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Autopsy of a reservoir: Facies architecture in a multidam system, Elwha River, Washington, USA

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ABSTRACT

The 2011–2014 removal of two large dams on the Elwha River, Washington State, the largest dam removal yet completed globally, created extensive cutbank exposures of reservoir sediments, allowing the first characterization of the facies architecture of sediments through direct observation in reservoirs worldwide and providing an unparalleled opportunity to assess the relationship between environmental influences, such as changes in sediment supply, and their expression in the stratigraphic record. Using a combination of facies description from observation of 49 measured sections and >100 exposures and analysis of digital elevation models and historic aerial photographs, we delineated the characteristic depositional zones of each reservoir and mapped the evolution of the subaerial delta over the life span of the reservoir. Former Lake Mills, the younger, upstream reservoir, was characterized by a tripartite, subaerial Gilbert-style delta that prograded >1 km into the main reservoir from 1927 to 2011. Sediments were composed of coarse-grained topset beds, steeply dipping foreset beds, and a fine-grained, gently dipping prodelta. While individual event horizons were discernible in fine-grained sediments of former Lake Mills, their number and spacing did not correspond to known drawdown or flood events. Former Lake Aldwell, impounded from 1913 to 2011, was initially defined by the rapid progradation of a Gilbert-style, subaerial delta prior to the upstream completion of Glines Canyon Dam. However, the 1927 closure of Glines Canyon Dam upstream caused the delta to evolve to a fine-grained, mouth-bar–type delta indicative of low, finer-grained sediment. This evolution, combined with a previously unrecognized landslide deposit into the upper delta plain, suggests that understanding the exogenic influences on reservoir sedimentation is critical to interpretation and prediction of the sedimentation within individual systems.

INTRODUCTION

As of 2018, there were an estimated 59,000 large (>15-m-high) dams worldwide, intercepting 40% of total river flow volume annually, impounding an area as large as 723,000 km^2, and increasing the terrestrial water surface area by >7% (Nilsson et al., 2005; Downing et al., 2006; Lehner et al., 2011; International Commission on Dams, 2018). These dams represent humans' greatest impact on global land-ocean sediment transport, with as much as 25% of annual global sediment discharge impounded (Vörösmarty et al., 2003). In fact, despite an estimated 2300 Tg yr^{-1} increase in global sediment transport during the Anthropocene, ~1400 Tg yr^{-1} less sediment reaches the world's oceans (Syvitski et al., 2005).

The resulting disconnectivity in river systems and the global transfer of sediment via the "sediment cascade" has been the subject of much study. However, most work has focused on estimating the net sediment volume impact at the local, basin, or global scale (cf. Walling and Fang, 2003; Vörösmarty et al., 2003; Syvitski et al., 2005; Kummu et al., 2010; Yang and Lu, 2014) and resulting downstream effects, both geomorphic and ecologic, of damming river systems (e.g., Nilsson and Berggren, 2000; Bunn and Arthington, 2002; Graf, 2005). The dynamics of in-reservoir sedimentation and, critically, the sediment dynamics of multiple reservoirs arranged longitudinally in a single river or watershed remain largely unexplored. As a result, our understanding of the character of sedimentation in individual reservoirs and the processes controlling them, as well as the response to changing sediment regimes in multidam systems, is limited.

At the scale of individual dams, most study has focused on developing approaches to aid managers in determining the local sediment yield or volumetric accumulation rate. In its comprehensive design manual *Small Dams* (a legacy title retained through multiple editions despite its expanded applicability to large dam design), the U.S. Bureau of Reclamation (USBR) developed a series of morphology- and operations-based type curves to plot the relationship between reservoir depth and deposition. These curves recognize that sedimentation is typically weighted toward the upstream, inflow-adjacent regions of reservoirs, with the assumed delta volume equal to the volume of sand-sized or greater sediment input to the reservoir (Strand and Pemberton, 1987). The USBR considers a "typical" delta profile to be defined by distinct topset and foreset slopes separated by a pivot point located at the median reservoir operating elevation, but notes that "the prediction of delta formation is still an empirical procedure based upon observed delta deposits in existing reservoirs" (p. 549) and requires extensive data collection.

The "typical" profile, as defined by the USBR, represents a Gilbert-style delta, first described in the deposits of Pleistocene Lake Bonneville (Gilbert, 1885). The Gilbert delta is a process-based paradigm, in which the decrease in slope and rapid expansion of flow abruptly decrease the competence of inflowing discharge, causing rapid, inertia-based sedimentation (Nemec, 1990a, 1990b). Accordingly,

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GSA Bulletin; https://doi.org/10.1130/B31959.1; 16 figures; 2 tables; Data Repository item 2018204.

incoming sediment is deposited as a prograding foreset wedge, defined by a gravelly, subaerial topset bed, heterolithic foreset slope prograding at about the angle of repose, and downstream-fining bottomset wedge. The Gilbert paradigm has informed a vast literature of delta dynamics and remains the dominant model in lacustrine delta interpretation (e.g., Colella and Prior, 1990; Talbot and Allen, 1996; Reading and Collinson, 1996; Wetzel, 2001; Snyder et al., 2006).

Examples of Gilbert-style reservoir deltas have been documented in Trinity and Englebright Lakes, two reservoirs in northern California (Spicer and Wolfe, 1987; Snyder et al., 2004, 2006). However, results from other studies of reservoir sedimentation suggest that the Gilbert paradigm is oversimplified or not applicable to many reservoirs. For example, studies in Lake Mead, located on the Colorado River and the largest reservoir in the United States, show that turbidity currents appear to be the primary mechanism of sediment transport to the stagnant-basin portions of the reservoir, modifying the shape and distribution of the delta front and transporting relatively coarse-grained sediments as far as the dam, >100 km downstream (Kostic et al., 2002; Twichell et al., 2005; Wildman et al., 2011). Additionally, research suggests that reservoirs operated for flood control, which are seasonally drawn down to create floodwater accommodation space, show patterns of sedimentation that are strongly influenced by seasonal progradation and reworking of sediment, further complicating interpretation (e.g., Ambers, 2001; Keith et al., 2016).

While endogenic (within-reservoir) dynamics can affect sedimentation patterns and sediment architecture, exogenic influences such as floods, droughts, and changes in sediment regime can be expected to similarly influence sediment transport and deltaic and lacustrine sedimentation in reservoirs downstream (cf. e.g., Schmidt and Wilcock, 2008; Grant, 2012; Romans et al., 2016; Grant et al., 2017). Events such as the completion of a dam upstream can be expected to influence both the volume of sediment transport and its grain-size distribution, as well as to modify daily discharge, which can further influence sediment transport. For example, in Englebright Lake, a sediment- and flood-control reservoir on the Yuba River in California, Snyder et al. (2004, 2006) noted a distinct transition in sedimentation rate upon the closure of a major upstream dam in the 1970s. This coring-based study, however, did not address changes in the progradation rate or style of the delta within Englebright Lake as a result of the upstream dam closure, and, with the exception of basin-scale volumetric estimates (e.g., Kondolf et al., 2014), few examples of sedimentation studies addressing cascaded reservoirs can be found.

Approach and Scope

The poorly understood dynamics of sediment deposition in reservoirs may be attributed in part to an absence of rigorous description and observation across a range of reservoir systems. Unlike natural lakes, which are well represented within the geologic record, the architecture of reservoir sediments has thus far been relatively inaccessible to detailed study except through coring and remote-sensing techniques. The accelerating pace of dam removals in the late twentieth century and early twenty-first century, however, has provided an unparalleled opportunity to examine reservoir sedimentation within a watershed context (O'Connor et al., 2015; Major et al., 2017; Foley et al., 2017). With the advent of intentional dam removal, we now have a brief window within which to examine the way in which sediment accumulates in reservoirs before the deposit is eroded by a free-flowing river. From this, many questions become more approachable, including how multiple reservoirs interact to affect sediment deposition and what this implies for calculating reservoir accumulation rates, trap efficiencies, and lifetimes.

The 2011–2014 demolition of Elwha and Glines Canyon Dams on the Elwha River, Clallam County, Washington State, represents the largest dam removals yet undertaken globally. These dams, completed in 1914 and 1927 in a watershed mostly protected from anthropogenic impacts by the basin's location in Olympic National Park, accumulated sediments for nearly a century before they were removed to restore fish passage to the upper Elwha watershed. As reservoir sediments were exposed and rapidly eroded during the dam removals, the extensive network of cutbanks and river terraces created an unparalleled, ephemeral opportunity to observe reservoir sediments in situ and reconstruct some of their depositional history, with the dual goals of (1) better understanding reservoir sedimentation, architecture, and processes within a watershed context, and (2) investigating the ways in which environmental changes (e.g., floods, droughts, or changes in sediment supply) are recorded in deltaic and lacustrine environments. To approach these questions, we utilized a combination of field-based stratigraphic analysis, historic aerial photograph analysis, and digital elevation model analysis to map the geomorphic surface features and depositional zones of former Lakes Aldwell and Mills, to determine the characteristic facies associations of each zone, and to analyze the morphologic styles of deltaic progradation over the course of the reservoirs' lifetimes. We then used these observations to broadly interpret how reservoir cascades with multiple impoundments can control depositional styles and rates and to assess the expression of known environmental events (e.g., an 18 m reservoir drawdown in 1989 or a 50 yr flood in 2007) in the stratigraphic record.

STUDY AREA

Elwha River Hydrology and Geomorphology

The Elwha River watershed (833 km^2) is located on the northern Olympic Peninsula, Washington (Fig. 1). Watershed elevation ranges from 2432 m in the glaciated core of the Olympic Mountains to sea level, where the Elwha River discharges to the Strait of Juan de Fuca. Most precipitation occurs from October to March, with snow dominating above ~1200 m. Precipitation is strongly controlled by elevation and ranges from more than 6000 mm yr^{-1} on Mount Olympus to only 1000 mm yr^{-1} at the mouth of the Elwha River; climate records (1948–2005) from the Elwha Ranger Station average 1430 mm yr^{-1} (Duda et al., 2011).

The Elwha River is 72 km long, with eight tributaries greater than third order and a total tributary length of ~161 km (Duda et al., 2008; Bromley, 2008). Annual peak discharges occur in winter, with a secondary discharge peak accompanying late spring snowmelt; the highest mean monthly discharge occurs in June, and the lowest occurs in September (Fig. 2). The average daily discharge, calculated using 95 yr of data, is 43 $m^3 s^{-1}$. The flood of record occurred in 1897 (coincidentally, the first year of the historical data) at 1180 $m^3 s^{-1}$; since then, seven measured annual peak discharges have exceeded 800 m s^{-1}, including a 50 yr flood on 3 December 2007, which was the largest of the dammed era (Fig. 2).

Sediment sources to the Elwha River are plentiful, due to both the history of Pleistocene glaciation in the watershed and rapid uplift rate of the Olympic Mountains. The southernmost extent of the Fraser Juan de Fuca lobe of the Cordilleran ice sheet reached ~13.5 km up the Elwha River ca. 14 ka, upstream (south) of Lake Aldwell but downstream (north) of Lake Mills (Long, 1975; Polenz et al., 2004; Mosher and Hewitt, 2004; McNulty, 2009). This glacial advance deposited extensive till, outwash, and glaciolacustrine formations in the lower Elwha River watershed. Upstream (south) of the continental ice extent, contemporaneous alpine glaciation advanced northward down the upper Elwha River canyon, although the extent is poorly

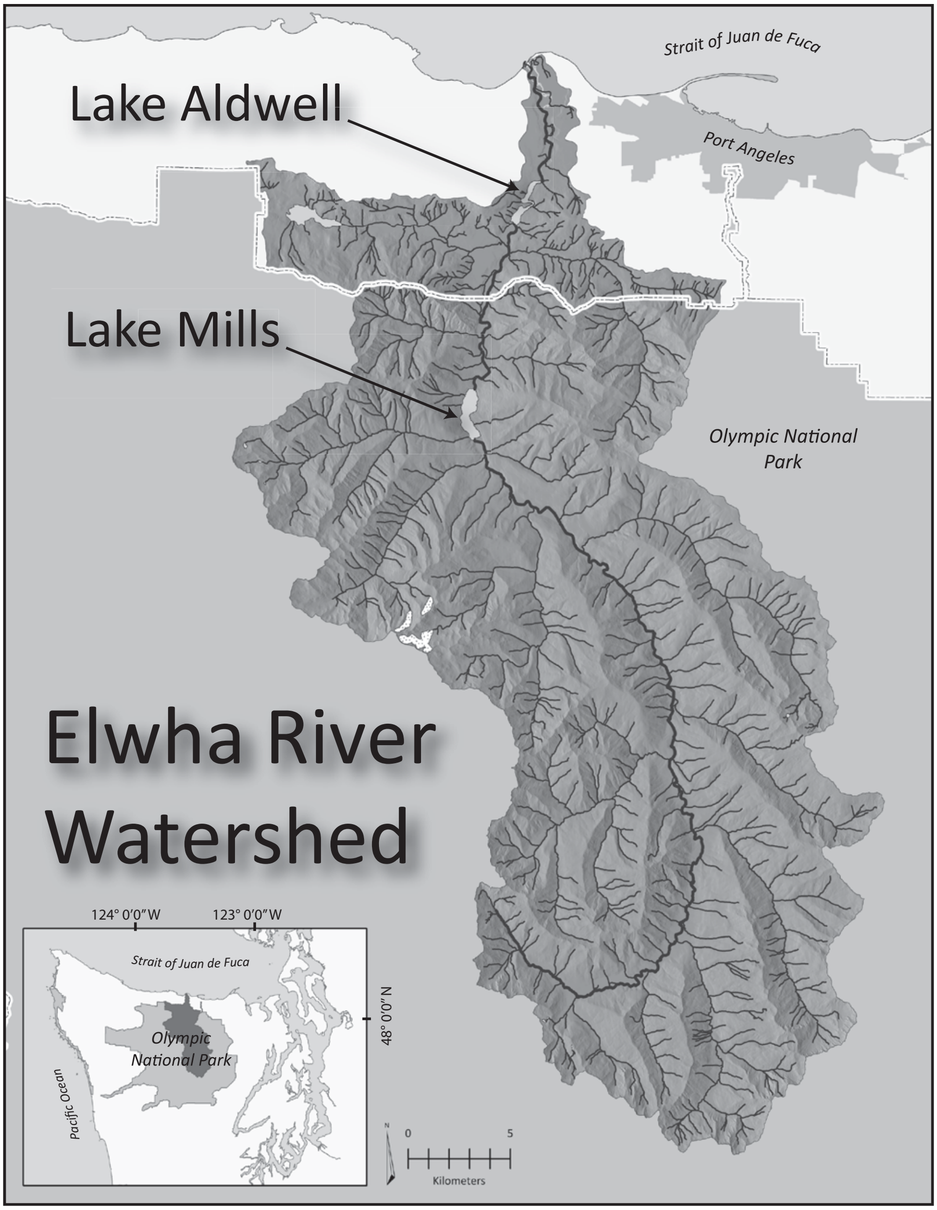


Figure 1. Map showing location of Elwha watershed on the Olympic Peninsula of western Washington State. Mainstem Elwha River with tributaries, former Lakes Mills and Aldwell as labeled; mainstem Elwha River indicated by thick gray lines; tributaries by thin gray lines. Eighty-three percent of the watershed is within Olympic National Park.

constrained. The alpine glaciers evidently retreated before the Juan de Fuca lobe, leaving fjord-like pro–Juan de Fuca lakes that deposited glaciolacustrine sediments in the upper Mills area (Tabor, 1982; Schuster, 2005).

The bedrock in the Elwha River watershed includes two of the major terranes on the Olympic Peninsula, a strongly deformed suite of marine sediments known as the "Eastern Core," and an outer horseshoe-shaped belt of Eocene basaltic rocks known as the Crescent Formation (Tabor and Cady, 1978). Accreted as part of Cascadian subduction, the Eastern Core is extensively faulted and has been metamorphosed to slate, schist, and phyllite, while the Crescent Formation is tilted but relatively undeformed (Tabor and Cady, 1978; Tabor, 1982). The rapid uplift rate (~0.6 mm yr^{-1}; Brandon et al., 1998; Batt et al., 2001) of the Olympic Mountains produces steep slopes that slide easily and supply ample sediment to the Elwha River (Acker et al., 2008; McNulty, 2009; Draut et al., 2011).

While sediment sources to the Elwha are plentiful, potential erosion associated with human land-use changes is relatively limited due to the protected status of much of the watershed. Eighty-three percent of the Elwha watershed is within the boundaries of Olympic National Park and a federally protected wilderness area, which was first established as the Olympic Forest Preserve in 1897. Prior to 1897, there were scattered efforts at farming, logging, and mining in the Elwha River Valley, but the density of vegetative cover and steep terrain discouraged significant development. Downstream of park boundaries, much of the lower Elwha watershed is composed of Olympic National Forest land, where "little to no recent [logging] activity" has occurred for decades (U.S. Department of the Interior, 1996); the remainder is private and tribal land, where limited timber harvest has taken place during the twentieth and early twenty-first centuries.

The Elwha River upstream of former Lake Mills is characterized by distinct alluvial reaches separated by bedrock canyons. The headwaters reach an average gradient of 16%, and the river exhibits a convex profile (Fig. 3A). Most sediment to former Lake Mills was sourced from the main-stem Elwha River; however, two significant and several minor tributaries also delivered sediment to the reservoir. The ~9 km reach between the upstream boundary of former Lake Aldwell and Glines Canyon is characterized by alluvial reaches of moderate gradient (~0.0065; Kloehn et al., 2008), separated by narrow canyons. There are few tributaries in this reach, and most of these drain predominantly basaltic terrain. Only Indian Creek and a short reach of the Little River drain semiconsolidated sediments; both of these downcut through Pleistocene till for much of their lengths. With the exception of Indian Creek, which entered the head of the reservoir, sediment supply to former Lake Aldwell was limited to the main-stem Elwha River.

