

REVIEW #1

We thank the reviewer for the detailed and very useful comments. Please find our response below.

(1) The authors note a big difference between the two sensor types they use: 4.5-Hz 1-C-geophones of unknown making that “appear to have a better response than the ZLand 5-Hz 3-C-stations”. It’s unclear what exactly “better response” means (the frequency response functions are not shown) but the ZLand data in Figure 5 simply shows no useful signal. I am quite surprised by that, and I know colleagues who equipped themselves with ZLand nodes because of their supposedly great sensitivity especially at low frequencies. To claim that those instruments perform poorly has a potentially large impact on the manufacturer, and such a claim must be well founded: The authors must do more to reveal the source of the apparently poor data quality of the ZLands! Is it possible that no instrument simulation was performed? The authors don’t write about it. It might explain the apparent differences. (It would also mean that the cross-correlations and the subsequent MASW would have to be re-done with the corrected data.) Or could it be a problem with the time-base?

>> This section was indeed poorly presented. There are no issues with the nodes, but the (apparently) “better” response of the Texans is mostly due to Geology and acquisition geometry. The nodes have been deployed in the northern part, where the basement comes close to the surface and the sedimentary cover represents a presumably thick layer of heavily weathered basement rocks mixed with young soil/debris, which tend to scatter surface waves. Additionally, most of the noise sources (including the shown examples) are situated in the south, so there is an overall decay in signal strength towards the north. It is further noted that it was easier to tightly ground-couple the small 1C geophones compared to the more bulky and more heavy ZLand stations.

We chose different data examples and simply increase the gain to avoid the wrong impression of faulty node data acquisition. We also adapted the description in the text.

(2) I find the interpretation section difficult to follow both how it is written and the conclusions it reaches. This paragraph should be rewritten for more clarity. I suggest the authors start this section summarizing all geologic information they have on the lithologies to be expected in this valley, including the geologic map and the well. More importantly, I find the lithologic description (clay/mud below ~1720 m in Figure 11) to be inconsistent with the reported P-wave velocity of 2700-3300 m/s. In their book chapter “Rock physics principles for Near Surface Geophysics” (In: SEG-Investigations in Geophysics No. 13, 2005), Knight and Enders report P-wave velocities for clay to be at most 2200 m/s. Indeed, all technical literature I am aware of specifies P-wave velocities for loose materials significantly below 2700-3200 m/s. If real, such velocity indicates lithified rocks, which might be an important finding. If not real, and if the material is indeed clay, it contradicts the statement that it is part of a 400-m-thick aquifer (13/25). Also, I find the interpretation of the GWT difficult. I fully understand that there are many reasons why V_P might not be indicative for the GWT but not in this case of unconsolidated sand, where one would expect a sudden increase of V_P at the GWT from maybe 800-1200 to ~1700-1800 (as seen in the well). It would be appropriate to make a first interpretation of the GWT from a contour line in the range ~1500-1800 m/s, and then check, if such a contour line coincides with the interpretation of the GWT from V_P/V_S -ratios.

>> We agree that the structure of the interpretation section is poor and adds more confusion than clarity. We tried to rearrange accordingly to the remarks above.

The conclusions on water saturation, GWT interpretation, and potential aquifer properties have also been revised. In particular the comment on high V_P -velocities has been addressed more clearly, also in the context of the reviewer’s comment (3) below. We point out that the interpretation of “clay” below the sand describes

the core for a few meters only, as drilling was stopped below the lacustrine sands. It has also been made more clear that the well is 5 km away, and as such cannot be used to exactly validate the results at the seismic location. Figure 11 has been updated as well.

(3) Please add some more detail about how the reflection-processing-based Vp-velocities were derived. (At an angle of 45°, as can be seen in the reflection section, NMO velocities would be 30% increased just from the dip, not to mention the potential distortions from the Dix formula.)

>> The NMO and interval velocities were derived from conventional CMP velocity analysis, with additional manual editing accounting for the U-shape. The extracted velocity profile is located at the center of the U-shaped structure, where reflections from the flat part of the U are actually observed. For the extracted vertical velocity profile, Vnmo velocity reductions larger than 20% for the bottom layers lead to unrealistic interval velocities (e.g. bouncing back to 1100 m/s at 250 m depth). We take this as a suggestion that the influence of the steep valley walls is not significant at this central location, but we are aware that this is a rather qualitative statement. There are also strong indications for out-of-plane reflections which might introduce non-physical layering in the velocity profile. As a result of all these uncertainties, we refrain from a detailed discussion of the lower section of the sediment fill. The text has been adapted accordingly.

2/32 – In their model, resistivity is increased for the aquifer.

> > Has been changed.

3/28 – I cannot see that road on the map.

>> This is because the narrow road in the map is masked by the signatures for receivers and shots. A description has been added to the map.

5/9 – Over-deepening is an effect along the river-bed. How can you identify it from a cross-section?

>> This interpretation has been expanded on in the text.

7/28 – 8/2 Your explanation for the observation would still require that the reflections were stronger than the incident waves.

>> This discussion has been changed/expanded.

8/10 – “refrain” – you mean this cancels out through stacking?

>> “refrain” has been changed to “attenuate”, as stacking(averaging) with limited data will not achieve total cancellation.

8/23 – Please clarify what you need density for. Maybe it's not so important but for unconsolidated saturated sediments, Gardner's relation tends to significantly overestimate the density.

>> We need density as one of the model parameters ($v_p/v_s/\rho/\text{thickness}$) for surface wave inversion, since the Rayleigh wave velocity is a function of v_p , v_s , and ρ . Many studies have shown that the phase velocity has low sensitivity to density (e.g., Xia et al., 1999), therefore usually just constant densities like (2.0 g/cm^3) are chosen for surface wave inversion. Recent research show that the use of constant density can lead to v_s overestimation as well as create inaccurate model structures, such as a low-velocity layer (Ivanov et al., 2016). Thus, we prefer a meaningful density model which could be associated with the earth model like v_p . Gardner's relation, even though it might overestimates densities, is already a significant improvement to commonly used and accepted constant densities.

9/13 – I agree that the ratio profile length to wavelength should be at least 1.5-2. But I fail to see how you can then say that it's supposedly okay to use a ratio of less than 0.5. How does the overall length of your profile change the length of your subprofiles to which you apply MASW?

>> As for passive MASW, there is no exact numerical relationship to indicate the maximum wavelength in relation to the linear array length. There's no clear maximum wavelength criterion, but only commonly accepted rules of thumb which will also change with the data quality, dispersion measurement, source-receiver configuration and chosen processing techniques etc. We chose the minimum frequency as 3.5 Hz due to the high-quality data and dispersion measurements (continued dispersion spectra extend as low as 2Hz) in our case. Depending on the velocity, this results in minimum wavelength-profile length factors between 0.3 and 0.7. The text has been changed accordingly.

6/25ff (Interpretation) – Overall, I don't understand what the authors want to say in this paragraph: In the beginning the argue that there is a systematic trend regarding V_p/V_s and pore fill, and then they discuss examples that all appear to contradict those trends. Also, references to lower crustal studies, or studies where the GWT is in fractured granite, should be avoided. It's not enough for a general overview, and too much for loose sand.

>> Despite a detailed literature search, we find very few papers which report measured V_p/V_s ratios in exploration depths corresponding to our study (e.g. below soil / weathering zone and above deep crustal targets), and in particular with relation to hydrology. Industry is expected to possess a lot of data on the reservoir level, but it is very rare that these get published. The cited studies on shallow soil structures are still considered as relevant, as they at least refer to similar material (sand, gravel). We also point out that sand represents only one among other materials (weathered granitic basement, alluvium, colluvium) which we interpret along our entire profile, so we further think that the reference to weathered granite is useful as well.

References to deep crustal studies have been eliminated.

It is not totally clear to us what the reviewer means by "[cited] examples that all appear to contradict those trends". All of the cited examples show an increase of the V_p/V_s ratio with increase of the degree of water saturation (or with the switch from dry to water-saturated materials). There was, however, a profound misphrasing in our description: Uyanik defines "saturation" as 100% water saturation of the pore space, and uses "water content" as the total amount of water in a volume of 100% saturated soil (defined via the weight ratio). We wrongly described the "10%-50% water content" as "10% to 50% water saturation". This error has been corrected

10/7ff – If V_p/V_s -ratios greater than 3.3 indicate “saturation” (100%, I assume), how can V_p/V_s of 5 indicate only 10% saturation?

>> This error has been corrected, see above.

12/23 – “Largely insensitive”: Not if you undershoot. “less sensitive” might be more sensitive.

>> Has been changed

12/23ff – is a discussion of the geophysical approach and could be a separate section.

>> We reorganized the discussion / interpretation section accordingly.

13/14 – I believe it is standard in the earthquake community that you remove events before X-correlation. Could you comment on why they/you do things differently?

>> The events (active blasts) comprise clear and strong dispersive surface waves, which we don't want to remove. A statement has been added to section 5.1

13/20 – I don't see how this is a conclusion. You did not use the horizontal components!

>> Has been removed.

13/24 – That should go to the interpretation section!

>> We have changed the “vertical extent of 400 m” to “100 m”, as we no longer interpret the V_p/V_s ratio below the sand. However, we think that this is a summarizing statement which fits into the conclusion section.

Fig.2: I find the colored lines/sidebars very confusing since they do not indicate profiles. It took me some time to realize that. I am not sure they are required but you could at least move them outside of the map. Also, the air photo doesn't really convey any useful information, at least none you refer to, and a simple line-drawing would do it. Perhaps the map is not even necessary at all, and Fig. 1 would suffice.

>> We like to keep the map as it shows the geometry of the acquisition, which is put into context into some parts of the manuscript (overall: extent of crooked line vs. 2D vertical plots; change of signal on ZLand vs. Texan recorders in relation to geology; variation of active source/signal strength along the profile has an impact of the assessment of the final velocity models). We moved the sidebars to the outside and added more useful information (elevation contours, location of the creek).

Fig 4: Please add a contour line at 1500 m/s, or adjust the color scale such that one can see this contour.

>> We tried to do this, but it looks odd to have an isolated contour line since the GWT is not discussed at this stage of the manuscript. However, we added Vp contour lines (1500 m/s, 1800 m/s) to the Vp/Vs plot (Fig.9) where the GWT is discussed.

REVIEW #2

We thank the reviewer for the comment. Please find our response below.

I agree with the summary of Prof Bleibinhaus. The part of the paper that needs revision is the interpretation section. To me the results seem to be somewhat 'overinterpreted'. I would prefer it if this section gets shortened. The most speculative parts should be removed completely. This concerns mainly the interpretation of the resulting Vp/Vs ratio section. I find that the interpretation lacks factual evidence. Further, in Fig 11 the velocities obtained from the processing of the active and passive seismic data are depicted next to a sonic log from a nearby well. There is a very significant difference between the seismic velocities and the sonic log velocities. This needs to be addressed in more detail.

>> We heavily edited the interpretation section. Due to the generality of review #2, we find it difficult to address specific points of criticism. E.g. it is not clear to us what "the lack of factual evidence" specifically addresses, e.g. if it (1) refers to a miscalculation/inaccuracy of the Vp/Vs ratio or that (2) other geological possibilities for a high Vp/Vs ratio should be discussed. In case of (1), we restricted the interpretation to the area of robust results (e.g. the very high Vp/Vs ratio in the lacustrine section. In the case of (2), our literature research indicates only saturation as a possible cause for high Vp/Vs ratios in similar geologic environments.

Regarding the difference in sonic log and seismic velocities, we point out that the locations are 5 km apart. We already discussed possible causes for difference (different composition/compaction, varying GWT) in the original manuscript at length, but we tried to improve on this description as well.

Passive processing of active nodal seismic data: Estimation of V_P/V_S - ratios to characterize structure and hydrology of an alpine valley infill

Michael Behm¹, Feng Cheng², Anna Patterson¹, Gerilyn S. Soreghan¹

¹School of Geology and Geophysics, University of Oklahoma, Norman, OK, United States

5 ²Lawrence Berkeley National Laboratory, Berkeley, CA, United States

Correspondence to: Michael Behm (Michael.Behm@ou.edu)

Abstract. The advent of cable-free nodal arrays for conventional seismic reflection and refraction experiments is changing the acquisition style for active source surveys. Instead of triggering short recording windows for each shot, the nodes are continuously recording over the entire acquisition period from the first to the last shot. The main benefit is a significant increase in geometrical and logistical flexibility. As a by-product, a significant amount of continuous data might also be collected. These data can be analysed with passive seismic methods and therefore offer the possibility to complement subsurface characterization at marginal additional cost. We present data and results from a 2.4 km long active source profile which has been recently acquired in Western Colorado (US) to characterize the structure and sedimentary infill of an over-deepened alpine valley. We show how the ‘leftover’ passive data from the active source acquisition can be processed towards a shear wave velocity model with seismic interferometry. The shear wave velocity model supports the structural interpretation of the active P-wave data, and the P-to-S-wave velocity ratio provides new insights into the nature and hydrological properties of the sedimentary infill. We discuss the benefits and limitations of our workflow and conclude with recommendations for acquisition and processing of similar data sets.

