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Creede Caldera, Colorado

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INTRACALDERA VOLCANISM AND SEDIMENTATION —CREEDE CALDERA, COLORADO

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ABSTRACT

Within the Creede caldera, Colorado, many of the answers to its postcaldera volcanic and sedimentary history lie within the sequence of tuffaceous clastic sedimentary rocks and tuffs known as the Creede Formation. The Creede Formation and its interbedded ash deposits were sampled by research coreholes *Creede 1 and 2*, drilled during the fall of 1991. In an earlier study of the Creede Formation, based on surface outcrops and shallow mining company coreholes, Heiken and Krier (1987) concluded that the process of caldera structural resurgence was rapid and that a caldera lake had developed in an annulus ("moat") located between the resurgent dome and caldera wall. So far we have a picture of intracaldera activity consisting of intermittent hydrovolcanic eruptions within a caldera lake for the lower third of the Creede Formation, and both magmatic and hydrovolcanic ash eruptions throughout the top two-thirds. Most of the ash deposits interbedded with the moat sedimentary rocks are extremely fine-grained. Ash fallout into the moat lake and unconsolidated ash eroded from caldera walls and the slopes of the resurgent dome were deposited over stream delta distributaries within relatively shallow water in the northwestern moat, and in deeper waters of the northern moat, where the caldera was intersected by a graben. Interbedded with ash beds and tuffaceous siltstones are coarse-grained turbidites from adjacent steep slopes and travertine from fissure ridges adjacent to the moat. Sedimentation rates and provenance for clastic sediments are linked to the frequent volcanic activity in and near the caldera; nearly all of the Creede Formation sedimentary rocks are tuffaceous.

Purpose and Conclusions:

The processes occurring within calderas after their formation may affect their thermal state. Structural deformation of larger calderas accompanies resurgence of the underlying magma body, which raises the

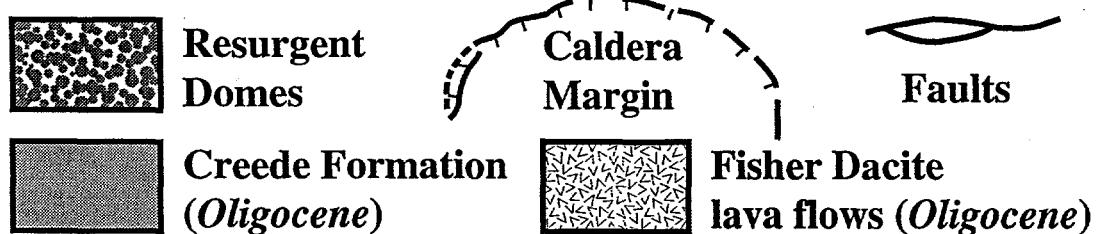
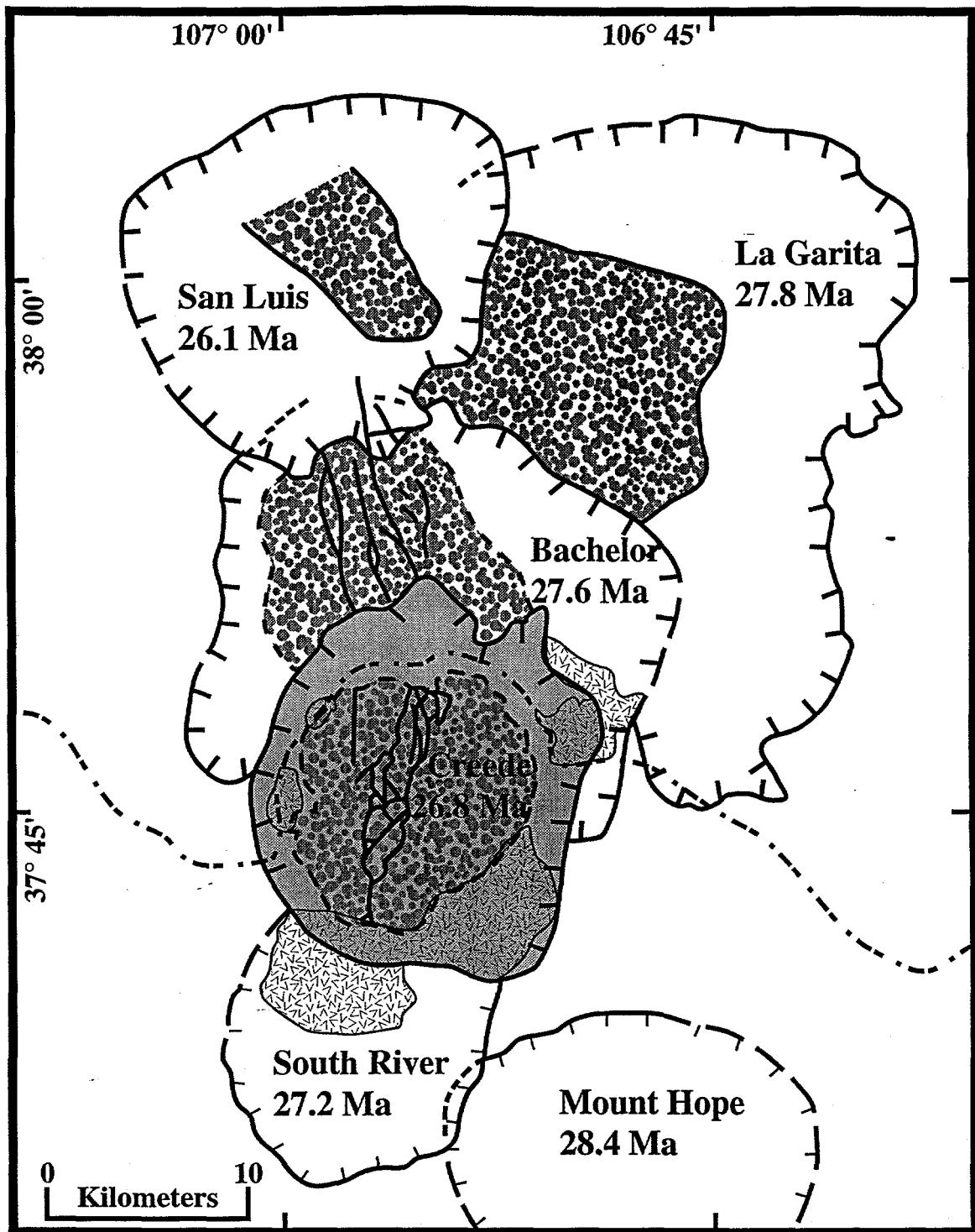
isotherms within and below caldera, and fractures and faults the overlying caldera-fill deposits, enhancing fluid circulation. Postcaldera eruptions of gas-poor lavas and ash provide yet more heat to the system, greatly affect the type of lacustrine sedimentation in the crater, and provide a window to the petrology of the cooling magma body. Within the Creede caldera, Colorado, many of the answers to its postcaldera volcanic and structural history lie within the moat deposits consisting of lacustrine clastic sedimentary rocks and tuffs known as the Creede Formation. The entire Creede sequence has now been penetrated by coreholes Creede 1 and 2 (CCM-1 and CCM-2; Fig. 1).

The purpose of our work, part of the Creede Drilling Program led by Phil Bethke and Jeff Hulen, was to evaluate the history of intracaldera volcanic activity and sedimentation and to determine if the clues concerning post-caldera volcanism and thermal history are preserved in any way in the intracaldera lacustrine moat deposits.

Our conclusions are that structural resurgence was rapid, perhaps occurring within a few thousand years after caldera formation. Deposition of the Creede Formation was limited to a ring "moat" lake. Intracaldera eruptions that produced ashfalls and pyroclastic flows were both hydrovolcanic and magmatic and all of the caldera moat sediments are ashy. There appears to have been little or no hydrothermal activity within the lacustrine sediments or an obvious connection between the caldera lake waters and the magma underlying the Creede caldera. However, there is evidence for circulation of fluids between the lake through the more permeable sandstones and conglomerates of an alluvial fan and delta that extends into the northern caldera moat, into what is now the Creede Mining District in a slightly older caldera complex.

Acknowledgements

This study began as an exercise to gather field evidence to determine the degree of interaction between caldera lakes and underlying magma bodies—to estimate the cooling histories and geothermal resources of large calderas. Creede caldera had excellent exposures of intracaldera lacustrine sedimentary rocks, had been mapped by the US Geological Survey, and



Central San Juan Caldera Complex
(After W.R. Campbell and the Creede Consortium, 1993)

heavily cored by industry. At the time, we had no idea that sediments and tuffs in the middle of the moat would be cored 10 years later.

We are grateful for the superb work by USGS pioneers, including Tom Steven, Jim Ratté, Peter Lipman, Phil Bethke, and their many associates. Without the maps and studies by these magnificent field geologists, we would have never chosen Creede for the study. Much of the third dimension around the moat margins and in the Creede alluvial fan/delta was supplied by cores willingly shared by the Homestake Mining Company, Minerals Exploration and Engineering Company, Pioneer Nuclear, Inc., Utah International, and Coronado Resources, Inc.

Just about the time when we were writing a paper to wrap up the project, Phil Bethke and Pete Lipman began the legwork on a project to drill the Creede Formation. We decided to wait for the third dimension in the moat. Chief Project Scientists Phil Bethke and Jeff Hulen, managers Wayne Campbell and Tom Moses, Tonto Drilling, and all of the well loggers and drillers came through with dazzling results.

Funding for our work came initially from internal research funds at the Los Alamos National Laboratory and, after the drilling of the moat coreholes, from the Engineering and Geosciences Division of the US Department of Energy's Office of Basic Energy Sciences.

Setting and Previous Work

Sedimentary rocks of the Creede Formation were named by Emmons and Larson (1923). Further work on the Creede Formation was done as part of the US Geological Survey project to map the San Juan Mountains volcanic field and its mining districts (e.g., Steven, 1967; Steven and Ratté, 1965, 1973; Steven and Eaton, 1975; Steven and Friedman, 1968; Steven and Lipman, 1973; and Steven and van Loenen, 1971). Bethke and coworkers (e.g., 1976, 1979) conducted comprehensive studies of the geology and geochemistry of ores in the Creede Mining District; their model for ore deposition involves fluids from a Creede caldera lake circulating northward into the Creede District where they recharged a geothermal system driven

by an intrusive body below the district. In the mid-1980's, the Creede Formation was studied to determine if there had been a connection between the moat lake and the underlying Creede magma body or bodies (Heiken and Krier, 1987; Zyvoloski et al., 1987).

Heiken and Krier concluded, based on field stratigraphy, mapping, and samples from industry coreholes, that the Creede Formation: (1) was deposited in a moat around the structural resurgent dome; (2) never completely filled the caldera; (3) includes fanglomerates and travertines deposited along caldera walls, which graded into lacustrine siltstones and tuffs of the moat lake; and (4) was never much thicker than it is now. As was later confirmed by the drilling, they also inferred minimal exchange of lake waters with the magmas under the Creede caldera. Intense hydrothermal circulation of the Creede lake waters was limited to the northern moat area in and below the alluvial fan and delta deposits, whose coarser grain sizes and higher permeabilities were further enhanced by faults and fractures crossing the mining district.

During the winter of 1991 and 1992, two research coreholes were drilled within the Creede caldera moat (Campbell, 1993). Corehole CCM-1 was drilled to a depth of 1371.5 ft (418 m) in the northeastern moat, where there appeared to be little faulting. Corehole CCM-2, located 4.8 km east of CCM-1 where the grabens of Willow Creek (cutting the caldera wall) and Deep Creek (keystone graben across the Creede resurgent dome) intersect the moat, was drilled to a depth of 2323 ft (708 m). The lowest part of the sequence is in Snowshoe Mountain Tuff (caldera-fill), interbedded with mesobreccias from the caldera walls and fine-grained tuffs. This sequence of tuffs, breccias, and ash below the Creede Formation was most likely deposited quickly, with rapid infilling of ash washed from caldera walls—or by the last gasps of the caldera-forming eruption. The Creede Formation, which is 1200 ft thick at CCM-1 and 1600 ft thick at CCM-2, consists of interbedded lacustrine tuffaceous siltstones, tuffs, debris flows, and thin-bedded limestones (Hulen, 1992).

In contrast with the high caldera walls on the southern, eastern, and northern caldera margins, the western margin of the Creede caldera is a topographic low across which the present Río Grande flows. Hogback Mountain, a rotational block that slumped into the caldera, is the last topographic expression of the caldera wall on the west side. The next piece

of preserved caldera wall is about 5 km southeast of Hogback Mountain, near Spar City, where it is buried by Fisher Mountain lavas erupted from vents outside of the caldera. Outcrops of Creede Formation—interbedded tuffaceous siltstones and sandstones, and tuffs—can be found outside of the caldera, as far as 5 km southwest of the projected caldera margin. Our interpretation is that western margin was a topographic low during the time of Creede deposition. This low margin coincides with the intersection of the western caldera margin with the NW-SE-trending, 5-km-wide Clear Creek graben. The graben may have been present before or shortly after the formation of the Creede caldera. If the graben was more or less in its present configuration during the deposition of the Creede Formation, it could have contained a river that flowed into the Creede crater lake, building a delta into that lake. The corehole CCM-2 sampled predominantly interbedded tuffaceous sandstones with carbonate interbeds, supporting a hypothesis that a prograding delta extended into the lake from the west.

DEPOSITS WITHIN THE CREEDE CALDERA

Below the Creede Formation

Snowshoe Mountain Tuff

The Snowshoe Mountain resurgent dome, 13 km in diameter at its present-day base and rising 980 m above the present-day moat floor, is composed entirely of Snowshoe Mountain Tuff and interbedded mesobreccias. The massive Snowshoe Mountain Tuff dacitic (quartz-latitic) ignimbrite is the caldera-forming and -filling tuff unit. Snowshoe Mountain was mapped by Steven and Ratté (1973), who determined that the dome was formed during structural resurgence. Erupted at 26.23 ± 0.05 Ma (Lanphere, this volume), the snowshoe Mountain Tuff is best exposed along the Deep Creek graben, a N-S-trending keystone graben that cuts the resurgent dome. Within Deep Creek, the Tuff is exposed to a depth of 365 m. In CCM-1, the Tuff is encountered at a depth of about 410 m. In the deepest corehole (CCM-2), the top of the Snowshoe Mountain Tuff was reached at a depth of 2140 ft (652 m) and sampled to a depth of 2323 ft. (708 m). The total thickness of the caldera-filling tuff is not known. Caldera-filling ignimbrites elsewhere have thicknesses ranging from a few hundred meters to over 3 km (Lipman, 1984; Hon, 1987).

MESOBRECCIAS AND INTERBEDDED TUFFS AND SEDIMENTARY ROCKS
 (After Hulen et al., 1992)

CCM-1

1202'—Base of Creede Formation

1202'-1242' (38')—Monomict breccia; mostly Willow Creek Member tuff clasts.

1242'-1268' (26')—Interbedded tuffaceous breccia and massive tuffs.

1268'-1370' (102')—Tuffaceous, matrix-supported breccia; mostly Willow Creek Member tuff clasts.

T. D. = 1371'

CCM-2

1606'—Base of Creede Formation

1606'-1638' (32')—Monomict breccia; mostly Willow Creek Member tuff clasts.

1638'-1681' (43')—Tuffaceous polymict breccia, with interbedded conglomerates.

1681'-1796' (61')—Monomict breccia; mostly Willow Creek Member tuff clasts.

1796'-1855' (61')—Interbedded tuffaceous breccia, conglomerate, and tuff.

1855'-1951' (96')—Tuffaceous, polymict breccia, Most clasts are nonwelded Snowshoe Mountain Tuff.

1951'-1979' (24')—Interbedded silty sandstone, tuffs, and conglomerates.

1979'-2000' (21')—Polymict, matrix-supported breccia. Densely-welded ignimbrite clasts.

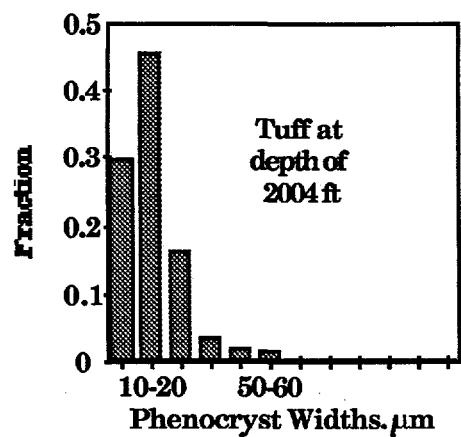
2000'-2037' (37')—Tuffs or interbedded tuffaceous sandstone and siltstone.

2037'-2132' (95')—Tuffaceous, polymict breccia. Most clasts are Campbell Mountain and Wasson Park ignimbrites.

