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RESEARCH ARTICLE

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The concept of tectonic provenance: Case study of the gigantic Markagunt gravity slide basal layer

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Abstract

Formation and evolution of the basal layer in large landslides has important implications for processes that reduce frictional resistance to sliding. In this report, we show that zircon geochronology and tectonic provenance can be used to investigate the basal layer of the gigantic-scale Markagunt gravity slide of Utah, USA. Basal layer and clastic injectite samples have unique tectonic chronofacies that identify the rock units that were broken down during emplacement. Our results show that basal material from sites on the former land surface is statistically indistinguishable and formed primarily by the breakdown of upper plate lithologies during sliding. Decapitated injectites have a different tectonic chronofacies than the local basal layer, with more abundant lower plate-derived zircons. This suggests clastic dikes formed earlier in the translation history from a structurally deeper portion of the slide surface and a compositionally different basal layer before being translated to their current position.

1 | INTRODUCTION

Volcanic terrains are among the most dynamic on the planet, with landscapes that evolve in response to magmatic ascent, eruption, regional tectonics, seismicity, erosion and gravity (e.g., Caricchi, Townsend, Rivalta, & Namiki, 2021; Walter et al., 2019). The late Oligocene-to-Miocene Marysvale gravity slide complex (MGSC), located in south-western Utah, USA, offers a unique perspective on the large-scale instability of volcanic fields in response to these factors, as the southern portion of the field experienced three sequential mega-scale collapse events. The MGSC comprises, from east to west, the Sevier, Markagunt (MGS) and Black Mountains gravity slides (Figure 1). Each is differentiated by geological mapping and preliminary isotopic dating of deformed and undeformed volcanic rocks, which indicate gravitational collapse occurred during the growth of the Marysvale volcanic field from the late Oligocene to early Miocene (Biek, Rowley, & Hacker, 2019; Hacker, Biek, & Rowley, 2014). These Markagunt, Sevier and Black Mountain gravity slides are distinct from smaller, volcanically induced debris avalanche deposits recognized in modern volcanic settings (e.g., Crandell, Miller, Glicken, Christiansen, & Newhall, 1984; Siebert, 1984) based on stratigraphy, kinematic indicators and internal deformation. Each gravity slide also displays three distinct segments (Figure 2) from proximal to distal reaches: (a) a northern breakaway segment in which movement occurred along bedding planes within subsurface volcaniclastic sedimentary rocks of the Eocene–Oligocene Brian Head Formation; (b) a ramp segment, ~1–2 km wide, that cuts obliquely up-section; and (c) a distal run-out segment where upper plate rocks moved southward over the former land surface. As much as a 1,000 m thickness of allochthonous rocks travelled more than 35 km over the <3 degree dipping former land surface, and the combined area (>8,000 km^2) of the MGSC ranks these collapse structures among Earth's largest terrestrial landslides (Biek et al., 2015, 2019; Biek, Hacker, & Rowley, 2014; Hacker et al., 2014). The characteristics of these large gravity slides suggest that these types of volcanic fields are pre-conditioned for large-scale collapse due to: (a) the large mass of available slide material that accumulates during volcanism and creates a thick, potentially unstable wedge; (b) a substrate of subhorizontal strata containing ash from early volcanism that weathers to frictionally weak clays; (c) an underlying batholith whose growth tilts overlying rocks outward from the centre of the volcanic pile; (d) shallow intrusive complexes (i.e. laccoliths and feeder dike systems) rising from the batholith amid seismicity; (e) lateral spreading towards the south on a weak detachment surface, contributing to flank destabilization (De Vries & Francis, 1997; Merle, Davis, Nickelsen, & Gourlay, 1993); and (f) possible pre-collapse development of summit fractures and normal faults by intrusive doming or during gradual lateral spreading that weaken the structural integrity of the volcanic field (Biek et al., 2019).

