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Taking the pulse of debris flows: extracting debris-flow dynamics from good vibrations in southern California and central Colorado

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Abstract

The destructive nature of debris flows makes it difficult to quantify flow dynamics with direct instrumentation. For this reason, seismic sensors placed safely away from the flow path are often used to identify the timing and speed of debris flows. While seismic sensors have proven to be a valuable tool for event detection and early warning, their potential for identifying other aspects of debris flows (such as sediment concentration) is less studied. Here, we use two monitoring sites to investigate the extent to which debris-flow dynamics can be decoded from ground vibrations. One site is a bedrock channel in a steep semiarid basin in central Colorado (Chalk Cliffs), and the other is in a debris-flow channel incised in alluvium in a recently burned area in southern California (Van Tassel). At both sites, seismic data are measured with geophones (4.5 Hz) mounted next to the channels and sampled at high frequencies (500-1000 Hz). Independent constraints on flow dynamics are provided by laser distance meters to record flow stage (at 10 Hz) and high-definition video cameras to record flow velocity and qualitative estimates of sediment concentration. The observed debris flows at Chalk Cliffs typically consist of a series of short-duration (~30 second) surges with total durations of <40 minutes and have coarse-grained fronts and fluid-rich tails. In contrast, the events at Van Tassel are longer duration flows (>40 minutes) that begin as debris flows and transform into more steady debris floods. The arrangement of sensors at both sites allows us to identify correlations between vertical ground velocity, frequency, flow stage, and qualitative estimates of sediment concentration.

Keywords: debris flow; flood; seismic; ground vibrations; post-wildfire; channel; frequency; spectrum; Colorado; California

1. Introduction

Debris flows and landslides generate seismic signals as they move downslope, which can be used to detect the event and provide early warning for communities downstream (e.g., Arattano, 1999; Hürlimann et al., 2003; LaHusen, 2005; Allstadt, 2013). A debris flow is a fast-moving flow, which carries a large amount of fine to coarse sediment downstream in steep mountainous areas. Debris flows may mobilize from the failure of a discrete landslide (e.g., Iverson, 1997), or they can be triggered by runoff and associated sediment entrainment (e.g., Coe et al., 2008). Runoff-generated debris flows, which are the focus here, typically occur in semiarid areas with abundant loose sediment situated downslope of low-permeability surfaces, such as bedrock in alpine areas or water-repellent soil in recent burn areas (Kean et al., 2013). Regardless of the style of initiation, the fast-moving and destructive nature of debris flows makes them difficult to monitor. Geophones, which can measure the ground vibrations produced by debris flows, are a robust monitoring tool because they can be placed a safe distance away from the flow path. Using seismic signals to understand debris-flow and sediment transport processes requires an understanding of how the seismic waves are generated. Quantitative models have developed specifically for bedload in rivers (e.g., Govi et al., 1993; Burtin et al., 2008, Tsai et al., 2011; Gimbert et al., 2014; Roth et al., 2016), but the equivalent for debris-flow processes is in its infancy (Huang et al., 2007; Kean et al., 2015; Lai et al., 2018; Allstadt et al., 2019). Here, we use ground vibrations created by debris flows at two sites with different flow and geologic characteristics to help extract information on flow dynamics that is not available from other instrumentation (e.g., stage sensors and videos) and to better understand the relation between a flow and the seismic signal it generates.

