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Yet another attempt to date the Banco Bonito rhyolite, the youngest volcanic flow in the Valles caldera, New Mexico

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Abstract

The Banco Bonito rhyolite flow is the youngest member of the El Cajete Series of the Valles Rhyolite Formation and represents the latest stages of extrusive volcanism associated with the Jemez Mountains volcanic field and the Valles caldera. The age of the Banco Bonito is important to understand the eruptive history and to evaluate volcanic hazards in the region. In this study we have applied optically stimulated luminescence (OSL) dating to a baked colluvial sediment layer immediately below the lava flow. Three distinct sets of ages emerged. OSL SAR ages from quartz sand averaged 140 ± 22 ka, corresponding to fission track ages for the Banco Bonito of ca. 130–140 ka (Marvin and Dobson 1979; Miyaji et al. 1985). Measured IRSL MAAD ages from polymineral fine silts averaged 20.7 ± 2.5 ka, corresponding to a sizable group of electron spin resonance (ESR) ages from members of the El Cajete Series (Ogoh et al. 1993). IRSL MAAD ages incorporating a regionally inferred data correction averaged 34.0 ± 4.2 ka, corresponding with cosmogenic ^{21}Ne ages for the Banco Bonito (Phillips et al. 1997). These correspondences may be linked to recurring thermal events in the caldera, as has been interpreted by past researchers but, ultimately, the OSL ages do not resolve the eruption age of the Banco Bonito flow.

Introduction

The Banco Bonito rhyolite flow is the youngest member of the El Cajete Series of the Valles Rhyolite Formation (Self et al. 1988, 1991). Along with the Battleship Rock ignimbrite and the El Cajete pumice fall deposits, the Banco Bonito rhyolite is a member of a group of rocks referred to as the southwestern moat rhyolites (Fig. 1) that represent the latest stages of volcanism associated with the Jemez Mountains volcanic field and the Valles caldera (Wolff et al. 1996). The volcanic history and stratigraphy of the Jemez Mountains has been studied extensively and reviewed in many publications (Gardner et al. 1986; Goff et al. 1986; Self et al. 1988, 1991; Toyoda et al. 1995; Reneau et al. 1996; and others). This communication is concerned with the age of the Banco Bonito flow and will focus on that aspect only.

The age of the Banco Bonito flow is important to understanding the eruptive history and cyclic nature of volcanism in Valles caldera as well as evaluating volcanic hazards in the region (Reneau et al. 1996). Several dating methods have been applied directly to the Banco Bonito including fission track dating, K-Ar dating, electron spin resonance (ESR) dating, ^{40}Ar/^{39}Ar dating, and cosmogenic ^{21}Ne analysis (see Toyoda et al. 1995 for a summary of early failures). Past results place the age of the Banco Bonito from as young as 26 ka to as old as 140 ka (summarized in Table 1). However, thermoluminescence (TL) and ESR dating of stratigraphically lower members of the southwestern moat rhyolites constrain the age of the Banco Bonito to less than ~50 ka (Toyoda et al. 1995; Toyoda and Goff 1996; Reneau et al. 1996). Many even younger ESR ages for the El Cajete pumice and the Battleship Rock ignimbrite, members of the El Cajete Series that lie stratigraphically below the Banco Bonito, have been reported. These ages, 12 in all—excluding samples from the VC-1 core, range from as young as 17 ± 3 ka to 45 ± 2 ka (Ogoh et al. 1993). However, these younger ages have been largely dismissed as deleteriously influenced by thermally induced ESR signal instabilities (Ogoh et al. 1993; Toyoda et al. 1995; Toyoda and Goff 1996). This interpretation of the ESR data has also been extrapolated to provide evidence of a caldera-wide hydrothermal event between 10 and 40 ka.

