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Progression and Dynamics of the Bingham Canyon Rock Avalanched (Utah, USA) Revealed from Topgraphic, Seismic, and Infrasound Data

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Progression and dynamics of the Bingham Canyon rock avalanches (Utah, USA) revealed from topographic, seismic, and infrasound data

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Key Points

- Cumulative 52 Mm^3 event consisted of two large rock avalanches and at least 11 smaller landslides
- Broadband seismo-acoustic data reveal slide volumes and trajectories as well as finer scale dynamics
- Combined methods provided complementary results allowing more powerful joint interpretation of landslide event

Abstract

The 2013 Bingham Canyon mine rock avalanches represent one of the largest cumulative landslide events in recorded U.S. history, and provide a unique opportunity to test remote analysis techniques for landslide characterization. Here we combine aerial photogrammetry surveying, topographic reconstruction, numerical runout modeling, and analysis of broadband seismic and infrasound data to extract salient details of the dynamics and evolution of the multi-phase landslide event. Our results reveal a cumulative intact-rock source volume of 52 Mm^3, which mobilized in two main rock avalanche phases separated by 1.5 h. We estimate the first rock avalanche had 1.5-2 times greater volume than the second. Each failure initiated by sliding along a gently-dipping (21°), highly-persistent basal fault before transitioning to a rock avalanche and spilling into the inner pit. The trajectory and duration of the two rock avalanches were reconstructed using runout modeling and independent force-history inversion of intermediate-period (10-50 s) seismic data. Intermediate- and shorter-period (1-50 s) seismic data were sensitive to intervals of mass redirection and constrained finer details of the individual slide dynamics. Back-projecting short-period (0.2-1 s) seismic energy, we located the two rock avalanches within 2 and 4 km of the mine. Further analysis of infrasound and seismic data revealed that the cumulative event included an additional 11 smaller landslides (volumes ~10^4-10^5 m^3), and that a trailing signal following the second rock avalanche may result from an air-coupled Rayleigh wave. Our results demonstrate new and refined techniques for detailed remote characterization of the dynamics and evolution of large landslides.

42 **Index Terms**

43 1810

44 4302

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50 **Keywords**

51 Rock avalanche runout modeling

52 Broadband landslide seismicity

53 Infrasound landslide detection

54 Seismic energy back-projection

55 Photogrammetric terrain modeling

56 Remote landslide characterization

57

1. Introduction

Rock avalanches are rare and powerful mass movements defined by the sudden release of large intact-rock volumes, extremely rapid and flow-like runout, and long travel distance [*Cruden and Varnes*, 1996; *Hungr et al.*, 2001]. Case histories from across the world attest to the potentially devastating consequences of these catastrophic mass movements, e.g. 1806 Goldau, Switzerland: 457 casualties [*Thuro and Hatem*, 2010]; 1881 Elm, Switzerland: 115 casualties [*Heim*, 1932]; 1903 Frank, Canada: 90 casualties [*Cruden and Martin*, 2007]; 1959 Madison River canyon, USA: 26 casualties [*Wolter et al.*, 2015]; 1987 Val Pola, Italy: 27 casualties [*Crosta et al.*, 2004]; 2009 Xiaolin, Taiwan: up to 600 casualties [*Kuo et al.*, 2011]. While the unusual flow-like character of rock avalanches was initially unexpected and contributed to the high toll of early disasters, today the runout behavior is well known and an increasing number of well-documented case histories are being used to probe the physics of rock avalanche movement [*Hungr et al.*, 2005; *Lipovsky et al.*, 2008; *Davies and McSaveney*, 2009; *Dufresne et al.*, 2010; *Guthrie et al.*, 2012; *Coe et al.*, 2016].

Among contemporary methods used to identify and describe these rare mass movements, regional seismic datasets have emerged as a powerful source for investigating landslide dynamics [*Deparis et al.*, 2008; *Schneider et al.*, 2010; *Hibert et al.*, 2011; *Yamada et al.*, 2012; *Hibert et al.,* 2014a,b; *Dammeier et al.*, 2015], and have greatly contributed to their remote characterization [e.g. *Lin et al.,* 2010; *Ekström and Stark*, 2013; *Iverson et al.*, 2015; *Coe et al.*, 2016]. Landslides have a distinct broadband seismic signature, characterized by a 'cigar-shaped' envelope with emergent onset, long duration, and a slowly decaying tail. High-frequency energy (>~1 Hz) is generally created by block-ground collisions, and can be observed at distances of 100's of kilometers even for relatively small landslides [*Tilling et al.*, 1975; *Dammeier et al.*, 2011]. Large landslides, on the other hand, are often rich in low-frequency energy, generated by unloading and bulk mass flux, and can be observed at greater distances [e.g. *Kanamori and Given*, 1982; *Weichert et al.*, 1994]. Recent research has demonstrated the potential for these data to describe fundamental parameters of landslides, such as event timing and volume, as well as more detailed descriptions of slide kinematics and dynamics [e.g. *Favreau et al.*, 2010; *Moretti et al.*, 2012; *Yamada et al.*, 2013; *Ekström and Stark*, 2013; *Allstadt*, 2013; *Levy et al.*, 2015; *Dammeier et al.*, 2016]. High-quality, broadband and continuous seismic data sets are routinely generated at the state and national level, with archives available for public access.

89 Here we document an exceptional case of two large rock avalanches that struck the
90 Bingham Canyon open-pit copper mine in Utah on April 10, 2013 (Figure 1). The mine is one of
91 the largest in the world, at over 950 m deep and 4.5 km wide, and has been in production for
92 more than 100 years. Originating from high on the northern pit wall, the two rock avalanches
93 were separated by ~1.5 hours and released in total 144 million metric tons of debris [*Sutherlin*
94 *and Davis*, 2014; *Pankow et al.*, 2014]. Movement had begun months earlier and the slides had
95 no recognizable trigger. Extensive geotechnical monitoring allowed successful prediction of the
96 time of failure, and all mine personnel were safely evacuated twelve hours in advance [*Gaida*,
97 2014]. Debris from the landslides, however, filled the pit bottom with waste, blocked access to
98 ore and destroyed a large amount of heavy equipment [*Lengerich and Ware*, 2014].

99 The proximity of the rock avalanches to a dense seismic network, as well as basic
100 information and photographs released from the mine, contributes to a uniquely rich data set
101 [*Pankow et al.*, 2014]. In contrast, *in-situ* data remain privately held and are currently
102 unavailable. Here we draw on public data sources, supplemented by our own aerial topographic
103 survey, to reconstruct the kinematics, progression and dynamics of the Bingham Canyon rock
104 avalanches. Aside from describing the landslide event in detail, our results add valuable
105 benchmarking and comparison tests of new and refined techniques used to remotely characterize
106 large landslides, and highlight the utility of combining multiple techniques to resolve fine-scale
107 details of landslide dynamics. As seismological (and infrasound) data are increasingly used to
108 detect and characterize landslides, it is critical to understand the utility and pitfalls of individual
109 techniques, and ultimately develop refined methods that accurately describe landslide event
110 parameters needed for hazard and risk assessment.

111

112 **2. Topographic and runout analysis**

113 ***2.1. Data sources***

114 We searched public sources for photographic and topographic data of the Bingham
115 Canyon mine. Press coverage after the slides generated a number of useful images, and the mine
116 owner, Rio Tinto Kennecott, released their own set of high-quality oblique aerial photographs,
117 some of which are reproduced in Figure 1. These were acquired on April 11, 2013, just one day
118 after the rock avalanches, and show many important details of the unmodified source area and

deposits. The State of Utah also collects high-resolution aerial orthoimages at relatively frequent intervals; the most recent image of the Bingham Canyon mine was acquired in July 2012 (Figure 1d). In addition, satellite images from one month after the slide are available from NASA (Figure 1d, May 2013) at slightly lower resolution.

