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SEDIMENTOLOGY OF NEW FLUVIAL DEPOSITS ON THE ELWHA RIVER, WASHINGTON, USA, FORMED DURING LARGE-SCALE DAM REMOVAL

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ABSTRACT

Removal of two dams 32 m and 64 m high on the Elwha River, Washington, USA, provided the first opportunity to examine river response to a dam removal and controlled sediment influx on such a large scale. Although many recent river-restoration efforts have included dam removal, large dam removals have been rare enough that their physical and ecological effects remain poorly understood.

New sedimentary deposits that formed during this multi-stage dam removal result from a unique, artificially created imbalance between fluvial sediment supply and transport capacity. River flows during dam removal were essentially natural and included no large floods in the first two years, while draining of the two reservoirs greatly increased the sediment supply available for fluvial transport. The resulting sedimentary deposits exhibited substantial spatial heterogeneity in thickness, stratal-formation patterns, grain size and organic content. Initial mud deposition in the first year of dam removal filled pore spaces in the pre-dam-removal cobble bed, potentially causing ecological disturbance but not aggrading the bed substantially at first. During the second winter of dam removal, thicker and in some cases coarser deposits replaced the early mud deposits. By 18 months into dam removal, channel-margin and floodplain deposits were commonly >0.5 m thick and, contrary to pre-dam-removal predictions that silt and clay would bypass the river system, included average mud content around 20%. Large wood and lenses of smaller organic particles were common in the new deposits, presumably contributing additional carbon and nutrients to the ecosystem downstream of the dam sites. Understanding initial sedimentary response to the Elwha River dam removals will inform subsequent analyses of longer-term sedimentary, geomorphic and ecosystem changes in this fluvial and coastal system, and will provide important lessons for other river-restoration efforts where large dam removal is planned or proposed. Published 2013. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: dams; dam removal; river restoration; sediment transport; fluvial geomorphology

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INTRODUCTION

Dams commonly block fluvial sediment transport, and dam operations can profoundly alter fluvial hydrology (e.g. Williams and Wolman, 1984; Chien, 1985; Grant *et al*., 2003; Magilligan and Nislow, 2005; Petts and Gurnell, 2005; Grams *et al*., 2007; Schmidt and Wilcock, 2008). Dam operations often affect not only the timing and magnitude of flows but also the number, volume and locations of sediment deposits downstream of dams (Schmidt and Graf, 1990; Hazel *et al*., 2006; Dade *et al*., 2011; Xu *et al*., 2013). Alteration of flow and sediment dynamics below dams in turn affects many facets of the ecosystem, from aquatic and riparian regions to areas above the flood zone (Ligon *et al*., 1995; Merritt and Cooper, 2000; Shafroth *et al*., 2002; Kunz *et al*., 2011; Draut, 2012; Kibler and Tullos, 2013; Zhou *et al*., 2013).

Dam removal is becoming an increasingly common component of river restoration (Grant, 2001; Pizzuto, 2002; Graf, 2003). Of the >75 000 large river-regulation structures in the continental USA (Graf, 1999), many are approaching the end of their intended use; the cost of maintaining ageing dams, along with growing understanding of their ecological effects, has prompted a recent increase in dam removal and associated studies. Most dam removals to date have involved relatively small structures (<10 m high) and modest volumes of reservoir sediment released (<10^6 m^3). Physical and ecological studies of dam removals on that scale are highly informative (e.g. Cheng and Granata, 2007; Burroughs *et al*., 2009; Pearson *et al*., 2011; Major *et al*., 2012; Evans and Wilcox, 2013), but scaling up the size of dam removals to include larger structures and greater reservoir-sediment volumes could have physical and ecological effects that are not yet well understood.

Removal of two large concrete dams on the Elwha River, Washington (Figure 1A), began in 2011, providing an opportunity to assess the effects of dam removal and controlled sediment release on a scale not possible in any previous river restoration. This, the largest dam removal and most intensively studied controlled sediment release in history, constitutes an unusual case study in fluvial sedimentology because this multi-staged dam removal involves a large artificial increase

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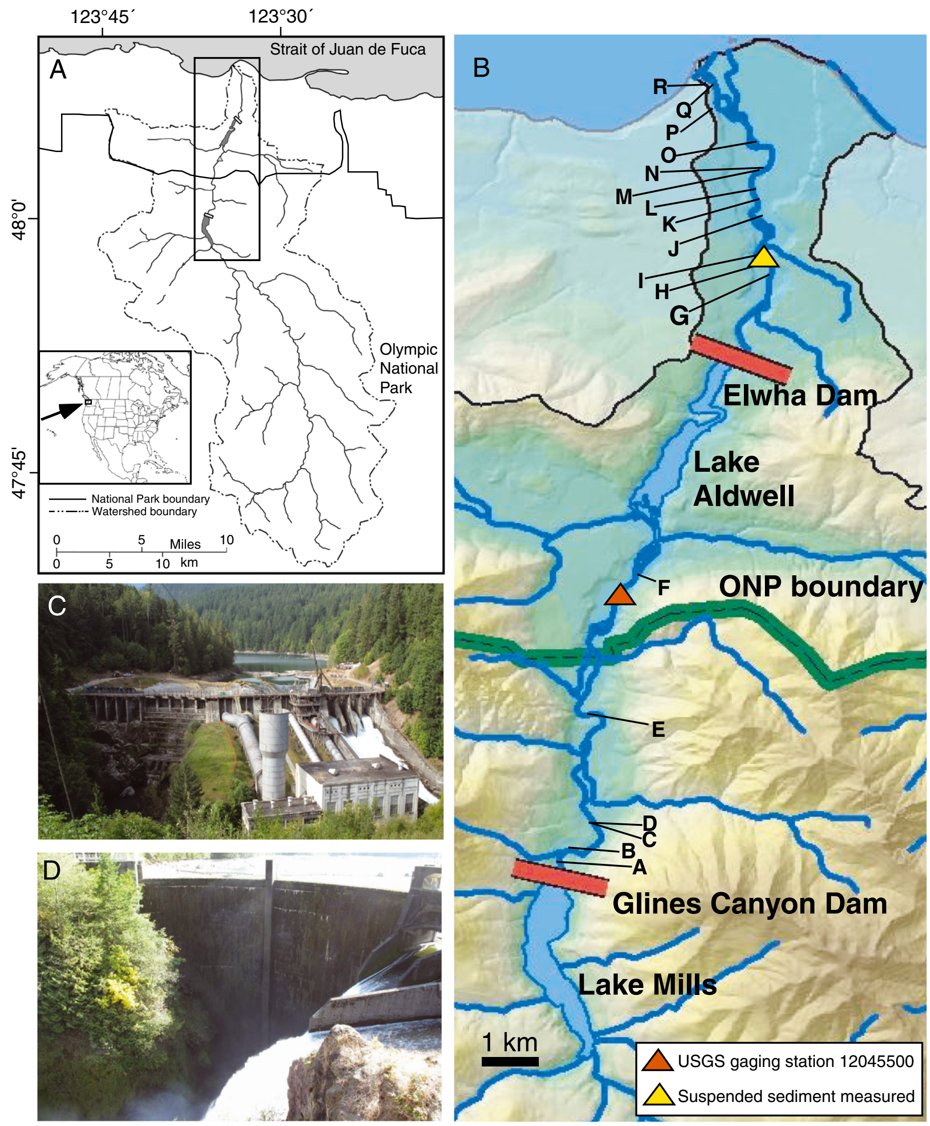

Figure 1. (A) The Elwha watershed, Olympic Peninsula, northwestern Washington, USA. Dashed line shows watershed boundary, solid line Olympic National Park (ONP) boundary. Box outlines the area shown in (B). (B) The ~26-km Elwha River reach affected by dam removal. Sites of Elwha and Glines Canyon Dams are shown as red bars. Former sites of Lakes Aldwell and Mills, which were reservoirs behind the dams, contain sediment deposits eroded by the river during and after dam removal. Labels A–R show locations of sedimentary profiles examined for this study (Appendix lists distances of each profile from the dams). Orange triangle is U.S. Geological Survey gauging station 12045500, where water discharge is measured; yellow triangle shows location of suspended-sediment monitoring station. The river between the two dams is known informally as the 'middle reach'; the reach downstream of Elwha Dam is known as the 'lower reach'. (C) Elwha Dam and (D) Glines Canyon Dam in September 2011 shortly before deconstruction began; photographs courtesy of the National Park Service. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

in sediment supply, with temporal decoupling of sediment supply and river transport capacity. Sediment availability is controlled by dam deconstruction progress, the phases of which often do not coincide with high flows that would move sediment downstream efficiently. The sedimentary response of the downstream river channel will determine short-term and possibly intermediate to long-term ecological responses to this multi-phase large dam removal and sediment influx.

This study of fluvial-deposit sedimentology composed part of a large, systematic effort by numerous researchers and agencies to measure response of the Elwha River channel, floodplain and coastal region to the physical and ecological disturbance of large dam removal. As such, the present work builds on pre-dam-removal studies of Elwha fluvial sediment and geomorphic conditions (Randle *et al.*, 1996; Pohl, 1999, 2004; Kloehn *et al.*, 2008; Curran *et al.*, 2009; Konrad, 2009; Bountry *et al.*, 2010; Draut *et al.*, 2011).

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Here, we present sedimentological analyses from new fluvial deposits formed on the Elwha River during dam removal, and we discuss their stratal formation, grain size and organic content. Understanding the sedimentary response of the Elwha River will inform analysis and prediction of ecosystem response in this watershed and will inform river-restoration efforts on other rivers where large dam removal is planned or proposed.