Statement of Significance

Long run-out landslides are increasingly recognized as ubiquitous features in both subaerial and subaqueous environments. Characterized by large lateral transport distances (up to several tens of kilometres) despite small changes in height, they present intriguing scientific problems that defy expectations from the basic physics of frictional sliding. In this study, we adapt the technique of detrital zircon geochronology—a standard tool for determining sedimentary provenance—in a novel way to identify the provenance of wear products generated during emplacement of the Markagunt gravity slide, one of the largest terrestrial landslide structures recognized on Earth. We observe distinct chronofacies in the basal layer of the Markagunt gravity slide that suggests local generation of frictional wear products and minimal mixing of basal material across large areas. The preservation of distinct chronofacies in clastic injectites also provides evidence of adhesion and transportation of wear products for great distances with the upper plate during emplacement. Future application of our tectonic provenance method may shed light on important related questions such as the residence time of basal material, the degree of accretion or deposition during transport and the role of rock properties in wear behaviour.

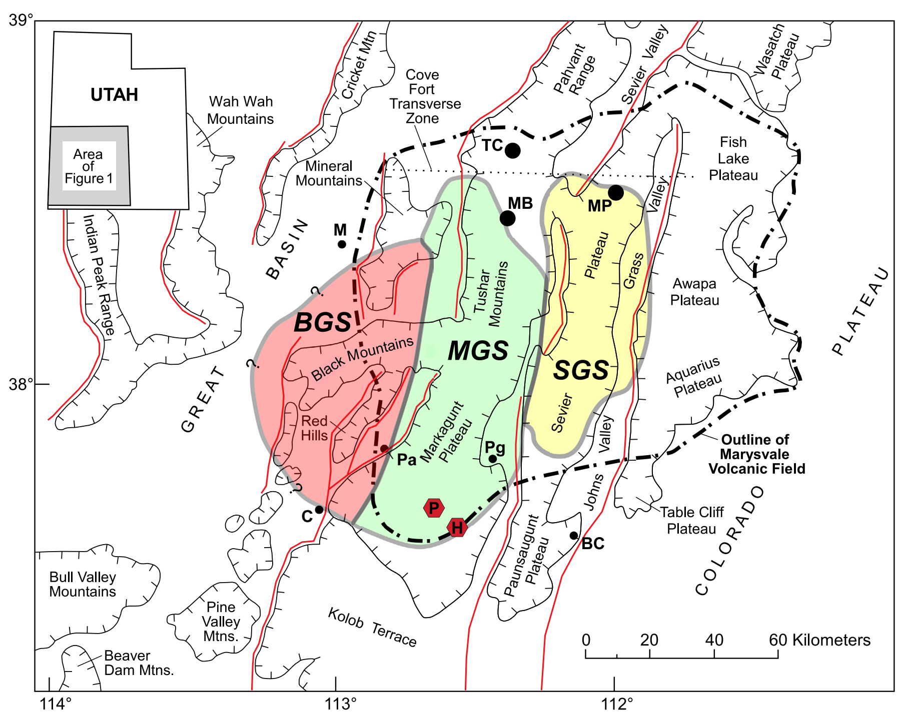

FIGURE 1 Map of the Marysvale volcanic field showing the location of the three prodigious gravity slides. Hachures enclose the various mountain ranges in the regions. Red lines = Tertiary normal faults, BGS = Black Mountains gravity slide, MGS = Markagunt gravity slide, SGS = Sevier gravity slide, P = Panguitch Lake sampling locality, H = Haycock Mountain sampling locality. Large black dots show central part of calderas (MB = Mount Belknap; MP = Monroe Peak; TC = Three Creeks). BC = Bryce Canyon; C = Cedar City; M = Minersville; Pg = Panguitch; Pa = Parowan. Modified from Rowley et al. (1994) and Biek et al. (2019). [Colour figure can be viewed at wileyonlinelibrary.com]

