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Historical sedimentation at an artificial lake margin, Bangudae Petroglyphs site, SE Korea

Jisu Kim and Young Kwan Sohn*

Department of Geology and Research Institute of Natural Science, Gyeongsang National University, Jinju 52828, Republic of Korea

ABSTRACT: The Bangudae Petroglyphs is Korea's National Treasure No. 285, carved on a vertical rock face on the riverside of a mountain stream (Daegokcheon) near Ulsan. Since the construction of the Sayeon Dam in the downstream area in 1965, the petroglyphs was repeatedly flooded and submerged, raising concerns of erosion and water damage of the prehistoric rock-art motifs. Recent excavation of the fluvial sediments in front of the petroglyphs provided an opportunity to investigate the changes in sedimentation pattern before and after the construction of the dam and the consequences of human activity on natural environments. Sedimentological observations of trench sections and radiocarbon, OSL, and garbage dating of sediments reveal that the sediments comprises gravelly to sandy fluvial sediments in the lower part that accumulated since the early to middle Holocene or early to middle Neolithic Era until 1965. Above this, 25 units of alternating horizontally laminated sand and massive, mottled mud with abundant rootlets occur. This sand/mud sequence is interpreted to have accumulated after the construction of the Sayeon Dam in 1965, which caused repetitive flooding and submergence of the study area every year or two. The alternations of horizontally laminated sand and massive mud are interpreted to have resulted from rainfall-induced floods and subsequent suspension settling of fines in stagnant water after the area was inundated and temporarily transformed into a lacustrine margin setting. Afterwards, the depositional site was exposed and vegetated until the next flood event. Comparison of the deposit features with the precipitation data in Ulsan area, the water level data of the Sayeon Dam, and age data suggests that this flood-related sedimentation occurred almost every year until 2005 when the water level of the Sayeon Dam was lowered permanently because of the construction of another dam in the upstream section of the stream. This study thus provides a good example of a dramatic environmental change of a mountain stream caused by artificial disturbance of a river system due to construction of dams and an example of high-resolution sedimentary records of meteorologically induced floods in an artificial lake margin.

Key words: Bangudae Petroglyphs, mountain stream, fluvial deposit, lake margin, flood, depositional environment

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1. INTRODUCTION

The Bangudae Petroglyphs, Korea's National Treasure No. 285, is an important piece of prehistoric art carved on vertical rock faces on the riverside of the Daegokcheon stream, which is a branch of the Taehwa River, running eastward and joining the East Sea at Ulsan (Fig. 1). The petroglyphs represent three hundred and four figures of animals and unidentified motifs, and is especially famous for the representations of whales (Kim, 1986; Jang, 2007). From the abundant representations of marine animals, the site is related with hunter-fishers in the Neolithic Era between 8,000 yrs BP and 3,500 yrs BP. The age has not been proven, however, because the age is extrapolated from the results of an analysis of animal bones and relics at other Neolithic sites distributed along the southeastern coasts of Korea (Kim, 1986; Jang, 2007). In addition to the uncertainty of the age, there have been issues of preservation of the site since the construction of the Sayeon Dam in the downstream area of the Daegokcheon stream, which was built from 1962 to 1965 and expanded between 1999 and 2002. The dam caused the rocks on which the petroglyphs are carved to be flooded for months every year. This periodic flooding has raised concerns of erosion and water damage of the rock-art motifs, which are considered to be masterpieces of prehistoric art and an invaluable source of prehistoric information.

In 2013, four trenches were dug into the fluvial sediments that

*Corresponding author:
Young Kwan Sohn
Department of Geology and Research Institute of Natural Science, Gyeongsang National University, Jinju 52828, Republic of Korea
Tel: +82-55-772-1476, Fax: +82-55-772-1479, E-mail: yksohn@gnu.ac.kr

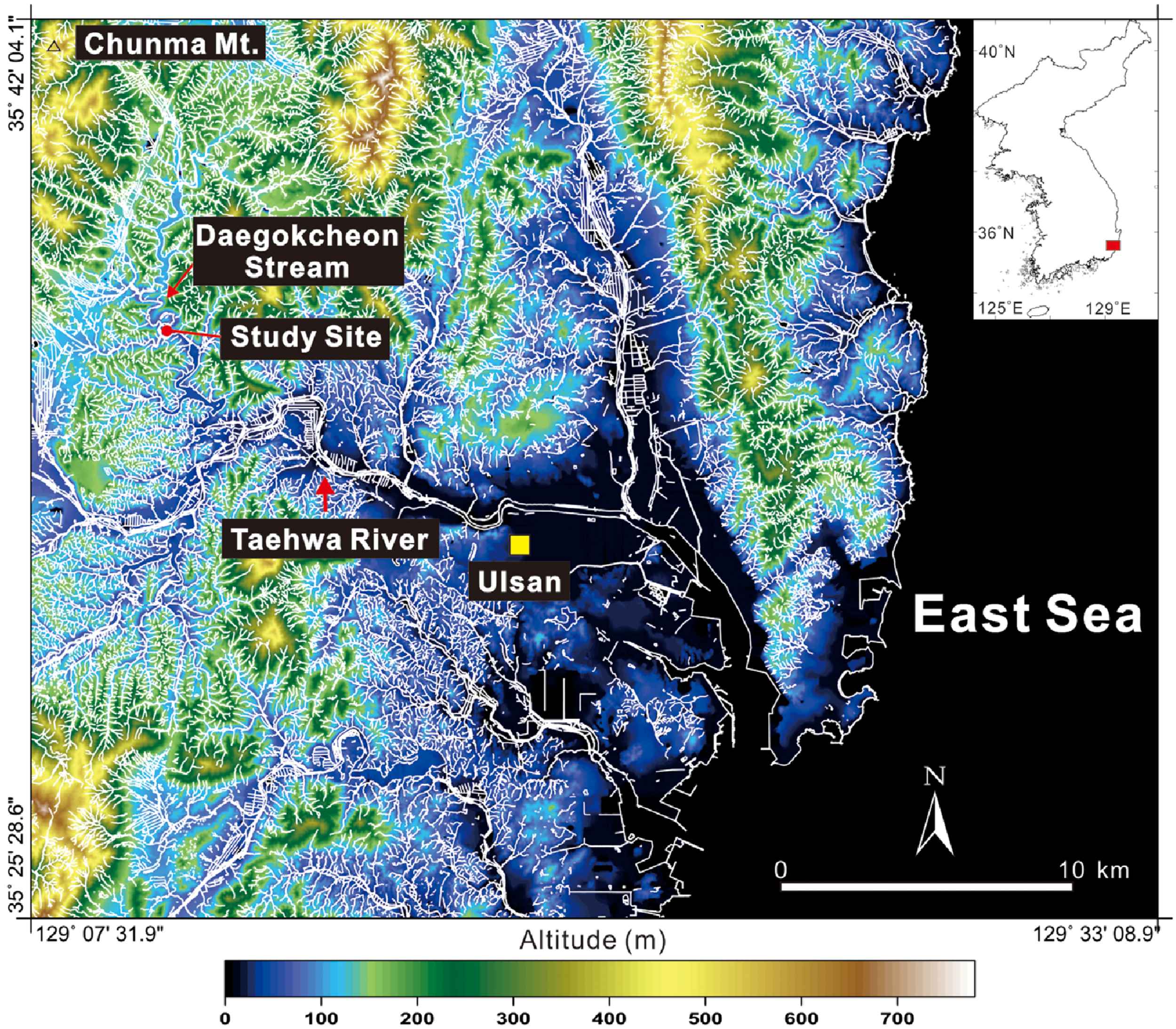

Fig. 1. Regional topographic map around the study area, showing the details of the river system.

accumulated on the riversides of the stream in front of the petroglyphs by the National Research Institute of Cultural Heritage (Fig. 2). The purpose was to find any archaeological relics in the sediments that can provide a more reliable age of the petroglyphs. The attempt was not successful, and the trenches were buried again immediately after the excavation. However, the excavation had unexpected results of exposing the full sequence of fluvial sediments that accumulated upon the Cretaceous sedimentary basement rocks at that site, providing an opportunity to investigate the changes in sedimentation pattern before and after the construction of the Sayeon Dam and the consequences of human activity on natural environments. The authors had an opportunity to observe and sample the fluvial sediments in one of the trenches (Trench B2; Fig. 2) for a few days. In this paper, we describe the deposit features of the alluvial sediments, provide radiocarbon and OSL ages of the sediments, and interpret the changing depositional processes in combination with the meteorological data and the water level data of the Sayeon Dam in the last fifty years. This study can provide a basis for the hydrologic characterization of the mountain stream, and thereby help in the conservation of the petroglyphs. In addition, this study can provide an opportunity to test how faithfully the meteorological phenomena such as precipitation are recorded in the sediments.

