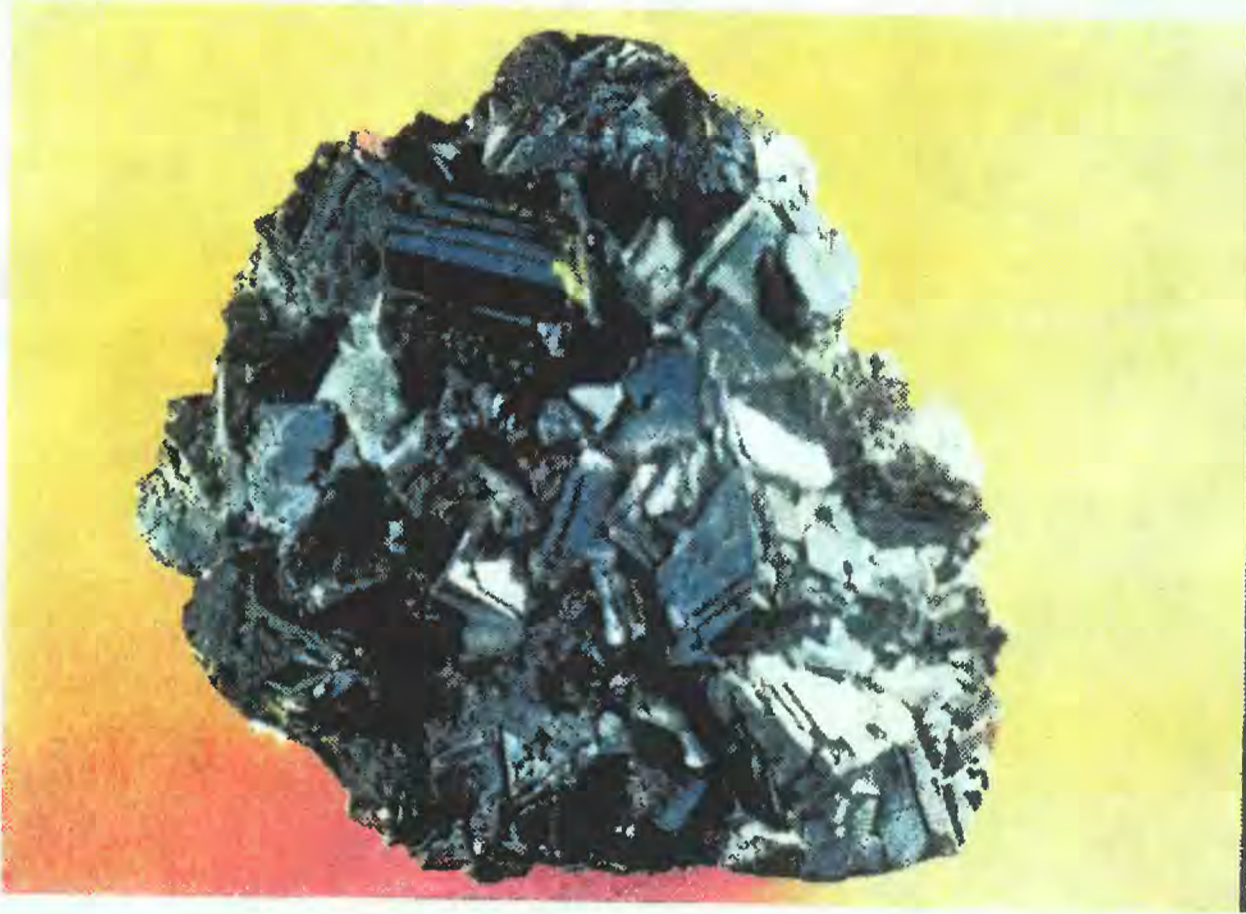
SLIDE 2:

Map of the Creede mining district (Modified from Steven and Eaton, 1975)



- | | |
|--|---|
| BLaf - Ashflows (Bachelor, LaGarita Calderas) | Cfl - Lake Facies - Moat Seds. (Creede Caldera) |
| Bms - Moat sediments (Bachelor Caldera) | Cfc - Clastic Facies - Moat Seds. (Creede Caldera) |
| Br - Resurgent Intrusion (Bachelor Caldera) | Saf - Ashflows (San Luis Caldera) |
| Caf - Ashflows (Creede Caldera) | Sr - Resurgent Intrusion (San Luis Caldera) |
| Cr - Resurgent Intrusion (Creede Caldera) | Sd - Lava Domes (San Luis Caldera) |
| Cd - Lava Domes (Creede Caldera) | Tab - Andesite-basalt stratovolcanoes |
| Ci - Ring Fracture Intrusion (Creede Caldera) | Mi - Mineralization-related Intrusion |

