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The $^{40}Ar/^{39}Ar$ chronology of caldera formation, intrusive activity and Mo-ore deposition near Questa, New Mexico

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THE ^{40}Ar/^{39}Ar CHRONOLOGY OF CALDERA FORMATION, INTRUSIVE ACTIVITY AND Mo-ORE DEPOSITION NEAR QUESTA, NEW MEXICO

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Abstract—^{40}Ar/^{39}Ar geochronologic techniques have been applied to the Questa, New Mexico, area to constrain the timing of magmatic events. The results document intrusive activity, commencing in the north and concluding in the south, over a period of 7 million years. After caldera formation and eruption of the Amalia Tuff at 25.7 ± 0.1 Ma, an episode of widespread intrusive activity, concentrated along the southern caldera margin, occurred at 24.65 ± 0.1 Ma. Deposition of coarse-grained molybdenite ore in the Sulphur Gulch pluton occurred some 0.4 million years later. The magmatic system was still capable of depositing Mo after emplacement of the southernmost, Lucero Peak pluton at 18.5 ± 0.1 Ma.

INTRODUCTION

In the vicinity of Questa, New Mexico, the Sangre de Cristo Mountains afford a rare opportunity to study the transition between volcanic rocks and high-level granitic intrusions (Lipman, 1983, 1984, 1988). These silicic plutons crop out in the vicinity of Questa caldera as nine discrete and distinctive bodies (Fig. 1) and, based on regional gravity data, are interpreted to represent cupolas above a composite batholith underlying an area of about 20 × 35 km. Although geologic mapping and previous geochronology establish the existence of precaldera and postcaldera lavas in the Latir volcanic field (Lipman, 1983; Lipman et al., 1986; Johnson and Lipman, 1988; Lipman and Reed, 1989), our focus has been on establishing the chronology of caldera formation, pluton emplacement and ore deposition. Our concentration on defining, within current ^{40}Ar/^{39}Ar capabilities, precise relative ages of these events has required an extensive analytical program. We cannot describe fully all facets of our study, which will be documented in later reports. We take this opportunity to outline those relations that may be of most interest to readers of this volume.

The results of earlier work are here discussed only briefly insofar as they bear on petrologic and age relations. Following Lipman (1983), recent investigators have used a threefold, spatial grouping of the plutons: (1) the resurgent, intracaldera plutons of Virgin Canyon, Cañada Pinabete, Rito del Medio and Cabresto Lake; (2) the southern-caldera-margin intrusions of Bear Canyon, Sulphur Gulch and Red River; and (3) the Rio Hondo and Lucero Peak plutons, which lie south of the caldera. The Virgin Canyon and Cañada Pinabete plutons are remarkably similar—both contain two, apparently autointrusive phases of metaluminous granite, the earlier of which is in sharp contact with seriate to porphyritic, mildly peralkaline granite that lies along their northern margins. This peralkaline granite and indistinguishable porphyry ring dikes are interpreted as representing a quenched residue of the magma that was largely erupted to form the Amalia Tuff (Lipman, 1983; Czamanske and Dillet, 1988). The slightly more siliceous, later metaluminous granite in these two plutons contains small miarolitic cavities, further evidence of high emplacement level. The granite of Rito del Medio is quite homogeneous, aside from minor feldspar-quartz pegmatites and unidirectional solidification textures along its upper contacts with Precambrian rock, and rare aplite dikes. It is characterized by miarolitic cavities, as much as 6 cm across, which have been calculated to constitute 3 to 4 vol% of the pluton. The Cabresto Lake pluton differs considerably from the other three intracaldera plutons: it is somewhat more mafic (71–72 weight percent SiO$_2$), contains abundant hornblende,

