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RESEARCH ARTICLE

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Emplacement age of the Markagunt gravity slide in southwestern Utah, USA

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Abstract

The Markagunt gravity slide (MGS) is a large-volume landslide in southwestern Utah that originated within the Oligocene-Miocene Marysvale volcanic field. Gravity slides are single emplacement events with long runout distances and are now recognized as a new class of volcanic hazard. Accumulation of volcanic material on a structurally weak substrate along with voluminous shallow intrusive events led to collapse. Here, $^{40}Ar/^{39}Ar$ data for landslide-generated pseudotachylyte, the landslide-capping Haycock Mountain Tuff and the deformed Osiris Tuff are combined with a Bayesian age model to determine an emplacement age of 23.05 + 0.22/−0.20 Ma for the MGS. The results suggest a lag time of <200 kyr between the caldera-forming eruption of the Osiris Tuff, additional buildup of the unstable volcanic pile and subsequent mass movement.

1 | INTRODUCTION

Large-volume gravity slides have recently been recognized as a class of volcanic hazard (Biek et al., 2019; Hacker et al., 2019). These mass movements are so large that they can remain undetected despite rigorous geological mapping because their structures may be mistaken for tectonic features. The term “gravity slide” refers to gigantic, geologically older (>Quaternary), commonly lithified and deeply eroded landslides, and are thus distinguished from smaller volcanic features such as sector collapses and debris avalanche deposits which are globally common (e.g. Carrasco-Núñez et al., 2011; Siebert et al., 2006). One of the first gravity slides to be recognized was the Heart Mountain gravity slide in Wyoming, USA (>3400 km^2). The low-angle movement of that slide is attributed to eruptions within the Eocene Absaroka volcanic field (Malone, 1995; Malone et al., 2017). In southwestern Utah, three large-volume gravity slides have been identified in association with the growth of the Oligocene-Miocene Marysvale volcanic field (MVF; Figure 1). The Marysvale gravity slide complex (MGSC) consists of three sequential collapses originating from a locus of stratovolcanoes that cover a combined area of >8000 km^2 (Biek et al., 2019). From east to west, these are the Sevier, Markagunt and Black Mountains gravity slides.