SLIDE 3: N -S Crossection from the San Luis to the Creede Caldera



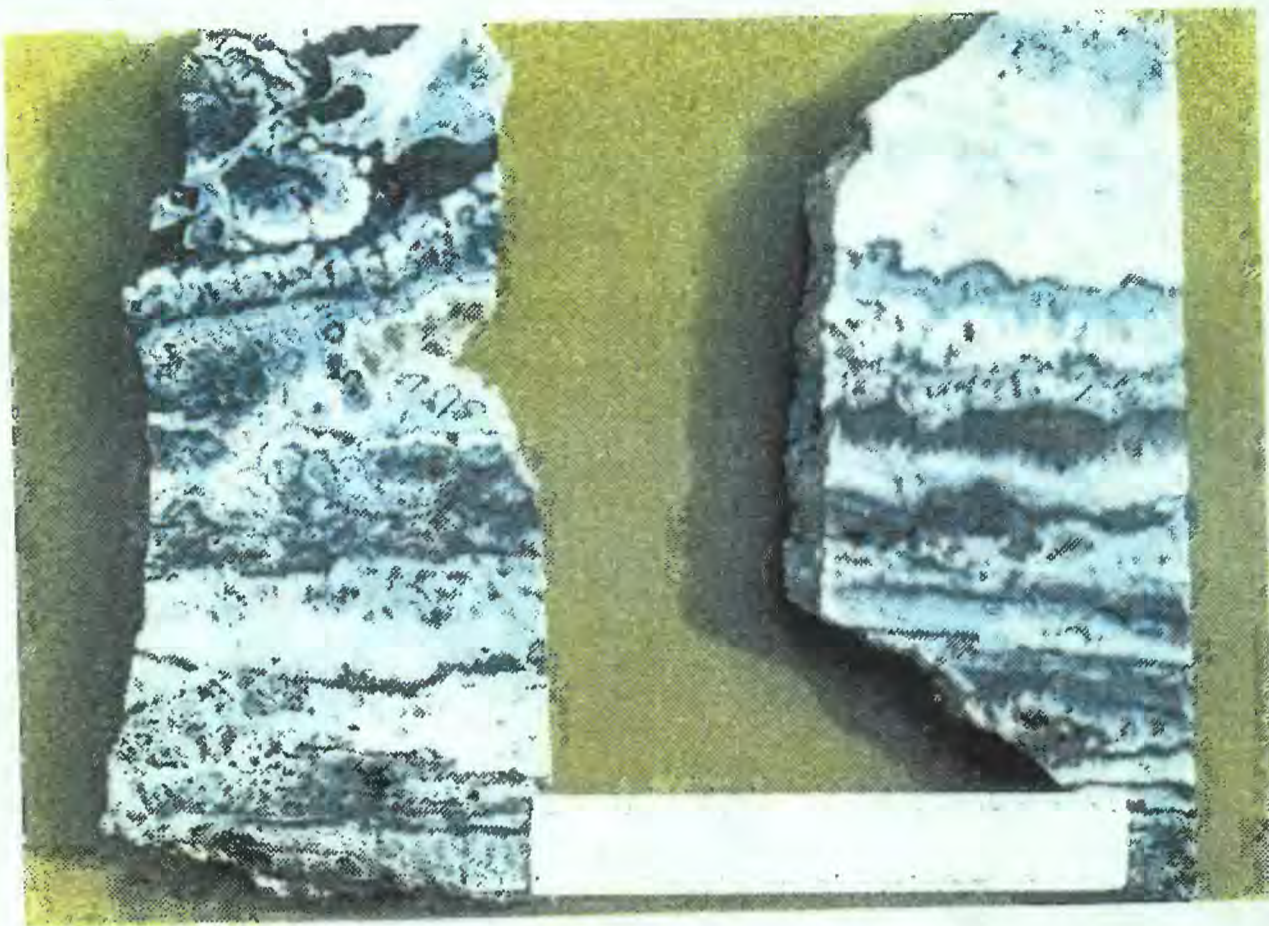
SLIDE 4:

Coarse sphalerite, galena and chalcopyrite; OH vein



SLIDE 5:

Rhodochrosite filling brecciated wallrock; Bulldog Mtn. vein system



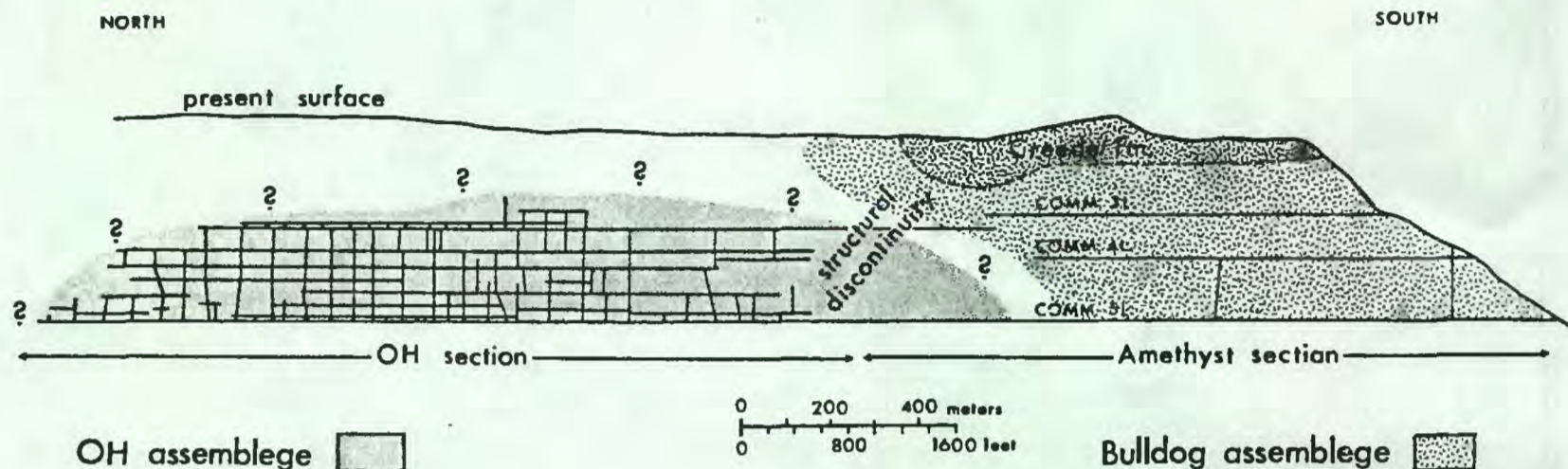
SLIDE 6:

Banded barite + sulfide; Bulldog Mtn. vein system



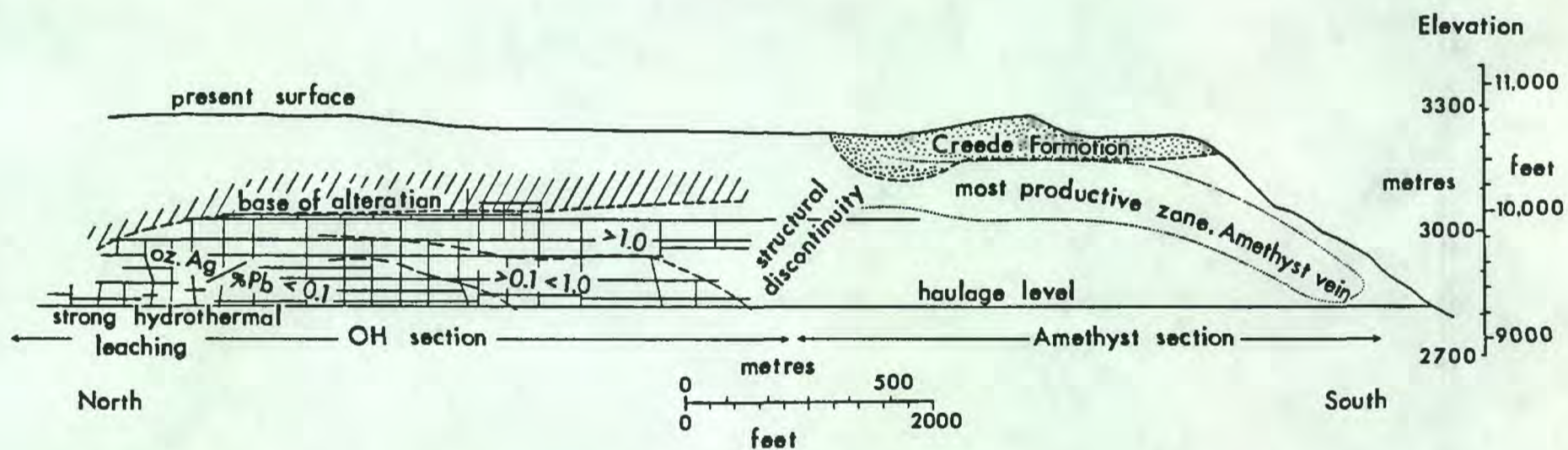
SLIDE 7:

Native Silver in banded barite + sulfide; Bulldog Mtn. vein system



SLIDE 8:

Mineral zoning on combined OH - Amethyst longitudinal section
(from Hayba, et al., 1985)



SLIDE 9:

Ag/Pb ratio zoning and alteration cap; OH vein (from Barton, et al., 1977)



SLIDE 10:

Sulfides on fresh rock; OH vein



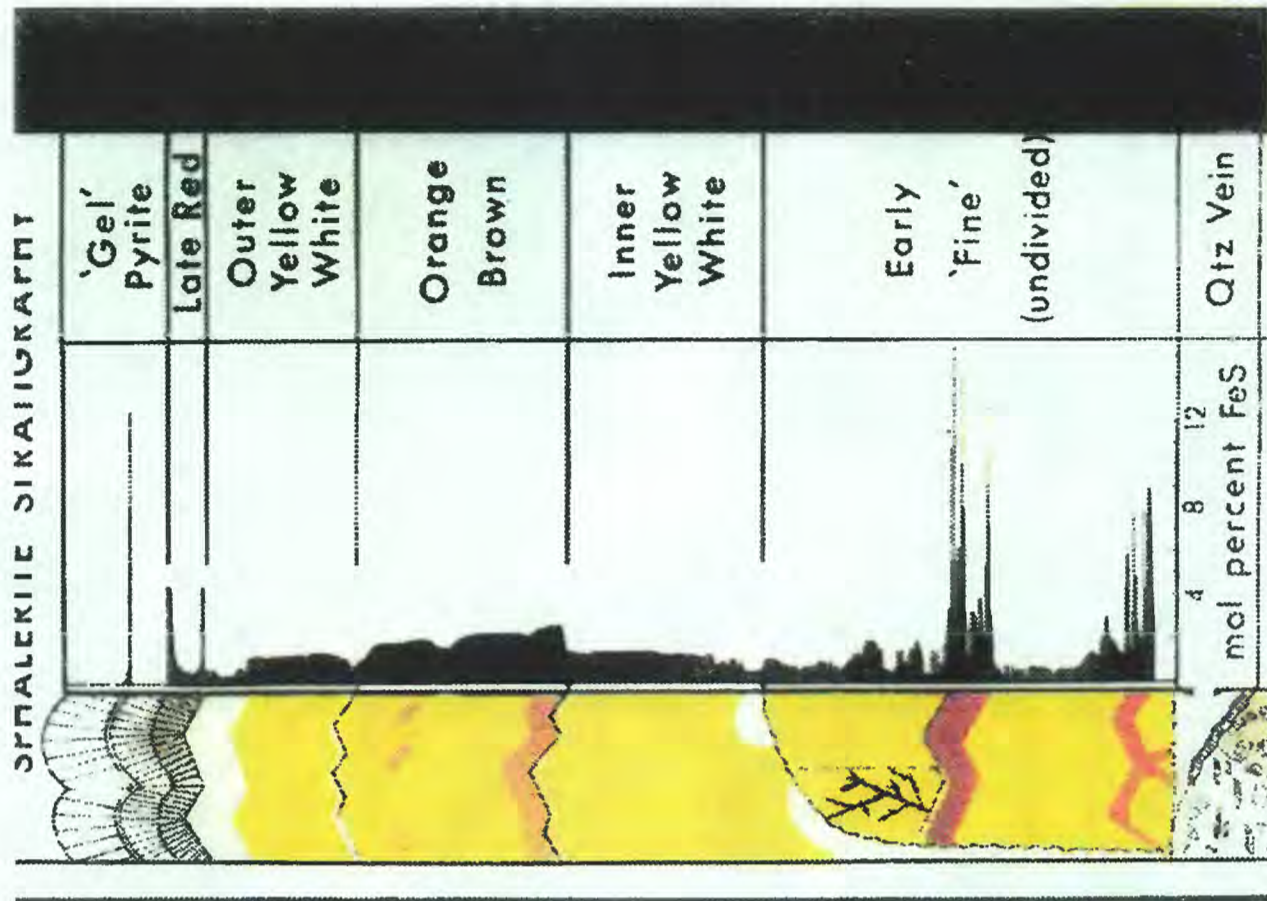
SLIDE 11:

Coarse sphalerite, galena and chalcopyrite; OH vein



SLIDE 12:

Doubly polished section of banded sphalerite: P vein



SLIDE 13:

Sphalerite stratigraphy column: OH vein

OH VEIN

(similar to P vein)

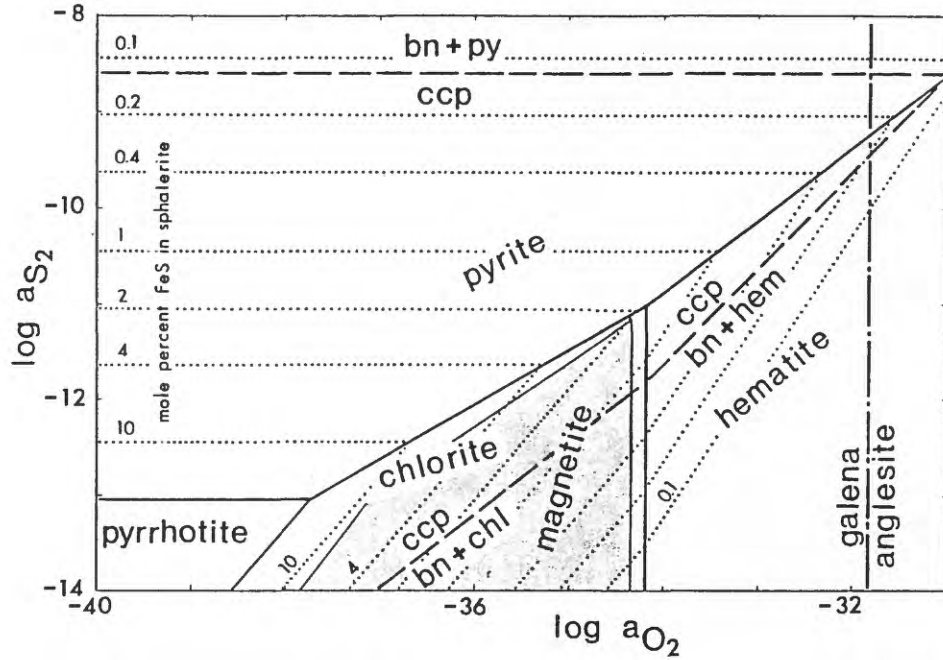
BULLDOG MTN
VEIN SYSTEM

(similar to so. Amy. vein)

PY, stib	E	V	PY, stib, pyrarg
SP, GN, cpy, hem, qtz	D	IV	SP, GN, cpy, td, pearc, ac
QTZ (amy, wh), fl, Mn-sid	C	III	QTZ (amy, wh), fl, Mn-sid
SP, GN, chl, hem, td, qtz, [bar]	B	II	SP, GN, BAR, td
QTZ, ad	A	I	RC, sp, gn, ad

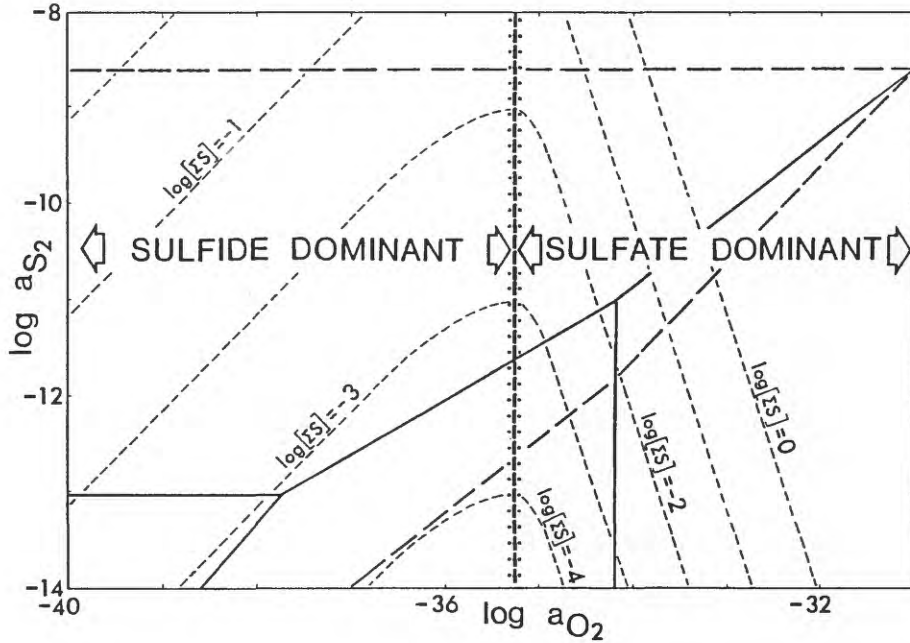
SLIDE 14:

Comparison, Paragenetic sequence: OH vs. Bulldog Mtn. vein systems
(Courtesy, P. Heald and G. S. Plumlee)