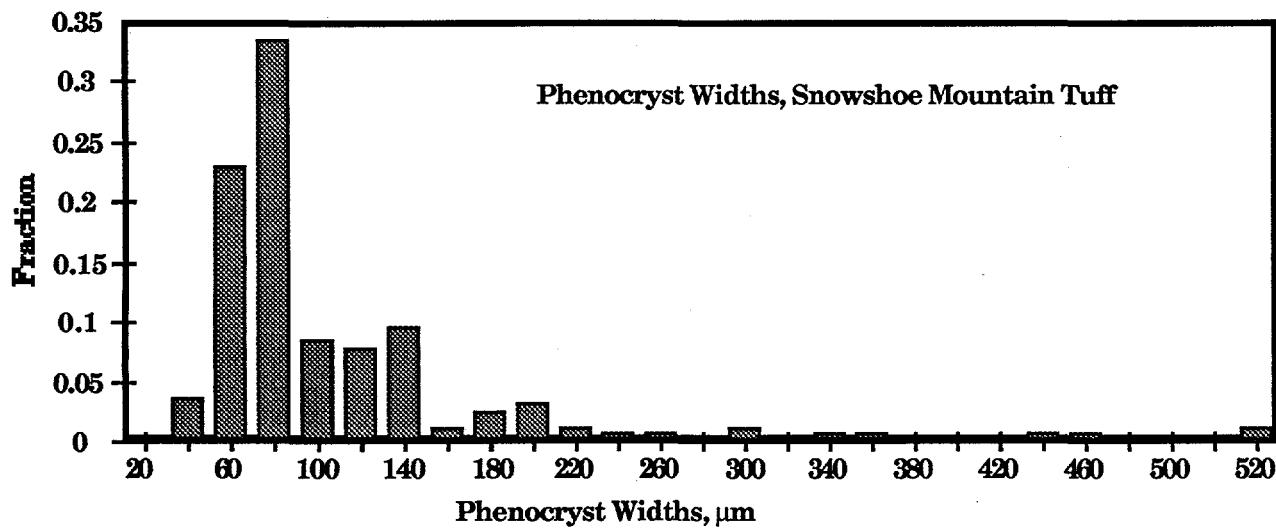
2132'-2323' (191')—Snowshoe Mountain Tuff (caldera-fill tuff).

T. D. = 2323'

Base of mega- and mesobreccias and associated tuffs and sedimentary rocks



Comparison of phenocryst size—Snowshoe Mountain Tuff (caldera fill) and Ash fallout tuff from a depth of 2004 ft (interbedded with mesobreccia)



Samples of Snowshoe Mountain tuff were collected from outcrops along Deep Creek at depths from 365 m to 15 m below the present-day surface of the resurgent dome. The tuffs range from welded crystal tuff at a depth of 365 m to partly-welded crystal tuff at a depth of 15 m. In contrast, in CCM-1, the top of the Snowshoe Mountain Tuff is nonwelded where it was shielded from erosion by the moat lake sediments. In the lithologic log by the Creede Drilling Team (Hulen, 1992), this tuff contains abundant pebble- to cobble-size, angular clasts of older welded tuffs, mostly from the Willow Creek and Mammoth Mountain Members and the Campbell Mountain welding zone of the Carpenter Ridge Tuff, and some intermediate spherulitic lavas or welded tuffs. Below 1355 ft in corehole CCM-1, pumice clasts are well-preserved and make up 20% of the rock; 0.6 to 3 mm long, with little rounding; original vesicularity was about 40% and vesicles are slightly-elongate. Shards consist of 50- to 200- μ m-long, curved vesicle walls. Some vesicular, relict glasses are still attached to feldspar phenocrysts (bubble-wall textures).

The average phenocryst content of the Snowshoe Mountain Tuff is 48 to 50% (the same as in the detailed study by Ratté and Steven, 1967), with plagioclase>>biotite>quartz>K-feldspar>hornblende, clinopyroxene, and Fe-Ti oxides. Biotite grain margins are increasingly altered to hematite with depth (from near the surface to a depth of 365 m (1,198 ft) below the summit of the resurgent dome), but Fe/Fe+Mg ratios stay about the same (0.561 ± 0.013), in spite of the alteration. The matrix in nonwelded zones consists of small relict pumice clasts and shards, most of which have been replaced with authigenic K-feldspar, smectite clays, and zeolites.

Mesobreccias and Interbedded Tuffs

In CCM-2, above the caldera-fill Snowshoe Mountain Tuff and below the base of the Creede Formation, there are 5 monomict and polymict breccia beds (mesobreccias), ranging in thickness from 6 m to 35 m (Fig. 2A). Interbedded with the mesobreccias are sequences of 1- to 10-m-thick tuff beds and tuffaceous siltstone laminae, which appear to be lacustrine.

The mesobreccias are interpreted as the products of collapsed, comminuted, unstable sections of caldera wall. As described by the Creede

Onsite Science Team (Hulen, 1992), the mesobreccias consist of sand- to cobble-sized angular clasts of densely welded ignimbrite in a silicified rock-flour matrix; most of the clasts appear to be from the Willow Creek Member of the Carpenter Ridge Tuff. The Willow Creek Member is the predominant rock type exposed in the caldera walls immediately north of the CCM-2 drill site and should represent most of the clasts in a mesobreccia formed during wall collapse.

Massive, fine-grained tuffs interbedded with the mesobreccias pose a problem as to how they were deposited. Mesobreccias are usually interpreted as having formed when unstable sections of caldera wall collapsed during a climactic, caldera-forming eruption, implying a short time period. If this were the case, how could tuffs have been deposited between avalanches? The other interpretation is that caldera wall collapse was a piecemeal process, occurring over weeks, months, or years after caldera formation, with intermittent intracaldera ash fallout during that time.

CCM-1 may not have penetrated the entire section of mesobreccias and associated rocks, but CCM-2 penetrated a 470-ft-thick section between the base of the Creede Formation and the top of the Snowshoe Mountain Tuff. Tentative correlations appear to be possible between the two wells for mesobreccias and interbedded tuffs in the upper 166 ft. in CCM-1 and the upper 136 ft. in CCM-2 (Fig. 2A).

Between a depth of 2002 ft and 2037 ft in CCM-2 is a massive crystal tuff, consisting of 35% phenocrysts in a matrix of relict shards and pumice clasts ($Md > 100 \mu m$). The shard relicts indicate that the ashfall consisted of mostly finely-communited phenocrysts, and thick-walled, curved platy and stubby vesicle wall junctions. The tuff bed appears to have been a massive fallout with little evidence for reworking; the delicate shards show little or no edge modification. It has been sorted, possibly as a fallout within standing water. Phenocrysts in this tuff are much finer-grained than those of the Snowshoe Mountain caldera-fill ignimbrite (Fig. 2B).

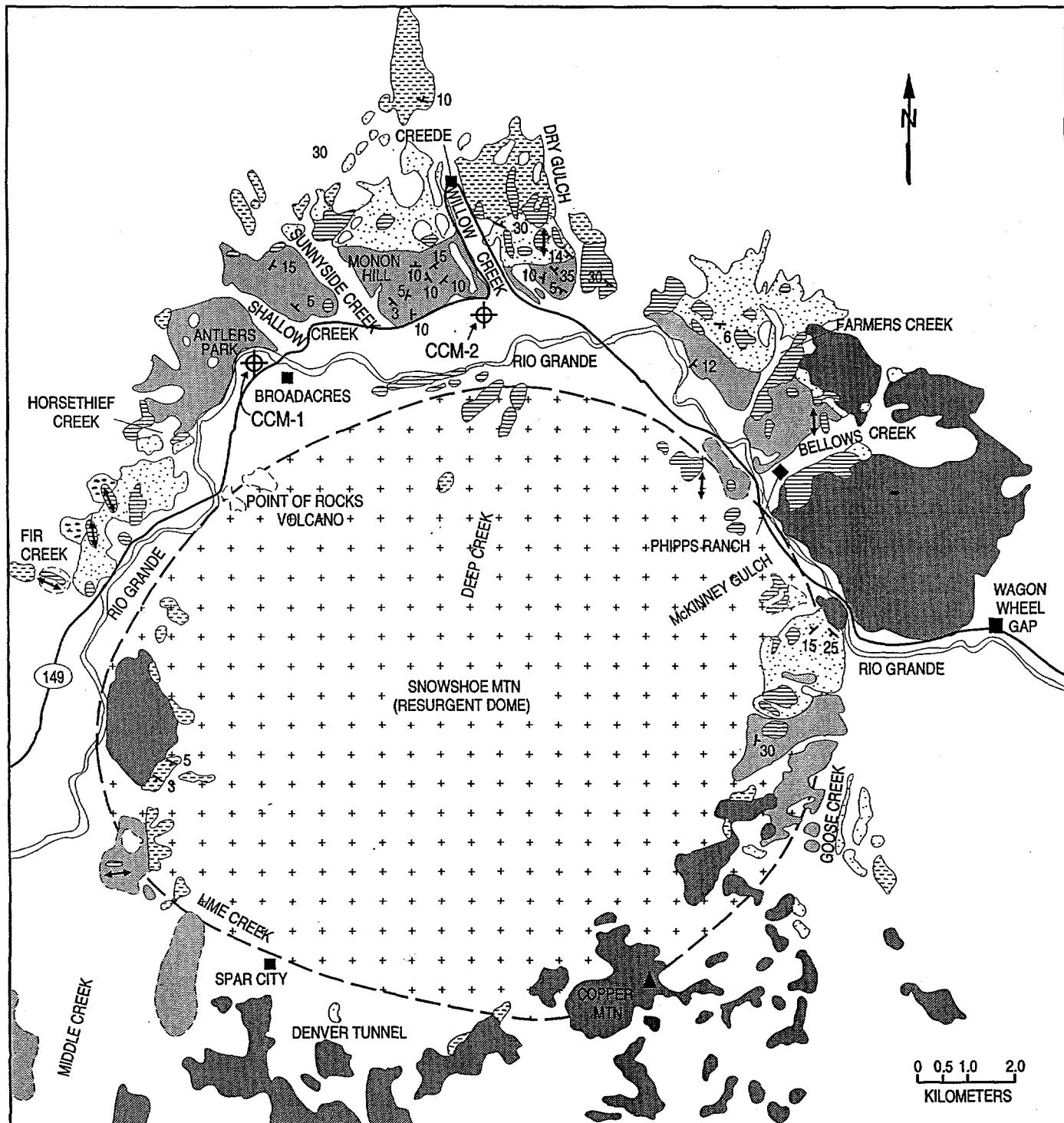
Another fallout tuff (at a depth of 1971 ft in CCM-2) is also a massive crystal tuff (49.6 ± 2.6 % phenocrysts; plagioclase>>biotite>K-feldspar>quartz>orthopyroxene). Most of the relict shards are curved, blocky forms in the size range of 30- to 50 μm . There are 7% lithic clasts, too small for unit identification.

Poorly-bedded, reworked ash beds interbedded with polymict breccias and conglomerates at a depth of 1837 ft in CCM-2, are crystal-vitric tuffs, consisting of $43.2 \pm 6.2\%$ fine-grained, broken phenocrysts (Mean grain size=9.7 μm).

A question about the interbedded tuffs and tuffaceous siltstones is the time required between deposition of mesobreccias. It is possible that the time represented could be as short as a few days, assuming that massive deposits of nonwelded Snowshoe Mountain Tuff slumped or washed back into the crater and a temporary (?) lake. In the recent eruption of Pinatubo Volcano, large volumes of ash and debris were deposited in large depressions in and around the volcano in hours or days (Pinatubo Volcano Observatory Team, 1991).

Sedimentary Rocks in the Creede Formation

The central resurgent dome (Snowshoe Mountain), which rises nearly a km above the structural moat and the caldera walls have controlled the distribution of the facies that make up the Creede Formation. We have also inferred the presence of a graben (Clear Creek graben) that was present before caldera formation or shortly thereafter; Creede Formation crops out well beyond the western caldera margin into this graben. Resurgence was caused by doming of the thick intracaldera ignimbrite facies after eruption of the Snowshoe Mountain tuff. Concurrent with or following structural doming, deposition of fluvial and lacustrine sedimentary rocks of the Creede Formation began within the enclosed moat basin. Landslide debris and fanglomerates from the unstable caldera walls deposited the turbiditic breccias interbedded with finer-grained lacustrine sedimentary rocks. Massive travertine bodies were deposited from mineral springs and are interbedded throughout the moat sequence. In addition to clastic materials brought in by streams and by avalanches, intracaldera eruptions deposited ashfalls and pyroclastic flows. We infer that these eruptions contributed most of the ash to the matrices of Creede Formation clastic rocks, and the abundant ash horizons interbedded with the moat fill (Steven and Ratté, 1965, 1973; Mathewson and Allison, 1981; Heiken and Krier, 1987; Hulen, 1992). The facies map of the Creede Formation (Fig. 3) is based on surface



INTRACALDERA LAVAS

FACES OF CREEDE FORMATION

FANGLOMERATES

INTERBEDDED FANGLOMERATES, TRAVERTINE AND LACUSTRINE ROCKS, AND/OR PYROCLASTIC FLOWS

LACUSTRINE ROCKS WITH INTERCALATED DEBRIS FLOWS AND TRAVERTINE

TRAVERTINE

SNOWSHOE MOUNTAIN TUFF

PRE-CREEDE CALDERA VOLCANIC ROCKS

HINGE LINE OF RESURGENT DOME

↔ ORIENTATION OF TRAVERTINE FISSURE RIDGES

↖ 12 STRIKE AND DIP

DISTRIBUTION OF CREEDE FORMATION OUTCROPS FROM STEVEN, 1967, STEVEN AND LIPMAN, 1973, AND STEVEN AND RATTE, 1973.

exposures, shallow coreholes drilled by mining companies and the two scientific coreholes CCM-1 and CCM-2 .

Alluvial Fan/Deltaic Deposits

The Creede Formation on the slopes of the Snowshoe Mountain resurgent dome consists of coarse-grained fanglomerates that, at the base of the mountain, grade outward into fluvial sandstones and lacustrine siltstones. The best outcrops are located along the western flanks of Snowshoe Mountain, where 10- to 40-m-thick deposits lie on 2° to 15° slopes. The fanglomerates consist of massive, matrix-supported boulder conglomerates, which are interbedded with massive coarse sandstones. Debris flow breccias can be traced off of the dome into lacustrine siltstones and bedded travertines. There was soft-sediment deformation of the underlying lacustrine sediments by these breccias. The boulders and cobbles within these fanglomerates are comprised of nonwelded to poorly-welded Snowshoe Mountain Tuff. The matrices within the boulder and cobble conglomerates are very immature lithic sandstones, which include clasts derived from mostly the Willow Creek Member of the Carpenter Ridge Tuff, and phenocrysts (plagioclase>>biotite>K-feldspar>quartz, Fe-Ti oxides, and hornblende) that appear to have been derived mostly from nonwelded Snowshoe Mountain Tuff.

Creede Formation fanglomerates on the northeastern caldera wall are best exposed in the drainage of Bellows Creek and consist of matrix-supported boulders of Fisher Quartz Latite lavas. These deposits are overlain by interbedded coarse sandstones, pebble conglomerates and massive and banded travertine. Provenance for caldera-wall alluvial fans is that of the older tuffs and lavas exposed in those sectors of the caldera walls (Heiken and Krier, 1987).

The best-characterized alluvial fan/delta plain is that of the Creede Alluvial Fan/delta, originating within the northern caldera wall and what is now the Creede Mining District (Fig. 4). These coarse-grained alluvial deposits fill a partly-resurrected paleocanyon and extend to the moat margin, where they are interbedded with lacustrine rocks (Steven and Ratté, 1965). The fan is about 7 km long and at most, 5 km wide (south of Creede); upper parts of the fan slope southward at 7° to 9°. Near the fan head, sediment thickness is >300 m; immediately above Creede, it is 220 m

