ABSTRACT

Beavers, once abundant and widespread in the Northern Hemisphere, are now substantially reduced. Although beaver dams trap sediment, the relative importance of this sediment in Quaternary valley aggradation remains uncertain. We use ground penetrating radar (GPR) and near-surface seismic refraction to quantify the magnitude of beaver-induced Holocene sedimentation in Beaver Meadows, Rocky Mountain National Park, Colorado (United States). GPR was used to identify radar packages of genetically related strata of glacial and non-glacial origins. We demonstrate that GPR is a useful tool for identifying buried beaver-induced sedimentation with little to no surficial expression. Seismic refraction was used to determine the total volume of sediment above bedrock. Beaver-induced sedimentation constitutes 30%–50% of surficial post-glacial sediments, and post-glacial sediments constitute ~13% of the total valley fill. Beaver damming in montane valleys was thus an important process trapping sediments within the Holocene at this site. If geoscientists ignore the contribution of beaver-ponded sediments to Quaternary stratigraphy in a wide variety of riverine environments, they neglect a potentially important biotic driver of valley sedimentation.

INTRODUCTION

The geomorphic and ecological effects of contemporary beaver dams include altered flow regime, increased storage of sediment and nutrients, increased habitat diversity and stability, and increased species diversity (Naiman et al., 1986, 1988; Wright et al., 2002; John and Klein, 2004; Varekamp, 2006; Burchsted et al., 2010; Westbrook et al., 2011). Questions remain, however, about the cumulative and persistent effects on valley aggradation of much more abundant historical beaver populations. Ives (1942) and Ruedemann and Schoonmaker (1938) proposed that post-glacial sedimentation behind beaver dams in headwater valleys was responsible for significant aggradation that could form broad, flat valley floors. Persico and Meyer (2009) demonstrated that pond sediments were locally a large proportion of Holocene fluvial deposits in Yellowstone National Park (Wyoming, United States), but net Holocene beaver-induced aggradation was limited. Although the ecological significance of beavers is well established, geoscientists have largely ignored beaver-induced sedimentation during the Holocene, partly because of the difficulty of identifying and accessing buried beaver deposits that lack any surficial expression. This is the first study to our knowledge to quantify volumes of beaver-induced sedimentation and evaluate the proportion of such sediments within Holocene sequences.

We use ground penetrating radar (GPR) and near-surface seismic refraction to quantify the magnitude of beaver-induced Holocene sedimentation in Beaver Meadows, a montane valley in the southern Rocky Mountains (Colorado). Our two primary objectives were to assess the usefulness of shallow geophysical techniques to differentiate stratigraphy associated with beaver damming and to estimate the proportion of total valley fill formed by beaver-related sedimentation. GPR was used to identify radar packages of genetically related strata corresponding to glacial, non-glacial, and beaver-induced sedimentation. Seismic refraction was used to determine the total volume of sediment above bedrock. Although GPR has been used effectively to image subsurface stratigraphy of fluvial, fluvioglacial and glacial deposits (Neal, 2004), to our knowledge this is the first study to use GPR to provide quantitative constraints on beaver-induced sedimentation. The GPR type facies developed here for interpretation of glacial till, alluvium, and beaver pond sediments will inform interpretation of GPR data in similar wet meadows elsewhere.