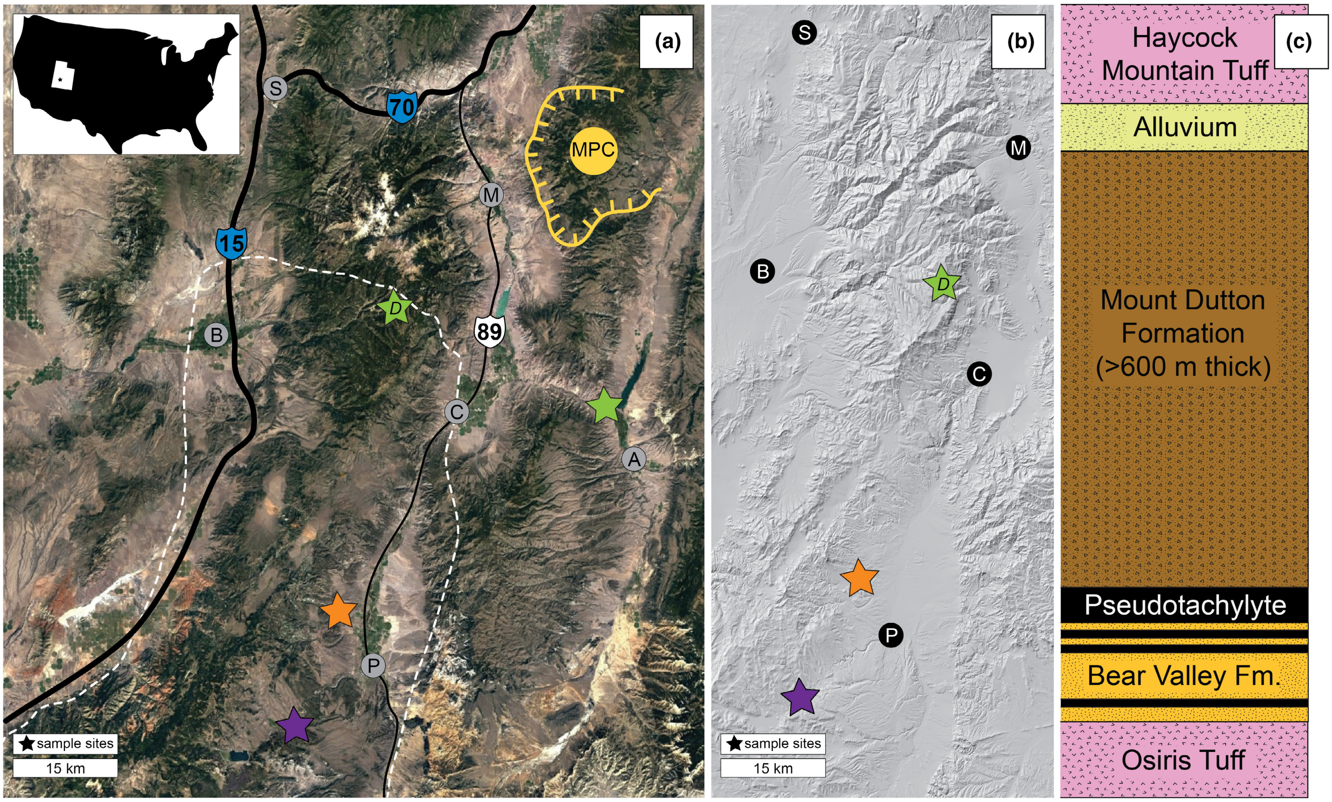

FIGURE 1 (a) Location of the Markagunt gravity slide, which occupies the region bounded by the dashed white line. Monroe peak caldera (MPC) is bound in yellow. Base map generated using Google Earth. (b) Digital elevation model of the Markagunt gravity slide area. Base map generated using 10 m USGS data through the Open Topography portal (USGS, 2021). Sample locations are indicated by the orange (pseudotachylyte), purple (Haycock Mountain Tuff), and green (Osiris Tuff; D = deformed) stars. Towns indicated are as follows: S: Sulphurdale; B: Beaver; M: Marysvale; C: Circleville; P: Panguitch; a: Antimony. (c) Generalized stratigraphy, not to scale, of the Markagunt gravity slide and units discussed within this work. The Haycock Mountain Tuff (~11 m thick) erupted after MGS emplacement. Pseudotachylyte (up to 3 cm thick) occurs within the upper 1 m of the Bear Valley Formation and at the contact between the Bear Valley and Mount Dutton formations (>600 m thick). The Osiris Tuff (typically 30–45 m thick) is sheared and brecciated in the slide breakaway zone (Biek et al., 2019), but undeformed east of the Markagunt slide

Like the Heart Mountain gravity slide, the >1 000-m-thick allochthonous package of rocks within the MGSC was displaced 35 km over a shallow (<3°) dipping former land surface (Hacker et al., 2014). The identification of multiple slides within the MGSC, the ability to mistake large gravity slide features for tectonic structures and the existence of similar volcanic fields elsewhere in the United States, may suggest that volcanically induced gravity slides are more common than previously thought.

The MVF straddles the boundary between the Colorado Plateau and the Basin and Range Province and likely formed through Farallon Plate subduction (Rowley et al., 1998). During the Oligocene and Miocene, volcanism produced andesitic to dacitic lava flows and ash-flow tuffs. These volcanic products underlie, overlie and intertongue with lahar deposits. Each of the MGSC's slides incorporate different stratigraphic units and volcanic products of the MVF. Pseudotachylyte generated through friction-induced melting during mass movement can provide an age constraint for the emplacement of the gravity slide. However, attempts to precisely ^{40}Ar/^{39}Ar date this type of glass are hampered by low potassium content and the potential of the glass to trap atmospheric Ar during generation of the pseudotachylyte (e.g. Kelley et al., 1994; Reimold et al., 1990; Sherlock & Hetzel, 2001; Spray et al., 1995). Here, an emplacement age for the Markagunt gravity slide (MGS) is determined by combining ^{40}Ar/^{39}Ar dating with a Bayesian age model to statistically optimize the age of landslide-generated pseudotachylyte. The model uses new ^{40}Ar/^{39}Ar dates of the undeformed landslide-capping tuff, deformed underlying tuff and pseudotachylyte generated during the gravity slide. Improved age constraints of the gravity slide aid in understanding the timing of the buildup of the MVF, examining potential cause and effect relationships between volcanic activity and catastrophic slope failure and contribute to the timing and evolution of landscape development of the ancestral Colorado Plateau.

