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PRELIMINARY SCIENTIFIC RESULTS OF THE CREEDE CALDERA CONTINENTAL SCIENTIFIC DRILLING PROGRAM

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STRUCTURAL RESURGENCE AND INTRACALDERA VOLCANISM - CREEDE CALDERA, COLORADO

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PURPOSE AND CONCLUSIONS:

The processes occurring within calderas after their formation may affect their thermal state and the geothermal systems developed there. Structural deformation of larger calderas follows resurgence of the underlying magma body, which raises the isotherms, 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 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 de posits consisting of clastic sedimentary rocks known as the Creede Formation. The entire sequence of caldera fluviatile and lacustrine rocks, and interbedded ash deposits has now been penetrated by coreholes CCM-1 and CCM-2.

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 intracaldera lake had any effect on the thermal history of the magma body or bodies under the caldera.

Our conclusions are that structural resurgence was rapid and that most deposition occurred within a lake limited to a ring moat, that intracaldera eruptions were mostly hydrovolcanic, that all of the caldera moat sediments are ashy, and that there was little hydrothermal activity involving the lake waters and the magma underlying the Creede caldera. Any intense hydrothermal circulation of Creede lake waters was limited to the northern moat, through the more permeable sandstones and conglomerates of an alluvial fan and delta fed by streams originating north of the caldera, and along faults in the northern caldera wall in what is now the Creede mining district.

SETTING AND PREVIOUS WORK

Sedimentary rocks of the Creede Formation were named by Emmons and Larsen in 1923. Further work on the Creede Formation was done as part of the U.S. Geological Survey project to map the San Juan Mountains volcanic field (e.g., Steven, 1967; Steven and Ratte, 1965, 1973; Steven and Eaton, 1975; Steven and Friedman, 1968; Steven and Lipman, 1973; and Steven and van Loenen, 1971). Steven and Ratte determined that, within the resurgent dome, the caldera-filling Snowshoe Mountain Tuff is at least 700 m thick; the total thickness is not known. Bethke and coworkers conducted thorough studies of the geology and geochemistry of ores in the Creede mining district; their model involves fluids from a Creede caldera lake circulating northward from the lake into a zone over a cooling intrusive body to form the geothermal system in which the ores were deposited. Before the drilling project began, there were numerous preliminary studies by government and university researchers. In 1987, the Creede Formation was studied to determine if there had been a connection between the 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 and mapping, and industry coreholes, that the Creede Formation: (1) was deposited in a moat around the structural resurgent dome; (2) never filled the caldera; (3) consisted of 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. It was, however, inferred from the distribution of facies within the Creede Formation (in outcrops and cores) that lake waters could have entered the Creede geothermal system along zones of greater permeability within an alluvial fan which headed in a graben-like structure that is part of the keystone graben of the Bachelor caldera.

Location of Coreholes CCM-1 and CCM-2

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 faults of graben-like structures of Willow Creek and Deep Creek 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 megabreccias from the caldera walls and fine ash. This sequence of tuff, 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 limestone.

ASH SEDIMENTATION IN THE CREEDE MOAT LAKE

Volcanic ash is an important component of the entire Creede Formation. Within the 1600 ft (488 m)-thick section of mostly lacustrine siltstones, there are 21 eruption sequences. Each 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 lamina.

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. In outcrops, thinning travertine laminae can be traced from fissure ridges outward into ashy lacustrine siltstones. If some of the calcium carbonate laminae that occur throughout the full thickness of the Creede Formation are similar, it would appear that springs along caldera walls and the hinge-line at the base of the resurgent dome were active throughout the history of the Creede lake.

ASH SEDIMENTATION BELOW THE CREEDE FORMATION

Above the caldera-fill tuff (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. Interbedded with the mesobreccias are sequences of 1- to 10-m-thick tuff beds and tuffaceous siltstone laminae, which appear to have been deposited in a lake.

The mesobreccias are interpreted as the products of collapsed, unstable sections of caldera wall. A question about the interbedded tuffs and tuffaceous siltstones is how long a time period do they represent between deposition of mesobreccias. It is possible that the time represented could be as short as a few days, assuming that:

(1) The rock masses involved in caldera collapse may have dewatered, quickly forming an intermittent caldera lake.

(2) Massive deposits of nonwelded Snowshoe Mountain Tuff slumped or washed back into the crater and its lake. In the recent eruption of Pinatubo Volcano, large volumes of ash and debris were deposited in depressions in and around the volcano in hours or days.

ASH CHARACTERIZATION AND GENESIS

The glass components of the ash deposits and ashy siltstones have all been replaced by illite-smectite, authigenic potassium feldspar, analcime, clinoptilolite, and carbonates. However, relict textures allow the study, in thin section, of pyroclast types and size; the phenocrystic and lithic components are little altered.

Eruption sequences within the Creede Formation begin with massive fine ashes, in some cases graded, which are overlain by sequences of thin (often less than 1 mm) laminae of ashy siltstone or ash. Within the lower half of CCM-1, the bases of these laminae are marked by calcium carbonate laminae or by disseminated pyrite. The interpretation is that these were deposited in relatively deep water at CCM-2, but on distributaries from a delta in CCM-1, where some of the beds were reworked. These tephra sequences are similar to those observed in closed basins elsewhere; e.g. Laguna de Ayarza, Guatemala.