Reservoir Descriptions and Project History

Elwha and Glines Canyon Dams were completed in 1913 and 1927, respectively, to provide hydropower for development of the northern Olympic Peninsula. Elwha Dam was 33 m tall, sited to take advantage of the natural constriction in a narrow bedrock canyon on the Elwha River. It impounded former Lake Aldwell, a 1.3 km^2 reservoir composed of two subbasins separated by a bedrock canyon colloquially referred to as "the gooseneck." Former Lake Aldwell had an initial water capacity of ~1.0×10^7 m^3, average depth of 7.6 m, a maximum depth of 29 m, and maximum fetch

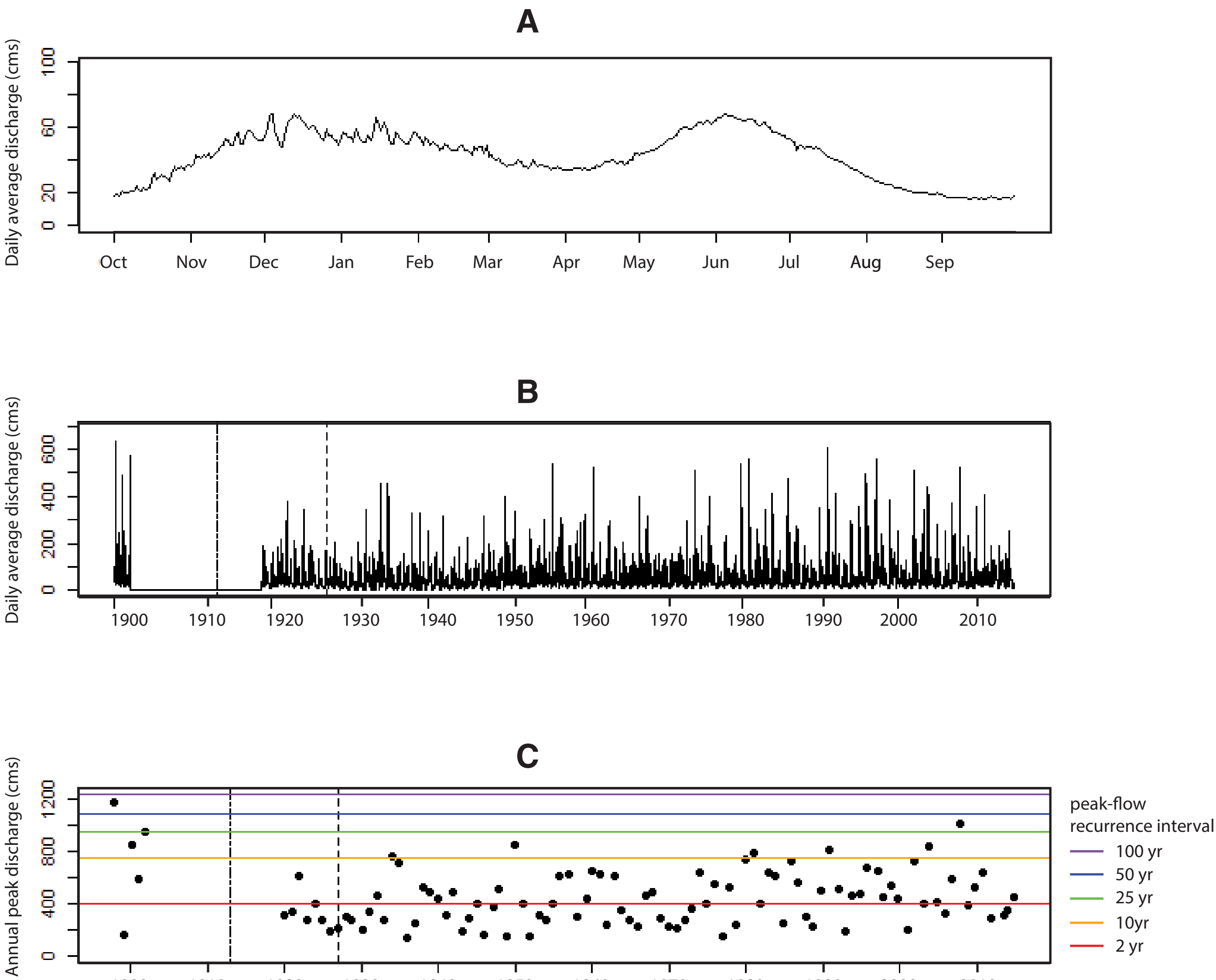


Figure 2. Hydrographs of the Elwha River at McDonald Bridge (U.S. Geological Survey gauging station 12045500). (A) Daily discharge, averaged over length of record. (B) Complete record, 1897–1901, 1918–2014. Dashed lines indicate closure of Elwha Dam (1913) and Glines Canyon Dam (1927). (C) Annual peak discharge with estimated peak-flow recurrence interval (Duda et al., 2011). Flood of record = 1180 cubic meters per second (cms), recorded 18 November 1897. Largest flood during the reservoir era (second largest ever measured) was recorded 3 December 2007 at 1020 cm.

of 2000 m (Table 1). Approximately 18 km upstream, Glines Canyon Dam was 64 m tall and impounded a steep-sided, ~0.5-km-wide alluvial valley confined at the upstream end by Rica Canyon and at the downstream by Glines Canyon. Lake Mills had a similar area to Lake Aldwell, but at twice the maximum depth, it had an initial water capacity approximately five times greater. During the decades of the dams' existence, the Elwha River built substantial deltas into both former reservoirs, significantly reducing their capacity, area, and average depth while increasing the shoreline complexity (Table 1; Figs. 4A and 4B).

The reservoirs were operated as "run of the river" (i.e., constant-head) facilities from 1975 onward (but possibly as early as the 1940s) until removal activities began, with 5.5 m drawdown experiments conducted in 1989 and 1994 and occasional drawdowns to augment downstream flows during spawning season for salmonid fish after the 2000 purchase of the dams by the National Park Service (U.S. Department of the Interior, 1996; Duda et al., 2008). Removal activities, the result of a 1996 Environmental Impact Statement, which found dam removal to be the only reasonable and prudent alternative to restore the once-abundant salmonid fishery in the Elwha watershed (Duda et al., 2008; Pess et al., 2008), began in 2011.

The removal of Elwha and Glines Canyon Dams was the largest dam removal undertaken globally to date (Randle et al., 2015; Warrick et al., 2015), and it required extensive study and planning. Of primary concern was developing a plan for the fate of the sediment accumulated

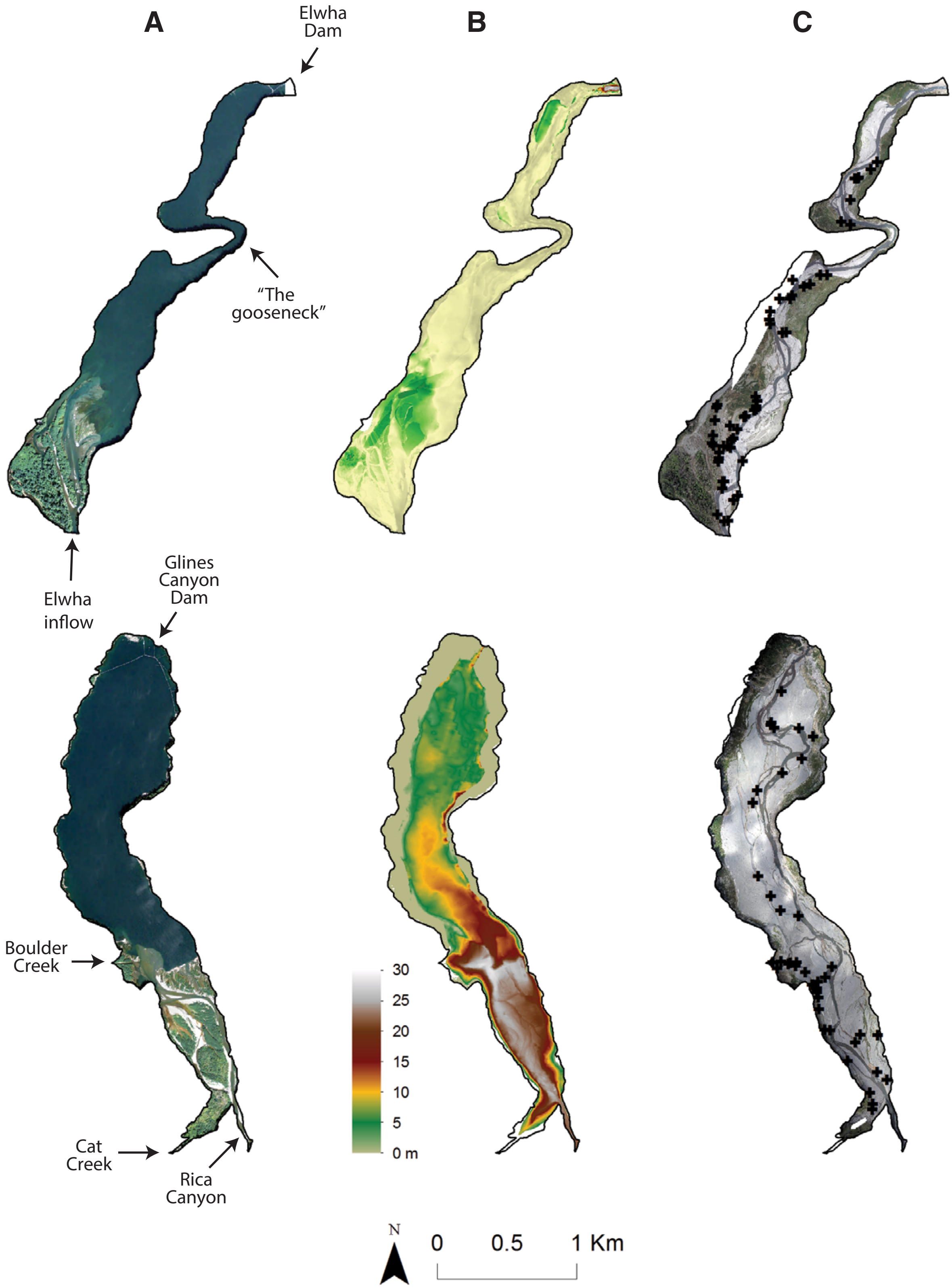


Figure 3. (A) Delta morphology, 2009; (B) sediment accumulation, dam closure to 2010; and (C) stratigraphic section location (black crosses), 2014. Sediment accumulation data were adapted from Bountry et al. (2011). Orthophoto was derived from 2014 structure-from-motion analysis (Andrew Ritchie, 2014, personal commun.).

TABLE 1. MORPHOLOGICAL AND TIME-LINE COMPARISON BETWEEN FORMER LAKES ALDWELL AND MILLS

Reservoir: Dam:	Lake Aldwell Elwha		Lake Mills Glines Canyon	
Dam height (m)	32		64	
Year of closure	1913		1927	
Year of breach	2011		2011–2014	
Inundated river length (m)*	4824		3719	
	Year			
	1913	2011	1927	2011
Area (m²)	1.31E+06	1.10E+06	1.82E+06	1.51E+06
Perimeter (m²)	1.02E+04	2.02E+04	1.08E+04	1.34E+04
Capacity (m³)†	1.00E+07	5.10E+06	5.12E+07	3.51E+07
Shoreline development index§	4.5	9.6	4.0	5.5
Average depth (m)#	7.6	4.6	28.2	23.2
Maximum depth (m)	29	28.5	53	45
Maximum effective length (fetch, m)	2.00E+03	1.20E+03	2.90E+03	2.10E+03
Watershed area (m²)	8.15E+08		6.36E+08	
Bed-load source area (m²)	8.15E+08	1.79E+08		
Watershed to surface area ratio	620		350	420
Bed-load source area to surface area ratio	620	741		

*Calculated as length of estimated former thalweg to end of inundation; estimate for Lake Mills does not include Rica Canyon portion of the reservoir, where flow is constrained.

†Bountry et al. (2011); Warrick et al. (2015). Aldwell capacity does not reflect underestimate of initial capacity as discussed herein.

§$D = [L/\mathrm{sqrt}(A)]$.

#Volume/surface area; Wetzel (2001).

behind the dams, the precise volume and character of which were unknown. From 1988 through 1990, a private consultant collected drill cores and bathymetric data from Lakes Aldwell and Mills to determine the volume and nature of sediments stored in the reservoir deltas (Hosey, 1990a, 1990b). As part of these studies, Lake Mills was drawn down and held 5.5 m (18 ft) below normal operating elevation for 4 wk in the spring of 1989. This drawdown experiment was repeated in the spring of 1994, when the reservoir was again dropped 5.5 m (18 ft) and held over a period of 2 wk. The estimated total sediment volume in each reservoir calculated from the 1994 experiments (Gilbert and Link, 1995; Childers et al., 2000) was subsequently updated and finalized in 2010, when additional surveying was performed, and a new sediment volume for Lake Mills was calculated (as discussed below; Bountry et al., 2011).

On the basis of the sedimentation surveys, drawdown experiments, and additional physical modeling (Bromley, 2008), a sediment management plan was developed that called for

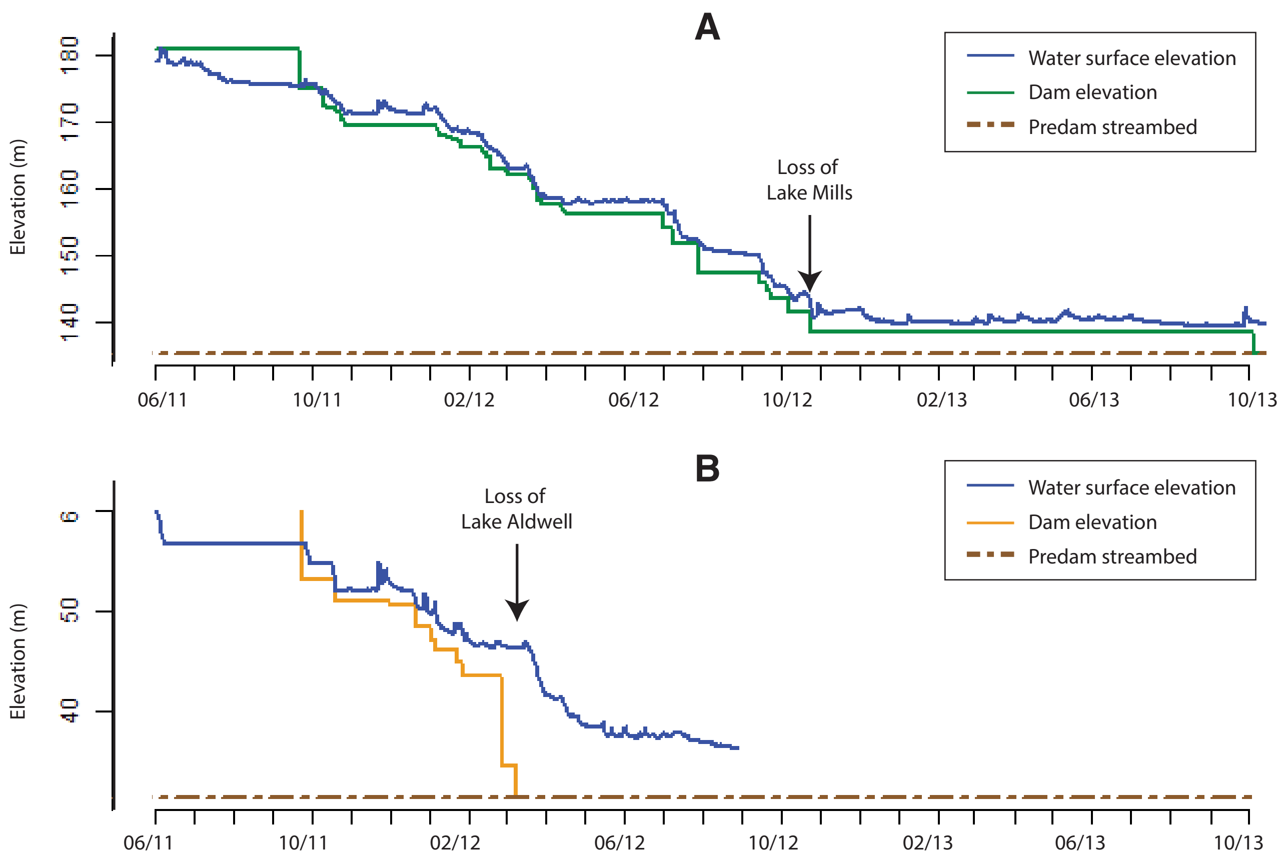


Figure 4. Dam crest and water-surface elevations during stepped removal of (A) Glines Canyon and (B) Elwha Dams. Loss of Lake Aldwell (i.e., dam control of water-surface elevation) occurred 9 March 2012. Loss of Lake Mills occurred 12 October 2013. Figure is adapted from Randle et al. (2015).

phased removal of both dams over a 2 to 3 yr period (Randle et al., 2015). Drawdown intervals were timed to balance impacts to fish and sediment erosion, with a goal of minimizing the number of fish generations effected by reducing the overall sediment load to the Elwha River during drawdown. Accordingly, Elwha Dam was removed over the course of a single season during the winter of 2011–2012, while Glines Canyon Dam was removed in steps from late 2011 to the summer of 2014, with the loss of Lake Mills occurring in October of 2012 (Fig. 5). During dam removal, the reservoirs were drained in a series of stepped drawdown events of 3–5 m. Each drawdown event initiated incision into the reservoir deltas, while hold periods between drawdown events allowed lateral migration, widening of the channel, and vertical

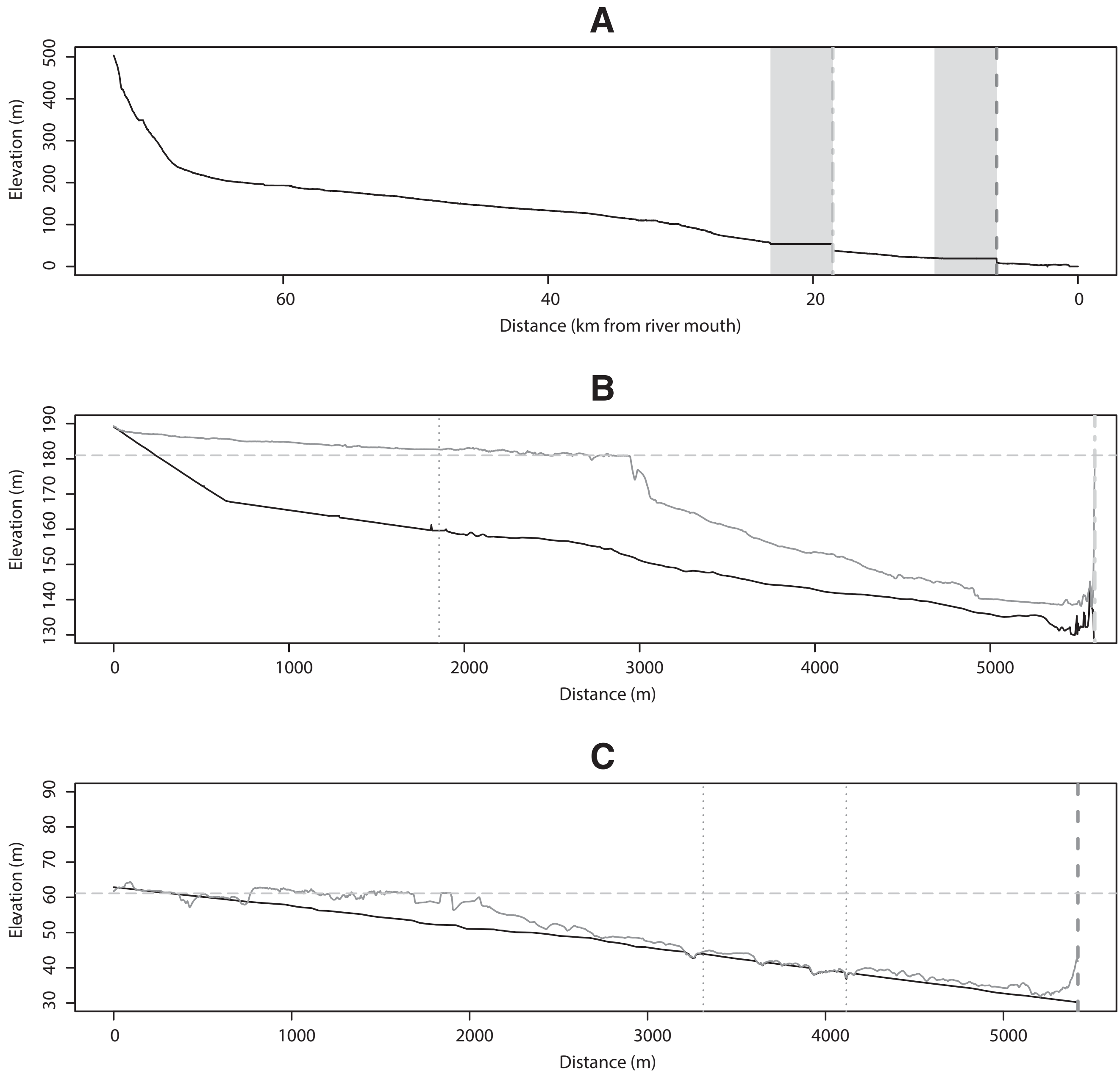


Figure 5. Thalweg profiles showing: (A) Elwha River gradient, Mount Olympus to river mouth at Strait of Juan de Fuca. Dams are indicated by light gray dot-dashed line (Glines Canyon) and dark gray dashed line (Elwha); gray shaded area indicates length of reservoir. (B) Profile of Lake Mills. (C) Profile of Lake Aldwell. Predam elevations are indicated by black solid lines. Pre–dam removal, 2010 surveyed elevations are indicated in gray solid lines. Typical water-surface elevation is indicated by horizontal gray lines. Glines Canyon (light gray, dot-dashed line) and Elwha (dark gray, dashed) dams are indicated with vertical lines. Dotted vertical line in B indicates lowermost extent of Rica Canyon, where Lake Mills basin opens. Dotted vertical lines C indicate "gooseneck" constricted region of Lake Aldwell. Thalweg profiles were computed along the estimated predam thalweg using the predam digital elevation models created by Bountry et al. (2011) and orthophotos from the National Park Service.

drawdown. Delta progradation as the result of this stepped approach caused the deposition of up to ~2–10 m of sediment in the deep-water portions of the reservoir; however, within 2 yr of removal initiation, 23% of the sediment in former Lake Aldwell and 37% of the sediment in former Lake Mills had been eroded (Randle et al., 2015).

