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Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming

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ABSTRACT

We use beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park. Although beaver damming has been considered a viable mechanism for major aggradation of mountain stream valleys, this has not been previously tested with stratigraphic and geochronologic data. Thirty-nine radiocarbon ages on beaver-pond deposits fall primarily within the last 4000 yr, but gaps in dated beaver occupation from ~2200–1800 and 950–750 cal yr BP correspond with severe droughts that likely caused low to ephemeral discharges in smaller streams, as in modern severe drought. Maximum channel gradient for reaches with Holocene beaver-pond deposits decreases with increasing basin area, implying that stream power limits beaver damming and pond sediment preservation. In northern Yellowstone, the patchy distribution and cumulative thickness of mostly <2 m of beaver-pond deposits indicate that net aggradation forced by beaver damming is small, but beaver-enhanced aggradation in some glacial scour depressions is greater. Although 20th-century beaver loss and dam abandonment caused significant local channel incision, most downcutting along alluvial reaches of the study streams is unrelated to beaver dam abandonment or predates historic beaver extirpation.

Introduction

The potential of beaver (*Castor canadensis*) damming to have a significant geomorphic impact on postglacial fluvial landscapes has long been suggested, including major aggradation of mountain valleys to form extensive "beaver meadows" (Ives, 1942; Ruedemann and Schoonmaker, 1938) that trap sediment and store groundwater. Sediment deposition measured in modern beaver ponds shows that aggradation of up to ~1 m is common within several years after damming (e.g. Butler and Malanson, 1995; McCullough et al., 2005; Pollock et al., 2007). Thus, reintroduction of beaver can accelerate filling of incised channels, at least to the height of a single dam (mostly <2 m; Warren, 1926), and expand the associated riparian area. However, aggradation of tens of meters or more would be required to create many of the broad, flat Colorado Front Range valley floors attributed to beaver damming by Ives (1942). Whether damming can cause vertical stacking of successive beaver-pond deposits to this extent over Holocene timescales has never been tested. Clearly, the rise in base level from beaver-related aggradation has some maximum in any fluvial environment, but that limit is presently unknown.

Beaver occupation of dam sites can extend for more than 46 yr (Johnston and Naiman, 1990), but is also commonly discontinuous. The temporal and spatial variability of beaver-pond sedimentation over centuries to millennia is unknown. Over such timescales, climatic change may limit beaver occupation by reducing streamflows or food resources. We address these questions using a well-dated Holocene geomorphic and stratigraphic record of beaver damming along small streams in the Northern Range of Yellowstone National Park (YNP), Wyoming (Fig. 1). Abandoned beaver dams and ponds mapped in the 1920s (Warren, 1926) provide models for northern YNP beaver-related deposits and landforms that are fundamental in interpreting the Holocene record.

Beaver dam abandonment often results in channel incision through accumulated pond sediments and upstream alluvium (e.g. Wohl, 2006). Previous investigators have inferred that 20th century extirpation of beaver from northern YNP initiated widespread channel incision, adversely impacting streams and riparian areas (Chadde and Kay, 1991; Wolf et al., 2007), but these conclusions are based on a few study reaches and limited data on the magnitude and timing of incision. To understand the significance of beavers in fluvial system change in Yellowstone's Northern Range, we document the nature and timing of beaver-pond sediment deposition, fluvial aggradation, and channel incision within Holocene time, focusing on the last 4000 yr. We also consider this activity over historic time, here defined as the period since park establishment in 1872.

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Beaver dams, landscapes, and climate

Habitat preferences control where beaver dams are built, and should thus influence the long-term geomorphic impact of beavers. In northern Yellowstone, favored food resources are aspen (*Populus tremuloides*), willow (*Salix* spp.), and alder (*Alnus* spp.) (Smith, 1998; Warren, 1926). Environmental controls and competition by other herbivores may limit food supplies (e.g. Baker et al., 2005), but beaver can also exhaust their own food resources. For example, beaver removed almost all aspen stands from reaches of the Truckee River, California (Beier and Barrett, 1987), and Warren (1926) and Jonas (1955) noted that beaver depleted aspen along Northern Range streams.

Geomorphic factors also strongly influence beaver dam distribution along mountain streams. In the Oregon Coast Range, the highest dam frequency occurs with channel gradients of 0.01–0.03, channel widths of 3–4 m, and valley-floor widths of 25–35 m (Suzuki and McComb, 1998). In general, beaver abundance declines as streams become wider and steeper (Beier and Barrett, 1987; Howard and Larson, 1985; Pollock et al., 2004; Retzer et al., 1956; Suzuki and McComb, 1998), suggesting that high total stream power limits their ability to maintain dams (McComb, 1990). On larger streams, beaver do not construct dams, but inhabit bank burrows (Smith, 1998). Beaver dams often fail episodically during floods and release stored pond sediments (Butler and Malanson, 2005). On small streams in the semiarid western USA, minimum discharges may be limiting to beaver populations. Wolff et al. (1989) documented a large increase in beaver ponds after human alterations produced perennial flow in a formerly ephemeral Wyoming stream. These studies indicate that discharge and stream power (the product of specific weight of water, discharge, and slope) are important in beaver habitat selection, dam location, and sediment storage in beaver ponds.

The small streams of Yellowstone's semiarid-subhumid Northern Range comprise diverse fluvial environments, from small, low-gradient channels in broad alluvial valleys to steep, higher-discharge bedrock-confined streams. This provides ample opportunity to

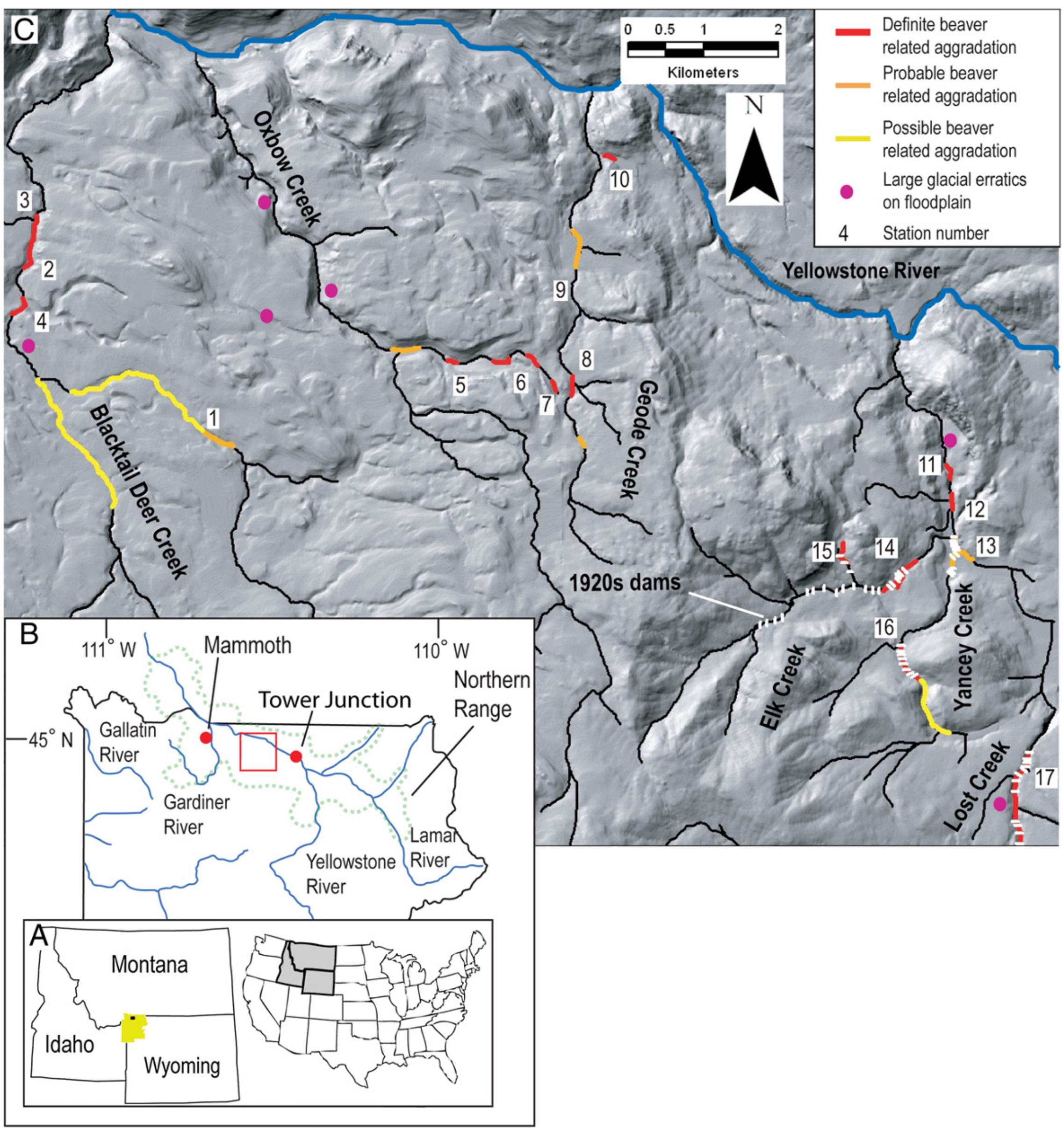

Figure 1. (A) Location map for Yellowstone National Park (YNP, yellow polygon). (B) Map showing Yellowstone's Northern Range (dotted green line). Study area shown in C is highlighted by the red box. C. Shaded DEM map of the study area showing reaches with beaver-related aggradation. White lines across streams mark dams mapped in the early 1920s by Warren (1926). Numbered station locations are shown for stratigraphic sections (Table 1) and radiocarbon samples (Table 2).

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investigate geomorphic controls on beaver dam location and pond sediment storage. In addition, Holocene climatic change may have significantly altered stream discharge, vegetation, and other habitat characteristics. We hypothesize that beaver damming in northern YNP was influenced by changes in climate and discharge regime, including minimum and peak flows.