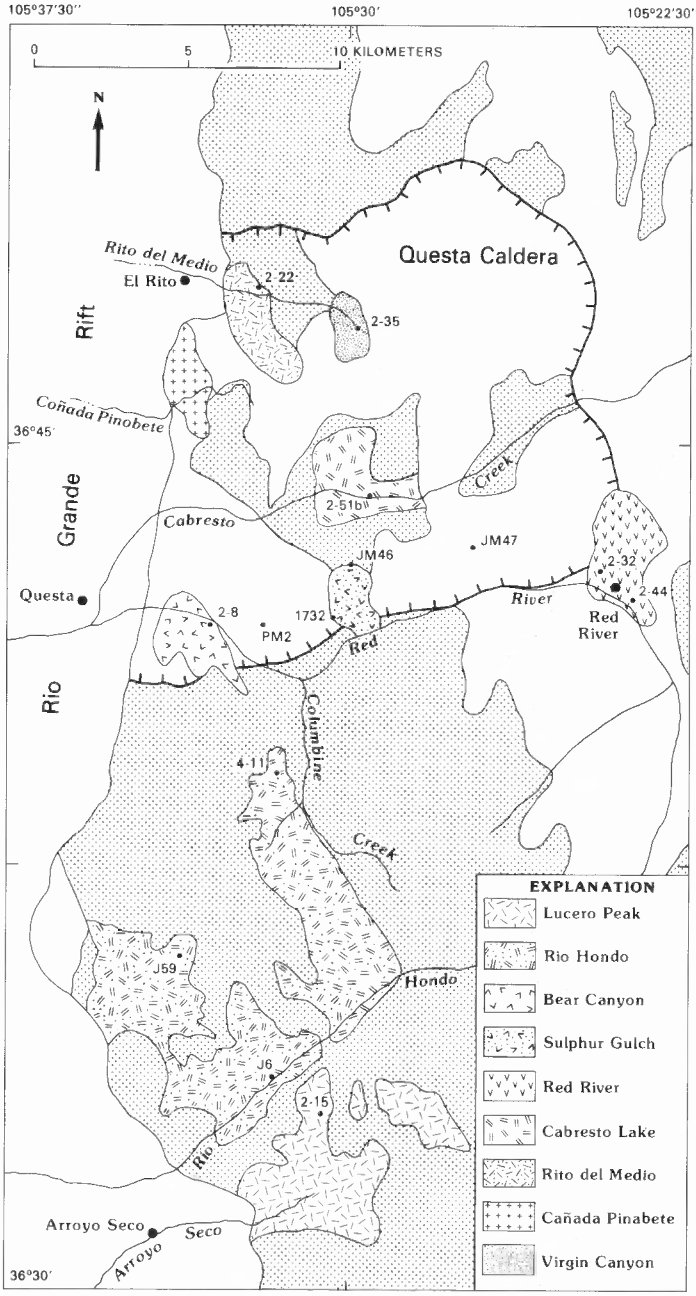

FIGURE 1. Generalized geologic map of the Latir volcanic field, Sangre de Cristo Mountains, northern New Mexico, emphasizing postcaldera intrusive rocks. Precambrian rocks in stipple pattern. Unpatterned area: to west of range front, rift sedimentary rocks; to east, Tertiary volcanic rocks of the Latir volcanic field. Abbreviated sample numbers correspond to Table 1.

biotite, titanite and apatite, and hosts several types of mafic inclusions.

The intrusions along the southern caldera margin may all be interconnected in the shallow subsurface, as established during exploratory drilling between outcrops of the Bear Canyon and Sulphur Gulch plutons. Silicic intrusions in the vicinity of Red River have been grouped into the "Red River intrusive complex" because poor exposures and alteration preclude a clear picture of their relations. In fact, the Bear Canyon pluton and the intensively mapped Sulphur Gulch pluton also consist of several distinct granitic to aplitic phases. Molycorp geologists have broadly considered the Sulphur Gulch pluton to consist of somewhat earlier "carapace granite" and later "source aplite" from which Mo-bearing solutions entered the overlying granite and its andesitic roofrocks (Leonardson et al., 1983). Whereas only the Sulphur Gulch pluton and its roofrocks have been mined for Mo, occurrences of pyrite and molybdenite in the Bear Canyon pluton and rocks of the Red River intrusive complex also support a close relation among the intrusions along the southern caldera margin.