15

1 Introduction

20 Seismic nodal acquisition systems (‘nodes’ thereafter) were introduced to the active source exploration community within the last decade with the promise of geometrical flexibility and a more efficient production, especially in rugged terrain (Freed, 2008; Dean et al., 2013). Nowadays several outfitters provide instruments for a wide range of applications with a focus on the energy industry (Dean et al., 2018), but nodal acquisition is also becoming widespread in the academic community (Karplus and Schmandt, 2018). Nodes differ from conventional cable-based systems in several aspects. During recording, each node is an autonomous data logger and recorder without required physical or non-physical connection to a central processing system. They are designed to record continuously throughout the entire acquisition period, which might last from days to months. In that regard, the acquired data can be considered as passive data which automatically include the shot windows from the active sources. For any active seismic exploration study, the shot windows are considered as the complete data set to represent the subsurface. In the case of continuous nodal acquisition, a significant amount of additional data is recorded outside the shot windows. The lack of well-defined sources outside the active shooting times does not mean that these periods are seismically quiet. The ambient noise spectrum covers a wide frequency range and stems from diverse natural and anthropogenic processes

25

30

(McNamara and Bulland, 2004; Riahi and Gerstoft, 2015). The location and timing of specific events within this noise spectrum might be known with some degree of uncertainty (e.g. local, regional, and global seismicity), thus inviting classical active processing methods like travel time tomography to derive local velocity models (Kissling, 1988; Byriol et al., 2013) or different forms of receiver-side reflectivity mapping (Ruigrok et al., 2010; Behm and Shekar, 2014, Behm, 2018). For the more general case of unknown locations and timing of the sources in the ambient noise spectrum (e.g. traffic noise, industrial activities) the seismic interferometry method (Snieder, 2004; Wapenaar, 2004; Schuster, 2010) has become a staple for subsurface modelling and interpretation. In particular, the extraction of surface waves travelling between receivers in locally deployed arrays can be feasible for even relatively short time spans of ambient noise. (e.g. Nakata et al., 2011; Behm et al., 2014; Cheng et al. 2016). The reconstructed surface waves are mostly used to image the local shear-wave velocity structure (e.g. Picozzi et al., 2009; Hannemann et al., 2014) or for interpretation of temporal changes in the subsurface (e.g. Planes et al., 2015; Riahi et al., 2013). Applied to active data, interferometric surface wave removal (Halliday et al., 2007, 2010) can successfully model and mitigate unwanted Rayleigh-wave energy in shot gathers. Although body waves are much more challenging to extract from surface recordings of ambient noise (Forghani and Snieder, 2010), the availability of many stations can facilitate signal processing routines to focus on the extraction of diving waves (Nakata et al. 2015) and reflected waves (Draganov et al., 2009) as well. Body waves caused by surface noise sources are also more likely to be detected in boreholes (Behm, 2017; Zhuo and Paulssen, 2017) or inside mines (Olivier et al., 2015).

Processing of passive data provides complementary information when compared to the active data. E.g. surface wave inversion obtained from interferometry results in shear wave velocity models, and travel time tomography using local or regional seismicity can increase the investigation depth. Strobbia et al. (2011) applied a workflow to isolate and invert Rayleigh waves from a dense active source 3D acquisition, and in a later step used the obtained near-surface shear wave velocity model to improve the filtering of Rayleigh wave energy for reflection processing. Most of the passive processing schemes provide subsurface models with significantly lower lateral resolution than models obtained from active data. However, robust low-resolution information can be beneficial when implemented into initial models for full waveform inversion (Sirgue and Pratt, 2004; Denes et al., 2009).

From a geologic point of view, our study focuses on the structure and sedimentary infill of an over-deepened alpine valley in Western Colorado (US). Alpine valleys are of interest for geophysical investigation because of their significance for landform evolution (e.g. incision rates, timing and effects of glacial overprinting; de Franco et al., 2009; Pomper et al., 2017) and their potential for harbouring significant groundwater resources (e.g. Pugin et al., 2014). Brueckl et al. (2010) provide an overview of geophysical exploration of glacially over-deepened valleys in the Austrian Alps of Europe. They report P-wave velocities and densities for Quaternary sedimentary infill, and in all cases, they find a deeper sedimentary layer ("old valley fill") above the bedrock with higher P-wave velocities. Bleibinhaus and Hilberg (2012) investigate one of the largest over-deepened valleys in the European Alps with seismic and electrical resistivity methods. Based on increased seismic velocities and ~~decreased~~ increased resistivity, they interpret an aquifer in the shallow part of the sediments.

In our study, we present data and results from a local 2D reflection line acquired for imaging Unaweep Canyon on the northeastern Colorado Plateau. Nodal instruments recorded continuously for the duration of 2.5 days and captured shots from an active source as well as traffic-induced ambient noise. We apply seismic interferometry to the continuous data to extract dispersive surface waves, which in turn are inverted for a 2D shear-wave velocity model of the valley structure. This model complements the results from active source processing, and the joint interpretation of the active P-wave velocity and passive S-wave velocity models allows for new insights on the nature and hydrologic properties of the sedimentary valley infill.

2 Area and Geology

The area of investigation (Fig. 1) is the western part of the NE-SW-trending Unaweep Canyon of the Uncompahgre Plateau, western Colorado. This plateau is a large Cenozoic uplift on the northeastern Colorado Plateau and had a late Paleozoic existence as the “Uncompahgre uplift” – one of several basement-cored uplifts with paired basins that formed as part of the Ancestral Rocky Mountains (ARM) of western equatorial Pangaea (Kluth and Coney, 1981). Unaweep Canyon is an enigmatic landform since the modern drainage divide occurs in the middle of the canyon, such that it hosts two creeks that drain to both of its mouths. The canyon is deep (>400 m in inner Precambrian-hosted gorge), wide (locally >6000 m, 800 m in inner gorge), and incised into Mesozoic strata and Precambrian crystalline basement. The canyon bottom hosts sedimentary fill of Quaternary and possibly older age, at least 330 m thick in some regions (Soreghan et al., 2007).

Most suggest that the canyon was formed by the ancestral Gunnison River, and/or Colorado River in the late Cenozoic and later abandoned (e.g., Cater 1966; Sinnock, 1981; Lohman, 1961; Hood, 2011; Aslan et al., 2014). Many attributes of the canyon, however, are inconsistent with a purely fluvial origin, such as the lack of dendritic tributary systems, and apparent glacial-like features such as U-shaped hanging valleys and truncated spurs (e.g. Cole and Young, 1983). However, Quaternary glaciation did not extend down to the elevation of Unaweep Canyon, and glacial deposits are lacking (Soreghan et al., 2007). An alternative hypothesis posits that the canyon was carved by glaciation in the late Paleozoic, and later exhumed by the ancestral Gunnison River (Soreghan et al., 2007, 2008, 2014, 2015). A pre-Quaternary glacial origin remains controversial, in part because the Uncompahgre uplift was equatorial during the late Paleozoic. Previous geophysical and drilling surveys (Davogustto, 2006; Haffener, 2015) suggested that the valley might be over-deepened but were inconclusive regarding the exact depths and the valley geometry. A recent approach focused on acquisition of high-resolution reflection seismic data in fall 2017 (Patterson et al., 2018a, 2018b), and these data are also the basis for the present study.

3 Acquisition

The 2.4 km long reflection profile crosses the canyon in of its widest parts along a 4WD road, except for its first and last few hundred meters (Fig. 2). Geophone installation, acquisition, and demobilisation was done within 2.5 days. Recording stations were equipped with 385 Reftek ‘Texans’ data loggers / 4.5 Hz 1C geophones and with 120 Fairfield ZLand 3C 5 Hz nodes at

a 5 m interval. The ZLand nodes recorded continuously, while the Texans were only active during daytime due to memory constraints. The shot spacing is 10 m in the northern part and 5 m in the southern part, where maximal over-deepening was expected. Along the 4WD road, the truck-mounted and nitrogen-pressured A200 P&S source (Lawton et al., 2013) was utilized. This source provided ample energy to record strong basement reflections from 400 – 600 m depth (Patterson et al. 2018a, 2018b; Fig. 3). Manual hammering with 18 lbs sledge hammer provided seismic energy off-road. For both the truck-mounted source and the sledge hammer shots, five individual blasts were stacked at each shot location. All shot times were synchronized to GPS time. Due to time constraints, the northern- and southernmost parts of the profile were shot simultaneously. Shooting was done on Saturday and Sunday to avoid seismic noise from the a nearby active gravel pit. The state highway 141 intersects the profile in the southern part. Traffic on this road was moderate (one car / truck every 1 to 5 minutes). All shot and receiver locations were surveyed with high-precision RTK GPS.

The geometry of acquisition design was optimized for reflection processing, resulting in dense receiver and shot spacing. The usage of nodal instruments was driven by logistical constraints, including partly steep and rough terrain, and a tight operational schedule. Receiver deployment and shooting was essentially completed in two working days without prior scouting, which would not have been possible with a conventional cable-based system and partly-fresh crew of mostly untrained of-student helpers. An additional advantage of nodal acquisition is the possibility of recording at all offset ranges. Therefore, low-frequency geophones were chosen deliberately to ensure registration of first arrivals at long offsets.

4 Active source data and processing

Reflection processing and interpretation is currently ongoing and initial results are presented by Patterson et al. (2018a) and Patterson et al. (2018b). Here we focus on first arrival travel time tomography. In general, the first arrivals are of high S/N (signal-to-noise) ratio, and they are visible up to 1.5 km offset (Fig. 3). The transition from low-velocity (1000 – 1500 m/s) sediments to high-velocity (> 4000 m/s) basement is indicated at most parts of the profile by a distinct kink in the first arrival travel time curve. This two-layer structure is not as clear towards the northern end of the profile, where the basement crops out but still exhibits low velocities at short offsets. This is indicative of pronounced erosion and weathering effects. In the area of expected over-deepening, refracted arrivals from the basement (Pb) are missing, while first arrivals through the sediments (Ps) occur over longer offsets.

Overall, 18,263 sediment (Ps) and 16,104 basement travel time arrivals (Pb) are picked from the shot gathers. Signal processing is limited to bandpass filtering (10-30-130-160 Hz) and Automated Gain Control (AGC). Travel time picks have been validated by their reciprocal counterparts, wherever possible. Pb travel times represent refractions from the top of the consolidated basement, and Ps travel times represent both sediments and weathered basement. Both Pb and Ps picks are integrated into one combined first arrival time pick set. In case of overlap (<0.1% of all picks), the minimum of Pb and Ps is designated as the first arrival.

3D first arrival travel time tomography is performed with the back-projection method of Hole (1992). Tests showed that a simple depth-dependent initial velocity model leads to poor data fit and partly unrealistic velocities (> 7000 m/s) in the southern part where the valley is expected to steepen. Therefore, we create a 2.5D initial velocity model from localized 1D inversions of CMP-sorted travel times. Using this improved initial model, the 3D travel time inversion converges to the final model shown in Fig. 4 after 9 iterations. Offset restrictions and smoothing filters are successively relaxed to build a detailed yet robust model from top to bottom. The RMS travel time error of the final model is 0.03 s. The velocity model is indicative of over-deepening in the southern part, where high basement velocities are missing. This is in accordance with the lack of Pb observations in the shot gathers. Fig. 4 also includes a preliminary result of reflection imaging (depth-converted Kirchhoff Prestack time migration; Patterson et al. 2018b) which allows unambiguous interpretation for [ever-deepening a U-shaped bedrock topography](#) along profile distances 1600 m – 2000 m. [The U-shape is in alignment with the concept of over-deepening caused by glacial carving, which is also indicated by multiple bedrock-parallel reverberations. These are attributed to out-of-plane reflections from a bedrock dipping perpendicular to the profile direction, e.g. along the longitudinal axis of Unaweep Canyon \(Patterson et al. 2018b\). Significant longitudinal depth variations are further suggested from previous geophysical and drilling campaigns as well as from downstream basement outcrops \(Davogustto, 2006; Soreghan et al., 2007; Haffener, 2015; Soreghan et al. 2015\).](#)

Interpretation of exact basement depths in smooth tomographic models is ambiguous due to inherent blurring of first-order velocity discontinuities. Therefore, the Pb travel times are also subjected to a delay time decomposition approach (Telford et al. 1990), providing the refractor structure in terms of delay times td and refractor velocities v_R :

$$t(x) = \frac{x}{v_R} + td_s + td_g \quad (1)$$

In equation (1), $t(x)$ represents the picked Pb travel time at a specific offset x . v_R is the refractor velocity and td_s / td_g are the source and geophone delay times, respectively. Observing multiple shots at the same geophone locations leads to an overdetermined linear equation system which is solved for v_R , td_s , and td_g . The delay time equation system can be generalized for laterally variable refractor geometry (Iwasaki, 2002). For a given vertical overburden velocity profile $v(z)$, refractor depths D and delay times td at a specific location are related by equation (2):

$$td = \int_0^D \sqrt{\frac{1}{v(z)^2} - \frac{1}{v_R^2}} dz \quad (2)$$

In equation (2), $v(z)$ is taken from the first arrival tomography velocity field (Fig. 4) after capping velocities at 1800 m/s to account for the blurring towards basement velocities. The obtained refractor depth coincides on average with the 2900 m/s - isoline in the first arrival tomographic model at most parts of the profile, as well as with the strongest gradient in this velocity field. The delay time solution is less reliable at the northern end of the profile where the assignment of Pb travel times is more challenging due to a more variable refractor velocity. This is possibly caused by significant shallowing and outcropping of the basement, which in turn leads to ~~more~~ stronger weathering effects, resulting in a more gradual velocity increase with depth. At the southern end, Pb travel time assignment is also difficult due to the steep dip of the refractor. In the over-deepened section, the lack of Pb travel times and large refractor dips prohibit delay time inversion. Refractor velocities range between 4300 m/s and 5600 m/s, with the lowest values in the center of the northern flat section. Considering the laterally varying reliability and resolution of the three approaches (travel time tomography, delay time modelling, reflection imaging), we manually build a combined interpretation of the consolidated basement (white line in Fig. 4).

5 Passive data and processing

The Texan data loggers recorded continuously during day time, and the ZLand nodes also recorded during night. Thus, a significant amount of passive ambient noise data was acquired in addition to the active data. It is tempting to use interferometric techniques (Wapenaar, 2010a; Schuster, 2010) to recover surface waves traveling between receivers from the ambient noise field. Observed surface wave dispersion can be inverted for vertical variation of shear wave velocity structure. At local scales with dense receiver spacing, most commonly phase velocity dispersion is obtained from Multi-Channel-Analysis (MASW; Xia et al., 1999). Data recorded at larger and irregular receiver spacing is subjected to the Frequency-Time-Analysis (FTAN; Bensen et al., 2007; Levshin et al., 1989; Hannemann et al., 2014) which provides group velocity dispersion.