2. SITE CHARACTERISTICS

The Bangudae Petroglyphs site is located in the middle reach of the Daegokcheon stream, which originates from the Mt. Chunma to the northwest of the site and flows about 26 km to join the Taehwa River in the southeast (Fig. 1). The drainage area of the Daegokcheon stream is 129.6 km^2. Topographic maps that were published before the construction of the Sayeon Dam

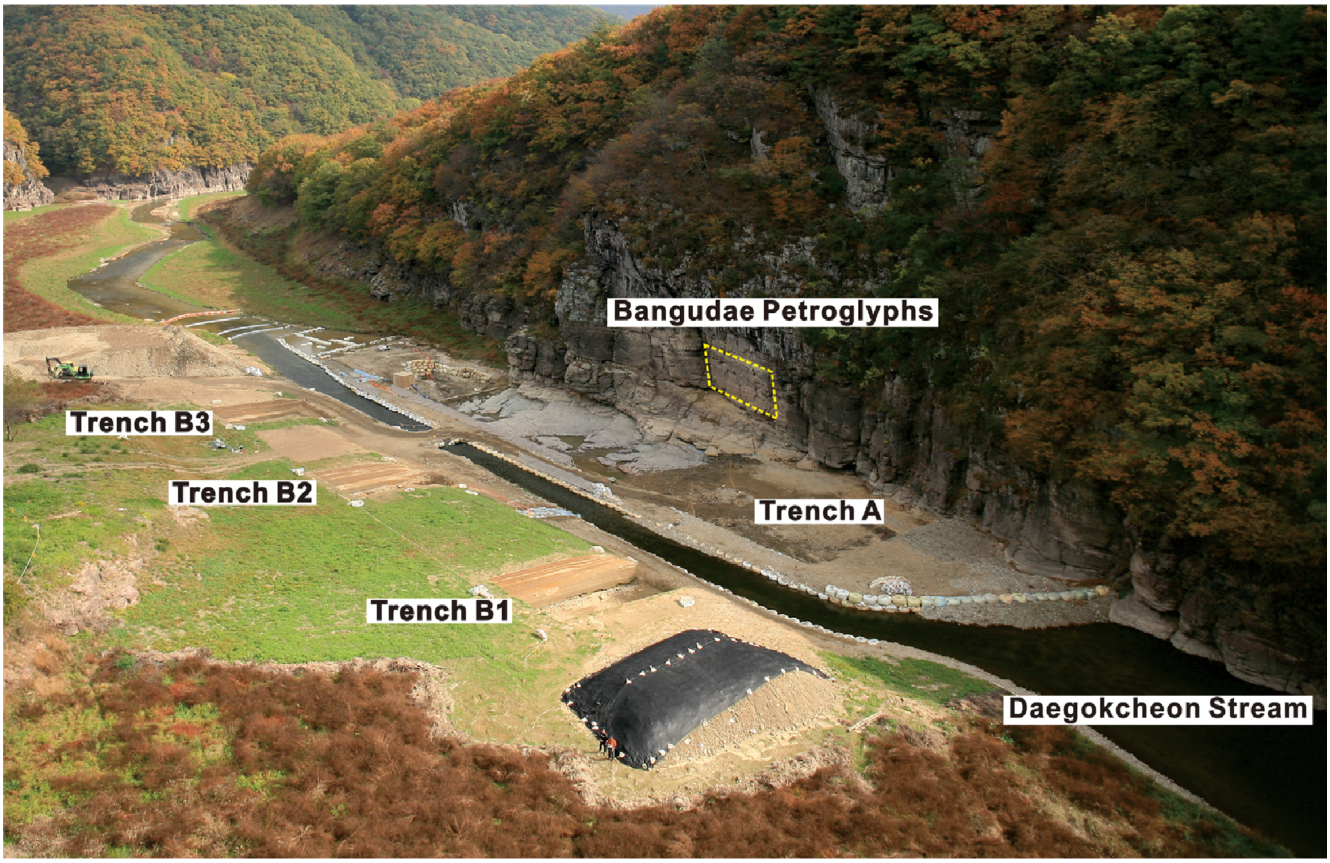

Fig. 2. Aerial view of the study area. Four trenches were dug into the fluvial sediments in front of the rock face on which the Bangudae Petroglyphs are carved. The trenches were immediately buried after excavation, only Trench B2 was studied in detail.

(Figs. 3a and b) show the meandering nature of the downstream section of the Daegokcheon stream, which was later submerged. An aerial photograph taken in 1967, i.e., two years after the construction of the dam (Fig. 3c), shows that the Sayeon Lake (reservoir) reached the high water level by that time. A recent topographic map shows another reservoir, named Daegok Lake, in the upstream section of the Daegokcheon stream, which was constructed in December 2005 (Fig. 3d).

Annual average precipitation in Ulsan area is 1,285 mm/yr with the minimum and maximum precipitations of 693 mm and 2,058 mm recorded in 1995 and 1991, respectively (Fig. 4). Precipitation occurs mainly during the rainy season between June and August, with frequent typhoons during this period. Hydrological data of the Sayeon Lake is available since April 1980. The lake level has fluctuated repeatedly according to the seasonal cycle. The lake level begins to fall from October to November and reaches the lowest level from January to May of the following year. High lake level is observed from June to September. After 2005, the overall water level of the Sayeon Lake decreased because of the construction of the Daegok Dam in the upstream. The petroglyphs site has been subject to repeated flooding and exposure every year or every two years because of the change of the lake level (Fig. 5). The alluvial sediments at the trench site occur between ca. 50 m and 55 m in altitude, and preserve the sedimentary records of the repeated flooding and exposure of the site.

3. STRATIGRAPHY AND AGE

Detailed sedimentological observations and sampling were made at two sections of a trench (Trench B2; Fig. 2), 20 m × 25 m in size and 5 m in depth. The two sections are cut either parallel or normal to the nearby stream (Fig. 6). The alluvial sediments overlie the sandstones of the Cretaceous Sinhwari Formation. The lower two meters of the sediments consist of well-sorted, medium to coarse sand intercalated with lenticular pebble gravel deposits, whereas the upper 2.5 meters of sediments consist of alternating fine sand and mud layers (Fig. 7). The sediments were divided into 31 depositional units based on sediment texture, structure, and color. Sedimentological observations were made on the trench sections in the field and on lacquer peels and CT (X-ray computed tomography) images that were obtained from sediment slabs (Fig. 8), which were sampled using plastic box samplers, 10 cm wide and 50 cm long (see Fig. 6 for the