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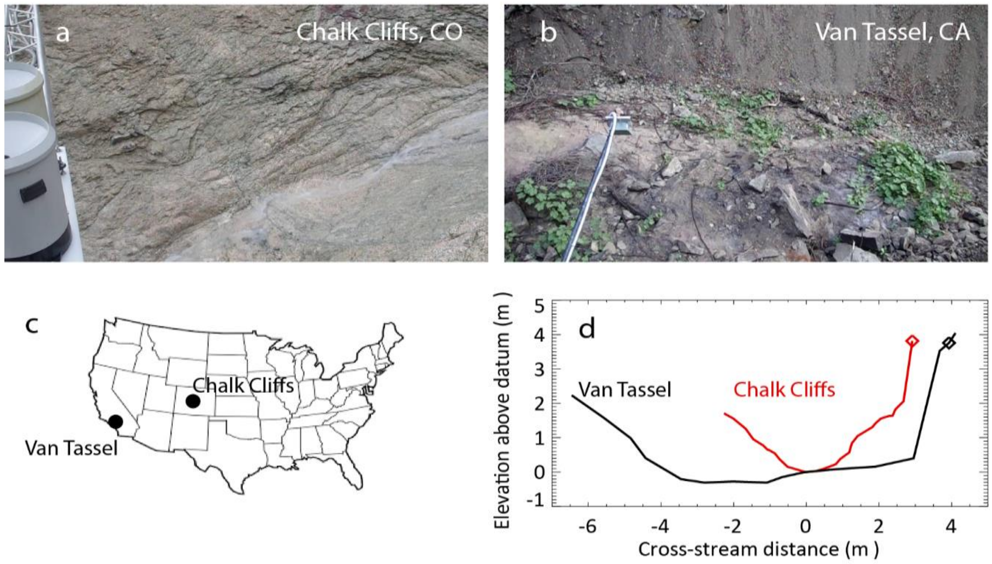

Fig. 1. Views from the banks of (a) the bedrock channel at Chalk Cliffs (5.5-m long reach), CO, and (b) the sediment covered channel at Van Tassel, CA (9.3-m long reach). (c) Locations of both study sites. (d) Cross section of Chalk Cliffs channel (red) and Van Tassel channel (black) at monitoring site locations. Diamonds show the locations of the geophones in the cross section.

2. Study Sites

The two study sites (Fig. 1 and Table 1) have semiarid climates and debris flows that are primarily triggered by runoff and associated sediment transport. One site is a narrow bedrock channel at the outlet of a 0.06 km^2 alpine basin in central Colorado (Chalk Cliffs), and the other site is a wider sediment-covered channel at the outlet of a recently burned 4 km^2 basin in southern California (Van Tassel). Although the two locations have similar debris-flow initiation processes, the two sites have substantially different drainage areas, channel dimensions, and geologic materials, and thus, have different flow characteristics and seismic signals. Both Van Tassel and Chalk Cliffs have similar instrumentation (described below) with high-frequency data recorded during rainstorms.

2.1. Van Tassel, California

The Van Tassel site is in the Angeles National Forest within the granitic San Gabriel Mountains in southern California. Most of the drainage area above the station was burned at moderate and high severity by the Fish fire, which began on June 20, 2016. Wildfires temporarily alter the hydrologic response of a watershed by decreasing the infiltration capacity of the soil and making soils easier to erode (Moody et al., 2013). These changes greatly increase the susceptibility of steep basins to debris flows for several years after the fire (Cannon et al., 2010). Between the fire and the first winter rainstorm in December 2016, the channels above the Van Tassel basin were loaded with dry ravel from the steep (>35°) burned hillslopes. The dry ravel further increased the sediment cover at the station (Fig. 1b). We analyze the first two flow events after the fire. The first event on December 16, 2016, was a debris flow (sediment concentration >40%), and the second event on January 20, 2017, was a debris flood (sediment concentration between 10% and 40%) (Fig. 2).

2.2. Chalk Cliffs, Colorado

Chalk Cliffs is in the Sawatch Range of the Rocky Mountains in central Colorado. The cliffs are a band of hydrothermally altered quartz monzonite that is highly fractured. Additionally, the area has very sparse vegetation cover and 60% of the drainage is exposed bedrock (Coe et al., 2008). The slopes in the basin are very steep, with colluvium slopes ranging from 25° to 40° and bedrock slopes ranging from 40° to almost vertical (Coe et al., 2008). Several debris flows occur each year between May and October, when intense rainfall produces runoff from the steep slopes that entrain loose channel material accumulated from winter rockfall. The debris flows at Chalk Cliffs are short in duration (<40 min) compared to Van Tassel and generally contain a series of surges (~30 seconds each). The channel at the monitoring station is typically covered with sediment from the beginning of the summer until debris flows scour the channel to bedrock by mid-summer. The sediment cover has a strong damping effect on the debris-flow ground vibrations (Kean et al., 2015). Here, we focus on two events when the channel had a bare bedrock bed, to contrast the signals with the sediment-covered Van Tassel channel (Fig. 1a, 1b).