The acquisition was performed during the seismically quiet weekend days to obtain high S/N ratio for the active data. Ambient seismic noise interferometry requires noise sources in order to reconstruct the waves traveling between receiver stations. Traffic on state highway 141 is moderate, but nonetheless contributes to the ambient noise spectrum. Two large 4WD trucks were used for deployment and transporting the source, and their movements along the profile also generate surface wave energy. Many other studies find traffic noise to be a dominant ambient noise source at local scales (Behm et al., 2014; Riahi and Gerstoft, 2015; Chang et al., 2016), and specifically designed surveys are used for traffic noise imaging in urban areas (Cheng et al., 2016). For our data set, active shooting during the day is also regarded as a major contributor to the ambient seismic wave field.

A comparison of those different noise sources in the FK-domain is shown in Fig. 5. Ground roll can be discriminated from air waves by its dispersive characteristics. Figs. 5a,d show the effects of ~~a passing the acquisition truck moving at profile distance 1800 m and of an additional vehicle at HW 141 (starting at ca. 23 seconds). Both on highway 141, which excites Rayleigh waves in the frequency range 42 – 15 Hz. Walking noise is initiated in the northern part of the profile. Non-dispersive sound waves from a passing thunderstorm are clearly-visible in Figs. 5b,e. This data subset also exhibits scattered ground roll with~~

variable velocities and high frequencies. These scattered waves are probably caused by the 4WD truck driving along the profile. Blasts from the truck-mounted source provide clear and dispersive surface waves (Figs. 5c,f), but lack energy at the low end of the spectrum ($< 2-3$ Hz). Since the penetration depth of surface waves is indirectly proportional to their frequency, the contribution of traffic noise (Fig. 5d) potentially enables ~~doubling of to increase~~ the investigation depth of surface wave analysis inversion. The shot in Figs. 5c,f is located at the switch from ZLand recorders (N) to Texans (S). The FK transform shows that the ZLand recorders have a stronger response at low frequencies (< 5 Hz), as it is indicated from higher amplitudes at negative velocities. The apparently poorer response at higher frequencies is partly attributed to the local geologic situation, as the ZLand deployments coincides with the transition to outcropping and heavily weathered basement. Additionally, tight coupling of the bulky and relatively top-heavy 3C - ZLand recorders to the ground is more difficult to achieve than for the conventional 1C geophones.

The 4.5 Hz 1C geophones appear to have a better response than the ZLand 5 Hz 3C stations.

5.1 Interferometry

Processing of the continuous data aims at deriving a 2D shear wave velocity model from the dispersive Rayleigh surface waves which are obtained from interferometric processing. ~~As Since~~ most of the stations were equipped with 1C geophones (Texans), we use the vertical component data only and extract Rayleigh waves. ~~As both the active shots and the ambient traffic noise excite Rayleigh waves (Fig. 5), we do not separate these data domains but instead use all data from the entire recording period.~~ The workflow starts with cutting the continuous data into 30 seconds long time windows. Pre-processing is limited to temporal normalization (1-bit normalization; Bensen et al. 2007). Spectral whitening is not applied since it is an intrinsic part of the following cross-coherence method used for the calculation of the interferograms. Tests with substituting 1-bit normalization by Automated Gain Control (AGC) did not result in significant changes in the interferograms. Interferogram calculation follows the virtual source method (Bakulin and Calvert, 2006), e.g. each 30 seconds long time window of each receiver station is cross-correlated with the corresponding time window of all other stations. The cross-correlation $G_{AB}(f)$ between a receiver station B and a virtual source station A is calculated in the spectral domain by equ. (3):

$$G_{AB}(f) = \frac{X_B(f) \cdot \overline{X_A(f)}}{\|X_B(f)\| \cdot \|X_A(f)\| + \varepsilon^2} \quad (3)$$

Equ. (3) is a measure of cross-coherence (Aki 1957; Prieto, Lawrence and Beroza 2009; Wapenaar et al. 2010b). In equ. (3), $X_A(f)$ and $X_B(f)$ denote the Fourier transformation of the recorded and pre-processed data at stations A and B, respectively. The overbar denotes complex conjugation. ε describes a stabilization term in case the product of the amplitude spectra approaches zero, and it is chosen as 1% of the average amplitude spectra. The interferogram in the time domain is obtained from the inverse Fourier transformation of $G_{AB}(f)$.

For each virtual source-receiver pair, the individual correlations of all 30 seconds long windows are stacked into one final interferogram. Finally, 486 virtual source gathers are obtained (Fig. 6). The gathers show clear move-outs with varying velocities in different frequency ranges, and with energy being distributed in the frequency range 2 – 15 Hz. The characteristics of the causal and acausal parts indicate that the main source of the ambient noise is located towards the south, and traffic from state highway 141 appears to be a significant contribution. Virtual source station 12040 (bottom panel in Fig. 6) is located directly at the road, but still most of the stations southward exhibit dominant acausal surface waves, indicating noise sources being located even further to the south. Besides road traffic and movements along the acquisition line, no other natural or anthropogenic activity is expected to generate seismic noise in the observed frequency band in this widely unpopulated region.

Additional noise might be presented by reflected surface waves related to the steeply dipping mountain front in the south. This front might backscatter seismic energy generated at the road and within the acquisition line towards the north. Observation of reflected low-frequency earthquake surface waves are reported by Stich and Morelli (2007), and scattered and reflected surface waves are common in exploration settings (Strobbia et al., 2011; Halliday et al., 2007, 2010). Behm et al. (2017) speculate on reflected high-frequency surface waves as ambient noise sources from data acquired in a local network on an East Greenland glacier. They also identify the steep basement cliffs as potential reflectors with providing and impedance contrast to the ice, and their environmental settings (e.g., limited anthropogenic and natural sources) are similar to this study. However, specific geometric relations between the noise -source(s), the reflecting surface, and the acquisition geometry are required to explain the absence of causal arrivals at the same time. A more detailed view at the causal arrivals at the southernmost stations shows offset-independent move-outs with very high to infinite apparent velocities at some stations. Such behaviour can be caused by non-stationary noise sources, and indeed a driveway oriented perpendicular to the profile orientation was used to access the southern end of the profile. We therefore suggest that driving along this off-profile road contributes to the ambient noise spectrum in this part of the profile.

We therefore propose that the steeply dipping mountain front in the south act as a reflector for surface waves generated at the road and within the acquisition line, and backscatters all seismic energy towards the north. Observation of reflected low-frequency earthquake surface waves are reported by Stich and Morelli (2007), and scattered and reflected surface waves are common in exploration settings (Strobbia et al., 2011; Halliday et al., 2007, 2010). Behm et al. (2017) speculate on reflected high-frequency surface waves as ambient noise sources from data acquired in a local network on an East Greenland glacier. They also identify the steep basement cliffs as potential reflectors with providing and impedance contrast to the ice, and their environmental settings (e.g., limited anthropogenic and natural sources) are similar to this study.

5.2 Inversion for S-wave velocity structure

The observed dispersion of surface waves in the virtual source gathers is inverted for the 2D shear-wave velocity structure along the profile. We start with subdividing the profile into 25 100-m-long sections and perform source-receiver sorting of the interferograms accordingly. All interferograms which have their virtual source and receiver station within one section are

assigned to this section. Within each section, all interferograms are stacked in 5 m – (absolute) offset bins, resulting in one virtual shot gather representative of that section. By this approach, we take advantage of the multi-fold coverage while still maintaining lateral resolution, and ~~refrain from the~~attenuate effects of the topography on the surface wave propagation (Köhler et al., 2012; Ning et al., 2018). Subsequently, each stacked virtual shot gather is subjected to surface wave phase velocity dispersion analysis, dispersion curve picking, and inversion for vertical shear wave velocity structure. This corresponds to the classical MASW workflow (Multichannel Analysis of Surface Waves; Xia et al., 1999).

We employ the wavefield transformation method of Park et al. (1998) to image dispersion of the spectra of the surface waves. We follow the energy peak to automatically pick the multimodal dispersion curves. Considering that the higher mode dispersion curves only exist in a few sections, we pick the fundamental mode dispersion curves only. We further resample the picked dispersion curve to ensure the efficiency of inversion as well as the coverage of multiple wavelengths. In this case, we resample the lower frequency (< 8 Hz) part dispersion data along the wavelength axis with a 50 m sampling step, and the higher frequency (> 8 Hz) part along the frequency axis with a 2 Hz sampling step.

The picked and resampled phase velocity dispersion curves are inverted for 1D shear wave velocity profiles $V_s(z)$ based on the classical damped least-square method and singular-value decomposition technique (Xia et al., 1999). We use P-wave velocities from the travel time tomography model (Fig. 4) and build the density model $\rho(z)$ from the P-wave velocities $V_P(z)$ with Gardner's relation (Gardner et al., 1974):

$$\rho(z) = 0.31 \cdot V_P(z)^{0.25} \quad (4)$$

We set the maximum inversion depth to be half of the obtained maximum wavelength for each dispersion data. In general, this method is fast and stable, and most inversions could be completed within 6~7 iterations with a minimum root-mean-squared error at ~20 m/s. This error represents the misfit between the picked and predicted surface wave velocities.

Fig. 7 presents examples of stacked virtual shot gathers (left panel), the measured and picked dispersion spectra (middle panel), and the inverted $V_s(z)$ functions (right panel). The clear dispersion curves indicate a high S/N ratio of the stacked virtual shot gathers. The virtual shot gathers refer to three locations (profile distances 350 m, 1150 m, 1950 m) as shown in Figure 8. The dispersion spectra shows energy being distributed from ~~3-2~~3-2 Hz to more than 35 Hz. We can also detect the air wave energy in the dispersion spectra in Fig. 7b where the yellow line indicates a velocity of 340 m/s. The cyan curves indicate the final dispersion curves used for inversion, where the error bar represents the width of the amplitude spectra which is used as a weight in the inversion. The white dashed lines indicate the sampling power of the virtual shot gathers ranging from the maximum to the minimum wavelength:

$$\frac{1}{\lambda_{min}} = \frac{1}{2 \cdot dx}, \quad \frac{1}{\lambda_{max}} = \frac{1}{L} \quad (5)$$

In equ. (5), dx and L refer to the geophone spacing (5 m) and the maximum offset (100 m), respectively. Therefore, the maximum and minimum wavelengths calculate to 100 m and 10 m, and we set the upper limit of the frequency range for the picked dispersion curves to be ~ 35 Hz. According to the rule of thumb used in active surface wave survey, suggests the minimum array length should to be 1.5 or 2 times of desired maximum wavelength (Xia et al., 2006; Foti et al., 2018). In our passive seismic survey case, the whole profile is 2.4 km long, but each subdivided section is only 100 m long. For passive surface waves, there is no established maximum wavelength criterion. The identification of maximum wavelengths varies also with the data quality, dispersion measurement, source-receiver configuration and chosen processing techniques. We chose the minimum frequency as 3.5 Hz due to the high-quality data and clear dispersion curves which appear meaningful down to frequencies as low as 2 Hz. Depending on the velocity, this results in minimum wavelength-profile length factors between 0.3 and 0.7.

We suppose it is acceptable to sample surface waves with ~ 250 m maximum wavelength for our profile, and the according lowest frequency of the dispersion data used for inversion is about 3.5 Hz. In Fig. 7 we Note-observe that the dispersion signature at the location $X=1950$ m is different from the two other ones and indicates a velocity inversion with depth (Shen et al., 2017).

The 25 $V_S(z)$ functions are assigned to the centre of their corresponding 100 m long sections and are interpolated along the profile (Fig. 8). We observe the same large-scale structure as derived from the active source processing, e.g. thickening of the low-velocity surface zone towards the south, lack of high velocities and decreased penetration depth in the over-deepened part, and high velocities close to the surface at the southern end of the profile. A significant discrepancy is the apparent increase in dip of the basement at the profile distance ~ 900 m when compared to the basement interpreted from active source data. However, there is an indication of a basement velocity decrease in the tomographic P-wave velocity (Fig.4) model as well as in the refractor velocity model, and basement reflections in the shot gathers suggest a sudden local change in dip at this location. A buried basement fault or significantly fractured basement may explain this feature, but this is subject to further investigation. The shallow S-wave velocity structure in the over-deepened section (profile distance $\sim 1600 - 2100$ m) is indicative of an inversion zone (see also Figs. 7h,i) and is discussed in more detail in the next section.

6 Interpretation and Discussion

Our discussion section is organized in three parts. Firstly, we provide an overview on the expected sedimentary stratigraphy based on a core from a distant well. Secondly, we calculate the ratio of P- to S-wave velocities and attempt an interpretation in the context of this expected stratigraphy and other studies in similar geologic settings. Lastly, we critically assess some aspects of our workflow and their impacts on our interpretation.

6.1 Local sedimentary stratigraphy

In 2006, two closely spaced wells were drilled in Unaweep canyon ca. 5 km eastwards of the seismic down to depths of 320 m and 329 m, respectively (Soreghan et al., 2007; Fig. 1), where only the deeper one penetrated basement. In the retrieved core of the sedimentary section, three distinct units were delineated, on the basis primarily of sedimentary facies and provenance (Soreghan et al., 2007; Balco et al., 2013; Soreghan et al., 2015). The uppermost ~160 m comprises clast- and matrix-supported conglomerate, with clasts ranging from granule to cobble/boulder size, of both Precambrian basement and Mesozoic sand/siltstone. Local sandy/clayey interbeds also occur, all poorly indurated. This fanglomerate unit also crops out at roadcuts further down the canyon, and is of Pleistocene age. This unit transitions, through a ~7 m interval of carbonate-rich paleosols, to an upwardly coarsening interval of well-sorted, poorly indurated sand yielding to underlying silt and well-compacted clay that extends to ~315 m depth. This Pleistocene unit is interpreted as lacustrine, with a provenance that includes volcanic lithics tied to the ancestral Gunnison River, in addition to Mesozoic sedimentary lithics. It was deposited 1.4 million years ago when a landslide on the western side blocked the ancestral Gunnison River (Balco et al., 2013). The basalmost ~5 m of the core comprises a moderately indurated diamictite consisting entirely of Precambrian basement clasts encased in a fine-grained matrix, and inferred to be of Paleozoic age (Soreghan et al., 2007).