Useful topographic data were less available. The State of Utah collected aerial LiDAR over the mine in 2006, but too much has changed in the pit area (due to ongoing excavation) for these data to be of substantial value. Similarly, we found that all publicly available topographic data (e.g. USGS digital elevation models) are outdated due to the brisk pace of mining. While the mine operators have high-resolution LiDAR data from before and after the slides, they have not shared these publically. Without topographic data of the source area and deposits from before and after the rock avalanches, detailed volume and runout analyses are impossible.

To supplement available data sources, we conducted our own reconnaissance in February 2014 to collect aerial imagery and digital topographic data. We operated a custom aerial photogrammetry system using a Nikon D800 camera with precise shutter timing using an event marker input to the onboard GPS/IMU. The photograph positions are derived from fully coupled GPS/IMU processing [*Larsen*, 2014, *Nolan et al.*, 2015]. In total, 1021 images were acquired on 17 parallel N-S tracks at a mean altitude of ~900 m. The resulting data were processed with Agisoft Photoscan software to produce a digital elevation model (DEM) with resolution of 0.5 m. Individual images were then merged into a 15-cm pixel resolution orthomosaic. Figure 1f shows a portion of the image mosaic, while a hillshade representation of the topography is shown later in Figure 2d.

2.2. Image analysis and topographic change

Figure 1d-f shows images of the Bingham Canyon mine before and after the April 2013 rock avalanches, highlighting the cumulative area released by the slides, the total reach of deposits, and the extent of the main deposit body. A few key points are evident from comparing these images: a) the source area was a steep bedrock ridge on the northern pit wall; b) some waste rock had been piled on the crest and northern side of this ridge, c) a persistent basal rupture surface is evident dipping gently to the west; d) the deepest part of the pit was an arcuate crescent on the southeast side of the floor; e) there was a large intact-rock mound in the center of the pit floor; f) runout of the rock avalanches involved a strong southward bend as material left

149 the source area and entered the inner pit, g) spill-over of debris to the south covered steep mine
150 benches, while the main body of the deposit filled the pit bottom; h) heavy modification of the
151 source and deposit areas had already taken place in February 2014.

152 Analysis of photos and topographic data reveal that the Bingham Canyon rock avalanches
153 initiated as sliding-mode failures on a highly-persistent basal fault (locally known as the
154 Manefay fault). Images of the northern pit wall before the failures show the trace of this fault, as
155 well as minor scars along its length from differential erosion. Figure 1 shows that the basal
156 rupture plane extends from the toe of the source area to near the crown, where material pulled
157 away from the crest leaving a ~120 m high cliff. The failed portion of the ridge was
158 approximately 1350 m long and 500 m wide, with an estimated area of 542,000 m^2. Topographic
159 profiles along the basal rupture plane reveal that it dips gently, just 21°, due west. The shallow
160 dip, high persistence (i.e. aerial extent), and fact that the source area was completely evacuated,
161 suggest low frictional resistance along this basal failure surface.

162 Cumulative deposits of the rock avalanches cover an area of approximately 1,336,000 m^2,
163 while the main deposit body on the pit floor has an aerial extent of ~75,000 m^2. The maximum
164 horizontal distance from crest to toe of the slides is 2950 m, and the vertical elevation drop along
165 the same curved path is 850 m [*Pankow et al.*, 2014], giving a Fahrböschung (or travel angle) of
166 16° (H/L = 0.29). Deposits of the first rock avalanche have a predominantly gray color
167 representing bedrock on the outer surface of the pit walls, while superposed deposits of the
168 second rock avalanche have a predominately orange color reflecting a greater proportion of
169 waste rock (estimated up to 25%) (Figure 1).

170 Images further reveal that deposits of the first slide are slightly elevated at their distal toe
171 (evident by alignment with mine benches in Figure 1a), which indicates slight impact and runup
172 against this wall. Deposits of the second rock avalanche do not appear to have impacted the
173 distal pit wall, but rather have a steep-fronted lobate form. Both rock avalanches super-elevated
174 as they left the source region traveling west and made a ~90° bend to the south. Stranded
175 deposits can be seen on the western pit wall from both slides (again distinguished by color
176 differences, see Figure 1c), which were captured and retained by mine benches. Super-elevated
177 deposits from the second rock avalanche (orange) reached higher on the pit wall than the first
178 (gray).

In order to quantitatively analyze topographic change resulting from the rock avalanches, it was necessary to construct topographic models of the slide source and deposit areas before and after the failures. To accomplish this, we worked backward from the post-slide, recent topography (February 2014), and recreated surfaces in the areas of change using aerial and satellite images as a guide. The goal was to generate one DEM representing the topography shortly before the slides and another representing topography shortly after the slides.

To recreate the source region we first cropped out the relevant area from the post-slide DEM, then used the July 2012 orthoimage to manually redraw 30-m interval contour lines using mine benches as a guide. Mine benches are generally level, and follow regular elevation intervals of 15 m (50 ft) at the Bingham Canyon mine. After recreating the new contour lines, we appended their coordinates to the cropped DEM data and gridded these together at 5-m spacing to regenerate the ridge in the source area. We followed the same procedure in the pit bottom. Topography in the pit bottom was, however, more challenging to recreate due to ramps and waste dumps of uncertain elevation, which created some artifacts when gridded. However, critical elements of the pre-failure pit topography were accounted for, i.e. deepest areas to the south and east, as well as the central pit mound. The final modification to the February 2014 topography we accounted for was post-slide reconstruction of the main access ramp. This 45 m wide road built atop a large berm was reconstructed after the slides to allow heavy trucks in and out of the pit (see Figure 1f). We cropped out the relevant area and recreated topography across the rupture surface.

Differencing the pre- and post-slide surfaces, we generated an elevation-change map shown in Figure 2c. Results reveal a maximum source thickness of 213 m, mean source thickness of 102 m, and a maximum deposit thickness of 132 m. However, we note that post-slide modification of deposits in the pit may have significantly reduced the maximum deposit thickness. We also performed volume analysis from the two surfaces. Results revealed a source volume of 52 Mm^3 and a deposit volume (in the pit bottom only) of 53 Mm^3. Rio Tinto Kennecott determined the total mass of the slides as 144 million tons [*Sutherlin and Davis*, 2014], which assuming a bulk density of 2600 kg/m^3 (a value that accounts for some waste rock) equates to a source volume of 55 Mm^3. Our value is within 6% of this number. Our deposit volume, on the other hand, appears low. Accounting for 20-25% fragmentation bulking as intact rock is converted to debris (a typical range for most rock avalanches, see *Hungr and Evans*

[2004]), we estimate a deposit volume of 62-65 Mm^3. At the time of our aerial survey in February 2014, heavy modification of the deposits and surrounding pit walls had already taken place, which likely accounts for some of this discrepancy, in addition to possible errors in our approximation of the pre-failure pit topography.

2.3. Runout simulation

Relative volumes of the two rock avalanches are unknown. Evidence suggests that the first failure was larger than the second, as deposits from the first rock avalanche completely filled the pit bottom while the second slide did not. Previous interpretation of high-frequency seismic data also supported this conclusion [*Pankow et al.*, 2014], as does new analysis of seismic data presented later in this study (Section 3). *Hibert et al.* [2014a] meanwhile estimated that the first rock avalanche had mass ~1.5 times greater than the second using seismic force history inversion. We manually subdivided our cumulative source volume into two events, using known information on the basal rupture surface and creating a plausible intermediate scarp similar in appearance to the final scarp, but with the first event volume slightly larger than the second. Due to uncertainties, this provides only a rough approximation of the geometry of the two slide sources. Our final interpretation yielded intact-rock source volumes for the two rock avalanches of 30 Mm^3 and 22 Mm^3. The dynamic model used in our runout simulations does not include fragmentation bulking, so we manually increased these source volumes by 20% in the model.