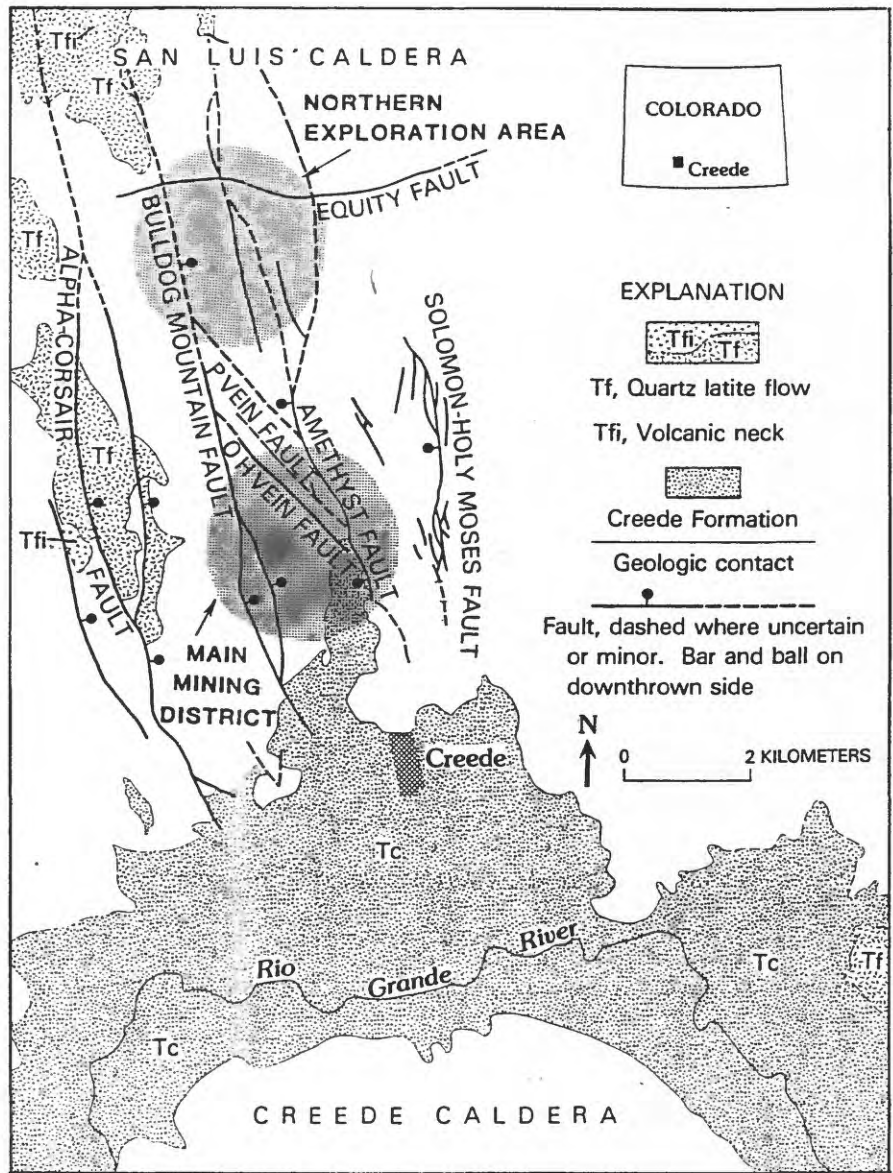
SLIDE 15:

log fS₂ - log fO₂ diagram; OH mineral assemblage
(from Barton et al., 1977)



SLIDE 16:

Aqueous sulfide-sulfate stability fields; log fS₂ - log fO₂ diagram
(from Barton et al., 1977)



SLIDE 17:

Map of the Creede mining district (repeat of slide 2)

COMPARISON
NORTHERN EXPLORATION AREA (NEA)
VS.
MAIN MINING DISTRICT (MMD)

SIMILARITIES:

IDENTICAL $^{40}\text{Ar}/^{39}\text{Ar}$ AGES (25.0 ± 0.2 Ma)¹

IDENTICAL Pb-ISOTOPES²

SIMILAR ORE, GANGUE, & ALTERATION MINERALOGY

DIFFERENCES:

ABUNDANT LOW-SALINITY FLUID INCLUSIONS IN NEA³

HIGHER Au:Ag RATIO IN NEA

EVOLVED AND UNEVOLVED STABLE ISOTOPES⁴

SLIDE 18:

Similarities and differences: NEA vs. MMD

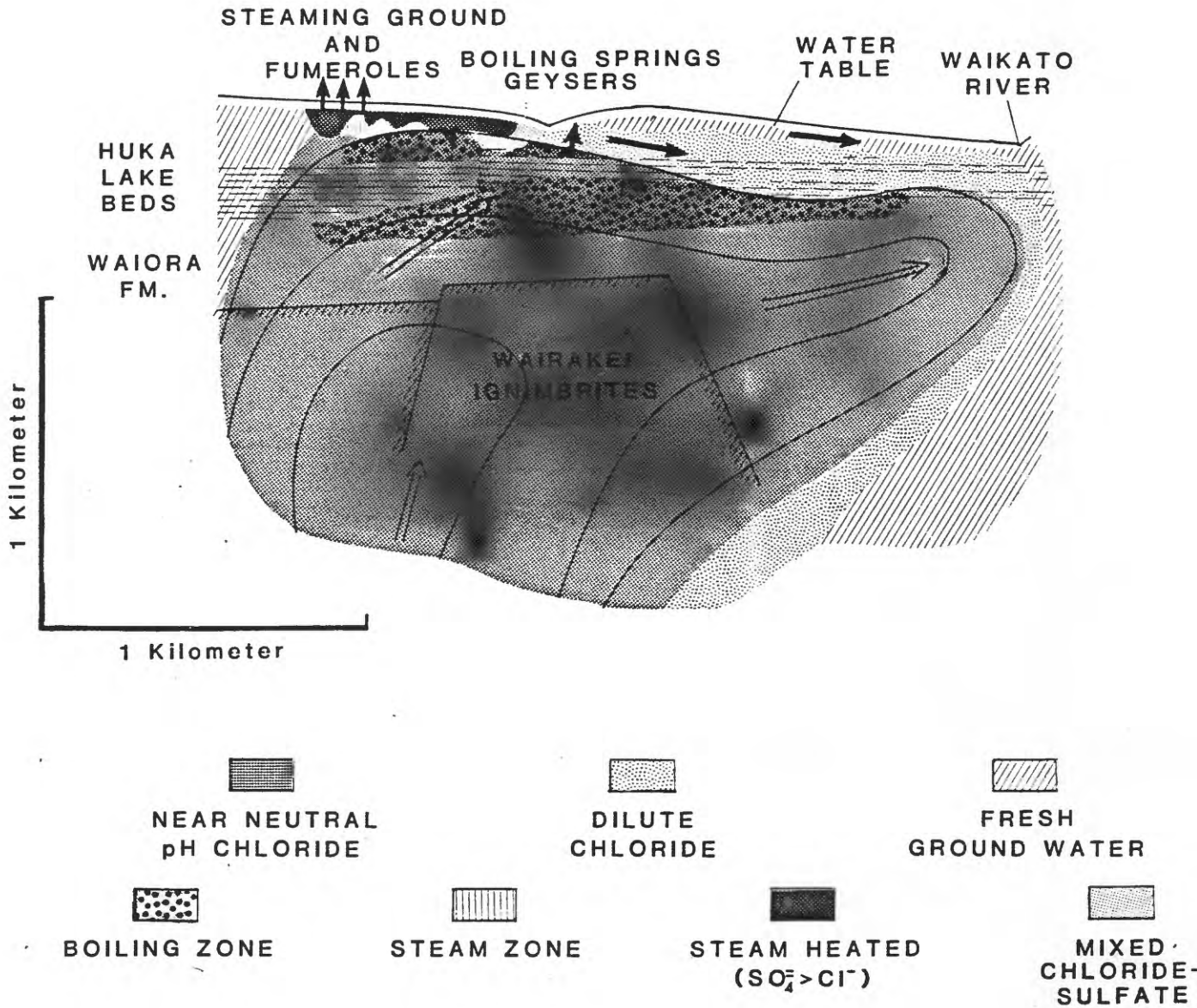
¹ M. Lanphere, pers. comm., 1986

² Foley, et al., 1987

³ Bazrafshan and Norman, 1987

⁴ Rye, et al., 1987

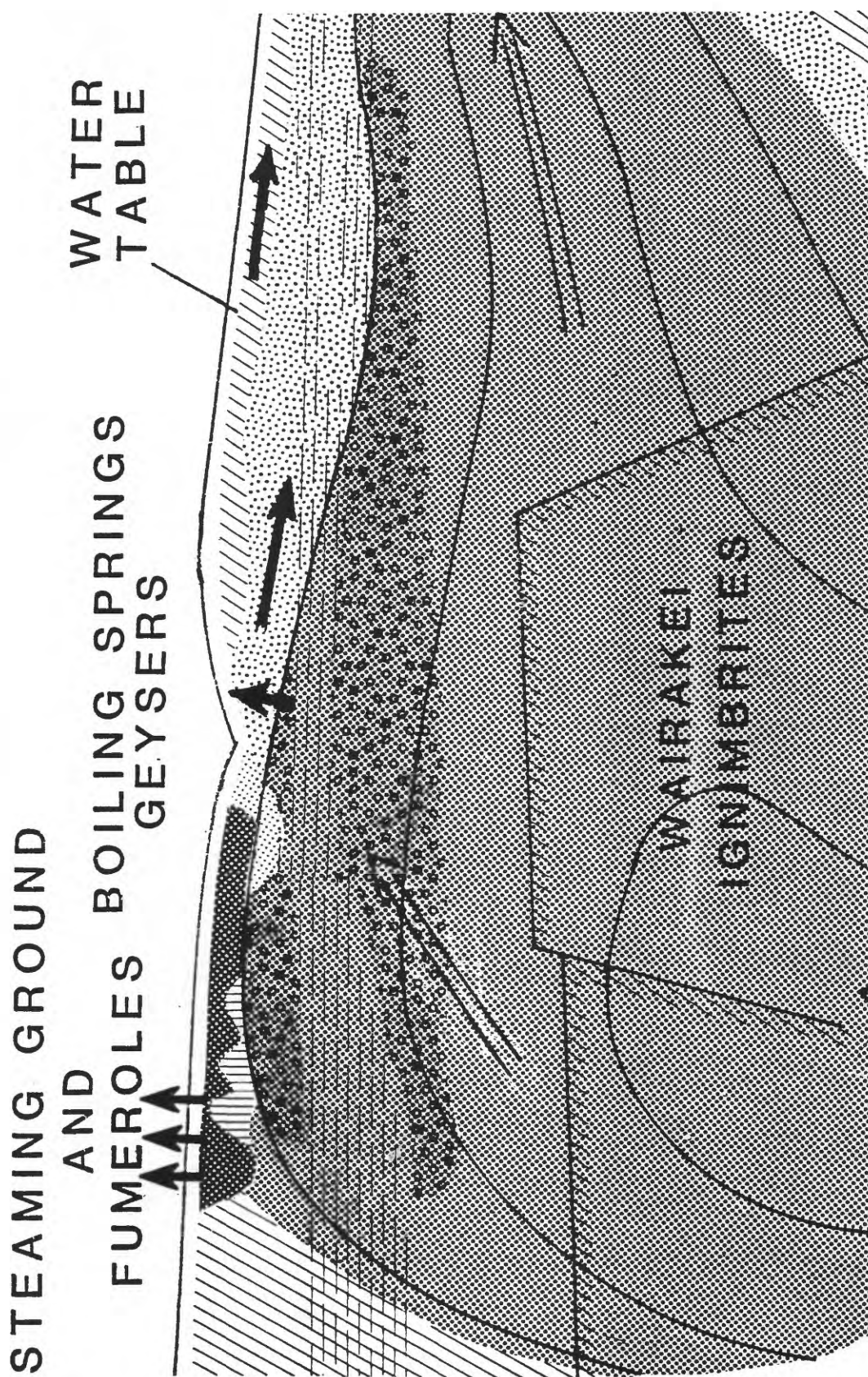
WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND LONGITUDINAL SECTION, PRE-EXPLOITATION