Optically stimulated luminescence (OSL) dating is a member of the family of dosimetric dating methods that includes TL, ESR, and fission track dating. These methods are developed around the central premise that geologic materials can record their exposure to ionizing radiation and this

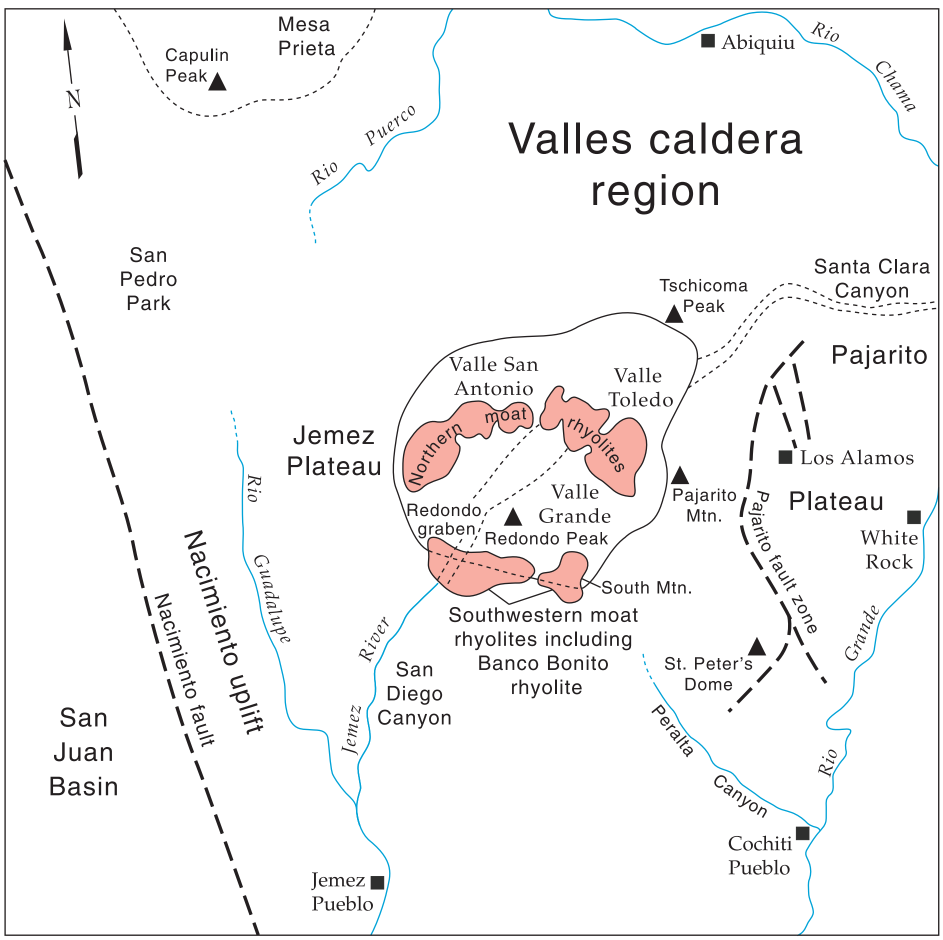

FIGURE 1—Map of the Jemez Mountains region. The southwestern moat rhyolites, which include the Banco Bonito rhyolite flow, are indicated just below center. Scale approximately 1:600,000. Modified from the frontispiece of Goff et al. (1996); reprinted by permission of the New Mexico Geological Society.

record (charge segregation, track damage) changes at a predictable rate over time. In its simplest form the OSL age equation can be expressed as:

$$t_{OSL} = \frac{D_e}{D'}$$

where t_{OSL} is the calculated age, D_e is the radiation dose absorbed by the sample, and D' is the local environmental dose rate. D_e can be obtained from various combinations of experimental and analytical techniques. Of the dosimetric dating methods listed above, only OSL has not been previously applied to the Banco Bonito. We report here OSL age analyses for the Banco Bonito rhyolite from measurements made on colluvial sediments immediately beneath the flow.