Table 1. Summary of site characteristics

Site Characteristics	Van Tassel	Chalk Cliffs
Setting	Recent burn area	Alpine
Drainage area	4 km^2	0.06 km^2
Channel width	7 m	3 m
Channel slope	7° (over 30 m)	17° (over 42 m)
Channel material	Sediment covered (Alluvium)	Exposed bedrock (Quartz monzonite)
Debris-flow duration	>40 min	<40 min with ~30 sec surges

3. Measurement Methods and Data Analysis

The debris-flow monitoring systems at Van Tassel and Chalk Cliffs are similar and record high-frequency data when a rainfall threshold is exceeded. The instrumentation at each site includes a rain gage, multiple geophones, a laser distance meter to measure flow stage, and a high-definition video camera to record flow characteristics and velocity. Rainfall is measured using a tipping-bucket rain gage, installed near the channel cross sections, and sampled every 2 seconds. Rainfall data are used to calculate 5-minute peak rainfall intensities (I_5), which have been closely correlated with debris flows in both study settings (Kean et al., 2013). Both sites use 4.5 Hz geophones connected to a seismic data recorder. Both seismic stations are digitized at a high gain of 32, have 629,327 counts per volt, and a geophone sensitivity of 32 v/m/s. At Van Tassel, there are three single-channel geophones mounted vertically along the channel and sampled at a rate of 500 Hz. At Chalk Cliffs, there are two triaxial geophones that are sampled at a rate of 1000 Hz. In this analysis, we focus on the records from a single vertical geophone at each site, which is located on the side of the channel at the same cross section where stage is measured (Fig. 1d). Laser distance meters are used to measure flow stage at both sites. They are suspended ~3 m above the channels and sampled at a rate of 10 Hz. The Chalk Cliffs laser is installed on a bridge section directly over the channel (Fig. 1a). Distance measurements are converted to flow stage above the bedrock channel bed. To avoid the possibility of being destroyed by large flows, the laser distance meter at Van Tassel was not mounted directly over the channel. Instead, the Van Tassel laser is suspended at an angle on the side of the channel (Fig. 1b). Flow stage at Van Tassel is estimated by multiplying the laser distance measurements by the cosine of the shot angle. High-definition cameras at both locations are used to record information on flow type and velocity during daytime events (see Smith et al., 2019). Video and seismic recording is triggered using a rainfall threshold. At Van Tassel, there is a single camera mounted on the side of the channel. At Chalk Cliffs, there are two cameras, one located at the bridge cross section at the channel (view in Fig. 1a) and another on the opposite side of the basin with a broader view of the channel (view in Fig. 2a and 2b). We use the videos and their audio to interpret how the flow characteristics, such as sediment concentration, vary with time and as a timeline of events to compare to seismic observations.

From each site, two events with different levels of sediment concentration were chosen for analysis. A low-water content (sediment-rich) debris flow at Chalk Cliffs occurred on August 4, 2017, and was triggered by a rainstorm with a peak I_5 of 20 mm/hr. The surges are typical at the site and consist of coarse-grained fronts and fluid-rich tails lasting less than a minute in duration (Fig. 2a). A second more watery debris flow at Chalk Cliffs occurred a day later, on August 5, 2017, when rainfall intensities were much greater (I_5 = 80 mm/hr) than the previous day. This debris flow lasted approximately 13 minutes and contained a series of sediment-rich surges embedded within a steadier, more watery flow. This event also had a higher peak surge velocity (7.2 m/s) than the previous day (2.6 m/s) (Fig. 2b). The maximum grain sizes in the August 5 debris flow (~0.3 m, Fig. 2a) were also larger than on August 4 (~0.1 m, Fig. 2b). At Van Tassel, the first event was a debris flow that occurred on December 16, 2016, during the first major