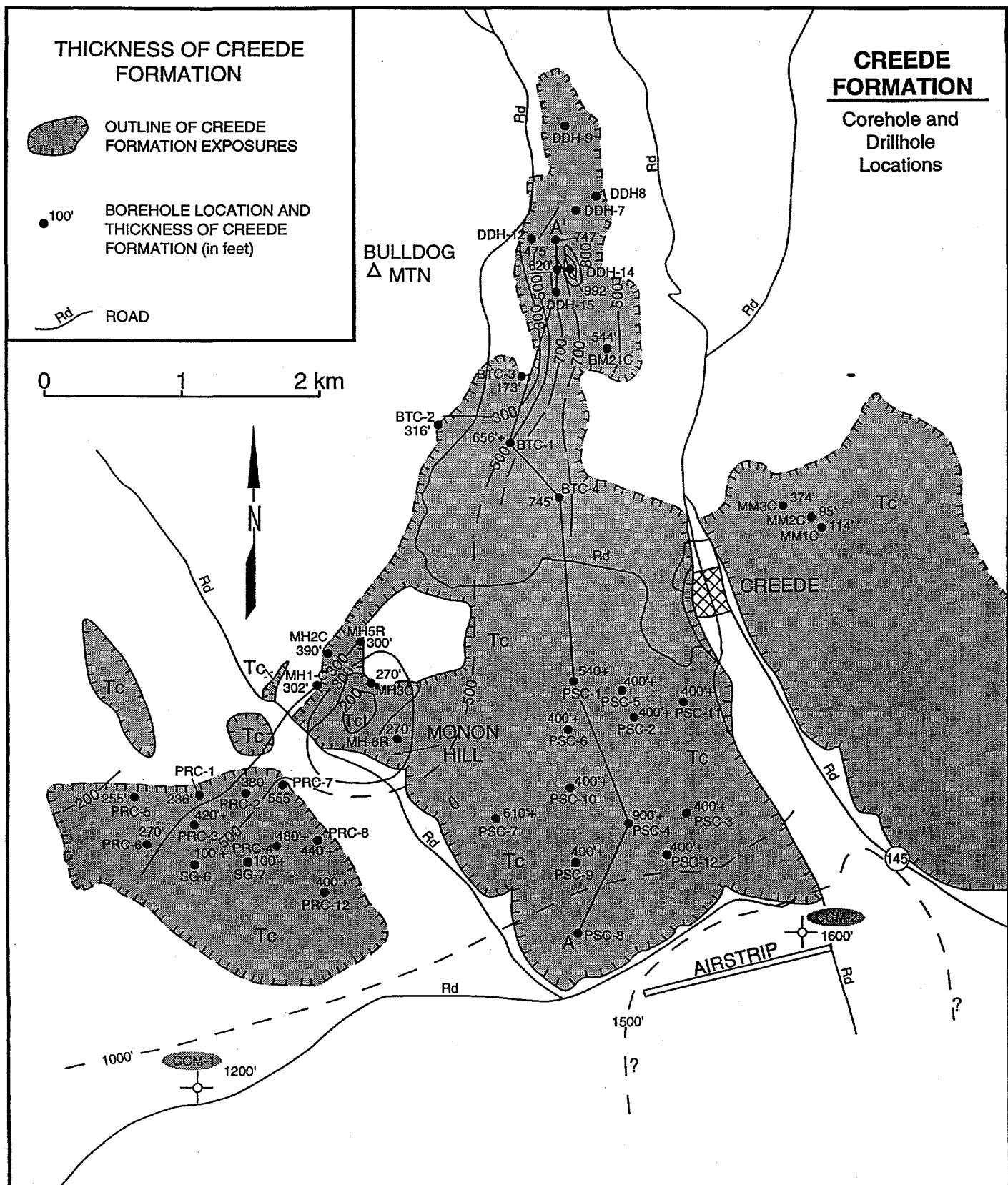
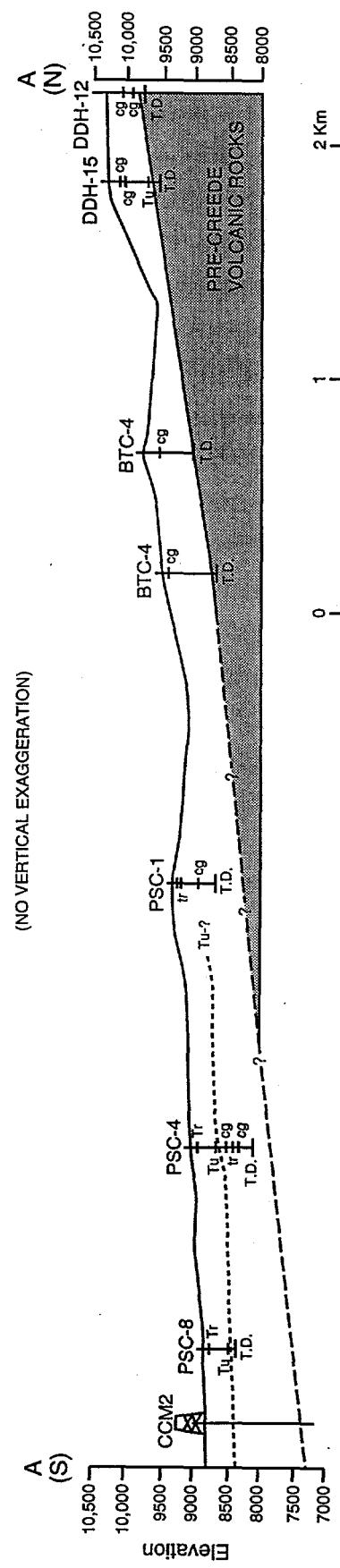


Fig. 4A



thick; on the flanks of the paleocanyon, measured thicknesses range from 35m to 80 m.

The thick, conglomerate-dominated deposit in the Bachelor Mountain area fans out into fluvial distributaries where it reaches the caldera margin and is interbedded with lacustrine siltstones and sandstones; many of the siltstones contain fossil leaves and twigs. Paleocanyon walls above the fan head have slopes of as much as 40° (based on industry corehole data). The conglomerates and coarser sandstones consist mostly of clasts derived from the Willow Creek and Campbell Mountain welding zones of the Bachelor Mountain Member of the Carpenter Ridge Tuff. Fluvial conglomerates near the fan mid-line have a larger variety of clast types. Within the upper half of the fan is the 10- to 25-m-thick Monkeymeyer Sandstone, which consists of interbedded coarse sandstone and pebble conglomerates (Rice, 1984). Volcanic ash is a common component of all sandstones within the Creede alluvial fan. Tuff beds have been described in outcrop and a 22-m-thick tuff has been described in the lower part of the fan/delta deposits (Mathewson and Allison, 1981); this tuff correlates with a similar unit in CCM-2 at a depth of 600 ft.

Much of the Creede Formation penetrated by well CCM-1 consists of tuffaceous sandstone and siltstone, with conglomerate, tuff and carbonate interbeds. The coarser-grained clastic rocks are dominant in the lowest 2/3 of CCM-1 (Fig. 5). The sandstones and sandy siltstones contain abundant convolute bedding and flame structures. The clastic sediments in CCM-1 are coarser-grained than those in CCM-2 and have fewer tuff interbeds. Above the level of the CCM-1 wellhead, in outcrops along the Río Grande, the Creede Formation is broken by low-angle unconformities (3° to 5°, with apparent dips to the east). This sequence could be interpreted as a lacustrine delta (Gilbert, 1885, cited in Fouch and Dean, 1982). Such a delta would have headed in a stream flowing from the west, down the ancestral Clear Creek graben.

Lacustrine Deposits

The best-known rock types of the Creede Formation are the tuffaceous siltstones and interbedded sandstones and tuffs that crop out within the

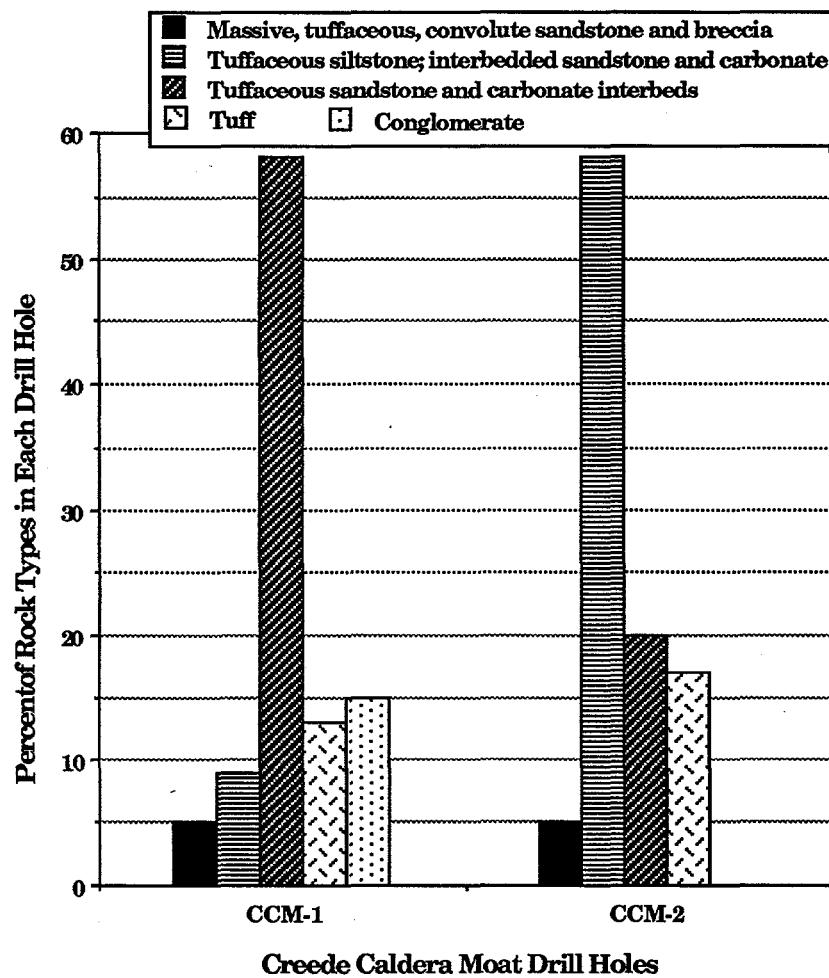


Fig. 5

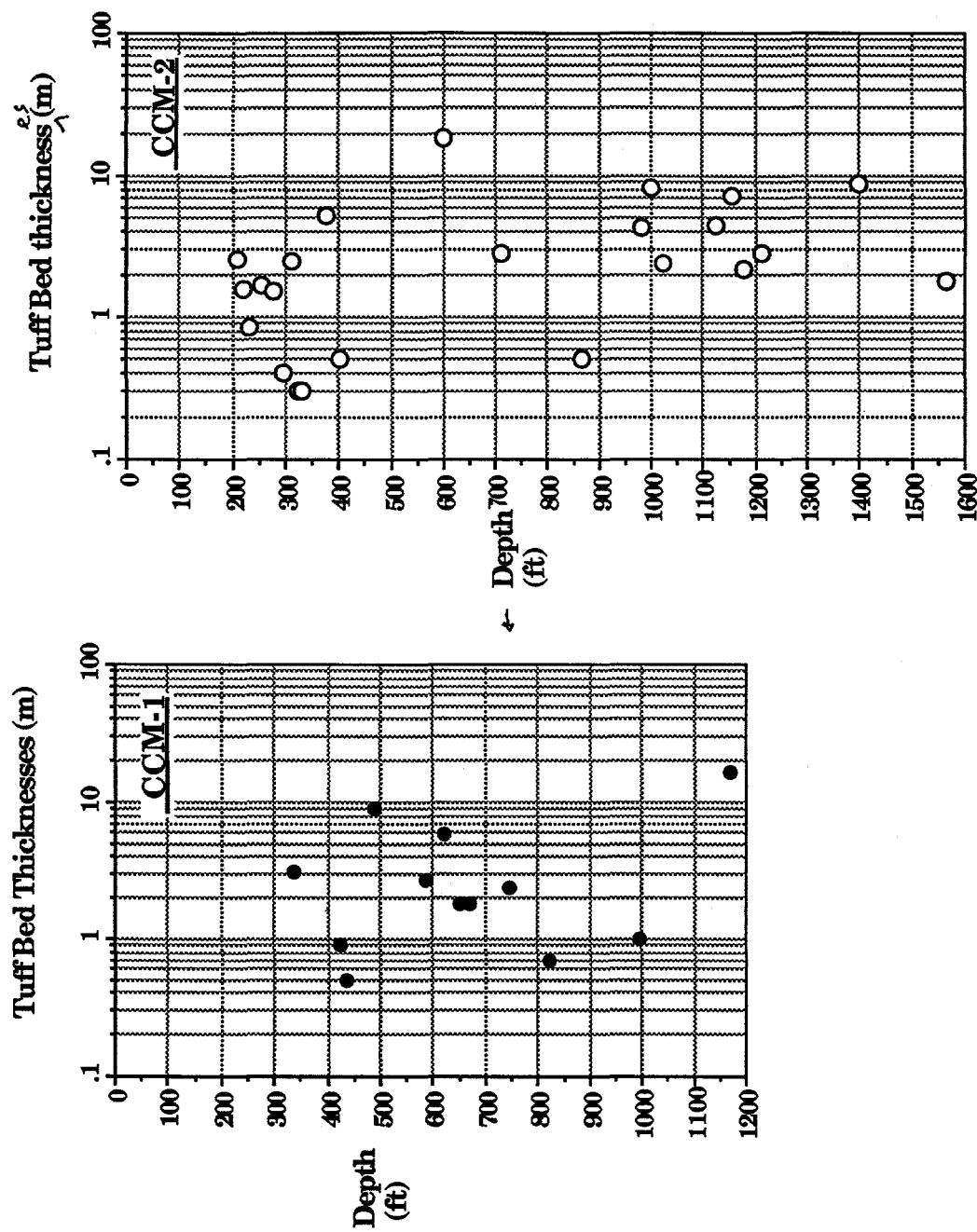
central portions of the moat along the Río Grande and along Lime, Trout, and Goose creeks. Tuffaceous siltstones make up 64% of the Creede Formation in corehole CCM-2. Excellent surface exposures of lacustrine facies can be seen along Highway 149, between Creede and the Creede airport. The rocks are light brown in outcrop, but in drill cores are gray. Interbedded with the siltstones are thin travertine beds, some of which can be traced into travertine fissure ridges located along the moat margins. Interbedded with the finer-grained lacustrine sediments are both massive and graded coarse-grained sandstones; these beds display convolute bedding and flame structures within underlying siltstones and appear to have been deposited as density currents from caldera-wall avalanches or floods. Nearly all of the sandstones, as well as the siltstones, have a tuffaceous component, mostly in the form of relict curved platy, and Y-shaped shards.

The lacustrine rocks of the Creede Formation, including siltstones and what may have been a sublacustrine delta, extend west of the caldera margin for at least 5 km, into the Clear Creek Graben.

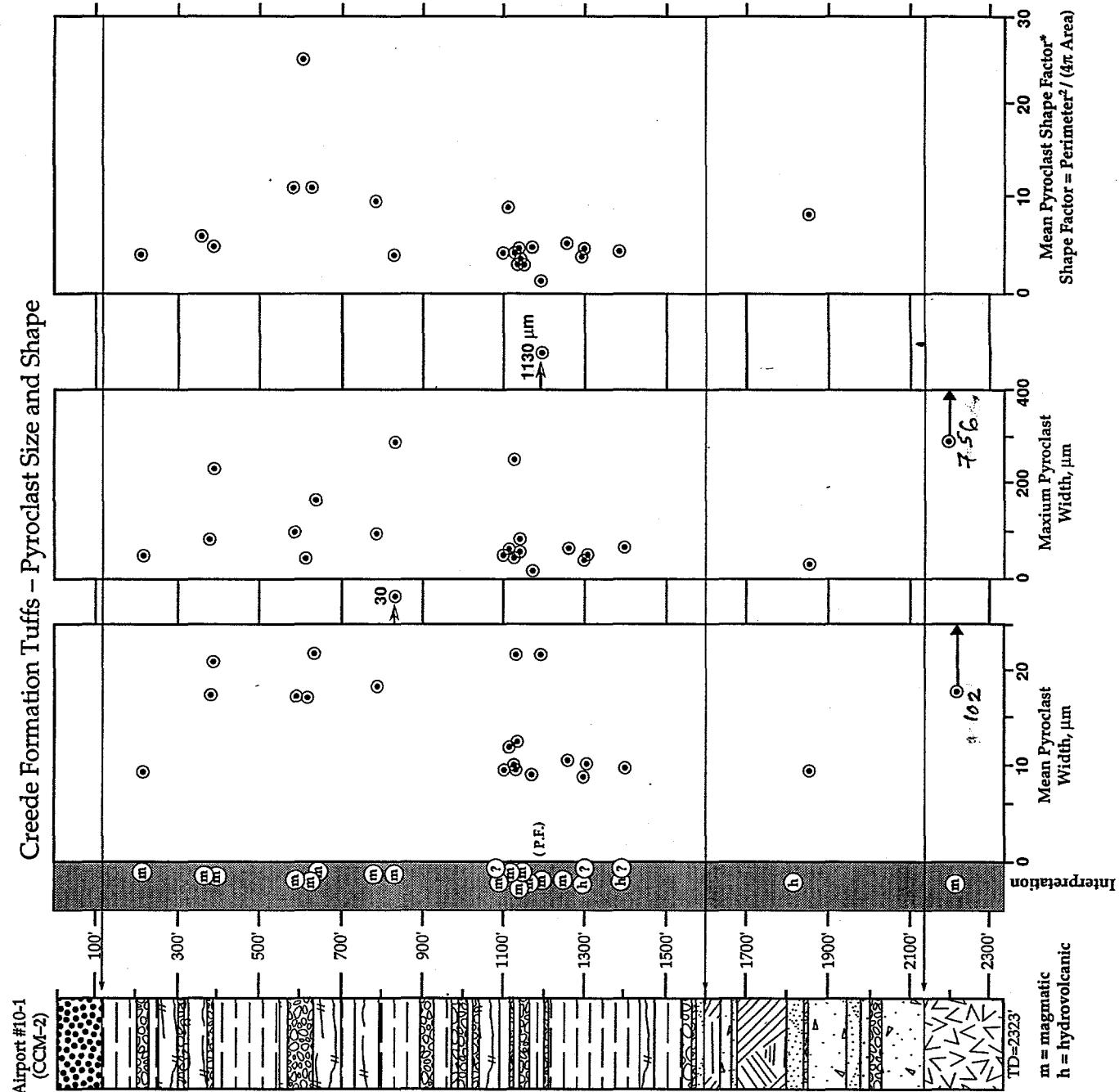
Travertine Deposits

Travertine deposits are interbedded with most clastic facies of the Creede Formation and crop out mainly along the base ("hinge line") of the resurgent dome and along the northern and eastern caldera walls. The deposits range in size from centimeter-thick laminae interbedded with lacustrine siltstones to massive bodies several hundred meters long and tens of meters wide. They were described by Steven and Ratté (1965), who noted that travertine laminae may extend outward from the massive bodies into adjacent sedimentary rocks. Some paleo-spring orifices were reported above the presumed levels of Creede moat lakes. Steven and Friedman (1968) concluded that deposition of the Creede Formation, including the travertines occurred after caldera resurgence. They estimated that water temperatures during deposition of these travertines were about 40° C.