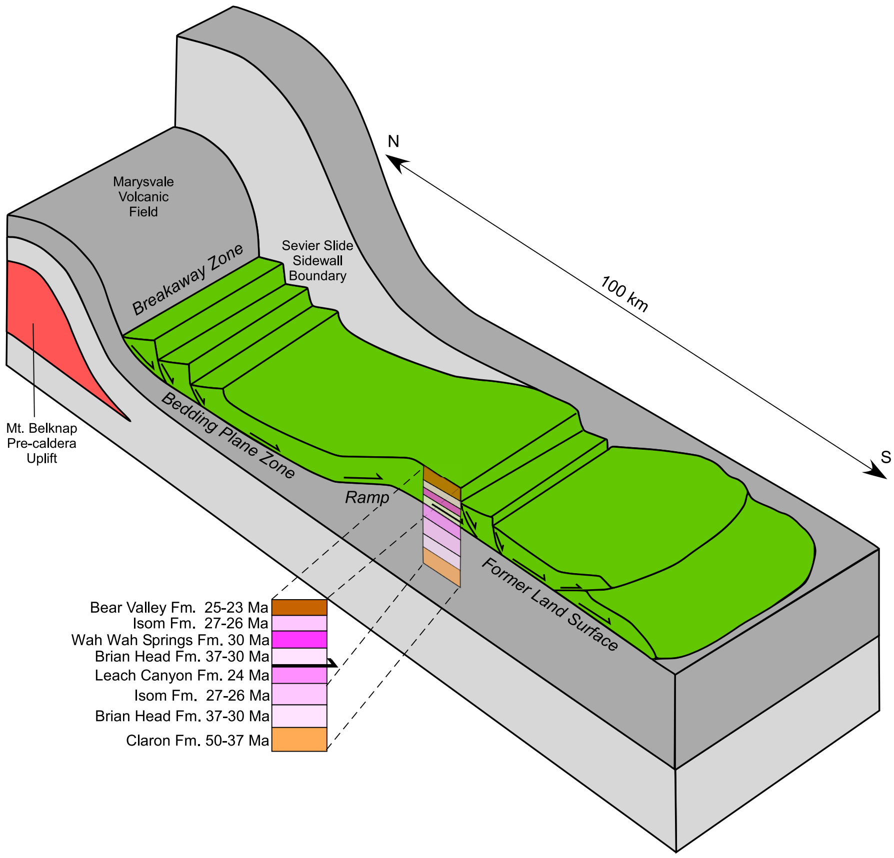

FIGURE 2 Cartoon of the anatomy of the MGS (modified from Biek et al., 2019). The breakaway zone is characterized by a series of synthetic normal faults that roll into a bedding plane zone in the mechanically weak Brian Head Formation. The slide mass eventually ramped up and was transported across the former land surface. The eastern boundary is a sidewall with the older Sevier gravity slide, and the western margin is poorly defined. Extensional deformation characterizes the proximal reaches of the MGS, whereas compressional deformation characterizes the distal toe. The main part of the gravity slide remains mostly intact, with individual blocks as much as tens of square kilometres in size, preserving the stratigraphy of the source area. Complexly deformed, attenuated strata and older-on younger stratigraphic relationships characterize the former land surface area. The various lithostratigraphic units that occur in the upper and lower plates of the MGS at the discovery site are indicated. [Colour figure can be viewed at wileyonlinelibrary.com]

The base of each gravity slide consists of a layer of cataclastic rock, herein referred to non-genetically as the "basal layer" (Biek et al., 2019; Malone et al., 2017; Malone, Craddock, Anders, & Wulff, 2014). The basal layer ranges in thickness from less than a centimetre to several metres and was formed through the frictional wear of upper and lower plate rocks during slide emplacement. Basal layer material also occurs as clastic dikes (injectites) intruded into upper plate rocks. Given the complexity of wear processes and great transport distance associated with the MGSC slides, the provenance of basal layer components is of interest. Basal layer characteristics have been previously ascribed as evidence of friction-reducing processes, and the formation and evolution of the basal layer may play an important role in the mechanics of translation (e.g., Anders, Aharonov, & Walsh, 2000). Zircon U/Pb geochronology is a standard methodology for provenance studies (e.g., Dickinson & Gehrels, 2003; Freiburg, Holland, Malone, & Malone, 2020; Johnson & Winter, 1999; Malone, Craddock, Stein, Stein, & Malone, 2020). Here, we apply zircon U/Pb geochronology in a novel way to understand the tectonic provenance of the basal layer and associated injectites of the MGS. Tectonic chronofacies of the MGS basal layer are also defined and used to constrain the upper and lower plate rock units that were broken down during slide emplacement. Thus, we use zircon geochronology to determine the provenance of zircon grains sampled from cataclastic rock, a method that to the best of our knowledge has not been implemented in this way before. The MGSC provides an excellent case study location for this technique as most zircon grains in the involved lithologies are derived from local volcanism coeval with deposition, providing clear and distinct chronofacies between rock units involved in the slides.