Methods

Before this study Goff identified an exposure of thermally altered (baked contact) colluvial sediment immediately below the Banco Bonito rhyolite flow along the wall of a tributary canyon to the Jemez River (N 35°50′13.9″ W 106°37′22.9″; 2,455 m [8,054 ft] elevation). The rhyolite here is extremely glassy but contains abundant phenocrysts of quartz, plagioclase, clinopyroxene, biotite, and hornblende. The colluvium is poorly sorted sandy silt with angular and subangular gravel to cobble-sized clasts. The former colluvial surface was in direct contact with the overflowing lava during eruption, resulting in color alteration of the sediment (reddening; Fig. 2) as well as an increase in the degree of sediment induration. Clasts also exhibit alteration rinds from heating. This type of volcanic "baking" has been shown to effectively zero the luminescence signal within sediment grains (e.g., Reneau et al. 1996). Samples for OSL dating were collected in the colluvium approximately 20 cm below the contact with the rhyolite by percussively inserting a thick-walled black PVC cylinder into the target deposits. The sample suffered some disaggregation during the sampling process but was considered acceptable for dating.

Quartz sand in the grain size range from 90 to 250 µm was obtained from the field sample using common procedures for luminescence dating studies, which include wet sieving, digestion of organic matter by H_2O_2, aggressive treatment with HF acid to etch quartz grains surfaces and dissolve feldspars, followed by HCl and Na-pyrophosphate rinses to remove precipitates and particulates. After drying, the clean sand grains were attached to stainless steel planchets for OSL measurements using a non-luminescent medical adhesive. These prepared sub-samples are referred to as aliquots. Only a small quantity of clean quartz sand was recovered from the field sample. Polymineral fine-grained silts were extracted from the field samples as well. Again, common luminescence dating pretreatment procedures were employed, which in this case included HCl and H_2O_2 treatments to remove carbonates and digest organic matter followed by Stoke's Law settling and centrifugation to isolate the 4–11 µm size fraction. Measurement aliquots were prepared by evaporation plating.

TABLE 1—Ages determined directly from the Banco Bonito rhyolite.

Age (ka)	Method	Source
140 ± 50	fission track	Miyaji et al. 1985*
130 ± 100	fission track	Marvin and Dobson 1979*
70 ± 11	^{21}Ne	Phillips et al. 1997
45 ± 6	^{21}Ne	Phillips et al. 1997
45 ± 2	ESR	Ogoh et al. 1993
37 ± 6	ESR	Ogoh et al. 1993
37 ± 4	^{21}Ne	Phillips et al. 1997
34 ± 2	^{21}Ne	Phillips et al. 1997
26 ± 3	^{21}Ne	Phillips et al. 1997

*As reported in Toyoda and Goff 1996

All measurements and irradiations were conducted in the Optical Dating and Dosimetry (ODD) Lab at North Dakota State University using a Risø DA-15 automated TL/OSL reader system. The system is equipped with a 40 m Ci $^{90}Sr/^{90}Y$ beta-source, a blue diode array (OSL; 470 ± 30 nm), an infrared laser diode assembly (IRSL; 830 ± 10 nm), and an EMI model 9235QA PMT. Stimulated luminescence was measured in the UV emission range (7.5 mm Hoya U-340) for all data sets in this report.

Dose response data were collected from the sand fraction using OSL single aliquot regenerative dose (SAR) procedures as presented in Murray and Wintle (2000, 2006) with the minor modification of maintaining uniform cut heat and preheat treatments of 160°C for 10s (Lepper et al. 2000).

Equivalent dose data were collected from the fine-silt fraction of the field samples using infrared stimulation and multi-aliquot additive dose procedures (IRSL MAAD; Wintle 1997; Aitken 1998; Forman et al. 2000) with preheats of 240°C for 60s. The D_e data were collected as three "standard" IRSL MAAD data sets, which consisted of four aliquots in each of six treatment groups with one treatment group being the "natural" or unaltered signal from the field sample. In addition, the "natural" signal was also measured from an independent set of 48 aliquots. Dose response calibration was based on extrapolation using a saturating exponential model. All data were dose normalized following primary IRSL measurements. Anomalous fading over a period of 32 days was documented at 7 ± 1% or 3.35%/decade (as prescribed by Huntley and Lamothe 2001).