Given that the fanglomerate comprises the modern surface, we infer that this unit also occurs in the western canyon, underlying the seismic profile. The landslide blockage that impounded the ancestral Gunnison River is inferred to have occurred in western Unaweep Canyon (Balco et al., 2013), hence the lacustrine section should also occur in this location at the same elevation. Given that this location is x km more distal than the Massey core, we infer that the lacustrine section here should be finer in general, and thus contain a higher proportion of compacted clay at depth. Beneath the lacustrine section Soreghan et al. (2007) posit the existence of an interval correlative to the Permian Cutler Formation (Werner, 1974; Soreghan et al., 2009) which is exposed at the western mouth of the canyon, and comprises a mixture of conglomerate, granule conglomerate, and silt/mudstone. The exposed Cutler Formation strata are very poorly consolidated and poorly sorted, and show signs of significant fluid alteration (Hullaster et al., 2019).

6.2 Calculation and interpretation of the V_P/V_S – ratio

In geological settings, low seismic velocities are usually associated with poorly consolidated soils and rocks. This applies to both P- and S-wave velocities, although S-wave velocities are more affected due to their sole dependence on the shear modulus. The additional knowledge of the ratio of P- to S-wave velocities can help to further constrain subsurface properties. For instance, a sudden increase of the P-to-S velocity ratio with depth is often used as an indicator for the groundwater table (GWT) as shear-wave velocities experience no significant change when pore space voids are filled with fluid. In the oil & gas industry, V_P/V_S – ratios are important in evaluating hydrocarbon saturation and lithology. Deep crustal studies rely on V_P/V_S – ratios to discriminate felsic from mafic rocks (Christensen, 1996; Carbonell et al., 2000; Morozov et al., 2001; Behm, 2009).

Formatted: English (United Kingdom)

Formatted: English (United States)

On the other end of the spatial scale, several V_P/V_S —studies for For near-surface soils (< 50 m depth), several studies can be found which exist as well report V_P/V_S —ratios based on seismic surveys. This is largely because of the interest in shallow soil structure for geotechnical and hydrological applications and the ease at which shallow P- and S-wave data can be acquired. Uyanik (2011) summarizes V_P/V_S —ratios of seismic measurements in shallow (< 20 m depth) saturated sediments (gravel, sand, clay-silt) with porosities ranging from 20% to 50%. He-For 100% water saturation, his data concludes that show water saturation is indicated by V_P/V_S —ratios larger than ranging from 3.3, and reports maximum V_P/V_S —ratios for low-saturation (40%—50%) soils of 57.02. Pasquet et al. (2015) combine P-wave refraction, S-wave refraction, and surface wave inversion to image a shallow GWT (< 20 m depth) in a weathered granitic basement. They state low V_P/V_S —ratios (<2.75) for the low-porosity/low-permeability granitic basement and higher ratios (3.0 – 4.0) for wet soil close to the surface.

In-between the shallow surface and deep crustal / reservoir targets, only a small number of studies report V_P/V_S —ratios for intermediate depths comparable to our study. Konstantaki et al. (2013) derive hydrological and soil mechanical parameters across the Alpine Fault in New Zealand. They apply P-wave tomography and MASW to data from active shot gathers and derive velocity models down to depths of 60 m. They find V_P/V_S —ratios larger than 3.0 and up to 9.0 for wet sand, gravel, and silt lithologies, and were able to interpret the GWT from their results. Bailey et al. (2013) conducted a deep P- and S-wave reflection survey in a geologic setting comparable to our study. Their site comprises a several hundred meters thick sedimentary sequence of Quaternary sands and clays of Pleistocene age, which also includes lacustrine sediments. They were able to derive V_P/V_S —ratios with high lateral and vertical resolution from the correlation of P- and S-wave reflections and from MASW. In the shallow surface (< 50 m depth), they find V_P/V_S —ratios as high as 10, which were interpreted as soil pockets with high potential for liquefaction. The deep structure (50 – 500 m depth) exhibits V_P/V_S —ratios between 3.0 and 6.0. Zuleta and Lawton (2012) present a similar dataset comprising multicomponent data with P- and S-reflections. They investigate a late Paleozoic sedimentary basin in British Columbia and derive V_P/V_S —ratios between 6.0 at the surface and 2.0 in depths of ca. 300 m. Their velocities are comparable to our studies, e.g. V_P is ranging from 1950 m/s to 2800 m/s, and V_S is varying between 350 m/s and 1400 m/s.

We calculate the ratio of the tomographic P-wave velocity and the S-wave velocity models (Figs. 4, 8, 9). In order to account for the different parameterization of the travel time tomography and the dispersion inversion, we average P-wave velocities within each surface wave inversion depth layer before we take the ratio. In the left part of the profile, we encounter V_P/V_S —ratios between 1.8 and 2.5 for both the sedimentary cover overburden and the basement. Between profile distances 700 m and 1100 m, the migration shows a pronounced reflector in the depth range 50 m to 100 m which could potentially represent a GWT. There is however no significant correlation of the V_P/V_S —ratio with this reflector. In combination with the actual velocities, these values suggest dry conditions for the overburden. In case of the basement in the left part of the profile, V_P/V_S —ratios larger than 2 and moderate P-wave velocities (4.0 – 5.5 km/s) are indicative of significant weathering and/or fracturing of the Precambrian granites. The V_P/V_S —ratio changes to significantly higher values (3.0 – 6.0) in the over-deepened part of the profile. The top of this zone of high V_P/V_S —ratios reaches the surface at the southern

part of the profile, where West Creek occupies the lowest topographic point. The zone dips towards the north and its top is found at ca. 120 meters depth at the presumed northern edge of the over-deepened section. A northward dipping reflector is found in a comparable depth range in the seismic image, and the P-wave velocities (1500 m/s – 1800 m/s) correspond to typical velocities of saturated near-surface sands and gravels (Knights and Endres, 2005; Everett, 2013). ~~we~~ We therefore interpret the increased V_P/V_S – ratio in the over-deepened section to represent the top of water-saturated sediments. Since the dip opposes the slope of the topography, this aquifer needs to be confined or it is leaking through fractured basement in the north. The latter hypothesis would be supported by the relatively low P- and S-wave velocities between profile distances 900 m to 1400 m (Figs. 4, 8).

Both the tomographic P-wave velocity model and the S-wave velocity model from the stacked gathers with a maximum offset range of 100 meters have only little penetration depth in the over-deepened section. To increase the investigation depth, we extend the tomographic velocity model with interval velocities obtained from reflection processing (Patterson et. al., 2018b). The two velocity ~~ies~~ models are tied together at an elevation of 1800 meters, where a smoothing filter is applied to account for their different nature (smooth travel time tomography vs. discontinuous interval velocities). A deeper reaching S-wave velocity model is derived from stacking all source-receiver sorted interferograms between the profile distances 1500 m and 2100 m. The resulting maximum offset of 600 m allows for picking a dispersion curve with minimum frequencies around 1 Hz, which in turn results in a significantly larger penetration depth of the inverted S-wave velocity model (Fig. 10). For both P- and S-wave velocity models, the increase in investigation depth comes at the expense of reduced lateral resolution. However, at this stage we are primarily interested in a representative 1D section of the over-deepened part. To calculate V_P/V_S , we again average the P-wave velocities in the corresponding layer depths of the S-wave velocity model.

Fig. 11 shows a compilation of the 1D-velocity models in the over-deepened section. In general, the P-wave velocities in the range 1200 – 2700 m/s correspond to those established for other Quaternary-Pleistocene alpine valley fills (Brueckl et al., 2010; de Franco et al., 2009). In Fig. 11, we also show the sonic log from the Massey well. ~~This~~ The well is located upstream West Creek and 5 km to the east of the seismic profile (Fig. 1), where the topographic elevation is also 80 m higher. The sonic log indicates a P-wave velocity decrease at an elevation of ca. 1830 m, which correlates with ~~a~~ the transition from Quaternary the fanglomerates to the lacustrine sands as seen in the core. ~~The sand is interpreted to represent lacustrine sediments which were deposited 1.4 million years ago when a landslide on the western side blocked the ancestral Gunnison River (Balco et al., 2013). Consequently, the top of the lacustrine sediments should be found at the same elevation everywhere along West Unaweep canyon.~~ The merged seismic P-wave velocity profile shows a discontinuity at this elevation, which however also indicates lower velocities above the sand. This discrepancy ~~might~~ can be explained by different heterogeneity-local composition and compaction of the Quaternary fanglomerate at the two locations. Another possibility for the difference is a variable groundwater table, leading to saturated fanglomerates at the well location and dry fanglomerate at the seismic profile. This is in fact supported by the V_P/V_S – ratio, which is low (2.0 – 2.5) above the top lacustrine horizon and raises to significantly larger values (3.4 – 4.0) below. Bleibinhaus and Hilberg (2012) also report a similar P-wave velocity increase for the transition from dry to saturated sand in Quaternary fill of the Salzach Valley in the European Alps. Lab analysis of the core (pers. comm.

O. Davugustto) provided an estimated porosity of 32% for the fanglomerate. This large value is qualitatively supported by observation of the excavated material in the local gravel mining pit, which in generally is very poorly sorted and comprises boulders with sizes up to a cubic meter and more. The increase in P-wave velocities correlates with a decrease of S-wave velocities, which also suggests a vertical change of lithology. Overall, we interpret the high V_P/V_S – ratios as an indicator for saturation in the lacustrine sands below the fanglomerate.

The base of the lacustrine sediments is interpreted close to the bottom of the well, as ~~the~~ The last few meters of the core transit into a mixture of basement clasts and Palaeozoic sediments. ~~clayey mud.~~ This transition ~~also~~ correlates with a velocity discontinuity in the interval P-wave velocities and the onset of a gradual increase of the S-wave velocities. The high P-wave velocities would suggest sediments other than clay or sands, which usually are characterized by velocities not larger than 2200 m/s (Knight and Endres, 2005). Soreghan et al. (2007, 2008, 2014, 2015) speculate that the over-deepening of Unaweep Canyon was caused by glaciation in a late Palaeozoic icehouse, and that the lacustrine sands lie on top of an upper Paleozoic sedimentary fill which could explain higher seismic velocities. Subsequently, ~~the~~ The high P-wave velocities also lead to high V_P/V_S – ratios below the sand is decreasing but still high (3.2 – 3.8).

The interval velocities were obtained from conventional velocity analysis and the Dix equation. Steep dips as the valley flanks can lead to an overestimation of the velocities in the deeper sections of the sediment fill. However, the extracted interval velocities are located at the centre of the U-shaped valley cross section, where both reflections from the flanks and from the flat bottom do occur. Out-of-plane reflections are also present and can introduce non-physical layering in the velocity profile. Given these uncertainties, we do not attempt to correct individual stacking and interval velocities for dip but investigate the sensitivity of the V_P/V_S – ratio on overall too high interval velocities in the deep section of the sediment fill. For that purpose, we reduce the P-wave velocities below the assumed bottom of the lacustrine sands by 25%. The resulting V_P/V_S – ratio (dashed blue line in Fig. 11) drops to values ranging from 2.5 to 2.9. This is a large discrepancy to the uncorrected values (3.2 – 3.8), and consequently we avoid the interpretation of V_P/V_S – ratio in the deep section. Our main new insight from both P- and S-wave velocity models at larger depths is the identification of the top and bottom of the lacustrine section, and a general increase of velocities below this section. Forward modelling of basement reflections could help to constrain deep interval velocities, but this is beyond the scope of this study.

Soreghan et al. (2007, 2008, 2014, 2015) speculate that the over-deepening of Unaweep Canyon was caused by glaciation in a late Palaeozoic icehouse, and subsequently that the lacustrine sands lie on top of an upper Paleozoic sedimentary fill. The prevailing upper Paleozoic strata in this region belong to the Cutler Formation (Werner, 1974; Soreghan et al., 2009). Exposed Cutler Formation strata at the western mouth of Unaweep Canyon are indeed very poorly consolidated and poorly sorted (Soreghan et al., 2007), and show signs of significant fluid alteration (Hullaster et al., 2019). Both observations qualitatively agree with low seismic velocities and high V_P/V_S – ratio, although the effect of burial and subsequent compaction has not been investigated yet. Overall, we interpret the high V_P/V_S – ratios as an indicator for significant saturation in the entire sedimentary column below the fanglomerate.

6.3 Methodological aspects

Our interpretation ~~of the V_P/V_S - ratio~~ is based on velocity models of different origins and of different parameterization. ~~However, b~~Both the tomographic P-wave model and the S-wave model from dispersion inversion do not explicitly comprise distinct velocity discontinuities such as the prominent sediment-to-basement transition. ~~Such an~~This interface will be represented as a strong gradient in an overall smooth velocity field, and the corresponding V_P/V_S - ratio will not allow for the exact definition of a groundwater table. Nonetheless, the lateral variation of the V_P/V_S - ratio in the over-deepened section correlates with the seismic image and the P-wave velocity model, and suggests the existence of an aquifer ~~in the over-deepened part~~ (Fig. 9). ~~an insight which could not be gained from P- or S-wave velocity models alone. Surprisingly, t~~The V_P/V_S - ratio does not give any indication for the transition from sediments to the basement in the northern part of the profile, even though both P- and S-wave models sample the basement at sufficient depth ranges. This ~~is~~can be indicative of significant weathering of the top of the Precambrian granite. ~~However, we are also aware that — subjective choices of parameters used in the surface wave processing and inversion sequence (minimum wavelength, dispersion measurement algorithm, or density, layer thickness, and P-wave velocity constraints) will impact the final S-wave velocity model. Therefore we prefer to interpret significant contrasts in the V_P/V_S - ratio only, e.g. such as the high values in the lacustrine sands.~~

The structural interpretation of the asymmetric valley structure and the steep and sudden dip at its southern rim is supported by both the P-wave and S-wave velocity models (Figs. 4, 8). Dispersion analysis also gives better evidence of velocity inversion zones than classical travel time tomography which is ~~largely-less~~ insensitive to velocity decrease with depth. ~~However, i~~In our ~~ease-interpretation~~ the vertical trends of S- and P-wave velocities are partly decoupled due to water saturation.