2 | BACKGROUND

The Marysvale volcanic field consists of voluminous, intermediate composition, calc-alkaline volcanic rocks of Oligocene and early Miocene age overlain by much less voluminous bimodal (rhyolite and basalt) volcanic rocks of Miocene and younger age (e.g., Rowley et al., 1994). Volcanic rocks overlie the late Eocene–early Oligocene fluvial and lacustrine rocks of the Brian Head Formation. Previous geologists mapped parts of what is now recognized as the MGSC, including (a) the "Markagunt Megabreccia," a chaos of displaced volcanic rocks then thought to cover >500 km^2 of the Markagunt Plateau (Anderson, 1993); (b) thrust faults interpreted to result from gravitational spreading of the south-eastern flank of the Marysvale volcanic field (Merle et al., 1993); and (c) a zone of inferred detachment at the base of the volcanic rocks on the field's southwest flank (Maldonado, 1995). More recently, workers interpreted the entire south-western flank of the MGSC as allochthonous, and thus defined the MGS (Biek et al., 2015; Hacker et al., 2014). Subsequent mapping delineated the Sevier gravity slide to the east of the MGS (Biek et al., 2019), and most recently, the western areas of the MGS have been reinterpreted as the younger Black Mountains gravity slide.

The MGS was formally defined by Hacker et al. (Hacker et al., 2014, Figure 2); it was then interpreted to cover an area of ~3,400 km^2, which is about the same size as the Eocene Heart Mountain slide in north-western Wyoming (e.g., Craddock, 2012; Craddock et al., 2009; Malone, 1995; Malone et al., 2014). The MGS was emplaced between ca. 23 and 21 Ma, near the end of peak calc-alkaline volcanic activity in the Marysvale volcanic field (Biek et al., 2019). This age range is based on the bracketing of the youngest rocks that the gravity slide overlies or deforms, and the oldest undeformed rocks that overlie the gravity slide. The stratigraphy of rocks involved is complex, and individual volcanic units erupted from both distant sources in the Great Basin to the west and more proximal volcanic centres in the Marysvale volcanic field itself (Figure 3). Our accompanying paper (Holliday et al., 2022) provides geochronological data used to interpret the emplacement age of the MGS.

Lithologically, the basal layer of the MGS is a poorly sorted, matrix-supported aggregate of crushed, deformed, sand- to boulder-size material that bears a strong resemblance to ready-mix concrete (Malone, 1996; Anders et al., 2000; see Biek et al., 2019 for a comprehensive description of the field relations of the MGS). In many places, there are small offsets along these fractures, known as jigsaw clasts, and the enclosing finer-grained matrix was injected between clast fragments. Fractures within the clasts do not penetrate the adjacent finer-grained matrix, and fracture patterns are variable. Irregular planar and curviplanar clastic dikes inject into upper (and less commonly lower) plate rocks from the basal layer throughout the MGS. Dikes range in width from a few centimetres to a few metres and are up to tens of metres in length; they have abrupt margins and are typically darker in colour and finer grained than the enclosing material. Clastic dikes indicate that the basal layer behaved as an overpressured fluid during gravity slide emplacement. Dark-coloured pseudotachylyte veins, 2 to 5 cm in thickness, occur on subsidiary shear planes and associated injectites (Zamanialavijeh et al., 2021).