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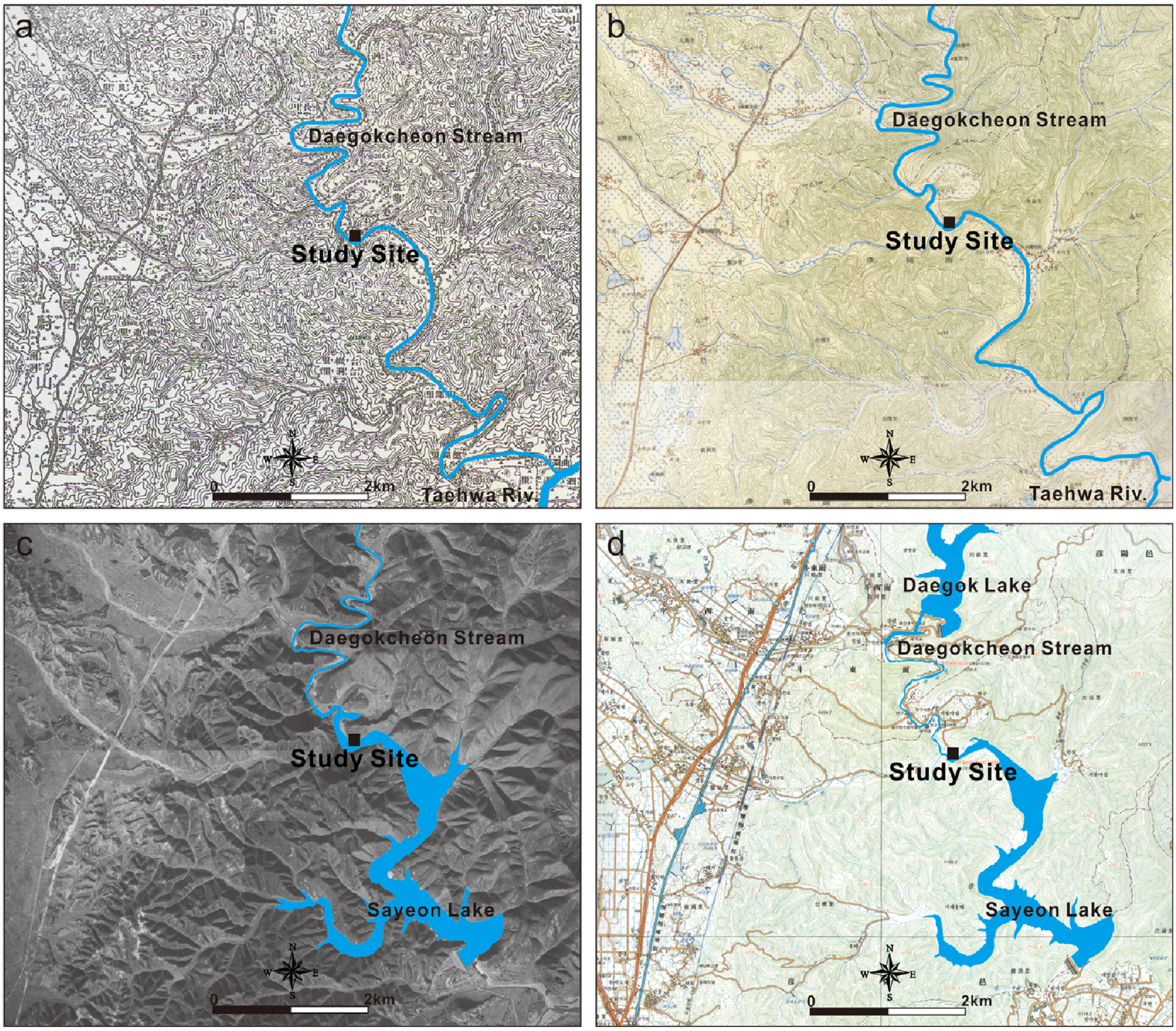

Fig. 3. Topographic maps and aerial photograph of the study area, published in 1918 (a), 1965 (b), 1967 (c), and 2014 (d).

locations).

Two sandy deposits of unit 2 and two of unit 4 were sampled for OSL dating. They were dated at Korea Basic Science Institute at Ochang. Three sediment samples were taken from units 2, 4, and 5 for AMS radiocarbon dating of organic materials in bulk sediment. The dating results (Fig. 7), together with the dramatic lithofacies changes across units 5 and 6, indicate that units 1 to 5 were deposited mainly by streamflows before the construction of the Sayeon Dam whereas the overlying units of alternating sand and mud layers resulted from repeated flooding and exposure of the site after the construction of the dam.

The deposition ages (years) of unit 6 to 31 could be further constrained by trashes in the sediments, such as plastic snack bags and noodle bags with the year of manufacture printed (Fig. 9) and a liquor (soju) bottle with the year of manufacture embossed. With an assumption that these products were consumed in the production year and discarded, the deposition years of post-Sayeon Dam sediments can be interpreted as follows: units 6 to 15 accumulated between 1966 and 1976, units 16 to 18 between 1978 and 1983, units 19 to 25 between 1984 and 1993, and units 26 to 31 after 1993 (Fig. 7). Sediment accumulation at the site is presumed to have ceased in 2005 when the Daegok Dam was constructed in the upstream section of the Daegokcheon stream and the level of the Sayeon Lake dropped by several meters (Fig. 4). Therefore, the 26 units of the post-Sayeon Dam sediments are interpreted to have accumulated over ca. 40 years between 1966 and 2005.

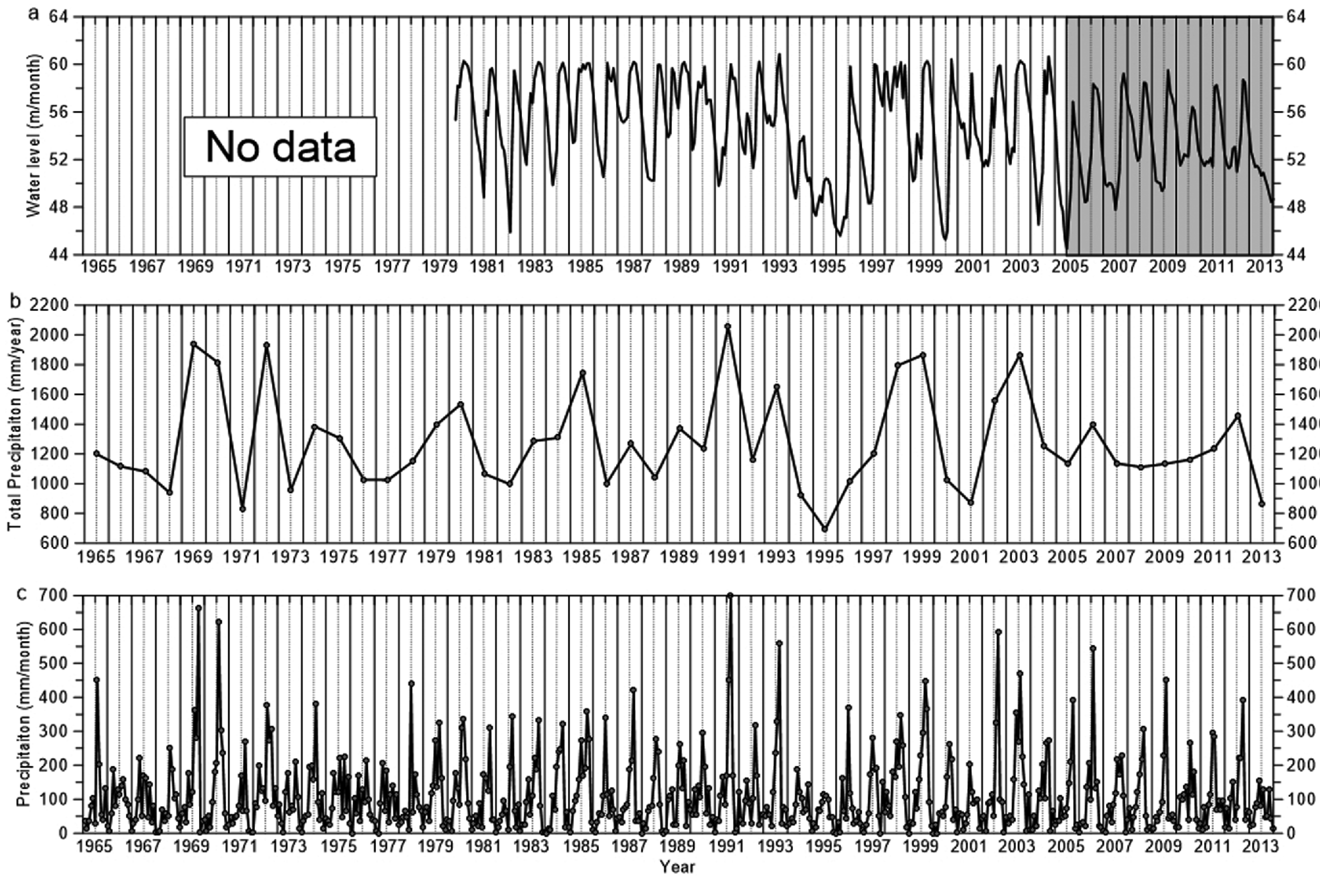

Fig. 4. Variations of precipitation in Ulsan area and water level of the Sayeon Lake. (a) Water level change of the Sayeon Lake since 1980. The water level of the lake dropped by several meters after 2005 when the Dagok Dam was constructed in the upstream section of the Dagokcheon Stream (data available at https://kwater.or.kr). (b and c) Variation of annual precipitation in Ulsan area since the construction of the Sayeon Dam (data available at https://www.weather.go.kr).