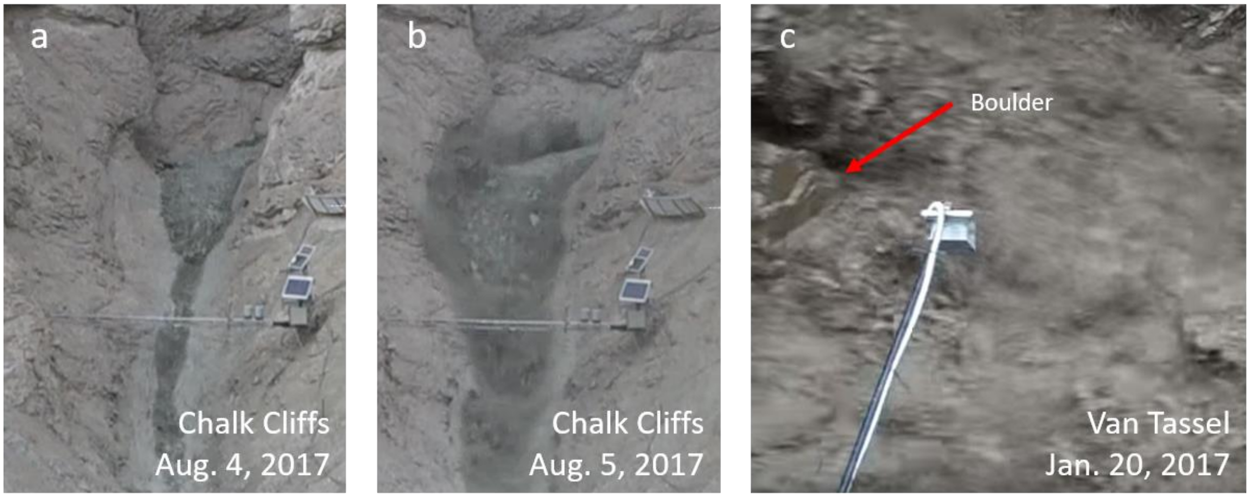

Fig. 2. (a) Low-water content debris flow at Chalk Cliffs on August 4, 2017; (b) High-water content debris flow at Chalk Cliffs on August 5, 2017; (c) Debris flood at Van Tassel on January 20, 2017. A ~1-m diameter boulder can be seen in the left of the image. An image of the December 16, 2016 debris flow at Van Tassel is not available because the event occurred at night.

rainstorm after the fire, with a peak I_5 of 60 mm/hr. The event occurred at night, and the video images were too dark to interpret. Although video cannot confirm the flow was a debris flow, we assume it was a debris flow based on the characteristics of the flow-stage time series, which show an abrupt rise in stage similar in shape to surge fronts measured in other post-fire debris flows in southern California (Kean et al., 2011). The second event at Van Tassel was a debris flood that occurred on January 20, 2017, following the third major rainstorm after the fire (I_5 = 40 mm/hr). This flow lasted approximately 40 minutes, had a flow velocity of approximately 5 m/s, and transported ~1-m diameter boulders (Fig. 2c) and large woody debris.

For each event, the seismic records were corrected to physical units of vertical ground velocity (*V*) and plotted with flow stage. Vertical ground velocity was determined from a function of the recorded counts, gain, and sensitivity of the geophone and digitizer. Spectrograms were then created with a 5-s window and were normalized by their respective absolute maximums. Most of the periods with high seismic power were correlated with times of high stage. However, raindrop impacts also contributed to the seismic signal at both sites with comparable amplitudes as vibrations generated by the flows. We isolated the seismic signature of rainfall impacts by analyzing the geophone time series during the intense triggering rainfall that occurred before the arrival of the flows. The timing of this rainfall noise was closely correlated with the time stamps of rain gage bucket tips. We found that rainfall impacts generally create high-frequency seismic energy on our sensors (~>30 Hz), whereas the seismic signal of the flows produced energy at both low and high frequencies (~<30 Hz and ~>30Hz, respectively). To remove rainfall noise, we applied a lowpass Butterworth, zero-phase filter to the geophone signals with a cutoff frequency of 30 Hz. After applying the filter and examining the time series of each event, it was clear that most of the effect from the rainfall had been removed while the low-frequency signal from the flows remained (Fig. 3b and 3d).