3 | METHODS

We analysed samples collected from two basal layer localities on the former land surface segment of the MGS at the Panguitch

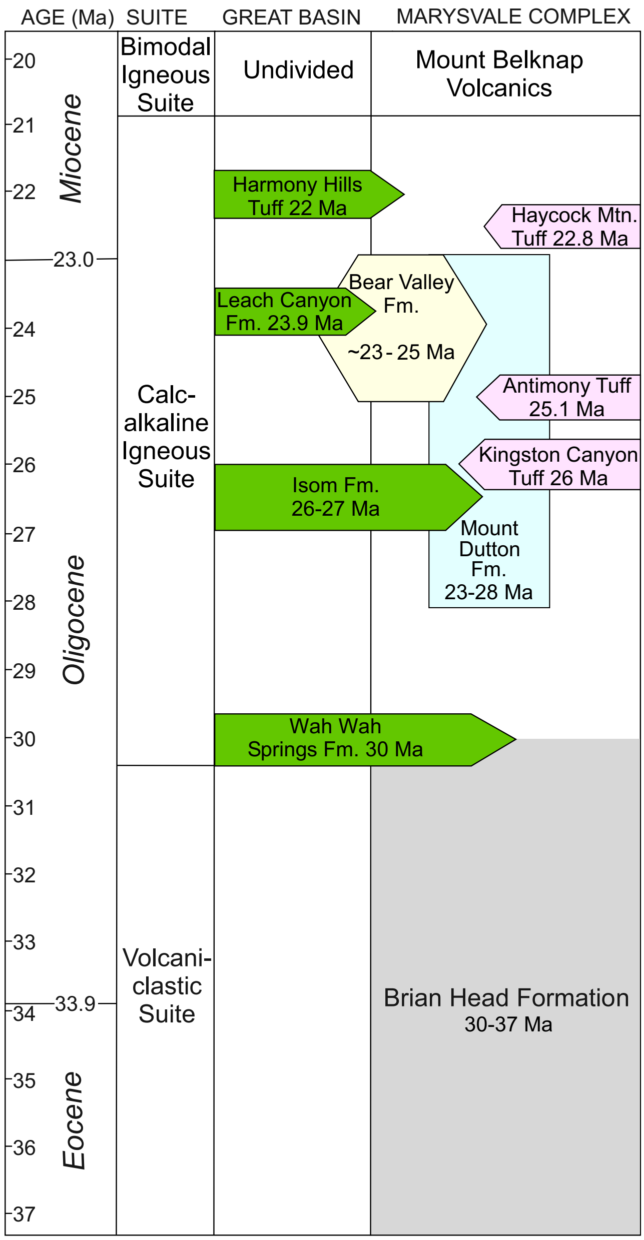

FIGURE 3 Stratigraphic column of principal rocks associated with the MGSC modified from Biek et al. (2019), which also summarizes ages from various isotopic systems. The oldest unit involved in the MGS is the Eocene–Oligocene Brian Head Formation, which occurs in both the upper and lower plates. The Brian Head is as much as 300 m in thickness, and consists of a succession of poorly resistant, light-coloured tuffaceous epiclastic volcanic rocks. The Wah Wah Springs Formation is a moderately welded dacitic ash-flow tuff as much as 100 m thick. The Isom Formation is as much as 110 m in thickness and is a densely welded trachydacitic ash-flow tuff. The Mount Dutton Formation is at least 600 m in thickness and consists of a complex succession of crudely stratified andesitic lava flows and polymict breccias. The Bear Valley Formation is as much as 200 m thick and consists of cross-bedded volcanic sandstone, polymict breccia and lithic tuff. [Colour figure can be viewed at wileyonlinelibrary.com]

Lake spillway (37.725378°, −112.628484°; basal layer only) and Haycock Mountain (37.710996°, −112.550880°; basal layer and injectite). About 5 kg of each sample was crushed and milled, and denser minerals were separated by panning, heavy liquids and magnetic separation techniques. U/Pb geochronology of separated zircon crystals was conducted by laser ablation–inductively coupled plasma–mass spectrometry at the Arizona LaserChron Center (Gehrels & Pecha, 2014; Gehrels, Valencia, & Pullen, 2006; Gehrels, Valencia, & Ruiz, 2008). The supplementary files provide a table of detrital zircon U/Pb ages and the details of our analytical methods.