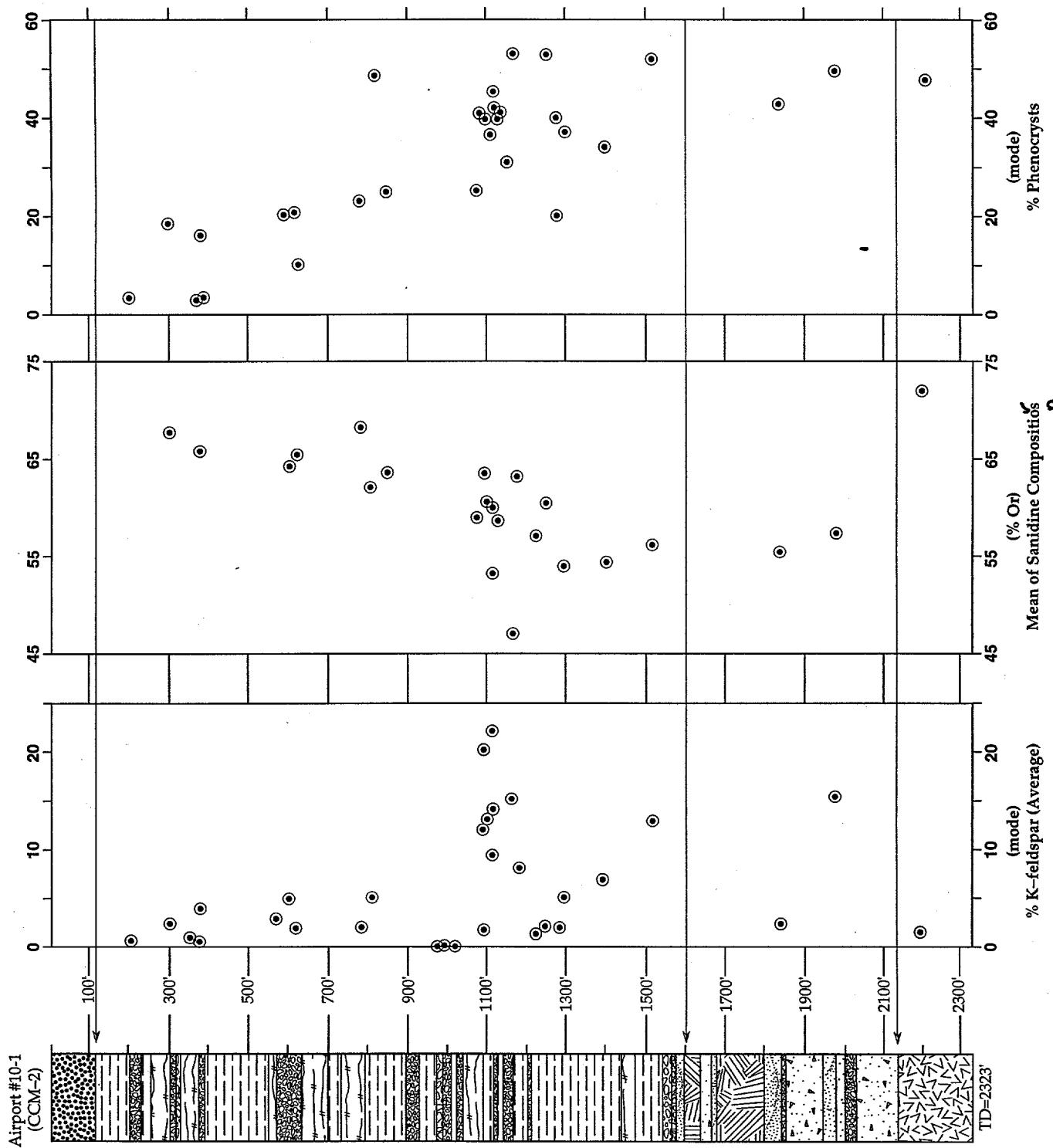
The best-exposed travertine deposits are elongate fissure ridges that occur along spring orifices over joints and faults. The fissure ridges range in size from 5 to 30 m high and up to 1.4 km long and are composed of interbedded massive and banded travertines, which dip steeply away from



(Fig. 6)



F15-7B



the ridge centers. Within adjacent clastic rocks, travertine laminae strike parallel to the long axes of the fissure ridges.

Travertine fissure ridges are found at the base of the resurgent dome and along normal faults that intersect the caldera wall; good examples can be seen at Monon Mine, Bellows Creek, at the mouth of Deep Creek, where the keystone graben of the resurgent dome intersects the moat, and parallel to the moat margin, south of the Río Grande. The ridge travertines consist of 2- to 5-mm-thick bands of sparry calcite, with some hematite stain along band boundaries and massive travertine consisting of irregular patches of sparry calcite in a micritic "groundmass." Fractures in these rocks are filled with chert, sparry calcite and smectitic clays.

Along the 8° slope between the northwestern caldera wall and the moat at Antlers Park there are low, massive travertine mounds, separated by relatively flat areas with intermittent outcrops of interbedded travertine lamellae and siltstone. Heiken and Krier (1987) interpreted these features as having been deposited as a series of travertine terraces overlying colluvium from the caldera wall. The massive facies are remnants of travertine dams, which held small pools where the silt and travertine lamellae were deposited. The slope deposits are similar to those described adjacent to rift lakes by Casanova (1986), who found them to occur both along lake margins or in shallow water.

The full extent of travertines at depth is well-documented near the Monon Mine, at the base of the northern caldera wall, by five industry coreholes (Figure 4A). Near the large fissure ridge above Monon Mine the Creede Formation is 92 m thick (corehole MH5R); the uppermost 30 m consists of interbedded travertine, sandstone, and siltstone. MH 3C was drilled through the top of a fissure ridge, through 36 m of travertine and into 36 m of interbedded shale and siltstone, into pre-Creede Formation tuffs.

Pyroclastic Rocks of the Creede Formation

Volcanic ash is an important component of all clastic (and some carbonate) sediments in the Creede Formation. Within the 1480 ft- (451 m-) thick section of mostly lacustrine siltstones in CCM-2, there are 21 eruption sequences, consisting of mostly fallout beds and several distal pyroclastic

flow deposits. Numerous ashfall beds and an ignimbrite are interbedded with Creede sedimentary rocks in outcrops of the caldera moat deposits (Heiken and Krier, 1987). Each ash fallout sequence begins with a massive, subtly-graded fine-grained ash bed (some begin with a pyroclastic flow deposit), which grades upward into thin, graded, ashy siltstones. Many of the 0.1- to 2 cm-thick ashy siltstone beds are separated by a <1mm-thick carbonate laminae. Interbedded with the tuffaceous siltstones are sandstone units that appear to have been deposited as debris flows.

Sedimentation within the Creede moat was governed by small-scale explosive eruptive activity within the lake (hydrovolcanic) and above lake level (magmatic), which deposited ash in the lake and on caldera walls. Erosion of unconsolidated ash fallout and debris from caldera walls and the headwaters of drainages emptying into the caldera lake provided most of the clastic material of the interbedded lacustrine siltstones and sandstones.

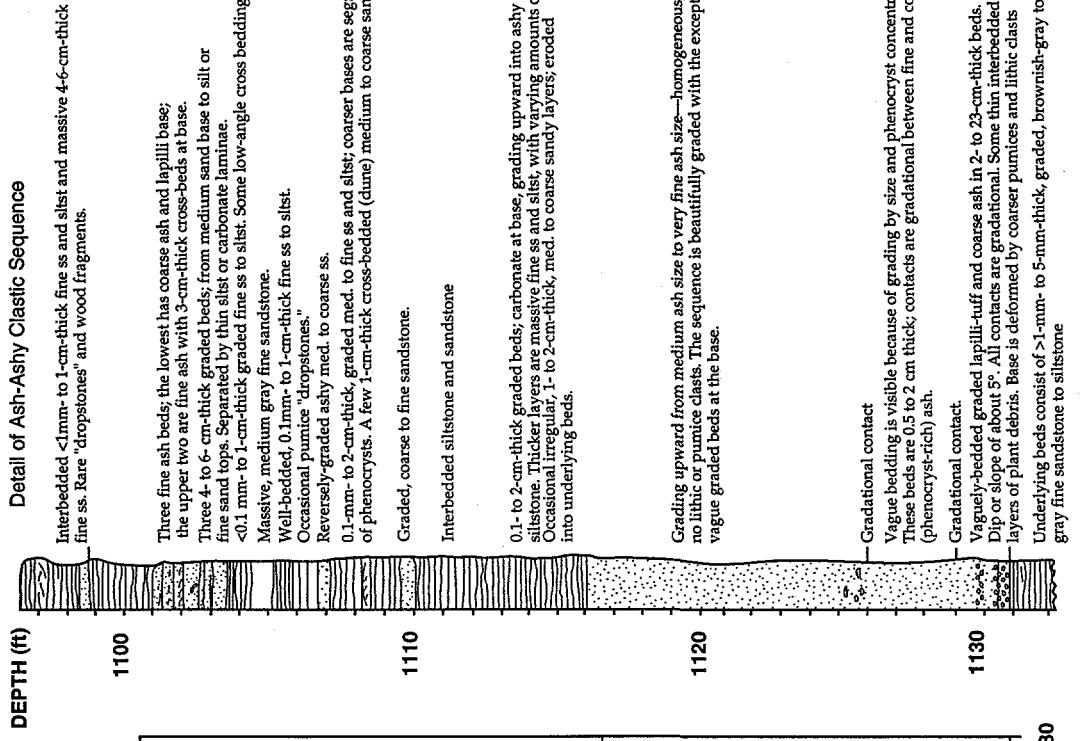
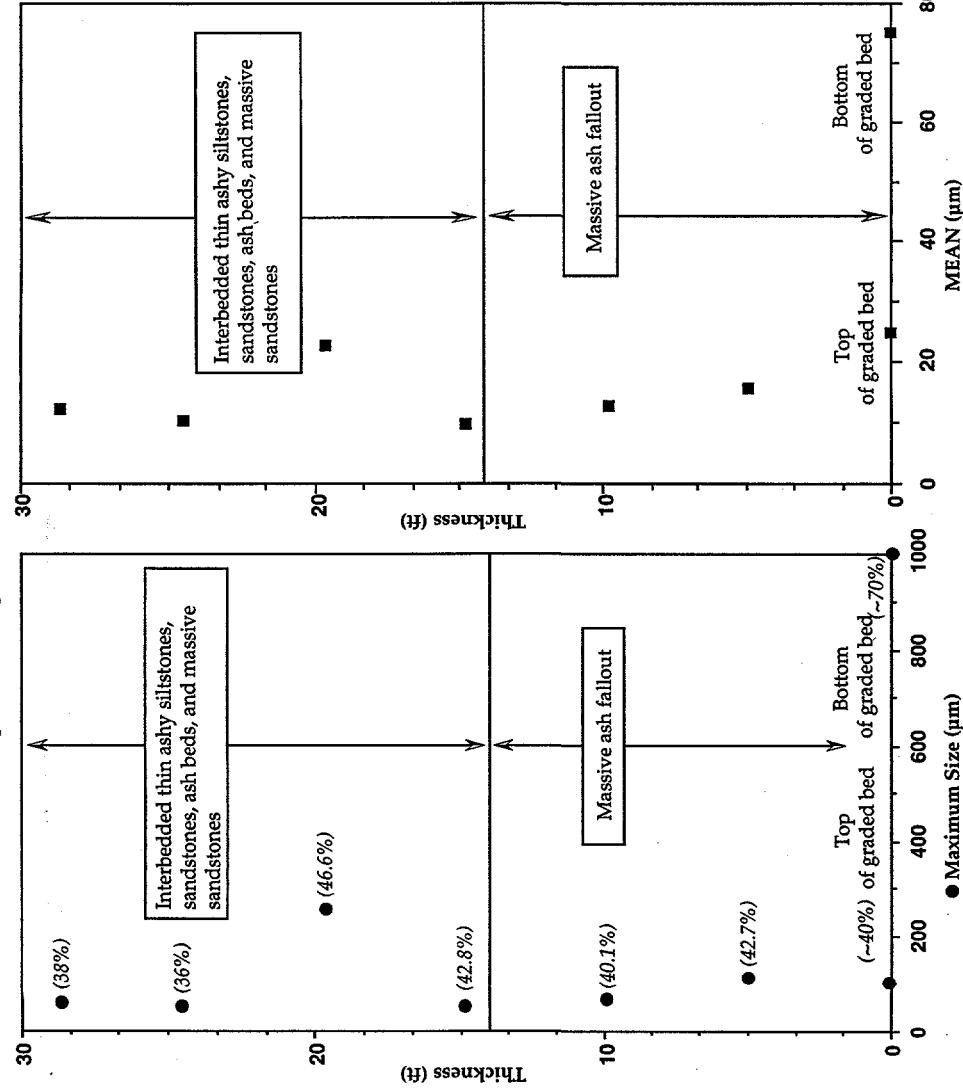
Analytical Techniques

Samples from industry coreholes were collected from storage facilities in the Creede area. Samples collected from coreholes CCM-1 and CCM-2 were from the USGS Core facility, Denver, Colorado. All samples were cut perpendicular to bedding and prepared as polished thin sections. Glass components of the ash deposits and ashy siltstones have nearly all been replaced by illite-smectite, authigenic potassium feldspar, analcime, clinoptilolite, and carbonates. However, relict textures allow thin section study of pyroclast types and size; the phenocrystic and lithic components are little altered.

Backscattered electron (BSE) images of relict textures were collected using a Noran Instruments (formerly Tracor Northern) Automated Digital electron microscope (ADEM), operating at 20 KeV and about 300 picoamperes sample current. The BSE images were used to generate binary images of phenocryst populations and/or relict shard textures. Particle analysis software was used to measure each binary image for area, length, width, shape factor, orientation, and aspect ratio for between 500 and 1000 pyroclasts per sample. Percentage (area) of pyroclasts was also calculated. Although changed slightly in size, the relict pyroclasts provide information on eruption type and grain size. Shard widths were chosen to represent grain size distributions and treated in the same way as grain size measurements determined for sandstones in thin section (Friedman, 1958). Phenocryst compositions were determined with a Cameca Model SX50 electron microprobe. Operating conditions were 15 KeV and 15 nanoamperes beam

(Phenocyst Percentages)

Particle Size variation within a sequence from depths of 1101' to 1132'



current; PAP (Pouchou and Pichoir) matrix corrections were used. A minimum 40 analyses were acquired per sample).

Ash Fallout (CCM-2; the "Airport" Corehole)

Within CCM-2, where the Creede Formation is thickest, there are 21 ashfall sequences, with the undisturbed remains of the ash fallout ranging in thickness from 0.52 m to 18.26 m (Figs. 6 & 7). One of these sequences is described in detail here. In addition to these more obvious sequences are hundreds of ash beds ranging in thickness from a few cm to as much as a meter; most appear to have been reworked and may have been deposited as ash washed into the moat lake rather than as the direct product of ash fallout.

A Typical Creede Formation Ashfall Sequence

Ashfall "sequences" within the Creede Formation consist of subtly-graded massive ash fallout, overlain by ashy siltstones. Detailed sampling from a depth of 1101 to 1132 feet (335.6 to 345 m) in CCM-2 was used to characterize one sequence (Figure 8). This tuff overlies interbedded laminae of graded fine sandstone and siltstone; the surface of the underlying sediment was deformed by pumice clasts of the overlying tuff. The ash sequence begins with 0.6 m of poorly-bedded lapilli-tuff and coarse ash (graded in phenocryst content from 70% at the base to 40% at the top). Overlying the coarse pumiceous beds is a subtly graded, 4-m-thick crystal tuff, grading from medium ash size at the base to very fine ash at the top. Because of the poor preservation of vitric shards, sizing was based on phenocryst fragments, which were similar in size range to the remnant relict shards still visible in the tuff. Mean grain sizes (grain widths) ranged from 75 μm at the base, to 15 to 12 μm through most of the fallout bed. Relict shards consisted of 20- to 100- μm -long curved platy to Y-shaped bubble walls.

Overlying the massive tuff are 0.1- to 2-cm-thick graded ashy siltstone beds, with a few interbedded coarse to fine sandstones; some of the sands exhibit low-angle cross-bedding and contain isolated pumice clasts. The base of each lamina is marked by disseminated, finely-crystalline pyrite. Mean grain sizes remain close to that of the tuffs, but the siltstones are

more poorly sorted (Fig. 8). The percentage of phenocrysts in the ashy siltstones was nearly the same as in the underlying tuff (36% to 43%). The relict shard shapes remain the same as seen in the underlying tuff.

Within the cores and in most beds visible at the surface, all of the glassy pyroclasts have been altered to clays and zeolites. However, the authors found a Creede Formation ash bed on the northeastern flank of Snowshoe Mountain in which the shards are still glassy (Heiken and Krier, 1987). This 2- to 3-m-thick ash has trace amounts of smectite. Another ash bed, located in the Creede Formation above Antlers Park (northern moat) has a glass component with minor clays (Batory, 1981).

The "sequences" are here interpreted as ashfalls into the moat lake, with some basal grading of saturated pumice clasts and coarser phenocrysts. The graded ashy siltstones overlying each tuff represent fine ash washed into the lake from ashfalls that covered the caldera walls and the slopes of the resurgent dome. The time period required to accumulate one of these sequences could not be quantified, but based on modern analogs, could be from weeks to years.