3.1. Low-water content debris flow at Chalk Cliffs on August 4, 2017

The first event consists of two 30-second surges about 1 min and 15 sec apart from each other (Fig. 3a and 3b). The spectrogram shows three identifiable peaks in amplitude (Fig. 3a). The first peak is an impact from a rock rolling down the channel, as confirmed in the video. The following two peaks in amplitude are broader and correspond to the two surges, labeled as high sediment concentration flows. The ground velocity time series displays an increase in *V* that tapers to a lower *V* as the surge passes the station (Fig. 3b). Surges often identified in debris flows are commonly characterized by a sediment-rich front followed by a water-rich tail. Surge fronts generally exert forces orders of magnitude greater and flow heights significantly higher than the rest of the flow (Iverson, 1997). The impacts of the large grain sizes that have accumulated at the front of the surges produce the peak amplitudes, and the amplitudes diminish as the flow tail passes the station (Huang et al., 2007).

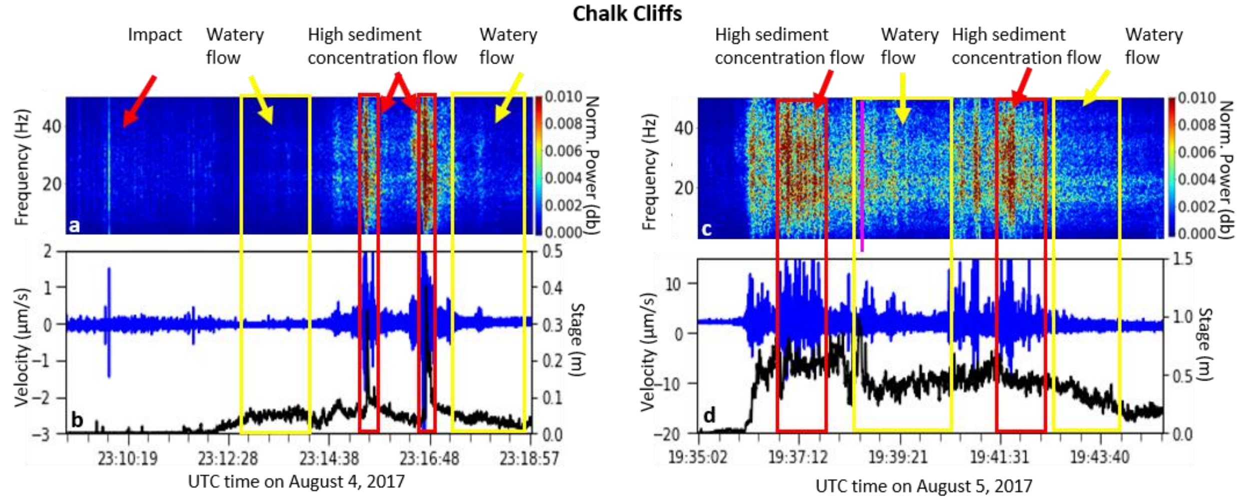

Fig. 3. Chalk Cliffs ground vibrations and flow stage for (a and b) low-water content debris flow on August 4, 2017, and (c and d) high-water content debris flow on August 5, 2017. (a and c) Normalized spectrograms of ground velocity. (b and d) Time series of lowpass filtered ground velocity (blue) and flow stage (black).

3.2. High-water content debris flow at Chalk Cliffs on August 5, 2017

The second event at Chalk Cliffs is a larger event, both in maximum *V* as well as flow heights (Fig. 3c and 3d). The time series shows periods of high ground motion velocity are longer in duration than the first event. The maximum flow height reaches 1 m, double the height of the flow of the other event. Although this debris flow was larger, similar characteristics to the previous day's event are visible in both the time and frequency domain. Short surges are identified within the larger flow by correlating values of high stage, high *V*, and high energy in the frequency domain (indicating a large amount of debris). Another good indicator of the surge is the sudden peak in ground velocity that slowly tapers, as seen in the previous event. The watery tail at the end of the surge has higher amplitude *V* than the tail of the previous event, suggesting that later tail had greater flow velocity and sediment concentration. The video shows that the high flow depths transport a larger variation in grain sizes in comparison to the event from the previous day. Unlike the first event at Chalk Cliffs, the highest amplitudes in *V* (t = ~19:37:12 and ~19:41:43) do not coincide with the peak stage (t = 19:38). This difference suggests that the flow during the peak stage had slightly lower sediment concentrations than at other times during the flow.