Three approaches were taken to the analysis of the IRSL MAAD data set. The first approach was traditional IRSL MAAD age calculations based on the three independent, standard data sets using ANALYST software and the cumulative plateau method of Duller (2003). The second approach was to combine the data from all 60 additive dose aliquots, 12 aliquots in each of five treatment groups, into a master growth curve. Data from each individual "natural" aliquot were then paired with the master curve, thereby calculating 60 unique but not fully independent equivalent doses. In the third approach we applied a resampling or bootstrapping technique to analyze the IRSL MAAD data (Lepper and Denton 2006). "Sampling with replacement" was used, meaning that the same experimental value can contribute to the D_e calculation multiple times. The resampling approach allowed 10,000 equivalent doses to be determined from the MAAD data sets. Both the second and third data analysis approaches resulted in MAAD-derived D_e distributions that could then be statistically interrogated.

Dose rates for samples in this investigation were determined from elemental concentrations of potassium (K), rubidium (Rb), thorium (Th), and uranium (U) in the colluvium by the method presented in Aitken (1998). Elemental analysis was obtained via instrumental neutron activation (INAA) at the Ohio State University research reactor and were: 41,330 ± 5,290 ppm K, 79.19 ± 7.56 ppm Rb, 12.93 ± 1.19 ppm Th, and 3.33 ± 0.38 ppm U. The cosmic ray dose at depth was calculated using the equations of Prescott and Hutton (1988, 1994) taking

FIGURE 2— OSL sampling of the baked contact (distinctively reddened sediments) in colluvium overridden by the Banco Bonito rhyolite. A metal canister is being used as a shield over and around the black PVC sample cylinder.

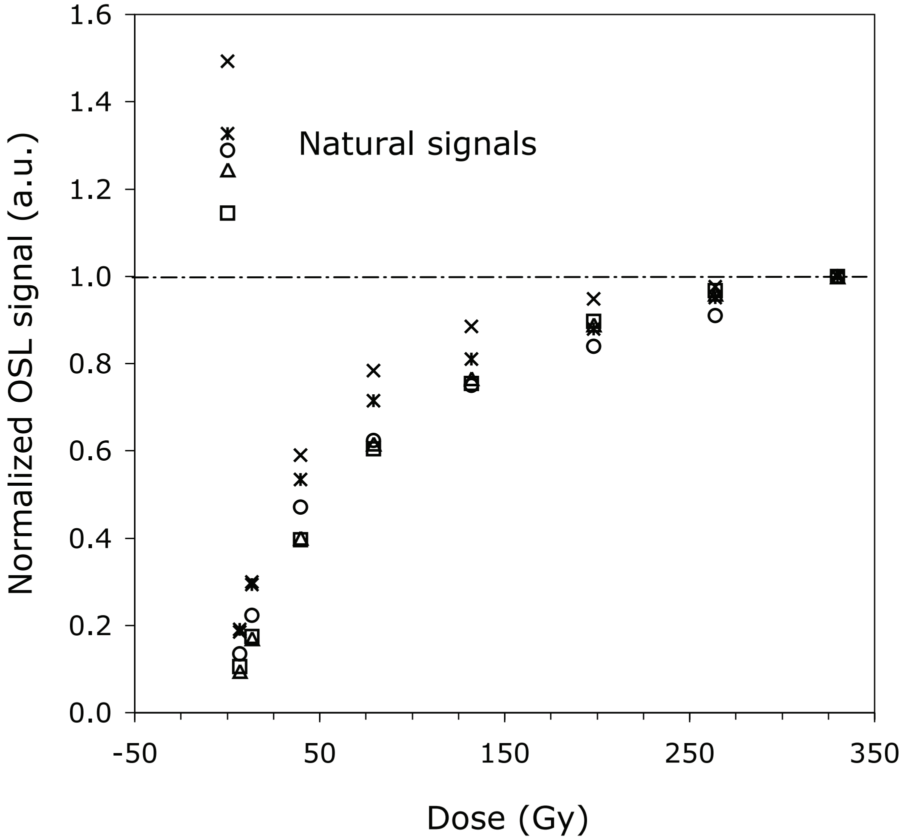

FIGURE 3—Graph showing natural OSL SAR signal levels and subsequently generated dose response curves for aliquots of quartz sand (90–250 µm) from colluvial sediment immediately below the Banco Bonito rhyolite. All data points were normalized to the signal recorded from the maximum administered dose (330 Gy).