Study area

The Northern Range is synonymous with the winter range of elk (*Cervus elaphus*) (Houston, 1982) in the relatively dry lower elevations of northern YNP (National Research Council, 2002). We studied several 1st to 4th order stream systems that drain the Washburn

Table 1
Beaver pond sediment unit characteristics

Strat section/station number	^{14}C sample code	Age (cal yr BP)[a]	Texture[b]	Organics[c]	Color[d]	Stratigraphy	Surface expression	Thickness (cm)	Total thickness of section (cm)	% of total[e]
Yancey Creek 1[f] 16	LP108YANCY3	405	SiC	LWCD	Gley 3/N	BT[g], cm sand lenses	Ramp	>95	150	63
Yancey Creek 2 16	LP102YANCY2	306	SiC	LWCD	Gley 4/5BG	BT	Berm	45	220	21
Yancey Creek 3 16	LP100Yag1	291	SCL	SWCD	2.5YR 4/3	BT	Berm	110	140	79
Oxbow Creek 1 6	LP464OXBOW21	505	SiCL	LWCD	10YR 2/1	BT	Berm	60	130	46
Oxbow Creek 2 5	LP095OXBOW5	332	NR[h]	LWCD	NR	BT	Berm	>60	60	100
Oxbow Creek 3 6	LP068Ox4	423	LS	LWCD	Gley 1 2.5/5GY	Laminations	Berm	25	150	17
	LP070OXBOW P4	1360	SiCL	LWCD	5YR 4/4	BT		80		53
Lost Creek1 17	LP438LOST T23	1205	SiCL	SCD	10YR3/2	Laminations	Broad	50	150	33
	LP439LOST T23	1259	SiCL	SCD	10YR2/1	Sand lenses	Berm	20		13
Lost Creek 2 17	LP435LOST T22	274	SL	SWCD	10YR 2/2	Laminations	Berm	85	130	65
Lost Creek 3 17	LP428LOST T21	125	CL	SWCD	10YR 3/2	BT	Ramp	40	100	40
Geode Creek 1 10	LP024GLD	214	L	LWD	10YR 2/1	BT	BCS; berm	~50 cm	50	100
Geode Creek 2 7	LP302GeAg2	Post-bomb	LS	LWCD	10YR 3/2	BT	Berm	70	250	28
	LP303GeAg2	Post-bomb	SiCL	SWCD	mottled	BT	Berm	10	250	4
Geode Creek 3 7	LP309GeAg3	149	SL	LWCD	2.5YR 2.5/1	BT	Berm	30	250	4
	LP310GeAg3	439	SiL	SWCD	2.5YR 2/1	BT	Berm	40	250	16
Lost Creek 1 12	LP421ELYP14	3051	CL	SWCD	10YR 2/1	BT	BCS, berm	55	110	50
	LP425ELYP14	3461	CL	LWCD	10YR 2/1	BT		20		18
Lost Creek 2 11	LP417ELYP13	3923	CL	SWCD	10YR 2/1	Laminations	NO[i]	35	115	30
	LP415ELYP13	10882	SiCL	LWD	10YR 2/2	Laminations		20		17
Lost Creek 3 13	LP405ELYP11	6062	SiL	SWCD	10YR 2/1	Laminations	Berm	32	110	29
Lost Creek 4 11	LP350ELYP1	3687	L	LWCD	2.5Y 3/2	BT	Berm	62	140	29
Elk Creek 1 14	LP458ELKT5	170	L	LWCD	10YR2/1	BT	Ramp	100	240	42
Elk Creek 2 14	LP123EKP5	154	L	LWCD	10YR3/2	Laminations	Berm	25	100	25
Elk Creek 3 14	LP123ELKP4	1052	NR	LWCD	10YR	BT	Berm	>90	>90	100
Elk Creek 4 14	LP090ELKT2	140	SL	LWCD	10YR 2/1	BT	Ramp	15		06
	LP091ELKT2	1127	SiCL	SWCD	10YR 2/1	Laminations		90	250	36
	LP093ELKT2	3737	L	SWCD	Gley 4/10 BG	Laminations		>45		18
Elk Creek 5 15	LP031ELKP3	3353	SiCL	LWCD	Gley 5/5 GY	Laminations	Berm	25	60	42
Blacktail Creek 1 1	LP219BTT3	7088	SiCL	LWCD	Gley 3/5 BG	Laminations	NO	40	240	17
Blacktail Creek 2 4	LP455BTT6	2561	SiCL	LWCD	10YR 2/1	BT	Berm	>115	115	100
Blacktail Creek 3 4	LP403BTT4	433	SiL	LWD	Gley 2.5Y/10GY	BT	Berm	80	80	100
Blacktail Creek 4 2	LP453BTT5	1014	SiL	LWD	Gley 3/5B	BT	BCS	100	100	100
Blacktail Creek 5 2	LP208BT2	632	SiCL	LWD	2.5/N	BT	Berm	58	80	73
Blacktail Creek 6 2	LP206BTT1	1595	SiL	LWD	10YR 2/1	BT	Berm	72	130	55

Note. Stratigraphic sections not containing beaver-pond deposits are not included here, but are found in Persico (2006).
[a] Radiocarbon dates in beaver pond sediment shown as weighted mean calibrated age, and include ages included in Fig. 4; other multiple ages for the same unit are in Table 2.
[b] Texture of sand fraction where LS = loamy sand, SL = sandy loam, L = loam, SiL = silty loam, SiCL = silt clay loam: and CL = clay loam.
[c] Organics where LWCD = large wood and charcoal debris, SWCD = small wood and charcoal debris, SCD = small charcoal debris, LWD = large wood debris.
[d] Munsell color values of the sediment.
[e] Percent of total observed stratigraphic section thickness that is definite beaver pond sediment.
[f] Bold indicates sites where dams were mapped in the 1920's.
[g] BT = bioturbated.
[h] NR = not recorded.
[i] No surface expression of beaver damming.

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Range and Blacktail Deer Plateau and flow into the Yellowstone River (Fig. 1). Basin areas range up to 90 km^2. Alluvial valleys are less than 125 m wide except in Yanceys Hole (Station 13, Fig. 1). Elevations lie 1700–2700 m above sea level, and mean annual precipitation is 374 mm at Mammoth (1900 m elevation) and 421 mm at Tower Junction (1910 m elevation), where maximum precipitation occurs in May through July. Annual hydrographs are dominated by snowmelt runoff during these same months. The study streams are mostly perennial, with channel widths typically ~2–5 m, but some small streams formerly occupied by beaver (Warren, 1926) have become ephemeral in recent droughts. Stream valleys lie in a glacially modified landscape (Pierce, 1979) and are cut predominantly in glaciofluvial deposits and till (Pierce, 1973, 1974). High-gradient, bedrock-confined channels occur within more resistant volcanic rocks (Christiansen and Wahl, 1999), including where lower reaches descend into the Yellowstone River canyon. Channel sinuosity is generally low, but are as high as 1.3–1.5 along some broader alluvial valleys of Blacktail Deer Creek. Willow, grasses, herbaceous dicots and sedge (Cyperaceae spp.) are common on modern floodplains, with some alder (Wolf et al., 2007). Fluvial terrace surfaces and hillslopes are dominated by big sagebrush (*Artemisia tridentata*) and grasses. Scattered conifer groves include lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea engelmannii*). A few mature aspen exist on hillslopes, but only small aspen shoots are locally present on valley floors. Aspen make up only 2–3% of the Northern Range forest cover (Houston, 1982).

Dated subfossil remains give direct evidence of beaver in YNP since at least the middle Holocene (Hadly, 1995). Cursory accounts suggest