Ash Fallout (CCM-1; the "Hosselkus" Corehole)

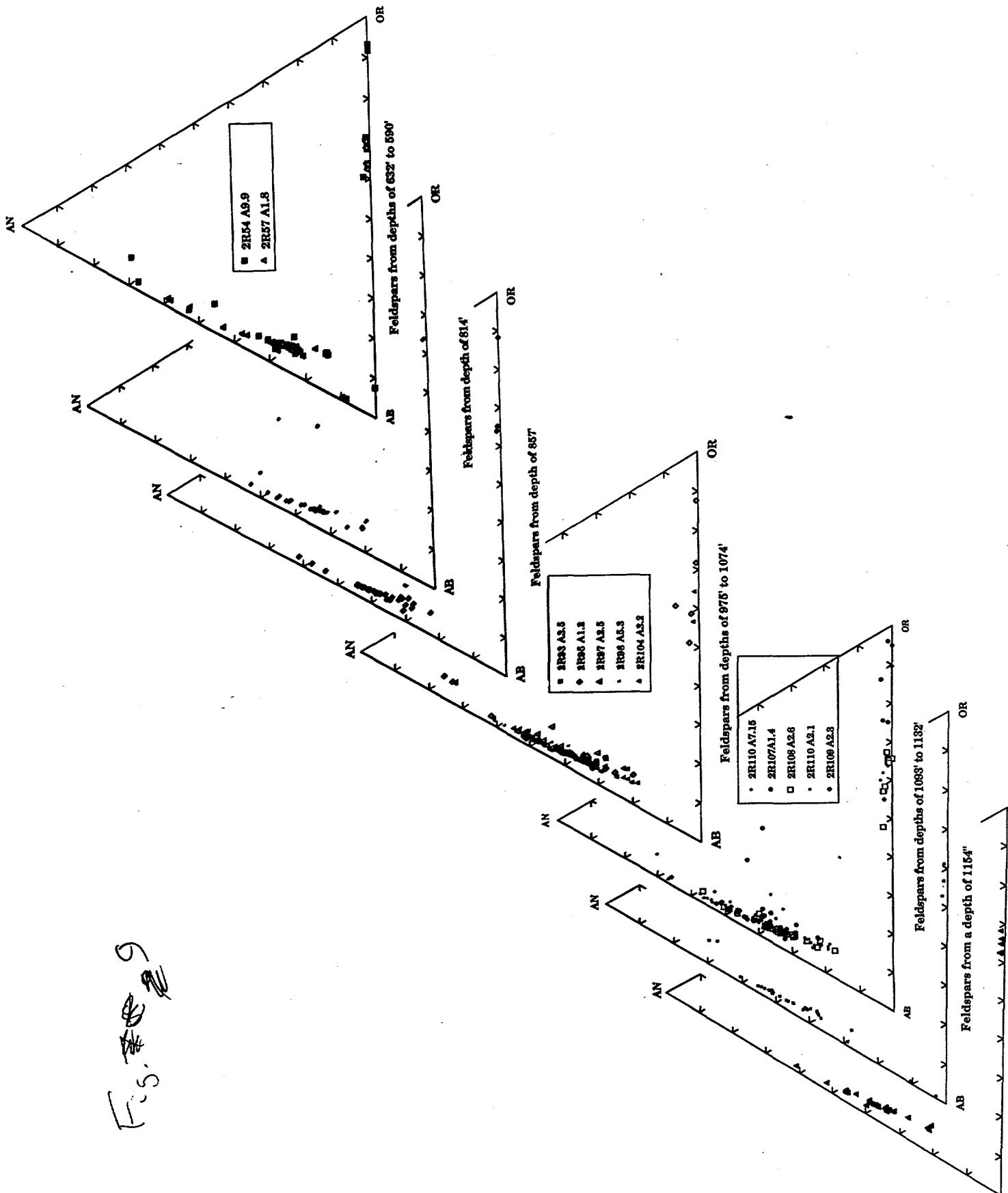
Corehole CCM-1 is within the north-northwestern moat, 4.8 km west of CCM-2. The setting is considerably different in that CCM-1 is located in what appears to be undisturbed moat, whereas CCM-2 is within the intersection of the Willow Creek graben (crossing the caldera wall) and the Clear Creek Graben (keystone graben on the resurgent dome). The Creede Formation within CCM-1 is 1200 ft thick (in CCM-2, the Creede Formation is 1601 ft thick). In CCM-1 the most common rock type is tuffaceous sandstone with carbonate interbeds. Conglomerates make up 15% of the deposits, contrasting with an absence of conglomerates in CCM-2.

There are 13 tuff beds described within CCM-1, ranging in thickness from less than 1 m to 15.5 m (Fig. 6).

Eruptive Activity During Deposition of the Creede Formation

Base of the Creede Formation in CCM-2, at 1601 ft to a depth of 1100 ft

In CCM-2, from the base of the Creede Formation, at a depth of 1601 ft, to a depth of about 1100 ft, the ashes are fine-grained (Mean pyroclast



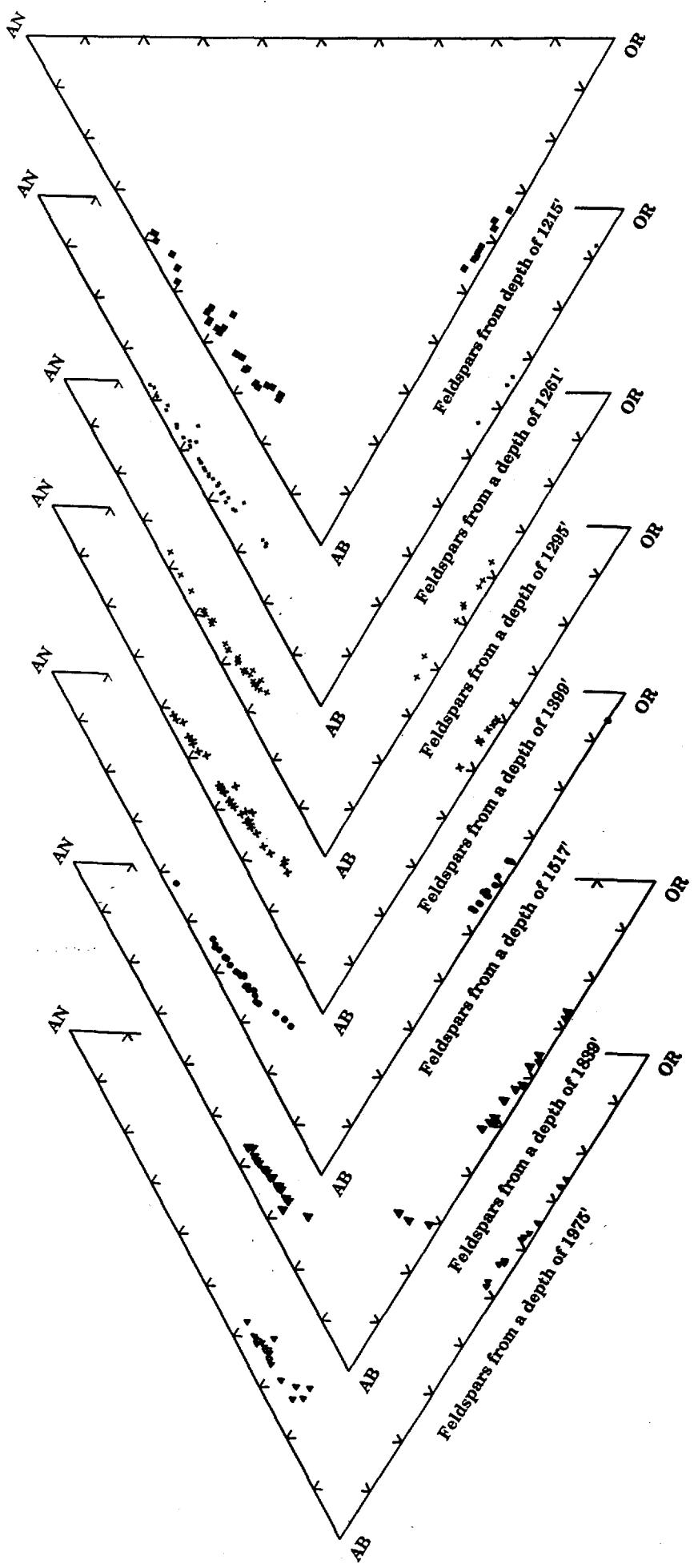


Table 2. Composition of the only fresh glass shards found in Creede Formation tuffs. This sample was from an outcrop of the Creede Formation at the base of the eastern flank of Snowshoe Mountain (McKinney Gulch). The base of the ash bed was not exposed, but is over 3 m thick. Average of 33 shard analyses by microprobe.

	Average (%)	1σ
SiO ₂	73.27	0.37
TiO ₂	0.09	0.01
Al ₂ O ₃	11.98	0.07
FeO	0.77	0.03
CaO	0.52	0.01
Na ₂ O	1.85	0.05
MgO	0.05	0.00
MnO	0.05	0.01
K ₂ O	5.70	0.05
P ₂ O ₅	0.01	0.00
Total	94.93	

widths of 9 to 12 μm) and have low shape factors (1.8 to 5.4). The most common shard types are Y-shaped bubble junctions and curved plates and triangular rod-like fragments. A few tuff beds contain highly-vesicular pumice clasts.

Most of the tuffs from below 1100 ft have 35% to 47% phenocrysts (crystal-vitric tuffs); these are mostly plagioclase, but each contains from 1% to 21% K-feldspar (Fig. 7B and Table 1). Most of the phenocryst assemblages consist of plagioclase>>biotite>K-feldspar, hornblende, quartz, and orthopyroxene. Sanidine compositions range from 47 % to 65% Or, but most are around 55% Or. (Fig. 9 and Table 1)..

Depth of 1100 ft to 121 ft, in CCM-2 and Creede Formation outcrops

Between a depth of 1110 ft and the top of the Creede Formation in CCM-2, at a depth of 121 ft, there is a distinct change in the tuff textures and compositions. Mean pyroclast widths range from 15 to 30 μm , and many have shape factors >10 and as high as 25. Overall, the pyroclasts in the upper 1100 ft are coarser-grained and more complex (grain shape) than the ashes below 1100 ft. Shard shapes are more complex and varied, and include thin- and thick-walled, curved platy forms, thick-walled vesicle junctions (Y-shapes), a few broken hollow spheres, and small pumices.

Above 1100 ft, the percentage of phenocrysts decreases to less than 25%, with some ash beds having as little as 2% (vitric-crystal to vitric tuffs) (Fig. 7B). Generally, phenocrysts consist of plagioclase>K-feldspar>biotite, quartz>hornblende. Sanidine compositions are >67% Or.

Tuffs outcrops that are topographically higher than the CCM wellheads are described by Steven and Ratté (1965), McCrink (1982) and Heiken and Krier (1987). Nearly all of these tuffs have been altered to a mixture of clays and zeolites, but excellent relict textures allow interpretation of eruption phenomena. Nearly all of the exposed tuff beds were vitric tuffs, similar to those sampled in the upper parts of the coreholes. An ash bed outcrop, interbedded with tuffaceous siltstones and sandstones along the moat margin on the eastern slopes of the resurgent dome (McKinney Gulch) consists of fresh rhyolitic glass shards with trace amounts of smectite (Table 2). This is one of two occurrences of fresh glass in any of the ash beds sampled in the Creede Formation.

Tuff Bed Correlations Between Coreholes CCM-1 and CCM-2

The traditional methods of tephra correlation (e.g., Hart et al., 1992) could not be used for correlating Creede Formation tuffs; the presence of only relict shards and pumices precluded the use of glass chemistry. Phenocryst compositions from tuff bed to tuff bed were not unique, disallowing their use for correlation. However, general variations with tuff bed sequences allow a rough correlation to be made between coreholes (Fig. 10). $^{40}\text{Ar}/^{39}\text{Ar}$ ages for tuffs in CCM-1 range from 27.1 ± 0.07 Ma to $26.97 \pm$ Ma, and from 27.1 ± 0.07 Ma to 26.13 ± 0.19 Ma for tuff beds in CCM-2 (Lanphere, this volume).

The base of the Creede Formation at 1201 ft in CCM-1 and at 1600 ft in CCM-2 is the first obvious marker horizon. Above the base in CCM-1 is a 16.4-m-thick, massive crystal tuff, which is similar in texture and mineralogy to a 22.3-m sequence of graded crystal tuff and tuffaceous sandstone beds in CCM-2 (Fig. 10).

From the base of the Creede Formation at 1600 ft in CCM-2, fine-grained (mostly $<10\mu\text{m}$ mean grain size), crystal to crystal-vitric tuffs dominate the section up to a depth of about 800 ft. A similar collection of fine-grained crystal to crystal-vitric tuff beds is present in CCM-1 from the base of the section up to a depth of 670 ft.

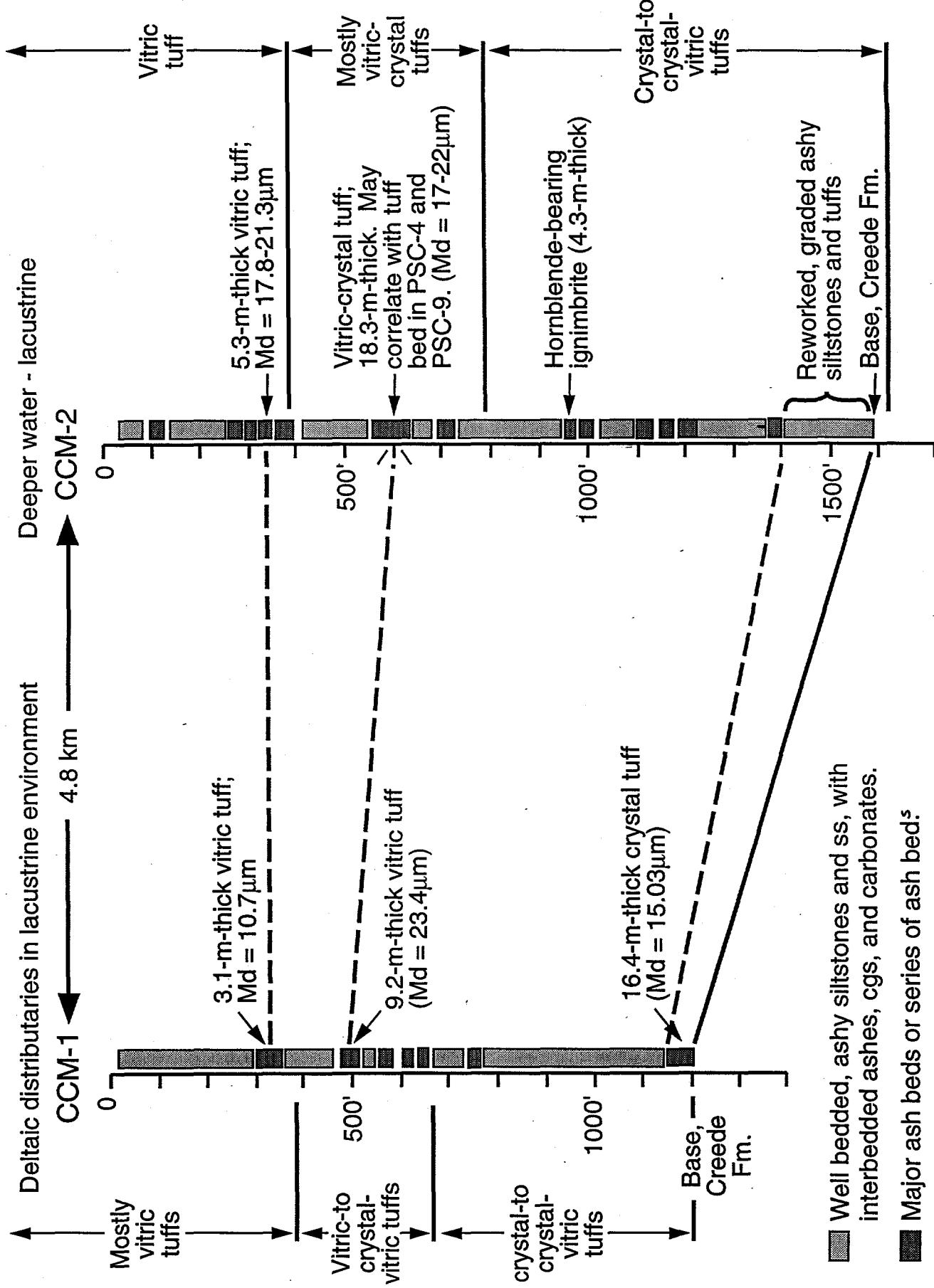
Coarser-grained ($\sim 30 \mu\text{m}$ mean grain size) vitric-crystal tuffs in CCM-2 comprise tuff beds from depths of ~ 800 ft to ~ 400 ft. An 18.3-m-thick vitric crystal tuff at a depth of ~ 600 feet is at the same level as a thick tuff bed described in auger holes (PSC-4 and PSC-8) in the Creede fan-delta by Mathewson and Allison (1981); it also may be correlative with a graded, 9.2-m-thick, vitric to crystal-vitric tuff at a depth of 490 ft in CCM-1.