We then simulated runout and deposition of the two rock avalanches. Our goal was to recreate the observed deposit extents and thickness distribution, and quantitatively investigate the dynamics of the slides. We used the equivalent-fluid code DAN3D [*Hungr*, 1995; *McDougall and Hungr*, 2004], which models rock avalanche movement over 3D terrain based on user input of pre-failure topography (slide path, source depth) and rheological parameters. DAN3D represents mass movements using three parameters: bulk density (ρ_b), internal friction angle of the slide mass (φ_i), and bulk basal shear resistance, where the latter can be defined by a variety of rheologies [*Hungr and McDougall*, 2009]. We adopt a new version of DAN3D that is modified to allow initial rigid-body motion, appropriate for coherent sliding-mode failures [*Aaron and Hungr*, 2016]. Our approach is trial and error; simulations are performed using trial parameters and results evaluated against their match to observed deposit characteristics as well as

independent velocity estimates from runup and super-elevation measurements. Parameters are updated (generally basal shear resistance) and new simulations performed until satisfactory match is achieved. Because of the approximate nature of our pre-failure topography, precise match in all areas was not expected.

We selected a frictional rheology for both the source area and pit floor, which represents the simplest assumption appropriate for most dry granular flows (REF). In the source zone, we assigned a low basal friction angle (φ_b) of 10°. This value ensured that the failure surface was completely evacuated, as observed, and is consistent with our hypothesized low-strength basal fault (Section 2.2). Outside of the failure surface, we increased the basal friction angle to 26° for the remainder of the runout path. This value is close to the 30° dynamic friction angle expected for dry, fragmented rock [*Hsu*, 1975]. We assigned a uniform internal friction angle of 35° and bulk density of 2000 kg/m^3 throughout.

We allow 30 s of initial rigid-body motion for the first rock avalanche, simulating coherent sliding at the onset of failure. During this time the source translates and rotates ~400 m to the southwest along the basal rupture surface (Figure 3). The slide mass is then converted into a 'frictional fluid', replicating the fragmentation process. *De Blasio* [2011] suggests mechanisms that can cause fragmentation of rock avalanches, including impact with topographic obstacles, free fall, and interaction with rugged topography. We consider it likely that the sliding mass fragmented as it left the planar rupture surface and interacted with the pit benches as the mass descended to the pit floor, consistent with our selected rigid motion distance. We note, however, that the version of DAN3D used here assumes that the entire slide mass is converted into a frictional fluid at the same time, while in reality it is likely that the rock mass fragmented progressively as it vacated the basal rupture surface.

Leaving the basal rupture surface, the first rock avalanche accelerates rapidly moving predominantly south, while some material spills out to the southeast over steep benches (Figure 3; Movie S1). At ~30 s, the main body has reached the southward bend and achieved maximum velocity of approximately 75 m/s. Debris super-elevates between 30-40 s as it rounds the bend and cascades down the steep wall of the inner pit. Moving over the ~45 m high central mound at velocities of around 55 m/s, the rock avalanche flows south, filling the deepest distal portions of the pit. After ~55 s debris has traveled roughly 2 km and reached the distal pit wall (average

velocity = 36 m/s); predicted incoming runup velocities are in the range of 45 m/s. After reaching the deepest, southern portion of the pit, material begins to progressively fill the northern and eastern regions generating a relatively thick deposit against the proximal northern wall. After ~70 s, the energetic period of runout has ceased and remaining material streams from the source area in a subdued manner; the failure surface is fully evacuated by ~140 s. The predicted final extent and thickness of deposits from the first rock avalanche match well with field observations (Figure 3).

Independent estimates of rock avalanche velocity can be generated from field observations of super-elevation and runup. The minimum incoming velocity (V_{min}) needed to achieve observed runup height (h) can be determined as [e.g. *Jibson et al.*, 2006]:

$$V_{min} = (2gh)^{0.5} \quad (1)$$

where g is gravitational acceleration. Meanwhile, the measured super-elevation height (d) as material flows around a bend with curve radius (r) and channel width (w) can be used to predict the minimum velocity (V_{min}) of the flow as:

$$V_{min} = [d(r/w)g]^{0.5} \quad (2)$$

Both formulations are minimum velocity estimates that neglect basal shear resistance. Based on Equation 2, we estimate that the first rock avalanche was traveling at least 60 m/s as it rounded the initial southward bend and spilled into the pit (d = 75 m, w = 300 m, r = 1500 m). To overcome the estimated h = 45 m high central mound, Equation 1 suggests debris must have been traveling at least 30 m/s, while to runup the distal wall by h = 90 m (as predicted from topographic reconstruction) requires an incoming velocity of at least 42 m/s. These results match well with velocities predicted from our DAN3D simulation (75, 55, and 45 m/s for the three locations, respectively).

We next added deposits from the first rock avalanche to the original slide path topography to generate the sliding surface for the second rock avalanche. Material and rheological parameters for the second rock avalanche were identical to those used for the first. The second rock avalanche originated from higher in the source area, and our simulation begins with material accelerating down the low-friction basal rupture plane to the west (Figure 4; Movie S2). We again allow 30 s (~600 m) of initial rigid-body translation, simulating coherent sliding

299 at the onset of failure until impact with the western pit wall. At ~40 s debris reaches the
300 southward bend at the end of the sliding plane, traveling at a maximum velocity of 85 m/s.
301 Between 40-50 s material cascades down the steep wall of the inner pit traveling south and east
302 to the lowest areas of the floor. Velocities decrease gradually. The maximum distal extent of
303 deposits is reached after ~60 s and represents ~2.5 km runout (average velocity of ~42 m/s).
304 Impact on the southern pit wall is not simulated, as observed (see Figure 1). After ~80 s, the
305 energetic period of runout has ceased, and the failure surface is fully evacuated by ~160 s.
306 Although the final extent of deposits matches field observations reasonably well for the second
307 rock avalanche, our simulations cannot fully reproduce the thickness of the deposited lobe on the
308 western margin of the pit (see Figures 1 and 2).

309 We again estimate the minimum slide velocity at the southward bend from observed
310 super-elevation (Equation 2), which yields V_{min} = 66 m/s (d = 135 m, w = 300 m, r = 1000 m).
311 Our DAN3D simulation predicted velocities of ~85 m/s in this region, approximately 30%
312 higher. No other independent velocity estimates are available for the second rock avalanche.

313 Lastly, we added deposits of the second rock avalanche to those from the first in order to
314 produce the final thickness and extent of simulated debris. Our final pit floor elevations were in
315 general similar, albeit slightly lower than observed, as illustrated in Figure 5. In the proximal
316 area of the deposit simulated elevations are up to 40 m higher than observed, while in the distal
317 region we underestimate deposit thickness by up to 60 m. Some of these discrepancies likely
318 arise from uncertainties associated with reconstruction of the pre-failure pit floor geometry,
319 while some may be due to large simulated debris accumulation on steep benches of the inner pit
320 wall. Nevertheless, our numerical simulations overall generated satisfactory match to observed
321 deposit extents and thickness, as well as independent estimates of slide velocities at different
322 points along the runout paths. We note that our runout simulations employed simplistic
323 assumptions with regards to slide path shear resistance, i.e. we assumed uniform frictional
324 material properties throughout with values close to nominal friction angles for dry granular rock
325 [*Hsu*, 1975]. The low shear strength used in the source zone is likely due to polishing and
326 removal of asperities along the planar basal fault (termed 'ultimate strength' by *Cruden and*
327 *Krahn* [1978]).

328

3. Broadband seismo-acoustic signals

Fundamental information about the Bingham Canyon rock avalanches is readily available from cursory examination of unfiltered seismic data. Most notable was recognition that there were two large landslides, as well as the timing of each [*Pankow et al.*, 2014]. The first rock avalanche occurred at 9:30 pm MDT (UTC-6), while the second rock avalanche occurred 1.5 hours later at 11:05 pm MDT. Closer examination of the seismic data in multiple frequency bands, combined with infrasound data, however, reveals a more complex progression of landslides, as well as intriguing details of the rock avalanches that can be compared to topographic and runout models.