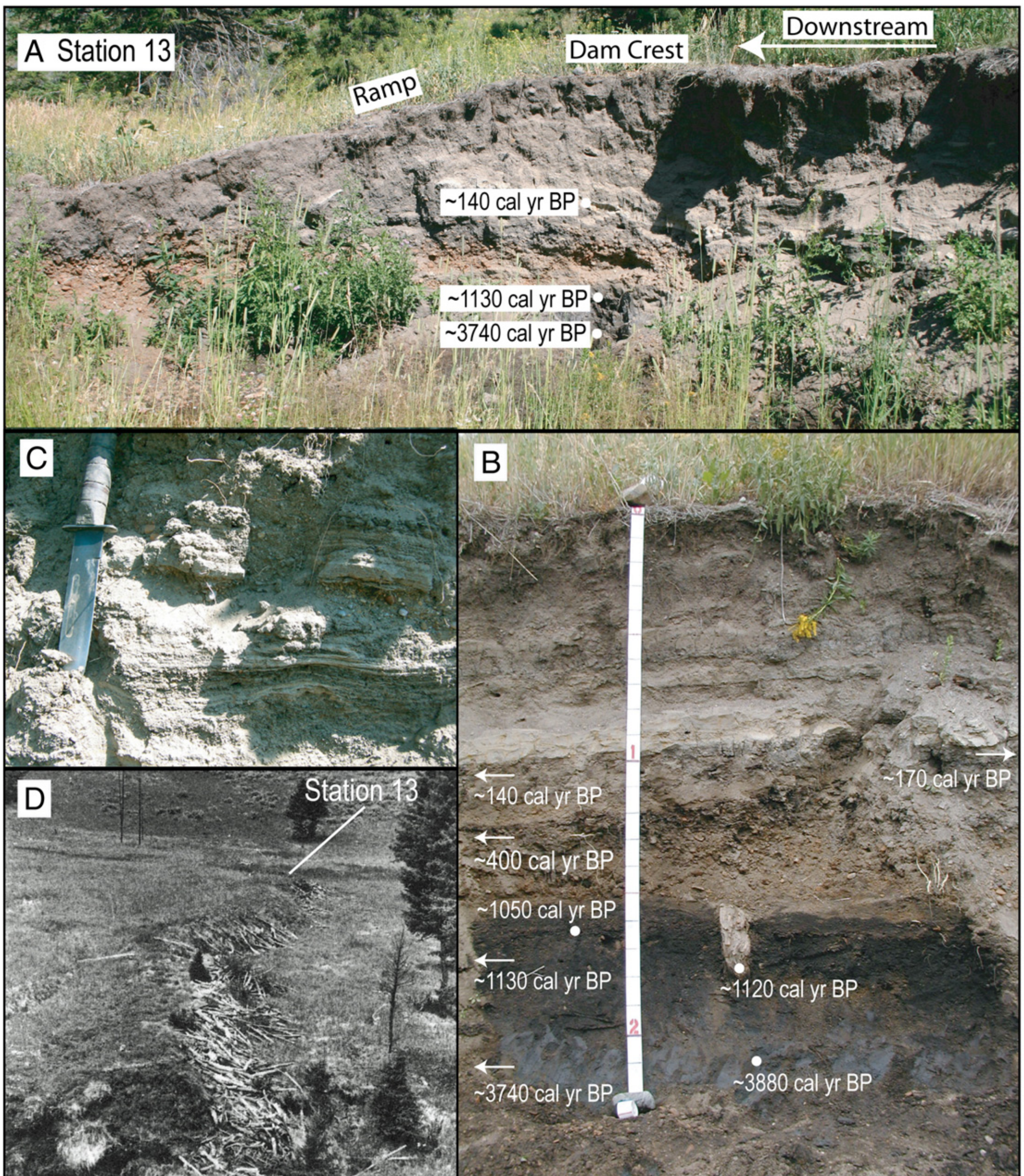

Figure 2. (A) Incised-channel exposure on middle Elk Creek (Station 13, section Elk Creek 4) showing ^{14}C-dated beaver-pond deposits separated by oxidized gravel, and ramp-like morphology of the historically abandoned dam and infilled pond above; compare to 1954 photograph of same dam in D. Calibrated radiocarbon ages are shown as the weighted mean of the calibrated probability distribution (Telford et al., 2004) and are approximate; see Table 2 for calibrated 1 σ ranges for these ages. (B) Elk Creek 4 section, ~2 m upstream (to right) of view in A. Tape shows depth in meters. Gravel at ~1.1–1.5 m depth is the same unit as above ~1130 cal yr BP age in A. Note similar stratigraphic position and age of ~1120 cal yr BP age, which is from a beaver-gnawed Douglas-fir (*Pseudotsuga*) stump in growth position. (C) Laminations in beaver-pond sediment at ~0.7 m depth in A, containing organic-rich layers, pebbles, coarse to fine sand, and silt. (D) Photograph taken in 1954 by Jonas (1955) of the same abandoned dam at Elk Creek; downstream is to right.

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Table 2
Radiocarbon samples, ^{14}C and calibrated ages and interpretation

Sample name	Stat[a]	Lab number[b]	Location		Material	Meth[c]	Age ^{14}C yr BP	±1 σ[d]	Calibrated ages and 1 σ ranges (cal yr BP)[e]	Weighted mean[f]	Interp[g]
			lat	long							
LP219BTT3	1	B196726	44.9444	110.5570	Diffuse porous hardwood	B	6190	60	7003–7167	7090	BP
LP223BTT3	1	AA64144	44.9445	110.5570	Softwood charcoal	A	4436	71	4884–4931, 4958–5068, 5109–5123, 5168–5173, 5181–5275	5080	FGO
48YE1564-05-1	1	B208727	44.9445	110.5570	Charcoal	B	1550	40	1394–1423, 1430–1444, 1457–1516	1450	H
LP442BTT3	1	AA67470	44.9445	110.5570	Hardwood charcoal	A	3107	54	3262–3383	3320	FGO
LP444BTT3	1	AA67471	44.9445	110.5570	Pine charcoal	A	3140	39	3335–3404, 3430–3439	3360	FGO[h]
LP208BT2	2	B196725	44.9666	110.5901	Diffuse porous hardwood	B	690	50	564–589, 641–681	630	BP
LP206BTT1	2	AA64143	44.9662	110.5902	Diffuse porous hardwood	A	1683	40	1537–1619, 1674–1687	1600	BP
LP453BTT5	2	AA67473	44.9677	110.5901	Diffuse porous hardwood	A	1109	35	971–1015, 1024–1055	1010	BP
LP403BTT4	3	AA67454	44.9719	110.5883	Diffuse porous hardwood	A	404	48	333–353, 435–511	430	BP
LP455BTT6	4	AA67474	44.9688	110.5893	Diffuse porous hardwood	A	2477	38	2472–2476, 2486–2549, 2557–2618, 2633–2704	2560	BP
LP095OXBOW5	5	B196721	44.9542	110.5110	Diffuse porous hardwood	B	270	40	155–166, 284–321, 378–427	330	BP
LP049Ox3	6	AA64126	44.9543	110.5102	Softwood charcoal	A	879	39	734–798, 815–823, 869–899	810	BP[i]
LP068Ox4	6	AA64129	44.9542	110.5109	Charred diffuse porous hardwood	A	384	38	332–355, 434–502	420	BP
LP464OXBOW21	6	B209095	44.9543	110.5102	Wood	B	470	50	489–541	510	BP
LP070OXBOW P4	6	AA67447	44.9542	110.5109	Diffuse porous hardwood	A	1474	36	1319–1322, 1327–1389	1360	BP
LP313OxAg11	7	AA64149	44.9507	110.5009	Charcoal	A	3793	44	4092–4128, 4141–4240	4180	PBP
LP302GeAg2	8	AA64130	44.9514	110.4982	Engelmann spruce cone	A	Post-bomb				BP
LP303GeAg2	8	AA64131	44.9514	110.4982	Seeds	A	Post-bomb				BP
LP309GeAg3	8	AA64132	44.9514	110.4982	Diffuse porous hardwood	A	157	38	−2–0, 2–32, 75–76, 83–97, 108–111, 137–153, 168–223, 255–282	150	BP
LP310GeAg3	8	AA64133	44.9514	110.4982	Diffuse porous hardwood	A	401	38	334–349, 439–445, 452–508	440	BP
LP213G-DT1	9	AA64140	44.9280	110.4427	Softwood charcoal	A	6870	120	7609–7829	7730	FGO
LP217GDT2	9	AA64141	44.9280	110.4427	Charcoal	A	8190	120	9007–9305, 9363–9372, 9386–9395	9150	FGO
LP214GDT1	9	AA67451	44.9280	110.4427	Pine charcoal	A	869	42	730–798, 817–822, 870–898	790	CGCF
LP218GDT2-C	9	AA67453	44.9280	110.4427	Softwood charcoal	A	5470	240	5946–5968, 5987–6493	6250	FGO
LP024GLD	10	AA67445	44.9785	110.4927	Diffuse porous wood	A	229	36	−1–9, 151–173, 179–182, 274–307	210	BP
LP350ELYP1	11	AA64150	44.9409	110.4348	Willow wood	A	3425	42	3617–3722, 3798–3815	3690	BP
LP405ELYP11	11	AA67455	44.9409	110.4348	Pine charcoal	A	5271	72	5943–5971, 5985–6032, 6037–6120, 6147–6178	6060	BP
LP415ELYP13	11	AA67458	44.9406	110.4350	Diffuse porous hardwood	A	9532	76	10707–10872, 10947–11074	10880	BP
LP417ELYP13	11	AA67459	44.9406	110.4350	Diffuse porous hardwood	A	3611	39	3873–3973	3920	BP
LP419ELYP13	11	AA67460	44.9406	110.4350	Wood	A	9688	67	10875–10944, 11076–11205	10750	BP[h]
LP425ELYP14	12	B209093	44.9356	110.4353	Wood	B	3230	60	3381–3485, 3528–3554	3460	BP
LP421ELYP14	12	AA67461	44.9356	110.4353	Pine charcoal	A	2905	38	2966–3079, 3094–3105, 3129–3137	3050	BP
LP336LsT12	13	AA64145	44.9329	110.4534	Diffuse porous hardwood char	A	1892	40	1742–1754, 1784–1792, 1811–1890	1830	FGO
LP332LsT12	13	AA64146	44.9329	110.4534	Pine charcoal	A	3380	43	3572–3646, 3656–3687	3620	PBP
LP321LsT11	13	AA64148	44.9326	110.4346	Softwood charcoal	A	3273	43	3451–3513, 3517–3557	3500	PBP
LP091ELKT2	14	AA67449	44.9280	110.4427	Softwood	A	1201	35	1076–1172	1130	BP
LP093ELKT2	14	AA67450	44.9280	110.4427	Douglas-fir charcoal	A	3464	48	3645–3657, 3687–3734, 3741–3777, 3788–3827	3740	BP
LP458ELKT5	14	AA67475	44.9277	110.4435	Outer ring of Douglas-fir	A	196	42	−1–15, 146–214, 268–293	170	BP
LP462ELKT5	14	AA67477	44.9277	110.4435	Soft wood	A	319	34	309–332, 355–434	390	CGCF
LP464ELKT4	14	AA67478	44.9305	110.4403	Charcoal	A	9809	79	11166–11314	11230	FGO
O1GM-EC4	14	AA45082	44.9280	110.4427	Charcoal fragment	A	3560	170	3638–4087	3880	BP[h]
O1GM-EC6	14	AA45083	44.9280	110.4427	Conifer cone scales	A	1136	49	968–1084, 1112–1122, 1164–1165	1050	BP[h]
O1GM-EC11	14	AA45084	44.9280	110.4427	Charred twig	A	339	41	317–343, 346–397, 423–462	400	CGCF
LP090ELK2	14	B196720	44.9280	110.4427	Diffuse porous hardwood	B	110	70	−3–1, 21–144, 216–266	140	BP
LP301ELKST	14	B196728	44.9280	110.4427	Douglas-fir	B	1190	50	1015–1023, 1055–1178	1120	BP[h]
01GM-EC1	14	B196729	44.9280	110.4427	Pine wood	B	180	70	−2–33, 74–78, 81–98, 106–113, 136–224, 254–297	170	CGCF
LP129EKP5	14	AA64136	44.9295	110.4424	Pine wood	A	898	39	744–752, 762–802, 810–829, 859–904	820	CGCF
LP123EKP5	14	AA64137	44.9295	110.4424	Charred pine	A	168	41	−2–31, 85–86, 94–95, 138–156, 165–223, 256–285	150	BP
LP204EKT4	14	AA64139	44.9305	110.4403	Charred diffuse porous hardwood	A	8876	91	9799–9801, 9819–9845, 9868–9873, 9887–10175	9960	FGO
LP300ELK4	15	B196727	44.9295	110.4414	Douglas-fir	B	1130	60	962–1088, 1109–1125, 1163–1166	1050	BP
LP210crAG12	15	AA64147	44.9329	110.4534	True fir wood	A	777	38	680–725	710	FGF
LP031ELKP3	15	AA67446	44.9303	110.4538	Fir wood	A	3132	38	3273–3282, 3331–3398	3350	BP
LP102YANCY2	16	B196722	44.9178	110.4436	Pine wood	B	260	40	0–2, 153–168, 282–319, 382–386, 392–426	310	BP
LP108YANCY3	16	B196723	44.9160	110.4411	Charred Douglas-fir wood	B	360	50	320–378, 389–391, 427–488	410	BP[h]
LP110YANCY3	16	B196724	44.9160	110.4411	Douglas-fir wood	B	190	50	−2–24, 141–220, 262–297	170	BP
LP098YP1	16	AA64134	44.9190	110.4442	Lodgepole pine charcoal	A	5673	73	6325–6326, 6351–6367, 6396–6556	6470	BP[h]
LP100Yag1	16	AA64135	44.9190	110.4442	Charred fir wood	A	255	38	0–2, 153–169, 282–317, 395–423	290	BP
LP433LOST T22	17	B209094	44.9065	110.4226	Conifer wood	B	250	60	−1–12, 149–187, 209–210, 270–330, 359 –369, 372–429	270	BP[h]
LP077LOST T3	17	AA67448	44.9009	110.4240	Pine charcoal	A	679	35	567–584, 647–672	630	PBP
LP428LOST T21	17	AA67462	44.9016	110.4243	Charred pine	A	85	36	−4–2, 32–74, 78–82, 98–107, 113–137	130	BP
LP435LOST T22	17	AA67464	44.9065	110.4226	Wood	A	373	34	331–357, 431–498	270	BP
LP438LOST T23	17	AA67465	44.9065	110.4226	Conifer charcoal	A	1266	36	1177–1262	1210	BP
LP439LOST T23	17	AA67467	44.9025	110.4242	Pine charcoal	A	1342	42	1186–1202, 1257–1304	1260	BP
LP440LOST T24	17	AA67468	44.9024	110.4243	Charcoal/charred conifer wood	A	600	1100	−6–1419, 1464–1511	700	FGO[j]
LP441LOST T24	17	AA67469	44.9024	110.4243	Douglas-fir charcoal	A	5601	56	6312–6413, 6428–6434	6380	FGO