4 | RESULTS

4.1 | Panguitch Lake basal layer

The basal layer at Panguitch Lake is 5 to10 cm thick and occurs between the lower plate massive Isom Formation ash-flow tuff and upper plate polymict breccias of the Mount Dutton Formation (Figure 4). Seventy zircon grains were analysed, and the $^{206}Pb/^{238}U$ age spectrum ranges from 1865 to 22.6 Ma; all but two grains are younger than Palaeogene (Figure 5). The most prominent age peak is at ~23.6 Ma, with smaller peaks at ~24.8 and ~25.9 Ma.

4.2 | Haycock Mountain basal layer and injectite

One sample each of MGS basal layer and injectite were collected from the Haycock Mountain discovery site (Biek et al., 2019). Here, allochthonous rocks of the Isom Formation overlie light-coloured volcaniclastic rocks of the Brian Head Formation. The basal layer is 25 to 50 cm thick and contains both angular Isom clasts and rounded volcanic clasts in a moderately cemented sandy matrix (Figure 6). Conspicuous rounded quartzite cobbles also are present in the basal layer. Clastic dikes of irregular geometries and 20 to 30 cm in width intrude the upper plate. The clastic dikes are of subtly different colour and texture than the basal layer and terminate at the top of the basal layer.

The basal layer zircon $^{206}Pb/^{238}U$ age spectrum includes 105 grains, with all but 12 (14%) post-Palaeogene in age (Figure 5). Eight grains are Proterozoic, two are Archaean and one each are Palaeozoic and Mesozoic in age. There is a prominent age peak at ~23.9 Ma and a secondary peak at ~33.2 Ma. The injectite zircon $^{206}Pb/^{238}U$ age spectrum includes 60 grains, with 52 being Palaeogene and Neogene in age, the balance are Proterozoic in age (Figure 5). The most prominent age peak is at ~31.4 Ma, with smaller peaks at ~28.3, ~32.8 and ~23.7 Ma.

FIGURE 4 Field photos of the Panguitch Lake, former land surface sampling locality. (a) Basal layer 5–10 cm in thickness resting on the Isom Formation ash-flow tuff. Upper plate rocks overlying the basal layer are of the Mount Dutton Formation. (b) N-S trending striations on the upper surface of the Isom Formation. [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

5.1 | Tectonic provenance of MGS basal layer

At Panguitch Lake, the basal layer occurs between the resistant ash-flow tuff of the Isom Formation and less resistant volcaniclastic rocks of the Mount Dutton Formation (Figure 4). Here, basal layer zircon grains were derived almost exclusively from the Bear Valley Formation exposed above the basal slide plane elsewhere upgradient, which indicates that emplacement in the Panguitch Lake area was accompanied by disaggregation of upper plate rocks. At Haycock Mountain, the basal layer occurs between the Brian Head Formation and Isom Formation (Figure 6). Like Panguitch Lake, Bear Valley Formation zircon crystals are the most ubiquitous in the basal layer, and K-S statistical analysis (e.g., Malone et al., 2020) demonstrates that the detrital zircon $^{206}Pb/^{238}U$ age spectrum of the basal layer at Haycock Mountain is statistically indistinguishable from that of the basal layer at Panguitch Lake. However, zircon grains incorporated from the underlying Brian Head Formation also are present at Haycock Mountain, indicating local zircon sourcing from the lower plate. Our data suggest that neither local upper nor lower plate rocks contributed to the basal layer zircon $^{206}Pb/^{238}U$ age spectrum at Panguitch Lake; however, lower plate zircon grains are present at Haycock Mountain.

The zircon $^{206}Pb/^{238}U$ age spectrum of the Haycock Mountain injectite has a statistically distinct tectonic chronofacies when compared with the two basal layer samples. Zircon grains here are mostly derived from the Brian Head Formation, with smaller contributions from the Isom, Wah Wah Springs and Bear Valley Formations. The zircon U/Pb age data support the field observations that the injectite was not derived directly from the basal layer at Haycock Mountain, but rather it was injected earlier in MGS emplacement from a basal layer of a different tectonic chronofacies. Due to the absence of Brian Head Formation at the MGS basal slip surface between the Haycock Mountain sampling site and the ramp fault located 15 km to the north, this implies that the injectite formed from basal material derived primarily from breakdown of subsurface Brian Head strata in the bedding plane segment of the MGS before being transported to its current position (Figure 7).