2 | GEOLOGIC SETTING

The MVF spans over 10 000 km^2 with a volume of 12 000 km^3 (Figure 1; Rowley et al., 1998, 2002). Three major caldera complexes and other volcanic events produced bimodal basalt-rhyolite lavas, andesites, dacites and high-alkali rhyolitic ash-flow tuffs

(Cunningham et al., 1998, 2007; Cunningham & Steven, 1979; Rowley et al., 1994, 1998; Steven et al., 1984). Significant lahar deposits throughout the MVF are evidence of the instability in the volcanic terrain, but the primary driver of the large-scale gravity slide failure remains unclear. The MVF demonstrates a trend of younger eruptions correlated to higher silica and potassium weight percent towards the southwest (Rockwell et al., 2000), coincident with the westward younging of the gravity slides. The transition from initial calc-alkaline to bimodal volcanism may be a direct result of the transition from arc volcanism to basin and range extension (Rowley et al., 2002).

The MGS consists of allochthonous lahar, lava flow and debris avalanche deposits derived from multiple volcanic centres. Key MGS units discussed in this work include the ~23–25 Ma Bear Valley (BV) Formation (Biek et al., 2019) and the ~23–30 Ma Mount Dutton Formation (Figure 1c). Pseudotachylyte occurs at the contact between the BV sandstone and the overlying Mount Dutton Formation, and within the BV sandstone (Figure 2). The basal layers of the slide deposit incorporate sediments from the BV, Isom, Brian Head and other formations and propagate into the upper plate as clastic dikes (Mayback et al., 2022). In the breakaway region, the slide deforms the trachytic Osiris Tuff (Figure 1a; Biek et al., 2019).