ALL FLUID BOUNDARIES GRADATIONAL

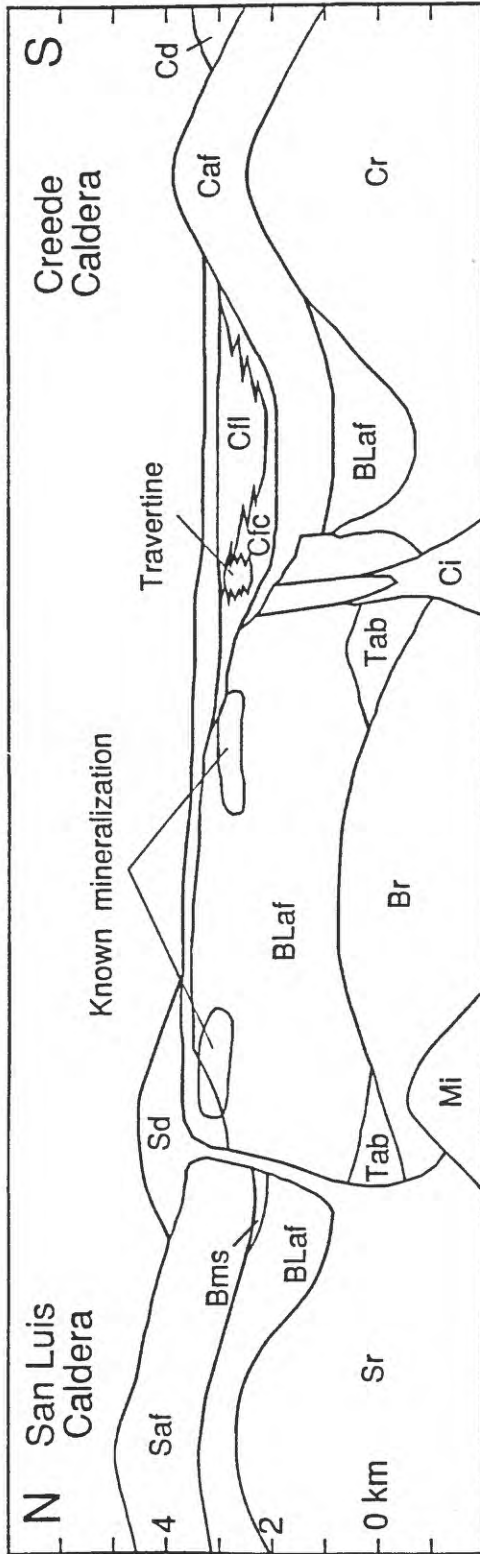
SLIDE 19:

Schematic section; Wairakei geothermal field (courtesy R. W. Henley)



SLIDE 20:

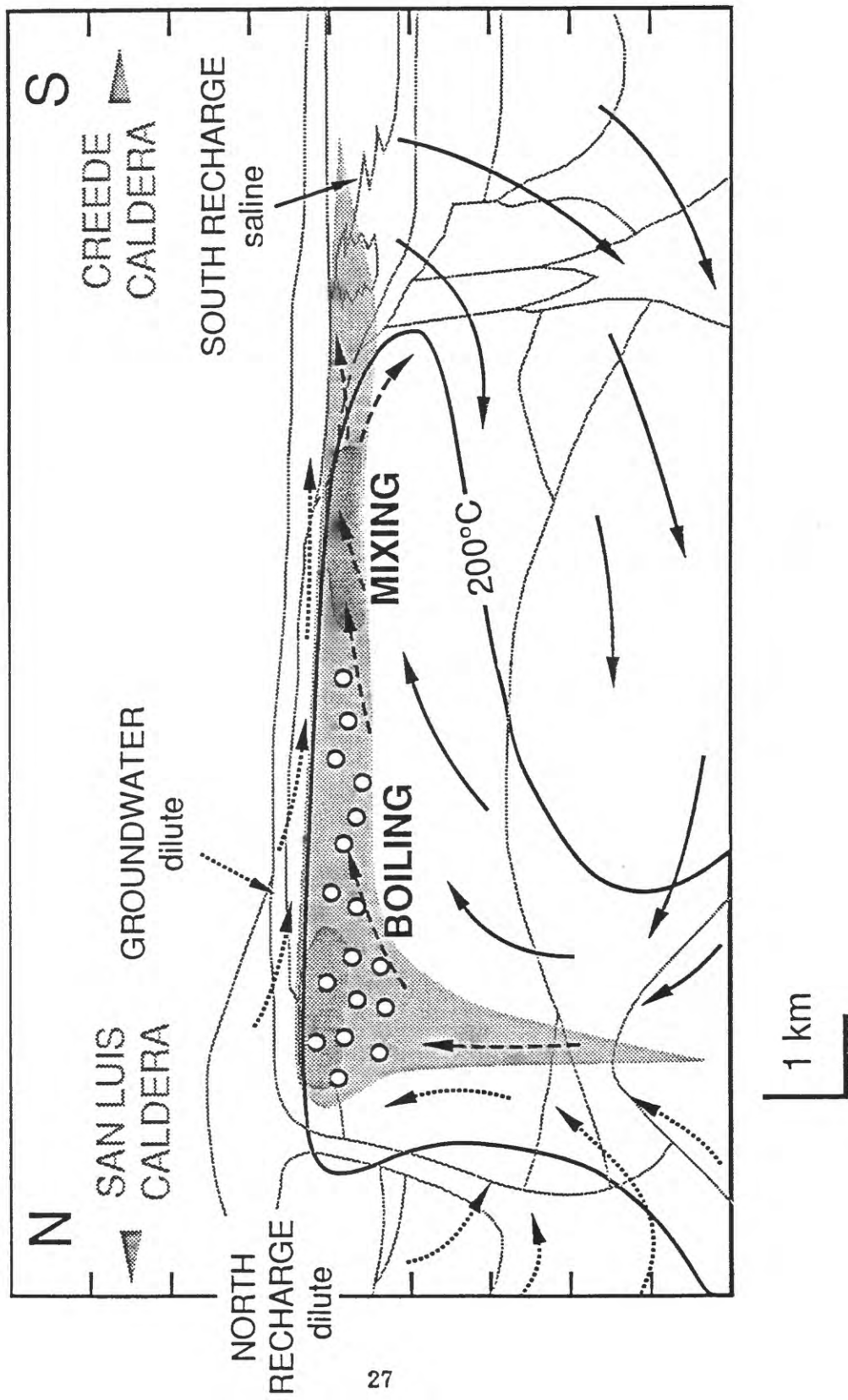
Blow-up of top of Wairakei schematic section (courtesy R. W. Henley)