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that beavers were abundant before park establishment in 1872 (Yellowstone National Park, 1997). Beaver were so numerous in the 1920s that the National Park Service, worried that beaver would destroy aspen stands, commissioned a study in the Northern Range (Warren, 1926). Warren mapped beaver dams on Elk Creek, Lost Creek, and other small streams near Tower Junction. Jonas (1955) found that by the early 1950s, all dams mapped by Warren had been abandoned, and only a few beaver colonies existed in the park. Warren's (1926) data provide a rare opportunity to locate historic beaver dams, assess their geomorphic setting and impact, and characterize associated pond deposits. We investigated the Warren study streams, plus others in the western Northern Range (Fig. 1).

Methods

Previous studies indicate that beaver-pond sediments have distinctive sedimentologic features, including beaver-gnawed wood fragments, that allow their recognition in fluvial stratigraphy (e.g. Baker et al., 1996; Dalquest et al., 1990; McCulloch and Hopkins, 1966). We considered both geomorphic and sedimentologic evidence to identify beaver-pond deposits. Now-abandoned beaver dams mapped by Warren (1926) provide unambiguous examples of relict dams and pond deposits for defining diagnostic characteristics (Table 1). The predominant morphologic expression of dams is a berm typically 5–50 m long across the floodplain, approximately perpendicular to the valley axis (Fig. 2). Berms range in height from ~0.3–1.5 m on the downstream side. At three locations, fine-grained sediment has almost completely filled in the pond so that only the downstream face of the dam is exposed, creating a ramp-like feature up to 2 m in height (Table 1, Fig. 2). Most surface wood of the Warren (1926) dams has decayed away, but beaver-gnawed stumps were used to locate some recent dam sites.

Diagnostic characteristics for deposits of beaver ponds mapped by Warren (1926) were determined by detailed field analysis of texture, sedimentary structures, Munsell color, and organic content, emphasizing features that distinguish beaver-pond deposits from other fluvial sediments (Table 1). We focused on deposits just upstream of abandoned dams, as characteristic fine-grained, deeper-water pond sediments are most likely to be deposited and preserved there (Dalquest et al., 1990). Soil textural classification (Birkeland, 1999) was used, being more accurate than typical sedimentary nomenclature (e.g. Folk, 1954) for poorly sorted sediments. Pond sediments mostly range from clay loam to loam, with minor sandy units (Table 1, Fig. 2). Pebbles and cobbles are sometimes scattered within deposits. Organic content in pond deposits is typically high, and large wood pieces >10 cm diameter (some with beaver-gnawed ends) are locally preserved, especially near dams (Fig. 2B). Gleying indicates persistent reducing conditions from saturation and high organic content and is common in pond deposits (Table 1). Redoximorphic features produced by alternating waterlogged and oxic conditions are also common. Low-energy flows into ponded water produce fine laminations, sometimes mostly containing small organic fragments, e.g. twigs, bark, and charcoal (Fig. 2C). Laminations are often discontinuous or absent in beaver-pond sediments, however, probably due to bioturbation by beavers themselves (Bigler et al., 2001), wading ungulates, and rooting and burrowing after abandonment. Well-laminated sandy deposits with coarser organic fragments were locally observed (Fig. 2C). These probably represent floods that produced relatively high flow velocities in the pond, but did not breach the dam.

Beaver-pond deposits are roughly similar in texture to overbank deposits, so additional characteristics must be used to differentiate these sediments (cf. Wolf et al., 2007). We examined overbank deposits where no morphologic evidence of beaver damming is present. These are mostly faintly bedded and laminated to massive silty sand, with clay content typically less (<20%) than in beaver-pond deposits (up to 45%). Overbank deposits may contain fine charcoal, but except where A horizons overprint them, they are lighter-colored than beaver-pond deposits (1–3 Munsell value and chroma steps), and unburned wood is very rare or absent. Overbank deposits on the study streams are usually thin (<10 cm) layers over gravel, but range up to ~0.5 m in thickness. Ponding and thicker fine-grained sediment accumulation may occur in abandoned channels, but no clearly bounded channels with fine-grained fills were observed in fluvial stratigraphy, despite numerous exposures. Surface morphologic evidence of cutoff meanders is correspondingly rare. Abandoned channel-fill sediment may also be less organic-rich than in ponds where beaver introduce abundant organic debris.

We applied the above criteria to identify beaver-pond deposits along the study streams. Station locations (Fig. 1) include 1–4 stratigraphic sections. Most sections were natural exposures, but seven pits and three auger holes were excavated at ten additional sites. At each section, thickness, texture, sedimentary structures, Munsell color, and organic content of deposits were described in the field, and material was sampled for ^{14}C analysis. All stratigraphic sections containing beaver-pond deposits are separated by long distances, or by a ramp or berm, indicating that each likely records a separate relict beaver pond. Sediments with clear diagnostic characteristics and associated relict dams were classified as definite beaver-pond deposits. In two sections, thick, fine-grained deposits not associated with a relict dam were interpreted as definite pond deposits by abundant beaver-gnawed wood fragments and laminations with organic detritus (Table 1). We interpreted 35 definite beaver-pond deposits in 27 stratigraphic sections along Blacktail Deer, Oxbow, Geode, Elk, Yancey, and Lost Creek and some tributaries. Thick, fine-grained, organic-rich deposits that exhibited large unburned wood fragments or laminations, but no evidence of relict dams, were designated as probable beaver-pond deposits. Unusually thick (>0.5 m) and organic-rich fine-grained deposits containing little unburned wood or laminations, and not associated with relict dams, were designated possible beaver-pond deposits.

To minimize ^{14}C dating errors associated with inbuilt age (e.g., wood from the center of a 300-yr-old tree) and reworking of organic materials, we used AMS analyses to date small single fragments of degradable material when possible (e.g., outer rings of small branches,

[a] Station number identified in Figure 1.
[b] Sample number assigned at dating laboratory. AA = NSF-Arizona Accelerator Facility of Isotope Dating; B = Beta Analytic, Inc.
[c] Meth. = carbon isotopic analytical method, where A = accelerator mass spectrometry; B = beta decay counting.
[d] Age ± 1 σ = conventional radiocarbon age and analytical standard deviation (^{14}C yr BP).
[e] Calibrated radiocarbon ages, given in format: minimum and maximum 1 σ calibrated age ranges where endpoints of 1 σ calibrated age ranges are calculated from intercepts of (^{14}C age + 1 σ) and (^{14}C age − 1 σ) with calibration curve INTCAL04 (Stuiver and Reimer, 1993).
[f] Weighted mean of calibrated probability distribution, rounded to nearest 10 yr.
[g] Interpretation = Interpretation of stratigraphic significance: BP = beaver pond/dam sediment; PBP = probable beaver-pond sediment; FGO = fine-grained overbank sediment; FGF = fine-grained fill sediment; CGCF = coarse-grained channel fill sediment; H = hearth.
[h] Age not included in probability summation curves to avoid duplication of an event.
[i] Age not included in probability summation curves because they are stratigraphically inconsistent with other ^{14}C ages and most likely represent reworked material or large inbuilt age.
[j] Age not included in probability summation curves because 1 σ uncertainty is too large for meaningful analysis.

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or rarely cones or seeds). Less degradable single fragments of charcoal were used in 25% of the beaver-pond deposit dates (Table 2). Heavily bioturbated sediment near floodplain and terrace surfaces was avoided when sampling organic material. Representative stream reaches were surveyed using GPS and total-station techniques to estimate incision and aggradation. Channels were digitized and contributing basin areas calculated from USGS 10-m DEMs using ArcGIS 9.1. Topographic maps were used to determine channel gradient between each 40 ft (12.2 m) contour. We estimated the length of stream network affected by beaver-related aggradation using reaches with contributing areas greater than 0.5 km^2 (Fig. 1), excluding very small tributaries unlikely to support beaver.

Results

Thickness, distribution and geomorphic setting of beaver-pond deposits

Beaver pond deposits were identified on parts of all streams examined (Fig. 1, Table 1). Individual pond deposits, i.e., those with no break in vertical sequence, range from 0.2 to >1.2 m thick. Deposits exceed 1.0 m thick in only 3 of 35 deposits described (Table 1), in glacial scour depressions with very low channel gradient on Oxbow, Geode, and Elk Creeks (stations 7, 8, and 15). Based on field surveys, formal stratigraphic sections (Table 1 and Persico, 2006), and stratigraphic observations over all reaches, we estimated lengths of the study stream network containing evidence for aggradation associated with beaver damming (Fig. 1). Reaches with clear morphologic and stratigraphic evidence for beaver-related aggradation constitute about 19% of the total network length. Reaches with probable and possible beaver-related aggradation make up an additional 8% and 2% of the network, respectively. The remaining 71% of the network has no clear evidence for beaver-related aggradation.