DATA COLLECTION AND ANALYSIS

During the summer of 2014, the Elwha had incised to its predam bed elevation through much of former Lakes Aldwell and Mills, creating extensive exposures of reservoir sediments in cutbanks where the river was actively eroding. These sediment exposures created an unprecedented opportunity to study the facies architecture of reservoir sediments through direct, spatially comprehensive observation, as opposed to remote sensing by bathymetric measurements or spot sampling by coring.

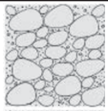
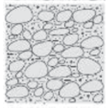
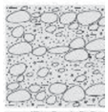
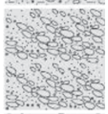
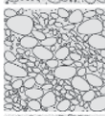
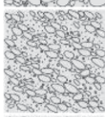
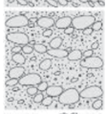
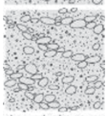
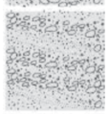
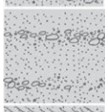
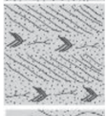
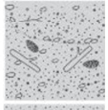
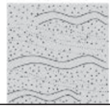
Mapping and Watershed Analysis

We mapped both former reservoirs using a combination of aerial photographs, digital elevation models, thalweg profiles, and ground truthing to define depositional zones and geomorphic features in the reservoirs. Historic aerial photographs of the Lake Aldwell and Lake Mills deltas were obtained from the U.S. Geological Survey's Long Term Archive at the National Center for Earth Resource Observations and Science (USGS EROS). Additional aerial orthoimagery generated based on structure-from-motion photogrammetry was provided by the National Park Service. Sediment deposition maps were created from digital elevation models produced by the U.S. Bureau of Reclamation (Bountry et al., 2011). All features were hand-digitized in ArcGIS applications at a scale of 1:2000 or finer, depending on the quality of the available photographs. Areas, volumes, and thalweg profiles were calculated using Spatial Analyst functions in ArcMap Version 3.7.1.

Stratigraphic Descriptions

We described reservoir sediments and facies architecture at over 100 locations in the former Elwha reservoirs, mapping exposures and completing 49 measured sections (Fig. 4C). The locations of sections were determined primarily by the accessibility and quality of exposure, and thus tended to favor recently abandoned cutbanks. In addition to those sections observed in person, we utilized photographs and samples collected by Wing (2014) to corroborate facies determinations and mapping extent.

TABLE 2. FACIES DESIGNATIONS, FORMER LAKES ALDWELL AND MILLS

Facies		Description	Bedding	Comments
G1		Unchannelized cobble-boulder gravels; massive to crudely stratified. Clast- to matrix-supported; matrix sandy to pebbly. Little silt.	Sheetlike, laterally extensive beds to 5 m thickness	Frequently associated with facies O1
G2		Unchannelized, poorly sorted large pebble to cobble gravels; similar to G1 but finer grained and consistently matrix-supported; some silt in matrix.	Sheetlike, laterally extensive beds to 2 m thickness	More common in Aldwell; frequently associated with facies O1
G3		Matrix-supported, very poorly sorted angular gravels; inverse grading and elevated clasts common.	Subhorizontal to 20° dip, maximum 0.5 m, local unit pinches out downstream	Marginal; minor unit
G4		Weakly graded, weakly channelized silty sandy gravel with lag. Lag shows imbrication, occasional weak channel form.	Multistory ~0.5 m bed; laterally extensive, pinches out over hundreds of meters	May be clast- or matrix-supported; organics rare
G5		Cross-stratified, well-imbricated pebble to cobble gravels. Open framework to clast-supported.	Steeply dipping cross-beds 20–30 cm thick; laterally extensive	Associated with G1; often overlying sheet sands
G6		Interbedded pebble, small cobble, and coarse sand to granule conglomerate. Individual beds moderately to well sorted; may be open framework.	Steeply dipping (25°–30°) beds to 0.5 m thickness, uniform geometry	Gilbert-style delta foreset; transition to toeset tangential; associated with O2 and HS3
G7		Crudely stratified, gently dipping pebble to cobble gravels. Matrix- to clast-supported; little silt.	Forms sigmoidal foreset on scale of 2–3 m; individual beds ~10 cm	Organics rare; where exposed, overrides facies F4
G8		Weakly channelized, well-sorted sandy gravel with prominent lag; little silt. Clast-supported, weakly imbricated to massive. Finer and less silty than G4.	Subhorizontal to broadly undulating; beds 10 cm to 0.5 m thick	Organics rare, but frequently associated with S2 and F6
G9		Tabular to channelized pebble gravels and pebbly sand. Clast-supported, rarely open framework. Little to no silt.	Complexly bedded; sheetlike tabular beds cut by channel forms with migration lag	Organics rare; geometry complex compared to other gravel facies
G10		Low-angle, tabular pebbly gravel beds interbedded with sigmoidally cross-bedded coarse and very coarse sands. Individual beds to ~1 m thick but pinch out.	Gently dipping to broadly undulatory, laterally extensive but variable	Organics rare to absent
S1		Well-sorted medium to coarse sand with granules forming well-developed cross-beds and planar-laminated beds.	Multiple cosets of sheetlike units, pinch out downstream; maximum thickness ~0.5 m	Relatively local unit; typically interbedded with G4, G5
S2		Medium to coarse or very coarse sand and fine pebbles; moderately to well sorted with little internal structure. No silt.	Laterally extensive, gently dipping; beds typically 10–20 cm	May occur in isolation but more typically interbedded with G8 and F6
S3		Well-sorted medium to fine sand with interbedded organics. Planar to sigmoidal cross-lamina, climbing ripples common. Beds typically ~10–50 cm.	Subhorizontal to undulating; extensive, relatively uniform	Organics prominent; tend to highlight internal bedding structure
S4		Very thick beds of massive to cross-laminated sand and silty sand with climbing ripples and load structures; gravel absent.	Beds to several meters thick; upper contact frequently channelized	Organics often prominent; tend to highlight internal structure where present
HS1		Variable, chaotic to channelized or weakly bedded, poorly sorted sand with medium to coarse organics and rare pebbles.	Sheetlike; extensive, bottom contact erosive; grades finer laterally, typically little fabric	Occasional mudballs
HS2		Fine to medium cross-laminated sand regularly interbedded with wave rippled or wavy-bedded muds to ~5 cm thick. Silt subordinate to sand beds.	Subhorizontal to gently dipping; silt interbeds pinch out but laterally extensive	Organics common but make up <25% of unit

(*Continued*)

TABLE 2. FACIES DESIGNATIONS, FORMER LAKES ALDWELL AND MILLS (*Continued*)

Facies	Description	Bedding	Comments
HS3	Well-sorted, interbedded sand and pebbles separated by thin silt beds. Beds laminated with pebbles imbricated along dip.	Steeply dipping (25°–30°) beds to 0.5 m thickness, uniform geometry	Organics rare
F1	Striped mud and sand lamina and beds, frequently with needles. Sand beds to 5 cm, cross-laminated, increase up section relative to silt beds.	Subhorizontal; laterally extensive; thickness from 0.5 m to many meters	Extensive across former Lake Mills; limited in former Lake Aldwell
F2	Interlaminated mud and silty sand with organics. Parallel to weakly wavy, rare ripple form sets or climbing ripples.	Subhorizontal, laterally extensive; thick bedded (to several meters)	Fine organics present but not prominent; major unit
F3	Laminated to massive very fine mud beds, typically blue-gray. Maximum bed thickness 10 cm, often representing single current ripple form set.	Subhorizontal, laterally continuous; interbedded with organics, gravels	Limited exposure
F4	Thick, massive to weakly laminated blue-gray clayey mud and brown silty mud. Beds to several meters thick.	Subhorizontal, laterally extensive; drapes preexisting topography	Major unit; homogeneous; finer grained in distal former Lake Mills than Aldwell
F5	Striped mudstone with fine organics. Silt beds with interlaminated organic mats (mostly leaves). Interbeds 1–3 cm, weakly wavy to planar	To 2 m total thickness, subhorizontal, laterally extensive	Organic interlaminar; well preserved, well-sorted broadleaves
F6	Thinly graded fine organic and silt interbeds with fine sand. Sticks, cones, and bark fragments constitute minor total area of unit but are not uncommon.	Subhorizontal; laterally extensive	Often interbedded with gravels
F7	Poorly sorted, thick-bedded silty sand to sandy silt capped by silt bed. Chaotic fabric with occasional climbing ripples and organics.	Variable, frequently erosive; laterally extensive.	Similar to S4 but finer grained; appears to be drawdown- exclusive unit
F8	Laterally migrating, channelized mud-clast conglomerate interbedded with pebbles, sands.	Laterally migrating channel form directly overlying forest floor	Rare; probably drawdown-only unit
O1	Interlocked, randomly oriented branches to 2–3 cm diameter forming open-framework lenses or beds. Sticks typically bark-denuded but angular.	Channelized lenses or planar beds pinching out within several meters	Typically associated with gravel facies; isolated but not uncommon
O2	Steeply dipping, well-bedded organics including branches, cones. "Clast"- to matrix-supported, matrix medium sand and granules.	Steeply dipping (25°–30°), to 1 m thick	Prominent in foreset beds; organics well preserved
O3	Clast-supported medium to coarse organics in a sandy matrix with common muddy interbeds. Fabric typically chaotic; organics may occur as lag.	Undulating channel form or as lenses; bottom contact typically erosional	Common in former Lake Aldwell
O4	Cross-stratified to cross-bedded channelized organic units in sandy matrix. Clast- to matrix-supported; organics are needles, bark fragments, cones.	Gently dipping or subhorizontal, channel cuts common	Appears to be drawdown- exclusive unit
OF1	Weakly bedded silt and organic unit. Organic units matrix-supported, densely packed, silty matrix to open framework	Beds 1 cm to 10 cm thick, subhorizontal to undulating	Upper contact shallow or subaerial at time of exposure
OF2	Coarse organics (branches to 10 cm diameter, sticks, root balls) in mud matrix. Tightly packed, clast-supported	Irregular; often in lee of stranded root ball	Discontinuous; isolated within other facies

Notes: Facies are coded by dominant grain size (G—gravel; S—sand; HS—heterogeneous [sandy]; F—fines [a field-scale determination including silt and clay]; O—organic; OF—organics in fine-grained units or with a fine-grained matrix). Numerical values indicate fining of dominant grain size within group based on field description (e.g., facies G1 is generally coarser grained than facies G8, but both are dominated by gravel).

The locations of sections were mapped using a survey-grade global positioning system (GPS) and/or a commercially available unit set to collect in average mode; accuracy of both survey- and commercial-grade units was variable (horizontal error <3 m was typical) and the steep canyon walls in upper Lake Mills occasionally prevented GPS usage. As a result, the mapped locations of stratigraphic sections were hand-adjusted using detailed orthoimagery of the reservoirs collected in July of 2014 (National Park Service, 2014, personal commun.).

On the basis of observed sections, we classified reservoir sediments into 32 distinct facies that encompass the total assemblage of sediments observed in sections in the reservoirs (Table 2). The 32 facies were assigned alphanumeric codes that represent a high-level grouping according to dominant grain size (G = gravel; S = sand; HS = heterogeneous [sandy]; F = fines [a field-scale determination including silt and clay]; O = organic; and OF = organics in fine-grained units or with a fine-grained matrix) followed by a numeric value that indicates a general fining of the dominant grain size within the group (e.g., facies G1 is generally coarser grained than facies G8, but both are dominated by gravel). We use the term facies in the descriptive rather than genetic sense and classified sediments based purely on similar grain size, sorting, and structural characteristics at the outcrop scale. Some facies (for example, those classified as "H," or heterogeneous) could arguably be considered facies associations and further subdivided. However, in making our facies designations, we tried to maintain a field-appropriate scale and thus group thin-bedded and heterogeneous, but consistent, units into single facies.

For the purposes of this study, sediments in the former Lake Mills and Lake Aldwell basins were classified into three time periods: predam, reservoir, and post–dam removal. The predam era represents any sediments deposited prior to dam closure in 1913 and 1927, respectively, while the post–dam removal era represents sediments remobilized by the delta progradation caused by the stepped removal of the dams, as well as any subsequent river deposition, beginning in September of 2011. We explicitly only considered the reservoir era of sedimentation in this study (i.e., 1913 and 1927 to 2011); however, several of the 32 defined facies resulted from drawdown processes, which operated from 2011 to 2013. Where exposed, the contact between predam and reservoir sediments was typically clear; the sedimentation resulting from dam removal activities, however, could be more challenging to distinguish and could not always be conclusively determined. Discussion of the predam and post–dam removal sediments, as well as more detailed criteria for facies characterization, is included in the supplementary materials.[1]

Sedimentation Rates and Reservoir Accumulation Volumes

Immediately prior to dam removal, Bountry et al. (2011) estimated that former Lake Mills stored 15.6 (±2.7) × 10^6 m^3 of sediment, 51% of which was in the delta, 38% on the reservoir floor and margins, and 11% in the Rica, Boulder Creek, and Cat Creek Canyons. This estimate for former Lake Mills was produced by comparing a survey completed in 2010 with a survey completed in 1994 (Gilbert and Link, 1995) and with a topographic map completed prior to the closure of Glines Canyon Dam; in it, Bountry et al. (2011) noted that the sedimentation rate from 1994 to 2010 was ~47% greater than from 1927 to 1994, an effect probably attributable to landslide activity in the upper watershed. Initial estimates of sediment storage in former Lake Mills appear to have been accurate within the margin of error; following dam removal, Randle et al. (2015) revised the total sediment accumulation in former Lake Mills to 16.1 (±2.4) × 10^6 m^3, based on better predam control following dam removal.

Based on the estimated sediment volume in former Lake Mills discussed above (Bountry et al., 2011; Randle et al., 2015), an estimated trap efficiency in former Lake Mills of 0.86 (Childers et al., 2000), and sediment load calculations from data collected during water years 1995–1998 and 2006–2007 (Curran et al., 2009), the average sediment yield of the Elwha watershed above former Lake Mills is estimated between 1.84 × 10^5 $m^{3\ yr-1}$ and 2.26 × 10^5 $m^{3\ yr-1}$. However, based on accumulation rates from 1994 to 2010, this rate may have been as high as 3.60 0^5 $m^{3\ yr-1}$ (after Bountry et al., 2011).

Calculation of sediment yield below former Lake Mills and accumulation rates in former Lake Aldwell was significantly more complicated. No data with which to calculate the sediment yield for the Elwha River above former Lake Aldwell were collected before the 1927 construction of Glines Canyon Dam or before its removal in 2012. Additionally, no formal topographic survey of the site of former Lake Aldwell was completed prior to the completion of Elwha Dam in 1913. As a result, estimates of sediment yield and accumulation rates are based exclusively on in-reservoir bathymetric surveys from 1994, 2010, and 2012–2014 (after dam removal) and interpolation of the predam valley floor. Prior to dam removal, the sediment volume in former Lake Aldwell was estimated as ~2.97 (±1.0) × 10^6 m^3 (Gilbert and Link, 1995; Bountry et al., 2011). Based on additional evidence following dam removal, this estimate was revised to 4.9 (±1.4) × 10^6 m^3 (Randle et al., 2015). We discuss this discrepancy using our stratigraphic interpretations and the process-based insight gleaned therefrom in the Discussion section.

RESULTS: DEPOSITIONAL CHARACTERISTICS OF THE FORMER RESERVOIRS

Here, we characterize the sedimentation in former Lakes Mills and Aldwell according to the geomorphology of reservoir sediments at the time of dam removal, the style and rate of delta progradation over the life span of the former reservoir, and the facies architecture of depositional environments within each reservoir.

Lake Mills

Geomorphology

At the time of removal, the Lake Mills delta was characterized by a subhorizontal delta plain extending nearly 1 km into the main body of the reservoir, with accumulation of coarse-grained sediments nearly 2000 m upstream into Rica Canyon (Fig. 4B). The delta geometry was characterized by a sharp break in slope ("pivot point," as typically referred to in reservoir literature; e.g., Morris and Fan, 1997) with an average delta slope gradient of 0.30. Beyond the delta slope, sediment accumulation formed a wedge of sediment thinning toward the main lacustrine basin. Beyond the influence of deltaic sedimentation, the thin sediment accumulation approximately paralleled the predam gradient (Fig. 3B).

As mapped in Figure 6A, the former Lake Mills reservoir consists of six depositional regions: the basin (i.e., lacustrine area), prodelta, delta slope, delta top, delta plain, and associated hillslope areas. Key geomorphic features within these regions (mapped only where visible in orthoimage or field mapping) included subaerial and subaqueous bars, vegetated regions of the delta plain, and accumulations of woody debris.