3.1. Seismo-acoustic event detection

At the time of the landslides, the University of Utah Seismograph Stations (UUSS) operated nine infrasound arrays in collaboration with Southern Methodist University and Los Alamos National Laboratory (Figure 6). Each array consisted of four sensors arranged in a triangular configuration with a center element. At each array, one of the acoustic elements was collocated with a seismic sensor. The closest infrasound array to the Bingham Canyon mine (NOQ, ~13 km) had one bad channel at the time of the rock avalanches, but was still useful for event detection.

Infrasonic detections were determined by batch processing infrasound array data in InfraMonitor3 [*Arrowsmith and Whitaker*, 2008] using a five-hour time window centered on the two rock avalanches. Infrasound data were instrument-deconvolved in the frequency domain with corners at 0.5 and 10 Hz, and then filtered using a fourth-order Butterworth bandpass (0.5-5 Hz) filter. Inframonitor3 performs array processing, and a detection is declared when the correlation coefficient across elements in the array exceeds 0.5, computed for each 10 s discretized time window, with 50% overlap and a 7200 s adaptive window. For the rock avalanche detections, the correlation coefficient exceeded 0.7. For the first rock avalanche, we identified detections at seven arrays consistent with energy traveling along the back-azimuth to the Bingham Canyon mine, while for the second rock avalanche we identified detections at five arrays. Details regarding the duration, amplitude, back-azimuth, and phase and group velocity are summarized in Table 1. Infrasound event detection analysis follows methodology described by *Hale* [2013].

359 Inspection of infrasound data from the WMUT array (~57 km from the mine) over a
360 longer time window reveals a third landslide detection (cross-correlation coefficient of 0.89,
361 back-azimuth 337°, and arrival time 04:05:53) consistent with an event originating from the
362 Bingham Canyon area at approximately 04:03:01 UTC, a half-hour after the first rock avalanche
363 and an hour before the second rock avalanche. This landslide was also well-recorded at seismic
364 stations out to 100 km (Figure 7; WMUT, array component 3 infrasound, red). This newly
365 identified landslide shares many of the same characteristics seen in the two larger rock
366 avalanches, notably a secondary pulse of energy evident at the closer stations [*Pankow et al.*,
367 2014]. Given the presence of this previously-unrecognized third landslide event, we inspected 24
368 h of continuous short-period and broadband vertical seismic data (from distances ≤100 km)
369 starting at 04/10/2013 17:00 UTC. At times of possible detections, seismic events were classified
370 by combining available data, visually inspecting the move-out of seismic energy to be consistent
371 with a source initiating in the Bingham Canyon area, and processed in order to determine the
372 coda (or duration) magnitude (Mc). As a result of this additional processing, 11 new, smaller (0.9
373 ≤ Mc ≤ 1.9) landslides were identified (Table 2, Figure 8). Eight occurred between the first and
374 second rock avalanches, while the remaining three occurred within 4 hours after the second rock
375 avalanche. For many of these newly detected landslides there is at least one secondary burst of
376 energy.

377 To estimate the volume of these newly detected landslides, we follow *Yamada et al.*
378 [2012] and calculate energy release by summing the square of ground velocity in a 1 to 4 Hz
379 passband for all stations within 100 km (Figure 8). Energy estimates for station NOQ and
380 extrapolated to a distance of 1 km from the mine are listed in Table 2. We then calculated
381 volumes using the relation in *Yamada et al.* [2012]. The energy from the two main rock
382 avalanches is four to five orders of magnitude larger and estimated volume two to three orders of
383 magnitude greater than the newly identified landslide events. All 11 newly-detected slides had
384 estimated volume in the range of 10^4-10^5 m^3. Volumes determined for the two rock avalanches
385 (21 and 18 Mm^3, respectively) are in relatively close agreement with our estimates from
386 topographic reconstruction (Section 2.2). The cumulative volume of all landslides estimated
387 from seismic energy is 41 Mm^3, ~20% lower than our reconstructed source volume (52 Mm^3) but
388 within reasonable agreement.

3.2. Force-time history

Beginning with long-period seismic data, we describe large-scale features of the rock avalanches. In subsequent sections, we analyze progressively shorter-period data to resolve finer scale details of the two main rock avalanches. *Hibert et al.* [2014a] inverted regional long-period data for the force-time history of the Bingham Canyon rock avalanches. Using stations up to 1000 km in distance and periods greater than 40 s, they calculated salient large-scale features of the landslides. On the other hand, *Yamada et al.* [2013] showed that data with periods down to 10 s could be in inverted for a simple force-history of the Akatani landslide in Japan.

We use data from 22 stations within 300 km of the Bingham Canyon mine, where nine are less than 100 km away, and periods down to 10 s to invert for the force-time history of the two rock avalanches. Three-component broadband seismic recordings from the UUSS and the U.S. National Seismic Network were obtained for stations within 300 km of the landslide (Figure 6). The data were instrument-deconvolved to ground velocity, filtered between 10 and 50 s with a 6-pole acausal Butterworth filter, and rotated to radial and transverse components of motion. The data are shown in Figure 9 along with the low-pass versions used by *Hibert et al.* [2014a]. The long-period waveforms (40-150 s) of both events are similar and differ only by a scale factor (Slide #1 / Slide #2 ≈ 2). However, the intermediate-period waveforms (10-50 s) show differences between the two rock avalanches (e.g., at station DUG), where a larger initiation phase is observed for the first slide in addition to a significant stopping phase that is absent in the second slide.

We followed the approach of *Ekström and Stark* [2013], in which three-component ground motion time histories are inverted for a time-varying force parameterized as a sequence of 100 partially overlapping triangles of half-width 1 s, which in total integrate to zero to satisfy zero motion before and after the slide. The Green's functions are calculated [*Herrmann*, 2002] for a shallow source in the simple layered velocity model WUS [*Herrmann et al.*, 2011], which *Whidden and Pankow* [2012] found to be suitable for moment tensor analysis in Utah. *Allstadt* [2013] describes algebraic details of the inversion. Figure 10a shows the results of the inversion for the landslide force history. The maximum force for the first and second rock avalanches is 120 GN and 40 GN, and the duration of the slides are 71 and 84 s, respectively. These duration estimates match well with results of our runout modeling (Section 2.3). *Hibert et al.* [2014a]

calculated maximum forces of the two rock avalanches of 138 GN and 79 GN, respectively. Also, the time of the maximum force in the first rock avalanche occurs near the end of our history at about 60 s, which is much later than *Hibert et al.* [2014a]. This may be due to the force required to produce the stopping phase in the waveforms, which is not observed in the longer period data. Ground velocity at different stations predicted by the force histories are given in Figure 11 compared to the seismic data.

Different methods are available to estimate the volume of the landslides from long-period seismic data. *Hasegawa and Kanamori* [1987] inverted the relationship for mean force F (where F is approximately half the peak force F_{max}), $F = V \rho g \sin \theta$, where V is volume, ρ is density, g is gravity, and θ is the average slope inclination. Using this relation for the first rock avalanche (F_{max} = 120 GN, ρ = 2000 kg/m^3, g = 10 m/s^2, and θ = 16°, which is the total travel angle calculated in Section 2.2) gives V = 11 Mm^3, and for the second rock avalanche (F_{max} = 40 GN) V = 4 Mm^3. Both values are significantly lower than our reconstructed volumes for the two slides (Section 2.2), which is most likely due to the time invariant assumptions of density and volume in the simple relationships. *Ekström and Stark* [2013] identified scaling relations between maximum force (F_{max}) and surface-wave magnitude, $M_{SW} = 5.4 + 0.45 \log_{10} (F_{max}$ [10^{12} N]), and F_{max} and landslide mass, m [10^{12} kg] = 0.54 (F_{max} [10^{12} N]). Using these relations, we obtain M_{SW} = 4.99 and 4.77, and m = 64.8 and 21.6 billion kg for the first and second rock avalanches, respectively (equivalent intact rock volumes: 25 and 8 Mm^3), values that are closer but still lower than our reconstructed source volumes.