Above 379 ft in CCM-2 and in nearby outcrops, the tuffs are vitric (interpreted from the relict shard textures). In CCM-1, most, but not all of the tuff beds above a depth of 400 ft are also vitric tuffs. Of special interest is a 5.3-m-thick vitric tuff at a depth of 379 ft in CCM-2 ($^{40}\text{Ar}/^{39}\text{Ar}$ age of 27.1 ± 0.07 Ma; Lanphere, 1993), which is most similar to a 3.1-m-thick tuff bed at a depth of 335 ft in CCM-1 ($^{40}\text{Ar}/^{39}\text{Ar}$ age of 26.97 ± 0.1 Ma; Lanphere, 1995).

Ignimbrites within the Creede Formation

Cropping out along Goose Creek, in the eastern caldera moat is a 15- to 20-m-thick, gray, massive hornblende-biotite tuff, a nonwelded to partly-

Approximate Correlation of tuff beds and tuff sequences



- Well bedded, ashly siltstones and ss, with interbedded ashes, cgs, and carbonates.
- Major ash beds or series of ash bed(s).

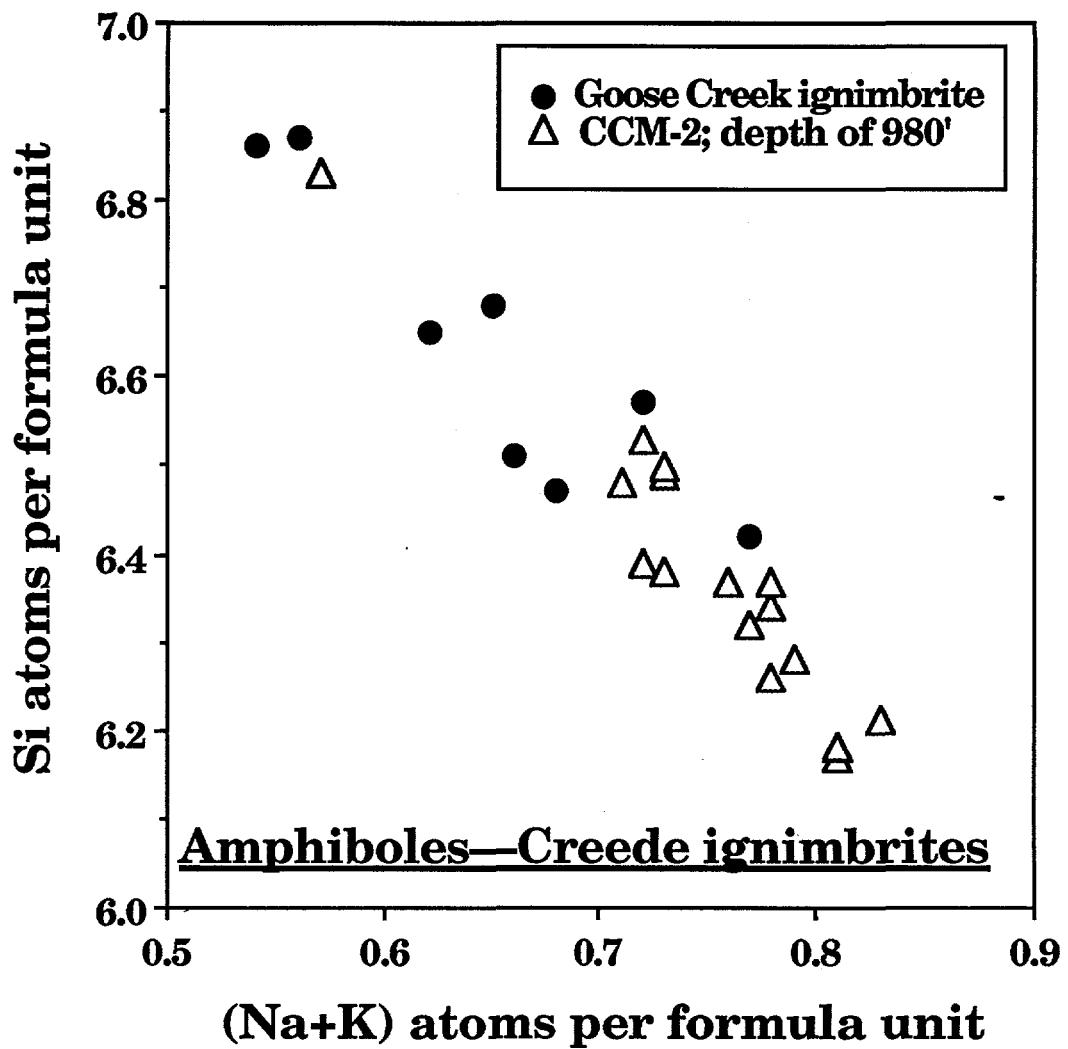


Fig. 5a & 11

welded ignimbrite. Phenocryst content is as high as 52%, with plagioclase>K-feldspar, hornblende>biotite>quartz.

A 4.3-m-thick, massive hornblende vitric-crystal tuff in CCM-2, at a depth of 980 ft, has been interpreted as a sublacustrine pyroclastic flow (Hulen, 1992). Phenocryst content is 24%, with Plagioclase>> hornblende> biotite> K-feldspar. This massive tuff is much coarser-grained than any of the fallout units within CCM-2 and contains relict pumices up to 2 mm long.

A working hypothesis was that the Goose Creek ignimbrite and the 980-ft-deep ignimbrite in CCM-2 were correlative. Modal analyses and hornblende compositions (Fig. 11) prove otherwise and the tuffs are not correlative. The Goose Creek ignimbrite may have originated at a source in or near the southern Creede moat, perhaps in the Copper Mountain area. The source for the sublacustrine ignimbrite could not be determined.

Discussion

The setting for deposition of the Creede Formation involved rapid structural resurgence of Snowshoe Mountain, perhaps achieving maximum relief in a few thousand years. Iwo Jima, a shallow submarine caldera of similar size, located south of Japan, is actively resurging structurally at a rate of 20 to 50 cm/year (Kaizuka et al., 1989); at this rate, the Creede resurgent dome could have been formed in 5000 years. The depositional basin for the Creede Formation was an annular moat, 4 km wide, located between the resurgent dome and caldera walls. The caldera walls and resurgent dome are partly buried by fanglomerates, which grade down and out into the fluvial and lacustrine sedimentary rocks of the moat. Travertine deposition was active along faults crossing the caldera walls and along the base of the resurgent dome.

Explosive Volcanic Activity during Deposition of the Creede Formation

Phenocryst-rich ash deposits in the lower halves of coreholes CCM-1 and CCM-2 appear to be mostly of mixed magmatic and hydrovolcanic origins, with mineralogies similar to those of the Carpenter Ridge Tuffs and Fisher rhyodacitic (quartz latite) lavas. Much of this activity is inferred to have taken place within the caldera lake. These may have been erupted from intracaldera sources, some of which may still be buried by moat

sediments and tuffs; $^{40}\text{Ar}/^{39}\text{Ar}$ ages of these tuffs overlap those of intracaldera Fisher rhyodacitic lavas. Similar fine-grained ashes have been described for intracaldera eruptions within a crater lake that occupied the Toledo Caldera of New Mexico (Heiken et al., 1986).

Within the upper half of the coreholes, vitric-crystal and vitric tuffs range from nearly aphyric to those containing 25% phenocrysts. Curved, platy shards, 100- 500 μm long, appear to be mostly of magmatic (not hydrovolcanic) origin, from a highly inflated, vesicular melts. The sources may have been intracaldera if vents were above lake level, or from sources located outside the Creede caldera.

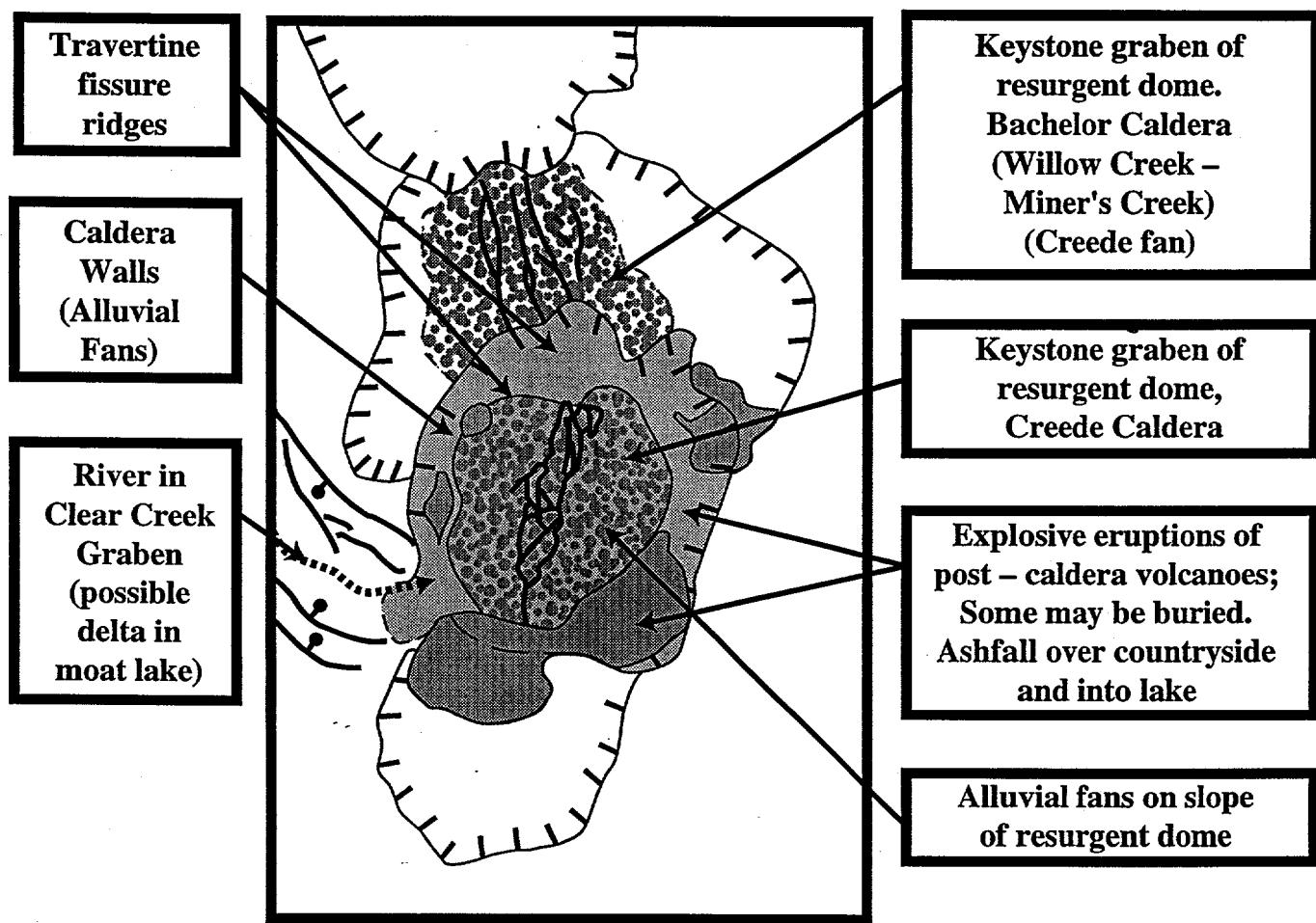
Several, massive, phenocryst-rich, pumice lapilli-bearing tuffs within the moat sediments are interpreted as sublacustrine pyroclastic flows. The sources for these ignimbrites are not known, but also may have been from intracaldera sources.

The Effect of Numerous Ashfall Beds on Moat Sedimentation

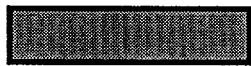
Tuff beds comprise 13% to 18% of the mid-moat Creede Formation (Fig. 5). Sedimentary rocks interbedded with the tuffs, ranging from pumice-bearing conglomerates to siltstones are all tuffaceous. The ash components (determined through the study of relict textures) range from traces to as much as 40%. Post-caldera explosive eruptive activity, from sources within and outside (?) the caldera draped the region with ashfalls and perhaps some pyroclastic flows or surges. We have not attempted to reconstruct the San Juan Volcanic field at the time of Creede moat deposition, but there appears to have been considerable relief within this region, broken by many overlapping calderas. Reconstructed drainages into the moat lake include Willow Creek (the Creede alluvial fan/delta), a stream along the Deep Creek graben (keystone graben across the resurgent dome) and a river entering along the ancestral Clear Creek graben from the west. Smaller creeks would have drained areas on caldera walls.

Depositional rates were most likely high. The thicker ash beds within the lacustrine facies of the Creede Formation consist of graded to massive tuff beds (depending on the variation in grain size of the material erupted), which are overlain by thin, graded, ash-rich siltstones. These eruption/sedimentary sequences are interpreted as massive fallout into the lake, followed by years (?) of ash being washed off of the surrounding hills

Sediment Sources, Creede Formation



Structurally Resurgent Domes



Post - Creede Caldera lava flows



Faults



Creede Formation



Caldera Wall (Topographic)

(Base map – After Creede Consortium, 1993)

Fig. 12

and settling into the lake. Ash fallout would have affected erosion rates in the region and provided a steady supply of fine-grained ash and coarser-grained clastic material entering the lake. This was certainly the case for the recent eruption of Mt. Pinatubo in the Philippines (Pinatubo Volcano Observatory Team, 1991).

The *maximum* duration of Creede Formation sedimentation was 660,000 years (Lanphere, this volume), as established by ages determined for the caldera-forming Snowshoe Mountain Tuff (26.89 ± 0.05 Ma) and the overlying Fisher Dacite lavas (26.23 ± 0.05 Ma). The maximum thickness of the Creede Formation sampled during this project is about 500 m; thus giving an average rate of deposition of 0.08 cm/year. This is considerably lower than depositional rates for Crater Lake, Oregon (1 cm/year; Nelson et al., 1986) and Laguna de Ayarza, Guatemala (3.4 cm/year; Poppe et al., 1985). Determination of an "average rate of sedimentation" is most likely a specious exercise, for sedimentation was most likely very high, as ashfall deposits were eroded from the surrounding countryside after an eruption, followed by quiet periods with very low sedimentation rates.

Outcrops of the Creede Formation extend well to the west of the caldera, into the Clear Creek graben. The graben appears to have been present before or shortly after formation of the Creede caldera. If so, then a stream flowing down the Clear Creek graben drained into the moat lake. Clastic sediments in the lower part of the CCM-1 sequence are definitely coarser-grained overall than in CCM-2 and may be the remnants of a prograding, sublacustrine delta (Fig. 12). The provenance of coarser-grained sandstones interpreted as having been deposited as density currents are the nearby caldera walls (Heiken and Krier, 1987); multiple sources from the caldera walls and the resurgent dome supplied clastic material in small streams and debris flows (Fig. 12).

All sedimentary facies have an ashy component (most are dominated by it), reflecting the stripping of ash beds from the terrain surrounding the Creede moat lake. It is clear that sedimentation was indirectly controlled by post-caldera explosive volcanic activity with fine-grained ash fallouts from hydrovolcanic eruptions in and near the lake and magmatic activity above lake level or from sources outside the Creede caldera.

References

Batory, B. L., Analysis of the lacustrine sediments of the Creede Formation, Mineral County, Colorado. M.Sc. Thesis, New Mexico Inst. Min. and Tech., Socorro, New Mexico, 120 pp, 1981.

Bethke, P. M., Barton, P. B. Jr., Lanphere, M. A., and Steven, T. A., Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: Part II. Age of mineralization. *Econ. Geol.*, 71, 1006-1011, 1976.

Bethke, P. M. and Rye, R. O., Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: Part IV: Source of fluids from oxygen, hydrogen, and carbon isotope studies. *Econ. Geol.*, 74, 1832-1851, 1979.

Campbell, W. R., Research drilling into the "fluid reservoir" of the Creede epithermal vein system, San Juan Mountains, Colorado—A preliminary report. *Soc. Econ. Geol. Newsletter*, 13, 1 and 12-16, 1993.

Casanova, J., East African Rift stromatolites. In: Frostick, L. E., Renaut, R. W., Reid, I., and Tiercelen, J. J. (eds). *Sedimentation in the African Rifts*. *Geol. Soc. Spec. Pub.*, 25, 201-210, 1986.

Emmons, W. H. and Larsen, E. S., Jr., Geology and ore deposits of the Creede district, Colorado. *U. S. Geol. Surv. Bull.*, 718, 198 pp, 1923.

Fouch, T. D. and Dean, W. E., Lacustrine and associated clastic depositional environments. In: Scholle, P. A. and Spearing, D. (eds), *Sandstone Depositional Environments*. *Amer. Assoc. Petrol. Geol. Mem.*, 31, 87-114, 1982.

Friedman, G. M., Determination of sieve-size distribution from thin section data for sedimentary petrological studies. *Jour. Geol.*, 66, 394-416, 1958.

Heiken, G. and Krier, D., Moat Deposits of the Creede caldera, Colorado. Los Alamos National Lab. Rpt., LA-10943-MS, 48 pp, 1987.

Hon, K., Geologic, alteration, and vein maps of the Redcloud Peak (Lake City caldera) and Handies Peak Wilderness study areas, Hinsdale County, Colorado. *U. S. Geol. Surv. Map*, MF-1949, 1987.

Hulen, J. B., Field geologic log summaries for coreholes CCM-2 (Airport 1-6) and CCM-1 (Hosselkus 1-10), Creede Scientific Drilling Project Rpt. ESL-920111-TR, 38 pp, 1992.