At about the time of dam removal, the Lake Mills delta plain was characterized by a well-vegetated, alluvial upper reach and cuspate delta mouth. Deposition in Rica Canyon was characterized by extensive alternate bars, while the Cat Creek Canyon was completely vegetated, with multithreaded stream channels extending to the main Mills delta plain. Immediately downstream of the mouth of Rica Canyon, where the main Lake Mills basin expanded, the mainstem Elwha River was split by a central "middle ground" bar (sensu Wright, 1977) heavily armored with woody debris. The upper delta plain formed an anastomosing floodplain, characterized by thickly vegetated bars, extensive subaerial bars, and stable, multithreaded channels with minor distributary splays. The lower delta plain was characterized by more complex morphology, with complexly interfingered subaqueous and subaerial bars. Progressive accumulation of woody debris and consequent armoring of channel banks appear to have deflected the main distributary channel to the left bank (west), forming a single deep channel that distributed the majority of the incoming Elwha discharge to the active delta mouth.

The majority of the delta front was characterized by a cuspate margin well armored by woody debris. At the time of dam removal, the main delta had prograded as far as Boulder Creek, a major, steep tributary with significant secondary delta accumulation. The Boulder Creek delta, protected by an upstream hillslope knob protruding into the main body of the reservoir, formed a lobate, Gilbert delta with a slope of 0.30. Where the Boulder Creek delta interacted with the main delta, the delta top (defined here as the subaqueous portion of the delta plain; i.e., subaqueous deposition upstream of the pivot point) was characterized by a shallow, subaqueous middle bar extending well beyond the cuspate delta margin. The mean gradient of the delta slope beyond this subaqueous mouth bar was considerably less than the main delta, at only ~0.18.

Downstream of the delta front, detailed geomorphic characteristics of the subaqueous regions (basin, prodelta, delta slope) were difficult to resolve at the scale of available bathymetric data. The prodelta wedge was characterized by low-angle, low-gradient (average 0.02) deposits and lacustrine sedimentation reflecting a subdued form of the predam topography.

Delta Evolution

We characterized the evolution of the delta and character of delta deposits in former Lake Mills using historic aerial photographs of the Lake Mills region. The earliest aerial imagery of Lake Mills was taken in 1939, when the reservoir had been impounded for only 12 yr and showed an irregularly lobate, subaerial delta extending ~225 m down the Cat Creek Canyon (Fig. 7). By 1956, the Cat Creek delta appears to have prograded ~0.37 km into the main reservoir

[1]GSA Data Repository item 2018204, geology of the Elwha catchment depicting named tributaries to Lakes Aldwell and Mills, and geologic data after Schuster (2005), is available at http://www.geosociety.org/datarepository/2018 or by request to editing@geosociety.org.

with ample accumulated sediment. The imagery shows the reservoir elevation below full pool, indicating at least occasional drawdown events. Still, by 1976 (after 49 yr of operation), no subaerial delta had yet established itself in the main reservoir. By 1981 (not pictured), aerial imagery shows a shallow subaqueous, cuspate delta with cuspate delta mouth extending nearly 700 m into the main Lake Mills. The upper 400 m section appears to have been at least partially subaerial, forming an irregular system of bars. The Boulder Creek delta appears to have been well established; while not subaerial, a distinct lobate form is visible.

Delta morphology appears to have been significantly altered by the drawdown experiment of 1989, which dropped and held the water-surface elevation of Lake Mills at 5.5 m below normal operating elevation for 4 wk in the spring of 1989 (Childers et al., 2000). This prolonged drop in base levels appears to have caused major erosion of the delta plain. Rather than an arcuate, well-defined delta mouth as shown in the 1981 aerial photograph, the delta in September 1990 was characterized by side bars in the lower delta plain and a major mid-channel bar at the upstream head of the basin

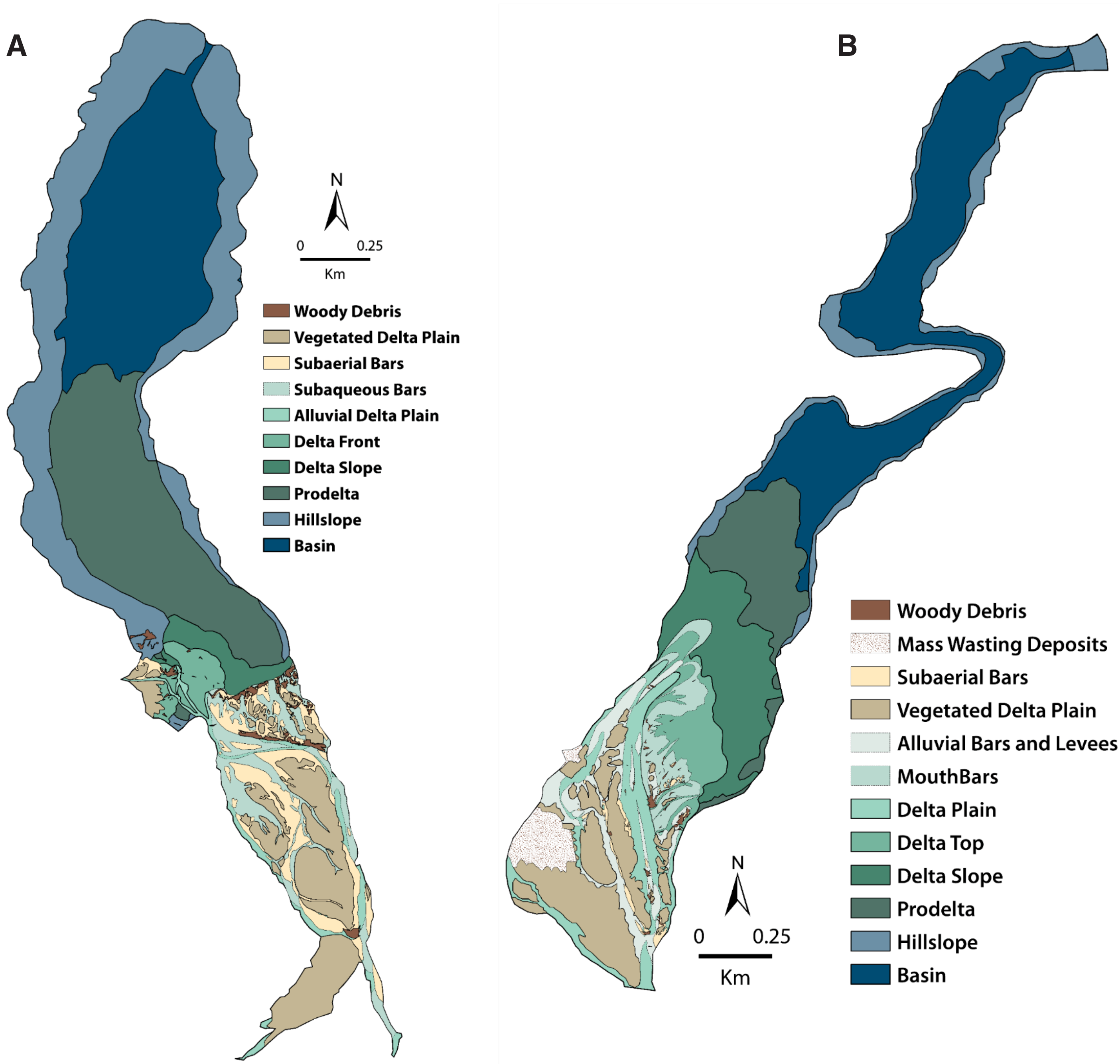


Figure 6. Geomorphic maps of (A) Lake Mills and (B) Lake Aldwell based on 2006 and 2009 aerial photographs. Heavy outline indicates depositional area (basin, hillslope, prodelta, etc.). Light outline indicates geomorphic feature within depositional area. Warm colors are subaerial; cool colors are subaqueous.

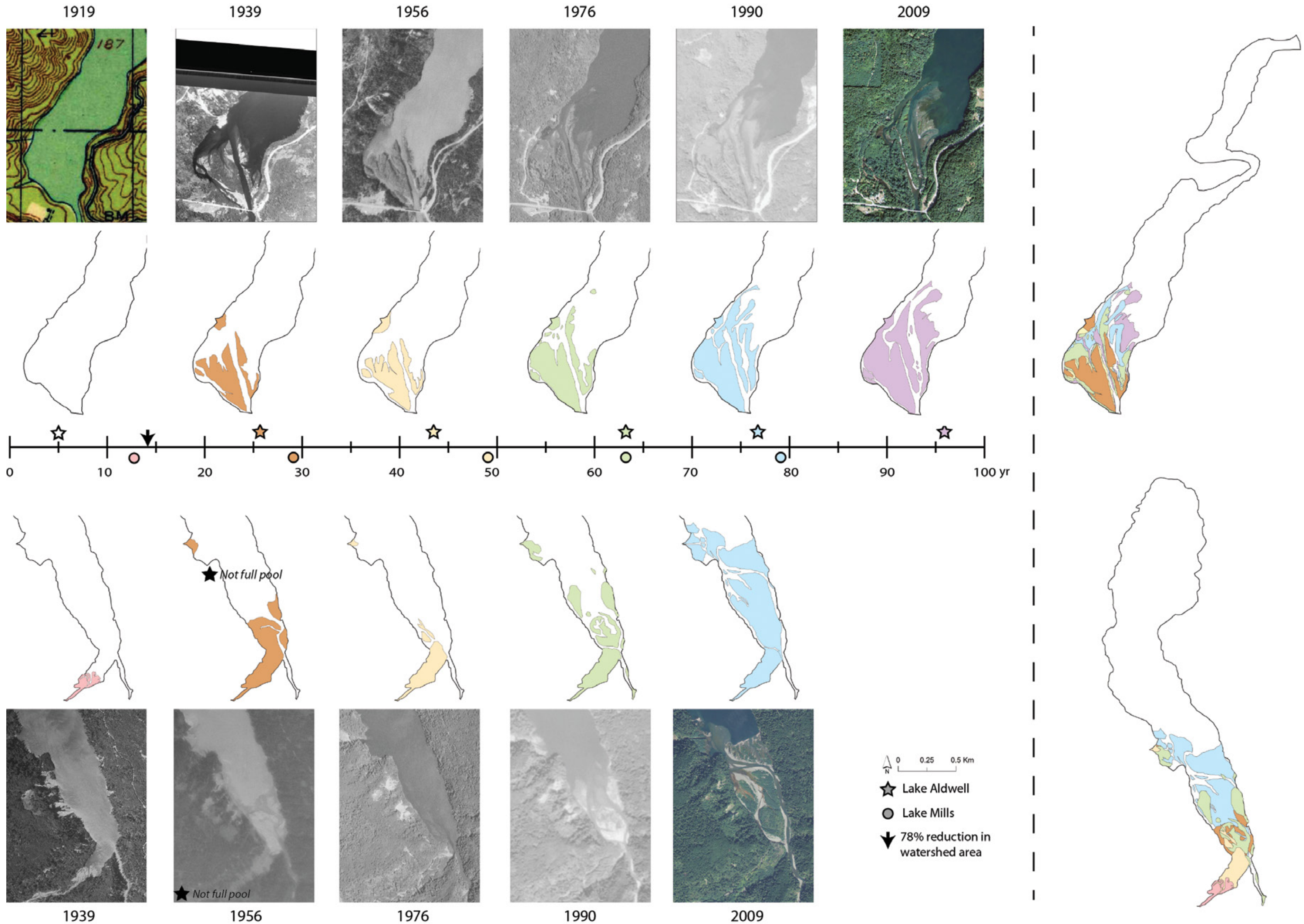


Figure 7. Relative subaerial delta growth and morphology for Lake Aldwell (above) and Lake Mills (below). Colors indicate reservoir age (yr since dam closure); absolute dates are given above/below aerial photographs.

(Fig. 7). The central delta front appeared to be rebuilding in the form of multistoried lobes of sediment prograding toward the original delta mouth. Significant woody debris appears to have accumulated at the head of the midchannel bar and on the side bars.

By 2004 (following an additional drawdown experiment in 1994), the Elwha River had reestablished a fluvially dominated delta plain that appears to have remained relatively stable until removal activities began in 2010. However, the active mouth bar near the mouth of Boulder Canyon (as described above) appears to have evolved from a lunate form in 2006 to the midchannel bar observed in 2009.

Facies Associations

Distinct facies were identified in the two Elwha reservoirs (Table 2). When mapped by depositional region, these facies were observed to occur in distinct groupings according to depositional area, as shown by the representative sections (Fig. 8). The patterns observed in these representative sections, as well as from those locations mapped in Figure 4C, were then used to create a series of idealized stratigraphic sections for former Lake Mills (Fig. 9) and a conceptual model of sedimentation (Fig. 10A). Working generally from upstream to downstream, these characteristic facies associations, as defined for former Lake Mills, are discussed next. Alphanumeric designations are keyed to stratigraphic sections as described above (Table 2).

Delta plain (G1, G5, S1, O1, F6). As the result of the stepped drawdown approach to dam removal discussed above (Fig. 5A; Randle et al., 2015), preservation and exposure of the former Lake Mills delta plain were limited. While supplemented with photographs from Childers et al. (2000) and unpublished photographs from the National Park Service, interpretations in former Lake Mills are thus heavily biased toward marginal sediments, which were characterized by stable, primary distributary channels over most of the evolution of the delta plain (Fig. 7). Marginal upper delta plain deposits were characterized by cobble to boulder gravels occurring as multistory sheet deposits, interbedded with pebble foreset and plane-bedded sand units (G5, S1; Figs. 8, 9A, and 9B). Beds were >1 m thick and massive to crudely stratified; where present, the matrix consisted of sand and pebbles, with little silt present. Lenses of clast-supported to open framework branches were common (O1).

However, better preservation in portions of the delta plain in Boulder Creek, a similarly steep-gradient, Gilbert-style delta, indicated that topset units were primarily composed of coarse gravels with occasional interbedded sand and organic units. Finer-grained facies, like OF1 and F6, composed of interbedded, subhorizontal silt and sand units with or without prominent organics, were present but appeared to occur only as thin veneers over the topset gravel beds. These facies appear to have been deposited in the inactive portions of the delta plain, allowing the establishment of stable vegetation.

Delta top (O3, G4, S1). At the time of dam removal, the active, subaqueous Lake Mills delta top was characterized by a lobate middle-ground bar prograding over the Boulder Creek prodelta (Figs. 6A and 8). Exposure in this region was poor by the summer of 2014, but stratigraphic sections showed O1 and HS2 foreset beds underlying delta mouth bar facies O3, G4, and S1. Unit G4 consisted of silty sandy gravel to sandy gravel, characterized by sheet-like geometry and medium gravel lag. It occurred as multistory units, sometimes interbedded with other facies. Where observed in Lake Mills, it tended to be interbedded with HS1, a poorly sorted sand and pebble unit characterized by thick (1 m) accumulations of clast-supported organic debris. The organic debris tended to occur as lenses, indicating channel lag, or as lateral accretion cross-beds in preserved channel forms.

Delta slope (S3, O1, O2, G3, G6, G10, HS2, HS3). Downstream of the delta top "pivot point," the delta slope in Lake Mills was characterized by steeply dipping (~30°) foreset beds with variable lithology and a sharp to tangential toeset (Figs. 3B and 8). No well-exposed beds were preserved in the main body of the reservoir; however, anecdotes and photographs from the 1994 drawdown experiment (Childers et al., 2000) recorded extensive, steeply dipping foresets that were progressively exposed as the delta adjusted to a lower base level. In the Boulder Creek delta, steep foresets consisting of facies G6, HS3, and O2 were well preserved (Fig. 8). Facies HS3 and O2 were similar to HS2 and O1 but steeply dipping. Facies O2 represents detrital organic accumulations up to 1 m thick, extending the length of the foreset bed. Toward the mouth of Boulder Canyon, toeset deposits were absent, and foreset beds were observed in sharp contrast with underlying, fine-grained deposits. More distally, where the Boulder Creek delta prograded to interact with prodelta deposits of the main Mills delta, foreset beds were observed to grade sigmoidally to finer-grained facies, forming extensive toeset deposits.

Toeset facies (gradational with the proximal prodelta facies) included S3, G10, F1, O1, and HS2 (Fig. 9A). These facies tended to be variably interbedded and to decrease in gradient down section. Complexly interbedded with S3, O1, and HS2 (all finer-grained facies, discussed further below), the G10 facies was composed of a low-angle sand to granule and pebble conglomerate. It tended to be well sorted and thickly bedded (average 0.5–1 m), pinching out downstream. Similarly interbedded but irregularly occurring, the O1 facies consisted of coarse, abraded organic detritus forming lenses and beds that pinched out downstream. These organic units tended to be interbedded with medium to coarse sands, but sometimes occurred independently and tended to have limited matrix. In the upper portion of the toeset facies, interbedded fine sand and silt represented a lower-energy regime. Facies HS2 tended to be complexly bedded and to exhibit wave ripples to wavy bedding. Facies G3, an angular, matrix-supported deposit, was interpreted as evidence of a debris flow extending into the toeset section (Table 2), and not representative of delta processes, and it is discussed below.

Prodelta (F2, F1, S3). The prodelta in former Lake Mills was dominated by the sand-dominated facies S3, grading to the fine-grained F1 and F2 deposits with distance from the influence of deltaic processes.

Proximal (bottomset). Close to the delta face, coarse-grained toeset facies decreased and graded to S3 (Fig. 9A), a longitudinally and laterally extensive deposit of well-sorted, fine to medium sand with little to no silt matrix and interlaminated to interbedded fine, medium, and coarse organics. Planar to sigmoidally shaped, cross-laminated beds occurred from 20 cm to ~1 m as stacked beds with broad lateral undulations. Climbing ripples were common. Bark fragments, conifer needles, and twigs with intact bark occurred as beds up to 10 cm thick proximal to the delta, 5 cm thick in the distal prodelta, and in the lee of climbing ripples. Closer to the delta, beds of the S3 facies were laterally extensive for tens for meters and were characterized by broad undulations and a variable but low-angle gradient of ~0.01.