STUDY SITE

Beaver Meadows is an east-west-trending montane valley at ~2530 m above sea level within Rocky Mountain National Park, Colorado (Fig. 1). The site is marginal to a lateral moraine and is bordered by granite, gneiss, and schist bedrock to the north and Pleistocene till to the south. The main meadow has a stream gradient of ~2% and a catchment size of 14 km². The north arm of Beaver Meadows (NBM), which trends northeast-southeast, has a valley bottom gradient of ~6% and a catchment size of 3.3 km². In 1947, six beaver lodges were noted on Beaver Creek, and the area was recognized as providing considerable habitat for future colonization as beaver populations rose (Packard, 1947). Today, there is no evidence of contemporary beaver activity and the meadow cannot support beaver colonies, mostly because of a loss of food source from oversurfing by elk, and a depressed water table (Mitchell et al., 1999). The only surficial evidence of beaver damming in the meadow are a few small berms (buried dams) and irregular patches of wetland vegetation and saturated soils (remnant beaver ponds). Beaver Meadows is an ideal site for GPR surveying because (1) the fine sediments do not contain sufficient amounts of clay minerals to cause rapid attenuation in the radar signal, (2) the lack of thick woody vegetation facilitates deployment of the GPR equipment, and (3) the presence of cutbanks within the meadow and upcrops adjacent to the meadow allows us to differentiate between radar signals characteristic of post-glacial alluvium, bedrock, and glacial deposits.

DATA COLLECTION AND PROCESSING

Approximately 6 km of common offset GPR data and six common midpoint (CMP) surveys were collected using a Sensors and Software Pulse Ekkko 100 system with 100 MHz antennae and a trace interval of 0.25 m (Fig. 1). 200 MHz and 50 MHz antennae were tested and did not greatly improve the resolution or depth penetration. Seismic refraction data were collected along four of the cross-valley GPR lines using a sledge
hammers and a 24-channel Geometrics Geode seismograph with 14 Hz vertical geophones spaced 2 m apart. Surficial field observations, descriptions of cutbank exposures, and hand auger cores were collected to augment the geophysical interpretation, as fully described by Kramer (2011).

The GPR data provide an average maximum imaging depth of ~7 m and an average vertical resolution of 0.32 m. Distinct radar packages were identified on the basis of similarity of overall reflector character within a package and large-scale (tens of meters wide) package geometry. Radar facies within packages were identified based on reflector continuity, amplitude, period, dip, and onlap, downlap, and toplap patterns. These facies were then interpreted in terms of depositional processes in order to identify bedrock and glacial, fluvial, and beaver-dominated sedimentation.

P-wave velocity profiles were generated from the seismic refraction data via tomographic inversion of first arrivals as described by Kramer (2011) (Fig. DR1 in the GSA Data Repository1). The sediment-bedrock interface was identified by its high vertical velocity gradient, corroborated by correlation to outcrop adjacent to the valley, drill holes (Welder, 1971), and a previous seismic study (Locke, 1987).

RESULTS

Identifying Beaver-Induced Sedimentation

Table 1 presents the type radar stratigraphy and interpretation of the radar packages (P1, P2, P2a) and facies (F0–F4). Figure 2 shows a GPR line with packages P1 and P2 identified. Subpackage P2a is shown in Figure 3. Radar facies identification is based solely on descriptive character and thus radar facies are non-unique; different depositional processes can generate radar signals of similar appearance. For example, facies F0, characterized by a lack of reflections, may be representative of either bedrock or poorly sorted glacial deposits (Table 1). Consequently, interpretation of depositional environments is made not only on the basis of the facies present at a given locality, but also within the context of its placement within the radar packages P1 (glacial deposits) and P2 (post-glacial alluvium), the character of their bounding surfaces, and surface field observations and auger descriptions (Fig. 1; Fig. DR2).

Subpackage P2a, containing a radar facies consisting of chaotic discontinuous reflectors (F1, interpreted to be the buried dam) that truncates a facies consisting of parallel continuous reflectors upslope (F3, interpreted to be pond deposits), is interpreted to represent strata associated with beaver dams. This was confirmed by co-locating two GPR profiles with a topographic berm identified in the field as a buried beaver dam (Fig. 3). P2a packages can appear in a chain distributed longitudinally along the valley and stacked with vertical en-echelon offset to one another. This is consistent with the observation that beavers typically build a chain of dams, and with the temporal and spatial variability of damming (Gurnell, 1998).

Beaver dams identified in the GPR data match well with dams and ponded areas visible on aerial photographs from A.D. 1938 to 2001, with the exception of a few areas of high dam density (Kramer, 2011). In these areas, the chaotic GPR reflectors associated with individual dams (facies F1) merge over a large area, making it difficult to identify individual dams.