The Rio Hondo pluton is the largest and most enigmatic in the Questa area. Largely composed of hornblende-biotite granodiorite, this pluton developed a thin zone of siliceous granite against its relatively flat-lying Precambrian roof and undergoes a poorly constrained northward transition into 77–78 weight percent SiO_2 granite. The predominant granodiorite is characterized by alkali feldspar and plagioclase megacrysts (as much as 5 cm across), mafic schlieren and fine-grained mafic enclaves considered to represent quenched basaltic magma. Lipman (1984) concluded from structural reconstructions that the deepest exposed levels of the pluton in Hondo Canyon may have crystallized as much as 5 km below the surface. The granitic part to the north displays unidirectional solidification textures against Precambrian rocks and is in part autobrecciated with open microfractures—it must have been emplaced at shallow depths. The Lucero Peak pluton does not possess the distinctive "high-level" attributes of the plutons associated with the caldera, but it also is quite dissimilar to the Rio Hondo pluton. It is a homogeneous pluton except near its contacts with overlying Precambrian rocks; there, notably on the west slope of Lucero Peak, which is interpreted to represent the exhumed roof of the pluton, chevron-folded quartz stringers are conspicuous, and the granite is fine grained. The South Fork outlier of the Lucero Peak pluton contains subeconomic pyrite and molybdenite mineralization (Jones and Norris, 1984).

SAMPLES STUDIED

Localities for the studied samples are shown in Figure 1; chosen samples of plutons are representative and as fresh as can be obtained, although biotite in some samples shows incipient bleaching or alteration to chlorite. Extensive data sets detail the petrography, mineralogy and mineral chemistry of most samples (Dillet and Czamanske, 1987), as well as their major-element, minor-element and isotope geochemistry (Johnson et al., 1989, 1990). On the basis of detailed mapping by Jeff Meyer (written commun., 1989), sample 82QC44 is now considered to represent a precaldera, quartz-latite feeder rather than part of the Red River intrusive complex. The two sanidine samples are splits of the separates used in the study by Lipman et al. (1986); they are both from the No. 1 Camp section (some 30 km NE of the caldera margin) and represent one of the best preserved and most complete sections of outflow Amalia Tuff. Sample 82L-42H is from low in the section, and sample 82L-42D represents the densely welded upper part of the section. Sample JM-87-46 represents the highest exposures of the Sulphur Gulch carapace granite. Sample JM-87-47 is from a NE-striking, steeply dipping, rhyodacitic to rhyolitic porphyry dike that is broken up by a major flat (listric) fault zone. The dike intrudes volcanic rocks, including the Amalia Tuff, that are tilted 80°–90°W. Finally, samples 1732A and PM-2 represent the early period of coarse-grained molybdenite deposition; each is from a vuggy vein filled with coarse-grained (as much as 4 mm across) molybdenite and phlogopitic biotite. All analysed biotite separates, prepared by the senior author, were >99% pure.

METHODS

^{40}Ar/^{39}Ar measurements (summarized in Table 1) were made in the laboratories at Ohio State University, using the general, established procedures described elsewhere (Foland et al., 1984, 1989). The only important difference was that incremental-heating analyses were conducted in a recently constructed double-vacuum heating system with precise temperature control and low line blanks. For all samples, total-fusion and step-heating measurements were performed, typically using aliquots of about 75 and 300 mg, respectively. To resolve possible small age differences with high relative precision, two experimental approaches were instituted. The first, as discussed by Randall and Foland (1986), involves referencing all samples to a single monitor of comparable age and similar composition. For this study, the monitor was a biotite with a well-constrained age of 23.2 Ma calibrated against the MMhb-1 interlaboratory standard, assuming a ^{40}Ar/^{39}Ar age of 518.9 Ma (Roddick, 1983). The second, as discussed by Foland et al. (1989), involves adjusting irradiation geometry to cancel the effects of neutron-fluence gradients (the J parameter); this approach, which involves aggregate analysis of several individual aliquots, was used for two subsets of the samples: (1) 82L-42D, 82L-42H and JM-87-47; and (2) JM-87-46, 1732A and PM-2. The results of this analytical approach serve to verify that the observed age differences for these samples are not an artifact of reactor fluence gradients. In addition, the ages listed in Table 1 are based on duplicate, or more, analyses. Our approach emphasizes precise age differences relative to a single monitor. The age uncertainties given (Table 1) are relative uncertainties only; a systematic uncertainty

TABLE 1. ^{40}Ar/^{39}Ar ages (in Ma) measured on biotite and sanidine. Ages based on total gas release (T_{tg}), good plateaus (T_p) or "discordant" plateaus (T_{dp}).