4. DEPOSIT FEATURES AND PROCESSES

4.1. Units 1 to 5

4.1.1. Description

Gravelly deposits of units 1, 3, and 5 consist of clast-supported, massive to crudely stratified pebble-cobble gravel set in a well-sorted, fine to medium sand matrix, commonly with erosional lower boundaries and lenticular to wedge geometry (Figs. 6, 7, and 10a). Gravel clasts are weakly imbricated and rarely inversely graded. The intervening fine-grained deposits of unit 2 are composed of dark yellowish brown (10YR 3/6), poorly sorted, fine to very fine-skewed, silty fine sand. The unit is massive and mottled, and contains rare charcoal fragments. Unit 4 is composed of bright yellowish brown (10YR 6/6), moderately sorted, medium to coarse sand. The sand is overall massive but locally shows low-angle cross-stratification (Fig. 10b).

4.1.2. Interpretation

The gravel deposits are interpreted to have formed by traction sedimentation in gravel sheets and bars in streamflow channels probably during floods or high flow stages (Boothroyd and Ashley, 1975; Hein and Walker, 1977; Miall, 1977). Rare inverse grading and imbrication of clasts suggests active clast collision in the basal bedload layer (Todd, 1989). The intervening sandy deposits, which are generally massive, are interpreted to have formed by rapid deposition of suspended sandy sediments in channel margins and on bar tops in association with fluctuations of flow power and discharge (Harms et al., 1982; Arnott and Hand, 1989; Todd, 1989). Local cross-stratification suggests generation and migration of dunes under lower flow regime conditions during low flow stages or recessional stages of floods (Harms and Fahnestock, 1965; McKee, 1965).

4.2. Units 6 to 31

4.2.1. Description

Units 6 to 31 consist of alternations of sand and mud layers (Figs. 6–8). The sandy layers are generally thin-bedded (1 to 12 cm thick) and horizontally laminated (Fig. 10c). Shallow internal

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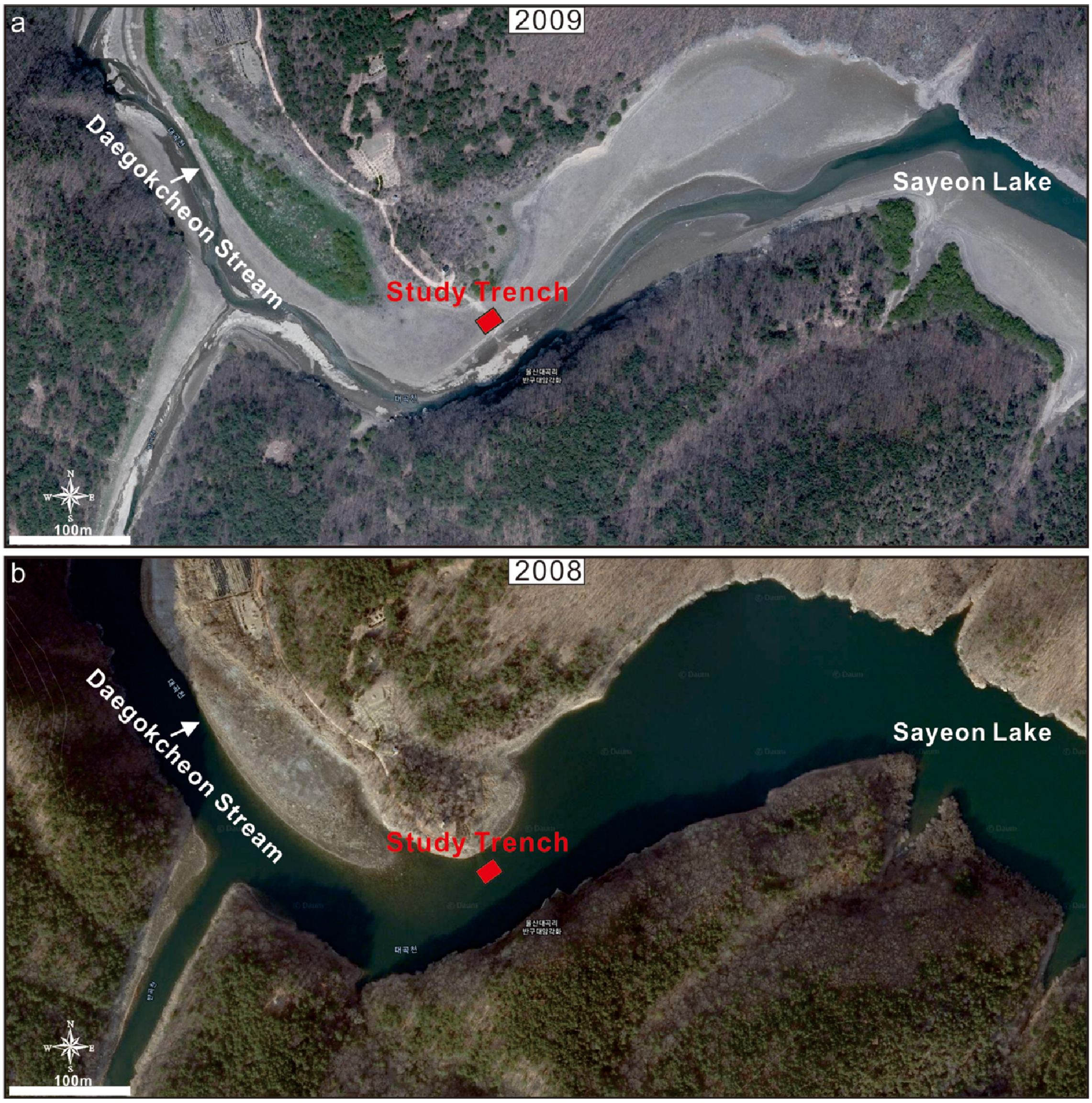

Fig. 5. Aerial view of the study area. (a) Aerial photograph taken in 2009 when the study area was exposed above the Sayeon lake level. (b) Aerial photograph taken in 2008 when the study area was submerged under water (photographs available at http://map.kakao.com).

scours and low-angle inclination of laminae are locally found. Mean grain size ranges between 2.69 and 5.16Φ (fine sand to medium silt), but is most commonly of very fine sand (~4Φ). Sorting is poor and skewness is positive (fine-skewed). The sandy layers are generally continuous on the stream-parallel trench section with subtle thickness changes (Figs. 6a and b), whereas they show marked thickening toward the channel on the stream-normal trench section (Figs. 6c and d). Erosion at the base is common but very shallow except near the stream channel (Figs. 6c and d). A few sand units (units 23 and 28) show ripple cross-lamination at the top (Figs. 8 and 10d).

The muddy layers are thin- to medium-bedded (2 to 18 cm thick), dark olive or dark grayish brown (2.5Y 3/3 and 2.5Y 4/2) in color, and generally massive. Mean grain size ranges between 5.09 and 6.57Φ (medium to fine silt). Sorting is poor and skewness is positive (fine-skewed). The contacts with the underlying sandy layers are generally gradational, but a thin layer of plant debris is intercalated in between in unit 13 (Fig. 8). The upper contacts are commonly deformed due to loading. The mud commonly contains plant debris, some of which are carbonized, and vertical to steeply inclined tubular cavities, centimeters in length and a millimeter or less in diameter, which are interpreted to be molds of plant roots. The mud surrounding these cavities is commonly reddish due to oxidation. Platy plastic debris are also common, especially above unit 14. Unit 22 is intermediate in character between the sandy and muddy layers, consisting of alternating dark-colored and light-colored coarse silt (4.55~4.75Φ) laminae.