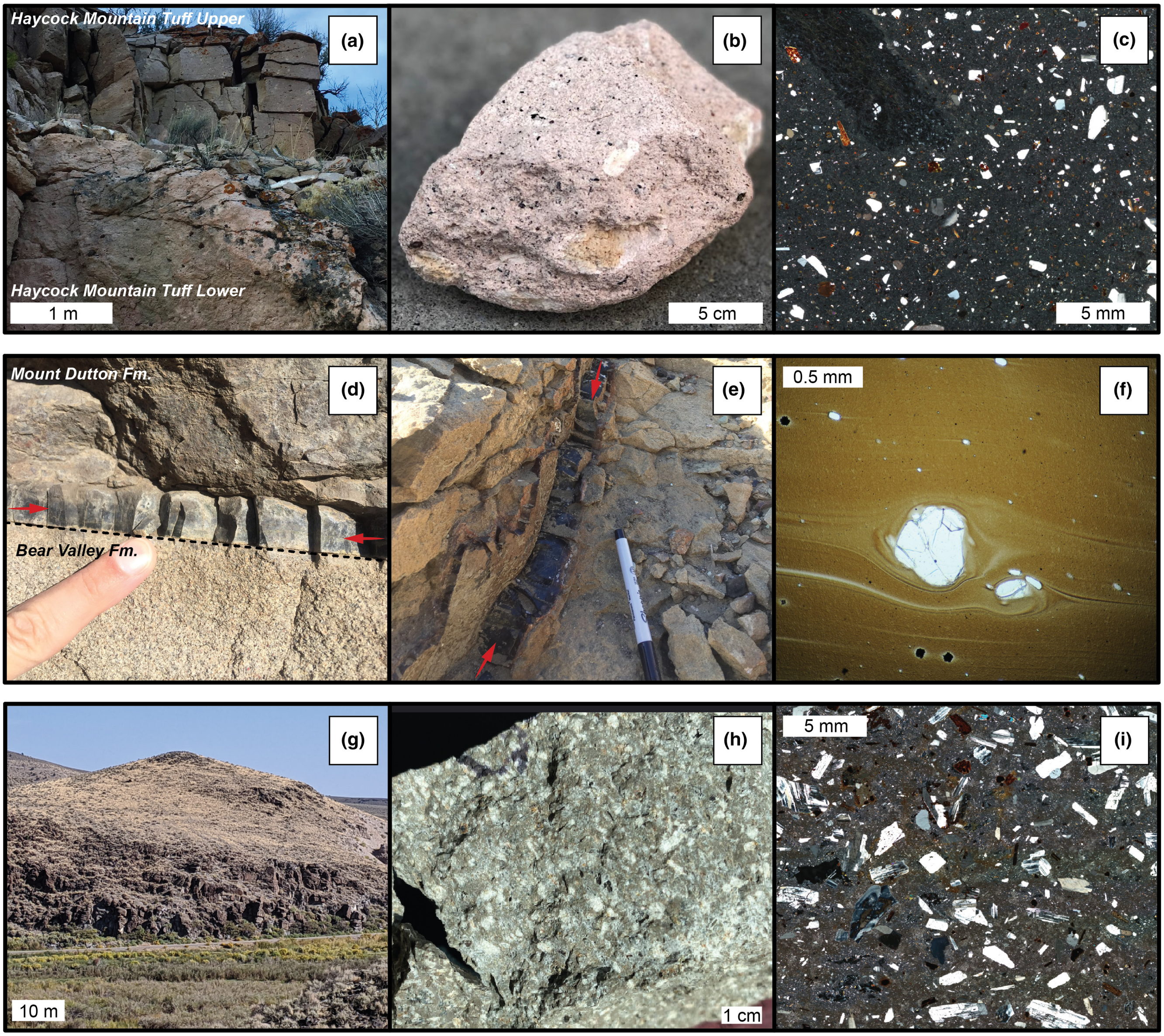

FIGURE 2 (a) Outcrop of Haycock Mountain Tuff showing the lower massive and upper densely welded units. (b) Hand sample of lower Haycock Mountain Tuff showing pumice fragments (white and brown, centre) and prominent biotite phenocrysts. (c) Portion of a thin section of the Haycock Mountain Tuff; cross-polarized light. (d) Pseudotachylyte vein (red arrows) between Bear Valley Formation sandstone and the Mount Dutton Formation. (e) Pseudotachylyte vein (red arrows) within the Bear Valley Formation sandstone. A ~ 2 mm thick chilled margin can be seen on the right side. (f) Pseudotachylyte and relict quartz in thin section; plane-polarized light. (g) Outcrop of undeformed Osiris Tuff. (h) Hand sample of Osiris Tuff showing feldspar dominating the phenocryst assemblage. (i) Portion of a thin section of the Osiris Tuff, cross-polarized light

The eruption of the Osiris Tuff led to the collapse of the Monroe Peak caldera; caldera outflow deposits of the Osiris Tuff are typically 30–45 m thick. The MGS is capped by the undeformed Haycock Mountain Tuff (HMT), whose source remains unknown, but exposures of this tuff are confined to the southern Markagunt Plateau (Rowley et al., 1994).

3 | MATERIALS AND METHODS

The Haycock Mountain Tuff (HMT) that caps the gravity slide consists of two cooling sheets (Figure 2a). The lower unit is massive and moderately welded, with xenoliths of basaltic material near its base. The upper unit is more densely welded and xenoliths become less abundant from bottom to top. Our sample comes from the interior of the lower unit. The tuff contains pumice clasts and phenocrysts of biotite, plagioclase, sanidine and rare quartz (Figure 2b,c); a glassy groundmass is observed in thin section (Figure 2c). Located on private land, the pseudotachylyte locality is ~15 km from the sampling location of the HMT (Figure 1). A prominent 2-cm-thick pseudotachylyte vein is exposed in an outcrop of ~1.5 m height where faulting places rocks of the Mount Dutton Formation above sandstone of the BV Formation (Figure 2d). The pseudotachylyte vein extends for ~8 m within this outcrop, and other pseudotachylyte veins are apparent on the ground surface or within outcrops of the BV sandstone at this location. Chilled margins are observed in some veins (Figure 2e) and relict quartz and biotite are observed in thin section (Figure 2f). The undeformed densely welded Osiris Tuff consists of a grey matrix, prominent plagioclase and K-rich feldspar up to 1 cm in length with subordinate biotite and pyroxene (Figure 2g–i). The dated sample comes from an undeformed outcrop located east of the MGS (Figure 2g); however, the Osiris Tuff is sheared and shattered in the breakaway zone of the MGS (Figure 1).