into account a hard component dose rate of 0.30 Gy/ka in the Jemez Mountains. An alpha-efficiency value of 0.055 was used for all IRSL MAAD calculations in this investigation based on the average of measured values from past dating studies using fine silts in the area (Berger 1999; S. Forman and J. Pierson, unpubl. data). A beta attenuation factor of 0.89 was used as an average for sands in the grain size range from 90 to 250 µm. An average water content of 15 ± 5% was estimated for the colluvium based on the site location in a forested mountain setting. These data resulted in dose rates of 5.910 ± 0.490 Gy/ka and 4.812 ± 0.436 Gy/ka for the polymineral fine silts and the quartz sands, respectively. Although the sample was collected near an igneous contact, adjusting the dose rate for the colluvium was not considered necessary because the dose rate reported in Ogoh et al. (1993) for the Banco Bonito itself was 5.38 Gy/ka.

Results and discussion

Results of OSL SAR measurements made on quartz sand isolated from the colluvial sample are shown in Figure 3. The data shown include a correction for sensitivity change that is built into the SAR data collection routine. Even so, all five aliquots approach saturation at a signal level below that recorded from the "natural" or field sample. Modeling of the dose response of these aliquots using a single saturating exponential model suggests OSL signal saturation for the quartz grains in this sample occurs at ~300 Gys (1 Gy = 1 J/kg) or the age-equivalent of ~60 ka. This "premature saturation" behavior has been observed in other studies of volcanically derived quartz sands extracted from sediments in the region (Lepper et al. 2003; Gardner et al. 2003).

An alternate approach would be to use a two-component dose response model incorporating both a saturating exponential and linear term to describe the quartz sand SAR data. In this scenario equivalent doses could be extrapolated from all five aliquots (Table 2). Such an analysis would result in

TABLE 2—OSL dating results.

Method	N[1]	Equivalent dose (Gy)	Uncorrected age (ka)	Sample corrected[2] age (ka)	Regionally corrected[3] age (ka)
Quartz sand: 90–250 µm					
Blue-OSL SAR aliquot 1	1/1	427 ± 76	89 ± 19		
Blue-OSL SAR aliquot 2	1/1	523 ± 70	109 ± 19		
Blue-OSL SAR aliquot 3	1/1	1,190 ± 150	248 ± 42		
Blue-OSL SAR aliquot 4	1/1	661 ± 30	137 ± 16		
Blue-OSL SAR aliquot 5	1/1	565 ± 16	117 ± 14		
Quartz sand average	—	—	**140 ± 22**		
Polymineral fine silt: 4–11 µm					
Standard IRSL MAAD trial 1	24/1	82.7 ± 3.1	14.0 ± 1.7	16.7 ± 2.0	27.0 ± 3.4
Standard IRSL MAAD trial 2	24/1	131.6 ± 6.4	22.3 ± 2.8	26.8 ± 3.4	44.7 ± 5.8
Standard IRSL MAAD trial 3	24/1	95.4 ± 4.6	16.1 ± 2.0	19.3 ± 2.4	31.4 ± 4.0
IRSL MAAD master curve distribution	120/60	101.2 ± 1.6	17.1 ± 2.0	20.5 ± 2.4	33.5 ± 4.0
IRSL MAAD bootstrapped distribution	72/10,000	100.6 ± 1.1	17.0 ± 1.9	20.4 ± 2.3	33.3 ± 3.9
Polymineral fine silt averages	—	—	**17.3 ± 2.1**	**20.7 ± 2.5**	**34.0 ± 4.2**