Double-integrating the force-time history and dividing by an average mass of the sliding body, we can estimate a horizontal displacement history from a defined origin point [*Ekström and Stark*, 2013]. Figure 10b shows displacement of the first and second rock avalanches on a contour map of the mine, assuming an average mass of 70 and 25 billion kg for the first and second slides, respectively (rounded values from above). Again, we note that this total mass is about 2/3 the total mass from our topographic reconstruction, and is most probably due to the assumption of a time invariant volume and mass. The paths compare well with our reconstruction from the slide deposits and runout modeling. Importantly, we learn that the track of the first slide apparently travelled further across the floor of the mine, whereas the second slide followed a similar path, but stopped short of where the first slide ended. We also observe

449 that the two rock avalanches, while similar, have subtle differences that might reflect the change
450 in topography on the pit floor between the slides.

451 ***3.3. Intermediate-period displacement records***

452 Inversion of intermediate- to long-period seismic data in this study allowed us to
453 reconstruct the force-time history of the two rock avalanches and estimate the slide trajectories
454 and volumes. However, as demonstrated by *Allstadt* [2013], long-period inversions average over
455 more subtle variations in the source time history, such as multiple failures. It is these subtle
456 variations that provide additional insight in reconstructing the rock avalanches. Because of
457 source dimensions and unknowns in the detailed subsurface velocity model, it is not feasible to
458 invert for the force-time history using shorter period data. As a proxy, we use seismic
459 displacement data to reconstruct the direction of the slide-imparted forces on the ground over
460 time.

461 For this analysis, we examine displacement time histories at station NOQ located ~13 km
462 north of the mine. Given the shallow source and close distance, path effects should be minimal,
463 and given the relative location between the station and the mine (azimuth 8.6°) the station is
464 naturally aligned to radial and transverse horizontal rotation, for the north and east components,
465 respectively. Raw data are instrument deconvolved and integrated to displacement in the
466 frequency domain, with corners at 0.01 and 100 s. The displacement records are then filtered
467 using a time domain 2-pole acausal Butterworth bandpass filter from 1 to 40 s (Figure 12). Most
468 notable in this bandpass are several rapid (<10 s) changes in polarity visible on all three
469 components.

470 For the first rock avalanche, there are four notable abrupt changes to the force-time
471 history (labeled A-D in Figure 12A). We estimate the onset of the slide at 5 s (start of the record
472 at 0 s is arbitrary). Between 5 and 25 s, the ground is moving mostly east as the rock avalanche
473 accelerates west along the basal rupture surface, in accordance with our runout modeling (Figure
474 3). At A (~31 s), the ground reaction force changes direction to the west and north. This change
475 is consistent with the slide turning and accelerating to the southeast. At B (~42 s), the direction
476 of the force changes abruptly to the south. Together with the other two components, which are
477 directed west and down, this phase is consistent with the rock avalanche decelerating as it arrives
478 on the bottom of the pit and climbs up and around the large central mound. Between B and C,

479 debris crosses the central mound heading for the most distal regions of the pit. At C (~56 s), we
480 see a change in the force direction to the southeast and up, which we interpret as the slide
481 decelerating as it begins to impact and runup the distal pit wall (see Figure 1a). At D (~70 s), the
482 force changes abruptly, with largest amplitude over the duration of the event. This we interpret
483 as the reaction of the distal pit wall rebounding to the northwest (and down) after stopping the
484 impacting slide debris. Displacement records from the second slide (Figure 12b) do not bear this
485 feature as it did not impact the distal pit wall.

486 For the second rock avalanche, there are again abrupt changes in the force-time history
487 (labeled A-E in Figure 12b). However, there are two major differences as compared to the first
488 slide: (1) partitioning of the vertical motion, and (2) small amplitudes at the beginning of the
489 second slide (also visible from the longer-period force-time history, Figure 10). Again we
490 estimate the onset of the slide at 5 s. For the first ~25 s, ground displacements are to the north
491 and east with little vertical movement, consistent with the mass sliding southwest on a shallow
492 plane (compare to Figure 4). At ~32 s (point A in Figure 12b), slide debris continues accelerating
493 to the southwest but abruptly begins accelerating downward, beginning to spill into the inner pit.
494 There is another larger acceleration phase at B (~43 s) where material moves southwest, which
495 we interpret as debris super-elevating and rounding the bend at the end of the failure surface as it
496 travels southwest along the western pit wall (Figures 1 and 4). At C (~53 s), the material
497 continues to accelerate to the south but is decelerating to the west and down. This motion is
498 consistent with the slide running down into the pit bottom along the western side of the pit
499 (compare to Figure 4). At D (~62 s), we again see material accelerating downward and later
500 west, likely spilling into the remaining deep portions of the pit along its distal southwest
501 margins. At E (~90 s), we see a late-arriving mostly vertical force followed by a force directed to
502 the north. This motion is not consistent with the movement of the rock avalanche, and it comes
503 after the bulk of material has likely stopped. It is also inconsistent with a subsequent landslide.
504 The frequency content is dominated by short-periods, and initiation of a subsequent slide would
505 have had to start earlier in the wavetrain, which is inconsistent with modeling of the long-period
506 energy. We revisit this packet of energy in the next section.

3.4. Short-period seismic signals

Short-period (<1 s) seismic signals from both rock avalanches (Figure 13) deviate from the typical cigar-shaped envelope of a landslide seismogram; a form where energy builds slowly and regularly before tapering out over 10's of seconds. Rather, the Bingham Canyon rock avalanches, as well as some of the smaller landslide events, show a double-peak envelope, especially evident at the nearest station NOQ (Figure 8), consisting of two packets of emergent and gradually decaying energy. For each slide, the first portion of the seismogram is rich in short-period energy (Figure 13), with strongest power in the 0.2-1 s band. This represents a typical buildup and decay of high-frequency energy caused by block impacts during landslide motion. However, the second packet of energy in the two rock avalanche seismograms shows differences between the slides: for the first rock avalanche this trailing packet is rich in low-frequency energy while for the second is rich in high-frequency energy.

We replicate the labels A-E from the preceding intermediate-period analysis (Section 3.3) for comparison with short-period seismic signals (Figure 13). For both rock avalanches, short-period energy builds slowly after the onset of sliding along the basal rupture surface for ~32 s until point A. Amplitudes increase between A and B as material begins to spill into the deep inner pit, and then again more strongly between B and C as debris runs out over the pit with high velocity. For the first rock avalanche, amplitudes begin to decrease after C, consistent with our interpretation of deceleration as material begins to impact and run up the distal pit wall. Amplitudes continue to decrease until abruptly increasing again at D, which we propose represents rebound of the pit wall and is consistent with this later packet of energy being enriched at lower frequencies. For the second rock avalanche, high-frequency amplitudes continue to increase between C and D, finally decreasing after D as material decelerates and comes to rest. We did not observe or simulate impact with the pit wall for this second slide. Here the trailing packet of seismic energy comes in later, around 90 s, which is inconsistent with movement of the second rock avalanche determined from our previous analyses.

We propose that the trailing signal following the second rock avalanche (E in Figure 13) represents an air-coupled Rayleigh wave, i.e. a surface wave created by a large atmospheric pressure disturbance. The energy in this packet is monochromatic (period ~1.2 s) and begins as near-retrograde elliptical motion that abruptly changes to near-prograde elliptical motion after a

few seconds. Similar, though not identical, properties have been documented for other instances of air-coupled Rayleigh waves generated from near-surface seismic sources [*Press and Ewing*, 1951; *Dobrin et al.*, 1951; *Gupta and Hartenberger*, 1981]. To generate an air-coupled Rayleigh wave, the phase velocity of the surface layer must match the velocity of sound in air at some unique frequency. At the time of the first rock avalanche, the pit bottom would have been composed of relatively high-velocity rock. However, after the first rock avalanche, the pit bottom was filled with a low-velocity debris layer, which would have been conducive to air-coupled seismic waves. Further, if we assume a phase velocity of 0.35 km/s (consistent with trace velocities measured from infrasound data; Table 1), coupling of the air wave would have occurred around the time when the rock avalanche was beginning to impact the pit bottom (i.e., around time C in Figure 13). It is also likely that the second packet of emergent energy noted for the smaller slides in section 3.1 may similarly be the result of air-coupled Rayleigh waves; however, we have not fully investigated waveforms for the smaller slides in this analysis.