Fluvial geomorphic characteristics were assessed at sites of historic beaver dams and preserved beaver-pond deposits. Reaches where dams were mapped by Warren (1926) have a maximum channel gradient of 0.100 and mean of 0.030 (Figs. 1 and 3). Reaches with preserved beaver-pond deposits have a maximum channel gradient of 0.054 and mean of 0.019. Maximum gradient in reaches with beaver-pond deposits decreases downstream with increasing contributing area, such that 60% of the study network lies above this apparent power-law threshold for pond-deposit preservation. In contrast, maximum mainsteam stream gradients are ~0.3–0.4, even at large contributing areas, and show no decreasing trend with increasing contributing area (Fig. 3). As discharge typically increases as a function of contributing area, these slope–area relationships indicate that stream power exerts a significant control on beaver damming (Pollock et al., 2004). Although some historic dam sites (Warren, 1926) with contributing areas <10 km^2 lie above this slope–area threshold (Fig. 3), no beaver-pond sediment was preserved at these sites, indicating low potential for beaver-related aggradation.

Dating of beaver-pond deposits

For simplicity, we report ^{14}C ages in this paper as a single value, the weighted mean of the calibrated probability distribution (e.g., "~1050 cal yr BP") (Table 2), as the best central point approximation of the true age (Telford et al., 2004). Uncertainties associated with these ages are shown by calibrated 1 sigma ranges in Table 2, which mostly span ~100–300 yr. Full calibrated probability distributions for 39 radiocarbon ages illustrate the chronology of beaver-pond deposition in Figure 4. Where multiple radiocarbon ages were obtained from a single beaver-pond deposit, we used the youngest age, assuming it has the smallest inbuilt or inherited age error. Nonetheless, most multiple ages were statistically indistinguishable after calibration, indicating that these ^{14}C ages are relatively accurate, and that sediment accumulates rapidly in individual ponds with a maximum a lifetime of a few hundred years (Table 1). Channel migration, floods, and decay of organic detritus likely removed

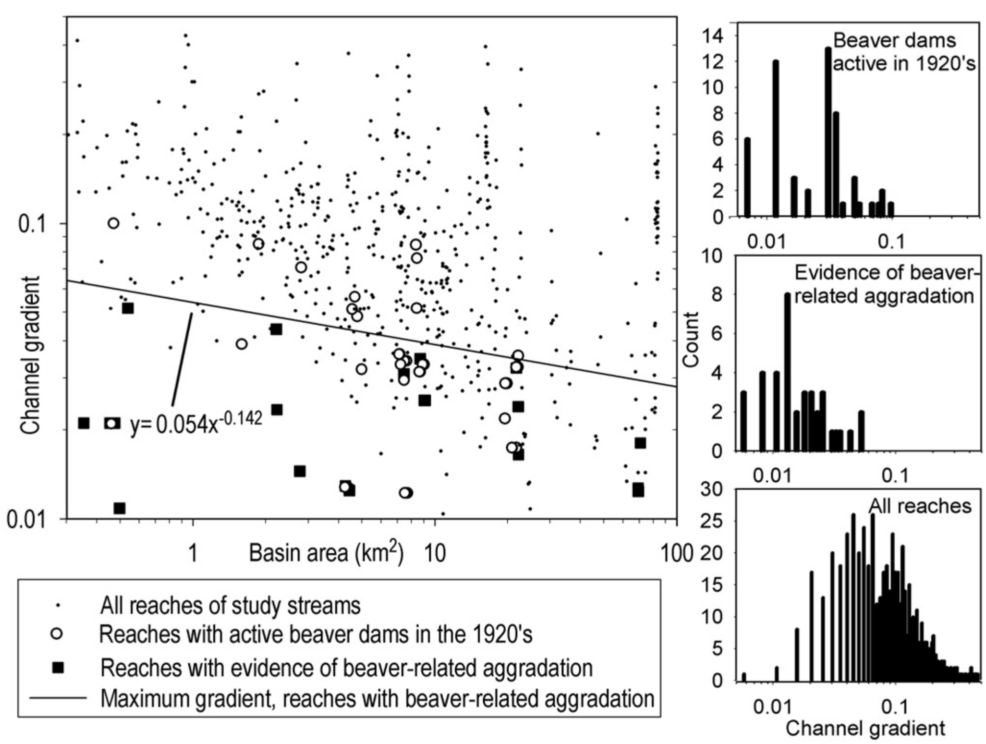

Figure 3. Plot of channel gradient as a function of contributing basin area for study stream reaches, with histograms of channel gradient at right. Data include all stream segments between 12.2-m (40-foot) topographic contour lines on the mainstems of Blacktail Deer, Oxbow, Geode, Elk, Yancey, and Lost Creeks, and all tributaries where active beaver dams were mapped in the 1920s by Warren (1926). Reaches with beaver-related aggradation were identified in our field surveys of abandoned beaver dams with preserved beaver-pond sediment. Solid line indicates the approximate maximum gradient for reaches with beaver-related aggradation.

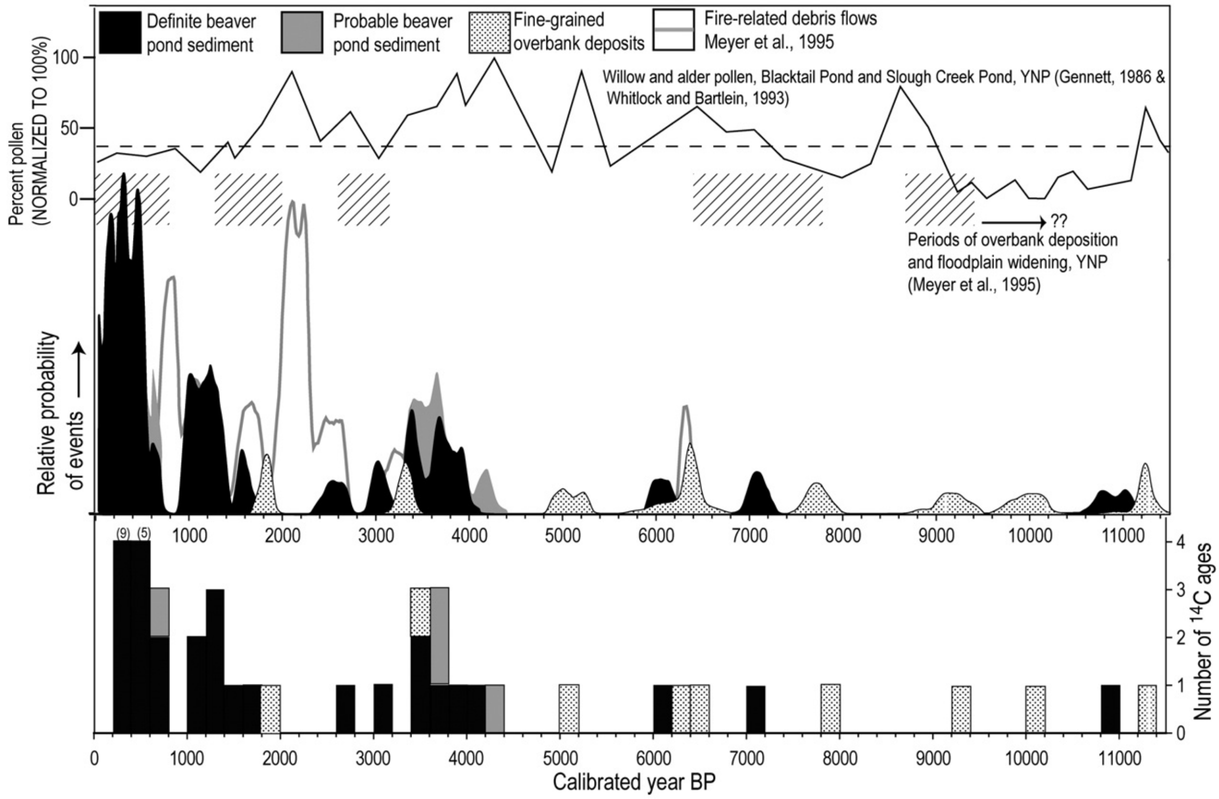

Figure 4. Chronology of beaver pond and overbank sediment in the YNP Northern Range area. Probability curves are derived by summing calibrated probability distributions for individual ^{14}C ages (e.g., Meyer et al., 1995), where each age distribution has unit probability, and then smoothing the summation using a 100-yr running mean. Histogram shows the number of ages in each data set contributing to probability curves, placing the weighted mean of calibrated age distributions in 200-yr age classes. In northeastern Yellowstone, fire-related debris flows are inferred to indicate severe fires from extreme droughts, and periods of overbank deposition and floodplain widening are interpreted to indicate higher mean streamflows (Meyer et al., 1995). Willow and alder pollen abundances in Blacktail Pond (Gennett, 1986) and Slough Creek Pond (Whitlock and Bartlein, 1993) cores represent <5% of the total pollen, therefore are rough indications of relative abundance. Individual pollen counts for willow and alder were normalized to the core maximum and summed. Linear interpolation was used to estimate pollen abundances in the Slough Creek Pond core for radiocarbon age increments in the Blacktail Pond core. Values for the two cores were averaged to produce a single curve.

evidence of some older beaver-pond deposits (Butler and Malanson, 2005; Meyer, 2001). A decrease in dated pond deposits with increasing age largely reflects decreasing preservation and exposure (e.g. Meyer et al., 1995; Schumm, 1991), but may not stem entirely from sampling bias. The late Holocene pond deposit chronology is thus more complete; 66% of the dated pond sequences were deposited since 1800 cal yr BP, and 92% since 4500 cal yr BP. Calibrated ^{14}C yr ages for late Holocene beaver-pond deposits tend to cluster three time periods: 0–700, 1000–1400, and 2500–4000 cal yr BP (Fig. 4).

Terrace deposits

Discontinuous fluvial terraces are present along middle reaches of Lost, Blacktail Deer, and Elk Creek. Deposits under terrace treads are typically sandy to silty overbank deposits overlying channel gravels. On middle Blacktail Deer Creek and its east fork, however, basal terrace deposits are commonly fine-grained. At Station 1, these sediments are rich in wood fragments and other organic material, and we interpret them as beaver-pond deposits (Fig. 5). In terrace deposits on middle Elk Creek, a late Pleistocene-early Holocene channel gravel and overbank deposit sequence is buried by 0.8 m of gravel and cobbles in an unusual example of substantial coarse-grained aggradation (Fig. 6). Eight dates from terrace overbank deposits across the study area span from 11,300–1800 cal yr BP, with no apparent grouping (Fig. 4).