3.1 | $^{40}Ar/^{39}Ar$ analysis

Sanidine and K-feldspar separation from the HMT and Osiris Tuff followed standard magnetic and density techniques. Pseudotachylyte glass chips (250–500 μm) were handpicked to eliminate cooling rinds or relict grains. Handpicked feldspar crystals and glass chips were irradiated in the Cd-lined facility of the Oregon State University TRIGA reactor with the 28.201 Ma Fish Canyon Tuff sanidine monitor (Kuiper et al., 2008). Single HMT and Osiris Tuff feldspar crystals were analysed via total fusion and bulk pseudotachylyte chips were analysed by incremental heating at the WiscAr Geochronology Lab, University of Wisconsin-Madison using a Noblesse 5 collector mass spectrometer. Full analytical procedures are provided in Jicha et al. (2016).

4 | RESULTS

Eighteen single sanidine crystals of the HMT produced dates ranging from 22.73 ± 0.06 Ma to 23.09 ± 0.05 Ma (1σ analytical uncertainty; Figure 3a). Fifteen of these grains define a single population with a weighted mean age of 22.84 ± 0.04 Ma (2σ includes uncertainty on *J*). Thirteen K-feldspars of the Osiris Tuff produced dates ranging from 23.16 ± 0.16 Ma to 23.37 ± 0.08 Ma (1σ analytical uncertainty; Figure 3b); a weighted mean of all crystals yields an age of

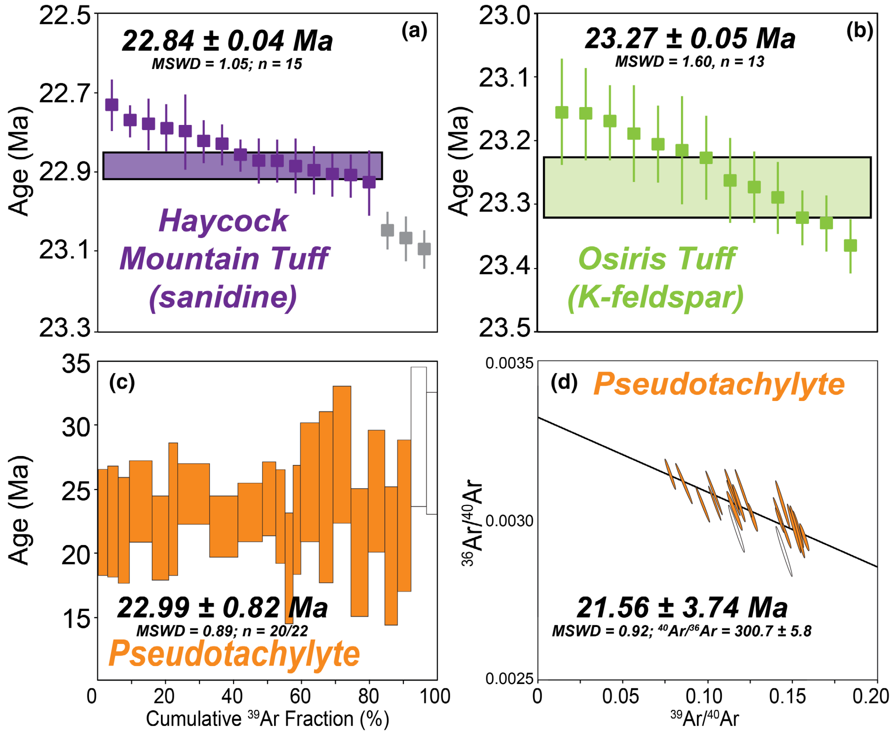

FIGURE 3 (a) Single crystal sanidine total fusion analyses for the Haycock Mountain tuff. Fifteen grains yield a weighted mean age of 22.84 Ma. (b) Single crystal K-feldspar total fusion analyses for the Osiris tuff. Thirteen grains yield a weighted mean age of 23.27 Ma. For both (a) and (b) data are plotted with 1σ uncertainties and weighted mean ages ±2σ are represented by solid horizontal bars. (c) Pseudotachylyte incremental heating age spectrum and (d) inverse isochron diagrams. The initial $^{40}Ar/^{36}Ar$ intercept is consistent with published values of atmospheric argon (Lee et al., 2006). The last two heating steps are excluded from both plateau and isochron age calculations

23.27 ± 0.05 Ma (2σ includes uncertainty on *J*). Incremental heating of the pseudotachylyte produced a plateau age of 22.99 ± 0.82 Ma (*n* = 20/22) and an isochron age of 21.56 ± 3.74 Ma (Figure 3c,d; 2σ includes uncertainty on *J*). The plateau age is preferred since the isochron intercept is within uncertainty of the atmospheric value thereby indicating that trapped excess Ar is negligible. Full analytical data are provided in the Supplementary materials.