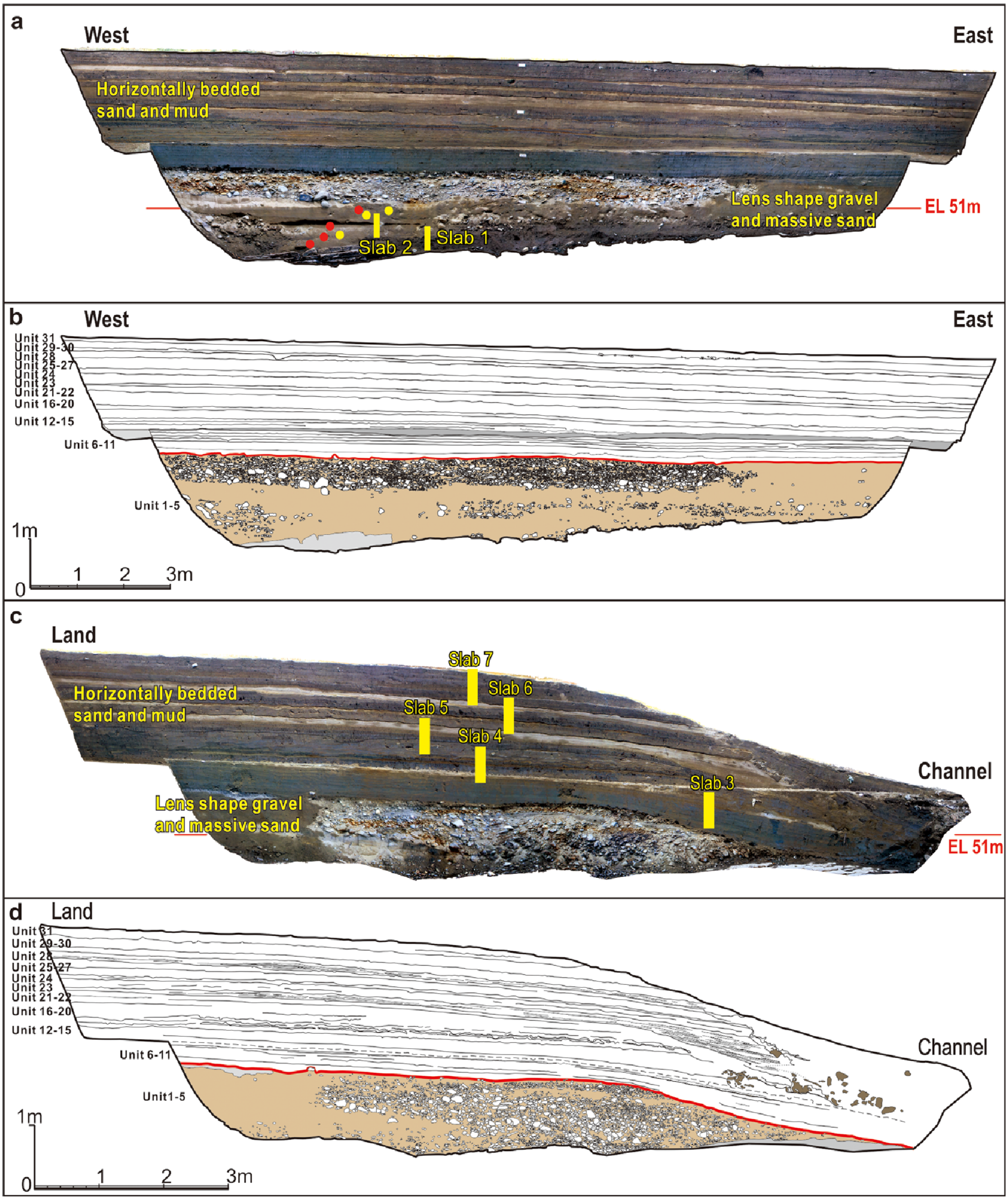

Fig. 6. Photographs and sketches of the trench sections. (a and b) Northern wall of Trench B2, cut parallel to the nearby stream. (c and d) Eastern wall of Trench B2, cut transverse to the nearby stream. Yellow circles are sample locations for radiocarbon dating; red circles are sample locations for OSL dating; yellow rectangles are locations of slab samples, from which lacquer peels and CT (X-ray computed tomography) images were obtained (Fig. 8). EL = elevation.

4.2.2. Interpretation

The horizontally laminated sand layers were produced most likely under upper plane-bed conditions when the depositional site was flooded by bank-full flows during floods or high flow stages (Harms and Fahnestock, 1965; Miall, 1977; Cheel, 1990). Local shallow scours and low-angle inclination of laminae suggest

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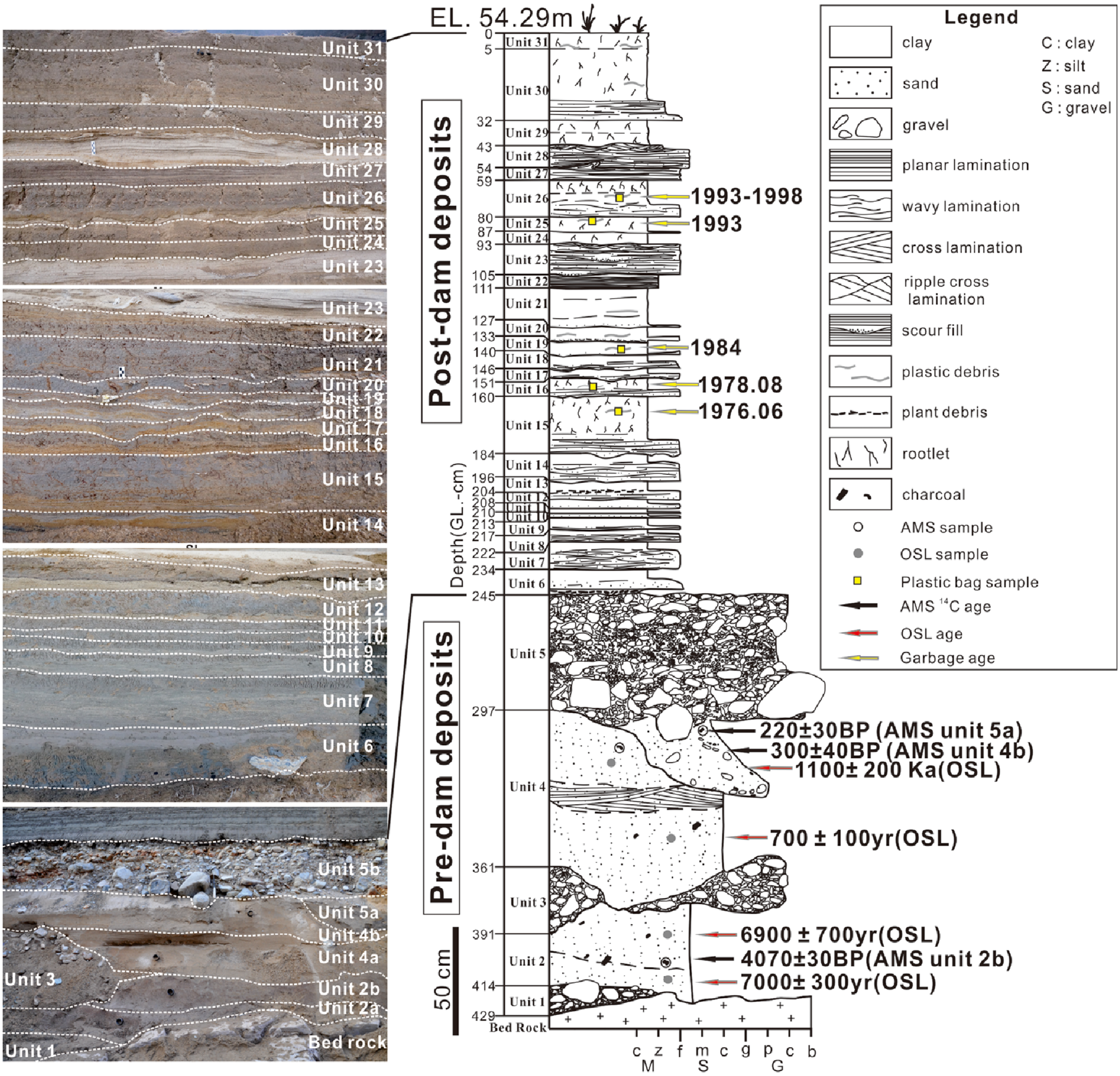

Fig. 7. Columnar log and photographs of the fluvial sediments upon the Cretaceous basement rock, with OSL, radiocarbon, and garbage ages.

local and temporary transition of the upper plane bed into low-relief in-phase waves or transitional dunes related with fluctuations of flow power and flow depth (McKee et al., 1967; Cheel and Middleton, 1986; Cheel, 1990). Gradual transition of horizontally laminated deposits into ripple cross-laminated deposits near the top of some layers (units 23 and 28; Fig. 10d) suggests gradual waning of the flows into lower regime condition as a result of waning of floods.