3.5. Short-Period Seismic Radiation

We further examined source properties of the landslides by back-projecting short-period energy recorded at 42 seismometers located within 200 km of the mine. The technique is similar to the source-scanning algorithms of *Kao and Shan* [2004] and *Jakka et al.* [2010], and has been shown to be effective at localizing energy from landslide sources that occur within a dense seismic network [*Yamada et al.*, 2013]. The vertical component waveforms were detrended and bandpass filtered at 1-5 Hz. Next, the envelope was taken, the values were squared, and a low-pass filter with a corner of 0.5 Hz was applied. Finally, the root-mean-square noise measured in the minute before the first arrival was subtracted, and each trace was normalized. The processed traces are proportional to short-period energy release as a function of time and, because of their proximity to the source, are dominated by source effects and less influenced by propagation effects. We selected seismograms with high signal-to-noise, generally greater than 10 after the preprocessing, and from stations that spanned distance and azimuth as evenly as possible. Energy from the array beam was back-projected to a near-source grid of points assuming S-wave propagation in the AK135 velocity model [*Kennett et al.*, 1995]. The grid spacing was 0.01° in latitude and longitude and the energy was measured every 1 s from a 4-s long array beam constructed with 4th-root stacking [*Muirhead and Datt*, 1976].

567 Back-projection results from the first rock avalanche are presented in Figure 14.
568 Spatially, the event is located remarkably well, especially considering that we used a 1D global
569 reference model for travel time calculation. The maximum time-averaged beam power occurs at
570 112.16° W, 40.54° N, less than 2 km away from the nominal epicenter of 112.142° W, 40.536°
571 N. There is significant smearing, however, with beam power 50% of the maximum extending to
572 distances of 55-60 km. The smearing exists in time as well, with the first and third bursts of
573 energy appearing as shoulders around the second burst maximum, although the total duration of
574 about 100 s is similar to what is visually observed on the closest records.

575 In an effort to sharpen the time-space localization, we experimented with back-projecting
576 data from subsets of the seismometers shown in Figure 8. In general we found that using fewer
577 records from closer distances reduced the smearing in time, however the smearing in space
578 increases and the spatial accuracy decreases. Fundamentally, smearing results from the use of
579 amplitudes only (i.e. seismogram envelopes) that is required by the incoherence of short-period
580 seismic data recorded at local-to-regional distances. In back-projection of longer-period data at
581 larger distances, the phase information can be used to substantially increase the resolution
582 because of the high coherence of teleseismic P waves at periods of 1 s and longer [*Xu et al.*,
583 2009; *Langston*, 2014].

584 Back-projection results from the second landslide are presented in Figure 15. Spatial
585 accuracy is again very high, with the maximum time-averaged beam power occurring at 112.17°
586 W, 40.51° N, just under 4 km away from the nominal epicenter. Smearing of beam power in
587 space and time is similar to that observed for the first rock avalanche, however the larger
588 amplitude of the third burst of energy in the second landslide results in a distinct peak in the time
589 evolution plot. There is also a rise in beam power beginning about 20 s after the peak from the
590 third burst dies away. This energy is related to an earthquake induced in the vicinity of the mine
591 by the landslide [*Pankow et al.*, 2014].

592

593 **4. Discussion**

594 Different methods used in our analysis generated varying estimates of the cumulative and
595 individual rock avalanche volumes, which we can compare to assess accuracy and consistency.
596 Our topographic reconstruction generated an estimate for the cumulative intact rock source

volume mobilized in the landslides of 52 Mm^3. This value is close to that obtained by the mine (~55 Mm^3), which we presume is accurate and was likely generated from comparison of pre- and post-event LiDAR data. Our value may be lower because our aerial photogrammetry survey was performed several months after the landslides and significant modification of the source and deposit areas had already taken place. Bulk topographic reconstruction, on the other hand, offered no concrete evidence as to partitioning of the volumes between the two main rock avalanches. We could only qualitatively note that the first rock avalanche appeared to be larger than the second from the distribution of deposits.

Seismic data analysis offers better insight into the volumes of the two rock avalanches, but different approaches generated different volume estimates. Analysis of short period seismic energy release (following *Yamada et al.* [2012]) provided the closest match with our topographic reconstruction, suggesting volumes of 21 and 18 Mm^3 for the first and second rock avalanches, respectively, and a total cumulative landslide event volume of 41 Mm^3. Here the volume of the first rock avalanche is approximately 1.2 times that of the second. Importantly, this analysis also revealed several additional landslides that likely occurred in the pit between and after the two main rock avalanches. Inversion of intermediate-period seismic, on the other hand, generated rock avalanche volume estimates of 25 and 8 Mm^3, for the two events respectively (following *Ekström and Stark* [2013]). The volume determined for the first slide is close to our reconstructed value and is consistent with results from short-period energy calculations. The volume for the second rock avalanche, however, is much lower. Here the volume ratio for slide 1 / slide 2 = ~2.6. By comparison, *Hibert et al.* [2014] estimated a volume ratio of ~1.5 for the two Bingham Canyon rock avalanches based on inversion of long-period seismic data. Comparing these results offers valuable insight on the expected level of accuracy for landslide volume estimates obtained solely from seismic data analysis.

We combined independent analysis of short- and intermediate-period seismic data together with 3D runout modeling to assess dynamics of the two Bingham Canyon rock avalanches, with consistent results. Both runout modeling and seismic data show that the first rock avalanche accelerated after initial failure taking ~25 s to leave the rupture surface. Around 35-40 s after failure, rock avalanche debris reached the pit bottom, decelerating slightly as it climbed and passed the central pit mound traveling predominantly south. Shortly after 50 s, the rock avalanche reached the distal pit wall and began decelerating, and both our runout modeling

and seismic data suggest relatively energetic impact (with accompanying rebound of the pit wall evident in seismic data). We obtained similar results for the second rock avalanche showing good agreement between runout modeling and seismic reconstruction of slide dynamics. Key differences to the first event include a longer phase of initial sliding as the rock avalanche traveled a farther distance along the basal rupture plane, and strong super-elevation as the landslide debris turned southward at high velocity. While our runout modeling and seismic analyses were conducted independently, their combined interpretation greatly enriched our ability to describe details of the landslides' dynamics. We found that runout modeling provided a valuable framework to describe the position of the landslide mass in time, while seismic data provided finer detail on the evolution of basal forces over time.

Moreover, seismic data revealed an anomalous trailing packet of energy for the second rock avalanche that we propose represents and air-coupled Rayleigh wave, as has been observed in the past for above-ground explosions. One hypothesis we can extend from this observation is that the second rock avalanche may have taken an airborne trajectory leaving the shallow-dipping basal sliding surface as it spilled into the inner pit. The air blast in this case could have resulted from impact of the slide debris on the pit bottom, which is consistent with the back-projected timing for the source of this signal. Topographic analysis and photographs (e.g. Figure 1) show a sharp inflection at this slope transition, and our runout modeling indicated peak velocities of 85 m/s, suggesting that an airborne phase of motion may have been possible (note DAN3D cannot simulate airborne motion). Unfortunately no eye-witness accounts are available to confirm or refute this hypothesis. Observation of similar trailing signals for other, smaller landslides suggests these too may have had an airborne phase to their runout as they transitioned from the failure surface to the steep inner pit.