PLUTON or UNIT	SAMPLE	T_{tg}	T_p	T_{dp}
Quartz latite	82QC44	26.0 ± 0.3	--	26.1 ± 0.3
Amalia Tuff	82L-42H [Sanidine]	25.7 ± 0.1	25.7 ± 0.1	--
"	82L-42D [Sanidine]	25.6 ± 0.1	25.5 ± 0.1	--
Rito del Medio	82QC22	24.9 ± 0.1	--	25.5 ± 0.3
Cabresto Lake	82QC51b	24.3 ± 0.1	--	25.0 ± 0.1
Virgin Canyon	82QC35	24.6 ± 0.2	24.7 ± 0.1	--
Red River	82QC32C	24.6 ± 0.1	24.6 ± 0.1	--
Porphyry dike	JM-87-47	24.7 ± 0.1	24.6 ± 0.1	--
Sulphur Gulch	JM-87-46	24.7 ± 0.1	24.6 ± 0.1	--
Mo-ore stage	1732A	24.3 ± 0.1	24.2 ± 0.3	--
"	PM-2	24.3 ± 0.1	24.1 ± 0.2	--
Bear Canyon	82QC8	23.9 ± 0.1	24.1 ± 0.1	--
Rio Hondo	84QC11	22.5 ± 0.2	--	23.3 ± 0.1
"	Q83J59	21.1 ± 0.1	--	21.2 ± 0.1
"	Q84J6	19.6 ± 0.2	--	19.7 ± 0.1
Lucero Peak	82QC15	18.6 ± 0.1	18.5 ± 0.1	--

* T_{tg} uncertainties are ± 1 sigma mean of duplicate runs but not less than 0.25%. For T_p and T_{dp}, uncertainties are 1/2 the range observed for replicate incremental-heating spectra. For biotite 82QC44, T_{dp} is based upon the average total gas age (26.0) and the difference between T_{tg} and T_{dp} for a single incremental-heating measurement. Uncertainties are relative; all ages also subject to ± 1% systematic uncertainty.

of ±1%, reflecting uncertainty in the monitor age, applies in addition to *all* the ages. The ages listed derive from an extensive data set for more than 75 mineral aliquots, and our presentation is highly condensed and simplified. Foland et al. (1990) have fully detailed the analytical results, and a complete discussion and geologic interpretation are in preparation.

Table 1 lists total-gas ages (either from total-fusion analyses or summation of all fractions of incremental-heating analysis) and plateau or "discordant plateau" ages from incremental-heating experiments. Plateau ages conform to the normal definition in which age differences among various gas fractions of the plateau may be considered within normal analytical uncertainties. Most samples produce good plateaus that generally agree well with total-gas ages; other samples show discordance with minor, yet analytically distinct, variation about a rather broad, flat region of the age spectrum. For these samples, "discordant plateau" ages are reported, based on all fractions contained in the flat part of the spectrum, excluding the highly discordant fractions of the early increments.

In our discussion, we use the ^{40}Ar/^{39}Ar age based on incremental-heating as the best value for each sample. The differences between total-gas and incremental-heating ages are small to insignificant for most samples. However, ages obtained from analysis of replicate discordant plateaus for biotite from the Rito del Medio and Cabresto Lake plutons and for the granitic phase (sample 84QC11) of the Rio Hondo pluton are distinctly older than those obtained from replicate total-gas counterparts. Although arguments for preferring each method could be advanced, we chose here to recommend consistently the ages based on the discordant plateaus. Our preference partly reflects the fact that for sample 82QC51b a discordant plateau age for hornblende is identical to that obtained for the coexisting biotite. Our interpretation is that the relatively minor discordance in these samples reflects ^{39}Ar recoil during irradiation of degraded biotite, and, as such, the integrated age is most appropriate.

RESULTS

Note that the Ar ages reported here represent the time when a mineral structure became closed to Ar loss, at about 300°C for biotite, and that hydrothermal alteration can produce spurious ages if Ar is mobile. Thus, the measured ages are open to interpretation based on thermal history. Because most of the plutons were emplaced at shallow levels, the reported ages are interpreted to reflect direct cooling from high temperatures and thus to approximate the timing of magmatic events. The ^{40}Ar/^{39}Ar ages are generally consistent with previous K-Ar measurements, especially the biotite ages reported by Lipman et al. (1986). However, as is to be expected, the new data permit greater resolution, and a closer examination of chronology.