A lower inset terrace with a tread that slopes gently toward the modern channel is present along reaches of Blacktail Deer Creek (stations 1 and 3) and Lost Creek (stations 11 and 17) (Fig. 1). The treads are underlain by bioturbated, fine-grained deposits a few decimeters thick. These features indicate gradual incision concurrent with channel migration. On the east fork of Blacktail Deer Creek, dated hearth charcoal in the inset terrace deposit shows that incision began before ~1450 cal yr BP (Fig. 5). Coarse cobble and gravel channel fills in paleochannels inset within older terrace alluvium on Geode Creek (Fig. 7B) and Elk Creek date within the past 1500 yr (Table 2). Overall, we observed up to ~3 m of channel incision below the highest local level of Holocene fill, but many alluvial reaches are unincised (Fig. 7A).

Discussion

Beaver-pond chronology and climate

We compared the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region, focusing on the more complete late Holocene record (Figs. 4 and 8). Gaps in the beaver-pond deposit record cannot be interpreted to indicate an absence of beaver from the stream network. However, beaver continuously bring in new wood for food, to repair existing dams, to raise dams (up to a few meters in height) as sediment infills ponds, or to construct new dams nearby. Therefore, deposition of new ^{14}C-datable materials is expectable when beaver are present, and the lack of dated pond deposits over multi-century intervals in the last 4000 yr suggests that beaver activity is significantly decreased at these times. Gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP (Fig. 8) are contemporaneous with increased charcoal accumulation rates in Yellowstone lakes (Millspaugh et al., 2000) and peaks in fire-related debris-flow

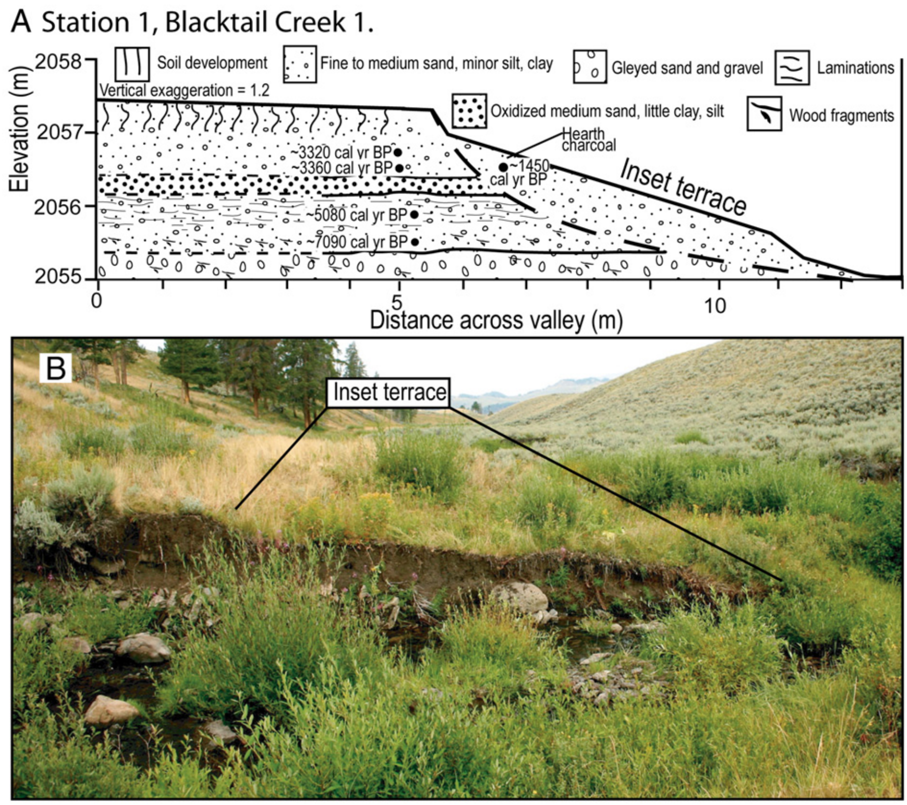

Figure 5. (A) Cross-section showing terrace morphology and stratigraphy at Station 1 (Fig. 1) on the east fork of Blacktail Deer Creek. Unit containing fine-medium sand, silt, and clay with abundant wood fragments at ~2055.5 m elevation is interpreted as an early Holocene beaver-pond deposit. Dated charcoal from the hearth shows that incision and formation of the sloping inset terrace (B) began prior to ~1450 cal yr BP.

activity, inferred to reflect severe drought and warmer temperatures (Meyer et al., 1995). The lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly (MCA), a time of widespread multi-decadal droughts and high climatic variability in YNP (Meyer et al., 1995) and the western USA (Cook et al., 2004a; Stine, 1998; Whitlock et al., 2003). These extended droughts likely caused major decreases in summer baseflow in Northern Range streams, which could reduce beaver populations (Curry-Lindahl, 1967; Wolff et al., 1989). In addition, unusually coarse, charcoal-bearing gravel dating to ~800 cal yr BP fills a narrow incised paleochannel at Geode Creek (Fig. 7B), and coarse gravel separating pond sediment sequences was deposited sometime between ~1000 and 400 cal yr BP at Elk Creek (Fig. 2B). These high-energy deposits may represent floods following severe forest fires (Meyer et al., 1995) that could destroy beaver dams or fill in ponds. Channel incision, as was common after the 1988 Yellowstone fires (Legleiter et al., 2003), could also remove stored beaver-pond sediment.

Meyer et al. (1995) found that episodes of extensive lateral migration of channels producing floodplain widening are recorded in Holocene terraces of Soda Butte Creek, a larger stream in northeastern YNP. Regional paleoclimatic data suggest that floodplain widening occurs during cooler, effectively wetter periods when snowmelt runoff is high, but not extreme, below the channel incision threshold (Meyer et al., 1995). Beaver activity tends to overlap these floodplain-widening episodes, without clear correspondence (Fig. 4), suggesting that discharge becomes a limiting factor for beaver occupation only in prolonged, severe drought. In the Little Ice Age ~650–100 cal yr BP (Cook et al., 2004b; Meyer et al., 1995; Millspaugh and Whitlock, 1995), abundant dated beaver-pond deposits correspond to floodplain widening and minimal fire-related sedimentation (Fig. 8). The prevalence of these young deposits is at least partly an artifact of better preservation and exposure, but may also indicate that a cooler, effectively wetter, and less variable Little Ice Age climate (Cook et al., 2004b) was more favorable for beaver in the semiarid Northern Range. The concentration of dated pond deposits in the last 4000 yr, essentially Neoglacial time (Luckman et al., 1993), may also partly reflect a generally cooler climate and more reliable streamflows.

Historical climate records in the Yellowstone area show a trend toward a warmer and generally drier climate from 1895–1990 (Balling et al., 1992a, 1992b) that has continued to the present (Lawrimore and Stephens, 2003; National Climatic Data Center, 2006). Jonas (1955) inferred that drought and reduced streamflows, especially in the 1930s (Graumlich et al., 2003), were partly responsible for the marked post-1920s decline in YNP beaver populations. In the current warmer, drought-prone climate, with earlier snowmelt (Westerling et al., 2006), some small streams that hosted beaver colonies in the 1920s (Warren, 1926) have become ephemeral (e.g., Station 15, Fig. 1).

Variations in food resources likely also affected Northern Range beaver populations over the Holocene, but the relationship between climate, aspen, and herbivores in Yellowstone is complex (Bartos and Mueggler, 1981; Romme et al., 1995). There is perhaps a broad correspondence of the apparent increase in beaver activity after ~4000 cal yr BP with increased willow and alder pollen (Fig. 4), but we see no clear relationship between these proxies of vegetation change and beaver activity.

Beaver pond deposits and fluvial aggradation

The amount of stream aggradation that can be attributed to a single beaver pond is small, as individual pond deposits are <2 m thick (Table 1). Five stratigraphic sections include dated pond sediments separated by deposits not clearly related to beavers, but the maximum total aggradation including interbedded deposits is 2.5 m, and the time interval between deposition of pond-sediment units is diverse (~7000, 2600, 900, 400, and 50 yr between weighted