Phenocryst-rich ash deposits in the lower 2/3 of CCM-2 appear to be mostly of hydrovolcanic origin, with mineralogies similar to those of the Carpenter Ridge Tuffs. This activity is inferred to have taken place within the caldera lake. It appears that these are from intracaldera sources, some of which may still be buried by moat sediments and tuffs. There is also a sublacustrine pyroclastic flow at 980 feet, which was originally thought to be correlative with the ignimbrites at Goose Creek in the southeastern moat, but is not, based on hornblende analyses.

Within the upper third of CCM-2, ashes range from nearly aphyric to having 20% phenocrysts. Curved, platy shards, 100-500 um long, appear to be mostly of magmatic (not hydrovolcanic) origin, from a highly inflated, vesicular melt. The sources may have been intracaldera if vents were above lake level, or sources outside the Creede caldera.

Distribution of the (present-day) near-surface Creede Formation extends well to the west, lapping into the Clear Creek graben. We believe that the graben was present before or shortly after formation of the Creede caldera. If so, streams flowing down the Clear Creek graben drained into the moat lake. The lower part of the CCM-1 sequence is definitely coarser-grained overall than the equivalent distance above base of the Creede Formation in CCM-2.

COMPARISON OF ASH AND ASHY SEDIMENT SEQUENCES BETWEEN COREHOLES (TEPHROCHRONOLOGY)

The ash sequences in CCM-1 are somewhat less well-defined. There is no correlation of the sublacustrine hornblende ignimbrite with outcrops of a hornblende-bearing ignimbrite of Goose Creek in CCM-2-The hornblende compositions are not the same. The source for this ignimbrite is not known.

The ashes in the lower half of CCM-1 are similar in many respects to those the lower 2/3 of CCM-2, with the exception of a 6-m-thick, nearly aphyric, very fine ash at a depth of 600 feet. One ash sequence at about 300 feet is similar in some respects to ashes in the upper 1/3 of CCM-2.

An attempt to establish correlations of ash beds between the two wells was made by analyzing phenocrysts in the samples. Compositions are similar throughout the section and is difficult to make any correlation other than those of general trends that are based on variations in pyroclast types. The less phyric ashes are similar to rocks of the Point-of-Rocks volcano (within the Creede caldera), but are thinnest in CCM-1, close to Point-of Rocks. These ashes could be from a buried source with composition similar to Point-of-Rocks or a source outside of the Creede caldera.

Tuff Phenocryst Compositions Throughout the Creede Formation

Feldspar compositions from intracaldera tuffs are similar in many respects to those of the Snowshoe Mountain Tuff and the Fisher Quartz Latite Flows. Intracaldera explosive activity appears to have been from the last bits of the magma body emplaced after caldera formation-at least in the lower 2/3 of the section, where the crystal tuffs are dominated by plagioclase. There is more variation in the upper third, where the less-phyric tuff phenocrysts are mostly K-feldspars.

CONCLUSIONS.

1. The caldera-fill tuff (Snowshoe Mountain Tuff) is >700 m thick, as measured within the keystone graben of the resurgent dome. The total thickness is unknown.

2. There was rapid structural resurgence, with subsequent deposition of intracaldera sediments and ashes in a ring "moat" with sediment sources from the resurgent dome, caldera walls, and streams in what is now Willow Creek and the Clear Creek graben. By analogy, the modern actively-resurging dome of Iwo Jima caldera is rising at over 20 cm/year. If such a rate were applied at Creede, the Snowshoe Mountain resurgent dome could have been formed in 5000 years.

3. There were numerous intracaldera eruptions; 21 volcanic ash sequences, not counting the Snowshoe Mountain Tuff, are interbedded with lacustrine rocks. Tuffs in the lower 2/3 of the section consist of fine-grained, phenocryst-rich hydrovolcanic ashes, with rare sublacustrine, pyroclastic flows. The upper 1/3 of the Creede Formation is mostly coarser-grained, poorly-phyric ash, which appear to be magmatic, with little evidence for magma/water interactions. Exceptions are a couple of sublacustrine ignimbrites, which appear to have flowed into the lake from sources above lake level.

4. Where the Willow Creek and Deep Creek grabens intersect the caldera, there appears to have been relatively deep water, with deposition of

undisturbed graded ash or ashy silt beds (CCM-2). The "Creede alluvial fan" was deposited at the head of this structural depression in the moat. Shallower water and perhaps a stream delta on the northwest side of the caldera, where the Clear Creek graben intersects the caldera margin, disturbed many of the ash beds, reworking them -- there are fewer volcanic ash sequences preserved in CCM-1 than in CCM-2, only 4.8 km east.

5. Sedimentation within the caldera lake was constantly affected and controlled by direct deposition of and erosion of ash deposits-At first from the Snowshoe Mountain Tuff, then by ashfalls from intracaldera eruptions that buried the countryside around the caldera. Many of the massive debris-flow deposits may have been associated with high-concentration stream flow into the lake, which is commonly generated when storms pass over an area covered with poorly-consolidated ash fallout.

6. If the Creede caldera lake were the source of water for the Creede mining district epithermal system it would have been along a combination of the faults bounding the graben-like structure of Willow Creek (coincident with the keystone graben of the Bachelor caldera resurgent dome) and the coarser-grained conglomerates and tuffaceous sandstones of the Creede alluvial fan. Other than low-T travertines, there is no evidence within the moat sediments for hydrothermal interaction between the lake and the Creede magma body. The only evidence of hydrothermal activity within the deep corehole (CCM-2), is within fractured, caldera-filling Snowshoe Mountain Tuff, well below the unaltered base of the Creede Formation lacustrine rocks. It appears that even a thin layer of tuffaceous siltstone can be an aquitard.

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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 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 Ratte, 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 fan was supplied by cores willingly shared by 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 middle of 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.

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