Seismic data analysis and runout modeling also generated comparable estimates of the duration of the two Bingham Canyon rock avalanches. Duration is a key metric discerned from seismic data commonly used in remote assessment of landslide volume [e.g. *Deparis et al.,* 2008, *Dammeier et al.,* 2011 *Hibert et al.,* 2011; *Levy et al.,* 2015; *Manconi et al.,* 2016]. Our inversion of intermediate-period seismic data (Figure 10) indicated a total duration for the first and second rock avalanches of 71 and 84 s, respectively. These values are consistent with our analysis of intermediate- and short-period displacement data (Figures 12 and 13), which indicated durations for the two rock avalanches of ~70 and ~90 s. Late arriving seismic energy complicated duration

estimates from these data however, as the end of the slides were partly obscured. Moreover, different frequency bands are sensitive to different aspects of landslide motion; long- and intermediate-period data indicate bulk motion of the landslide mass while short-period data include energy produced by block-ground collisions that often continue slightly beyond the end of bulk mass movement. For comparison, our runout models indicated slide durations of ~70 and ~80 s for the first and second rock avalanches, respectively, with minor trailing movements continuing for 10's of seconds after the end of the bulk flows (Figures 3 and 4), in good agreement with our seismic estimates.

Lastly, we tested a new method of locating landslides from back-projected short-period seismic energy (Figures 14 and 15), a classically challenging aspect of seismic landslide characterization [e.g. *Lin et al.,* 2010; *Hibert et al.,* 2014b]. The results can be benchmarked against the known locations of the rock avalanches within the Bingham Canyon mine. For the first slide, back-projection results gave a predicted location within 2 km of the actual source, while for the second slide the predicted location was 4 km from the mine. These results compare well with recent attempts to improve seismic landslide localization using new techniques, e.g. grid-based moment tensor inversion [*Dammeier et al.,* 2015], in place of traditional arrival time triangulation, which generally place a detected landslide within several kilometers of the known location when recorded by an existing regional or national instrument network.

5. Summary and Conclusions

Our ability to remotely characterize landslide events continues to increase with the addition of new and refined analysis techniques based on high-resolution seismic, infrasound, and topographic data. Here we analyzed a rich dataset with the goal of characterizing one of North America's largest historical landslide events, the 2013 Bingham Canyon rock avalanches. Because the slides were located near a densely instrumented (and seismically active) urban area, we have access to a large amount of high-quality geophysical data. This is contrasted, however, against the limited access to on-site ground investigation data because the slides occurred on private property\.

Results of our analyses show that the Bingham Canyon landslide event consisted of two main rock avalanche phases and 11 additional smaller landslides. The former were clearly visible

in raw seismic data, allowing rapid interpretation of essential details shortly after the events, e.g. slide timing [*Pankow et al.*, 2014]. The smaller landslides, which occurred between and after the rock avalanches, were previously unrecognized. We initially discovered these additional slides through analysis of infrasound data, then through detailed inspection of broadband seismic records. While their total volume is comparably small, their discovery adds detail to the event progression, useful in reconstructing the cumulative hazard scenario and extending lessons learned to future studies.

The two Bingham Canyon rock avalanches occurred on the evening on April 10, 2013, separated by 1.5 h at 9:30 and 11:05 pm MDT. Combination of broadband seismic data analysis with a new topographic survey and numerical runout modeling revealed several salient details of the rock avalanches. We determined a cumulative landslide volume of 52 Mm^3, a value which is very close (within 7%) to the total mass of debris reported by the mine owner. Based on seismic data analysis and photographs, we estimated the volume of the first rock avalanche was between ~1.5 and 2 times greater than that of the second rock avalanche. Both failures initiated by sliding along a highly-persistent, low-angle (21°) basal fault zone, which by the observed full evacuation of the source area must have been a relatively low-strength surface.

After initiation, the first rock avalanche traveled west/southwest before turning and spilling into the deep inner pit. Traveling with maximum predicted velocity of 75 m/s, the rock avalanche super-elevated leaving stranded deposits on benches of the western wall, before making its way across the pit bottom. Encountering a large central mound on the pit floor, the rock avalanche flowed energetically over and around this obstacle, traveling south/southeast. Reaching the opposing pit wall with predicted incoming velocity of ~45 m/s, debris decelerated as it impacted and ran up leaving a counter-sloping deposit surface. At this point the rock avalanche had traveled roughly 2 km in ~55 s (average velocity = 36 m/s). By ~70 s, the energetic portion of the rock avalanche had ceased.

The second rock avalanche began in a similar manner, but due to the higher position of the source, debris moved west down the failure surface for ~30-40 s reaching maximum predicted velocity of ~85 m/s. The rock avalanche super-elevated as it left the source area turning sharply to the south and spilling into the inner pit. Proximal pit topography had been partly smoothed by deposits from the first slide, and the second rock avalanche moved over these

719 deposits decelerating as it traversed the floor; this second slide did not reach the distal pit wall.
720 The front of the slide traveled roughly 2.5 km in ~60s (average velocity = 42 m/s), and energetic
721 runout had ceased by ~80 s. We interpret a trailing packet of seismic energy following the
722 second rock avalanche as an air-coupled Rayleigh wave, which may have been generated by
723 impact of landslide debris on the pit floor.

724 Methods used in this study relied on relatively few assumptions (e.g. our runout models
725 used a common rheology with typical values, while seismic analyses employed only basic 1D
726 velocity models). The net result we demonstrate is that with high-quality, publicly-available
727 geophysical data, descriptions of remote or inaccessible landslide events are and becoming
728 increasingly detailed. However, limitations of the methods and the range of possible errors must
729 also be recognized. This creates new opportunities to analyze rare large landslide events across
730 the globe. While early scientific analyses relied on uncommon eye-witness descriptions, we are
731 no longer restricted by this limitation, allowing rapid expansion of the dataset of well-described
732 events that can be used to better understand rock avalanche runout phenomena and ultimately
733 their associated hazard.

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936

937 **Table 1:** Infrasound data for the two rock avalanches detected at different stations.

Rock avalanche 1

Array	Time (UTC)	Distance (km)	Highest Correlation Coefficient	Trace Velocity (km/s)	Group Velocity (km/s)	Azimuthal Deviation (°)	Duration (s)	Peak-to-Peak Amp. (Pa)
BRPU	3:40:41	168	0.969	0.425	0.272	3.137	97	0.186
FSU	3:37:51	140	0.815	0.319	0.311	-6.560	46	0.040
FSU	3:39:41	140	0.858	0.332	0.250	0.796	105	0.047
HWUT	3:39:16	128	0.756	0.431	0.241	-15.518	81	0.089
LCMT	3:55:56	403	0.844	0.350	0.263	7.370	46	0.036
NOQ	3:31:41	13	0.909	0.350	0.166	-10.207	91	0.954
PSUT	3:46:56	267	0.781	0.341	0.268	-8.831	48	0.019
PSUT	3:48:41	267	0.744	0.516	0.243	-7.631	40	0.021
WMUT	3:33:46	57	0.972	0.385	0.281	0.027	157	1.620

Rock avalanche 2

Array	Time (UTC)	Distance (km)	Highest Correlation Coefficient	Trace Velocity (km/s)	Group Velocity (km/s)	Azimuthal Deviation (°)	Duration (s)	Peak-to-Peak Amp. (Pa)
BRPU	5:15:26	168	0.894	0.425	0.278	3.137	100	0.107
HWUT	5:14:01	128	0.940	0.431	0.245	-15.518	182	0.036
LCMT	5:30:21	403	0.949	0.357	0.269	3.839	35	0.052
PSUT	5:21:21	267	0.706	0.379	0.278	3.493	62	0.036
PSUT	5:23:11	267	0.942	0.410	0.251	-3.501	69	0.169
PSUT	5:24:16	267	0.988	0.457	0.235	-5.331	95	0.378
WMUT	5:08:31	57	0.866	0.425	0.303	16.191	106	1.472

938

939 **Table 2:** Energy and volume estimates for all detected landslides, including the two main rock
940 avalanches (UTC 3:30 and 5:05, bold). The total estimated volume by this approach is 40.5
941 Mm^3.