Kaizuka, S., Newhall, C., Oyagi, N., and Yagi, H., Remarkable unrest at Iwo-Jima caldera, Volcano Islands, Japan. (abs) New Mexico Bur. Mines Min. Res., Bull., 131, 146, 1989.

Lanphere, M. A. Duration of sedimentation of the Creede caldera. (this volume), 1975.

Lipman, P. W., The roots of ash flow calderas in western North America: Window into the tops of granitic batholiths. Jour. Geophys. Res., 89, 8801-8841, 1984.

Mathewson, D. E. and Allison, A. E., Final report—Creede West Project, Mineral County, Colorado. Utah International Inc. Rpt., 13 pp. plus maps, 1981.

McCrink, M. P., Diagenesis in the Creede Formation, San Juan Mountains, Creede, Colorado. M. Sc. Thesis, New Mexico Inst. Min. and Tech., Socorro, New Mexico, 113 pp, 1982.

Nelson, C. H., Meyer, A. W., Thor, D. and Larsen, M., Crater Lake Oregon: A restricted basin with base-of-slope aprons of non-channelized turbidites. Geology, 14, 238-241, 1986.

Pinatubo Volcano Observatory Team, Lessons from a major eruption: Mt. Pinatubo, Philippines, Eos, Trans. Amer. Geophys. Union, 72, 545, 552-553, and 555, 1991.

Poppe, L. J., Paull, C. K., Newhall, C. G., Bradbury, J. P. and Ziegos, J., A geophysical and geological study of Laguna de Ayarza, a Guatemalan caldera lake. Jour. Volc. Geotherm. Res., 25, 125-144, 1985.

Steven, T. A., Geologic map of the Bristol Head Quadrangle, Mineral and Hinsdale Counties, Colorado. U. S. Geol. Surv. Map, GQ-631, 1967.

Steven, T. A. and Eaton, G. P., Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: I. Geologic, hydrologic, and geophysical setting. Econ. Geol., 70, 1023-1037, 1975.

Steven, T. A. and Friedman, I., The source of travertine in the Creede Formation, San Juan Mountains, Colorado. U. S. Geol. Surv. Prof. Paper, 600-B, B29-B36, 1968.

Steven, T. A. and Lipman, P. W., Geologic map of the Spar City quadrangle, Mineral County, Colorado. U. S. Geol. Surv. Map, GQ-1052, 1973.

Steven, T. A. and Ratté, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado. U. S. Geol. Surv. Prof. Paper, 487, 90 pp, 1965.

Steven, T. A. and Ratté, Geologic map of the Creede quadrangle, Mineral and Saguache Counties, Colorado. U. S. Geol. Surv. Map GQ-1053, 1973.

Steven, T. A. and Van Loenen, R. E., Clinoptilolite-bearing tuff beds in the Creede Formation, San Juan Mountains, Colorado. U. S. Geol. Surv. Prof. Paper, 750-C, 98-103, 1971.

Zyvoloski, G., The effect of structural resurgence on the thermal evolution of the Creede caldera. Geol. Soc. Amer. Abs. with Prog. 19, no. 5, 1987.

Figure Captions

1. Location of the Creede Caldera in the Central San Juan caldera complex. After Campbell, 1993.

2A. Mesobreccias and interbedded tuffs and sedimentary rocks penetrated by coreholes CCM-1 and CCM-2 in the Creede caldera moat. These deposits overlie the Snowshoe Mountain Tuff (Creede caldera-forming tuff) and underlie the Creede Formation moat lake deposits.

2B. Phenocryst grain size (widths measured on backscattered electron (BSE) images of polished thin sections), comparing the caldera-fill Snowshoe Mountain Tuff and an ashfall tuff interbedded with mesobreccias penetrated in CCM-2.

3. Facies within the Creede Formation and distribution of the post-caldera Fisher Dacite intracaldera lavas. From Heiken and Krier, 1987.

4A. Distribution and thickness of the Creede alluvial fan/deltaic complex that heads in the Willow Creek area in the Creede Mining District. Thicknesses based on mining company coreholes and auger holes; note the location of research coreholes CCM-1 and CCM-2 and line of cross-section for Fig. 4B.

4B. North-south cross section of the Creede alluvial fan/deltaic complex, from Willow Creek, north of Creede to Corehole CCM-2 (offset). Cg=major conglomerate units; Tr=travertine; Tu=major tuff bed; intersected at a depth of 600 ft in CCM-2.

5. Percentages of rock types in caldera moat coreholes CCM-1 and CCM-2.

6. Tuff Bed thicknesses (in m) in coreholes CCM-1 and CCM-2.

7A. Variations in pyroclast width and shape in tuff beds sampled by corehole CCM-2.

7B. Variations in phenocryst percentages, per cent K-feldspar, and feldspar compositions in tuff beds sampled by corehole CCM-2.

8. Detailed description and particle size variations in a tuff sequence sampled by corehole CCM-2 from depths of 1131 to 1097 feet.

9. Feldspar compositions, tuffs sampled by corehole CCM-2.

10. Tentative correlations of tuff beds within the Creede Formation between coreholes CCM-1 and CCM-2.

11. Amphibole compositions, comparing ignimbrites sampled from Creede Formation outcrops in Goose Creek (southeastern moat) and at a depth of 980 ft in CCM-2.

12. Sources of clastic sediment for the Creede Formation sandstones, siltstones, and conglomerates. The entire system is dominated by a constant source of volcanic ash, either from intracaldera and outside eruptions or ash washed from the surrounding countryside into the moat.

A+B

Table 1. Stratigraphy of Ashfall beds within the Creede Formation Moat Coreholes 1 and 2. This illustrated summary shows groups of ash beds that are close to one another and similar in petrographic makeup and shard shapes. All shard descriptions are of relicts; there is no glass preserved anywhere in the sedimentary rocks and tuffs penetrated by the coreholes. Depths are in feet (to compare with other studies in this volume), thicknesses are in meters, "SEM Description" includes thin section petrography and modes, and "Mean GS" refers to mean grain size of the tuffs.

Included in the stratigraphic description of Corehole CCM-2 are the massive ash beds interbedded with mesobreccias, below the Creede Formation and above the Snowshoe Mountain Tuff caldera fill.

DISCLAIMER

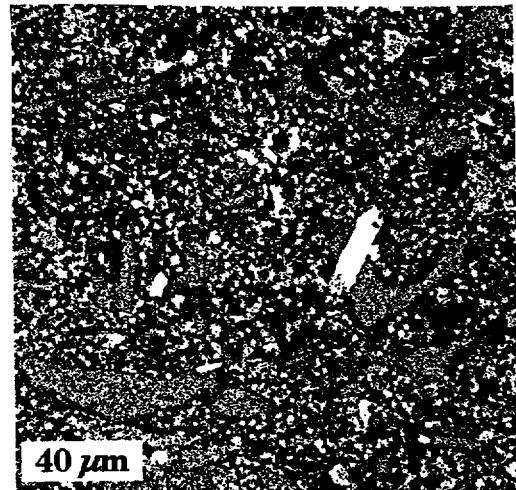
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Table 1A. Summary tuff descriptions—Ashfall tuffs in CCM-1

Depth in feet

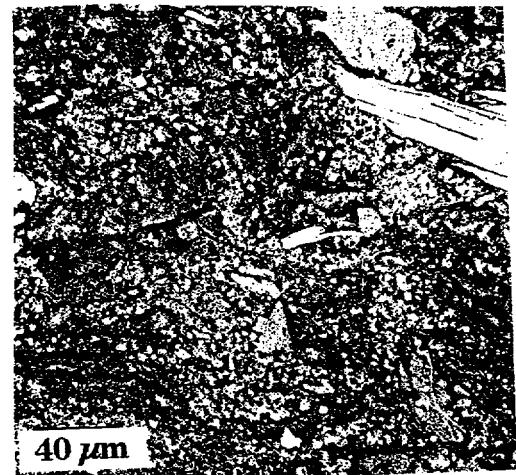
Sample Number SEM description

0334.1	Thinly bedded, fine-grained vitric tuff well-oriented elongate phenocrysts parallel to bedding.
1R036 A1.8	Good relict shards; bubble walls and elongate, angular shards; rare shards attached to plagioclase phenocrysts (~ 40 μm long). Shards are scattered homogeneously throughout the matrix, which is now cemented. 0.4-1.9 % very fine-grained angular phenocrysts. Shards have been replaced by an Al, Si, Ca, Fe phase (low relief, sometimes fibrous). In matrix are irregular patches of auth. quartz and k-spar, about 0.5 mm in diameter. Soft sediment deformation at hand specimen scale. 26.97±0.1 Ma (Lanphere, this volume)



40 μm

0439.2	Fine-grained vitric-crystal tuff . Sand-size mineral and lithic clasts in a smectitic matrix (shrinkage cracks throughout). Phenocrysts include biotite, ilmenite, plagioclase. Angular porphyritic lava clasts, which could be tachylitic. Other than biotites, which are parallel to bedding, the rock is massive.
1R048 A6.5	Some relict shards (?)



40 μm

Table 1A. Summary tuff descriptions—Ashfall tuffs in CCM-1

Depth in feet

Sample Number SEM description

0493.21	Vitric tuff 8.2 % phenocrysts of plag, K-spar, and biotite. Poorly preserved, 100 μm -long elongate and triangular bubblewall shards. Some relict bubbly glass attached to plagioclase phenocrysts. Relict shards are open molds; Patches of chlorite, which have replaced small pumices surrounded by k-spar cement.
1R054 A5.0	<p><u>Crystal-vitric tuff</u> at the base of this 9.2-m-thick deposit. Angular phenocrysts=36.5%\pm1.36 .</p> <p>27.1\pm0.07 Ma (Lanphere, this volume)</p>

0613.2	Fine-grained vitric tuff at top of a 5.8-m-thick tuff bed. Hollow shard relicts in calcite cement. The shard relicts range in size from 4 μm to 30 μm in length and consist of elongate, triangular forms and some curved pyroclasts that were bubble-wall shards. Some small, broken phenocrysts, mostly plag.
1R070 A1.7	<p>Scattered throughout this very fine ash are occasional coarse-grained pumice clasts, up to 350 μm x 300 μm. The pumice is about 60% vesicles; ovoid to nearly circular (in thin section). The pumices are rimmed with bands of 20 to 30 μm long apatite crystals.</p> <p>If this ash were erupted locally, it must be hydrovolcanic.</p> <p>Base of the 5.8-m thick <u>vitric-crystal tuff</u>. No sizing in either fine or coarse laminae. 14.6% phenocrysts.</p> <p>Coarse lamina= subangular to subrounded, 40 to 250 μm long grains of plagioclase, k-spar, biotite, and irregular, SA lava and tuff lithic clasts. Cemented with a smectite(?). Lithic clasts are rimmed with a corona of fine pyrite.</p> <p>Finer Lamina= 10 to 50 μm-long mineral clasts and relict shards in a fine clay matrix. Shard relicts are now voids. Relict forms include curved, elongate, and triangular shapes and small pumices. There is some parallel orientation of elongate clasts parallel to bedding.</p>

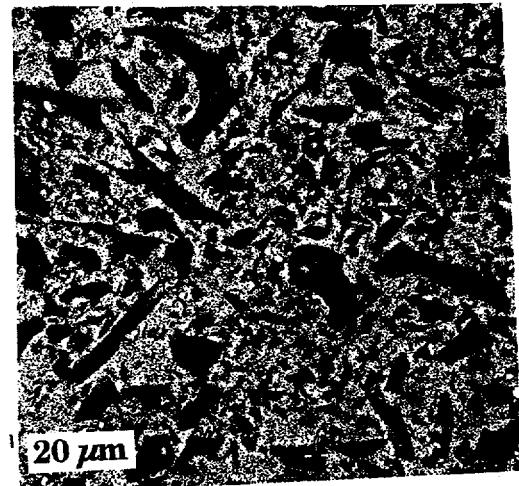


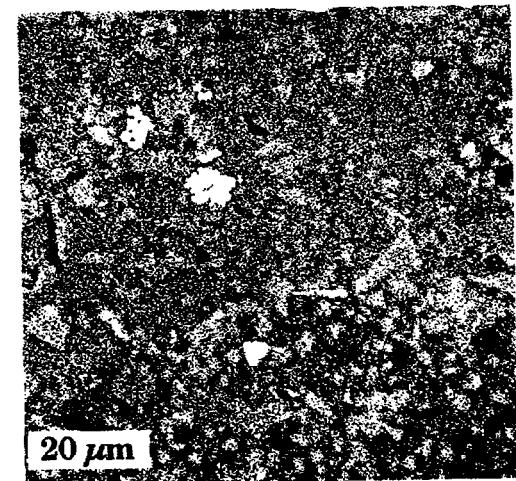
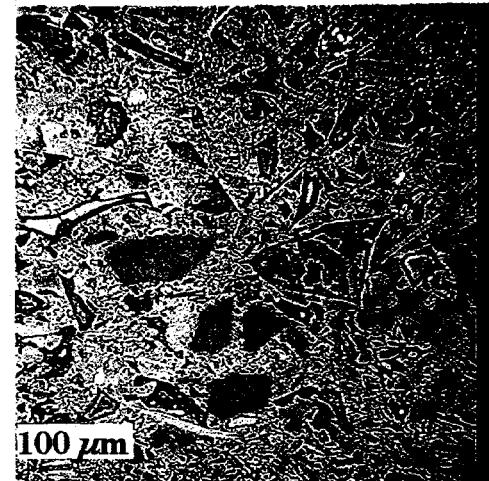
Table 1A. Summary tuff descriptions—Ashfall tuffs in CCM-1

Depth in feet

Sample Number SEM description

0672.3 The thin section was cut across the boundary between a fine ash bed and a very fine, ashy silt.

1R076 A0.6 The crystal-vitric tuff consists of shards 10 to 250 μm long; all angular bubble wall relicts. The relicts are molds, surrounded by calcite cement, with scattered pyrite crystals. The relicts are about 50% angular and bubble-wall shards and 50% small pumice clasts. The pumices are very vesicular, with >50% vesicularity. About 40% of the ash consists of phenocrysts, in the same size range as the shards and small pumice clasts. This ash had a lot of original permeability, now replaced by calcite cement.



0749.1
1R085
A0.6 Massive, very fine-grained crystal-vitric tuff, with scattered 100- to 150- μm -diameter patches tightly cemented with a silica phase. In layers with calcite cement, there are relict shards (void spaces). Most are broad, curved bubble wall shards, or triangular forms. Make up ~20%, with 80% carbonate cement.

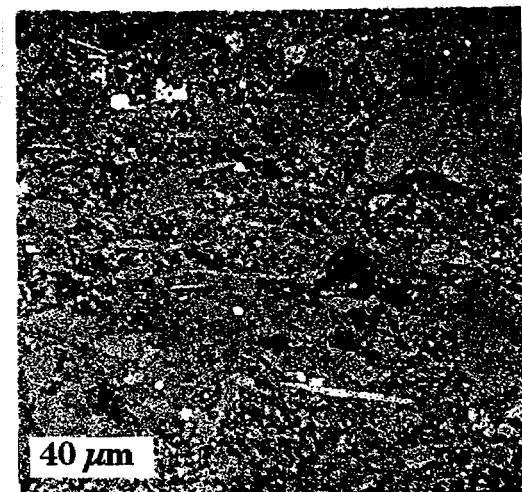
~25% 25 to 50- μm -long mineral phases in a finer matrix

Table 1A. Summary tuff descriptions—Ashfall tuffs in CCM-1

Depth in feet

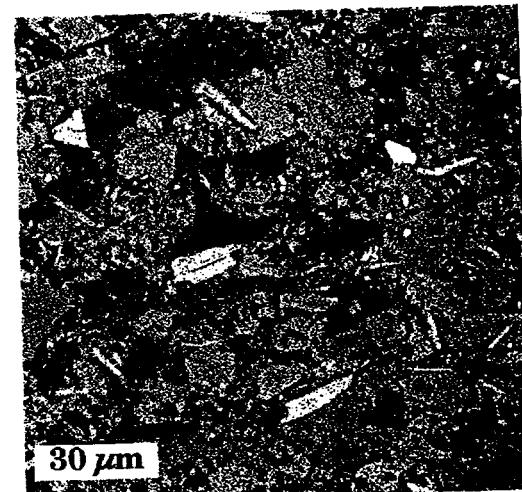
Sample Number SEM description

0821.4	Very fine-grained tuff in thin, graded laminae. 10- to 30- μm -long phenocrysts and some poorly-preserved shard relicts. Shard relicts are 10- to 60- μm long; curved, elongate, and triangular or polygonal forms. Biotites are oriented parallel to bedding.
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40 μm

1148.6	Crystal tuff. Bimodal population; a few large (>several mm long) biotites in a very fine-grained ash. The rock consists of ~70% 5- to 200 μm long, angular phenocrysts; mostly equant (except the biotite); plag, K-spar, biotite.
1R129 A8.0	Relict shards are in the range of 10- to 25 μm and consist of curved triangular and elongate, bladed forms. 0-20% 200- to 400- μm lithic clasts.