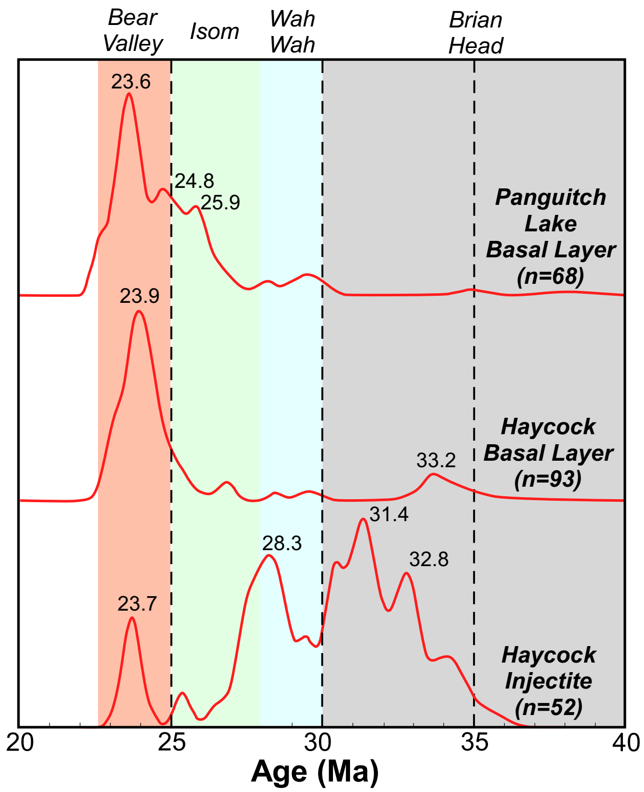

FIGURE 5 Stacked probability plots of Palaeogene zircons analysed in the basal layer at Panguitch Lake and Haycock Mountain and in the Haycock Mountain injectite. [Colour figure can be viewed at wileyonlinelibrary.com]

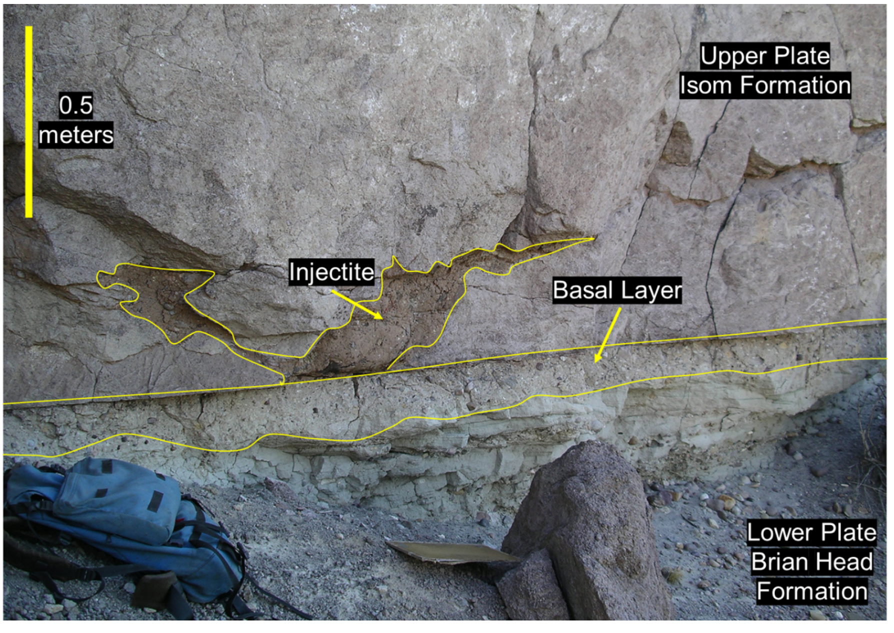

FIGURE 6 Haycock Mountain locality showing lower plate Brian Head Formation epiclastic rocks overlain by allochthonous Isom Formation cataclasite. The basal layer here is about 25 cm thick. The injectite is within the Isom Formation and is truncated at the upper plate/basal layer contact. [Colour figure can be viewed at wileyonlinelibrary.com]