Field setting: the Elwha River, Washington

The 833-km^2 Elwha watershed drains steep, mountainous terrain of the Olympic Peninsula (Figure 1A), which contains metasedimentary and igneous rocks within the forearc region of the Cascadia subduction zone (e.g. Brandon *et al*., 1998). Steep slopes in this tectonically active basin produce landslides that episodically generate large sediment quantities upstream of the dam sites (Acker *et al*., 2008). Additional Elwha River sediment sources include sedimentary rocks, glacial outwash alluvium and proglacial lacustrine deposits exposed in bluffs, canyons and valley walls along the lower Elwha River (Tabor and Cady, 1978; Polenz *et al*., 2004). The river flows through alternating bedrock canyon and alluvial floodplain reaches. Within its alluvial reaches, the Elwha channel is best classified as an anabranching or island-braided channel (cf. Harwood and Brown, 1993; Knighton and Nanson, 1993). Although in some reaches there is one wandering channel (as in order B2 of Nanson and Croke, 1992; see also Church, 2002), in other reaches, bars and vegetated islands separate multiple channel threads. Before dam removal, bed sediment in the Elwha River downstream of the dams was dominantly granule-sized to cobble-sized. This armoured bed, significantly coarser than the natural bed sediment above the dams, resulted from the dams having blocked downstream sediment transport (Pohl, 2004; Draut *et al*., 2011). The Elwha floodplain is heavily vegetated with hardwood and conifer trees, and smaller shrubs and saplings.

Elwha and Glines Canyon Dams, 32 m and 64 m high, respectively, were concrete dams situated 13.7 km apart on the Elwha River (Figure 1). The dams were completed in 1913 (Elwha Dam) and 1927 (Glines Canyon Dam) to provide hydropower and water to a paper and timber-mill operation and to the city of Port Angeles. Dam operations largely mimicked natural hydrology, but with more rapid daily flow fluctuations and lower daily minimum flows (Johnson, 1994; Pohl, 1999). Annual peak discharges on the Elwha River occur during storms between October and March; secondary peaks with longer duration occur in late spring snowmelt. The dams virtually eliminated upstream sediment supply to the middle and lower Elwha River (between and below the dam sites, respectively), except for suspended-sediment passage during large floods; before dam removal, fluvial sediment transport to the coastal ocean was estimated to be around 2% of the pre-dam load (Environmental Impact Statement (EIS-2): Implementation EIS, 1996). Estimating from measurements at the upstream end of Lake Mills (Figure 1), the pre-dam sediment load would have been ~217 000–513 000 t/year (Czuba *et al*., 2011).

Removal of both dams should restore the Elwha watershed by allowing unimpeded flow along the entire mainstem river, most of which is undeveloped wilderness within Olympic National Park. A major goal of dam removal is to restore spawning habitat of anadromous fish species whose populations declined substantially over the dammed era (Nehlsen, 1997; Beechie *et al*., 2001; Pess *et al*., 2008; Kocovsky *et al*., 2009; Brenkman *et al*., 2012). Spawning-habitat restoration occurs both by removing the dams that prevented upstream fish migration (neither dam included fish-passage facilities) and by restoring natural sediment supply to the middle and lower river reaches, decreasing the grain size of the armoured, dammed riverbed to be within the particle size usable by salmonids as spawning gravel (generally 5–75 mm; Kondolf and Wolman, 1993).

The two dams on the Elwha River impounded an estimated 21 to $26 \times 10^6\,m^3$ of sediment in their reservoirs before dam removal. The majority was stored in the upstream reservoir, Lake Mills ($21.6 \pm 3.0 \times 10^6\,m^3$), where the reservoir delta contained approximately half silt-sized and clay-sized material (<63 μm) and half coarser sediment. The Lake Aldwell delta comprised one-fifth as much sediment, $4.6 \pm 1.5 \times 10^6\,m^3$, and was approximately two-thirds silt and clay; its coarse fraction was finer than the coarse fraction of Lake Mills delta sediment (U.S. Bureau of Reclamation, unpublished revisions of original estimates by Gilbert and Link, 1995; Randle *et al*., 1996). Between one-third and one-half of the total sediment volume in the two Elwha River reservoirs was projected to move downstream during and after dam removal (Randle *et al*., 1996; Konrad, 2009), transported by natural flows without mechanical assistance. The Elwha River restoration involves substantially greater reservoir-sediment volumes than did several previous removals of large and moderate-sized dams. Removal of 38-m-high Condit Dam on the White Salmon River, Washington, in 2011, opened a reservoir containing $1.8 \times 10^6\,m^3$ (Mead and Hunt *et al*., 2011). The 15-m-high Marmot Dam on the Sandy River, Oregon, removed in 2007, impounded a reservoir containing $0.7 \times 10^6\,m^3$ (Major *et al*., 2012). Savage Rapids Dam, removed in 2009 from the Rogue River, Oregon, stood 12 m high and impounded $0.15 \times 10^6\,m^3$ of sediment (Bountry *et al*., 2013). Milltown Dam, which stood 13 m high and was removed from the confluence of the Clark Fork and Blackfoot Rivers, Montana, in 2008, impounded $5.5 \times 10^6\,m^3$ of sediment, almost half of which was mechanically removed to manage mining-waste contamination (U.S. Environmental Protection Agency, 2004; Envirocon, 2004; Woelfle-Erskine *et al*., 2012). For the

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Elwha River to mobilize one-third to one-half of its 21 to $26 \times 10^6\,m^3$ stored reservoir sediment during and after dam removal therefore constitutes a much greater sediment release than did any prior dam removals.

Removal of Elwha and Glines Canyon Dams began in September 2011 and progressed in carefully timed stages of drilling and blasting scheduled to last approximately three years. Stages of dam deconstruction were timed to minimize impacts to the downstream ecosystem, with deconstruction halted during anadromous fish migrations. The timing of removal was intended to be rapid enough to limit ecological impacts to a few year-classes of fish, but slow enough to minimize floodplain aggradation and other impacts to downstream infrastructure that must accommodate high sediment loads (Environmental Impact Statement (EIS-2): Implementation EIS, 1996).

During dam removal, as expected, sediment from the two reservoirs has moved downstream (Warrick *et al*., 2012). Elwha Dam removal was completed in April 2012. With the associated draining of Lake Aldwell, suspended-sediment export from the former Aldwell reservoir deposits increased in spring 2012 (Figure 2). Suspended-sediment loads increased more substantially in fall 2012 in response to draining of Lake Mills as Glines Canyon Dam deconstruction progressed; bedload export from the Mills reservoir began in late October 2012 after the delta deposits there had prograded all the way to the dam. As of mid-2013, the final ~15 m of Glines Canyon Dam remained to be removed. Volumetric change estimates using 'Structure-from-Motion' photogrammetric topography analysis (cf. Westoby *et al*., 2012) from a novel aerial imaging system indicate that a total of $6.1 \times 10^6\,m^3$ of sediment had moved downstream from both of the reservoir-sediment deposits as of spring 2013 (A. C. Ritchie, unpublished data). The first two years of dam removal included above-average winter snowpack and spring snowmelt flows, but below-normal storm flood discharge in winter. Although flows resulting from several winter storms moved sediment downstream, flood peaks during winter 2011–2012 and winter 2012–2013 were substantially below that of the 2-year flood (Figure 2).

Before dam removal began on the Elwha River, projections included mainstem bed aggradation, pool filling and consequent increased flow over former floodplain areas during non-flood flows (Environmental Impact Statement (EIS-2): Implementation EIS, 1996). Predictions in the EIS also assumed that the finest sediment fraction (mud, consisting of silt and clay particles finer than 63 μm) would pass through the river system to the ocean, forming a negligible proportion of channel and floodplain deposits (Environmental Impact Statement (EIS-2): Implementation EIS, 1996; Gelfenbaum *et al*., 2011). It is also generally assumed, not only during the Elwha restoration but also in many sedimentologic and geomorphologic studies, that suspended-sediment deposition occurs almost exclusively in quiescent regions of a river

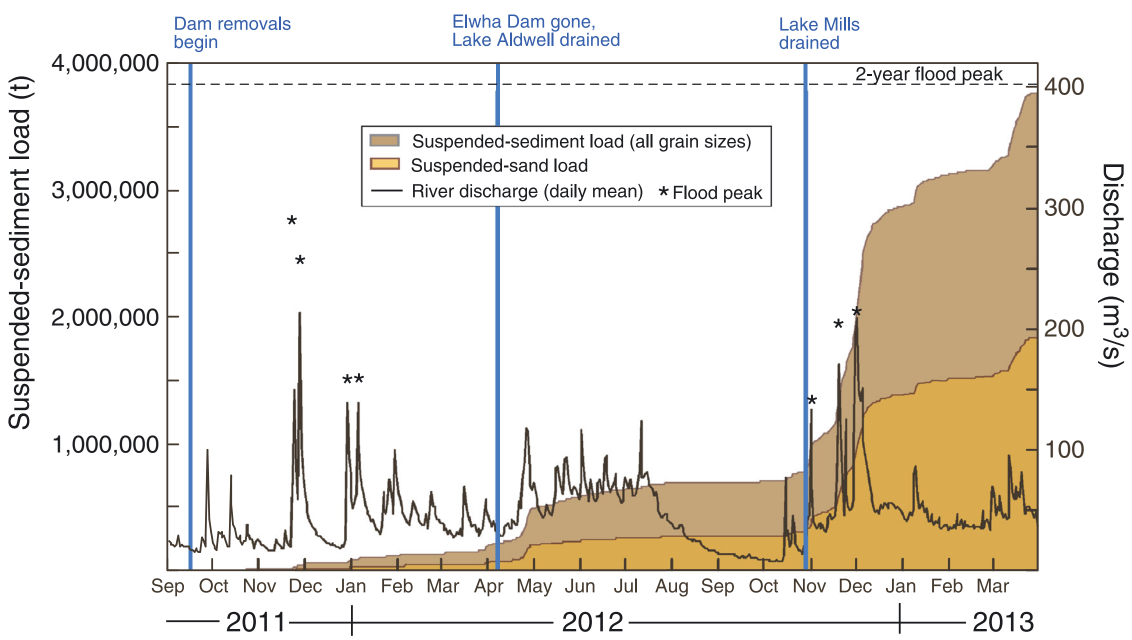

Figure 2. Hydrograph, suspended-sediment load (all grain sizes) and suspended-sand load measured during the first 18 months into dam removal on the Elwha River. Discharge is measured at USGS gauging station 12045500 (Figure 1B). Solid black line shows daily mean discharge; asterisks indicate instantaneous flood-peak discharge. Dashed line shows 2-year flood flow ($401.6\,m^3/s$) calculated from a log Pierson type III frequency analysis using discharge data from 1898 through 2012. Suspended-sediment-load data are those of Curran *et al*. (2013), measured at the location shown by the yellow triangle on Figure 1B. Dam removal progressed in graduated stages between September 2011 and November 2012. Glines Canyon Dam deconstruction did not proceed any further between November 2012 and profile sampling in March 2013, but resumed in October 2013. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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channel—filling eddies and in the lee of obstacles, such as the downstream sides of cobble bars or log jams (from the classic Hjulström diagram of grain size relative to entrainment velocity; e.g. Sundborg, 1956; Boggs, 1995). Using the new Elwha fluvial deposits, we assess whether those assumptions were correct given the highly unusual geomorphic context of large dam removal. In this setting, sediment supply has been made available for downstream transport in much larger quantities than would occur in an undisturbed system where, except at times immediately following large natural sediment input (e.g. landslides in the upper watershed), sediment supply and transport generally scale in proportion to water discharge.