5 | DISCUSSION

Attempts to determine the timing of MGS emplacement have yielded a variety of ages. Biek et al. (2019) placed the timing of the MGS between 21 and 23 Ma based on an earlier sanidine $^{40}Ar/^{39}Ar$ age and zircon $^{206}Pb/^{238}U$ dates of the Haycock Mountain Tuff (22.75 Ma) and ~23 Ma volcanic rocks in the northern breakaway area of the slide. Previous workers have attempted to date pseudotachylyte and produced either older dates (i.e. 28 Ma, Biek et al., 2019) or inconclusive results (Utah Geological Survey and Apatite to Zircon, Inc., 2013). Filkorn (2021) used $^{40}Ar/^{39}Ar$ dating of two volcanic blocks sampled near the base of the MGS. Plagioclase isochron ages for these two andesite blocks yielded ages of 23.0 ± 0.4 Ma (2σ), leading Filkorn (2021) to conclude that the gravity slide was concurrent with an eruption. Mayback et al. (2022) present zircon $^{206}Pb/^{238}U$ dates for two basal layers and a clastic dike within the gravity slide. These authors report the youngest prominent age peaks of 23.6 Ma and 23.9 Ma for the basal layers and 23.7 Ma for the clastic dike.

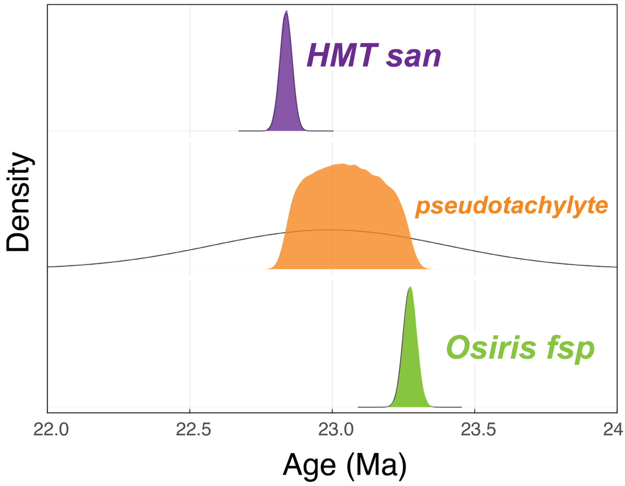

FIGURE 4 Summary of geochronology and Bayesian modelling results. The solid lines are the probability distribution functions of the $^{40}Ar/^{39}Ar$ date for each sample. The shaded regions are posterior density estimates of age from the Bayesian recalibration considering the relative order of events. The modelled age for the gravity slide pseudotachylyte is 23.05 + 0.22/−0.20 Ma (median ± 95% credible interval)

In this work, the new $^{40}Ar/^{39}Ar$ eruption ages of the HMT and Osiris Tuff along with the $^{40}Ar/^{39}Ar$ pseudotachylyte formation age are used to estimate the emplacement age of the MGS. Because the pseudotachylyte was generated during the gravity slide, it could provide the most accurate emplacement age. However, the low K and high atmospheric Ar content of the glass (Supplementary materials) results in large uncertainties for each heating step of the experiment and thereby preclude a precise age determination. To overcome this challenge, a probabilistic Bayesian age model for the pseudotachylyte was developed that uses knowledge about the formation order of each dated sample as prior information.

Bayesian models attempt to estimate probable values of unknown parameters by observed data with prior information. For the MGS, the prior information is the rank order of formation for each sample: the pseudotachylyte (PST) must be older than the overlying HMT and younger than the deformed Osiris Tuff. By ranking each event from oldest to youngest and using a "stacked bed" algorithm (Buck et al., 1991; Ramsey, 2008), the prior probability of a proposed age (θ) is defined as follows:

$$P(\theta) = \begin{cases} 1 & \theta_{Osiris} \geq \theta_{PST} \geq \theta_{HMT} \\ 0 & \text{otherwise} \end{cases}$$

In the pseudotachylyte age model, the radioisotopic dates and their uncertainties were used as the data likelihoods. The age model was implemented in R (R Core Team, 2022) using an adaptive Markov Chain Monte Carlo Metropolis algorithm (Haario et al., 2001) to generate a representative posterior sample of age for each dated event (Figure 4). The modelling code and results are available at https://github.com/robintrayler/gravity_slide.