The age of the Amalia Tuff and formation of Questa caldera appears well constrained at 25.7 ± 0.1 Ma by two sanidine samples that are essentially analytically equivalent. Our results for these Amalia Tuff sanidine separates are marginally younger, considering analytical uncertainties, than the K-Ar ages reported for them by Lipman et al. (1986). The new ^{40}Ar/^{39}Ar ages fall within the uncertainty of most K-Ar sanidine ages for the Amalia Tuff and related rocks reported by those authors. The 25.7-Ma age of caldera formation is also consistent with the age of 26.1 ± 0.3 Ma obtained for biotite from sample 82QC44 that has been interpreted to represent a precaldera quartz-latite feeder at Red River.

^{40}Ar/^{39}Ar ages for the later metaluminous phase of the Virgin Canyon pluton and samples of the Sulphur Gulch pluton, a silicic dike and granite of the Red River intrusive complex firmly establish a major intrusive episode at 24.65 ± 0.1 Ma. This date is earlier than that previously ascribed to the intrusions along the southern caldera margin and, for the first time, relates this activity to intracaldera plutonism. The interval of 1 million years between eruption of the Amalia Tuff and this episode is very well constrained. The comparable ages of these bodies, which extend over a large area, argue against differential cooling or thermal disturbance having had an important influence on biotite closure.

The age of 25.5 ± 0.3 Ma obtained for the Rito del Medio pluton agrees well with the K-Ar biotite age of 25.4 ± 1.0 Ma reported by Lipman et al. (1986). Because the Virgin Canyon and Cañada Pinabete plutons crop out less than 2 km from either side of the Rito del Medio pluton, their emplacement possibly could account for the biotite alteration, the discordant plateaus and the younger total-gas age observed for sample 82QC22.

Czamanske and Dillet (1988) and Johnson et al. (1989) argued that the mildly peralkaline Amalia Tuff magma evolved at the top of the batholitic magma chamber through processes of feldspar fractionation and possible alkali and halogen fluxes. Johnson et al. (1989, figs. 5D and 5E) showed that rare-earth-element plots for the most evolved rocks of the Cañada Pinabete pluton are strikingly similar to those that characterize the Rito del Medio pluton, and speculated from major- and minor-element considerations that the Rito del Medio pluton is an ultimate product of intracaldera magmatic differentiation. Virtually contemporaneous, possibly complementary processes apparently gave rise to peralkaline magma and to the body of volatile-rich metaluminous magma that was emplaced at a high level and crystallized as the Rito del Medio pluton. However, age relations between the Rito del Medio and Cañada Pinabete plutons are undefined because no attempt was made to date the Cañada Pinabete pluton in view of its remarkable petrologic similarity to the nearby Virgin Canyon pluton. Allowing comparable emplacement ages for the later metaluminous rocks of the Cañada Pinabete and Virgin Canyon plutons and assuming that the Rito del Medio pluton represents a derivative magma, we suggest that vagaries of "plumbing" caused the more evolved magma to be emplaced about 0.8 million years before representatives of its parental magma. Alternatively, one might propose that this specific magmatic lineage and identification of parental and derivative melts on the basis of chemistry alone is misleading. Rather, repeated processes of similar magma evolution might have produced these compositions at different times. On the basis of the new data indicating that plutonic activity in the Questa area was 7 million years in duration, we suggest that complex relations between differentiation, plumbing and emplacement can be realistically entertained.

The age of 25.0 ± 0.1 Ma for the Cabresto Lake pluton is in reasonable agreement with the K-Ar biotite age of 24.6 ± 0.9 Ma reported by Lipman et al. (1986). This age suggests that emplacement of this petrologically distinct intracaldera pluton, like that of the Rito del Medio pluton, was an isolated event. Although much of the pluton is distinctive, rocks along its southern margin, as well as spatial proximity, have led some workers to propose that this pluton may be related to the Sulphur Gulch pluton. In the sense that all the plutons under discussion are ultimately related, it must be; however, more likely the major intrusive events along the southern caldera margin were somewhat later and, indeed, may have been responsible for the discordant plateaus and younger total-gas age observed for sample 82QC51b.