[1]number of aliquots measured/number of equivalent doses calculated
[2]corrected for the fading rate documented for the sample in this study (correction method from Huntley and Lamothe 2001)
[3]corrected for a regionally inferred fading rate (correction method and inferred fading rate from Huntley and Lamothe 2001)

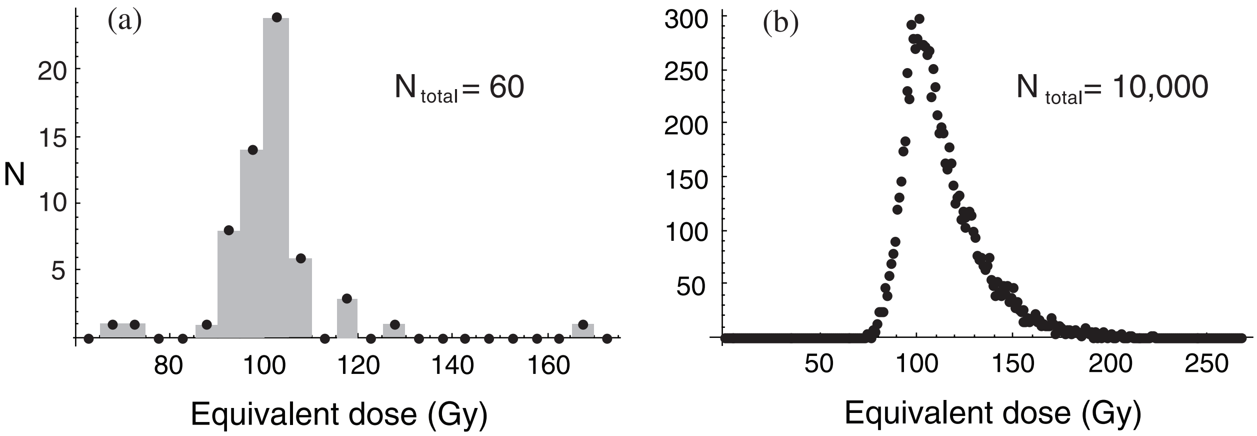

FIGURE 4—IRSL MAAD dose distributions obtained from the polymineral fine-silt fraction of the baked colluvium sample using the (a) master growth curve and (b) bootstrapping data analysis approaches. In panel (a) the distribution is shown as a typical histogram with vertical bars and also as a set of points representing the bin center and the number of occurrences in each bin. The vertical bars have been omitted from panel (b) because of the large number of observations.

an average OSL SAR age of 140 ± 22 ka, which is interestingly coincident with fission track ages of 140 ± 50 ka reported by Miyaji et al. (1985) and 130 ± 100 ka by Marvin and Dobson (1979) for the Banco Bonito rhyolite. However, we believe the summation of many past studies, in particular Toyoda et al. (1995) and Reneau et al. (1996), accurately constrain the age of the Banco Bonito to less than ~50 ka.

Ages calculated from IRSL MAAD data collected from the polymineral fine-silt fraction of the baked colluvium sample are presented in Table 2. Graphical results in the form of dose distributions produced from the master growth curve and bootstrapping data analysis approaches are shown in Figure 4. In the table the ages are given in three forms: (i) uncorrected, (ii) sample corrected, and (iii) regionally corrected. In the first case no attempt was made to compensate for anomalous fading, an athermal signal instability observed only in feldspars (Wintle 1973), and is therefore not relevant to the quartz sand SAR data. In the second and third cases the ages were computationally corrected for anomalous fading using the method of Huntley and Lamothe (2001). In case two a fading rate of 3.35%/decade was documented for the sample in this study and used in the correction equations. In case three a fading rate of 9.5%/decade was used based on broad regional categorizations presented in Huntley and Lamothe (2001).