METHODS

Topographic change and bed-sediment grain size have been monitored biannually on the Elwha River by the U.S. Geological Survey (USGS), among other research groups, since 2006 (continuation of work discussed by Draut *et al*., 2011). Channel change and sediment deposition have been observed and quantified throughout dam removal by that study and complementary work by the U.S. National Park Service, Bureau of Reclamation, and National Oceanic and Atmospheric Administration. The suite of work, from which comprehensive results will be discussed in subsequent publications, has included widespread observations of new sediment deposition patterns, amounts and locations, and formed the basis for selecting the study sites discussed here. Specific site selection for this study involved sampling random locations where the new deposits could be safely accessed (with regard to local flow conditions and log-jam hazards).

Eighteen vertical profiles through sedimentary deposits on the Elwha River were described and sampled in late March 2013 to characterize depositional styles and quantify thickness, grain size and organic content of new, post-dam-removal material. The timing of this fieldwork followed the winter storm season (in which discharge events were few and relatively small; Figure 2), but preceded the onset of spring snowmelt high flow. Therefore, the studied deposits represented net sediment accumulation over the first 18 months of dam removal.

Of the 18 profiles, 15 were measured from channel-margin sediment deposits. Two other profiles were analysed from areas that had been part of the floodplain before dam removal began, but were inundated by water and sediment even at non-flood discharge during winter 2012–2013 as the river occupied a wider course in response to mainstem bed aggradation. One profile was measured from the subaerial portion of a mid-channel bar. This selection of study sites underrepresents new deposits that were not subaerially exposed, a necessary limitation given that visual descriptions are essential for characterizing bedding and horizon contacts; coring was not feasible given the rapid current and uncompacted sediment in much of the channel. In some profiles, however, subaqueous material was described and collected if the base of a profile (pre-dam-removal bed) was <50 cm beneath the water surface, that is, within range of a trowel.

Profiles were described in terms of sediment thickness above the pre-dam-removal bed surface, which was identified by the presence of either coarse cobbles and boulders (coarser than any observed post-dam-removal sediment) or a soil horizon containing plant roots and rootlets in growth position. At most profile locations, the appearance and character of the pre-dam-removal bed was verifiable using photographs taken before dam removal began; several profiles also were located along transects surveyed biannually (Draut *et al*., 2011), allowing their pre-dam-removal bed elevation to be confirmed from earlier topographic data. Data from sedimentary profiles were combined with observations from pre-dam-removal and post-dam-removal photography to characterize the river's sedimentary response to dam removal. We also refer to observations made between September 2011 and March 2013 at some locations not profiled in detail.

Selected sedimentary units within the profiles were sampled for laboratory analysis of their grain size and organic content at the USGS laboratory in Santa Cruz, California. Grain-size-sample selection included sedimentary units for which grain size could not be identified adequately from visual description alone (such as sandy muds or muddy sands) and massive, apparently homogenous units (to check for subtle vertical gradation). Samples analysed for organic content were those in which organic matter was visually identifiable. For samples on which both grain size and carbon content were measured, the two analyses used separate subsamples. Grain size was measured using a ROTAP™ sieve shaker for particles >2 mm, and using a Coulter laser particle-size analyser for particles <2 mm, after having removed organic matter with a hydrogen peroxide solution. Carbon content was determined by coulometric titration. Total carbon (TC) was determined by combusting dry, powdered samples at 1000 °C in a UIC, Inc., CM5200 furnace. Total inorganic carbon (TIC) content was obtained by digesting the sample in an acid solution with a UIC CM5130 acid digestion system, running the resulting CO_2 stream to a CM5015 coulometer, through a solution that turned the CO_2 into a weak acid, and electronically back-titrating the acid to an equally strong base by the coulometer; the amount of current was used to calculate the carbon content of each sample. Total organic carbon (TOC) was calculated as the difference between TC and TIC.

RESULTS

The first 18 months of dam removal on the Elwha River resulted in highly heterogeneous amounts and patterns of sediment deposition (Figures 3–7). Post-dam-removal

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Figure 3. Orthorectified aerial images showing contrast between pre- and post-dam-removal channel configuration and fluvial sediment. (A) and (B) show a location 2 km downstream of the Elwha Dam site (15.7 km downstream of the Glines Canyon Dam site) in September 2011 and March 2013, respectively; engineered riffle at the top of these images is part of the Elwha Surface Water Intake facility diverting water toward a fish hatchery and municipal water-treatment plant. (C) and (D) show a location 7.2 km downstream of the Elwha Dam site (20.9 km downstream of the Glines Canyon Dam site) in September 2011 and March 2013, respectively. Locations of sedimentary profiles sampled for this study are shown in (B) and (D). Differences between (A) and (B) and between (C) and (D) include the appearance of new sediment that is finer than the pre-dam-removal cobble bed, and formation of new mid-channel bars. The post-dam-removal fine sediment also has a dark grey colour distinct from that of the older cobble bed. Discharge in the September 2011 images (A) and (C) is 18 m^3/s; discharge in the March 2011 images is 45 m^3/s. 2011 images courtesy of the U.S. Department of Agriculture, National Aerial Imaging Program. 2013 images by A.C. Ritchie. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

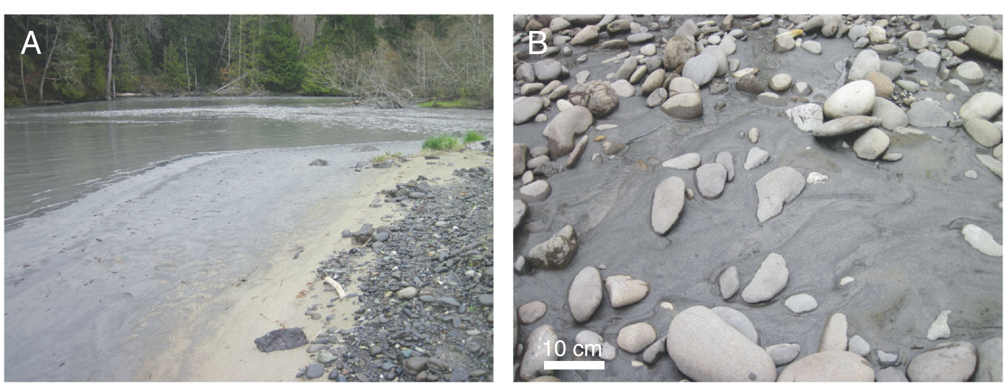

Figure 4. Post-dam-removal sedimentary deposits on the Elwha River as of April 2012. (A) At a location 2.15 km downstream of the Elwha Dam site (15.9 km below Glines Canyon Dam) new deposits <20 cm thick comprised grey mud, inferred to be sourced from Lake Aldwell reservoir material, overlying greyish brown sand reworked from coffer-dam destruction at Elwha Dam. Pre-dam-removal pebble–cobble bed is visible at right side of image. (B) Downstream of Elwha Dam, the pre-dam-removal cobble bed commonly contained new mud filling interstitial spaces, but bed elevation had not yet increased substantially (photo location 4.70 km below Elwha Dam site, 18.4 km below Glines Canyon Dam). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Figure 5. Post-dam-removal sedimentary deposits on the Elwha River as of late March 2013. (A) Coarse sand and woody debris dominate the post-dam-removal deposit 1.7 km below the Glines Canyon Dam site at the upstream end of Altair Campground, Olympic National Park, at Profile C location. The pre-dam-removal cobble bed surface is visible beneath the new, finer sediment and wood. (B) View facing upstream at the site of Profile O, 5.42 km downstream of Elwha Dam site (19.2 km below Glines Canyon Dam site), showing sand and woody debris deposited during dam removal. (C) Floodplain setting 1.94 km below Elwha Dam site (15.6 km below Glines Canyon Dam site), showing Profile G. Base of arrow is at pre-dam-removal forest-floor surface. (D) Flood deposit from a December 2012 high-flow event, dominated by coarse sand and granule layers, at Profile A, 0.25 km downstream of Glines Canyon Dam site. Scale card at base is 15 cm long. (E) Uppermost two sedimentary units within Profile H (2.19 km below Elwha Dam site, 15.9 km below Glines Canyon Dam site), including an organic-rich sandy horizon (TOC content 7.02%; Sample H3, Table I). (F) Sand and woody debris at Profile P location, 6.86 km below Elwha Dam site (20.1 km below Glines Canyon Dam site). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

sediment was substantially finer, in general, than the underlying pre-dam-removal bed sediment (Figures 3, 4, 5A) and dominantly grey to dark grey (5Y 5/1 to 5Y 4/1 on the Munsell colour classification scale), consistent with the colour of sediment in the upper Elwha watershed and with most locations in the Mills and Aldwell reservoir deltas. The 18 sampled profiles exhibited no common vertical sequence of sediment grain size, bedding style or organic content, and had variable post-dam-removal sediment thickness—ranging from 16 to 160 cm, with mean thickness 59 cm and standard deviation 33 cm. Thickness variations could be attributable to sampling-site selection, and larger-scale patterns of bed aggradation will be evaluated as quantitative topographic data become available. However, it is notable that even the profiles sampled from the same geomorphic setting (channel margin) in close proximity to each other had no common sequence of depositional horizons (Figure 6), and neither basal nor surficial grain size showed any spatial trend with distance downstream (Figure 7). It was not possible to trace individual sedimentary units from one profile to another, suggesting that over the distance between profiles, there was substantial interbedding of local depositional units each with limited three-dimensional extent.