The intervening mud layers are interpreted to have formed by settling of fine-grained suspended sediments when the flooded water was stagnant or slow-moving (Miall, 1977). Possibly, the depositional site might have been submerged under water for months because of the rise of the water level of the Sayeon Lake after a flood, and the deposition might have occurred in a temporarily lacustrine condition. Abundant molds of plant roots and reddish oxidation of mud suggest that the mud was immediately exposed, vegetated, and oxidized under a subaerial condition. Irregular upper contacts of muddy layers are interpreted to be due to loading and local erosion by the overlying sandy layers, but the possibility of deformation due to human activity such as riverside picnics cannot be ruled out.

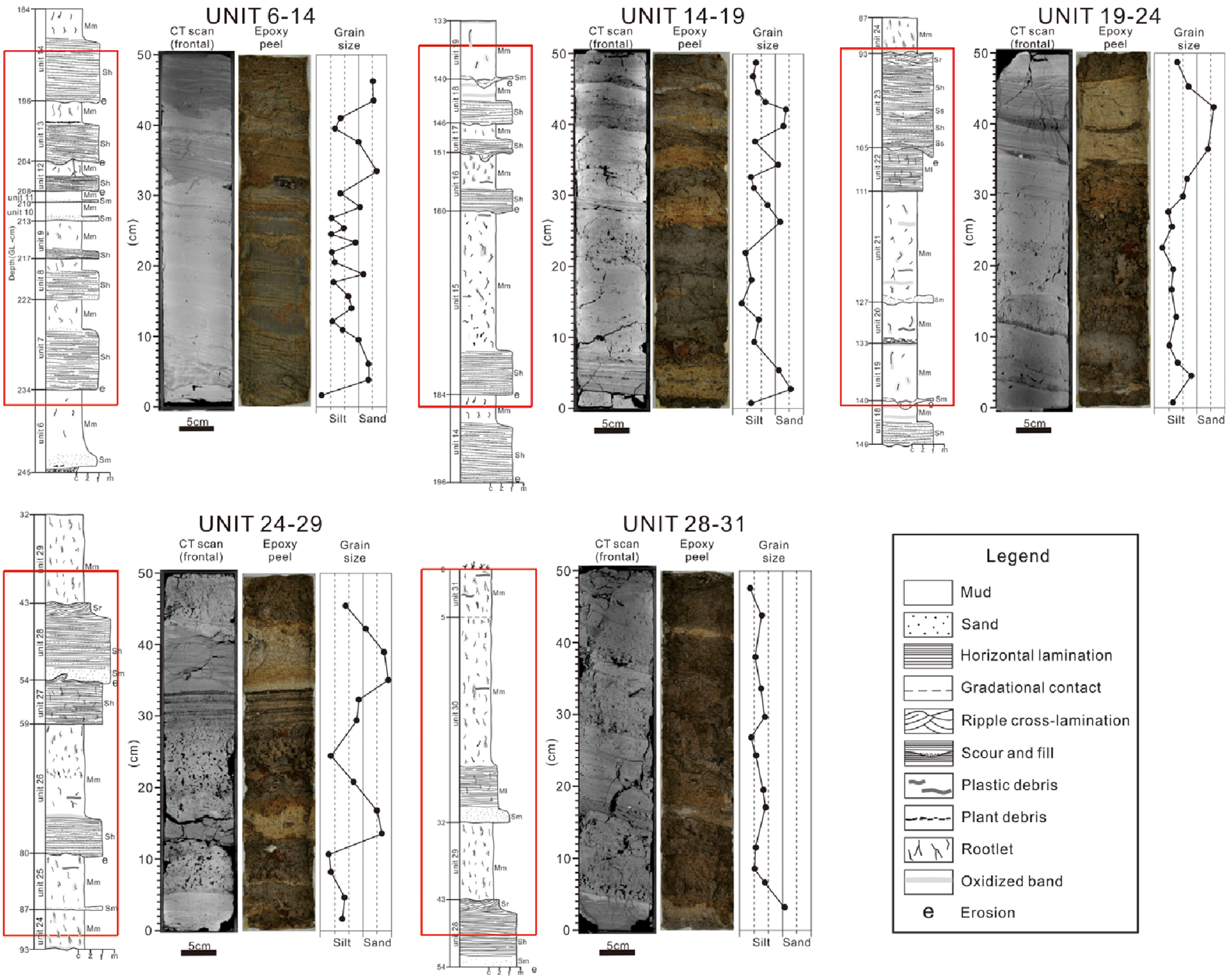

Fig. 8. Detailed columnar logs, CT (X-ray computed tomography) images, and lacquer peel images of the post-Sayeon Lake sequence (units 6 to 31) with grain size data.

5. DEPOSITION HISTORY

The deposit features and ages of the alluvial sediments at the study site clearly demonstrate a dramatic environmental change of a mountain stream caused by artificial disturbance of a river system. The pre-Sayeon Lake sequence of units 1 to 5 shows typical features of gravelly streams. Radiocarbon and OSL ages obtained from unit 2 are 4,070 ± 40 yr BP and 7,000 ± 300 to 6,900 ± 700 yr, respectively (Fig. 7). In spite of the discrepancy between the radiocarbon and the OSL ages, deposition of units 1 and 2 is interpreted to have commenced in the early to middle Holocene or early to middle Neolithic Era. The fluvial activity was probably enhanced by the wetter and warmer climatic conditions in the Holocene (Williams et al., 1998), resulting in increased fluvial incision and/or channel enlargement of the Daegokcheon stream. Deposition of the silty unit 2 suggests modification of the stream profile and occasional flooding of the channel in association with rising Holocene sea level (Pirazzoli, 1991, 1996), resulting in deposition of fine-grained deposits in channel margins and banks. The overlying sandy to gravelly units 3 to 5, which are dated to have accumulated in the last one millennium (Fig. 7), are interpreted to be gravelly channel lag and bar deposits. Superposition of these units upon the silty deposits of unit 2 suggests lateral migration or expansion of the channel in the generally confined mountain stream. The fluvial activity prevailed until the construction of the Sayeon Dam in 1965.

Over the years of dam construction between 1962 and 1965, the discharge and channel width of the Daegokcheon stream was greatly reduced because of artificial conversion of the water course. This resulted in exposure of most of the stream sediment and the development of thick vegetation upon the sediment. This