Regardless of the analytical approach used, the IRSL MAAD results are consistent for each case (i–iii). The two dose distribution methods yield indistinguishable ages, and the D_es from traditional analyses fall within the range of both distributions. The uncorrected ages range from 14.0 to 22.3 ka and would certainly be among the youngest reported for members of the El Cajete Series. Sample corrected ages (case ii) range from 16.7 to 26.8 ka with an average of 20.7 ± 2.5 ka. These ages would span the range from the youngest reported ESR ages for any members of the El Cajete Series (17 ± 3 ka; Ogoh et al. 1993) to the lowest in the set of ^{21}Ne ages for the Banco Bonito (26 ± 3 ka; Phillips et al. 1997). These "sample corrected" ages are most consistent with ESR ages of Ogoh et al. (1993) from lower members of the El Cajete Series that have been used as evidence for a caldera-wide heating event, but have been largely dismissed as valid ages (Toyoda et al. 1995; Toyoda and Goff 1996).

The regionally corrected IRSL ages (case iii) range from 27.0 to 44.7 ka with an average of 34.0 ± 4.2 ka. This range of ages and average is coincident with the range and average of the ^{21}Ne ages, 26–45 ka with an average of 37 ± 5 ka (excluding one extraneously large value). We believe there is merit in considering the regional correction value because a fading rate of ~3%/decade would be unexpectedly low for sediments derived from volcanic parent materials (Lamothe, pers. comm. 2006) and the thermal shock experienced by sediment grains in the baked colluvium could alter the mineral's defect structure (annealing), which in turn could have led to an erroneously low characterization of the samples' anomalous fading rate. However, we emphasize here, for the sake of clarity, that the fading rate used for regional correction (case iii) was based on inference from work published by Huntley and Lamothe (2001) not on a measured value as in case ii above.

Conclusions

Three distinct sets of ages have emerged from this OSL investigation of a baked colluvial sediment layer immediately below the Banco Bonito rhyolite flow. OSL SAR ages from quartz sand average 140 ± 22 ka, corresponding to fission track ages of ca. 130–140 ka (Marvin and Dobson 1979; Miyaji et al. 1985). Measured IRSL MAAD ages from polymineral fine silts average 20.7 ± 2.5 ka, corresponding to a sizable group of ESR ages from members of the El Cajete Series (Ogoh et al. 1993). IRSL MAAD ages incorporating a regionally inferred data correction average 34.0 ± 4.2 ka, corresponding to cosmogenic ^{21}Ne ages for the Banco Bonito (Phillips et al. 1997). These correspondences may be linked to recurring thermal events in the caldera, as has been interpreted by past researchers, but ultimately, these OSL analyses do not resolve the eruption age of the Banco Bonito rhyolite flow.

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References

Aitken, M. J., 1998, An introduction to optical dating: New York, Oxford University Press, 267 pp.

Berger, G. W., 1999, Optical dating of sediments from Pajarito fault trenches at Los Alamos, New Mexico: Desert Research Institute, Reno, Nevada, Unpublished report for Los Alamos National Laboratory, New Mexico, USA.