30 μm

Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Depth in feet	Sample Number	SEM description
0205.4'		Vitric tuffs, consisting of mostly coarse-grained shards, consisting of (1) thin- to thick-walled platy, curved shards, (2) some thick-walled vesicle junctions, and (3) a few broken hollow spheroids. 2.5% phenocrysts.
2R009		
A4.4		
		26.39±0.16 Ma (Lanphere, this volume)
0379.3		Vitric tuff, consisting of a mixture of relict shards; (1) <10 to 10- μ m-wide, 200- μ m-long curved, platy shards and some thin-walled, Y-shaped shards, along with (2) 100- μ m-long thick-walled shards that are blocky, Y-shaped vesicle junctions or platy fragments. 1.9% phenocrysts.
2R28		
A0.3		Coarser-grained shards have hollow centers, which are partly filled with bladed zeolites.
		27.1±0.07 Ma (Lanphere, this volume)
0590.6		Vitric-crystal tuff. Good relict shards, outlined and filled with an open framework of clay; Triangular, curved elongate, and Y-shaped bubble wall shards. Also a number of straight needle-like shards; some micropumice; size range 10 μ m to 200 μ m long. Phenocrysts = 20.2%±4.2 (plag, k-epar, biotite, quartz, and hornblende). Matrix is massive, crystalline, appears to be a mixture of clay, pyrite (?), and zeolite(?).
2R052		
A9.6		Slightly coarser at base, with shard lengths up to 500 μ m.

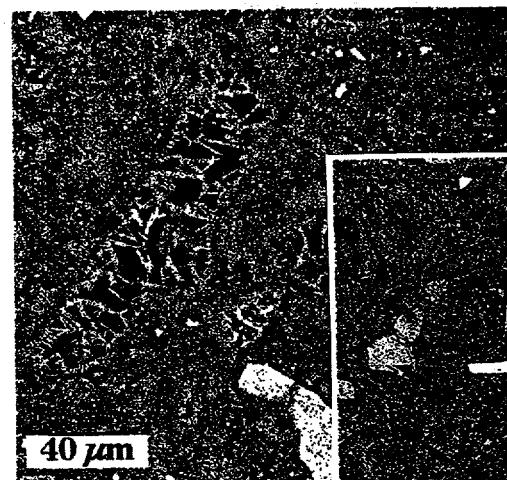
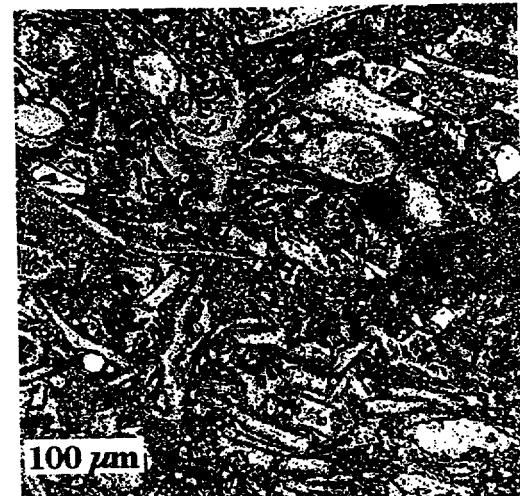
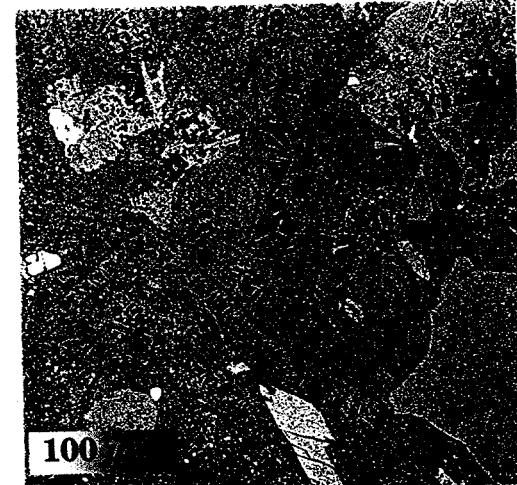
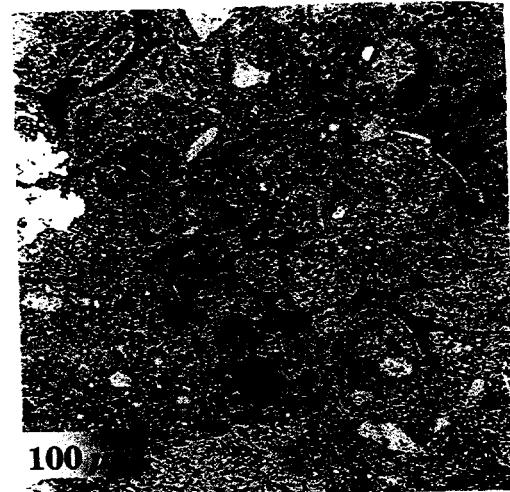


Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Sample Number	Depth in feet	SEM description
0787.5		Massive <u>vitric-crystal tuff</u> . Shards make up about 40% of the rock; Many more may have been absorbed into the clay matrix. Elongate, curved, needlelike (flat plates) and multiply-terminated bubble-wall junctions form large shards, in the range of 50- to 700 μm long. Shard relicts are mostly voids, but lined with tabular (zeolite) crystals. Phenocrysts = $23\% \pm 3.4$; plаг, biotite.
2R073 A6.5		
0814.8		Massive, coarse <u>crystal-vitric tuff</u> . Nonwelded. Phenocryst population = $44.28\% \pm 4.62$. Relict shards are voids partly filled with rims of fibrous and internal framework of a smectite(?). They range in size from 40- to 300- μm long (most are 100 to 200 μm); mostly elongate flat or slightly-curved plates, but some triangular and Y-shaped forms.
2R076 A3.8		
0857.6		Nonwelded, coarse <u>crystal-vitric tuff</u> . 25% phenocrysts of plаг, K-spar (qtz(?)), and biotite. Pumice and shards make up about 65% of the rock (including former pore space. The remaining 10% is unspecified matrix and lithic clasts. Pumices are 300 to 600 μm long, equant to slightly elongate, and have sharp, irregular surfaces; most had about 60% vesicularity and spherical to ovoid vesicles. Most have been replaced by smectites, but some have been replaced by pyrite. Shards are elongate, slightly curved or flat plates, some are micropumices; sizes from 80 to 400 μm long. Relict are mostly void space, but lined with smectitic minerals. (Possibly zeolites)
2R081 A0.6		



100



100

Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Depth in feet	Sample Number	SEM description
1000.0		Very fine-grained vitric-crystal to crystal-vitric tuff . 15% to 25% 25 to 100 μm -long phenocrysts (plag>biotite>hornblende> K-feldspar (?). Poorly-preserved shard relicts; flat platy bubble walls and small pumice pyroclasts.
1122.2		Massive crystal-vitric tuff . Phenocrysts = 40.1% \pm 2.0; Plagioclase, quartz, trace of biotite. 0.3% allanite (?).
2R109		Ragged relict shards
A7.2		Shards are 40- to 1000- μm -long bubbles, plates and Y-shaped forms. These were derived from a highly-inflated magma, with ovoid vesicles of 200- to 300- μm long axis and a pumiceous melt with ~ 80% vesicle volume.
1154.2		Massive crystal-vitric tuff . Relict shards have been replaced with a low-relief mineral with Al, Si, Ca, and Fe. Equant, elongate platy, and Y-shaped shards (some attached to phenocrysts) 20- to 120 μm long.
2R112		Percent phenocrysts = 31.1% \pm 9.4; Plag., biotite. Anthigenic apatite in places. biotites are oriented parallel to bedding.
A9.2		

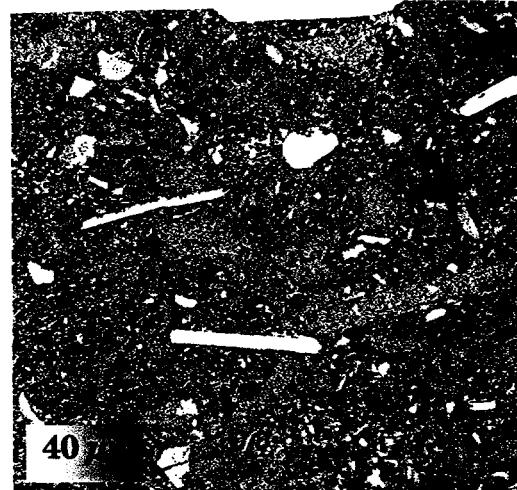
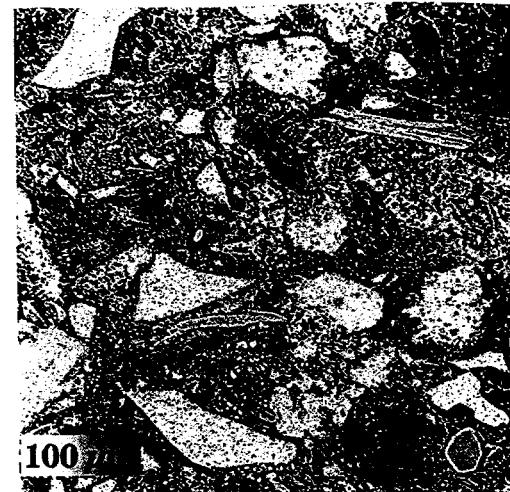


Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Depth in feet

Sample Number

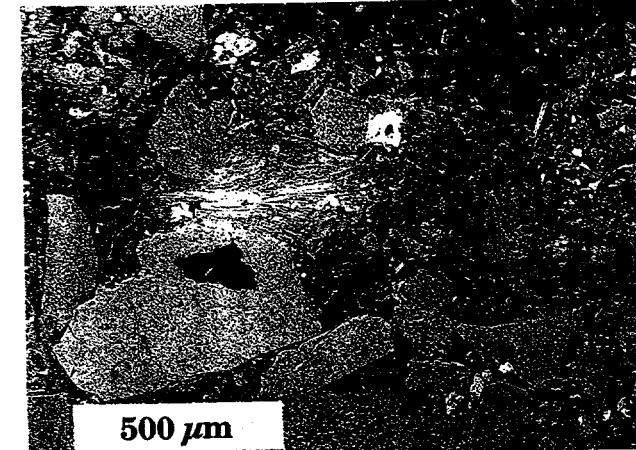
SEM description

1185'

Crystal-lithic tuff. 20% lithic clasts of spherulitic tuff. Faint shard relicts; pumices (highly inflated, with large vesicles) up to 1 mm long.
Percentage of phenocrysts = 52.9%±5.2;
plagioclase, k-spar, biotite.

2R116

A4.0

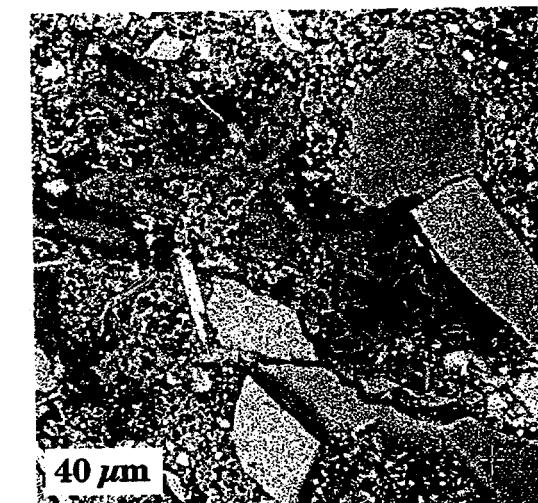


1215.4

Massive crystal tuff. 53 % phenocrysts; 20- to 100- μm -long, angular clasts of plagioclase, quartz, k-spar, and biotite. Relict shards are mostly filled with a latticework of a zeolite (?-Al, Si, Ca) or are voids. Y-shaped, triangular, and curved platy forms, 30- to 80- μm long.
Percentage of phenocrysts= 52.9%±5.2;
plagioclase, k-spar, biotite.

2R119

A4.4



1261'

2R124

A0.0

Thin interbeds of (1) vitric tuff with smectite (?) cement and shard replacement, and (2) vitric tuff in which the cement is calcite and the shards are replaced by a silica phase. Long axes of relict shards range from 5 to 120 μm . Shard types include micropumices, equant, curved, tabular, forms (bubble walls), which are nearly equant (in contrast with some of the shallower tuffs). Pyrite scattered throughout.

26.13±0.19 Ma (Lanphere, this volume)

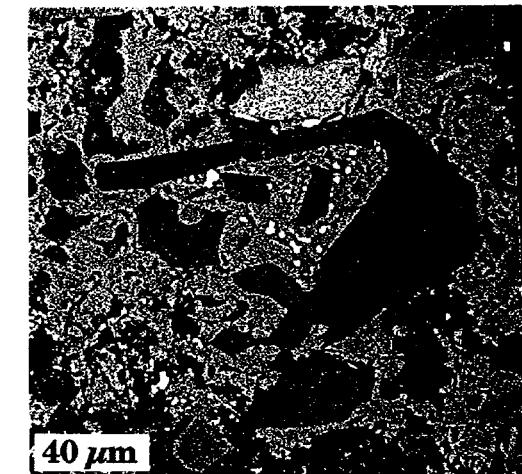


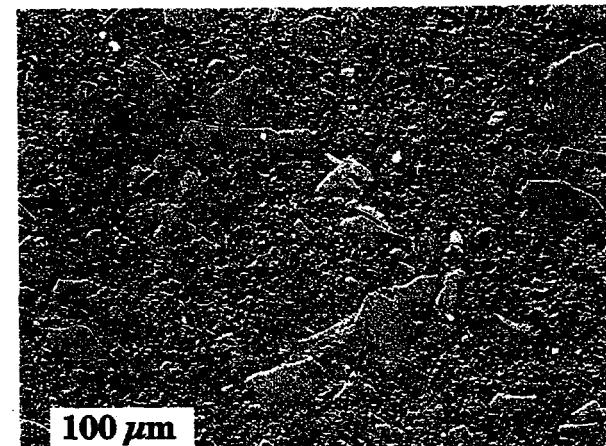
Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Depth in feet

Sample Number

SEM description

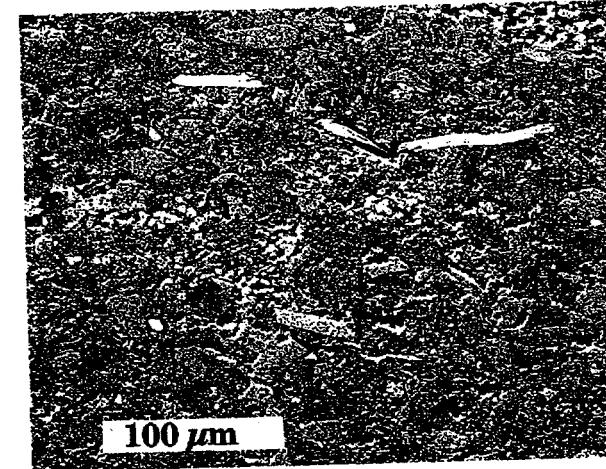
1295.5	Fine-grained vitric-crystal tuff with a strong authigenic overprint. 80% matrix, includes relict shards; 10- to 120- μm -long, triangular, polygonal, blocky shards; mostly hollow, with a latticework of authigenic mineral inside. Phenocrysts = 19.8% \pm 6.3; angular plagioclase, K-spar, quartz, biotite. Grades down into: Crystal-vitric tuff . Rare relict shards There appear to be some equant, triangular shard relicts in the area of 40- to 50 μm . Phenocrysts = 37.0% \pm 5.0; Plagioclase, K-spar, and biotite.
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1399'

2R138
A0.0

Crystal-vitric tuff. Relict shards are difficult to make out, but appear to be 10- to 50- μm -long blocky, curved forms.
Phenocrysts = 34.2% \pm 2.4; plagioclase, ilmenite, biotite.



1513.6

2R150
A2.6

Crystal tuff. Angular phenocrysts in range of 20 to 200 μm ; Phenocryst population = 51.8% \pm 7.6; Plagioclase, K-spar, and biotite.
Relict shards and matrix make up about 50% of the rock. Relict shards, now void spaces lined with smectites, have triangular and curved, platy forms; 30- to 80 μm long.



Table 1B. Summary tuff descriptions—Ashfall tuffs in CCM-2

Depth in feet	Sample Number	SEM description
	1839.3	Crystal-vitric tuff. About 55% matrix and relict shards. Triangular, blocky, tabular relict shards; 30- to 50- μm long; poorly preserved. Some are voids, but most are filled with a zeolite(?). Phenocrysts = 43.2% \pm 6.2; plagioclase, K-spar, and biotite. A lot of overgrowths affect the shapes, but not so much the sizing.
	2R183	INTRA-MESOBRECCIA TUFF, BELOW THE CREEDE FORMATION, BUT ABOVE THE SNOWSHOE MOUNTAIN TUFF
	A1.3	
	1975.4	Massive crystal-vitric tuff. Relict shards and matrix ~50%. Curved triangular, blocky forms; poorly defined, but in the size range of 30- to 50 μm . Phenocrysts=49.6% \pm 2.6; plag, K-spar, ilm.
	2R200	INTRA-MESOBRECCIA TUFF, BELOW THE CREEDE FORMATION, BUT ABOVE THE SNOWSHOE MOUNTAIN TUFF
	A4.4	
	2004?	Massive crystal-vitric tuff; near the top of a massive 10.5-m-thick tuff. Some orientation (horizontal) of the platy shards and biotite phenocrysts. ~35% phenocrysts, including Plag, K-spar, biotite, opaques. Relict shards and pumices (Md \sim 100 μm) ;thick-walled, curved platy and stubby vesicle junctions.
	2R203	INTRA-MESOBRECCIA TUFF, BELOW THE CREEDE FORMATION, BUT ABOVE THE SNOWSHOE MOUNTAIN TUFF
	A2.6	