Distal. With distance from the delta, the S3 facies thinned and graded to the F1 facies, which consisted of mudstone to silty sand closely interbedded with fine to medium sand beds, forming a "striped mudstone" (Table 2; Figs. 9A and 9C). Sand beds in the F1 facies averaged ~5 cm thick and consisted of fine to medium sand typically preserved as discrete current ripple form sets. At their maximum, sand beds reached 15 cm thickness with prominent cross-bedding and planar bedding, often highlighted by conifer needles preserved in the ripple lee. Both the thickness and frequency of well-sorted sand beds decreased down section, eventually grading to facies F2. These units consisted of subhorizontal, interlaminated to interbedded muds and silty fine sand with well-sorted fine sand interbeds at irregular intervals. Subtle draping of preexisting topography was occasionally

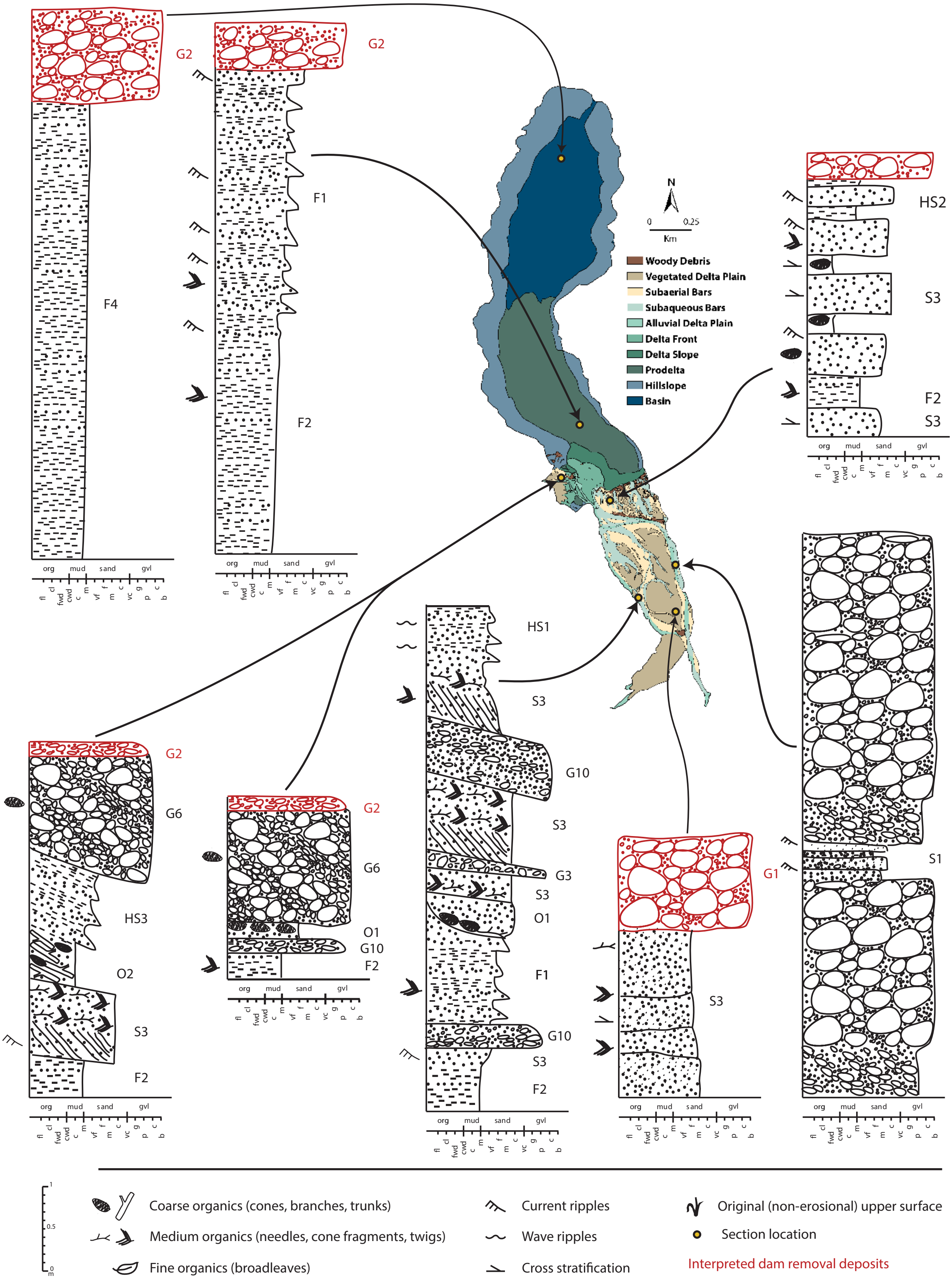


Figure 8. Representative stratigraphic sections within geomorphic depositional zones for former Lake Mills. Explanation of facies terminology is given in Table 2. Detailed view of geomorphic map is given in Figure 6. Grain size abbreviations as follow: org—organics (fl—fine litter, cl—coarse litter, fwd—fine woody debris, cwd—coarse woody debris); mud (c—clay, m—mud [undifferentiated clay and silt]); sand (vf—very fine, f—fine, m—medium, c—coarse, vc—very coarse); gvl—gravel (g—granule, p—pebble, c—cobble, b—boulder).

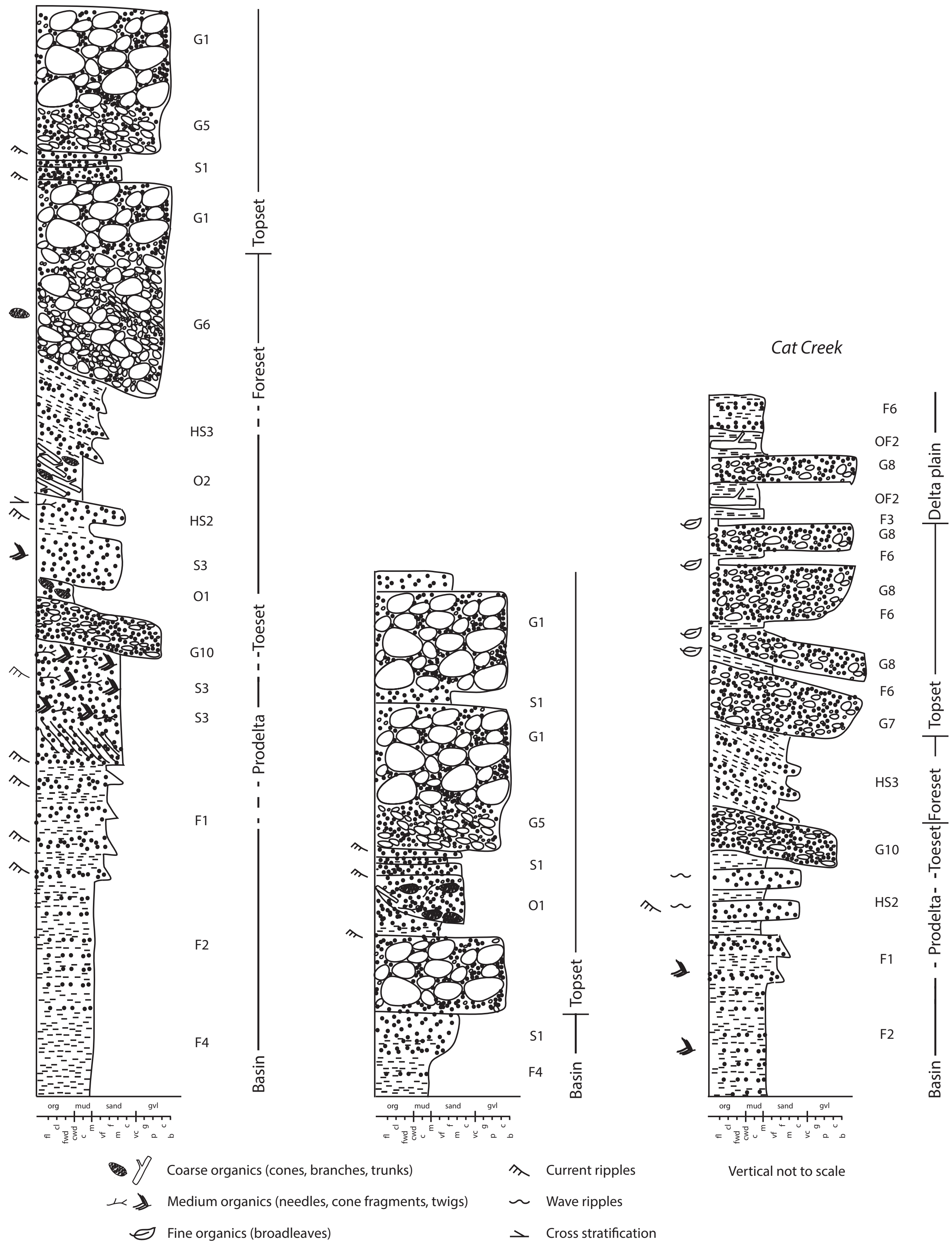


Figure 9. Idealized stratigraphic columns for former Lake Mills: (A) composite stratigraphic column occurring in the main body of the basin, (B) composite column that would occur closer to the head of the reservoir (near Rica Canyon), and (C) composite column for the Cat Creek tributary, the only complete, exposed section preserved in reservoir sediments as of 2014. Facies terminology given in Table 2. Grain size abbreviations as in Figure 8.

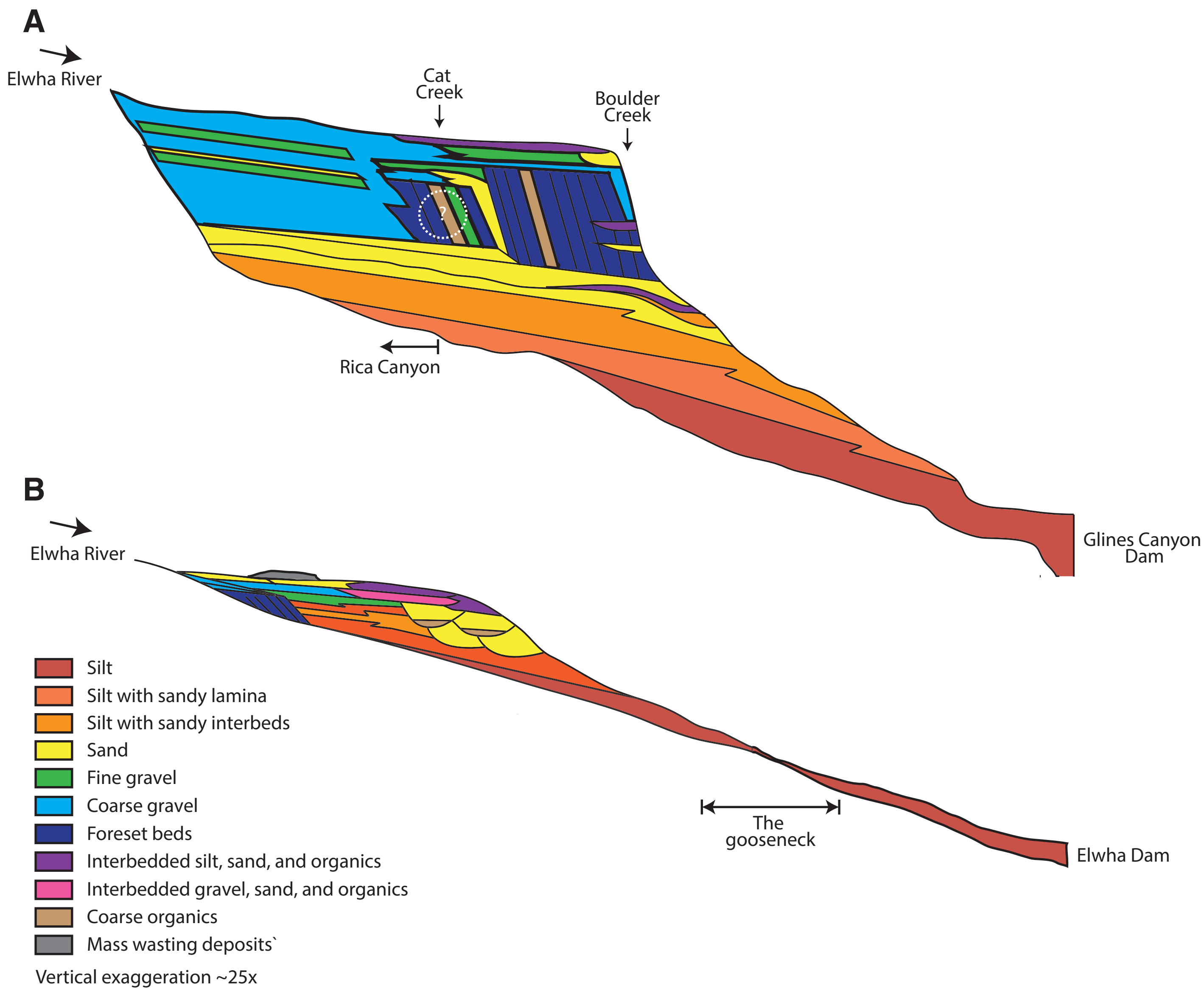


Figure 10. Conceptual cartoon model of cross-sectional sedimentation patterns in former Lakes Mills (A) and Aldwell (B). Total sediment accumulation profiles are approximately representative of actual conditions in 2010, but all stratigraphy is interpretive.

visible but tended to be muted by the underlying lakebed facies (discussed below). Sandy interbeds were uncommon but not rare, occurring as single, discrete form sets of current ripples or as beds of subcritical climbing ripples to ~10 cm thickness. F2 deposits were observed to be infrequently interrupted by chaotic lenses or channelized units of coarse organics consisting of sticks, bark fragments, cones, and needles in a matrix of poorly sorted silty sands.

In Lake Mills, the F1 facies was extensive and thick, forming the majority of >5-m-thick sections exposed throughout the prodelta area. The F1 facies appears to have been dominant compared to F2, which was marginal in thickness and occurrence; however, the relative scarcity of F2 may reflect poor preservation in the distal prodelta. An erosional scallop exposing an east-west face of prodelta sediments showed F2 deposits along the reservoir margins, which graded to F1 facies both above and laterally toward the depositional axis of the reservoir basin.

Basin (F4, F2). Downstream of the distal prodelta, basin deposits in former Lake Mills graded from F1/F2 to the F4 faces, which were thick, laterally extensive, and homogeneous. The F4 facies were composed of silty deposits with millimeter- to centimeter-scale, subhorizontal laminations. Interlamina composed of very fine sand or degraded organic detritus were present but uncommon. Lower F4 sediments tended to drape underlying predam features (including both topography and old-growth stumps left in place at the time of reservoir filling). With thickness, however, this draping became muted, and the majority of F4 and F2 sediments were subhorizontal. In section, basin sediments were distinctive due to a tendency to form competent bluffs that weathered in blocky or conchoidal fracture patterns. Incomplete sections composed entirely of the F4 facies were observed in excess of 5 m thick ~400 m upstream of Glines Canyon

Dam, while immediately downstream of the mouth of Rica Canyon, F4 was observed with a maximum thickness of <0.5 m. While generally homogeneous across its full thickness, the F4 facies was occasionally interrupted by laterally extensive interbeds of the F1 facies, which may have extended well into the distal portions of the reservoir (close to the dam).

Colluvial and shoreline deposits. In most areas, the reservoir margins were characterized by steep, submerged former hillslopes (Fig. 4C). Deposition on the reservoir margins appears to have been net accretionary (as opposed to erosional, as is common in reservoirs operated with large seasonal drawdowns). In most areas, deposition reflected the characteristics of the broader depositional zone (i.e., F4 in basin margins, G1 in upper delta plain margins) but tended to be thinner and to follow the angle of the hillslope. In shallow-water margins influenced by deltaic sedimentation, stumps and standing trees remaining from the predam era formed barriers to flow, resulting in complex imbrication patterns and fine-grained sedimentation in their immediate lees. In the upper portion of former Lake Mills, aerial photographs and facies G3 showed evidence of nonfluvial sediment transport to the reservoir. Unvegetated, sharp scarps in Pleistocene outwash and lacustrine deposits in the hillslopes above former Lake Mills (Fig. 7) suggested some influx due to mass wasting, while the angular G3 facies indicated that incursions of hillslope material contributed at least minor sediment volume to the reservoir.

Cat Creek delta (G10, G8, HS3, F6, OF2, F3). The only complete sections observed in former Lake Mills, as well as the only interdistributary portions of the delta plain, were preserved in the Cat Creek delta (Fig. 9C), located immediately downstream of the main Rica Canyon inflow to the reservoir. Basinal and prodelta deposits were characterized by the F2 and F1 facies, as in the main Lake Mills basin (Fig. 9A). Similarly, the toeset deposits were characterized by the G10 and HS1 facies. However, as compared to Lake Mills, the foreset facies in Cat Creek were less steeply dipping and finer grained (G7, HS3). Active topset channels were characterized by coarse gravels, but interdistributary areas were characterized by well-sorted gravels, cross-bedded gravels (G8), massive clay (F3), coarse organic detritus in a clay matrix (OF2), and interbedded silt and poorly sorted sand (F6).

Lake Aldwell

Geomorphology

In the years immediately prior to dam removal, upper Lake Aldwell was characterized by a low-gradient, irregularly shaped, shoal-water or slope-type delta, defined by a subhorizontal subaerial delta plain and shallow, subaqueous delta front (average gradient 0.04) separated from a low-gradient (average gradient 0.03) prodelta wedge by a moderate-gradient delta slope (average gradient 0.08; Figs. 5B and 6B). The lacustrine portion of the basin was characterized by thin accumulations of sediment with similar gradients to the predam topography, while the constriction separating the main basins appears to have had little sediment deposition.

We subdivided and mapped the former Lake Aldwell basin into six depositional areas, similar to former Lake Mills (Fig. 6B). However, Lake Aldwell did not have a distinct pivot point as described in Lake Mills, but it was characterized by a low-gradient, subaqueous delta top and a broad delta slope defined by the lee angle of major mouth bars. This delta slope was gradational in nature and, as discussed below, was not characterized by foreset beds, as in Lake Mills. In addition to those geomorphic features mapped in former Lake Mills, distinctive features in former Lake Aldwell included prominent mouth bars and mass-wasting deposits.

In the years immediately prior to dam removal, most of the upper delta plain was vegetated by mature broadleaf trees. A subtle but distinct break in crown height along the western margin of the delta plain is evidence of a landslide deposit (Fig. 11; discussed below). Additional, immaturely vegetated areas point to the development of incipiently stable conditions over the life span of the reservoir. Alluvial areas within the delta plain were characterized by a primary active channel with multiple partially abandoned distributary channels. By 2009, the main fluvial channel extended nearly 1 km into the reservoir with little sinuosity; it was marked by subaqueous levees and crevasse splays on the northern bank toward the delta front. As in Lake Mills, subaerial or incipiently subaqueous bars were commonly "armored" by accumulations of large woody debris at the head (Fig. 6B).

In the lower reaches of the delta plain, crevasse splays from the main fluvial channel coalesced into a broad, irregularly shaped delta front (Fig. 6B). Where the main fluvial channel opened into the Aldwell basin, series of lunate mouth bars prograded beyond the intermittently active portion of the delta front. The active portion of the delta appears to have been prograding along its western margin, where Indian Creek, which entered the reservoir near its head but was channelized along the western margin of the reservoir for nearly a kilometer, opened to the main delta. Muted lunate sedimentation patterns visible on the digital elevation model indicate that mouth-bar progradation was previously active along the eastern margins of the reservoir.

Downstream of the deltaic deposits, Lake Aldwell was characterized by a prodelta wedge with average gradient of 0.03 that appears to have prograded primarily along the western margin of the reservoir. Beyond the prodelta wedge, reservoir sedimentation is reflective of lacustrine, suspension fallout processes, with sedimentation mirroring and muting predam topography. In areas, the predam channel thalweg was clearly visible. Sedimentation in the constricted "gooseneck" portion of Lake Aldwell was very low; the lower basin of Lake Aldwell shows evidence of lacustrine sedimentation and creeping slump block movement. Similar to former Lake Mills, the reservoir margins appear to have been net accretionary.