Duller, G. A. T., 2003, Luminescence ANALYST soft-

ware: Aberystwyth, University of Wales, Institute of Geography and Earth Sciences, 38 pp.
Forman, S. L., Pierson, J., and Lepper, K., 2000, Luminescence geochronology; *in* Sowers, J. M., Noller, J. S., and Lettis, W. R. (eds.), Quaternary geochronology—methods and applications: American Geophysical Union, AGU Reference Shelf 4, pp. 157–176.
Gardner, J. N., Goff, F., Garcia, S., and Hagan, R., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 91, pp. 1763–1778.
Gardner, J. N., Reneau, S. L., Lavine, A., Lewis, C. J., Katzman, D., McDonald, E. V., Wilson, J., Goodwin, L., Kelson, K. I., Lepper, K., and Wilson, C., 2003, Paleoseismic trenching in the Guaje Mountain fault zone, Pajarito fault system, Rio Grande rift, New Mexico: Los Alamos National Laboratory, Report LA-14087-MS, 68 pp.
Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), 1996, Jemez Mountains region: New Mexico Geological Society, Guidebook 47, 484 pp.
Goff, F., Rowley, J., Gardner, J. N., Hawkins, W., Goff, S., Charles, R., Wachs, D., Maassen, L., and Heiken, G., 1986, Initial results from VC-1, first Continental Scientific Drilling Program core hole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, no. B2, pp. 1742–1752.
Huntley, D. J., and Lamothe, M., 2001, Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating: Canadian Journal of Earth Science, v. 38, pp. 1093–1106.
Lepper, K., and Denton, A., 2006, Equivalent dose distributions from MAAD data sets (abs.): New World Luminescence Dating and Dosimetry Workshop, Denver, Colorado, Abstracts, v. 4, p. 14.
Lepper, K., Agersnap-Larsen, N., and McKeever, S. W. S., 2000, Equivalent dose distribution analysis of Holocene eolian and fluvial quartz sands from central Oklahoma: Radiation Measurements, v. 32, pp. 603–608.
Lepper, K., Wilson, C., Gardner, J., Reneau, S., and Lavine, A., 2003, Comparison of SAR techniques for luminescence dating of sediments derived from volcanic tuff: Quaternary Science Reviews, v. 22, pp. 1131–1138.
Marvin, R. F., and Dobson, S. W., 1979, Radiometric ages: compilation B, U.S. Geological Survey: Isochron/West, no. 26, pp. 3–32.
Miyaji, M., Izett, G. A., Naeser, C. W., Naeser, N. D., and Andreissen, P. A. M., 1985, Zircon fission-track ages on some volcanic rocks and pyroclastic flow deposits on the Jemez Mountains, New Mexico: Bulletin of the Volcanological Society of Japan, v. 30, pp. 90–91.
Murray, A. S., and Wintle, A. G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, pp. 57–73.
Murray, A. S., and Wintle, A. G., 2006, A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols: Radiation Measurements, v. 41, pp. 369–391.
Ogoh, K., Toyoda, S., Ikeda, S., Ikeda, I., and Goff, F., 1993, Cooling history of the Valles caldera, New Mexico, using ESR dating method: Applied Radiation and Isotopes, v. 44, pp. 233–237.
Phillips, W. M., Poths, J., Goff, F., Reneau, S., and McDonald, E., 1997, Ne-21 surface exposure ages from the Banco Bonito obsidian flow, Valles caldera, New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 29, no. 6, p. A-419.
Prescott, J. R., and Hutton, J. T., 1988, Cosmic ray and gamma ray dosimetry for TL and ESR: Nuclear Tracks and Radiation Measurements, v. 14, pp. 223–227.
Prescott, J. R., and Hutton, J. T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations: Radiation Measurements, v. 23, pp. 497–500.
Reneau, S. L., Gardner, J. N., and Forman, S. L., 1996, New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico: Geology, v. 24, pp. 7–10.
Self, S., Kircher, D. E., and Wolff, J. A., 1988, The El Cajete Series, Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, no. B6, pp. 6113–6127.
Self, S., Wolff, J. A., Spell, T. L., Skuba, C. E., and Morrissey, M. M., 1991, Revisions to the stratigraphy and volcanology of the post-0.5 Ma units and the volcanic section of VC-1 core hole, Valles caldera, New Mexico: Journal of Geophysical Research, v. 96, no. B3, pp. 4107–4116.
Toyoda, S., and Goff, F., 1996, Quartz in post-caldera rhyolites of Valles caldera, New Mexico: ESR finger printing and discussion of ESR ages; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 303–309.
Toyoda, S., Goff, F., Ikeda, S., and Ikeda, M., 1995, ESR dating of quartz phenocrysts in the El Cajete and Battleship Rock Members of the Valles Rhyolite, Valles caldera, New Mexico: Journal of Volcanology and Geothermal Research, v. 67, pp. 29–40.
Wintle, A. G., 1973, Anomalous fading on thermoluminescence in mineral samples: Nature, v. 245, pp. 143–144.
Wintle, A. G., 1997, Luminescence dating: laboratory procedures and protocols: Radiation Measurements, v. 27, pp. 769–817.
Wolff, J. A., Gardner, J. N., Reneau, S. L., 1996, Field characteristics of the El Cajete pumice and associated southwestern moat deposits of the Valles caldera; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 311–316.