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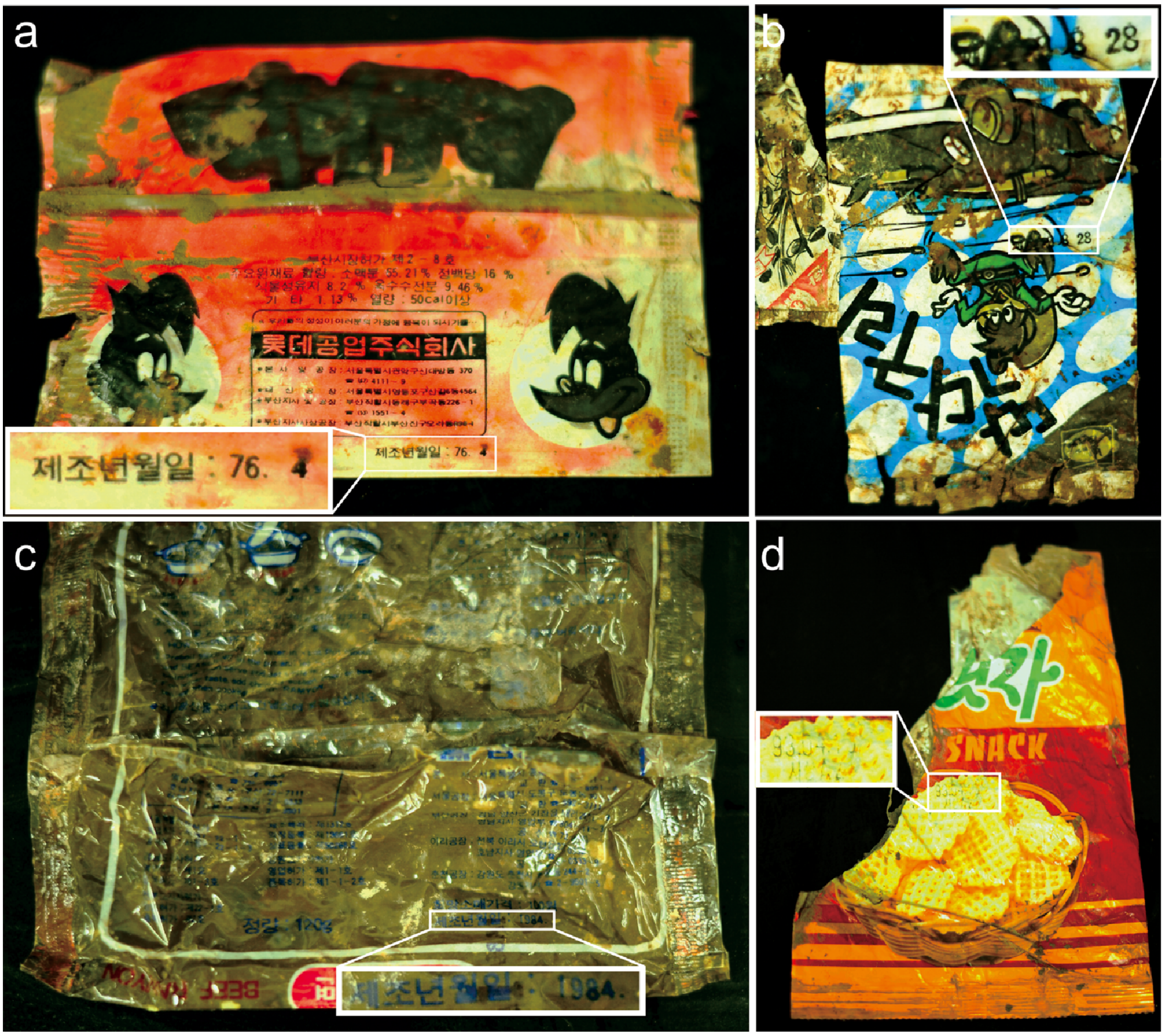

Fig. 9. Plastic garbage that was used to infer the deposition years of some depositional units. (a) A snack bag manufactured in April, 1976, found in unit 15. (b) A snack bag manufactured in August, 1978, found in unit 16. (c) A noodle bag manufactured in 1984, found in unit 19. (d) A snack bag manufactured in April, 1993, found in unit 25.

inference is supported by the intercalation of a few cm-thick layer of plant debris between units 5 and 6 (Fig. 8).

Immediately after the construction of the Sayeon Dam, the fluvial activity was greatly reduced in the downstream reach of the Daegokcheon stream because this area was periodically submerged under water and transformed into a transient lacustrine environment (Fig. 5), depending on the fluctuation of the precipitation and the change of the water level of the Sayeon Lake (Fig. 4). The deposition therefore became dominated by vertical accumulation of relatively fine-grained sediments as a result of repetitive flooding, lake level rise, and submergence/emergence of the depositional site. The post-Sayeon Lake sequence can be compared to the sedimentary sequences of 'low-lying benches', which form in channel margins at an early stage of floodplain development (Woodyer et al., 1979; Pizzuto, 1994; Allred and Schmidt, 1999; Moody et al., 1999). These benches form by vertical accretion of sandy to muddy sediments upon gently sloping to flat surfaces mostly during floods or high flow stages (Woodyer et al., 1979; Pizzuto, 1994; Dean et al., 2011). The vertical aggradation of sediment was probably enhanced by the development of vegetation during the periods of exposure of the depositional site, which can trap and stabilize sediment (Tal and Paola, 2007; Braudrick et al., 2009; Dean and Schmidt, 2011).

The discovery of modern artifacts, i.e., plastic garbage with the year of manufacture identifiable (Fig. 9), in some depositional units enabled us to interpret the depositional history of the post-Sayeon Dam sequence on an annual to decadal basis in relation to the change of the water level of the Sayeon Lake, of which the data are available after 1980 (Fig. 4).

The lowermost ten units (units 6 to 15) are interpreted to have

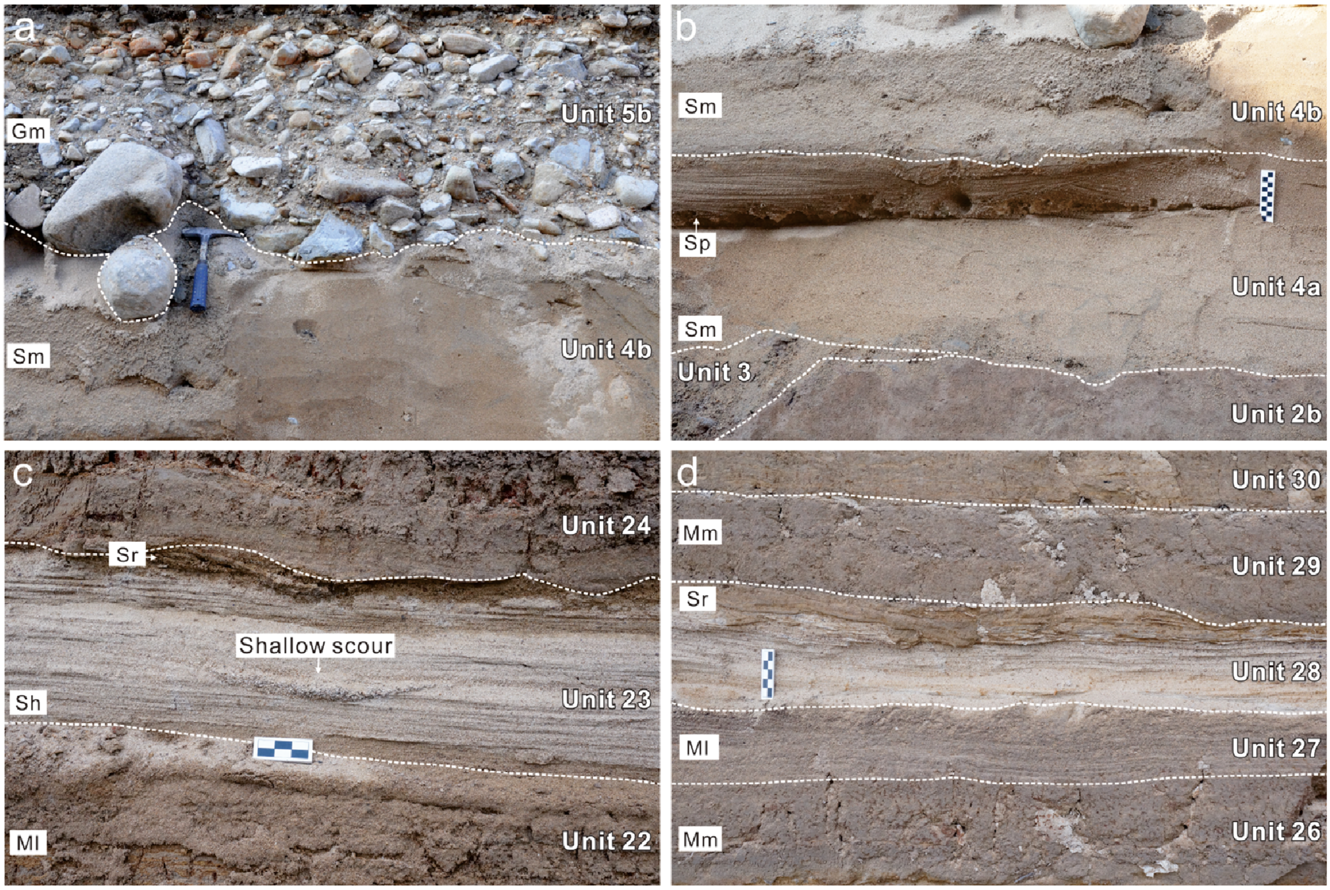

Fig. 10. Deposit features of fluvial sediments. (a) Fluvial sediments of units 4 and 5, composed of massive sand (Sm) and massive to crudely stratified, clast-supported gravel (Gm). (b) Close-up of the sandy deposits of units 2 to 4, which are generally massive (Sm) but is locally cross-laminated (Sp). (c and d) Post-Sayeon Lake sequence composed of alternating sandy and muddy layers. Sandy layers are generally horizontally laminated (Sh), and locally ripple cross-laminated (Sr) near the top of the layers. Muddy layers are generally massive (Mm) and rarely crudely laminated (Ml). The photo scale is graduated in centimeters.

accumulated over the eleven years between 1965 and 1976. Although the lake level data are not available in this period, the ten alternations of sandy and muddy layers in these units are interpreted to reflect ten flooding events in this period. The overlying three units (units 16 to 18) are interpreted to have been deposited between 1978 and 1983.