Delta Evolution

The earliest available depiction of the Lake Aldwell basin is a 1919 topographic map (surveyed 1917–1918, <5 yr after dam closure), in which no subaerial deltaic exposure was indicated (Fig. 7). By 1939 (~25 yr after dam closure and 12 yr after the upstream closure of Glines Canyon Dam), a subaerial delta had prograded nearly 650 m into Lake Aldwell. The 640 m main channel appears to have been artificially straight and showed crosscutting relationships with transverse channels and vegetation growth in the lower delta, suggesting that the reservoir delta had been dredged to establish a channel into the main body of the reservoir and away from significant, abandoned channels along the western and eastern margins of the main Aldwell basin. Much of the delta appeared to have been well vegetated, indicating that by 1939, it had already been stable and subaerial for some time. The delta appears to have been active primarily along the northwestern front, where sediment from both the main-stem Elwha River and Indian Creek, which entered the reservoir ~400 m west of the Highway 101 bridge but was channelized against the western basin margin, entered the main body of the reservoir. In contrast to later years, the delta slope appears to have been well defined.

From 1939 to 1956, the subaerial delta extent appears not to have changed appreciably. The previously exposed subaerial bars were densely vegetated by 1956, however, and the river appears to have reoccupied the channel along the eastern basin margin, depositing the reworked sediment further into the deltaic margins. By 1976, the eastern subaerial deltaic margin had prograded nearly 400 m from the point of divergence with the main channel, while a lunate, subaqueous bar was evident beyond. Mass-wasting deposits from two scarps in the western

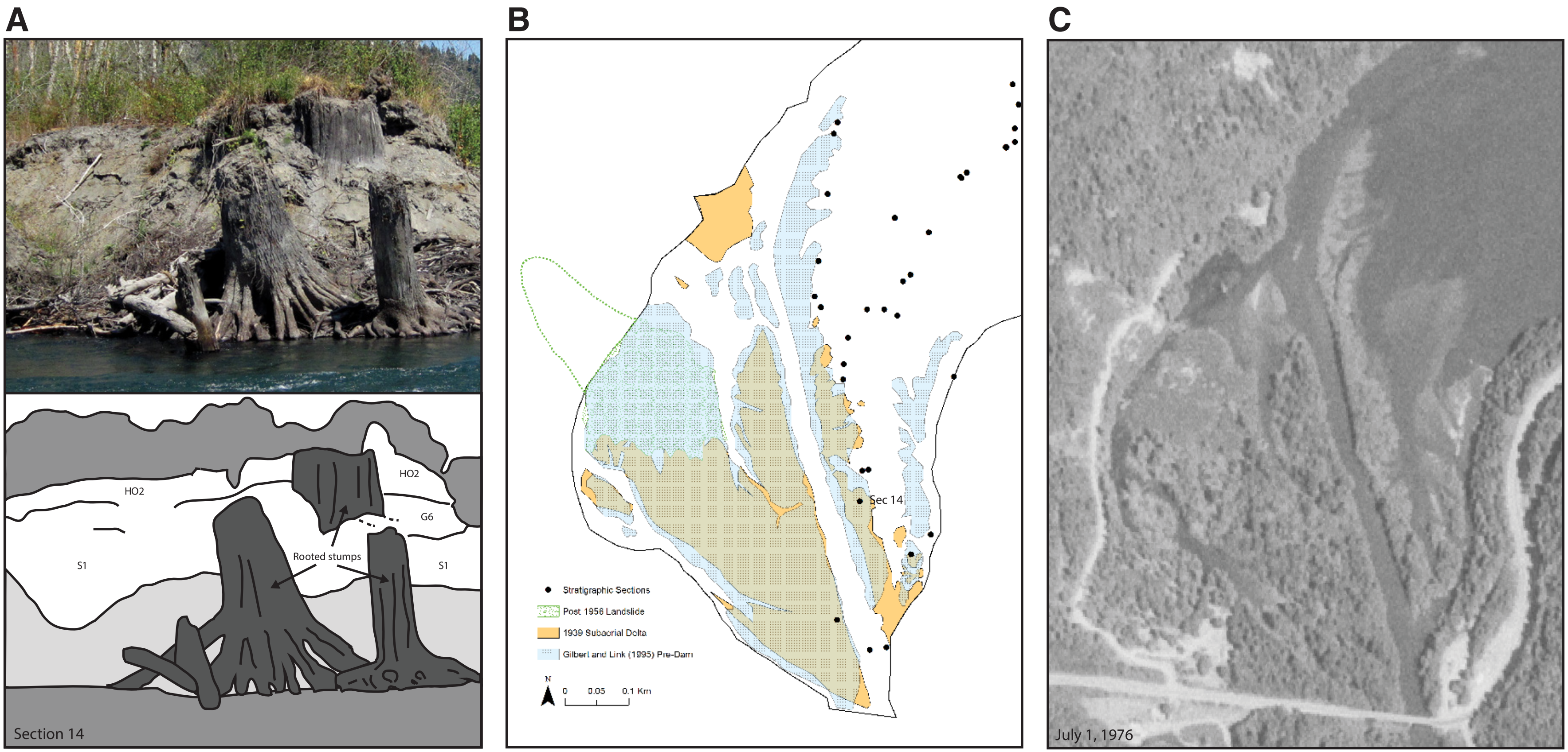


Figure 11. Evidence of extensive upper delta plain development in former Lake Aldwell early in the reservoir history: (A) rooted, logged stumps eroding from delta plain sediments (location in part B), (B) landslide deposits, delta extent as of 1939, and "predam" extent as mapped by Gilbert and Link (1995), and (C) July 1976 aerial photograph showing clear outline of slope failure and runout zone. Rooted stump with prominent roots visible is approximately 1 m diameter. Scale of Panel C as Panel B.

hillslope nearly filled the western portion of the upper basin sometime before 1976 (Figs. 11B and 11C); given the re-establishment of the Indian Creek delta channel and the prominent vegetation on both scarp and landslide runout, this slide probably occurred relatively soon after the 1956 aerial photograph was taken. Probably as the result of this new source of sediment, the elongate central bar of the main delta had prograded an additional ~250 m into the reservoir, with well-developed subaqueous central levees and mouth bars beyond.

From 1990 to 2009, the Lake Aldwell subaerial delta did not prograde appreciably, but the Elwha River continued to rework the uppermost delta plain, nearly abandoning the original and easternmost channels to shallow-water backwaters and reworking portions of the vegetated delta plain. Riffles evident in a 2006 aerial photograph show that avulsion was active during this time; by 2008 and 2009, the river had established a relatively broad, main channel to the active delta front.

While the subaerial portion of the delta remained relatively inactive from 1976 onward, the subaqueous delta front evolved considerably. Prior to 1976, the delta front appears to have been well defined, with a distinct delta slope and well-defined, lobate mouth bars (Fig. 7). After 1976, the delta developed an extensive shallow subaqueous front, with prodelta lunate bars extending well into the basin. By 2009, as discussed above, the main delta distributary channel was characterized by midchannel and lateral levees, with extensive crevasse splays forming a subaqueous delta front composed of welded mouth bars.

Facies Associations

As in former Lake Mills, described stratigraphic sections in former Lake Aldwell were mapped and assigned to facies associations to create a composite stratigraphic column of the facies architecture of the reservoir (Fig. 12). These descriptions utilized the same facies codes and descriptions as former Lake Mills (Table 2), but they were combined to form unique characteristic associations (Fig. 13). These facies associations, discussed according to depositional zone and illustrated by a conceptual model (Fig. 10B), are discussed below.

Delta plain (G2, G4, G8, G9, F3, F6, S1, O1, OF1). The delta plain in former Lake Aldwell was characterized by a variety of alluvial and deltaic environments, leading to deposition of diverse facies (Figs. 12 and 13). At the time of removal, much of the upper delta plain was emergent and had been stably vegetated for decades, forming a variety of side channels, overbank areas, and quiescent interdistributary areas (Fig. 6B). This environment most closely approximates an alluvial floodplain and was characterized by well-sorted channel sands and gravels (G9, S1), clay beds (F3, O1), and interbedded fine sand, silt, and organics in crevasse splays (OF1). The upper alluvial channels, grading to delta distributary channels, were characterized by extensive, massive to weakly stratified sheets of coarse gravels (G2, G4), which appear to have been relatively limited in extent, as further discussed below.

Given the relatively low gradient of the uppermost Aldwell basin (Fig. 3C), the massive old-growth stumps that had been logged and left in place during dam construction protruded into the shallow-water delta plain sediments (Fig. 11A). These appear to have created localized pockets of complex sedimentation immediately downstream but not to have broadly influenced sedimentation in the delta plain. Exceptions to this appear to have been where stumps served as a focal point for rafts of woody debris to accumulate; in several instances, subaerial delta bars armored by woody debris appear to have been anchored by these old-growth, rooted stumps.

Delta top (O3, F5, HS1, S1, S2, G8). In contrast to former Lake Mills, the active delta mouth in former Lake Aldwell was characterized by broad distributary channels leading to a large, shallow subaqueous area (Fig. 6). Where preserved, the delta mouth bars formed broad, overlapping channels eroded into the underlying delta slope sands Fig. 13B). These channels preserved significant accumulations of clast-supported woody debris in a sandy matrix (O3), which occurred as channel lag or formed lateral accretion surfaces. Thick accumulations of the F5 facies, a muddy unit finely interlaminated with well-preserved broadleaf lamina and well-preserved wave ripples, occurred in interdistributary areas.

Where the mouth bars merged to form a low-gradient sandy delta top, the HS1 and S1 facies, characterized by coarse sand and accumulations of coarse woody debris in poorly sorted, sheet-like geometry, were common. Facies HS1 was characteristic of the dam-removal flood deposits in both reservoirs, but it occurred broadly as a primary depositional unit in the delta top of former Lake Aldwell. Its occurrence is somewhat puzzling, but it may represent similar processes to those that created the F1 facies in former Lake Mills, i.e., the alternation between event-flow deposits and background, suspended sediment deposition. In section, the unit appears chaotic due to the disruption of woody debris, but it is actually well sorted. Where present in primary reservoir deposits, the absence of fine-grained material suggests that the HS1 facies was caused by winter flood deposition to the delta top, which was then winnowed by summertime distributary flows to the delta top combined with the disturbance of wave action.

Upstream of the delta mouth bars, the preserved, distal distributary channels were characterized by the S2 facies, which was composed of interbedded medium to coarse sand that was typically capped by laminated organics and silt to form multistoried couplets (Figs. 11A and 11B). Near the uppermost head of the reservoir, the S2 facies coarsened to form thick (~0.5 m) beds of fine, well-sorted gravels interbedded with silts and organics (G8).

Delta slope (S3, HS2, G7). In contrast to Lake Mills, the active delta slope in former Lake Aldwell was not part of a tripartite topset-foreset-bottomset morphology; instead, the delta slope tended to be characterized by mouth bar sands (S3) without a distinct break in slope (Figs. 6 and 10). The S3 facies was similar on a local scale to former Lake Mills, but it tended to be both thinner bedded and less extensive (or absent). In longitudinal section, it did not display the same prominent undulations as in Lake Mills, but it tended to form relatively uniform, low-gradient beds demarcated by climbing ripples or plane bedding. In lateral section, minor silt beds formed subtle lenses. Overlying or instead of S3, the HS2 facies was characterized by thinly bedded, well-sorted sand and silt couplets, which often exhibited wavy bedding.

Coarse-grained foreset beds were not entirely absent in former Lake Aldwell, however. While gravels were absent in the portion of the delta slope that was active at the time of dam removal, in the upper reservoir, matrix-rich gravels forming distinct foreset beds (G7) and horizontal topsets were exposed along the reservoir margin (Fig. 14). The G7 facies in former Lake Aldwell had a lower angle than similar deposits in former Lake Mills and appears to have prograded directly over F2/F4 basin sediments (in contrast to the expansive prodelta sands of former Lake Mills). At the time of dam removal, the overlying topset beds were nearly subaerial.

Prodelta (F4, F2). Prodelta deposits in Lake Aldwell were similar to the more distal portions of the prodelta in former Lake Mills, but they lacked the extensive deposits of the F1 facies in that reservoir. Lakebed deposits fined both down section and downstream, typically grading from F2, distal prodelta deposits, to fine-grained lacustrine-style deposits (F4; discussed below; Fig. 12). The F2 units consisted of subhorizontal, interlaminated to interbedded muds and silty fine sand with well-sorted fine sand interbeds at irregular intervals. Subtle draping of preexisting topography was sometimes visible but tended to be muted by the underlying

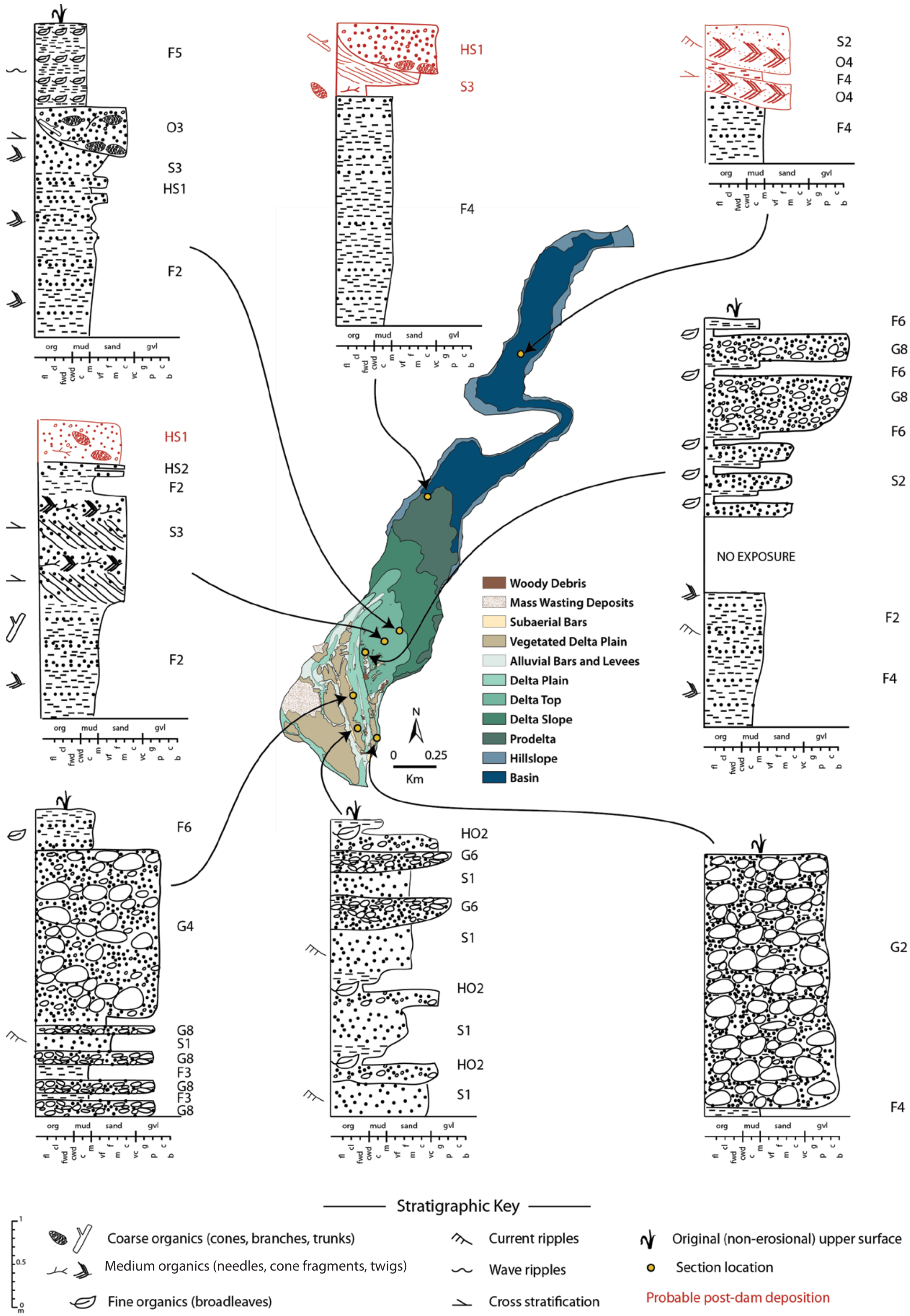


Figure 12. Representative stratigraphic sections within geomorphic depositional zones for former Lake Aldwell. Explanation of facies terminology is given in Table 2. Detailed view of geomorphic map is given in Figure 6. Grain size definitions as in Figure 8.

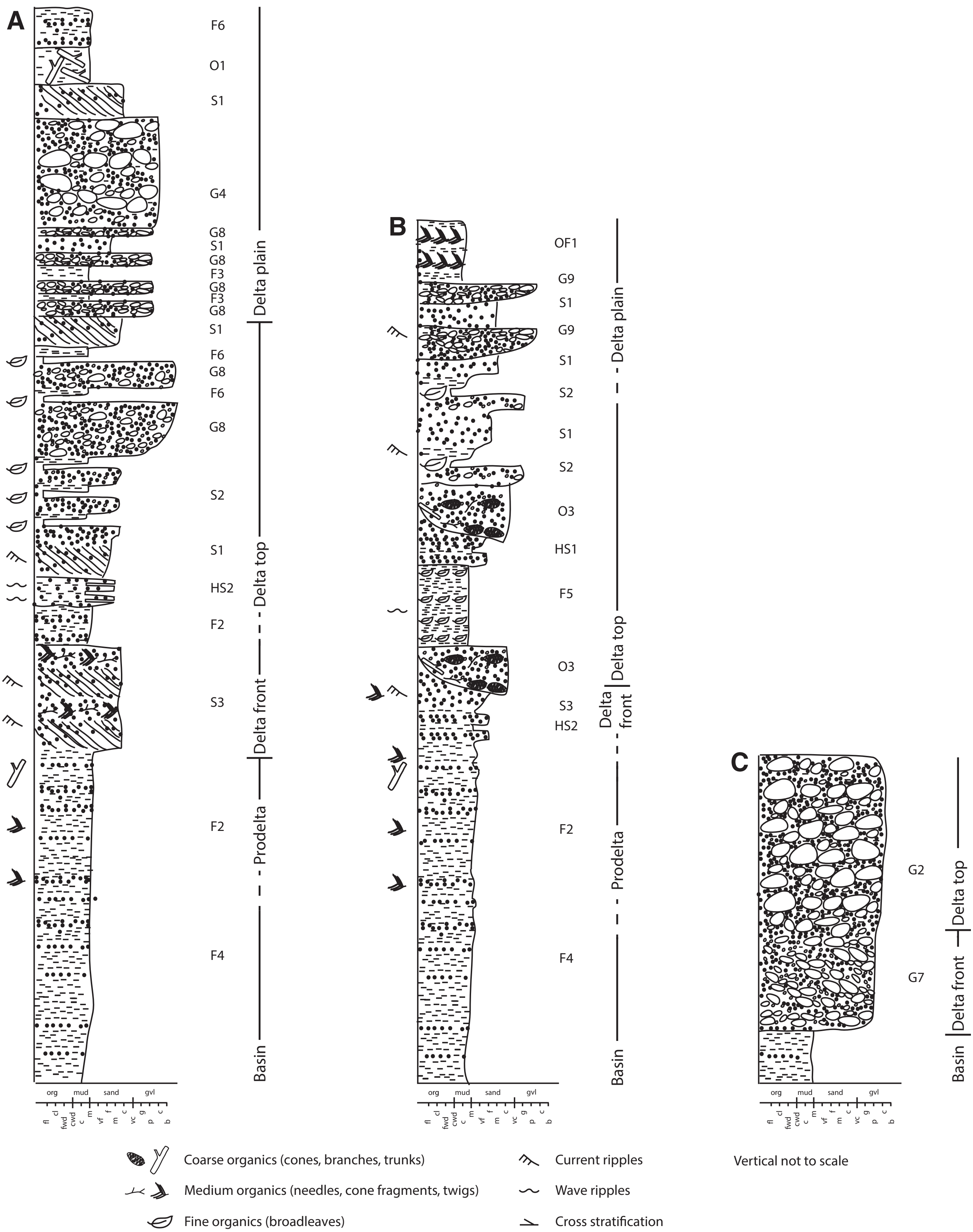


Figure 13. Idealized stratigraphic columns for former Lake Aldwell: (A–B) complete sections likely to occur lower in the basin, and (C) conditions in the uppermost delta plain. The upper delta plain of former Lake Aldwell was heterogeneous.