The dense receiver spacing allows for relatively high lateral resolution of the S-wave velocity model through sorting and stacking in source / receiver and offset bins, which comes at the expense of a loss in investigation depth. Nonetheless, even with these short offsets the investigation depth is comparable to the P-wave travel time tomography using long offsets. This compares to the results of Pasquet et al. (2015) who find larger penetration depths of surface wave inversion over S-wave refraction. Improved S-wave velocity imaging and higher lateral resolution might be obtained from simultaneous inversion of adjacent source / receiver cells (Konstantaki et al., 2013), or by calculating group velocity dispersion between individual receiver pairs (Bensen et al., 2007; Hannemann et al, 2014). The latter approach would be applicable to irregular receiver spacing but requires automatization of dispersion picking in case of a large number of receivers.

Sorting and stacking using larger offsets enables imaging of significantly larger depths, if low-frequency seismic energy is present. In our case, the inclusion of traffic-induced ambient seismic noise provides frequencies as low as 1 Hz, which extends the frequency spectrum of the active source (Fig. 5). Seismic interferometry and the virtual source method provide a very efficient approach to merge the contributions from different active and passive seismic sources without the need for data selection or tailored processing schemes.

7 Conclusions

We have combined active and passive processing schemes to derive P- and S-wave velocity models of an over-deepened alpine valley. Both approaches complement each other in several aspects: (1) The P-wave velocity model is used to constrain the shear wave velocity inversion; (2) Ambient noise sources extend the spectrum to lower frequencies, thus enabling the imaging of deeper structures; (3) Independently derived P- and S-wave velocity models allow to calculate the V_P/V_S – ratio which adds significantly to the geologic and hydrologic interpretation.

The calculation and interpretation of the V_P/V_S – ratio is challenged by different parameterization of the models, and subsequently by the different sensitivity to lateral and vertical variation of the seismic structure. Information on subsurface lithology is essential to derive robust conclusions on hydrological and geological properties, and wherever this information missing the interpretation remains ambiguous. In particular the calculation of S-wave velocities from surface wave measurements is still impacted by poorly quantified uncertainties, and future research is needed to address this topic.

Our dataset shows that a deployment period as short as 30 hours in an area with little anthropogenic and natural seismic activity still contains ample ambient noise. Much of this noise stems from acquisition down-time when the active source truck is moving. Scattering and reflection of surface waves generate secondary sources which contribute to stationary phase sources required for the application of ambient noise interferometry. Interferometry and the virtual source method naturally blend active and ambient seismic sources without a need for separation of the two data domains, which broadens the frequency spectrum and the investigation depth-

Large-scale 3D seismic acquisition projects, as routinely performed in the energy sector or other industrial applications, involve tens of thousands of active receivers, and those experiments might take weeks to months to be accomplished. If nodes are used, then the sheer amount of passive data acquired with dense spatial sampling invite the application of processing workflows like our study. Given the simplicity and high degree of automatization, detailed and robust subsurface models can be obtained quickly and at marginal additional costs.

Equipping nodes with 3C sensors enables additional possibilities for processing of the acquired data. The observation of both Rayleigh and Love waves increases the reliability of surface wave inversion. Well established 3C methods from the global seismology community (e.g. receiver functions, H/V ratio) can be adapted and downscaled to exploration applications.

To our knowledge, our study is the first one to report on the variation of V_P/V_S – ratios in sedimentary infills of alpine valleys. Combined with reflection imaging and geologic extrapolation from a distant well, The data suggest that Unaweep canyon hosts a significant aquifer as ~~it is~~ indicated by V_P/V_S – ratios significantly larger than 3 over a vertical extent of ~~ca. 400 m~~ at least 100 m. Since the resolution and accuracy of the seismic interpretation decreases with depth, a dedicated drilling campaign would be beneficial to provide ground truth and calibrate the seismic models. Given the fact that quaternary sedimentary strata cover a large range of the continental US (Soller and Garrity, 2018), our results invite the application of V_P and V_S measurements in non-alpine regions as well. Many areas in the US mid-west are prone to droughts while at the same time

facing increased urbanization pressure, and influences by climate change. Mitigating these effects requires substantially expanding our knowledge on the distribution and characterization of potential groundwater resources (Taylor et al. 2012).

Author contribution

M.Behm did the active and passive processing of the data and wrote the manuscript, except the parts noted below. F.Cheng provided processing and description of the steps in section 5.2, and also contributed to processing of the active refraction data. A.Patterson processed the active reflection data and contributed to processing of the active refraction data. G.Soreghan provided section 2 in the manuscript, and contributed to the interpretation

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

Texan data loggers were provided by the IRIS PASSCAL instrument center. Acquisition was done in cooperation with the Seismic Source Facility (SSF) based at University of Texas at El Paso. The dedication and competence of Galen Kaip, and Steve Harder, and Jefferson Chang contributed greatly to a successful acquisition. The Gateway community is thanked for local support. The project is partially funded from NSF-EAR-1338331. ~~The geologic map (Fig. 1) has been created by Eccles, T.M., Soreghan, G.S., Kaplan, S.A., Patrick, K.D., and Sweet, D.E.~~ Andy Elwood Madden, Kato Dee, and Jim Blattman are thanked for discussion and helpful advice.

References

Aki, K.: Space and time spectra of stationary stochastic waves, with special reference to micro-tremors, Bulletin of the Earthquake Research Institute 35, 415–457, 1957

Aslan, A., Hood, W.C., Karlstrom, K.E., Kirby, E., Granger, D.E., Kelly, S., Crow, R., Donahue, M.S., Polyak, V., and Asmerson, Y.: Abandonment of Unaweep Canyon (1.4–0.8 Ma), western Colorado: Effects of stream capture and anomalously rapid Pleistocene river incision: Geosphere, 10, 2014, doi:10.1130/GES00986.1.

Bailey, B. L., Miller, R.D., Peterie, S., Ivanov, J., Steeples, D., and Markiewicz, R.: Implications of Vp/Vs ratio on shallow P and S reflection correlation and lithology discrimination, in: Expanded Abstracts of the 83rd Annual SEG Meeting, Houston, USA, 22 – 27 September 2013, 1944-1949, 2013

Bakulin A., and Calvert, R: The virtual source method: Theory and case study, *Geophysics* 71, SI139–SI150, 2006

Balco G., Soreghan G.S., Sweet D.E., Marra K.R., and, Bierman P.R.: Cosmogenic-nuclide burial ages for Pleistocene
5 sedimentary fill in Unaweep Canyon, Colorado, USA, *Quaternary Geochronology*, 18, 149-157, 2013

~~Behm, M.: 3-D-modelling of the crustal S-wave velocity structure from active source data: application to the Eastern Alps
and the Bohemian Massif, *Geophys. J. Int.*, 179, 265–278, 2009~~

10 Behm, M., Leahy, G. M., and Snieder, R: Retrieval of local surface wave velocities from traffic noise - an example from the
La Barge basin (Wyoming), *Geophys. Prospect.*, 62, 2014, doi:10.1111/1365-2478.12080, 2013

Behm, M., and Shekar, B.: Blind deconvolution of multichannel recordings by linearized inversion in the spectral domain.
Geophysics, 79, V33-V45, 2014

15 Behm, M.: Feasibility of borehole ambient noise interferometry for permanent reservoir monitoring, *Geophysical Prospecting*,
65, 563–580, 2017, doi:10.1111/1365-2478.12424

Behm, M., Walter, J.I., Binder, D., and Mertl, S.: Seismic Monitoring and Characterization of the 2012 Outburst Flood of the
20 Ice-Dammed Lake AP Olsen (NE Greenland), AGU Fall Meeting, New Orleans, USA, New Orleans, 11-15 December 2017,
C41D-1260, 2017

Behm, M.: Reflections from the Inner Core Recorded during a Regional Active Source Survey: Implications for the Feasibility
of Deep Earth Studies with Nodal Arrays, *Seismological Research Letters*, 89, 1698-1707, 2018, doi:10.1785/022018001

25 Bensen, G.D, Ritzwoller, M.H, Barmin, M.P., Levshin, A.L, Lin, F., Moschetti M.P., Shapiro, N. M., and Yang, Y.: Processing
seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, *Geophysical Journal
International*, 169, 1239–1260, 2007

30 Biryol, C. B., Leahy, G.M., Zandt, G., and Beck, S.L.: Imaging the shallow crust with local and regional earthquake
tomography, *Journal of Geophysical Research*, 118, 2289–2306, 2013, doi: 10.1002/jgrb.50115. B

Bleibinhaus, F., and Hilberg, S: Shape and structure of the Salzach Valley, Austria, from seismic traveltime tomography and
full waveform inversion, *Geophys. J. Int.*, 189, 1701–1716, 2012

Brückl, E., Brückl, J., Chwatal, W., and Ullrich, C.: Deep alpine valleys: Examples of geophysical explorations in Austria, Swiss J. Geosci, 103, 329–344, 2010

- 5 Cater, F.W., Jr.: Age of the Uncompahgre Uplift and Unaweep Canyon, west-central Colorado: U.S. Geological Survey Professional Paper 550-C, C86–C92, 1966

~~Carbonell, R., Gallart, J., Perez-Estaun, A., Diaz, J., Kashubin, S., Mechie, J., Wenzel, F., and Knapp, J.: Seismic wide-angle constraints of the crust of the southern Urals, J. geophys. Res., 105, 13775–13777, 2000~~

- 10 ~~Chang, J.P., de Ridder, S.A.L., and Biondi, B.L.: High-frequency Rayleigh-wave tomography using traffic noise from Long Beach, California, GEOPHYSICS, 81, B43–B53, 2016, doi.org/10.1190/geo2015-0415.1~~

~~Cheng, F., Xia, J., Luo, Y., Xu, Z., Wang, L., Shen, C., Lio, R., Pan, J., Mi, B., and Hu, Y.: Multi-channel analysis of passive surface waves based on cross-correlations, Geophysics, 81(5), EN57–EN66, 2016, doi.org/10.1190/GEO2015-0505.1~~

15

~~Christensen, N.: Poisson's ratio & crustal seismology, J. geophys. Res., 101, 3193–3156, 1996~~

- Cole, R.D., and Young, R.G.: Evidence for glaciation in Unaweep Canyon, Mesa County, Colorado, in Averett, W.R., ed., Northern Paradox Basin–Uncompahgre Uplift (Grand Junction Geological Society Field Trip Guidebook): Grand Junction, Colorado, Grand Junction Geological Society, 73–80, 1983
- 20

Davogustto, O.E.: Soneo Gravimetrico en el Canon Unaweep: En Busca del Basamento y su Forma, B.S. Thesis, Simon Bolivar University, Caracas, Venezuela, 56 pp, 2006

25

Dean, T., O'Connell, K., and Quigley, J.: A review of nodal land seismic acquisition systems, Preview, 164, 34–39, 2013, doi: 10.1071/PVv2013n164p34

Dean, T., Tulett, J., and Barnwell, R: Nodal land seismic acquisition: The next generation, First Break. 36, 47–52., 2018

30

~~Chang, J.P., de Ridder, S.A.L., and Biondi, B.L.: High-frequency Rayleigh-wave tomography using traffic noise from Long Beach, California, GEOPHYSICS, 81, B43–B53, 2016, doi.org/10.1190/geo2015-0415.1~~

~~Cheng, F., Xia, J., Luo, Y., Xu, Z., Wang, L., Shen, C., Lio, R., Pan, J., Mi, B., and Hu, Y.: Multi-channel analysis of passive surface waves based on cross-correlations. *Geophysics*, 81(5), EN57–EN66, 2016, doi.org/10.1190/GEO2015-0505.1~~

Denes, V., Starr, E., and Kapoor, J.: Developing Earth models with full waveform inversion: The Leading Edge, 28, 432–435,
5 2009, doi: 10.1190/1.3112760

Draganov, D., Campman, X., Thorbecke, J., Verdel, A., Wapenaar, K. Reflection images from ambient seismic noise, *Geophysics*, 74, A63–A67, 2009

10 Dou, S., Lindsey, N. J., Wagner, A., Daley, T. M., Freifeld, B. M., Robertson, M., Peterson, J., Ulrich, C., Martin, E.R., and Ajo-Franklin, J. B: Distributed acoustic sensing for seismic monitoring of the near surface: A traffic-noise interferometry case study. *Scientific Reports*, 7, 11620, 2017

Everett, M.E.: Near-Surface Applied Geophysics, Cambridge University Press, 2013

Formatted: English (United States)

15 Forghani, F., and Snieder, R.: Underestimation of body waves and feasibility of surface-wave reconstruction by seismic interferometry, *The Leading Edge*, 29, 790–794, 2010, doi: 10.1190/1.3462779.