Three phases of sediment accumulation occurred between the start of dam removal in fall 2011 and profile sampling in March 2013. First, as of spring 2012, following the first winter of dam-removal progress, new sediment had begun to fill

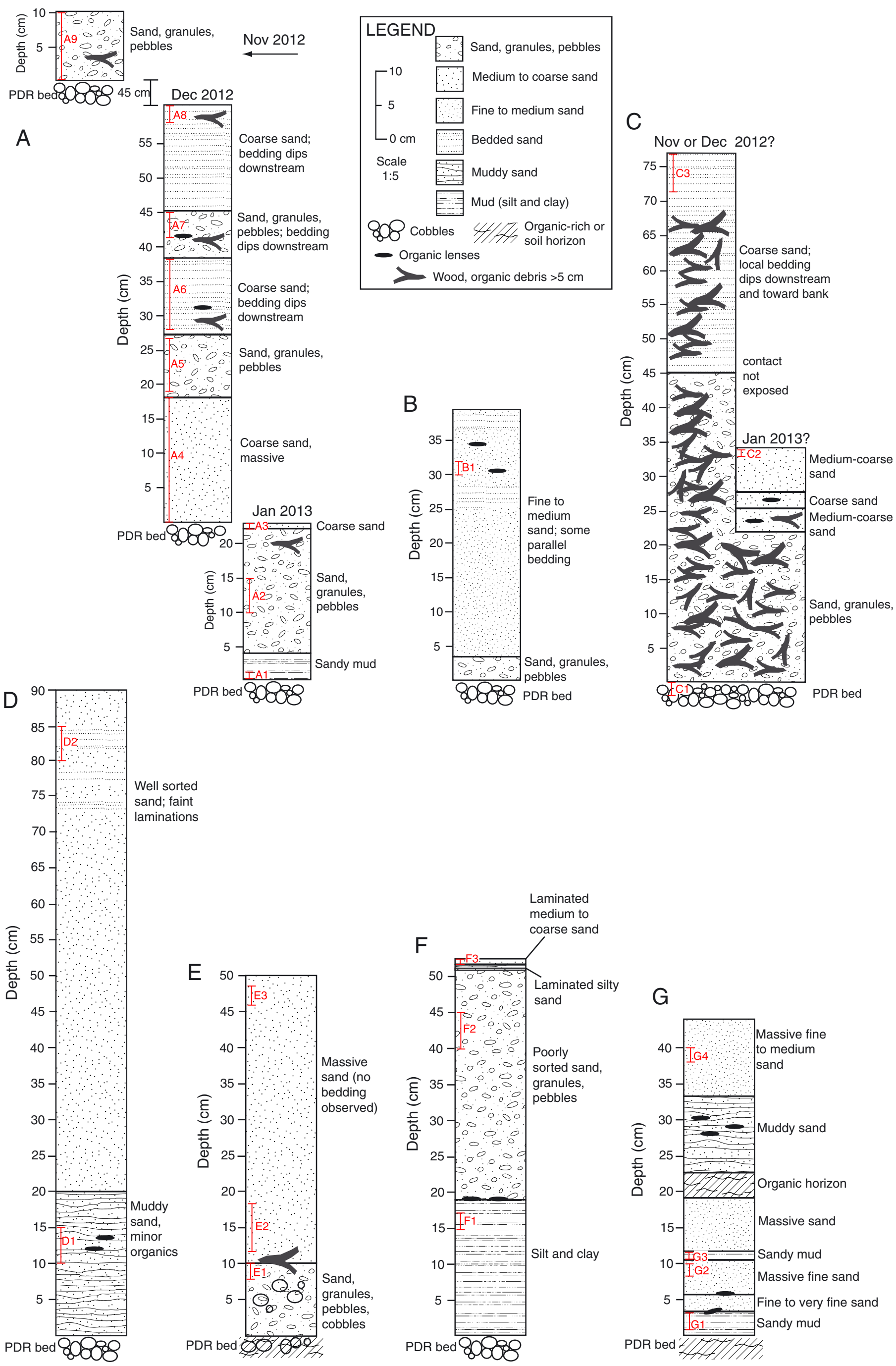

Figure 6. Sedimentary profiles through new fluvial deposits on the Elwha River described in late March 2013. Diagrams are to scale on the vertical axis. Locations of profiles A–R are shown on Figure 1B; numerical distances of each profile with respect to the dams are listed in the Appendix. Samples analysed for grain size and carbon content are indicated in red (see Table I). (A) and (C) represent deposits of more than one flood event, which formed separate deposits at those locations in November 2012, December 2012, and January 2013. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

interstitial spaces in the underlying cobble bed but did not increase bed elevation substantially (<20 cm bed aggradation). This initial new deposition consisted of grey to dark grey sediment dominated by silt, and also, at most locations, a greyish brown (2.5Y 5/2) sandy material (Figure 4A). The grey to dark grey mud was likely deposited from suspended sediment exported from Lake Aldwell reservoir deposits as Elwha Dam deconstruction gradually lowered the lake level

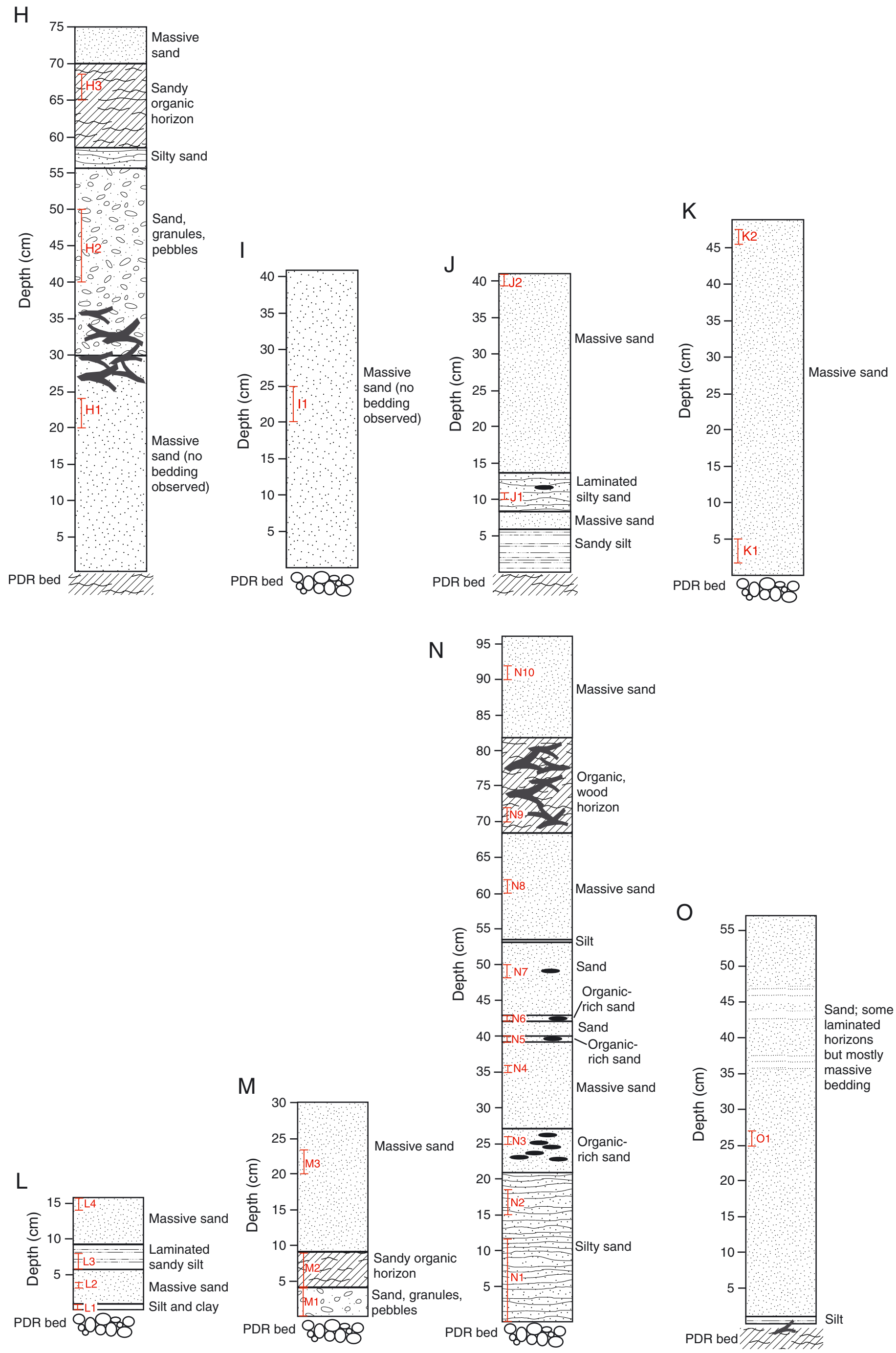

Figure 6. (Continued)

and suspended load accordingly increased (Figure 2). The greyish brown sandy unit, which underlay the grey mud along the lower Elwha River banks in April 2012 (Figure 4A) and whose colour did not match that of typical Elwha watershed sediment, was probably reworked material from some of the ~80 000 m^3 of fill used to build temporary earthen coffer dams at the Elwha Dam site during its deconstruction. In spring 2012, although the new fine sediment had not yet caused appreciable bed aggradation, it filled interstitial spaces in the pre-existing cobble bed (Figure 4B) in quiescent eddies, along non-eddy channel margins, and on the upstream and downstream sides of cobbles bars. Fine sediment was not observed in the channel thalweg in early spring 2012.