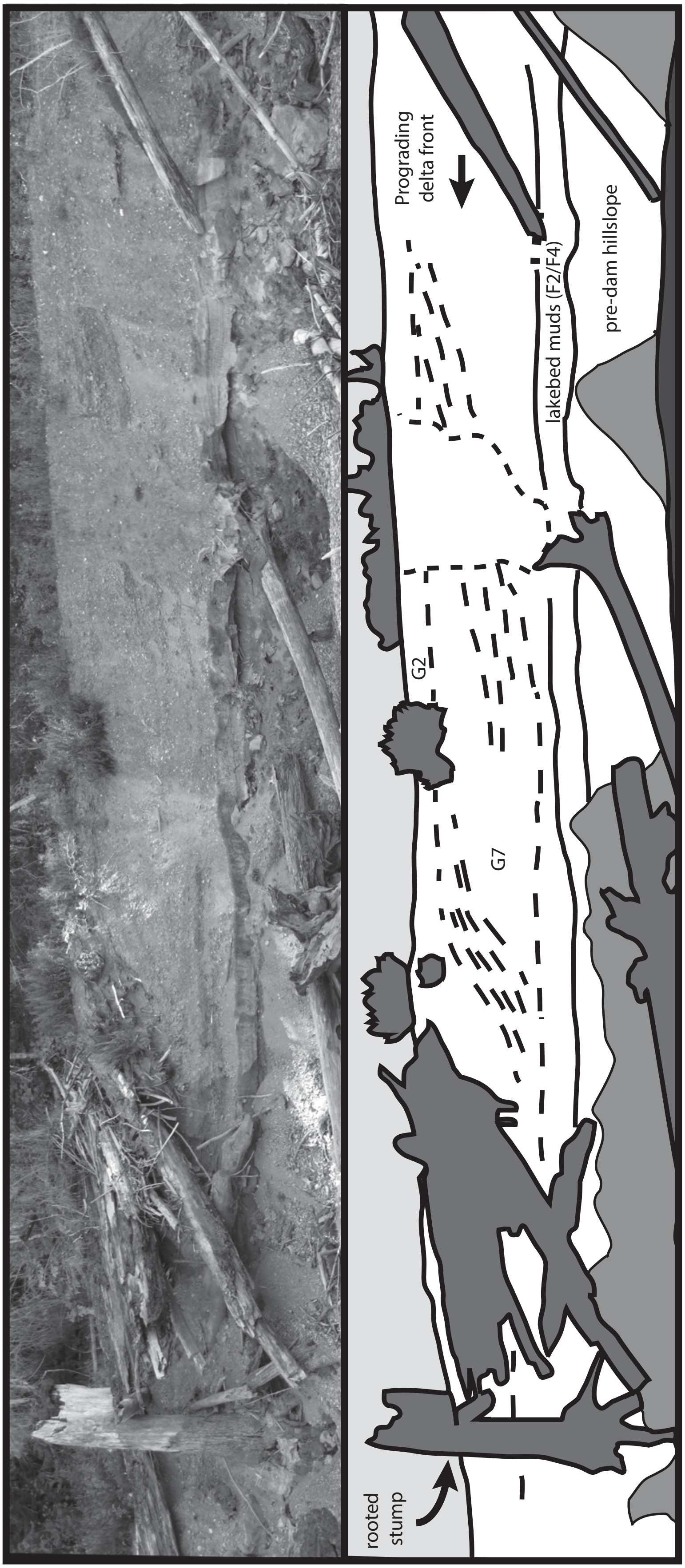


Figure 14. Photographic panorama and cartoon showing Gilbert-style progradation in former Lake Aldwell. Flow is to the left. "Rooted stump" is approximately 0.5 m diameter.

lakebed facies. Sandy interbeds were irregular but not rare, occurring as single, discrete form sets of current ripples or as beds of subcritical climbing ripples to ~10 cm thickness. F2 deposits were infrequently interrupted by chaotic lenses or channelized units of coarse organics consisting of sticks, bark fragments, cones, and needles in a matrix of poorly sorted silty sands. In former Lake Aldwell, packages of F2 overlying F4 were observed as thick as 3.5 m, with an erosional upper contact.

Basin (lakebed) deposits (F4). Basin deposits in Lake Aldwell were extensive and homogeneous, consisting primarily of the F4 facies. Closer to the delta, they tended to consist of silty deposits with millimeter- to centimeter-scale, subhorizontal laminations and occasional very fine sand or degraded organic interlaminae, while the lowermost and/or distal basin deposits tended to be clayey (Fig. 12), with a distinct blue-gray hue. Lowermost F4 sediments draped preexisting topography at both the individual cobble and section scale, though the draping effect was eventually muted by continued sedimentation. F4 sediments were subhorizontal and laterally contiguous for tens of meters, with a tendency to weather as competent bluffs with blocky to conchoidal fracture patterns. In Lake Aldwell, F4 deposits were observed as thick as 2.5 m, with an erosional upper surface, thinning to ~1.3 m of complete section immediately above the gooseneck.

Colluvial and shoreline deposits. Mass wasting appears to have played a significant role in the sedimentation of Lake Aldwell (Figs. 11B and 11C), as is discussed in detail below. However, no mass-wasting deposits were exposed for characterization of the facies. Similar to former Lake Mills, the former Lake Aldwell shorelines were characterized by thin, draping deposits of F4 and F2, or by a variety of coarse-grained delta plain facies. Many trees growing along shoreline at the time of reservoir inundation persisted throughout the reservoir life span; these appear to have influenced sedimentation significantly by serving as initiation points for rafts of organic debris to accumulate, creating areas of complex hydraulics and sedimentation (similar to the effect in the delta plain discussed above; for examples, see stumps in Figs. 11A or 14).

DISCUSSION

The architecture, geomorphology, and evolutionary sequences in the two reservoirs record both their underlying depositional processes and the distinctive environmental histories of the two reservoirs. Here, we consider how depositional processes, as revealed by stratigraphy, varied between the reservoirs and implications for interpreting sequences of reservoir deposits in rivers having multiple dams. Because the entire life span of both reservoirs existed within the historical record (as opposed to natural lakes), these environments provide a unique record with which to assess the connection between exogenic events and their stratigraphic expression, creating the potential for great insight into interpretation of paleoenvironments and the preservation of environmental events in the deep stratigraphic record.

Lake Mills

The morphology and sedimentation patterns in former Lake Mills closely approximate an ideal coarsening-upward Gilbert sequence, defined by a tripartite structure consisting of coarse-grained, subhorizontal topset beds, steeply dipping foreset beds, and a downstream-fining bottomset wedge (Fig. 10A). The close correlation between the sedimentation patterns observed in former Lake Mills and those of the ideal Gilbert-style delta indicates that the processes operating to deliver and deposit sediment in the reservoir are well described by the lacustrine-based Gilbert paradigm and are in keeping with the "typical" reservoir profile described by the USBR (Strand and Pemberton, 1987). However, the heterogeneity of deltaic slope deposits in the Boulder Creek delta, the importance of the F1 "striped mudstone" facies in the prodelta, and the occurrence of sandy interbeds in the lacustrine basin all suggest additional complexity in the processes influencing downslope transport in former Lake Mills.

Progradation in Gilbert deltas typically occurs by a variety of avalanching processes down the delta slope, ranging from continuous transport of sediment over the delta front to mass movement in response to oversteepening or flood events (Nemec, 1990b). The range of avalanching processes tends to produce relatively heterolithic assemblages controlled by and traceable to individual storm or flood events (Ambers, 2001; Pondell and Canuel, 2017). This morphology is reproduced well in the delta slope region of former Lake Mills (Figs. 8 and 9A), with low-angle interbedded fine gravels, coarse organics, and sands (G10, O1, S3, and HS2) overlain by steeply dipping sand, organic, and coarse gravel beds (O2, HS3, and G6), and coarse gravel, subhorizontal topset beds (facies G1, S1, G5, and O1) to form the typical heterolithic, tripartite Gilbert delta.

Beyond the delta slope, the occurrence of coarser-grained material in the deep-water, suspended sediment–dominated portions of lakes and reservoirs is typically attributed to storm-triggered turbidity currents, which have been extensively documented in lakes and reservoirs (e.g., Forel, 1892; Sturm and Matter, 1978; Giovanoli, 1990; Nemec, 1990b; Kostic et al., 2002; Twichell, et al., 2005). Resistance to mixing created by the density difference between nonturbid lake waters and sediment-laden density flows allow turbidity currents to maintain flow competence for great distances into stagnant basins (cf. Thornton et al., 1990). These flows tend to deposit characteristic turbidite deposits, in which fining-upward graded beds record deposition from peak flow to the waning limb of the event (Reading and Collinson, 1996).

However, little evidence of graded bedding was observed in former Lake Mills. Instead, the proximal prodelta was dominated by the F1 "striped mudstone" facies (Fig. 9A), consisting of laminated silts regularly interbedded with well-sorted sandy interbeds characterized by single cosets of climbing ripples or by rhythmic, isolated form sets of current ripples. We interpret this facies as the result of density flows, but we suggest that it may be the result temperature-derived plunging flow instead of a flood-derived turbidity current. The Elwha River experiences a major discharge peak during the summer, resulting from melting of the heavy snowpack in its high-elevation headwaters (Fig. 2). These summer high flows remain very cold, in contrast to the warm surface temperatures of the stratified reservoir waters, creating a temperature-derived resistance to mixing and causing river inflows to flow for great distances along the reservoir bottom before mixing with the reservoir hypolimnion (Thornton et al., 1990; Munn et al., 1999). We suggest that temperature-derived plunging flows provided a mechanism to sort and redistribute sands and silts from the delta slope into the distal prodelta, well beyond the occurrence of sand predicted by the Gilbert model of sedimentation.

This observation is in keeping with Snyder et al. (2006), who noted that the ideal progradation of the simple Gilbert delta is in reality rather rare. In former Lake Mills, as the delta slope prograded, the active distributary of the Elwha River flow into Lake Mills migrated laterally across the width of the basin, causing the active portion of the delta slope to migrate accordingly (Fig. 7). As a result, the two-dimensional progradation of evenly spaced foreset beds typically depicted in literature actually consists of series of complexly interfingering lobes (Nemec, 1990b). Observations of the foreset beds preserved in former Lake Mills (particularly in the vicinity of Boulder Creek) show beds that vary significantly both longitudinally and laterally, depending on proximity to tributary inputs, main distributary flow, reservoir morphometry, and water depth (accommodation space). Additionally, debris flows (facies G3) and other mass-wasting mass wasting deposit into the reservoir provided triggers for delta slope avalanching not directly tied to flow events (and with the potential for relatively localized influence). Further, observation of the F1 facies discussed above shows that sandy interbeds were thickest and most plentiful with proximity to the delta slope along the main longitudinal axis of the reservoir, suggesting a dependence on the location of the active delta distributary.

Erosion and delta progradation associated with two drawdown experiments, as well as non–run-of-the-river operations (for example, in 1956[?]; Fig. 7) or drought years, should be preserved in the reservoir sediments. The progradation of the delta during the 1989 and 1994 drawdown experiments were well documented (Childers et al., 2000; however, no formal stratigraphic descriptions were made at the time, and most strata potentially recording these sequences had been eroded or were thickly covered with coarse-grained sediment by the summer of 2014, when this field work was conducted). However, mouth bars forming the delta top in the 1990 aerial photograph (1 yr after the 1989 drawdown experiment; Fig. 7) stand in contrast to the sharp delta front depicted in the 2009 aerial photograph and our geomorphic mapping (Fig. 6A). We hypothesize that this mouth-bar morphology (similar to that observed in former Lake Aldwell; discussed below) reflects the shallower conditions created by the drawdown delta, resulting in progradation by the mouth-bar deposit and the deposition of sand higher in the reservoir body (Wright, 1977).

No evidence of transgressive-regressive sequences was observed in the limited exposures of foreset beds, except for secondary deposits resulting from dam removal activities; however, this may have been due to the poor preservation of sediments along the main axis of the reservoir by 2014. A complete section in Cat Creek, a tributary inflow located near the upstream end of former Lake Mills, showed the interbedding of several well-sorted, sandy gravel deposits between fine-grained prodelta deposits (Fig. 9C). Aerial photographs of the reservoir (Fig. 7) showed that the Cat Creek delta had been filled and stably vegetated since the 1970s, but may have been subject to a drawdown event in 1956. Given the location of Cat Creek in the uppermost reservoir, any subsequent low-water periods would most likely have been expressed as erosional gaps in the sediment record.

Additional evidence of low-water periods in former Lake Mills was preserved by the

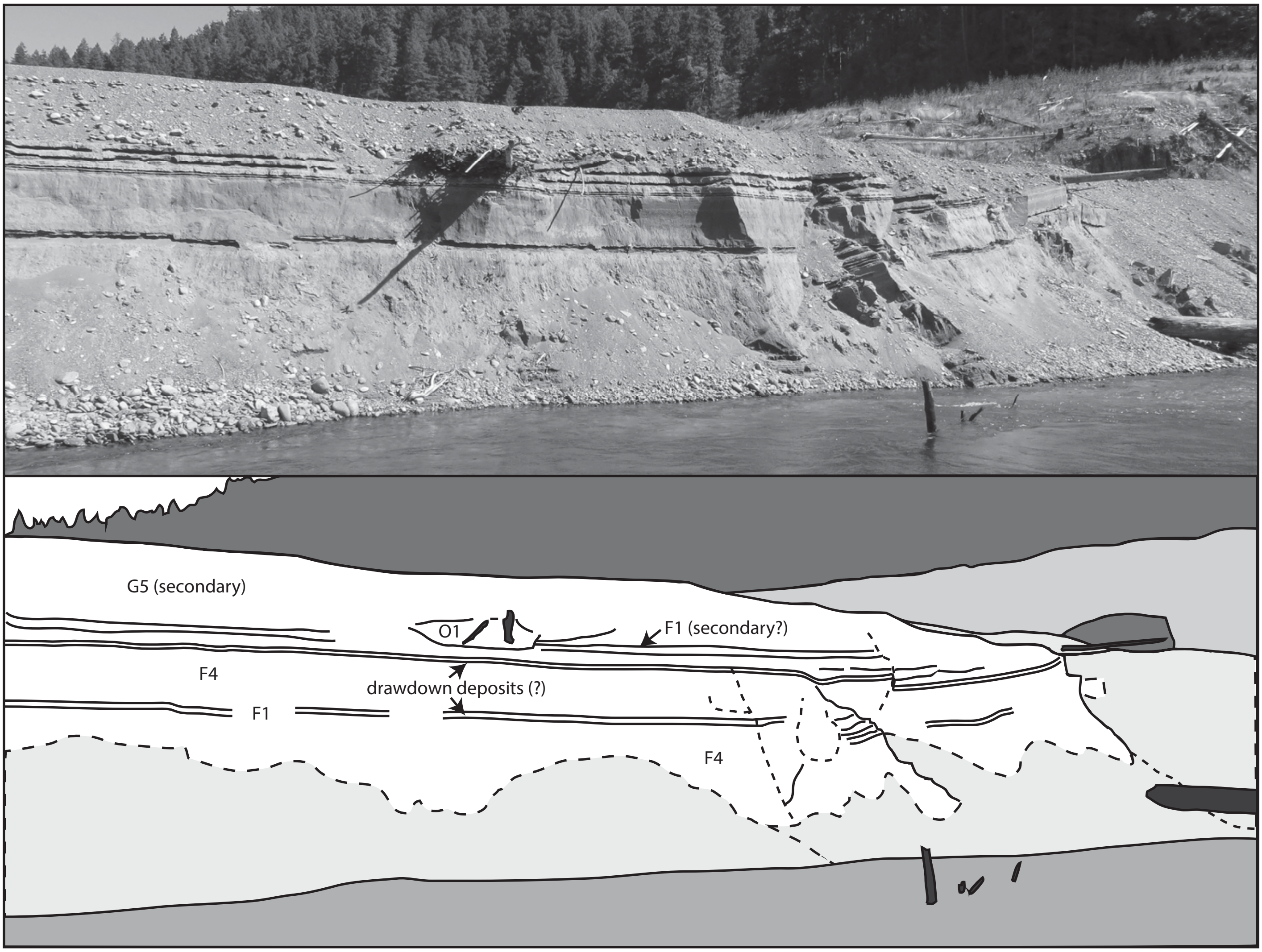


Figure 15. Photograph with cartoon depicting sandy interbeds in lacustrine basin of former Lake Mills. Flow is to the left, but camera is oriented north along the main axis of the reservoir (toward Glines Canyon Dam). Sandy interbeds are approximately 10 cm.

occurrence of several laterally extensive sandy interbeds within the distal portion of the main lacustrine basin (Fig. 15). These interbeds were observed in a cross section with complete exposure to the base of the reservoir sediments but with an upper unconformity. Given the pattern of a single isolated bed, separated by ~1 m of fine-grained sedimentation, followed by three closely spaced beds, it is tempting to assign these interbeds to a >10 yr flood that occurred in 1950 (Fig. 2), followed by the drawdown experiments of 1989 and 1994, and the >50 yr flood of 2007, which were in turn followed by coarse-grained, dam removal–related deposition. However, the observed bed spacing does not conform with the nearly 50% increase in sedimentation rate from 1927 to 1994 and from 1994 to 2010 estimated by Bountry et al. (2011) and offers no evidence of other ~10 yr floods documented in the Elwha hydrograph.