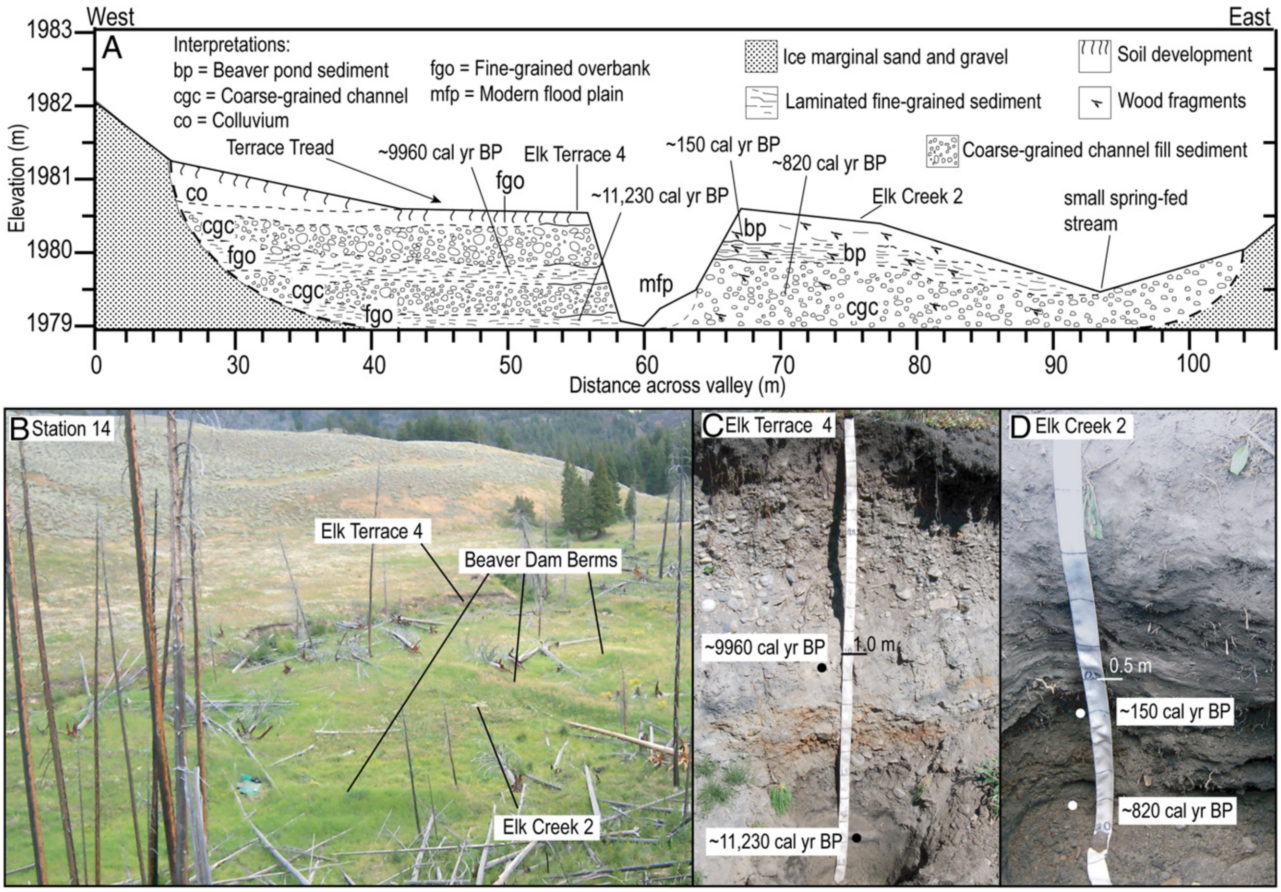

Figure 6. (A) Cross-section, and B. photograph of Station 14 area of Elk Creek, looking downstream. A ~2 m terrace is preserved on the west side of the cross section (left side of photo (B). Abandoned dams are preserved as sinuous berms across the valley. (C) Early Holocene fluvial terrace deposits in Elk Terrace 4 stratigraphic section (see A and B for location). (D) Coarse channel gravels dating to the Medieval Climatic Anomaly and overlying beaver-pond deposits (east side of cross section in A). These deposits are inset in the early Holocene terrace deposits to the west of the present channel. Incision of Elk Creek followed beaver-pond sediment deposition roughly 150 cal yr BP, but large uncertainty exists in this calibrated age (Table 2), so incision may or may not be historic. Beaver ponds above dams (berms) shown in B were mostly on a spring-fed tributary, not mainstem Elk Creek, and were abandoned before 1921 (Warren, 1926).

mean ages). Dated early Holocene (~7000–11,000 cal yr BP) deposits lie <2 m below the terrace surface, indicating limited net Holocene aggradation on Blacktail Deer, Elk, and Geode Creeks (Figs. 5 and 6; Table 2). Also, glacial erratic boulders along several reaches of Blacktail Deer, Lost, and Oxbow Creeks have not been buried by beaver-pond or fluvial deposits, indicating little net postglacial aggradation (Fig. 1). Along ~4.4 km of middle Blacktail Deer Creek and its east fork, fine-grained terrace deposits lack unambiguous evidence of former beaver ponds, but are thicker (>0.5 m) and more organic-rich than is typical for overbank deposits in the study area. We consider these reaches to show possible beaver-pond aggradation (Fig. 1).

Pond-sediment sequences thicker than a few meters may exist that were not exposed or accessed by augering, especially in ponded or low-gradient reaches in glacial scour depressions (Pierce, 1973, 1974). In one depression on Geode Creek (Station 8, Fig. 1), over 2 m of beaver-related aggradation has occurred since ~440 cal yr BP (1 σ ranges 319–392 and 426–516 cal yr BP). In the Colorado Front Range, Ives (1942) inferred that beavers raised the base level of Arapaho Creek a few meters by damming low points on a moraine crest, causing aggradation of the low-gradient valley above. In the same general manner, beaver in northern YNP have taken advantage of glacial topography by damming low-gradient valleys to create large ponds. However, some infilling of these low-gradient reaches would also occur in the absence of beaver.

The decreasing threshold of maximum channel slope with increasing basin area on reaches with preserved beaver-pond sediment (Fig. 3) implies that stream power imposes a limit on beaver damming *per se* and (or) pond deposit preservation. Although reaches with dams mapped by Warren (1926) have slopes exceeding this threshold, up to ~0.1, they fall well below maximum slopes over the full range of contributing areas, and none significantly exceed the threshold at areas above 10 km^2. Reaches above the threshold on Elk Creek where Warren (1926) mapped beaver dams retain no evidence of either dams or pond deposits, implying that although beavers may dam steeper reaches, subsequent erosion removes deposits and prevents sustained aggradation.

In summary, ~29% of the mainstem stream network in northern YNP has been influenced by beaver-related aggradation, typically of <2 m. Constraints imposed by stream power and episodic beaver-pond sedimentation (Figs. 3 and 4) have resulted in limited Holocene aggradation in both space and time. Although beaver have been a strong local influence along Northern Range streams, there is no evidence that they caused many meters of aggradation and consequent valley widening, forming broad, flat "beaver meadows" (Ives, 1942; Ruedemann and Schoonmaker, 1938). Ives'(1942) inference of major postglacial valley filling caused by beaver is inconsistent with his estimated beaver-related aggradation rate of 0.076–0.25 mm/yr, for which no supporting stratigraphic or geochronologic data are provided. This could account for only ~0.8–2.8 m of Holocene aggradation, insufficient to alter the form of large glacial trough valley floors. In northern YNP, the greatest aggradation has occurred in glacial depressions that would fill in to form

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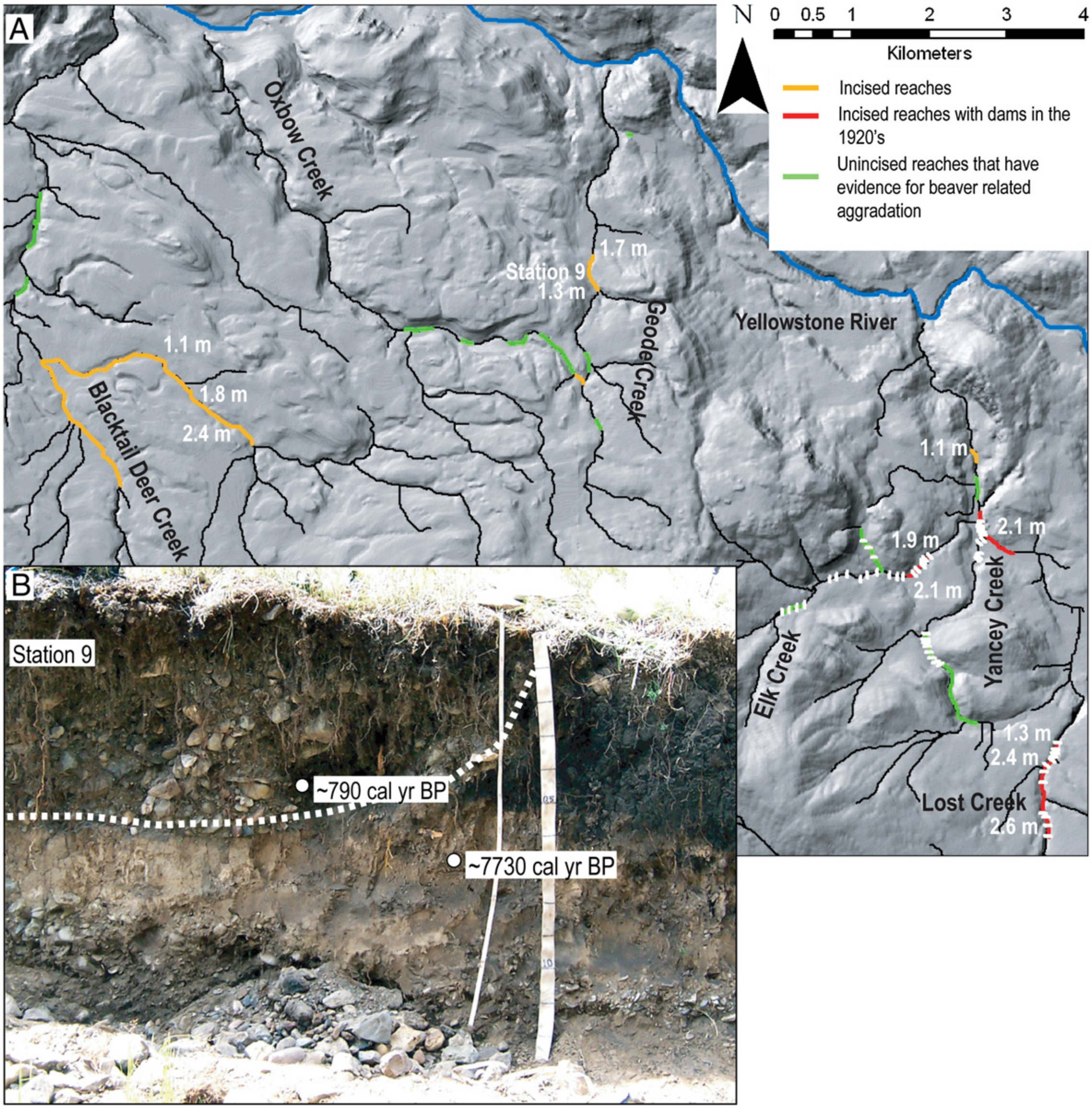

Figure 7. (A) State of channel incision in the study area. Incision depths (white numbers) are reported as the difference between highest local terrace surfaces and the modern floodplain. Red channels indicate incised reaches where active beaver dams were mapped in the 1920s (white lines; Warren, 1926); orange indicates incised reaches outside of the Warren (1926) study area; and green indicates unincised reaches where we documented beaver-related aggradation. (B) Exposure in wall of incised channel of Geode Creek at Station 9. No evidence of beaver damming or pond sediments was found in this reach. Coarse channel gravels with associated ~790 cal yr BP age fill a paleochannel incised into fine-grained early Holocene fluvial deposits overlying gravel at base of section. Dark-colored area at upper right is a well-developed cumulic A horizon, in sediments with no preserved evidence for beaver-pond sedimentation.

wet meadows regardless. Aggradation not clearly associated with beaver damming occurred in the early Holocene on Elk, Geode (Figs. 6 and 7) and Lost Creeks, possibly from paraglacial reworking of voluminous glaciofluvial deposits (Church and Ryder, 1972; Pierce, 1974). Paraglacial sediment availability tends to wane rapidly, however (Ballantyne, 2002), and likely could not sustain aggradation throughout the middle and late Holocene.