20 Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P.-Y., Comina, C., Cornou, C., Cox, B., Di Giulio, G., Forbriger, T., Hayashi, K., Lunedei, E., Martin, A., Mercerat, D., Ohrnberger, M., Poggi, V., Renalier, F., Sicilia, D., and Socco, L.V.: Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project, *Bull. Earthq. Eng.*, 16, 2367–2420, 2018

25 de Franco, R., Biella, G., Caielli, G., Berra, F., Guglielmin, M., Lozej, A., Piccin, A., and Sciunnach, D: Overview of high resolution seismic prospecting in pre-Alpine and Alpine basins, *Quat. Int.*, 204, 65–75, 2009

Freed, D.: Cable-free nodes: The next generation land seismic system, *The Leading Edge*, 27, 878–881, 2008

30 Gardner, G.H.F., Gardner, L.W., and Gregory, A.R.: Formation velocity and density - the diagnostic basics for stratigraphic traps, *Geophysics*. 39, 770–780, 1974

Haffener, J.: Gravity modeling of Unaweep Canyon: Determining Fluvial or Glacial Origins: B.S. Thesis, University of Oklahoma, Norman, Oklahoma, 25 pp, 2015

Halliday, D. F., Curtis, A., Robertsson, J. O., and van Manen, D.-J.: Interferometric surface-wave isolation and removal, *Geophysics*, 72, A69–A73 2007

- 5 Halliday, D. F., Curtis, A., Vermeer, P., Strobbia, C., Glushchenko, A., van Manen, D.-J, and Robertsson, J.O.A.: Interferometric ground-roll removal : Attenuation of scattered surface waves in single-sensor data, *Geophysics* 75, SA15-SA25, 2010

- 10 Hannemann, K., Papazachos, C., Ohrnberger, M., Savvaidis, A., Anthymidis, M., and Lontsi, A.M.: Three-dimensional shallow structure from high-frequency ambient noise tomography: New results for the Mygdonia basin-Euroseistest area, northern Greece, *J. Geophys. Res.*, 119, 4979–4999, 2014

Hole, J.A.: Nonlinear high-resolution three-dimensional seismic travel time tomography, *J. Geophys. Res.*, 97, 6553–6562, 1992

- 15 Hullaster D.P, Elwood-Madden, A.S., Soreghan, G.S., and Dee, K.T.: Redox interfaces of the proximal Permian Cutler Formation, western Colorado: Implications for metal reactivity, American Chemical Society Annual Meeting, Orlando FL, 2019

- 20 [Ivanov, J., Tsoflias, G., Miller, R. D., Peterie, S., and Morton, S.: Impact of density information on Rayleigh surface wave inversion results, *Journal of Applied Geophysics*, 135, 43–54, 2016](#)

Iwasaki, T.: Extended time-term method for identifying lateral structural variations from seismic refraction data, *Earth Planets Space*, 54, 663–677, 2002

- 25 Karplus, M., and Schmandt, B.: Preface to the Focus Section on Geophone Array Seismology, *Seismological Research Letters*, 89, 1597, 2018

[Kissling, E.: Geotomography with local earthquake data, *Reviews of Geophysics*, 26, 65-698, 1988](#)

- 30 Kluth, C.F., and Coney, P.J.: Plate tectonics of the Ancestral Rocky Mountains, *Geology*, 9, 10–15, 1981, doi:10.1130/0091-7613

Knight, R.J., and Endres, A.L.: An Introduction to Rock Physics Principles for Near-Surface Geophysics, in: Near Surface Geophysics, edited by: Butler, D., Tulsa, Society of Exploration Geophysicists, 2005

Kissling, E.: Geotomography with local earthquake data, Reviews of Geophysics, 26, 65-698, 1988

Lawton, D.C., Gallant, E.V., Bertram, M.B., Hall, K.W., and Bertram, K.L.: A new S-wave seismic source, CREWES Research Report, 25, 2013

Konstantaki, L.A., Carpentier, S., Garofalo, F., Bergamo, P., and Socco, L.V.: Determining hydrological and soil mechanical parameters from multichannel surface-wave analysis across the Alpine Fault at Incheon, New Zealand, Near Surface Geophysics, 11, 435-448, 2013, doi:10.3997/1873-0604.2013019

Lawton, D.C., Gallant, E.V., Bertram, M.B., Hall, K.W., and Bertram, K.L.: A new S-wave seismic source, CREWES Research Report, 25, 2013

Levshin, A.L., Yanovskaya, T.B., Lander, A.V., Bukchin, B.G., Barmin, M.P., Ratnikova, L.I. & Its, E.N.: Seismic Surface Waves in a Laterally Inhomogeneous Earth, ed. Keilis-Borok, V.I., Kluwer, Norwell, Mass., 1989

Lohman, S.W.: Abandonment of Unaweep Canyon, Mesa County, Colorado, by capture of the Colorado and Gunnison Rivers, in Geological Survey Research 1961: U.S. Geological Survey Professional Paper 424, p. B144-B146, 1961

Maupin, V.: On the effect of topography on surface wave propagation in the ambient noise frequency range, J. Seismol., 221-231, 2012

McNamara, D.E., and Buland, R.P.: Ambient Noise Levels in the Continental United States, Bulletin of the Seismological Society of America, 94, 1517-1527, 2004 doi: https://doi.org/10.1785/012003001

Morozov, I., Smithson, S., Chen, J., and Hollister, L.: Generation of new continental crust and terrane accretion in Southeastern Alaska and Western British Columbia: constraints from P- and S-wave wide-angle seismic data (ACCRETE), Tectonophysics, 341, 49-67, 2001

Nakata, N., Snieder, R., Tsuji, T., Larner, K., and Matsuoka, T.: Shear-wave imaging from traffic noise using seismic interferometry by cross-coherence, Geophysics, 76, SA97-SA106, 2011

Nakata, N., Chang, J. P., Lawrence, J. F. and Boué, P.: Body wave extraction and tomography at Long Beach, California, with ambient-noise interferometry, *J. Geophys. Res. Solid Earth*, 120, 1159–1173, 2015, doi:10.1002/2015JB011870

Ning, L., Dai, T., Wang, L., Yuan, S., and Pang, J.: Numerical investigation of Rayleigh-wave propagation on canyon topography using finite-difference method, *J. Appl. Geophys.*, 159, 350–361, 2018

Olivier, G., Brenguier, F., Campillo, M., Lynch, R., and Roux, P.: Body-wave reconstruction from ambient seismic noise correlations in an underground mine, *Geophysics* 80, KS11-KS25, 2015

10 Pasquet, S., Bodet, L., Longuevergne, L., Dhemaied, A., Camerlynck, C., Rejiba, F., and Guérin, R.: 2D characterization of near-surface Vp/Vs: surface-wave dispersion inversion versus refraction tomography, *Near Surface Geophysics*, 13, 315–331, 2015, doi:10.3997/1873-0604.2015028

Patterson, A., Behm, M., and Soreghan, G.S.: Seismic investigation of Unaweep Canyon (Colorado): Implications for Late Paleozoic alpine glaciation in the tropics, EGU General Assembly, Vienna, Austria, 8-13 April 2018, *Geophysical Research Abstracts*, 20, EGU2018-8868, 2018a

Patterson, A., Chwatal, W., Behm, M., Cheng, F., and Soreghan, G.S: Seismic Imaging of and over-deepened alpine valley: Implications for Late Paleozoic alpine glaciation of the Uncompahgre uplift (Western Colorado) , GSA Annual Meeting in Indianapolis, Indiana, USA, 4-7 November 2018, *Geological Society of America Abstracts with Programs*, 50, 2018b, doi: 10.1130/abs/2018AM-319703

Picozzi, M., Parolai, S., Bindi, D., and Strollo, A.: Characterization of shallow geology by high-frequency seismic noise tomography, *Geophys. J. Int.* 176, 164–174, 2009

25 Planes, T. et al.: Time-lapse monitoring of internal erosion in earthen dams and levees using ambient seismic noise. *Géotechnique*, 2015, doi:10.1680/jgeot.14.P.268

Pomper, J. et al.: The glacially overdeepened trough of the Salzach Valley, Austria: Bedrock geometry and sedimentary fill of a major Alpine subglacial basin, *Geomorphology*, 295, 147–158, 2017

30 Prieto, G., Lawrence, J.F, and Beroza, G.C: Anelastic Earth Structure from the Coherency of the Ambient Seismic Field, *Journal of Geophysical Research* 114, B07303, 2009

Pugin, A. J. M., Oldenborger, G. A., Cummings, D. I., Russell, H. A. J., and Sharpe, D. R: Architecture of buried valleys in glaciated Canadian Prairie regions based on high resolution geophysical data, *Quat. Sci. Rev.* 86, 13–23, 2014

Riahi, N., Bokelmann, G., Sala, P., and Saenger, E. H: Time-lapse analysis of ambient surface wave anisotropy: A three-component array study above an underground gas storage, *J. Geophys. Res.*, 118, 5339–5351, 2013

Riahi, N., and Gerstoft, P.: The seismic traffic footprint: Tracking trains, aircraft, and cars seismically, *Geophys. Res. Lett.*, 42, 2674–2681, 2015, doi:10.1002/2015GL063558.

10 Ruigrok, E., Campman, X., Draganov, D., and Wapenaar, K.: High- resolution lithospheric imaging with seismic interferometry, *Geophysical Journal International*, 183, 339–357, 2010, doi: 10.1111/j.1365-246X.2010 .04724.x.

Schuster, G.T.: ~~2010.~~ Seismic Interferometry, Cambridge University Press, ~~2013.~~

15 Shen C.: Dispersion characteristics and inversion of high-frequency surface waves in horizontal layered models with velocity not increasing with depth (in chinese), Phd thesis, China university of Geosciences, 2017

Sinnock, S.: Pleistocene drainage changes in the Uncom- pahgre Plateau–Grand Valley region of western Colo- rado, including formation and abandonment of Unaweep Canyon: A hypothesis, in Epis, R.C., and Callender, J.F., eds., *Western Slope Colorado: New Mexico Geological Society 32nd Field Conference Guidebook*, 127–136, 1981

20 Sirgue, L., and Pratt, R.: Efficient waveform inversion and imaging: A strategy for selecting temporal frequencies, *Geophysics*, 69, 231–248, 2004, doi: 10.1190/1.1649391.

25 Snieder R.: Extracting the Green’s function from the correlation of coda waves: A derivation based on stationary phase. *Phys. Rev. E*, 69, 046610, 2004

Soller, D.R., and Garrity, C.P.: Quaternary sediment thickness and bedrock topography of the glaciated United States east of the Rocky Mountains, U.S. Geological Survey Scientific Investigations Map 3392, 2 sheets, scale 1:5,000,000, 2018, doi.org/10.3133/sim3392.

30 Soreghan, G.S., Sweet, D., Marra, K., Eble, C., Soreghan, M., Elmore, R., Kaplan, S., and Blum, M.: An exhumed late Paleozoic canyon in the Rocky Mountains, *Journal of Geology*, 115, 473–481, 2007, doi:10 .1086/518075.

Soreghan, G.S., Soreghan, M.J., Poulsen, C.J., Young, R.A., Eble, C.F., Sweet, D.E., and Davogustto, O.C.: Anomalous cold in the Pangaeen tropics, *Geology*, 36, 659–662, 2008

5 Soreghan G.S., Soreghan M.J., Sweet D. and Moore K.: Hot Fan or Cold Outwash? Hypothesized Proglacial Deposition in the Upper Paleozoic Cutler Formation, Western Tropical Pangea., *J Sediment Res* 79, 495–522, 2009

Soreghan, G.S., Sweet, D.E., and Heavens, N.G.: Upland glaciation in tropical Pangaea: Geologic evidence and implications for late Paleozoic climate modeling: *Journal of Geology*, 122, 137–163, 2014, doi:10.1086/675255.

10 Soreghan, G. S., Sweet, D. E., Thomson, S. N., Kaplan, S. A., Marra, K. R., Balco, G., and Eccles, T. M: Geology of Unaweep Canyon and its role in the drainage evolution of the northern Colorado Plateau, *Geosphere*, 2015, <http://doi.org/10.1130/GES01112.1>

15 Strobbia, C., Laake, A., Vermeer, P., and Glushchenko, A.: Surface waves: use them then lose them. Surface-wave analysis, inversion and attenuation in land reflection seismic surveying, *Near Surface Geophysics*, 9, 503–513, 2011 doi:10.3997/1873-0604.2011022

Taylor, R. et al.: Ground water and climate change, *Nature Climate Change*, 3, 322–329. 2012, doi:10.1038/nclimate1744

20 [Telford, W.M., Geldart, L.P., and Sheriff, R.E.: Applied Geophysics, 2nd edn., Cambridge University Press, Cambridge, 1990](#)

Uyanik, O.: The porosity of saturated shallow sediments from seismic compressional and shear wave velocities, *Journal of Applied Geophysics*, 73, 16–24, 2011

25 Wapenaar K.: Retrieving the elastodynamic Green’s function of an arbitrary inhomogeneous medium by cross correlation, *Phys. Rev. Lett.*, 93, 254301, 2004

Wapenaar K., Draganov D., Snieder R., Campman X. and Verdel A.: Tutorial on seismic interferometry: Part 1 – Basic principles and applications, *Geophysics*, 75, 75A195–75A209, 2010a

30

Wapenaar K., Slob E., Snieder R. and Curtis A: Tutorial on seismic interferometry: Part 2 – Underlying theory and advances. *Geophysics*, 75, 75A211–75A227, 2010b

Formatted: English (United States)

Werner W.: Petrology of the Cutler Formation (Pennsylvanian-Permian) near Gateway, Colorado, and Fisher Towers, Utah, *Journal of Sedimentary Research* 44, 292–298., 1974

Xia, J., Miller, R. D. , and Park, C. B.: Estimation of near-surface shearwave velocity by inversion of Rayleigh wave:
5 *Geophysics*, 64, 691–700, 1999, doi: 10.1190/1.1444578.