Further, evidence from the lacustrine basin in former Lake Aldwell suggests that drawdown deposits associated with dam removal produced thick (>2 m in several instances) accumulations of laminated silt deposits in single events. This suggests that the lowermost interbed could thus be the result of the 1994 drawdown experiment, and the upper interbeds could represent evidence of dam removal–related delta progradation. However, in this scenario, both the 1989 drawdown experiment and the 2007 flood are unaccounted for. Given the evidence of drawdown events in both Cat Creek and the lacustrine basin of the reservoir, we include a hypothetical transgressive-regressive sequence in our conceptual model of reservoir sedimentation (Fig. 10A) but note that this is an area worthy of additional study in other systems.

Lake Aldwell

In contrast to former Lake Mills, which closely approximates the ideal Gilbert delta in both morphology and facies architecture, the depositional portrait of former Lake Aldwell is significantly more complex (Fig. 10B). As the result of a shallower basin, sedimentation processes in former Lake Aldwell tended to be more influenced by bed friction than in former Lake Mills, resulting in a shoal-water, mouth-bar style of delta progradation characterized by active, channelized distributaries depositing large bodies of sand that interfingered to form a delta front (Wright, 1977). Additionally, the interpretation of sediment deposition in former Lake Aldwell is complicated by the influence of two major exogenic processes not observed in former Lake Mills: the 1927 closure of Glines Canyon Dam upstream, and catastrophic influx of sediment from nonfluvial sources from a large landslide into the upper reservoir sometime before 1976.

The basin gradient at the head of former Lake Aldwell is significantly lower than in former Lake Mills, which is headed by the steeply dipping Rica Canyon (gradient ~0.006), creating a comparatively flat, shallow upper reservoir (Fig. 5C). At the time of dam removal, the active delta in former Lake Mills was characterized by a broad delta top, apparently prograding by deposition of middle-ground and lunate mouth bars without distinct a foreset form (Fig. 6B). The active bars were characterized by a gradual transition from sandy gravels in the distributary channel to coarse sands interbedded with silt and laminated organics that probably represented deposition during the waning limb of high-flow events. The mouth bars themselves appear to have been characterized by well-sorted sands distally (facies S3; similar in nature to the S3 sands in former Lake Mills, but not associated with foreset beds), cut by broad, undulatory channels typically characterized by laterally accreted coarse organics in a sandy matrix. This style of progradation is commonly associated with shallow water and may be referred to as "shoal-water" or "shelf-type" deposits (Nemec, 1990a; Reading and Collinson, 1996); when characterized by lunate bars, it is also indicative of inertial deposition with "small to moderate bed load" (Wright, 1977, p. 866).

In contrast to former Lake Mills, the "striped mudstone" (F1) facies was almost entirely absent in former Lake Aldwell. This may have been a function of both reduced sand supply and lower gradient. Incoming flood waters probably carried both less sediment and encountered little sand available for entrainment and redistribution at the delta mouth due to the upstream capture by Glines Canyon Dam. Thus, plunging summer currents would encounter less sediment available for reworking and transport into the reservoir basin. Additionally, the absence of foreset beds in the former Lake Aldwell delta suggests that gravity-driven transport (whether through continual sediment avalanching, oversteepening, or either of these processes' evolution to a fully turbulent density current) was not a significant process in the transport of sand to the prodelta.

However, this type of delta progradation appears to typify sedimentation in former Lake Aldwell only in its later years. As discussed in the "Sedimentation Rates and Reservoir Accumulation Volumes" section, estimates of sediment storage in former Lake Aldwell were revised from ~2.97 (±1.0) × 10^6 m^3 (Gilbert and Link, 1995; Bountry et al., 2011) to 4.9 (±1.4) × 10^6 m^3 (Randle et al., 2015). Randle et al. (2015, p. 712–713) attributed this revision to "findings from the newly exposed landscape following dam removal that revealed additional reservoir sedimentation [in areas]..." These fluvial landforms and predam terraces were identified by Gilbert and Link (1995), who correctly determined that there was no reservoir process-based explanation for sediment in the upper portions of former Lake Aldwell 2.4 and 4.9 m above the maximum operating water-surface elevation. Based on this evidence, the juxtaposition of fine-grained sediments (i.e., reservoir sediments) immediately over river cobbles, and the observation of several rooted stumps with their root flares exposed (indicating little sedimentation), Gilbert and Link mapped a large portion of the upper reservoir as representing predam sedimentation processes (Fig. 11B). However, the erosion of massive rooted stumps from within this "predam sediment" following dam removal indicated that it was, in fact, the result of deltaic sedimentation (e.g., Fig. 11A). As a result, Randle et al. (2015) included these areas in a revised estimate of sedimentation in former Lake Aldwell.

This estimate of Randle et al. (2015) provides probably the most accurate assessment of sediment volume in former Lake Aldwell; however, without considering the processes involved, it suggests an erroneously high rate of sediment transport by the Elwha River downstream of Glines Canyon Dam. The total sediment load to former Lake Aldwell prior to the completion of Glines Canyon Dam was estimated between 1.85 × 10^5 m^3 yr^{-1} (Curran et al., 2009; Bountry et al., 2011) and 2.26 × 10^5 m^3 yr^{-1} (Randle et al., 2015). Assuming a conservative trap efficiency of 0.65 for former Lake Aldwell itself, between 1.20 × 10^6 and 2.05 × 10^6 m^3 would have been deposited in Lake Aldwell prior to the 1927 closure of Glines Canyon Dam upstream. This volume represents between 34% and 42% of the total sediment volume estimated by Randle et al. (2015), deposited in only the first 14% of the reservoir's life span. However, according to aerial photographs (Figs. 7 and 11C), an area along the western margin of former Lake Aldwell was inundated by a landslide runout sometime between 1956 and 1976 (providing a mechanism for the anomalously high elevations in this region noted by Gilbert and Link, 1995). Depending on the estimated volume of the landslide deposit, these figures suggest that as much as half the total Elwha-derived sediment load to former Lake Aldwell would have been delivered in the first 14 yr of its existence, while the remaining half was deposited over the course of the remaining 84 yr.

The dramatic reduction in sediment supply precipitated by the closure of Glines Canyon Dam is clearly evident in the geomorphic evolution of the delta (Fig. 7). Where the subaerial delta had prograded ~640 m into the reservoir by 1939, the rate of progradation (with the exception of the post-1956 landslide into the upper delta plain) in subsequent years was minor. Indeed, from 1995 (the year of a detailed sedimentation study of former Lake Aldwell; Gilbert and Link, 1995) to 2010, the delta evolved so little that the USBR, preparing sedimentation estimates for the upcoming removal of Elwha Dam with a 2010 bathymetric survey, determined no substantive change in the delta (Bountry et al., 2011).

A second and more subtle effect of dams on sediment transport in river systems is to alter the grain-size distribution of downstream sediment. Dams like Glines Canyon and Elwha, which were constructed without deep outlets, can be assumed to trap 100% of incoming bed load. However, they pass a variable but significant proportion of fine-grained sediment carried in suspension. Thus, while the bed-load catchment area of former Lake Aldwell was reduced by 78% with the completion of Glines Canyon Dam (Fig. 16), the Glines Canyon Dam captured only a portion of fine-grained sediment from the upper watershed: The entire 14% of sediment (2.59 × 10^4 m^3 yr^{-1}) estimated to escape trapping by Glines Canyon Dam would have been in suspension. As a result, the transport of fine-grained sediment through the middle Elwha reach would have been disproportionately enriched in fine sediment post-1927.

The sediments of former Lake Aldwell show evidence of this shift in sediment regime. As calculated by Randle et al. (2015), the total sediment load in former Lake Aldwell was composed of 53% fine-grained sediment and 47% coarse-grained sediment, while former Lake Mills was composed of 56% coarse-grained sediment and 43% fine-grained sediment. Gilbert and Link (1995) noted accumulations of fine-grained sediments directly over coarse gravels in channels in the main delta and Indian Creek delta areas during underwater dives in 1994 and 1995; a similar record is preserved in stratigraphic sections of the delta plain. This juxtaposition probably records the abrupt shift in sediment regime resulting from the closure of Glines Canyon Dam. Additionally, the absence of the F1 facies in former Lake Aldwell (which

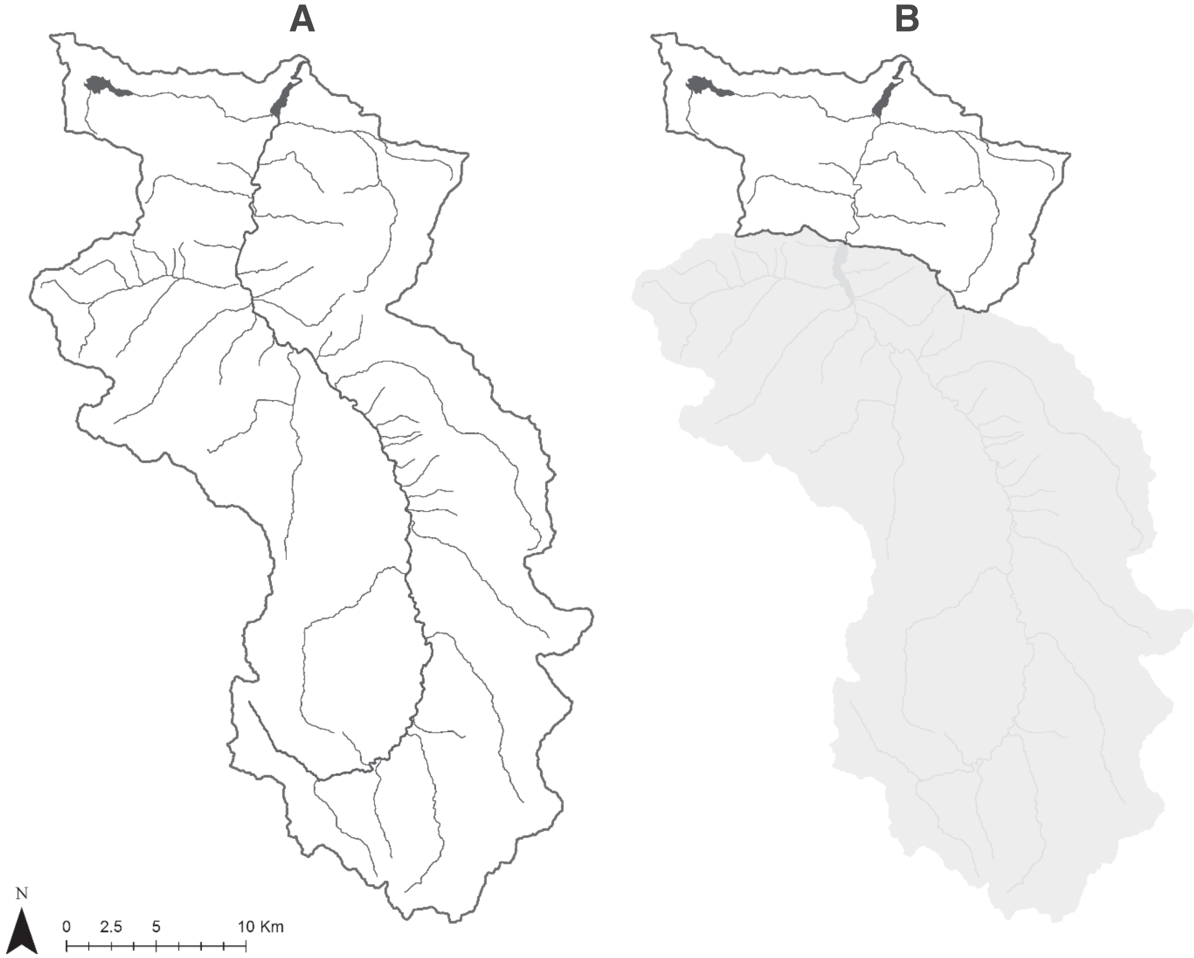


Figure 16. Map depicting 78% reduction in bed-load source area to Lake Aldwell (A) before versus (B) after the closure of Glines Canyon Dam (1927).

comprises the most prominent prodelta facies in former Lake Mills) probably reflects the lower proportion of available sand versus silt between the two reservoirs.

Additionally, as discussed above, the delta in former Lake Aldwell was well developed by 1939 (Fig. 7), in keeping with the high incoming sediment load prior to the completion of Glines Canyon Dam. At that time, the subaerial delta appears to have been characterized by a relatively lobate delta margin, which is more typical of Gilbert-style accumulation than shelf-type deltaic deposition, and is similar to former Lake Mills (Fig. 6). Further, marginal exposures in the upper portion of former Lake Aldwell show a well-developed tripartite Gilbert sequence, consisting of gravel foreset beds prograding over fine-grained basin deposits, overlain by subhorizontal, coarse-grained topset beds (Fig. 14). These foreset beds have lower gradients than those in former Lake Mills, which probably reflects the lower gradient of the Aldwell basin, but they also provide evidence of Gilbert-style sedimentation processes early in the reservoir's history.

We interpret the evolution of former Lake Aldwell from Gilbert-style to mouth-bar progradation, accompanied by significant reworking of the delta top (Fig. 10B), to reflect both a natural shallowing of the reservoir basin and the 1927 shift in sediment regime. The presence of Gilbert-style foresets and the surface morphology show that, despite the relatively shallow nature of the former Lake Aldwell basin, Gilbert-style deposition was active for a period of time in former Lake Aldwell. With the closure of Glines Canyon Dam, this deltaic deposition was apparently overprinted by the characteristics of a fine-grained, sediment-limited system.

SUMMARY AND CONCLUSIONS

The removal of Glines Canyon and Elwha Dams represents, to our knowledge, the first opportunity to examine the composition and architecture of reservoir sediments through direct, spatially comprehensive observation, providing a window into the structure of reservoir sediments, the processes involved, and the evolution of sedimentation styles over the lifetime of a reservoir.

Former Lake Mills probably represents the simplest end member of reservoir sedimentation. Given its relatively simple perimeter, long, narrow morphology, pristine watershed, and operational history as predominantly run-of-the-river, former Lake Mills was similar to a deep-water, glacier-carved lake, making it interpretable in the context of the classic Gilbert delta paradigm. Gilbert-style deltas, as observed in former Lake Mills, are characteristic of abundant coarse-grained deposition into deep, typically freshwater basins (Nemec, 1990a); as described by the USBR, this paradigm forms the basis for the "typical" reservoir (Strand and Pemberton, 1987).

Given the relative simplicity of this depositional model, the excellent hydrograph record, the historical operation of Glines Canyon Dam for near-constant head, and the rich stratigraphic data set described herein, former Lake Mills provides an opportunity to assess our understanding of the dynamics of natural Gilbert-style systems and basinwide correlations of facies. The use of marker beds for stratigraphic correlation across systems is common in investigations of marine and lacustrine environments, both ancient and modern. For example, with the aid of detailed isotopic dating, Ambers (2001) was able to tie laterally continuous sediment horizons to individual flood events in the reservoir sediments of Lake Dorena, a flood-control reservoir on the Row River in Oregon, providing excellent age control on sediments and the ability to make detailed interpretations of the influence of land-use change on the reservoir. However, the lateral and longitudinal variability in the reservoir sediments of former Lake Mills, the stochastic nature of delta slope failure, and the variety of endogenic and exogenic influences on sediment transport suggest that correlation of individual flow events in systems this dynamic may be more speculative than currently appreciated. While we identified evidence of transgressive-regressive sequences within the sediments of former Lake Mills, we could not conclusively correlate them to either known flood or drawdown events. While this may be a function of the marginal- and bottom-sediment bias of our data set, as more dams are removed worldwide, additional opportunities for the study of cross-basin correlation will yield a rich field of study.

In contrast to former Lake Mills, the sediments of former Lake Aldwell were characterized by complex facies architecture influenced by (1) the major reduction in total sediment load following the upstream closure of Glines Canyon Dam, (2) the relative fining of the remaining sediment load due to differences in the rate of bed load versus suspended load capture by the dam, and (3) the influx of a significant landslide runout to the upper delta plain. Exposures of Gilbert-style tripartite deltaic assemblages, as well as the evolution of the surface expression of the delta plain, suggest that former Lake Aldwell was characterized by a high-volume, bed load–dominated, Gilbert-style delta prior to the upstream closure of Glines Canyon Dam in 1927, after which it was overprinted with the characteristics of a fine-grained, sediment-starved system dominated by mouth-bar, shoal-water style of sedimentation. While some of the drivers influencing former Lake Aldwell are inevitably case- specific, the resulting delta represents a system not found in natural systems: that of a steep-profiled but fine-grained system. Existing frameworks developed for lacustrine systems do not describe these systems well, suggesting that robust characterization of reservoir sedimentation in many systems requires the development of new conceptual frameworks.

Additionally, the disparity between sediment volume estimates completed before versus those completed after dam removal (Gilbert and Link, 1995; Bountry et al., 2011; Randle et al., 2015) illustrates the importance of understanding both endogenic and exogenic process dynamics when assessing sedimentation rate and characteristics in depositional systems. Without recognizing the presence of a landslide deposit in the upper delta of former Lake Aldwell, Gilbert and Link (1995) made the obvious conclusion that sediments above the normal reservoir pool elevation could not have been emplaced by reservoir processes and were thus the result of predam fluvial terraces. However, this conclusion then led to the erroneous assumption that abrupt transitions in sedimentation style could only represent the transition from fluvial to reservoir processes rather than an abrupt shift in the sediment regime during the life span of the reservoir. Similar to the landslide deposits, without accounting for extremely high sedimentation rates prior to the closure of Glines Canyon Dam, the extensive sedimentation of the upper Aldwell delta prior to 1927 would appear to have no mechanism and also require the alternate explanation of predam deposition.

Again, while the drivers of major changes in sediment regime to former Lake Aldwell are case specific, given the prevalence of multidam systems worldwide (Minear and Kondolf, 2009; Lehner et al., 2011; Foley et al., 2017), a majority of the world's reservoirs can be expected to have been subject to abrupt reductions in sediment regime. Conversely, logging, watershed development, mining activities, or naturally caused landslides upstream have all been cited as drivers of increased sedimentation in reservoirs and natural lakes (Ambers, 2001; Snyder et al., 2004, 2006; Thothong et al., 2011; Bountry et al., 2011). Our analysis of the sediments in former Lakes Aldwell and Mills suggests that these changes are recorded by both the geomorphic expression of delta progradation and the facies architecture of the systems; however, the nature of this evolution is complex, and interpretation of event horizons may be hindered by the heterogeneous nature of sedimentation. The increasing number of dam removals under way worldwide (Foley et al., 2017) offers the opportunity to develop robust conceptual models of sedimentation across a variety of reservoir systems, providing better tools for the prediction of reservoir sedimentation and offering insight into interpretation of lake sediments, both modern and ancient.

ACKNOWLEDGMENTS

We wish to thank Andrew Ritchie, Tim Randle, Jennifer Bountry, and Seth Wing for field assistance and access to unpublished data. We also thank Roy Haggerty and Sarah Lewis for valuable discussion and Caroline Nash for the title inspiration.

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Science Editor: Bradley S. Singer
Associate Editor: Joan Florsheim

Manuscript Received 2 November 2017
Revised Manuscript Received 4 May 2018
Manuscript Accepted 19 November 2018

Printed in the USA