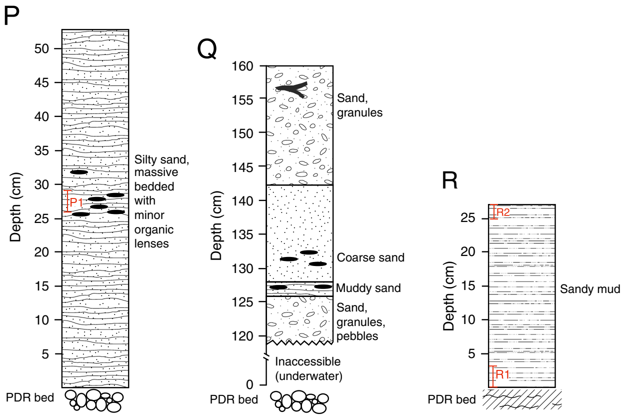

Figure 6. (Continued)

The second phase of new deposition began with bedload export from Lake Aldwell during spring snowmelt flows in May 2012, at which time that lake had been drained and Elwha Dam was entirely removed. New sand, granule and pebble deposits formed in the first several km downstream of the Elwha Dam site during late spring and summer 2012 as the mainstem bed in the lower river aggraded ~0.5 m (more when filling pools, essentially none over hydraulic controls such as riffles), with deposition in the thalweg as well as along channel margins.

The third phase of new sediment transport and deposition greatly exceeded the magnitude of the first two, when in fall 2012, Glines Canyon Dam deconstruction had progressed sufficiently that Lake Mills was drained and its reservoir delta sediment had prograded downstream far enough to abut the dam. The river then transported large amounts of suspended sediment and bedload from deposits of the former Lake Mills (Figure 2). Winter 2012–2013 therefore included widespread bed aggradation (commonly 1.5 to 2.5 m in the mainstem channel, and locally >5 m near Glines Canyon Dam), new bar formation, increased flow

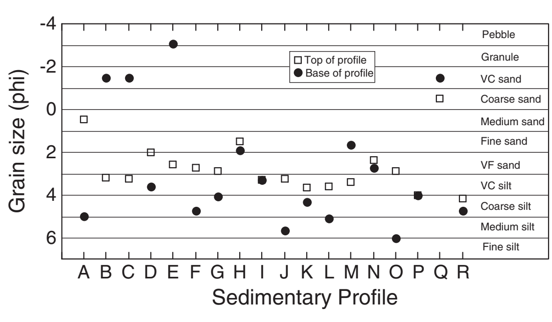

Figure 7. Basal and surficial sediment grain size in post-dam-removal sediment of profiles A–R (lowermost and uppermost sedimentary units above the pre-dam-removal bed), presented in order of increasing distance downstream (distance not to scale). Grain size in the 18 profiles was spatially heterogeneous, with no downstream trend in either basal or surficial grain size

into floodplain areas even during non-flood flows, filling of side channels, and deposition of a range of sediment grain sizes and organic material (Figures 3, 5 and 6). Late fall and winter 2012–2013 deposition occurred not only in quiescent zones of the channel such as in eddies and on the downstream sides of obstacles but also throughout the channel (including the thalweg) and over any inundated floodplain regions.

In the 18 sedimentary profiles studied in March 2013, fewer than half began with a basal mud deposit that would suggest continued preservation of initial suspended-sediment deposition; at least five profiles had a basal unit coarse enough to have been clearly bedload (gravel and pebbles in Profiles B, C, E and M, and underwater portion of N; Figure 6). Of the 12 profiles downstream of the Elwha Dam site, seven contained a basal mud-rich horizon above the pre-dam-removal bed (Profiles G, J, L, N, O, P and R; Figure 6). None of the profiles, however, still contained the greyish brown (2.5Y 5/2) sandy material that had been nearly ubiquitous along the lower Elwha River in April 2012 (Figure 4A) and that would have been a recognizable marker horizon if still present in 2013. This implies that the initial deposits that formed during the first fall and winter of dam removal (2011–2012) were removed by flows after April 2012 and replaced by newer material.

Despite the rarity of basal mud deposits, silt and clay nevertheless composed a substantial part of most sedimentary profiles studied in March 2013 (Figure 6; Table I). The thicknesses and mud content of mud-bearing sedimentary units were used to calculate an equivalent mud thickness for each profile, that is, an estimate of the proportion of total sediment thickness that was silt and clay (Figure 8; see Appendix for detailed calculations). For sedimentary units judged in the field to contain both sand and mud (those described as muddy sand, silty sand or sandy mud) but for which no grain-size analyses were performed, mud content was estimated conservatively to be 10% (cf. Boggs, 1995). Therefore, equivalent mud thickness estimates (Figure 8) should be considered minimum values. The 18 profiles were thereby estimated to have a mean mud content of 21%, with a median value of 17%. No significant trend existed in mud content with distance downstream (in Figure 8), nor was there a significant difference between mud content in the middle-reach profiles (between the dam sites) and lower-reach profiles (below Elwha Dam) even though the channel slope in the middle reach is greater than in the lower reach (0.006 vs 0.004). This may have been a function of limited sites sampled, especially in the middle reach.

Organic particles of widely variable sizes were abundant in post-dam-removal Elwha River deposits (from tree trunks to sub-centimetre particles; Figure 5). Of the 12 sedimentary units tested for organic carbon content, which were targeted because organic matter was visible within them in the field (Figure 6), all 12 had TOC content <10% (Table I). These measured

Table I. Grain size and organic content of sediment samples collected on the Elwha River, Washington, in March 2013. Sample locations within sediment profiles are shown in Figure 6. D_{10}, D_{50} and D_{90} indicate the 10th, 50th and 90th percentile for grain size

Sample	Height in profile (cm)	% granule >2 mm	% sand 0.063–2 mm	% silt 0.004–0.063 mm	% clay <0.004 mm	% mud <0.063 mm	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)	% TC	% TOC
A1	A, 0–2 (Jan 2013)	0.00	24.8	64.2	10.9	75.2	0.00	0.03	0.10	–	–
A2	A, 10–15 (Jan 2013)	42.6	54.0	2.51	0.86	3.37	0.21	1.57	7.48	–	–
A3	A, 22–23 (Jan 2013)	7.46	86.3	4.76	1.46	6.22	0.12	0.40	1.33	–	–
A4	A, 0–18 (Dec 2012)	1.91	92.0	4.57	1.54	6.12	0.12	0.40	1.02	–	–
A5	A, 19–27 (Dec 2012)	53.7	43.6	2.07	0.65	2.72	0.28	2.22	5.39	–	–
A6	A, 28–38 (Dec 2012)	0.00	84.2	12.2	3.58	15.8	0.02	0.16	0.40	–	–
A7	A, 42–45 (Dec 2012)	41.1	55.6	2.52	0.74	3.26	0.19	1.70	5.31	–	–
A8	A, 58–61 (Dec 2012)	12.1	80.9	5.34	1.66	7.01	0.10	0.34	2.21	–	–
A9	A, 0–10 (Nov 2012)	10.4	71.0	14.7	3.84	18.5	0.02	0.17	2.05	–	–
B1	B, 30–32	0.00	69.4	24.6	5.99	30.6	0.01	0.11	0.24	1.32	1.31
C1	C, –2–0	62.0	34.1	3.10	0.81	3.92	0.16	3.94	7.74	–	–
C2	C, 10–11	0.00	67.7	26.6	5.70	32.3	0.01	0.10	0.27	–	–
C3	C, 72–77	64.9	32.4	2.10	0.61	2.70	0.20	4.11	6.51	–	–
D1	D, 10–15	0.00	57.5	35.4	7.08	42.5	0.01	0.08	0.24	1.04	1.03
D2	D, 80–85	0.00	93.3	5.12	1.62	6.74	0.09	0.25	0.58	–	–
E1	E, 8–10	73.0	22.9	3.28	0.83	4.12	0.14	8.35	15.0	–	–
E2	E, 12–18	0.00	83.6	12.8	3.61	16.4	0.02	0.17	0.41	–	–
E3	E, 46–48	–	–	–	–	–	–	–	–	0.26	0.24
F1	F, 15–17	0.00	31.4	57.1	11.5	68.6	0.00	0.04	0.11	–	–
F2	F, 40–45	64.6	32.2	2.35	0.89	3.24	0.24	3.19	7.10	–	–
F3	F, 52–54	0.00	80.8	14.8	4.45	19.2	0.01	0.15	0.28	–	–
G1	G, 1–3	0.00	48.5	45.0	6.50	51.5	0.01	0.06	0.13	–	–
G2	G, 8–10	0.00	68.0	26.0	5.96	32.0	0.01	0.09	0.19	–	–
G3	G, 11–12	0.00	22.2	65.1	12.7	77.8	0.00	0.03	0.09	–	–
G4	G, 38–40	0.00	81.8	13.8	4.44	18.2	0.01	0.14	0.25	–	–
H1	H, 20–24	8.43	81.7	7.32	2.51	9.83	0.07	0.27	0.88	–	–
H2	H, 40–50	73.9	23.2	2.31	0.64	2.95	0.19	3.41	8.30	–	–
H3	H, 65–68	–	–	–	–	–	–	–	–	7.02	7.02
I1	I, 20–25	0.00	68.4	25.0	6.54	31.6	0.01	0.10	0.23	–	–
J1	J, 10–11	0.00	38.5	52.9	8.51	61.5	0.00	0.05	0.12	2.86	2.84
J2	J, 39–41	0.00	69.4	23.7	6.97	30.6	0.01	0.11	0.22	–	–
K1	K, 3–5	0.00	41.0	47.2	11.8	59.0	0.00	0.05	0.13	–	–
K2	K, 46–48	0.00	62.1	32.1	5.84	37.9	0.01	0.08	0.17	–	–
L1	L, 0–1	0.00	21.7	66.9	11.4	78.3	0.00	0.03	0.11	–	–
L2	L, 3–4	0.00	61.8	31.2	6.96	38.2	0.01	0.08	0.18	–	–
L3	L, 6–8	0.00	23.2	65.7	11.2	76.8	0.00	0.03	0.09	–	–
L4	L, 14–16	0.00	66.6	28.3	5.05	33.4	0.01	0.08	0.14	–	–
M1	M, 0–4	40.8	36.5	18.9	3.80	22.7	0.01	0.32	5.92	–	–
M2	M, 4–9	–	–	–	–	–	–	–	–	4.30	4.28
M3	M, 20–23	0.00	70.2	25.2	4.63	29.8	0.01	0.10	0.20	–	–
N1	N, 0–12	0.00	78.7	16.1	5.17	21.3	0.01	0.15	0.38	–	–
N2	N, 15–18	0.00	69.1	25.5	5.47	30.9	0.01	0.10	0.20	–	–