Xia, J., Xu, Y., Chen, C., Kaufmann, R.D., and Luo, Y.: Simple equations guide high-frequency surface-wave investigation techniques, *Soil Dyn. Earthq. Eng.*, 26, 395–403, 2006

10 Zhou, W., and Paulssen, H: P and S velocity structure in the Groningen gas reservoir from noise interferometry. *Geophysical Research Letters*, 44, 11,785–11,791, 2017, doi.org/10.1002/2017GL075592

Zuleta, L.M., and Lawton, D.C.: Vp/Vs characterization of a shale gas basin, northeast British Columbia, Canada, in: Expanded Abstracts of the 82nd Annual SEG Meeting, ~~XXX~~, Las Vegas, 4 – 9 November 2012, 1944-1949, 2012,
15 doi.org/10.1190/segam2012-1172.1

Figures

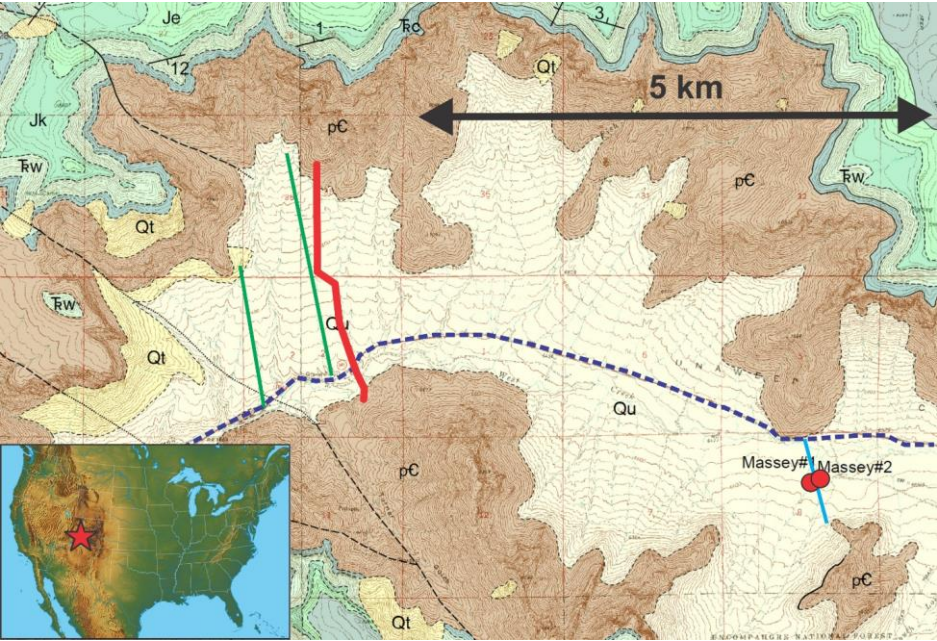


Figure 1: Surface geology of Western Unaweep Canyon and location of geophysical transects. pC: Precambrian granites (basement); Qu: Unconsolidated Quaternary deposits; Qt: Talus deposits; TRC, TRW, Je, Jk: Mesozoic sediments; Red line: Seismic acquisition 2017 (this study); Blue line: Seismic acquisition 2005; Green lines: Gravimetric acquisition 2006, 2014. Massey #1, #2: Wells (TVD 320 m). The geologic map (Fig. 1) has been created by Eccles, T.M., Soreghan, G.S., Kaplan, S.A., Patrick, K.D., and Sweet, D.E.

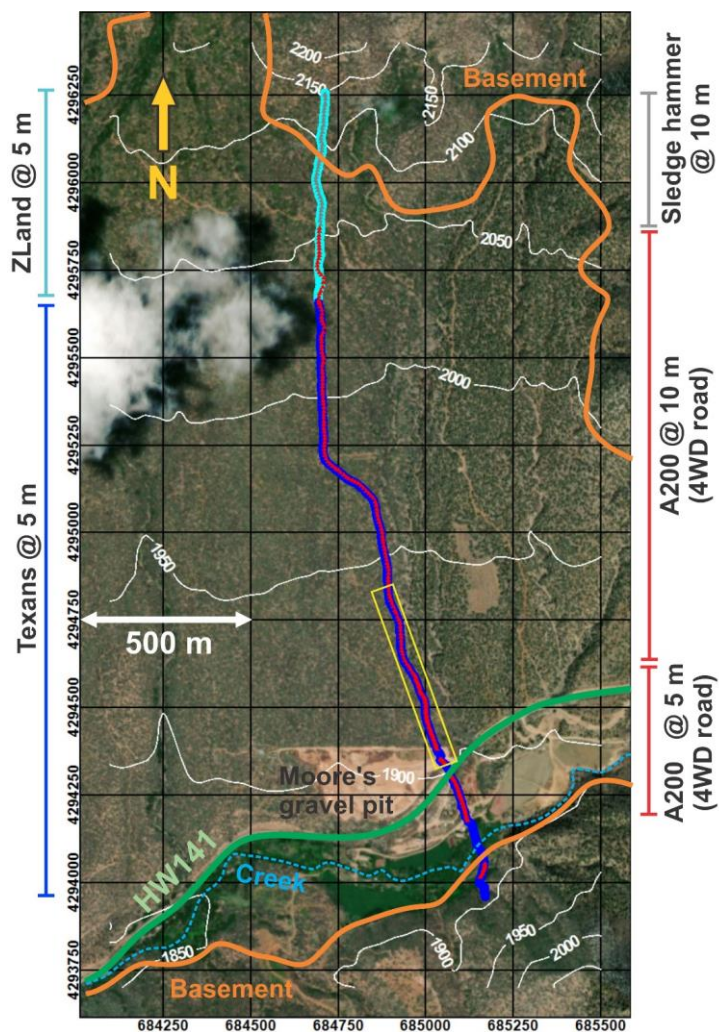


Figure 2: Geometry of the 2017 seismic acquisition. Thick blue line: Texan 1C receivers; Thick cyan line: Fairfield 3C nodes; Red triangles: Shot locations of the A200 P&S source; Grey triangles: Shot locations of the sledge hammer; Green line: Road 141. White lines: Elevation contours in meters ASL. Blue dashed line: West Unaweep creek. The yellow rectangle outlines the representative area for Fig. 10.

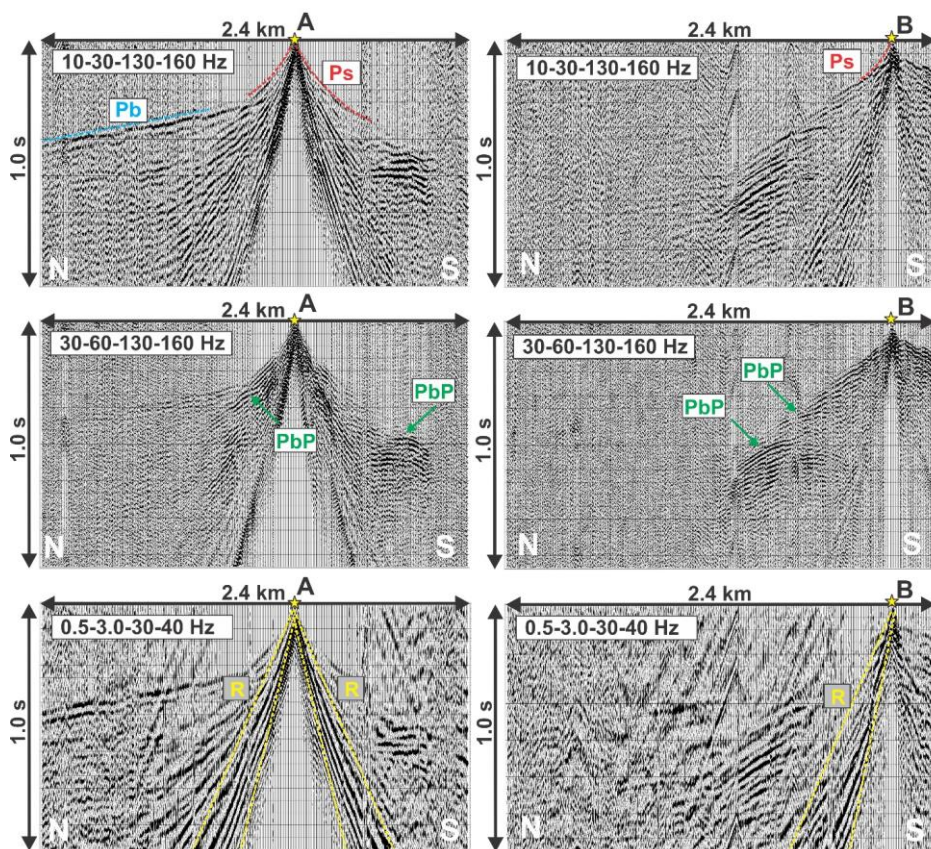


Figure 3: Seismic data examples: Shot gathers A, B (location see Fig. 4) filtered in different frequency bands. Pb: refractions from the basement; Ps: refractions from the overburden (sediments); PbP: basement reflections; R: Rayleigh waves from the active source, but not also traffic-induced ground roll.

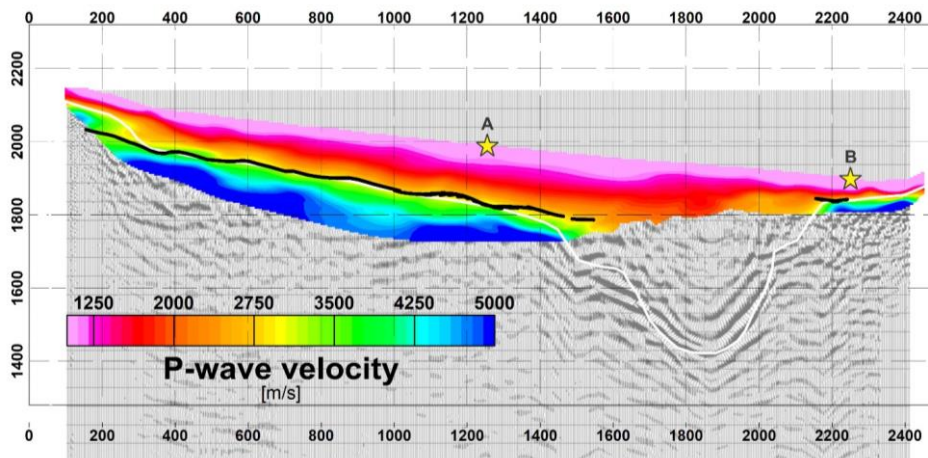


Figure 4: P-wave velocity model obtained from travel time tomography. Backdrop is depth-converted prestack-migration (Patterson et al. 2018b). Black line: depth-converted delay time refractor. White line: Interpreted top of the consolidated Precambrian basement based on refraction and reflection data. A, B; location of shot gathers shown in Fig. 3.

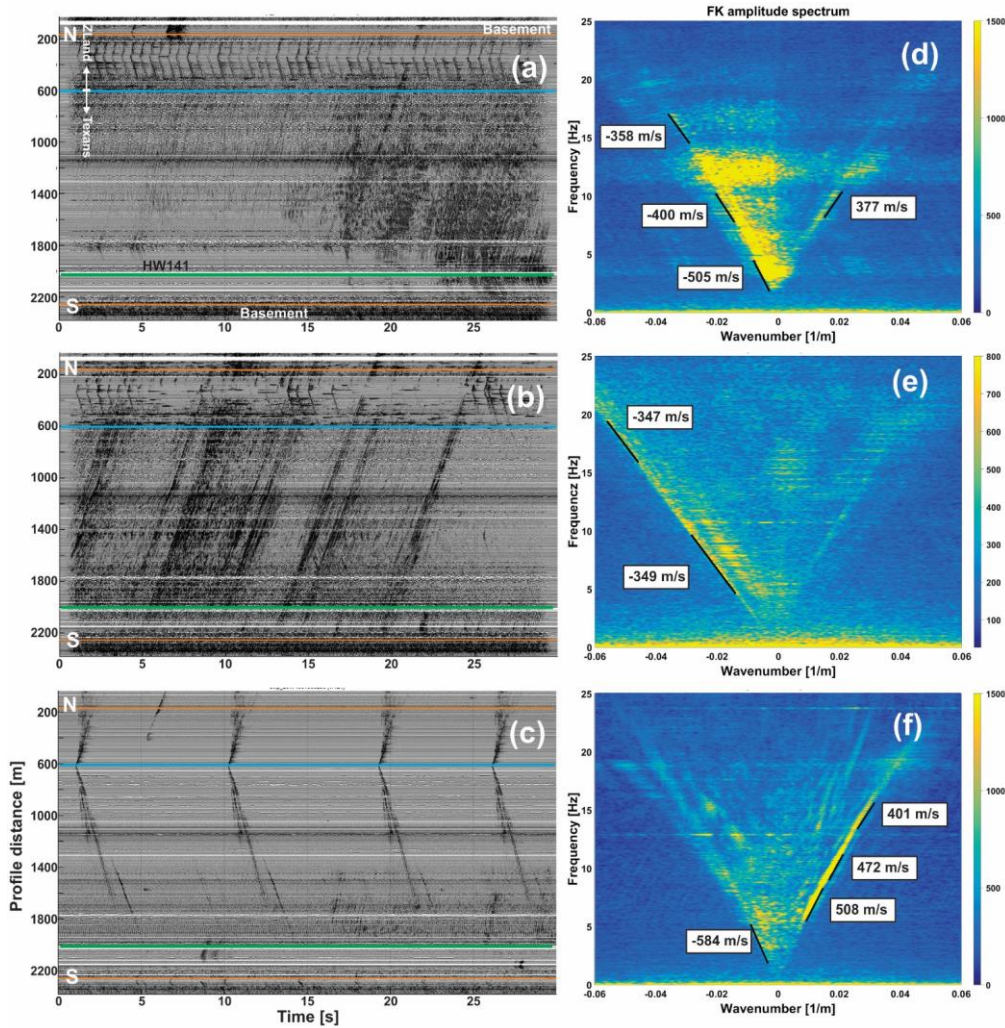


Figure 5: Three 30-seconds long slices of continuous data (a-c) and their representation in the FK-domain (d-f). Traces are arranged horizontally from north (top) to south (bottom). Vertical axis: Profile distance. Blue line discriminates ZLand 3C nodes (north) from Texan 1C geophones (south). Green line: Road 141. Measured slopes in the FK gathers represent group velocities. (a,d): Traffic and walking noise ~~from road 141~~. (b,e): Passing thunderstorm ~~and scattered surface waves~~. (c,f): Succession of several blasts from the A200 source.