Two samples of the coarse-grained molybdenite ore give ages of 24.2 ± 0.2 Ma, comparable to earlier K-Ar biotite ages for ore-stage biotite as summarized by Lipman et al. (1986). Because of irradiation design, we can be confident that about 0.4 million years elapsed between cooling of the Sulphur Gulch carapace granite and Mo mineralization. The age of 24.1 ± 0.1 Ma obtained for Bear Canyon sample 82QC8 shows that it represents younger intrusive activity along the caldera margin, comparable to the time of ore deposition. Unaltered samples of the Sulphur Gulch pluton are rarely observed in underground workings, but inasmuch as granitoids are continuous in the shallow subsurface, some phases of that pluton may have been emplaced contemporaneously with the dated Bear Canyon intrusive phase and could well have been a source of the ore-forming fluids.

Understanding the anomalous mesozonal aspect of the Rio Hondo granodiorite, in view of its suggested emplacement age of 25–26 Ma (Lipman et al., 1986), was one of the principal stimuli for the present study. The story remains complex, possibly owing to the considerations noted in the opening paragraph of this section. Samples Q84J6 and Q83J59 represent the dominant, granodioritic phase of the pluton. The age of 19.7 ± 0.2 obtained for sample Q84J6 is comparable to the K-Ar biotite age of 18.9 ± 0.9 reported by Lipman et al. (1986) for sample 80L-6A from nearby in Hondo Canyon. However, Hagstrum and Johnson (1986) and Johnson et al. (1990, figs. 5 and 6) have shown by paleomagnetic and stable-isotope measurements on whole-rock samples and mineral separates that parts of the Rio Hondo pluton, especially as exposed in Hondo Canyon, have undergone extensive high-temperature alteration. This alteration has also affected samples J-12 and J-35 of Johnson et al. (1990), resulting in spuriously old Rb-Sr ages. The significance of our 19.7-Ma result is clouded by uncertainties surrounding the timing and effect of the alteration and the potential influence of the distinctly younger Lucero Peak pluton just to the south. Hagstrum and Johnson (1986) conclude that the alteration took place above 350°C in a meteoric-hydrothermal system generated by the cooling Rio Hondo pluton, not by adjacent younger plutons.

Sample Q83J59, from well north of Hondo Canyon (Fig. 1) gives an age of 21.2 ± 0.1 Ma, which five additional lines of evidence indicate should be taken as a best estimate for the date of emplacement of the Rio Hondo granodiorite: (1) Johnson et al. (1990) report a biotite/whole-rock Rb-Sr age of 21.5 ± 0.2 Ma on their unaltered sample J-8; (2) Lipman et al. (1986) reported a K-Ar age of 21.8 ± 1.1 Ma for biotite in sample 78L-126A collected in the Columbine Creek drainage; (3) Lipman et al. (1986) reported a zircon fission-track age of 21.4 ± 1.0 Ma for the same sample; (4) Kelley and Duncan (1986, table 4, samples 81WP5 and 81WP6) reported apatite fission-track ages of 21.8 ± 3.6 and 21.3 ± 3.6 Ma for two Rio Hondo samples; and (5) Ian Williams (written commun., 1990) obtained a U-Pb zircon age of about 22 Ma for the Rio Hondo pluton using the SHRIMP ion probe. The close convergence of these ages by methods with widely different closure and annealing temperatures provides strong support not only for emplacement of the granodioritic part of the Rio Hondo pluton at about 21 Ma but also for its rather rapid cooling from magmatic temperatures. Thus, we prefer this emplacement date over the previously proposed date of 25–26 Ma (Lipman et al., 1986) and conclude that the ^{40}Ar/^{39}Ar ages significantly younger than those in the vicinity of the caldera cannot be attributed to later Ar closure due to differential erosion and protracted cooling.

Sample 84QC11 from the northern, granitic part of the pluton yields a discordant plateau age of 23.3 ± 0.1 Ma. Aside from proximity, mineral chemistry and assemblages link the granitic and granodioritic phases of the Rio Hondo pluton. Our interpretation is that the granitic phase of the Rio Hondo pluton was emplaced at a shallow level 2 million years before biotite closure in the dominant, granodioritic part of the pluton.

Biotite from the southernmost, Lucero Peak pluton gives an age of 18.5 ± 0.1 Ma, in good agreement with the K-Ar biotite age of 18.8 ± 0.9 Ma reported by Lipman et al. (1986, sample 80L-20). Molybdenite and pyrite mineralization in the South Fork body (Jones and Norris, 1984), considered an eastern outlier of the Lucero Peak pluton, indicate that ore-bearing fluids were available in the system for at least 6 million years.

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