Time UTC	Energy at NOQ [1]	Energy at 1 km [1]	Estimated volume (m^3) [1]	Coda magnitude Mc
3:30:22	**2E-08**	**1E-04**	**2.1E07**	**4.2**
3:37:50	5E-13	9E-10	7E04	1.4
3:39:10	4E-13	8E-10	7E04	1.1
4:03:01	1E-12	1E-09	8E04	1.5
4:08:09	3E-13	8E-11	2E04	1.4
4:41:33	2E-12	3E-09	1E05	1.6
4:44:56	1E-13	8E-11	2E04	0.9
5:00:23	1E-11	3E-08	4E05	1.2
5:03:52	5E-12	1E-08	2E05	1.2
5:05:23	**2E-08**	**8E-05**	**1.8E07**	**3.5**
5:41:26	4E-13	1E-09	7E04	1.2
5:54:58	5E-13	2E-09	1E05	1.9
9:39:41	9E-13	6E-10	6E04	1.3

942 [1] Following *Yamada et al.* [2012]

943

944 **Figure captions**

945

946 **Figure 1:** a-c) Photographs of the 2013 Bingham Canyon rock avalanches (images courtesy of
947 Rio Tinto Kennecott, used with permission): a) Overview of pit, source area and slide deposits;
948 view is to the north. Predominantly gray colored deposits of the first slide can be seen around the
949 perimeter with superposed orange-colored deposits of the second slide. b) Source area: basal
950 rupture surface dips west with truck shop indicated in the foreground. c) View from the source
951 area highlighting the southward turn and super-elevated slide deposits indicating rapid runout
952 velocity. d-f): Time-lapse images of the Bingham Canyon mine: d) July 2012, nine months
953 before the landslides (image: State of Utah); e) May 2013, shortly after the landslides (image:
954 NASA); f) February 2014, following modification of slide deposits and continued mining. Slide
955 source area is outlined in pink, total deposit area in light blue, main deposit body in deep blue.

956 **Figure 2:** a) Recreated topography of the Bingham Canyon mine before the rock avalanches,
957 based on July 2012 aerial photograph. The source area is a steep ridge on the northern pit wall,
958 the deepest part of the pit is to the south and east. Contour interval is 50 m. b) February 2014
959 topography with rebuilt access ramp removed from the source area. c) Elevation change
960 (absolute value) between February 2014 and recreated pre-slide topography. Elevation change is
961 negative in the source area and positive in the deposit area. Maximum source thickness is 213 m;
962 maximum deposit thickness is 132 m. d) Hillshade of the February 2014 DEM. Modification to
963 the source area and deposits includes terracing around the scarp, reconstruction of the pit access
964 ramp, and removal of slide debris in the pit bottom. Elevation profiles along the runout path
965 (yellow line) can be seen in Figure 5.

966 **Figure 3:** DAN3D model results for the first Bingham Canyon rock avalanche: Top panels show
967 a time-lapse sequence of the slide runout. Super-elevation at the southward bend occurs at 30-40
968 s, material descends the steep slope of the inner pit wall by 40 s, followed by energetic runout
969 across rough topography of the pit bottom. The distal pit wall is reached by 55 s and energetic
970 runout ceases by ~70 s. Bottom panel shows the slide after all material has come to rest.

971 **Figure 4:** DAN3D model results for the second Bingham Canyon rock avalanche: Top panels
972 show a time-lapse sequence of the slide runout. Super-elevation at the southward bend occurs at

roughly 30-40 s, material descends the steep slope of the inner pit wall between 40-50 s, while runout across previous slide deposits occurs between 50-70 s. Energetic runout ceases by ~80 s Bottom panel shows the slide after all material has come to rest.

Figure 5: Elevation profiles along curved runout path (for profile line see Figure 2d). Source area for the first rock avalanche is the frontal region of the ridge between the pre-failure surface and path 1. Source area for the second rock avalanche is the region between path 1 and path 2. Simulated accumulation of deposits in the pit bottom can be seen along with the recreated pre-failure and February 2014 topography.

Figure 6: Map showing locations of seismic stations (triangles) and infrasound arrays (circles) in Utah, plus two neighboring broadband stations located in Nevada and Idaho. Many of these stations were used for location and magnitude analysis. Infrasound arrays and seismic stations used for detailed force-time history analysis and for determining the radiated short-period energy are labeled.

Figure 7: Seismic (black) and infrasound records (red, WMUT array component 3) for a third landslide identified using seismo-acoustic data. Start time for the record section is 04:03:01 UTC. The infrasound arrival is delayed relative to the seismic arrival because of lower propagation velocities in the atmosphere compared to average seismic velocities.

Figure 8: a) Envelope functions (1-4 Hz passband) calculated from the vertical component sensor located at NOQ using a Hilbert transform aligned by the origin time for the 11 newly detected landslides compared to the two rock avalanches (03:30:22 and 05:05:23 UTC). b) Energy calculations [after *Yamada et al.*, 2012] for all seismic stations <100 km from the mine that recorded the event. Symbols match labels for the envelope functions in a). Open symbols show stations with known sensor issues. Volumes esimated for the newly detected landslides are given in Table 2.

Figure 9: Data (in raw counts) for the first and second rock avalanches (black and red traces, respectively) in two filter bands (40-150 s and 10-50 s), where the amplitude of waveforms for slide 2 filtered between 40 and 150 s are doubled. The vertical (Z), east (E), and north (N) components are shown in each column, while the recording station name, distance, and azimuth

1001 are given to the left of each trace. Amplitudes are normalized to the maximum of the three
1002 components of motion per station.

1003 **Figure 10:** a) Landslide force history for the first (Slide #1, top panel) and second (Slide #2,
1004 bottom panel) rock avalanches. b) Contour map (20 m intervals) of the Bingham Canyon mine
1005 with doubly-integrated landslide force history to obtain horizontal motion, where the origin of
1006 each rock avalanche was specified by the reconstructed center of mass (Section 2.3, Figure 5).

1007 **Figure 11:** Velocity waveforms filtered between 10 and 50 s (black) and best-fit synthetic traces
1008 for the first (red) and second (orange) rock avalanches. The vertical (Z), radial (R), and
1009 transverse (T) components are shown in each column, while the recording station name, distance,
1010 and azimuth are given to the left of each trace. The maximum amplitude of the three components
1011 is given in μm/s to the right of the traces.

1012 **Figure 12:** Displacement waveforms for station NOQ filtered between 1 and 40 s. Vertical
1013 dashed lines indicate times when there were sudden changes to the forces or direction of the rock
1014 avalanches. a) First rock avalanche; start time of the record is 03:30:20 UTC, we estimate the
1015 onset of the slide at 5 s. b) Second rock avalanche; start time of the record is 05:05:02 UTC,
1016 estimated onset of sliding is 5 s.

1017 **Figure 13:** High-frequency seismograms for a) the first Bingham Canyon rock avalanche, and b)
1018 the second rock avalanche. Start times of the records are 03:30:20 and 05:05:02 UTC,
1019 respectively. Seismic data are high-passed (>1 Hz) displacement traces from station NOQ, 13 km
1020 north of the mine. Time markers for both rock avalanches are duplicated for comparison with
1021 intermediate-period data in Figure 12.

1022 **Figure 14:** Back-projection analysis of short-period (1-5 Hz), vertical component energy for the
1023 first of the two large landslides on 11 April 2013. The traces used in the back-projection are
1024 shown in the left panel and the corresponding seismometer locations are shown with grey
1025 triangles in the map on the right. The white star in the map is the landslide epicenter, and the
1026 color in the inset panel indicates time-averaged back-projection energy. The graph in the upper
1027 right shows the time evolution of back-projection energy.

Figure 15: Back-projection analysis of short-period (1-5 Hz), vertical component energy for the second of the two large landslides on 11 April 2013. The traces used in the back-projection are shown in the left panel and the corresponding seismometer locations are shown with grey triangles in the map on the right. The white star in the map is the landslide epicenter, and the color in the inset panel indicates time-averaged back-projection energy. The graph in the upper right shows the time evolution of back-projection energy. The small rise in energy after ~110 s is created by an earthquake that was triggered by the landslide [*Pankow et al.,* 2014].