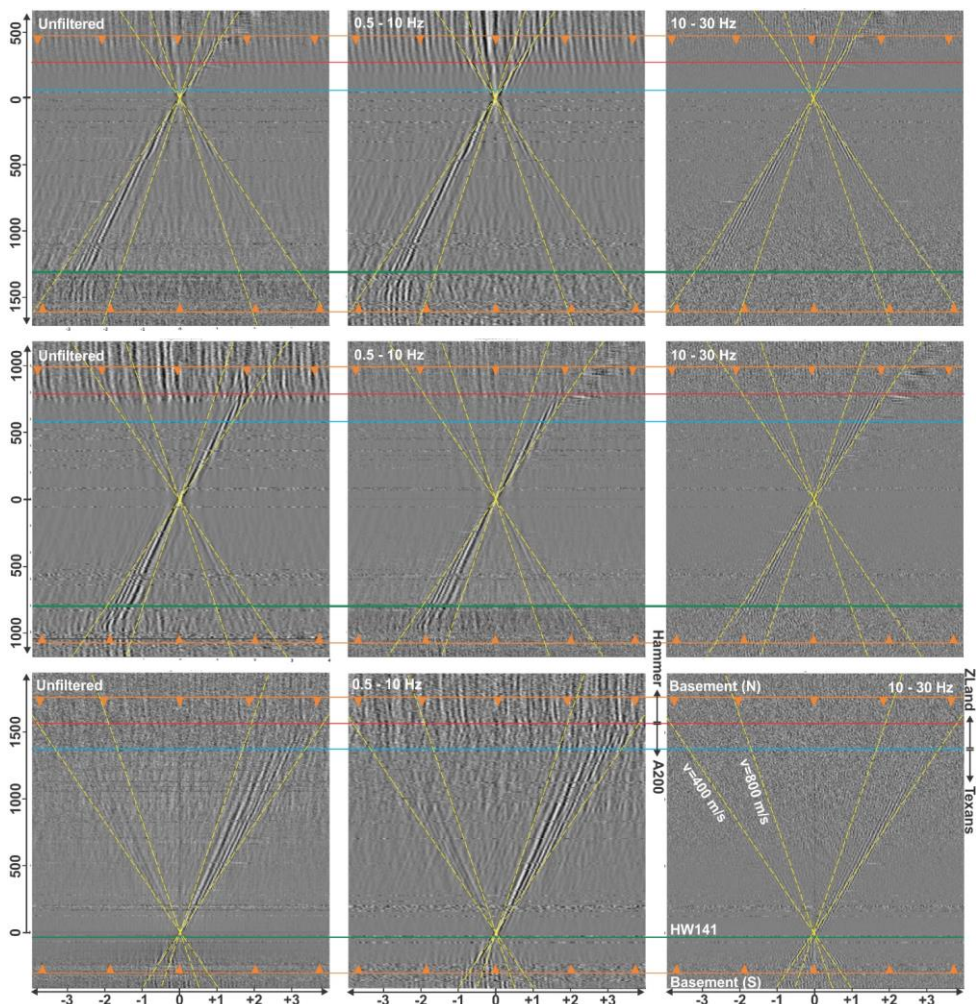


Figure 6: Three virtual source gathers in three different frequency bands. Traces are arranged horizontally from north (top) to south (bottom). Vertical axis: Virtual source – receiver offset. Blue line discriminates ZLand 3C nodes (north) from Texan 1C geophones (south). Red line discriminates area with hammer shots (north) from area with A200 blasts (south). Green line: Road 141. Yellow lines: Moveouts for velocities of 400 m/s and 800 m/s, respectively.

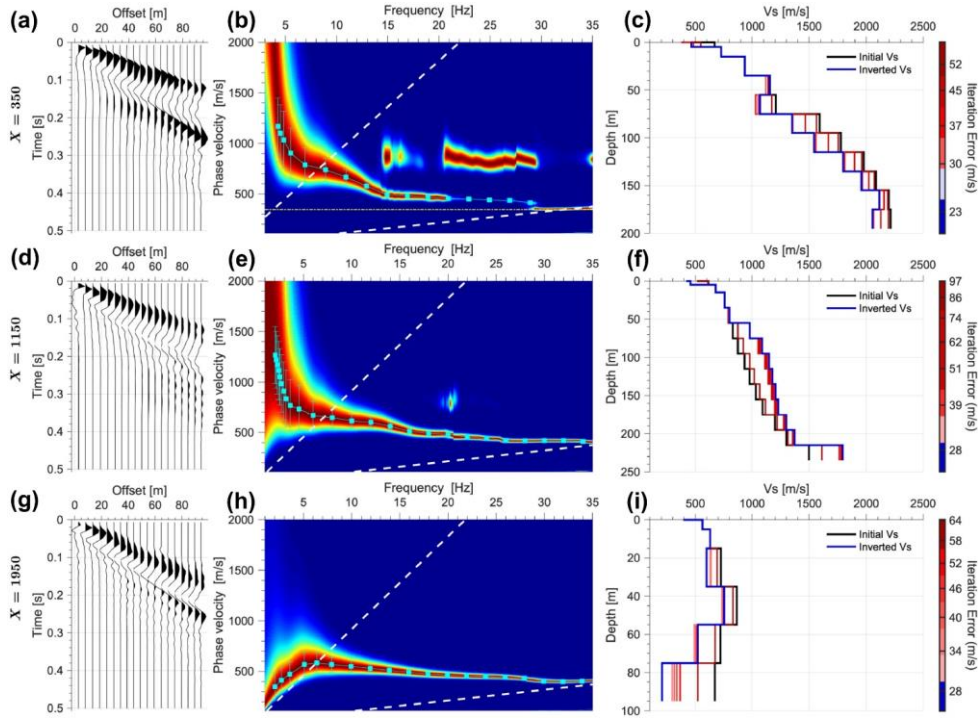


Figure 7: Three examples of dispersion curves obtained from source / receiver sorting and offset stacking. Each dispersion curve is representative of a 100 m long section along the profile (see Fig.8 for location). Left panel (a,d,g): Stacked virtual source gather; Middle panel (b,e,h): dispersion curves and picks. (c,f,i): Inverted $V_s(z)$ for all iteration steps. Blue curve (lowest data misfit) represents the accepted final model.

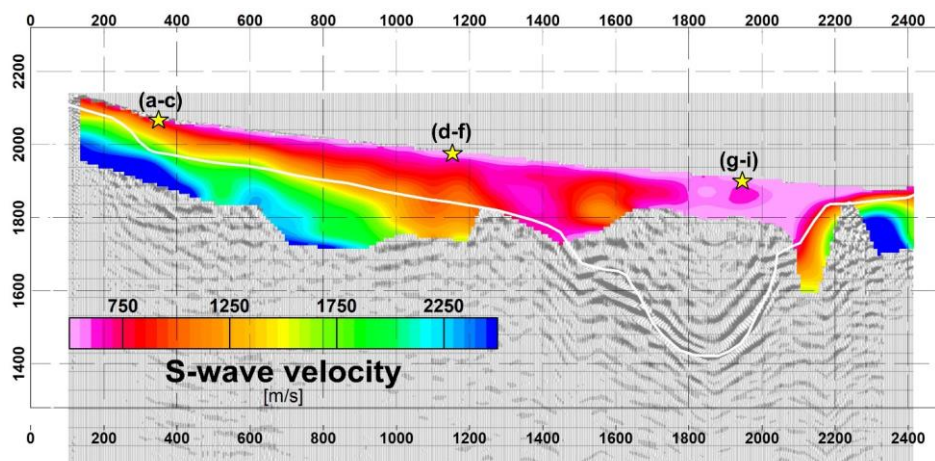


Figure 8: S-wave velocity model obtained from interpolation of local 1D shear wave velocity profiles. Stars: Location of the corresponding 1D-inversions shown in Fig. 7. White line: Interpreted top of the consolidated Precambrian basement based on P-wave refraction and reflection data.

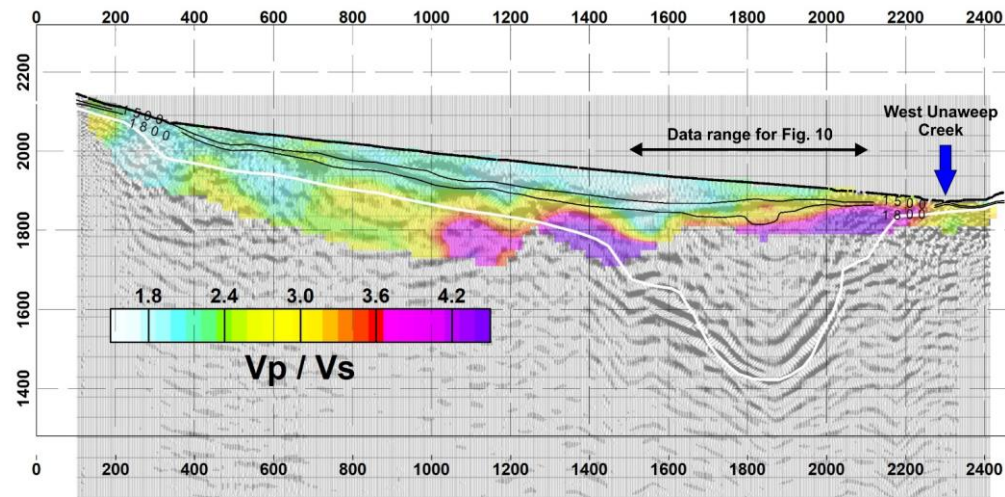


Figure 9: V_p/V_s ratio. White line: Interpreted top of the consolidated Precambrian basement based on P-wave refraction and reflection data. Thin black lines: Contour lines of the P-wave velocity model (Fig. 4) for 1500 m/s and 1800 m/s.

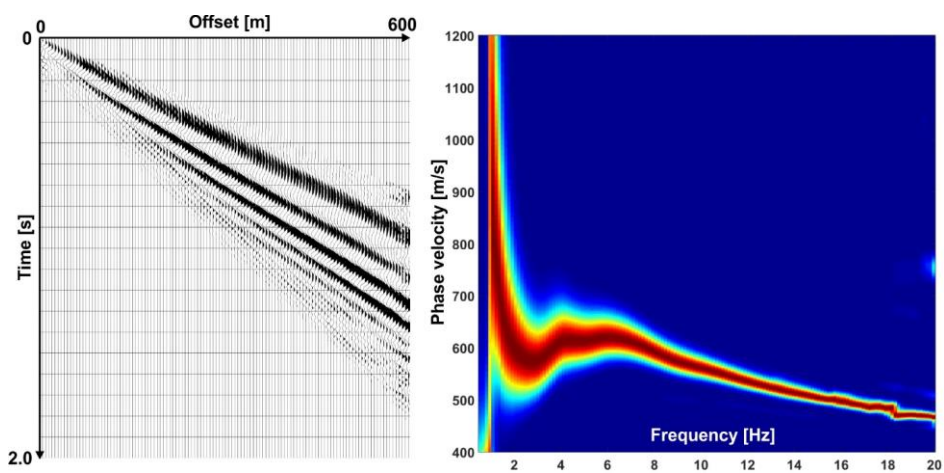


Figure 10: Dispersion curve obtained from source / receiver sorting and offset stacking of all virtual source gathers within the over-deepened section (profile distance 1500 – 2100 m).

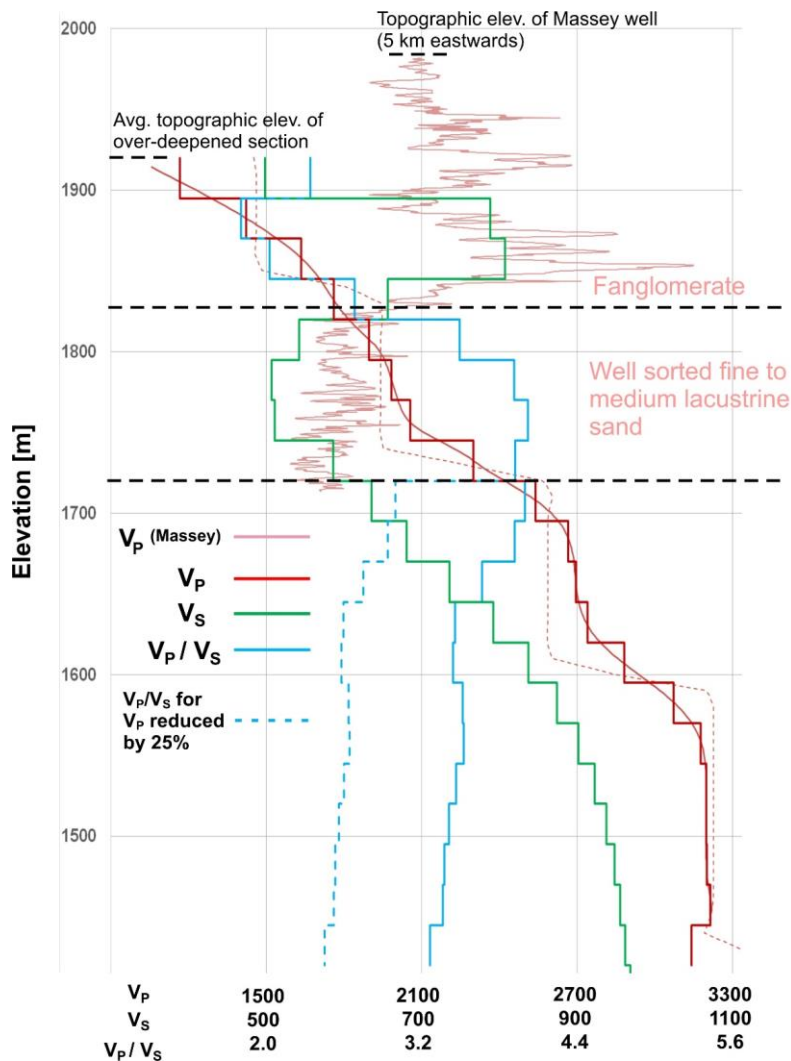


Figure 11: Compilation of several 1D velocity models representative of the over-deepened section. Dashed red line: Interval P-wave velocity model from reflection processing (Patterson et al., 2018b). Smooth solid red line: P-wave velocity model from combination of interval and tomographic velocities. Solid red stair case line: Averaged P-wave velocities used for V_P/V_S calculation. Green stair case line: Shear wave velocities from dispersion inversion. Blue stair case lines: V_P/V_S ratio. Lithologic interpretation and sonic log (bright red line) are from the Massey well located at 5 km distance to the seismic section.