3.3. Debris flow at Van Tassel, December 16, 2016

The first major rainstorm after the fire produced a debris flow at Van Tassel (Fig. 4a and 4b). At the start of the flow, there are several short impulsive signals in the amplitude (duration <1 s) that correspond to a broad range of frequencies and high power in the spectrogram. Two possibilities for the source of the impulsive signals are thunder and impacts from large clasts, which have been shown by Hsu et al. (2011) and McCoy et al. (2013) to create large excursions from the mean normal force. Audio from the nighttime video footage did not record any thunder. We therefore interpret the brief spikes in *V*, which have high power across a broad frequency range, to be impacts from large clasts in the flow (labeled as "impacts" in Fig. 4a). Two minutes after the beginning of the flow, the stage time series ends, because mud splatter covered the laser. Five minutes after the beginning of flow, there are two 90-second periods of high power (labeled "High sediment concentration flow" in Fig. 4a). The power is greatest at the beginning of the period and gradually tapers with time. We interpret these periods to be pulses of high sediment concentration with large clasts. Unlike the two events at Chalk Cliffs, the high amplitude *V* is sustained for a long period of time (as opposed to occurring briefly during surges), suggesting that the first flow at Van Tassel had high sediment concentrations during most of the flow. It is not until around 11:38 UTC that a signal suggesting a watery tail arrives as evidenced by the lack of high power in the spectrogram, but we cannot confirm with the video because this event occurred at night.

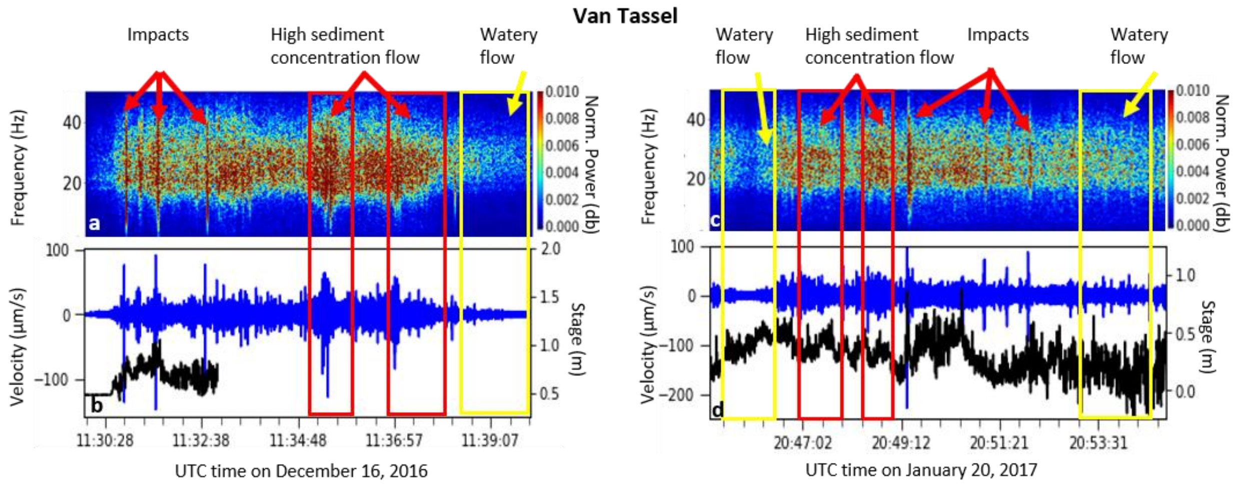

Fig. 4. Van Tassel ground vibrations and flow stage for (a and b) debris flow on December 16, 2016, and (c and d) debris flood on January 20, 2017. (a and c) Normalized spectrograms of ground velocity. (b and d) Time series of lowpass filtered ground velocity (blue) and flow stage (black).