Historic and prehistoric channel incision in the Northern Range

Historic beaver dam abandonment and ensuing channel incision are important ecological concerns in northern Yellowstone, given potential impacts on riparian areas. Chadde and Kay (1991) inferred that beaver dam abandonment was a major cause of channel incision in the Northern Range over the past 50 yr. Wolf et al. (2007) described incision following dam abandonment as widespread and possibly unprecedented in the past two millennia. These conclusions are largely based on local observations, especially the Elk Creek dam site in Figure 2. This is among the highest (~2 m) abandoned dams we documented and the largest mapped by Warren (1926), ~100 m long and forming a pond extending 30 m upvalley. Incision on this 300 m reach of Elk Creek is unambiguously associated with dam abandonment (Fig. 2). This channel was further incised and widened by increased runoff after the 1988 fires (Legleiter et al., 2003; Meyer et al., 1995) and large floods in 1996 and 1997 (Graumlich et al., 2003; Meyer, 2001). At ~2 m, this reach shows the greatest clearly historic incision we measured on the study streams (Fig. 7A). Below the large dam, Warren (1926) mapped only abandoned dams along a small spring-fed tributary, not mainstem Elk Creek (Fig. 6), and it is unclear whether the variable incision along this lower reach is of historic age. In this same reach, early Holocene fluvial deposits are cut by a paleochannel that was filled by coarse gravel ~820 cal yr BP, demonstrating an earlier episode of channel cutting and filling (Fig. 6). Middle Lost Creek also exhibits significant but variable incision related to historic beaver dam abandonment. However,

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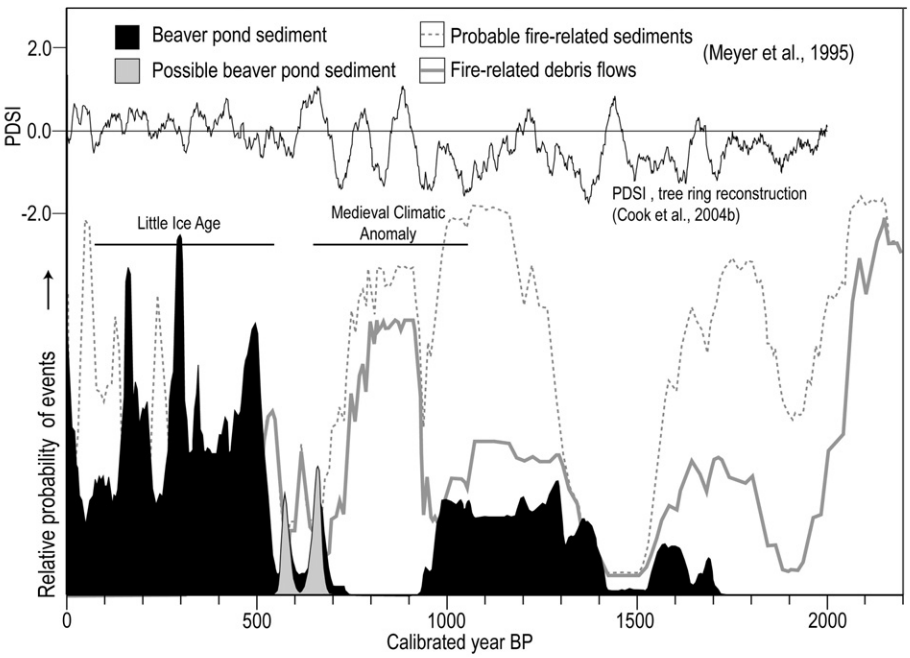

Figure 8. Chronology of beaver-pond deposits over the last 2000 yr. Major peaks in fire-related debris flows ~800 and 2200 cal yr BP indicate severe late Holocene droughts (Meyer et al., 1995) and correspond to minima in beaver-pond sedimentation probability. Less relation is evident with probable fire-related sedimentation. Palmer Drought Severity Index (PDSI) reconstructed for grid point 110° W, 45° N (Fig. 1) from tree-ring records in the Western USA (Cook et al., 2004b) was smoothed using a 50-yr running mean; negative values indicate drought. Severe droughts, high PDSI variability, and minimal beaver-pond sedimentation characterize the Medieval Climatic Anomaly. Maxima in beaver-pond sedimentation probability from 550–150 cal yr BP in the Little Ice Age in part reflect better preservation and exposure of young sediments, but correspond with near-normal values and low variability in PDSI, and minima in fire-related sedimentation.

channels have not incised where Warren (1926) mapped dams on several reaches of Yancey, Elk, and lower Lost Creek, and incision directly related to abandonment of mapped historic beaver dams affects about 9% of the total length of these streams (Fig. 7A).

Incision below terrace treads varies greatly at present, but is nowhere greater than 3 m. Incision and formation of a sloping inset terrace along the east fork of Blacktail Deer Creek began before ~1450 cal yr BP. Given the presence of a similar terrace along other reaches of Blacktail Deer and Lost Creeks, it is unlikely that this history is unique. Also, paleochannels on Elk and Geode Creeks (Figs. 6 and 7B) were cut before ~790 and ~820 cal yr BP, respectively. Thus, historic incision has precedent within the last 2000 yr (cf. Wolf et al., 2007). Of all reaches with documented possible, probable, and definite beaver-related aggradation, 64% are incised. If prehistoric incision on the east fork of Blacktail Deer Creek is excluded, the incised proportion is 45%. The upper mainstem of Blacktail Deer Creek has possible beaver-related aggradation, but no clear evidence for historic dams. If this reach is also excluded, then 26% of all reaches with some evidence for beaver-related aggradation experienced incision that is potentially related to historic dam abandonment (Fig. 7A).

The ~1.5 m deep vertical-walled channel of Geode Creek (Fig. 7) indicates recent incision, but the exposed fluvial deposits contain no evidence of beaver damming. About 1.5 km upstream of the incised reach, a low drainage divide between Geode Creek and Oxbow Creek is formed by a small alluvial fan in a glacial scour depression near Station 7 (Fig. 1). This fan was built by a tributary that formerly flowed west into Oxbow Creek. During the large floods of 1996 and (or) 1997, gravel deposition diverted all flow onto the Geode Creek side of the fan, likely resulting in downstream channel incision. Overall, the varied timing and magnitude of incision on Northern Range streams, including along reaches with no evidence of beaver damming, demonstrate that historic beaver dam abandonment is not solely or predominantly responsible for channel incision.

Historic environmental change and beaver in northern YNP

Historic fluctuations in beaver abundance in YNP have been interpreted in relation to environmental and ecological changes, including climatic variations (e.g., Jonas, 1955) and competition from elk browsing (Kay, 1990). Aspen was relatively abundant when Warren (1926) surveyed beaver dams, following major regeneration of stands in 1870–1890 (Romme et al., 1995). Wolves, the major predator of beaver, were extirpated in YNP by the 1920s, and beaver trapping had also ceased (Yellowstone National Park, 1997). The concurrence of abundant aspen, lack of wolves, and a wetter climate (Balling et al., 1992a; Cook et al., 2004b; Graumlich et al., 2003) in the early 20th century produced conditions favorable for major beaver expansion.

Some beaver dam sites mapped by Warren (1926) lie on small streams in apparently marginal habitat, including several along a small Elk Creek tributary below a spring-fed glacial scour pond (Station 15, Fig. 1). Warren (1926) mapped limited willow and aspen in this area, and observed that beaver were consuming much Douglas-fir bark and using an unusually large number of rocks to construct the dams. Few willow and large aspen trees currently exist there, and in severe summer drought in 2004–2005, the stream was dry. These observations suggest that beaver numbers were unusually high in the 1920s, when optimal climatic, ecologic, and vegetation conditions allowed beavers to occupy currently uninhabitable sites. Overall, multiple anthropogenic and natural influences in the early decades of YNP suggest that the 1920s are not an appropriate ecological reference period for beaver abundance in the park.

Causes for the post-1920's loss of Northern Range beaver are also debated. Large aspen stems have declined (e.g. Romme et al., 1995), limiting food and dam material. Some attribute this loss of mature aspen largely to elk overbrowsing (Bartos et al., 1994; Kay, 1990; Larsen and Ripple, 2005), but Warren (1926) and Jonas (1955) inferred that beaver themselves caused major aspen depletion along

Northern Range streams. Over the twentieth century, winter precipitation decreased and summer temperatures increased in YNP (Balling et al., 1992a), and drought has intensified over the past decade (Lawrimore and Stephens, 2003). The current resurgence of willow along Northern Range streams (Ripple and Beschta, 2006) should promote beaver recolonization, but if warming continues, both low streamflows and aspen scarcity may limit future beaver activity.

Conclusions

Along northern Yellowstone streams, about 29% of mainstem stream reaches have experienced beaver-related aggradation, where net aggradation is mostly <2 m. Greater beaver-related aggradation has occurred in some low-gradient reaches in glacial scour depressions. The threshold of maximum channel gradient at sites where beaver-pond sediment is preserved decreases with increasing contributing basin area, implying that high stream power prevents beaver-related aggradation along ~60% of the mainstem stream length. Along with the episodic character of Holocene beaver damming, these observations indicate that overall valley filling caused by beaver in the Northern Range is small.

No beaver-pond deposits were dated to 2200–1800 or 750–950 cal yr BP, and severe droughts are evident at these times in regional paleoclimatic records. The latter period corresponds with severe multi-decadal droughts of the Medieval Climatic Anomaly (e.g. Cook et al., 2004b). Deposition of atypical coarse gravels on Geode Creek and Elk Creek also suggests major floods at this time. Causes of channel incision on the study streams include beaver-dam abandonment, stream capture, and fire-related floods in historic time. Downcutting on the east fork of Blacktail Deer Creek initiated before ~1500 yr ago, and prehistoric episodes of channel incision were also documented on Elk Creek and Geode Creek. Of all reaches with evidence for beaver-related aggradation, we estimate that 26% incised following historic dam abandonment.

The current absence of beaver on Northern Range streams is likely due to both the scarcity of aspen and other food resources along these streams, and at least on smaller streams, severe and persistent drought that limits flows. The loss of beaver has caused locally significant incision of Northern Range channels, and could certainly have greater impact on fluvial systems in other settings where beaver occupation has been more widespread and continuous, and where beaver-related aggradation has been greater.

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