(*Continues*)

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Table I. (Continued)

Sample	Height in profile (cm)	% granule >2 mm	% sand 0.063–2 mm	% silt 0.004–0.063 mm	% clay <0.004 mm	% mud <0.063 mm	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)	% TC	% TOC
N3	N, 25–26	–	–	–	–	–	–	–	–	9.19	9.18
N4	N, 33–35	0.00	83.7	12.2	4.10	16.3	0.01	0.16	0.33	0.25	0.25
N5	N, 39–40	–	–	–	–	–	–	–	–	4.65	4.65
N6	N, 42–43	–	–	–	–	–	–	–	–	5.50	5.49
N7	N, 48–50	0.00	79.2	16.8	3.99	20.8	0.02	0.12	0.24	–	–
N8	N, 60–62	0.00	94.0	4.24	1.80	6.04	0.13	0.35	0.72	–	–
N9	N, 70–72	–	–	–	–	–	–	–	–	5.27	5.27
N10	N, 90–92	0.00	91.0	6.89	2.11	9.00	0.07	0.19	0.41	–	–
O1	O, 25–27	0.00	82.0	14.8	3.23	18.0	0.02	0.13	0.27	–	–
P1	P, 26–29	–	–	–	–	–	–	–	–	1.48	1.48
R1	R, 1–3	0.00	31.7	57.0	11.3	68.3	0.00	0.04	0.11	–	–
R2	R, 25–27	0.00	44.4	48.3	7.29	55.6	0.01	0.06	0.13	–	–

(–) = not analysed; % TC = percent total carbon; % TOC = percent total organic carbon.

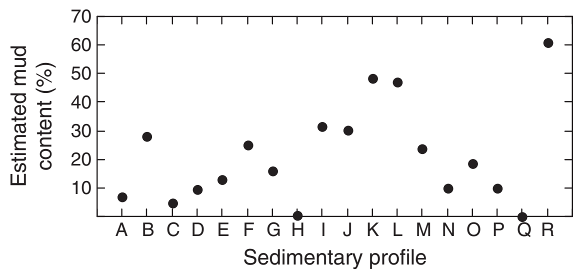

Figure 8. Estimated mud content of 18 sedimentary profiles A–R, presented in order of increasing distance downstream. Mud content (sum of silt and clay) is shown as the proportion of post-dam-removal deposit thickness composed of mud. This was calculated by multiplying the mud content in sedimentary units for which grain size was analysed (Table I) by the thickness of each stratum (Figure 5). For sedimentary units judged to contain both sand and mud in the field but for which no grain-size analyses were performed, mud content was estimated conservatively to be 10% (after Boggs, 1995). Therefore, equivalent mud thickness estimates should be considered minimum values. Details of calculations are given in the Appendix

values from strata with organic particles small enough to be sampled (e.g. Figure 5E) must underrepresent the actual organic carbon content in the new deposits, because it is not feasible to include larger woody debris in samples analysed by standard methods (Figure 5A, B, F). Nevertheless, it is notable that two-thirds of the profiles (12 of 18) included visible organic matter in the new deposits, either as distinct wood fragments or as diffuse lenses of smaller particles (Figure 6).

DISCUSSION

The new Elwha River sedimentary deposits that formed during dam removal are products of a unique imbalance between fluvial sediment supply and transport capacity. While flows during dam removal were essentially natural, lowering of the two reservoirs and the consequent abundance of unvegetated, unstable reservoir sediment made available for fluvial transport resulted in conditions of extreme oversupply of sediment with respect to transport capacity, leading to widespread new deposition throughout the river system (and also in the coastal zone, though this was not included in our study).

The degree of imbalance between sediment supply and transport capacity was not constant over the first 18 months of dam removal, however. Suspended-sediment concentrations and resulting sediment load during dam removal varied by nearly two orders of magnitude for any given discharge, indicating strong hysteresis as a function of dam-removal progress (Curran *et al.*, 2013). Measured just upstream of Lake Mills before dam removal, a flow of 50 m^3/s, for example, typically contained ~10 mg/L of sediment (Konrad, 2009). In contrast, during the first 18 months of dam removal,

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50 m^3/s flows had suspended-sediment concentrations that fluctuated up and down by orders of magnitude, ranging from 100 to 7890 mg/L (Curran *et al.*, 2013), the latter having occurred in late November 2012. No flows during dam removal thus far have even approached the 2-year flood (Figure 2), but concentrations in the highest flows during dam removal (e.g. 292 m^3/s in November 2011) have approximated 10 000 mg/L (Curran *et al.*, 2013). As expected, sediment load during dam removal, totalling almost 4 000 000 t in the first 18 months (Figure 2), has thus greatly exceeded the natural sediment supply from the upper watershed, estimated to be 217 000–513 000 t/year based on a regression equation applied to suspended-sediment and bed-sediment discharge measured during 2006 and 2007 (Curran *et al.*, 2009; Bountry *et al.*, 2010; Czuba *et al.*, 2011). The timing with which sediment supply becomes available in the Elwha River is controlled primarily by dam-removal progress rather than by natural watershed processes, and is decoupled from the timing of high flows that would move sediment downstream efficiently. The timing of when that sediment moves downstream in large quantities and deposits in places such as those sampled in this study is, however, a function of when natural flow events occurred.

These conditions of sediment supply and transport capacity on the Elwha River, where river restoration involves gradual, multi-stage dam removal, are fundamentally different from those of an instantaneous (so-called 'blow-and-go') dam removal, as occurred with the removals of Marmot Dam on the Sandy River, Oregon, or Condit Dam on the White Salmon River, Washington. At Condit Dam, 1.5 h after an explosion opened a 6-m-wide hole in the base of the dam, allowing rapid sediment erosion as the reservoir drained completely over several hours, fluvial sediment concentrations exceeded 700 000 mg/L (O'Connor *et al.*, 2012)—a mudflow 70 times more concentrated than the highest concentrations measured during staged dam removal on the Elwha River, in a discharge of only 31 m^3/s (J. E. O'Connor, pers. comm.). Downstream of Condit Dam, the highly concentrated dam-breach flow left mud, sand and gravel deposits that were variably massive to stratified. The new fill, >1 m thick, incised rapidly as the fluvial sediment 'wave' propagated downstream, leaving behind incised channel-margin deposits (O'Connor *et al.*, 2012). During and after the instantaneous Marmot Dam removal, sediment-transport rates increased greatly as a metres-tall knickpoint migrated rapidly upstream over several hours after dam breaching, and suspended-sediment concentration peaked at 49 000 mg/L within the dam-breach flow pulse (Major *et al.*, 2012), nearly five times greater than any measured on the Elwha River. Deposition below Marmot Dam site included a coarse, gravel-dominated wedge as thick as 4 m that formed within days after the dam breaching and tapered downstream along 1.3 km, with further sand deposition in pools within a bedrock canyon 2–9 km below the dam site; mud deposition was not quantified explicitly, but was deemed insignificant below the Marmot Dam site (Podolak and Wilcock, 2009; Major *et al.*, 2012). In the Sandy River system, reservoir-sediment knickpoint retreat controlled downstream geomorphic effects more strongly than did post-dam-removal flows (Major *et al.*, 2012).

On the Elwha River during multi-stage dam removal, deposits took more time to attain thickness comparable with the maximum depositional thickness downstream of the Condit or Marmot dam sites (months rather than hours or days). As of March 2013, some incision of the new Elwha deposits was beginning in the middle reach, between the two dam sites, but along the lower river incision was not yet widely evident. These observations of sediment concentration and deposit thickness are consistent with expectations that a staged dam removal would cause less-pronounced short-term effects than would instantaneous dam removal, but will impact a river system over a longer duration. However, so few large dams have been removed thus far that it is not easy to generalize river response to staged versus instantaneous dam removal; dam-removal response will be a function of the style of dam removal, local morphology, hydrology during and for years after dam removal, sediment amount and grain size particularly in the reservoir(s), and other factors.

Despite the highly heterogeneous nature of Elwha dam-removal sedimentation and the rapid and large-magnitude changes occurring in this system, the state of new fluvial deposits 18 months into large-scale dam removal indicates important physical and potential ecological responses. Deposition patterns observed in March 2013 may not persist over multi-year time scales; subsequent flows could remove much of the sediment sampled in this study and either incise the new deposits, causing net export and degradation, or replace it with new, coarser sediment. It is notable, however, that the sampled deposits contained a substantial proportion of mud—on average, about one-fifth of the new channel-margin and floodplain material was silt and clay (Figure 8), which had been predicted to bypass the river system (EIS, 1996; Gelfenbaum *et al.*, 2011)—and that mud deposition was nearly ubiquitous along the channel margins and floodplain rather than being confined only to quiescent flow regions. Before dam removal, predictions using a one-dimensional (1D) sediment-transport model, HEC-6 (Randle *et al.*, 1996), did not include deposition of mud-sized material. Non-deposition of mud was assumed because, given the riverbed slope and hydrologic conditions in the Elwha River, downstream transport should occur at velocities orders of magnitude faster than the settling velocity of silt and clay particles (cf. the Hjulström diagram), such that 'fine-grained materials would pass through the river system and would not be deposited in the Elwha River channel'

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(Environmental Impact Statement (EIS-2): Implementation EIS, 1996). Konrad (2009) subsequently used a 1D transport model for suspended sediment based on the Rouse equation (Bennett, 2001) to consider Elwha River transport conditions and bed aggradation for examples of wet and dry water years, but did not make specific predictions for mud-sized material. Because inherently multi-dimensional flow and depositional processes remain difficult to constrain or predict, particularly for mud-sized material, a high degree of uncertainty for these predictions was expected (Environmental Impact Statement (EIS-2): Implementation EIS, 1996; Konrad, 2009; Czuba *et al*., 2011). Similarly, 1D sediment-routing models did not predict well all aspects of fluvial response to Marmot Dam removal on the Sandy River, largely owing to local topographic influences (Cui and Wilcox, 2008; Major *et al*., 2012). Both the unexpected abundance and ubiquitous spatial distribution of mud on the Elwha River are attributed to the great fine-grained sediment supply during dam removal coincident with unusually low fluvial transport capacity, especially the lack of winter flood flows, that apparently produced spatial and/or temporal flux gradients that favoured mud deposition.