The GPR lines were spaced ~200 m apart (Fig. 1) and may not cross all buried beaver dams within the valley. Consequently, we interpret F3 as beaver pond deposits whether or not they are part of a P2a package that contains both facies F1 and F3. This interpretation of F3 is consistent with the stratigraphy of alluvium from augers and cutbank exposures (Fig. DR2). The thick, laterally continuous horizontal reflectors are also similar to those observed in low-energy lacustrine deposits elsewhere. At Beaver Meadows, the two plausible explanations for ponding are beaver damming or glacial damming. Moraine damming can be disregarded because the ponded deposits are post-glacial in age (Polvi-Pilgrim and Wohl, 2012).

<table>
<thead>
<tr>
<th>Facies</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>F0</td>
<td>Glacial deposits when above bedrock contact and bedrock when below bedrock contact</td>
</tr>
<tr>
<td>F1</td>
<td>Poorly sorted glacial deposits, channel gravels and cobbles, buried beaver dam, fractured bedrock</td>
</tr>
<tr>
<td>F2</td>
<td>Re-worked glacial or stratified drift, re-worked alluvium including floodplain deposits.</td>
</tr>
<tr>
<td>F3</td>
<td>Soil, stacked sequences of flat-lying ponded silts, clays, and fluvial sands associated with beaver damming</td>
</tr>
<tr>
<td>F4</td>
<td>Channel fill, colluvium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Packages</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>P1</td>
<td>Wedge which includes F0, F1 and F2. This package thins to the north and is absent in NBM. It is concordant with bedrock.</td>
</tr>
<tr>
<td>P2</td>
<td>Filled drape which includes F1, F2, F3 and F4. This package concordantly drapes over the underlying topography.</td>
</tr>
<tr>
<td>P2a</td>
<td>Wedge within P2. Parallel continuous reflectors (F3) are abruptly truncated by and thin away from chaotic discontinuous reflectors (F1) downslope.</td>
</tr>
</tbody>
</table>

Note: Interpretations of radar descriptions are italicized.

1GSA Data Repository item 2012022, Figures DR1–DR4, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Table 2 summarizes the metrics computed from the geophysical profiles for main Beaver Meadows and NBM. We use valley fill to refer to all sediments, glacial and non-glacial, whereas alluvium refers to non-glacial sediments stratigraphically above glacial deposits.

Sediment volumes were estimated from isopach maps generated by interpretively contouring depths from ground surface down to the bedrock-valley fill contact (Fig. DR1) and the glacial-alluvium contact. Mean sediment thicknesses were calculated by taking the estimated volumes and dividing by the total surface area. The maximum thickness of alluvium is ~6 m and the maximum thickness associated with beaver-induced sedimentation is generally <3 m.

We estimated a ratio of the cross-sectional area of beaver-induced sedimentation to the area of alluvium for each GPR profile located within the valley margins. The ratio of areas along profiles does not necessarily represent the average ratio across the entire meadow. To estimate the volume of beaver-induced sedimentation within the alluvium throughout the meadow, we raised the ratios of areas calculated along each profile to the exponent 1.5 ($V = L^{1.5}$), so $V = A^{1.5}$). This scaling relation is rigorously correct only if beaver-induced sedimentation is uniformly distributed laterally away from the plane of the GPR profile. Although we recognize that this is probably not the case, this provides a first-order approximation of the percentage of beaver-induced sedimentation within the alluvium. This approach indicates that 30%–50% of the alluvium is beaver-related sedimentation, which is consistent with cores throughout Beaver Meadows (Polvi-Pilgrim and Wohl, 2012).

**DISCUSSION AND CONCLUSIONS**

Beavers maintain a beaver meadow (Westbrook et al., 2011) by creating spatially heterogeneous patches of sediment that overlap with other patches in time and space. Ruedemann and Schoonmaker (1938)
intuitively hypothesized that successive layering of these patches of sediment post glaciation significantly contributed to river valley development.