3.4. Debris flood at Van Tassel, January 20, 2017

Based on video observations, the second event at Van Tassel was a debris flood (Fig. 4c and 4d). The flow lasted for over 40 minutes, although we focus our analysis on the 10 minutes around the time of peak flow. Despite the fact the flow has lower sediment concentrations than a debris flow, the time series of V resembles patterns like the Chalk Cliffs surges, displaying periodic peaks in V that gradually taper. Along with these surges, large spikes in V with high power across the frequency domain indicate that there were periodic large impacts from boulders such as the one seen in Fig. 2c.

Like the first event at Van Tassel, the flow has high vertical ground velocities and high power distributed throughout much of the flow, showing debris is consistently being transported. However, the event on January 20 also has periods of low power within the spectra during times of high stage (labeled watery flow in Fig. 4c and 4d). We interpret these periods as times when the flood had much lower sediment concentrations than times when the spectra had high power.

4. Discussion and Conclusions

Comparison of the events at the two field sites with different sediment concentrations has shown that a significant amount of information can be derived from near-channel ground vibrations. At Chalk Cliffs, we observed that a flow in a bare bedrock channel produced a seismic signal with a broad frequency range (5 Hz to 400 Hz), whereas the sediment-covered channel at Van Tassel had a limited frequency range, with similar low-frequency characteristics but much lower peak frequencies (5 Hz to 100 Hz). The effect of sediment cover on the frequency content is best seen in the unfiltered spectrograms shown in Fig. 5. In a previous study conducted by Kean et al. (2015), it was observed that the maximum amplitude of V recorded from ball drop tests on loose sediment was orders of magnitude smaller than the maximum amplitude of V recorded on bare bedrock. For this reason, the difference of frequency bands seen between the two sites is thought to be due to the bare bedrock channel of Chalk Cliffs as compared to the dampening that occurred from the sediment-covered channel of Van Tassel. Additional differences between the ground vibration response at the two sites may be due to differences in flow speed, channel gradient, grain size distribution, instrument response, and seismic attenuation between the two sites. We also found that rainfall was an important source of seismic noise at high frequencies. For this reason, it was important to remove the rainfall signal using a lowpass filter to isolate the signal from the flow. In addition, we were able to infer times where large debris such as boulders or trees were transported within the flow by using the deviations from the average frequencies. The large impacts (Figs. 3 and 4) stand out as an impulse on the time-series signal and in the spectrogram and are especially clear during periods of lower sediment concentration.

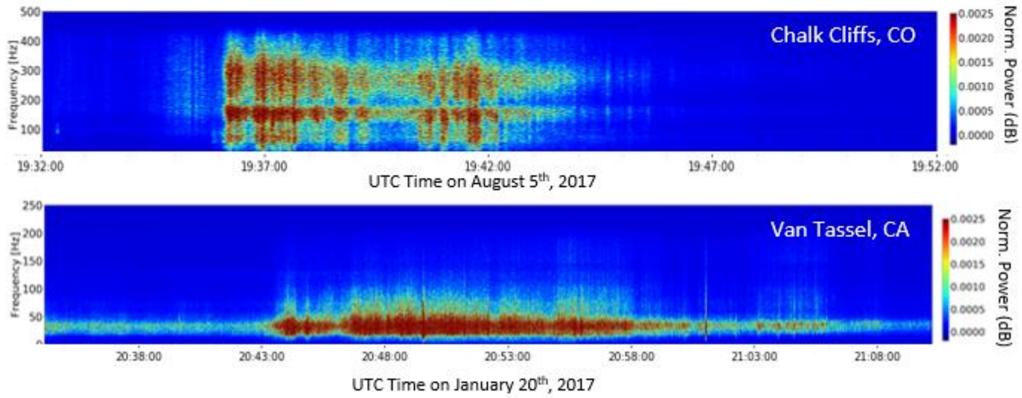

Fig. 5. Comparison of unfiltered spectrograms for events at Chalk Cliffs (bedrock channel) and Van Tassel (sediment-covered channel). The presence of loose sediment on the bed of the Van Tassel channel substantially damps the high-frequency vibrations relative to Chalk Cliffs.