It is likely that new sediment deposits in the highest-energy regions of the Elwha River channel, such as the thalweg, have lower or absent mud content compared with the channel-margin and floodplain deposits sampled in this study; the one mid-channel bar sampled (Profile Q) had negligible mud. Even though mud may be rare in the central channel, the amount and composition of channel-margin and floodplain deposition is relevant to river-restoration managers and the public because of the association between floodplain aggradation and the potential for increased risk to property and infrastructure during subsequent flooding. Before dam removal on the Elwha River, the 100-year flood stage was predicted to increase by as much as 1 m owing to aggradation after dam removal (Environmental Impact Statement (EIS-2): Implementation EIS, 1996), and flood-protection levees were raised accordingly. It is currently unknown whether the ~20% mud content in new Elwha deposits means that the total aggradation will be ~20% greater than predicted, potentially raising the 100-year flood stage more than 1 m, or whether the accumulated sediment volume is similar to that predicted but simply finer grained.

The abundant fine material in new sediment deposits could have important effects for the Elwha ecosystem as it adjusts to dam removal. In addition to complex ecological effects of increased suspended sediment, particularly over long duration (e.g. Newcombe and MacDonald, 1991; Jones *et al*., 2012), it is potentially important that muddy deposits filled pore spaces in the pre-dam-removal cobble bed even months before wholesale bed aggradation began (Figure 4B). Fine-sediment infiltration into gravel and cobble beds, which also occurred downstream of the Milltown Dam site in Montana for the first several years after dam removal (Evans and Wilcox, 2013), reduces pore space in the bed. Pore filling subsequently alters both river morphodynamics (e.g. by inhibiting bedload entrainment; Barzilai *et al*., 2013) and aquatic ecosystems; fine-sediment infiltration limits the flow of oxygenated water through bed material, potentially reducing survivability of fish redds and other aquatic organisms (Lisle, 1989; Wood and Armitage, 1997; Greig *et al*., 2005; Jones *et al*., 2012). An important goal of Elwha River restoration is to restore natural sediment conditions in the middle and lower river such that gravel beds become available as spawning habitat. This is likely to occur as muddy deposits are gradually replaced by gravel over time; however, the early response of mud filling pore spaces in a coarse-grained bed likely reduced habitat quality for spawning and incubation on the Elwha River over time scales of months in 2011–2012, even though most initial mud deposits had been remobilized and replaced by March 2013. Fine-sediment infiltration also may have altered groundwater hydrology locally on the Elwha floodplain, as at least one groundwater-fed side channel had a much lower water table in summer 2012 than at any time in the preceding 6 years (within Reach 2 of Draut *et al*., 2011). The substantial mud content could potentially lead to more rapid vegetation growth on new channel-margin and floodplain deposits, as a muddy substrate retains water more effectively than would a more permeable sand or gravel deposit.

The presence of organic matter in the new Elwha River fluvial deposits is consistent with restored natural delivery of wood and other vegetative matter from the upper watershed (being no longer restricted by log booms in front of the dams or settling in the reservoirs) and delivery of organic matter reworked from within the Mills and Aldwell reservoir deltas. The reservoir sediment contained much organic material because construction of the reservoirs in the early 1900s flooded forest floors. The organic debris of all particle sizes in the Elwha deposits likely has transferred abundant nutrients and carbon to the middle-river and lower-river ecosystem, in addition to emplacing new large woody deposits that could increase physical habitat complexity and quality (e.g. Fetherston *et al*., 1995; Montgomery *et al*., 1996; Collins *et al*., 2002; Wohl, 2013). Ecological effects of this and other aspects of Elwha River restoration will become more apparent and quantifiable as response to the dam removals evolves over the coming years.

CONCLUSIONS

This study analysed sedimentology of new fluvial deposits on the Elwha River that formed under unique conditions as fluvial sediment supply greatly increased relative to transport capacity during the largest-scale dam removals yet undertaken. The new sedimentary deposits exhibited substantial spatial heterogeneity in thickness, stratal-formation patterns, grain size and organic content. Initial mud deposition filled pore spaces in the pre-dam-removal cobble bed, potentially causing ecological disturbance but not aggrading the bed substantially at first. The early mud deposits were later replaced by newer and in some cases coarser basal deposits during the second winter of dam removal. By 18 months into dam removal, channel-margin and floodplain deposits were commonly >0.5 m thick and, contrary to pre-dam-removal predictions that silt and clay would bypass the river system, included average mud content around 20%. Large wood fragments and lenses of smaller organic particles were common in the new deposits, presumably contributing additional carbon and nutrients to areas downstream of the two dam sites. Multi-stage large dam removals on the Elwha River apparently have caused less-pronounced short-term effects than would instantaneous large dam removal, but will likely impact the river system over a longer duration. Understanding the physical, sedimentary response to the first 18 months of these staged dam removals will inform subsequent analyses of longer-term sedimentary, geomorphic and ecosystem changes in the Elwha system, and will provide important lessons for other river-restoration efforts where large dam removal is planned or proposed.

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APPENDIX

ESTIMATES OF MUD (SILT AND CLAY) CONTENT IN SEDIMENTARY PROFILES.

Mud content of each sedimentary profile was estimated by using sediment samples that contained at least 10% mud (sum of silt and clay content; Table I). Sample locations within profiles are shown in Figure 6. For sedimentary horizons that were judged in the field to have both sand and mud content (those described as muddy sand, silty sand or sandy mud) but on which no grain-size analyses were performed, the mud content is estimated conservatively to be 10% (Boggs, 1995). Therefore, estimates of mud content given below should be treated as minimum values because sedimentary units called 'sandy mud', 'muddy sand' or 'silty sand' may well have mud content substantially greater than 10%.

PROFILE A:

The three flood deposits composing Profile A are located at the former site of the Glines Power House, 0.25 km downstream of the Glines Canyon Dam site on the river-left bank. Sediment at this location forms a channel-margin deposit in a small eddy. Three distinct deposits were apparent in March 2013 that formed inset depositional terraces against the pre-dam-removal cobble bed, as shown in Figure 6A. The three deposits each culminated in a near-horizontal surface representing the top of deposition during individual flood flows in November 2012, December 2012 and January 2013 (based on observations immediately after each of those floods by A. C. Ritchie). The horizon containing sample A1 (described as sandy mud in the field) is 4 cm thick and includes 75.2% mud, yielding an equivalent mud thickness of 3.01 cm. The horizon containing sample A6 (coarse sand, as described in the field is 10 cm thick and includes 15.8% mud, yielding 1.57-cm mud thickness). The horizon containing sample A9 (poorly sorted composition, dominated by sand, granules and pebbles but with some mud noted in the field) is 10 cm thick and contains 18.5% mud, yielding 1.85-cm mud thickness. The equivalent mud thickness for Profile A is therefore estimated to be 6.43 cm out of 94 cm total profile thickness, or 6.84%.

PROFILE B:

Profile B was sampled within a channel-margin deposit on the river-left bank 0.77 km downstream of the Glines Canyon Dam site. The horizon containing sample B1 (described as fine to medium sand in the field) had no grading evident visually and only isolated parallel bedding. The unit is 36 cm thick and contains 30.6% mud. Equivalent mud thickness for Profile B is therefore estimated to be 11 cm out of 39 cm total profile thickness, or 28.2%.

PROFILE C:

Profile C was sampled in a channel-margin deposit at the upstream end of the Altair Campground within Olympic National Park, 1.73 km downstream of the Glines Canyon Dam site. Sample C2 was collected from the uppermost part of a fluvial deposit left by a January 2013 flood in an inset terrace atop slightly older deposits left by November and/or December 2013 floods (Figure 6C). The total new (post-dam-removal) deposit thickness at this location is considered to be 77 cm, most of which was deposited by the November–December 2013 floods and does not contain appreciable muddy sediment. The horizon containing sample C2 is 11 cm thick and is 32.3% mud. The equivalent mud

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thickness for Profile C is therefore estimated to be 3.55 cm out of 77 cm, or 4.61%.

PROFILE D:

Profile D was sampled in a channel-margin deposit at the downstream end of the Altair Campground within Olympic National Park, 1.86 km downstream of the Glines Canyon Dam site. The horizon containing sample D1 (muddy sand with minor organics) is 20 cm thick and includes 42.5% mud. Equivalent mud thickness for Profile D is therefore estimated to be 8.49 cm out of 90-cm total thickness, or 9.43%.

PROFILE E:

This profile was sampled in a channel-margin deposit on river right along a riffle, 4.54 km downstream of the Glines Canyon Dam site. The horizon containing sample E2 (described in the field as a massive sand unit, without bedding) is 40 cm thick and includes 16.42% mud. The equivalent mud thickness for Profile E is therefore estimated to be 6.57 cm out of 50 cm total thickness, or 13.1%.