Persico and Meyer (2009) have shown that there are episodes of beaver-related aggradation marked by periods of no aggradation, aggradation unrelated to beavers, or incision relating to fluctuations in climate and predator-prey relationships which inhibit successive layering of sediment. In the absence of beaver, sites of aggradation may become sites of incision and sediment removal.

Our results suggest that low-gradient montane valleys, like Beaver Meadows, with limited sediment supply and hillslopes decoupled from valley bottoms (Caine, 1986), are not sites of continuous sediment deposition through the Holocene, but that a thickness of alluvium approximately equal to the height of one beaver dam is maintained by beavers across the valley bottom through time. The efficiency of beavers at trapping sediment, the abundance of historic beaver populations, and the punctuated absence of beavers at any given site may greatly impact Holocene rates of sedimentation, and thus should not be ignored when studying valley-bottom sedimentation.

Disagreement and substantial uncertainty regarding the magnitude of beaver-induced sedimentation and its cumulative importance to Holocene valley aggradation result in part from the fact that geologists have not examined this issue using tools now commonly applied to other aspects of Quaternary stratigraphy, including GPR. We have demonstrated that GPR and seismic refraction provide quantitative constraints on the relative volume and distribution of beaver-induced sedimentation in Holocene valley fill. GPR can also be used to locate buried beaver dams, greatly facilitating quantification of the cumulative effects of beaver dams on sediment storage over time scales of hundreds to thousands of years.

Most of the valley fill in the main Beaver Meadows is glacial in origin, with a thin (<0.5 m) alluvial drape. In NBM, which is outside the maximum glacial extent, the alluvial drape continues with similar thickness as in the main valley, and lies directly on top of bedrock. These results suggest minimal aggradation at this site (~1.5 m in ~15 k.y.), despite being a wide, low-gradient valley segment that should facilitate sediment accumulation. Although there has not been much post-glacial aggradation, beavers did play a significant role in the aggradation that has occurred, with beaver-induced sedimentation constituting >30% of the alluvium. However, the geomorphic importance of beaver-induced sedimentation is site-specific and dependent on glacial history.

Although beaver-related sedimentation expands the main valley margin in places (Fig. DR3), the broad valley floor (width ~200 m) was set by glacial deposits and it is unlikely that subsequent Holocene alluviation greatly altered its form. Unlike the main meadows, NBM was never glaciated. The valley bottom is 75% narrower than Beaver Meadows but contains the same thickness of alluvium. The alluvium is not just a drape over bedrock, but a wedge tapering toward the valley sides, which in-filled and broadened the valley bottom, giving it a U-shaped profile in a valley that would otherwise be V-shaped. We conclude that a thin cover of alluvium was great enough to alter the valley form in NBM (catchment size ~1 km²), but was insufficient in the main meadows (catchment size ~14 km²).

The mean thickness and the number of dams per cross-sectional area in NBM are comparable to the main meadows (Table 2), even though the basin area is 76% smaller and the stream gradient is 150% greater. Similar thicknesses of sediment accumulation in drainage basins of such different sizes and stream gradients suggest that aggradation did not result solely from fluvial processes, but was mediated by beaver dams. Furthermore, the mean thickness of alluvium, ~1.3 m, is approximately the same height as a beaver dam. This result is consistent with work done by Persico and Meyer (2009) in Yellowstone, and thus the thickness of Holocene beaver-related aggradation may be similar across diverse regions.

In summary, our use of GPR to develop a first-order approximation of beaver-induced sedimentation indicates that shallow geophysical methods can be quite effective in differentiating this type of sedimentation, and that these sediments can be a major component of Holocene valley-bottom alluvium in sites otherwise likely to have low sedimentation rates. By largely ignoring the contribution of beaver-ponded sediments to Quaternary stratigraphy in a wide variety of riverine environments, geologists have neglected an important biotic driver of valley sedimentation.

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