- | | |
|--|---|
| BLaf - Ashflows (Bachelor, LaGarita Calderas) | Cfl - Lake Facies - Moat Seds. (Creede Caldera) |
| Bms - Moat sediments (Bachelor Caldera) | Cfc - Clastic Facies - Moat Seds. (Creede Caldera) |
| Br - Resurgent Intrusion (Bachelor Caldera) | Saf - Ashflows (San Luis Caldera) |
| Caf - Ashflows (Creede Caldera) | Sr - Resurgent Intrusion (San Luis Caldera) |
| Cr - Resurgent Intrusion (Creede Caldera) | Sd - Lava Domes (San Luis Caldera) |
| Cd - Lava Domes (Creede Caldera) | Tab - Andesite-basalt stratovolcanoes |
| Ci - Ring Fracture Intrusion (Creede Caldera) | Mi - Mineralization-related Intrusion |

SLIDE 21:

N - S crosssection from the San Luis to the Creede caldera
(Repeat of Slide 3)



SLIDE 22:

Conceptual model of the Creede hydrothermal system

FLUID CHARACTERISTICS

SOUTH – CREEDE MOAT

HIGH SALINITIES (>12 wt% NaCl)

ISOTOPICALLY EVOLVED HEAVY H, O, S*

NORTH – SAN LUIS HIGHLANDS

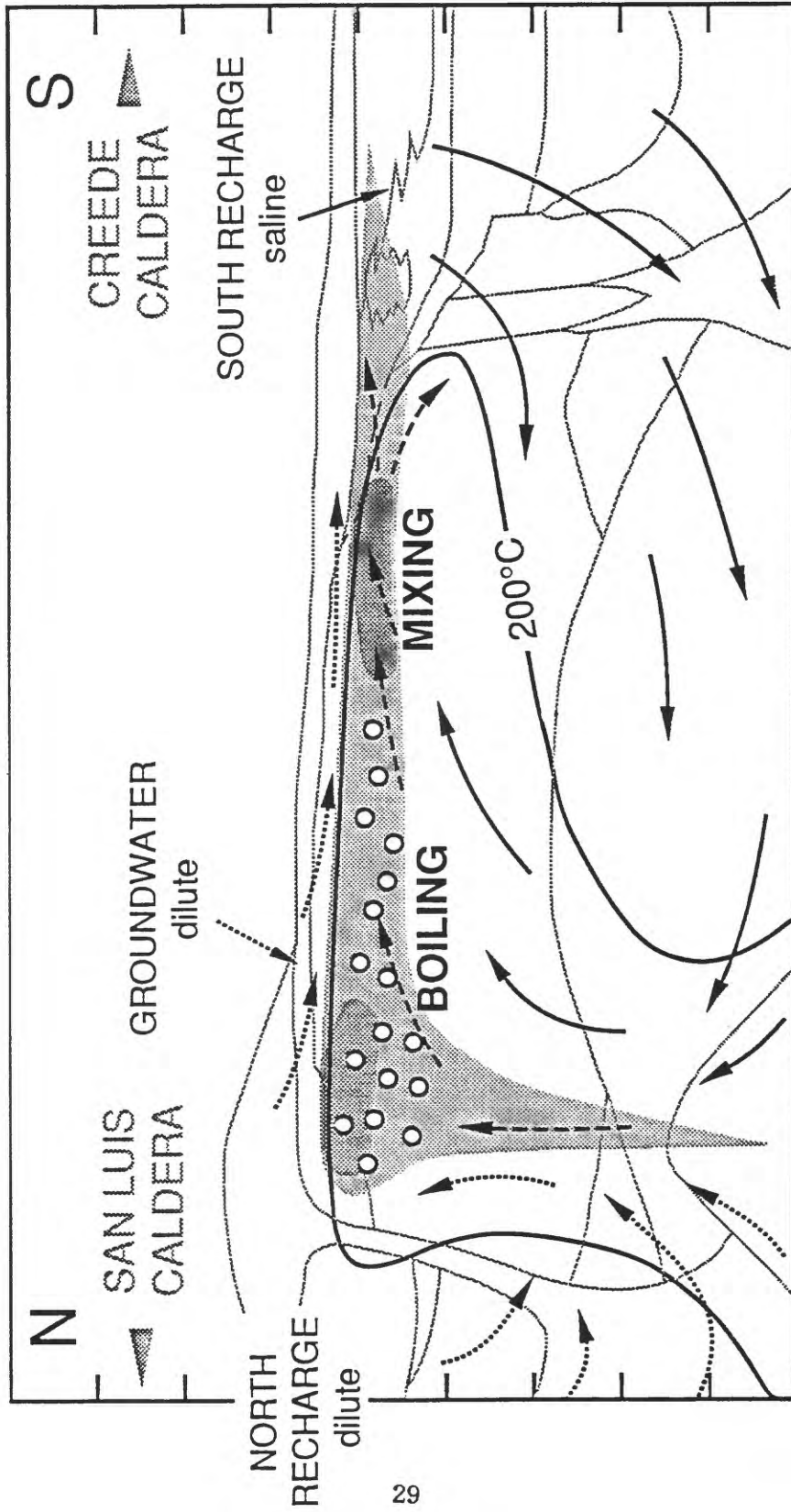
LOW SALINITIES (<2 wt% NaCl)

ISOTOPICALLY LIGHT H, O, S*

SLIDE 23:

Comparison of salinities and isotopic characteristics;
southern vs. northern waters

* Deuterium in water; Oxygen and Sulfur in Aqueous Sulfate, (Rye, et al., 1987)



SLIDE 24:

Conceptual model of the Creede hydrothermal system
(repeat of slide 22)