The unit 19 was evidently deposited between 1984 and 1985/1986 because multiple pieces of plastic snack bags and a liquor bottle wrapped in noodle bags, all of them manufactured in 1984, are found in the unit. The unit occurs at an altitude between 52.4 and 52.9 m, and the water level of the Sayeon Lake was as low as 50 m by April, 1984 (Fig. 11). Deposition of the unit probably began with a flood in the summer of 1984, and the deposition of the upper muddy layer continued until early 1986 when the water level of the Sayeon Lake was maintained above the altitude of the depositional site. Afterwards, the water level of the Sayeon Lake was lowered, and the depositional surface at the study site was exposed.

The lake level rose again to 58 m in the summer of 1986 as a result of heavy rainfall. The generally muddy deposit of unit 20 is interpreted to have formed in 1986 and 1987 when the lake level was maintained above the altitude of the depositional site (Fig. 11). The lake level was lowered to an altitude of ca. 50 m between March to June, 1988, exposing the depositional site. Deposition of unit 21 is interpreted to have been caused by a flood event due to the concentrated rainfall in July of that year, and continued until early 1990. Deposition of unit 22 is presumed to have occurred throughout 1990. Deposition year of unit 23 is inferred to be 1991 because the fairly thick sandy deposits of the unit (Fig. 8) can be ascribed to the unusually high rainfall in the summer of 1991 (Fig. 11). Deposition of the overlying muddy units 24 and 25 is interpreted to have occurred in 1992 and 1993 when the water level of the Sayeon Lake was maintained above the altitude of the depositional site.

Deposition years of units 26 to 31 are poorly constrained because a plastic garbage in unit 26, of which the production

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year is not marked on it, but was produced between 1993 and 1998, is the only one artifact that can provide the information on the deposition age (Fig. 7). We presume that the deposition of these units might have begun as early as 1993 and ceased before 2005. As stated earlier, another reservoir, named Daegok Lake, was constructed in the upstream section of the Daegokcheon stream in December 2005. As a result, the water level of the Sayeon Lake was lowered by several meters afterwards (Fig. 4), and further deposition of sediment is inferred to have terminated at the study site. Instead, the discharge and channel width of the Daegokcheon stream are interpreted to have been reduced after the construction of the dam, resulting partial erosion of the post-Sayeon Lake sequence, as seen in the transverse section of Figure 6c, where multiple erosion surfaces are found, dipping toward the channel.

6. DISCUSSION AND CONCLUSIONS

Nanson and Croke (1992) proposed a genetic classification of floodplains based on nine factors, which are mostly floodplain-forming processes, including three main classes of 1) high-energy non-cohesive, 2) medium-energy non-cohesive, and 3) low-energy cohesive floodplains. The study area is situated in a mountain stream valley where lateral stream migration is restricted and sediment accretion is dominantly vertical. The post-Sayeon Lake sequence of the study area can thus be compared to the "confined vertical-accretion sandy floodplain" of Nanson and Croke (1992), which forms episodically by vertical accretion along high-energy, laterally stable channels (e.g., Nanson, 1986). In this type of floodplain, overbank deposition gradually builds a floodplain of fine-grained alluvium over a period of hundreds or thousands of years, which is eroded by a single large flood or a series of moderate floods, leaving a basal lag deposit. Afterward, accumulation of fine-grained floodplain deposits resumes slowly upon the basal lag deposit. In contrast to the "confined vertical-accretion sandy floodplain", however, evidence for erosion by large floods is not found in the post-Sayeon Lake sequence. This is probably because the lake level rose rapidly during a flood, submerging the study site and causing rapid deceleration of the incoming flood water at the study site.

Previous studies of floodplains have mainly dealt with floodplains in the downstream reach of a dam (Dean et al., 2011) or floodplains unaffected by man-made dams (Nanson, 1986; Moody et al., 1999; Friedman et al., 2005). The study area is located upstream of a dam, and also downstream of another dam, and provides an example of fluvial sedimentation that distinguishes it from previous studies. One unique feature of the study area is the high preservation of the flood events in the deposit records, as revealed by the comparison of the depositional units with the water level data of the Sayeon Lake, the precipitation data in Ulsan area, and the garbage dates (Fig. 11). Comparison of the sedimentary records with the water level data was possible from 1984 to 2005. During this period, there were about 14 flooding events, and sediments could deposit during these events. The number of actual depositional units that have formed by floods during this period is 12 (units 19 to 30). Considering possible

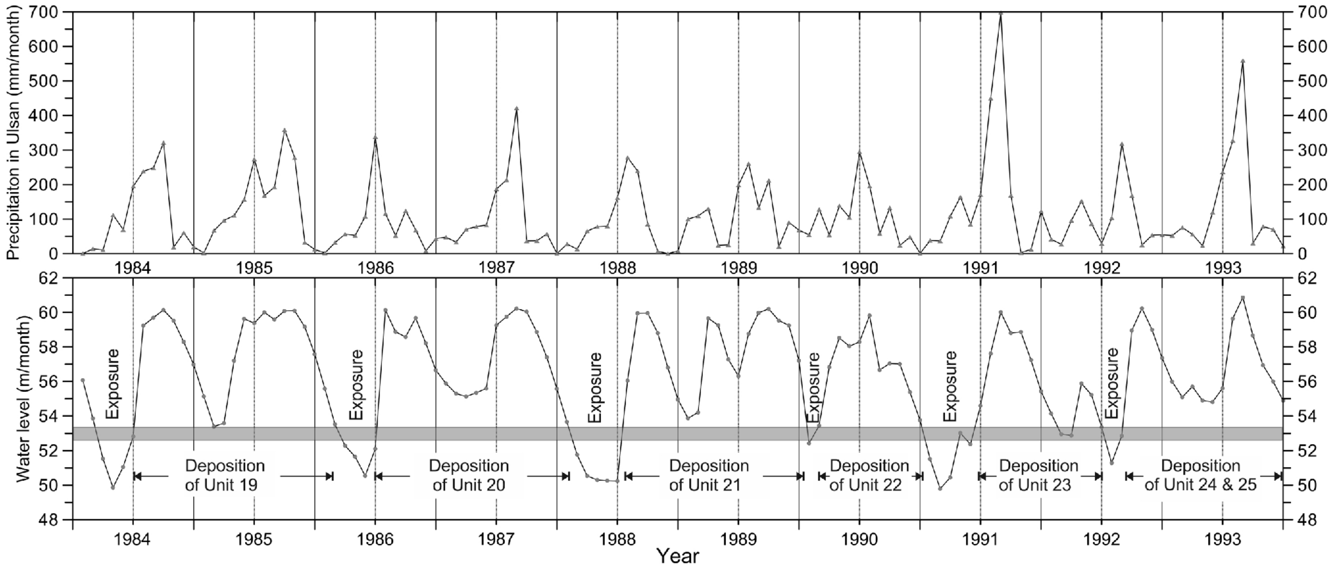

Fig. 11. The relationship between precipitation in Ulsan area and the water level of the Sayeon Lake between 1984 and 1993. Deposition of individual sandy and muddy units is interpreted to have occurred through traction and suspension sedimentation, respectively, when the depositional site was swept by a flood or high flow stage streamflow and then submerged under water. During the intervening periods of subaerial exposure, the depositional site was vegetated with grass, leaving numerous imprints of rootlets in muddy layers (Fig. 8). The gray horizontal bar indicates the altitude of the post-Sayeon Lake sequence.

removal of a few units by erosion or non-deposition during a few flood events, the number of depositional units is in good agreement with the number of flooding events at the depositional site. As mentioned earlier, such good preservation of the flooding events seems to be due to a rapid rise of lake level during a flood, submergence of the deposition site, rapid deceleration of incoming flood water, and rapid deposition of sediments. This study therefore appears to provide an example of a dramatic environmental change of a mountain stream caused by artificial disturbance of a river system, both downstream and upstream of the study site.

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