All four events had substantial contrasts in relative frequency amplitudes between times of high-sediment concentration flows and low-sediment concentration flows. These contrasts are well illustrated by the amplitude spectrums of ground velocity during 15-s time windows in each event (Fig. 6). Flow periods with higher sediment concentrations (orange lines) have greater ground velocity amplitudes than flows with lower sediment concentrations (blue lines), though these comparisons are not normalized by stage or flow velocity.

Our observations show that complementary observations of flow stage, video, and ground vibrations reveal a more complete picture of debris-flow and debris-flood dynamics than can be obtained with a single style of measurement. Moreover, the combination of sensors provides measurement redundancy that can fill gaps in observation when one sensor does not work (such as when a laser is destroyed or splattered with mud, or a nighttime event that cannot be observed with video). However, much additional work is needed to move beyond the qualitative observations of sediment concentration presented here to quantitative estimates of sediment volumes and grain size. Our data show that one challenge to making quantitative measurements of sediment concentration is the different seismic properties of the channel bed (i.e., the seismic properties of loose bed sediment versus bedrock and attenuation and scattering of the signal between station and source), which can vary during a flow. Emerging theory, such as Lai et al. (2018), and laboratory-style observations, such as Allstadt et al. (2019) are providing new insights into the seismic signature of debris flows that should further unlock the potential for seismic measurements to aid the understanding of debris-flow dynamics.

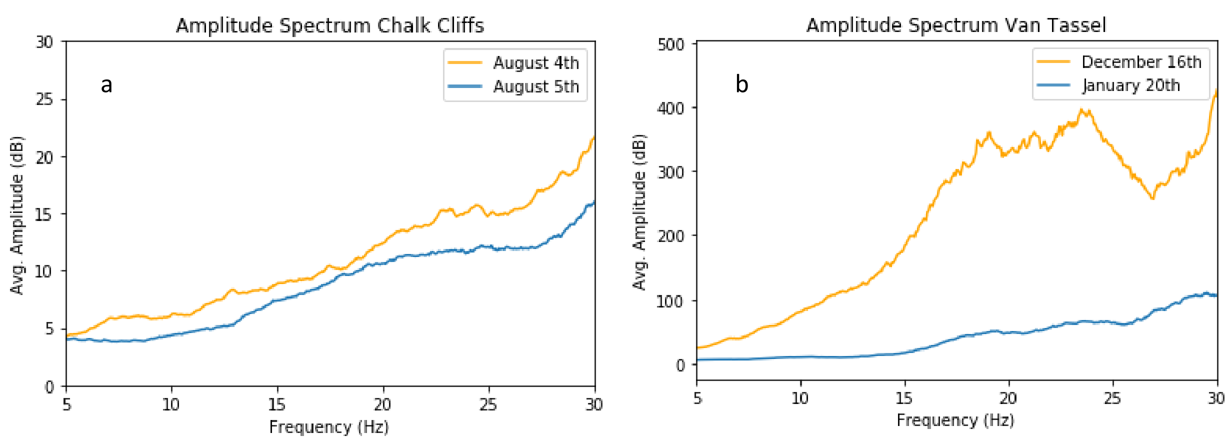

Fig. 6. Comparison of amplitude spectrums in 15-s time slices of ground velocity during flows with comparatively lower (orange) and higher (blue) water contents at (a) Chalk Cliffs and (b) Van Tassel. The events and time windows are: Chalk Cliffs low-water content debris flow on August 4, 2017, 23:16:38 to 23:16:53 (a, orange); Chalk Cliffs high-water content debris flow on August 5, 2017, 19:39:45 to 19:40:00 (a, blue); Van Tassel debris flow on December 16, 2016, 11:35:15 to 11:35:30; and Van Tassel debris flood on January 20, 2017 (b, blue). Amplitude spectrums are averaged over a 0.2-s window.

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