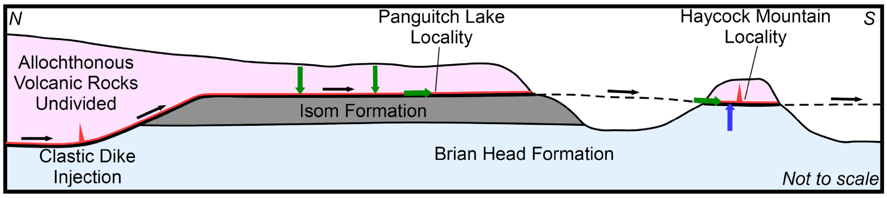

FIGURE 7 Schematic cross section of MGS indicating the site of origin of the clastic dike, and where it came to rest after being truncated during slide emplacement. The clastic dike is largely composed of lower plate Brian Head Formation material derived from the bedding plane region of the MGS. The basal layer (red line) at Panguitch Lake was derived through the incorporation of the Bear Valley Formation from the upper plate (along with other units is part of the undivided allochthonous volcanic rocks). The Bear Valley Formation tectonic detritus, along with locally incorporated lower plate Brian Head Formation detritus comprises the basal layer at Haycock Mountain. [Colour figure can be viewed at wileyonlinelibrary.com]

5.2 | Implications for wear processes

The results of this work provide information regarding wear processes in landslide transport and highlight potential applications of this technique in analysing the provenance of wear products in both landslide and fault surfaces. Frictional sliding in rocks results in abrasive and adhesive wear (Scholz, 1987), producing basal layers in landslides, and gouge and cataclastite in faults. In faults, the thickness of fault zones scales linearly with total slip, and this relationship has been explained in terms of self-affine roughness of fault surfaces (e.g., Power, Tullis, & Weeks, 1988). The thickness of the basal layer in the MGS, on the other hand, is highly irregular (Biek et al., 2019; Hacker et al., 2014). This observation, along with results of this study, suggests that basal layer material is produced locally in some cases and transported laterally with the upper plate in others. Decapitated clastic injectites like those investigated here offer clear cases of adhesive wear processes. Together these have the potential to help us address important questions about the competition between abrasive and adhesive wear in long run-out landslides. For example, an increase in adhesive wear and related accretion of basal material with landslide transport has been associated with slowing of the landslide mass (Hanes & Inman, 1985; Legros, 2002; Straub, 1997), whereas deposition of upper plate-derived material can potentially play a role in influencing transport distance for long run-out landslides (Cannon & Savage, 1988; Van Gassen & Cruden, 1989). Future application of our tectonic provenance method may shed light on important related questions such as the total residence time of basal material, the degree of accretion or deposition during transport and the role of rock properties in wear behaviour.

6 | CONCLUSIONS

The following conclusions are derived from this research:

1. At least two distinct tectonic chronofacies are defined in the basal layer of the MGS, one reflected in the basal layer sampled at Panguitch Lake and Haycock Mountain, and the other from an injectite at Haycock Mountain. This indicates that zircon chronofacies of the basal layers at these two locations were not uniform and suggests that basal layer material was generated throughout MGS emplacement, with some material being emplaced during early transport.
2. Both basal layer samples were largely derived through the disaggregation of upper plate Bear Valley Formation.
3. The injectite zircon $^{206}Pb/^{238}U$ age spectrum includes grains derived mostly from the Brian Head Formation, which were likely derived from lower plate rocks in the bedding plane segment of the MGS at least 15 km to the north. This provides insight into the MGS emplacement in areas where it is more poorly exposed.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Appendix S1 Supporting information 1.

Appendix S2 Supporting information 2.

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