The input ages and resulting modelled ages for each dated sample are provided in Table 1 and depicted in Figure 4. The modelled pseudotachylyte age of 23.05 + 0.22/−0.20 Ma is significantly more precise than the $^{40}Ar/^{39}Ar$ age and continues to be consistent with earlier estimates for the timing of the MGS. However, the Bayesian method allows for the estimation of realistic uncertainties, which previously proposed emplacement ages have lacked.

TABLE 1 Summary of geochronology and Bayesian modelling results. Radioisotopic ages are reported as weighted mean ages (see Figure 3), and modelled ages are reported as the median and 95% credible interval

Sample	Input Age ± 2σ (Ma)	Modelled Age +/− 95% CI (Ma)
Haycock Mountain Tuff; $^{40}Ar/^{39}Ar$ sanidine	22.838 ± 0.043	22.84 + 0.04/−0.04
Pseudotachylyte; $^{40}Ar/^{39}Ar$ glass	22.990 ± 0.820	23.05 + 0.22/−0.20
Osiris Tuff; $^{40}Ar/^{39}Ar$ sanidine	23.272 ± 0.047	23.27 + 0.05/−0.05

6 | CONCLUSIONS

The MGS is one of three gravity slides tied to the growth and collapse of the Marysvale volcanic field as indicated by the numerous tuffs and lahars present below, within and above each slide. New $^{40}Ar/^{39}Ar$ data of underlying and capping tuffs along with pseudotachylyte present on subsidiary shears and injectites near the base of the MGS shows emplacement at 23.05 +0.22/−0.20 Ma, near the Oligocene-Miocene boundary. The MGS deforms the Bear Valley Formation, voluminous overlying and poorly dated lahar deposits of the Mount Dutton Formation and the 23.27 ± 0.05 Ma Osiris Tuff, and is capped by the undeformed, small-volume, locally derived 22.84 ± 0.04 Ma Haycock Mountain Tuff. Our geochronology shows that accumulation of BV sandstone and several hundred metres of Mount Dutton lahar deposits, emplacement of the gravity slide and eruption of the capping tuff all occurred within ~0.5 million years.

The 23.27 ± 0.05 Ma Osiris Tuff produced the Monroe Peak caldera and ~250 km^3 of caldera fill and outflow sheet deposits (Cunningham et al., 2007). This new high-precision eruption age is important to understanding the eruptive history of the MVF and the timing of the MGS and older Sevier gravity slide to the east. The modelled age for the MGS suggests slide emplacement was ~200 kyr following caldera formation. However, volcanic activity in the Monroe Peak caldera continued with eruptions of lava flows and domes, and several caldera-related intrusions are now exposed (Steven et al., 1984). While we cannot yet identify a cause for the gravity slide, caldera-forming eruptions, shallow intrusions and the accumulation of thick volcaniclastic deposits have been hypothesized as the trigger mechanism for slope failure (Hacker et al., 2014). Here, the geochronology suggests that these processes occur on geologically short timescales, with lag time between igneous activity and mass movement as <200 kyr.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supplementary material of this article.

STATEMENT OF SIGNIFICANCE

The Markagunt gravity slide (MGS) is one of three mega-landslides in the Oligocene-Miocene Markagunt gravity slide complex. The presence of primary and transported volcanic deposits within the Marysvale volcanic field offers an opportunity to apply geochronologic and statistical methods to constrain the timing of MGS emplacement. Here $^{40}Ar/^{39}Ar$ feldspar ages of tuffs and pseudotachylyte are used as inputs into a Bayesian age model to determine an MGS emplacement age of 23.05 +0.22/−0.20 Ma. This is the first study of its kind to provide an age constraint for the MGS using high-precision $^{40}Ar/^{39}Ar$ dating and statistical modelling and the results can be used in future work to understand the nature of low-frequency, high-risk natural hazards and the development of the ancestral Colorado Plateau landscape during the mid-Cenozoic ignimbrite flare-up.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1

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