PROFILE F:

Profile F was sampled in a channel-margin deposit on river right, 7.85 km downstream of the Glines Canyon Dam site. The horizon containing sample F1 (described as silt and clay in the field) is 19 cm thick and contains 68.60% mud, yielding 13.03 cm equivalent mud thickness. The horizon containing sample F3 is 3 cm thick and is 19.24% sand, yielding 0.58 cm equivalent mud thickness. Equivalent mud thickness for Profile F is therefore estimated to be 13.6 cm out of 54 cm total thickness, or 25.2%.

PROFILE G:

Profile G is located on the river-left floodplain within Reach 1, Transect 3 of Draut *et al*. (2011), at a location 1.94 km downstream of the Elwha Dam site (15.6 km downstream of the Glines Canyon Dam site). Before dam removal, the area where the profile is situated received river flow only during flood events, but beginning in winter 2012–2013, this location began to receive river flow intermittently even during non-flood flows, in response to mainstem bed aggradation. The horizon from which sample G1 was obtained is 3 cm thick and contains 51.47% mud, yielding an equivalent mud thickness of 1.54 cm. The overlying unit, described in the field as fine to very fine sand, was not analysed for grain size and is assumed to have no mud because no further information is available about this horizon. The horizon containing sample G2 is 5 cm thick and includes 31.99% mud, yielding an equivalent mud thickness of 1.60 cm. The horizon containing sample G3 is 1 cm thick and is 77.80% mud, yielding an equivalent mud thickness of 0.78 cm. The 11-cm-thick unsampled unit described in the field as muddy sand (spanning 22.5–33.5 cm height in the profile), but from which no samples were collected, is assumed to have 10% mud content, yielding an equivalent mud thickness of 1.10 cm. The horizon containing sample G4 is 10.5 cm thick and includes 18.24% mud, giving an equivalent mud thickness of 1.92 cm. The total equivalent mud thickness for Profile G is therefore estimated to be 6.94 cm out of 44 cm total thickness, or 15.8%.

PROFILE H:

Profile H was documented within a channel-margin deposit on the left bank 2.19 km downstream of the Elwha Dam site (15.9 km below the Glines Canyon Dam site), across the river from the instrument station where suspended sediment is measured by the USGS (e.g. Figure 2). The three samples from Profile H contained <10% mud. However, an unsampled horizon described in the field as silty sand, which spanned a height from 56 to 58 cm within the profile, is assumed to have (a minimum of) 10% sand. Being 2 cm thick, this yields an equivalent mud thickness of 0.2 cm. Equivalent mud thickness for Profile H is therefore estimated to be 0.2 cm out of 75 cm total thickness, or 0.27%.

PROFILE I:

Profile I was measured in a channel-margin deposit on river right 2.56 km below the Elwha Dam site (16.3 km below the Glines Canyon Dam site). Profile I contained only one horizon, a massive sand unit with no visually evident grading or bedding. Sample I1 contained 31.55% sand, so the equivalent mud thickness is estimated to be 31.55% of 41 cm total thickness (12.9 cm).

PROFILE J:

This profile was measured in a channel-margin deposit on river right, 3.95 km downstream of the Elwha Dam site (17.7 km below the Glines Canyon Dam site). The lowermost unit in Profile J, described as a sandy silt, was 6 cm thick and is assumed to contain 10% mud, for an equivalent mud thickness of 0.60 cm. The horizon containing sample J1 is 5.5 cm thick and includes 61.5% mud, for an equivalent mud thickness of 3.38 cm. The massive sand horizon containing sample J2 is 27.5 cm thick and is 30.6% mud,

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giving an equivalent mud thickness of 8.42 cm. The equivalent mud thickness for Profile J is therefore estimated to be 12.4 cm out of 41 cm total thickness, or 30.2%.

PROFILE K:

This profile was documented in a floodplain area 4.04 km downstream of the Elwha Dam site (17.7 km below the Glines Canyon Dam site). Its location, on river right with respect to the mainstem channel, is at the head of a side channel that, before dam removal, only received surface-water flow during flood discharge greater than ~420 m^3/s. Beginning in winter 2012–2013, this area began to receive surface-water flow even at non-flood discharge. The increase in non-flood flow into the side channel and Profile K floodplain area were caused both by mainstem bed aggradation as a result of dam removal, by channel alteration during construction of an engineered log jam 10–50 m upstream of this location. The total thickness of Profile K was 49 cm, described as one horizon of massive sand. Grain-size analysis showed a slight fining upward from 59.0% mud in sample K1 to 37.9% mud in sample K2. With the use of an average mud content of 48.5% throughout this profile, the equivalent mud thickness is taken to be 23.7 cm (48.5%).

PROFILE L:

Profile L was sampled from a channel-margin deposit on river right of the mainstem river 4.21 km downstream of the Elwha Dam site (17.9 km below the Glines Canyon Dam site). This deposit formed in the lee of an engineered log jam newly constructed during winter 2012–2013. The lowermost unit in Profile L, from which sample L1 was obtained, is 1 cm thick and included 78.3% mud for a mud equivalent thickness of 0.78 cm. The horizon containing sample L2 is 4.5 cm thick and is 39.2% mud, for a mud equivalent thickness of 1.72 cm. The horizon containing sample L3 is 3.5 cm thick and is 76.8% mud, yielding a mud equivalent thickness of 2.69 cm. The horizon containing sample L4 is 7 cm thick and includes 33.4% mud, for a mud equivalent thickness of 2.34 cm. The total equivalent mud thickness for Profile L is therefore estimated to be 7.53 cm out of 16 cm profile thickness, or 47.1%.

PROFILE M:

This profile was located in a channel-margin deposit at the left side of the Elwha River's eastern anabranch in a reach with two major anabranches separated by an island several hundred metres wide (the western anabranch, which carries slightly more than half of the flow as of 2013, is known as the Hunt Road channel; Draut *et al.*, 2011). Profile M is located 4.72 km below the Elwha Dam site (18.4 km below the Glines Canyon Dam site). The lowermost unit, where sample M1 was collected, is poorly sorted and dominated by sand, granules and pebbles (Table I) but also contained 22.7% mud. Being 4 cm thick, this yields an equivalent mud thickness of 0.91 cm. The horizon containing sample M2 was not sampled for grain-size analysis (only for organic content) and as it was described as a sand, is assumed to contain <10% mud and so is not included in this calculation. The horizon containing sample M3 is 21 cm thick and is 29.8% mud, for a mud equivalent thickness of 6.26 cm. Equivalent mud thickness for Profile M is therefore estimated to be 7.17 cm out of 30 cm total thickness, or 23.9%.

PROFILE N:

Profile N was sampled from a central bar within the eastern anabranch described above, at a site 4.82 km below the Elwha Dam site (18.5 km below the Glines Canyon Dam site). This sediment bar is situated in the lee of an engineered log jam that has been in place since 2000. The bar accumulated substantially more sediment and wood debris during winter 2012–2013. Samples N1 and N2 were collected from the lowermost horizon, described as silty sand. The average of the mud content in those two samples is 26.1%, which, over the 21-cm thickness of that unit, yields a mud equivalent thickness of 5.48 cm. The horizon containing sample N3 was not sampled for grain-size analysis and was not described as containing mud in the field. The horizon containing sample N4 is 12 cm thick (spanning 27–39 cm in the profile) with 16.3% mud, for a mud equivalent thickness of 1.96 cm. The unit containing sample N7 is 10 cm thick (43–53 cm in the profile) is 20.8% mud, for a mud equivalent thickness of 2.08%. A silt horizon at height 53 cm in the profile is disregarded in this calculation because it spans only a few millimetres of thickness. The equivalent mud thickness for Profile N is therefore estimated to be 9.52 cm out of 96 cm total thickness, or 9.92%.

PROFILE O:

This profile was sampled from a channel-margin deposit on the left bank of the eastern anabranch mentioned earlier, at a location 5.42 km downstream of the Elwha Dam site (19.1 km below the Glines Canyon Dam site). Profile O contained a basal unit described as a silt, for which grain size was not analysed. This 1-cm-thick unit is assumed to have 50% mud content (cf. Boggs, 1995), giving a mud equivalent thickness of 0.5 cm. The locally laminated sand unit that composes the remainder of Profile O is 56 cm thick,

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with 18.0% mud, for a mud equivalent thickness of 10.1 cm. Equivalent mud thickness for Profile O is therefore estimated to be 10.6 cm out of 57 cm total thickness, or 18.6%.

PROFILE P:

Profile P was documented within a channel-margin deposit on the left bank of the mainstem river, 6.86 km below the Elwha Dam site (20.6 km below the Glines Canyon Dam site). This profile contained silty sand with local organic lenses. It was not sampled for grain-size analysis and is conservatively assumed to contain 10% mud based on its field description. Over the 53-cm-thick profile, this equates to 5.30 cm mud thickness. A 10% mud content for this profile is certainly a minimum value.

PROFILE Q:

Profile Q was measured within a mid-channel bar 7.14 km below the Elwha Dam site (20.8 km below the Glines Canyon Dam site), in Reach 3 of Draut *et al*. (2011), along their Transect 4. The lowermost 118 cm of the 160-cm-thick post-dam-removal sediment at this site were underwater at the time of sampling and could not be described as part of the profile (Figure 6Q). This profile was not sampled for grain-size analysis, but one unit was judged in the field to contain mud: a muddy sand 2 cm thick. Assuming a minimum 10% mud content, this gives an equivalent mud thickness of 0.2 cm. For this 160-cm-thick profile the equivalent mud thickness is therefore taken to be 0.13%.

PROFILE R:

This profile was sampled from a channel-margin deposit on river left within Reach 3 of Draut *et al*. (2011), at a location 7.20 km below the Elwha Dam site (20.9 km downstream of the Glines Canyon Dam site). Profile R was described in the field as having only one sedimentary unit, a sandy mud that spanned its entire 27-cm thickness and was found to contain 68.3% mud at its base (sample R1) and 55.6% mud at its top (sample R2). Using an average mud content of 61.0%, an equivalent mud thickness for Profile R is estimated to be 16.5 cm (61.0%).

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