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Research Article

Overnight formation of a bouldery alluvial fan by a torrential rain in a granitic mountain (Mt. Seoraksan, Republic of Korea)

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ABSTRACT Mt. Seoraksan, Korea, is a rugged granitic mountain where extremely steep slopes and strongly seasonal rainfall have facilitated bedrock exposure and geomorphic changes mainly by rockfalls and streamflows. Although the environment was not suitable for alluvial fan formation, a bouldery alluvial fan, 170 m long and 330 m wide, formed overnight by a heavy summer rain in 2006. The fan consists of several meter-high boulder mounds and gently undulating cobble bars/sheets that are arranged in a fluvial longitudinal bar-like pattern. They are interpreted to have formed by highly competent and turbulent sheetfloods, which temporarily had the properties of hyperconcentrated flood flows. Formation of the whole alluvial fan by a single, casual hydro-meteorological event is inferred to have been possible because a threshold condition was reached in the source area. A rainfall event, which would have had no extreme effects before reaching the threshold, could probably trigger massive remobilization of bouldery sediments on the valley floors. The Seoraksan alluvial fan thus demonstrates the role of a geomorphic threshold in causing drastic changes in the hydrologic performance of the watershed. The morphology and sedimentology of the Seoraksan alluvial fan suggest that the fan is a modern example of a sheetflood-dominated alluvial fan, which has largely been ignored in spite of their potential diversity and abundance in glacial to periglacial, tropical, and temperate environments.

KEYWORDS alluvial fan, geomorphic threshold, sheetflood, debris flow, boulder mound

INTRODUCTION

Alluvial fans occur in diverse settings, from humid to arid regions and from tectonically active mountain fronts to stable footslopes and valley junctions. Their morphology and sedimentology are determined by the availability of water and the amount and type of sediment, which are in turn controlled by the tectonics, climate, and bedrock lithology in the catchment area (Bull, 1977, Blair and McPherson, 1994, McDonald et al., 2003). Catastrophic storms or intense rainfalls, which can occur independently of climate change and tectonic activity, also play a significant role in forming alluvial fans (Wells and Harvey, 1987, Marchi et al., 2009, Cabré et al., 2020), in some cases giving greater impacts than earthquakes (LaHusen et al., 2020). Deposition on alluvial fans can be very infrequent and inconstant. Sheetfloods and debris flows can deposit significant volumes of sediment within hours (Wells and Harvey, 1987), whereas streamflows can erode or rework the surficial sediments for over tens to hundreds of years (Harvey, 2007). In spite of a number of studies on alluvial fans, interpreting their formative processes is challenging because of the extreme variability of the frequency and magnitude of processes and the roles of multiple controlling factors. In particular, the lack of careful documentation of single geological or hydro-meteorological events in diverse settings makes it difficult to develop sedimentological models that can be applied to diverse types of alluvial fans. In this paper, we introduce a bouldery alluvial fan that was formed overnight during an intense rainfall in a granitic mountain of Korea in 2006. Based on field surveying in 2020 and comparative analysis of aerial photographs taken over a decade, we discuss the processes and controls of alluvial fan formation in a humid-temperate region affected by the Asian Monsoon, and highlight the role of intrinsic geomorphic processes in forming an alluvial fan.

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SITE CHARACTERISTICS

Mt. Seoraksan is a national park of South Korea, belonging to a coastal mountain range that runs along the eastern side of the Korean Peninsula (Fig. 1A). It is characterized by sharp-crested ridges and deeply incised valleys (Fig. 1B) with the highest peak rising to 1,708 m a.s.l. The mountain is built predominantly of Proterozoic to Meso-

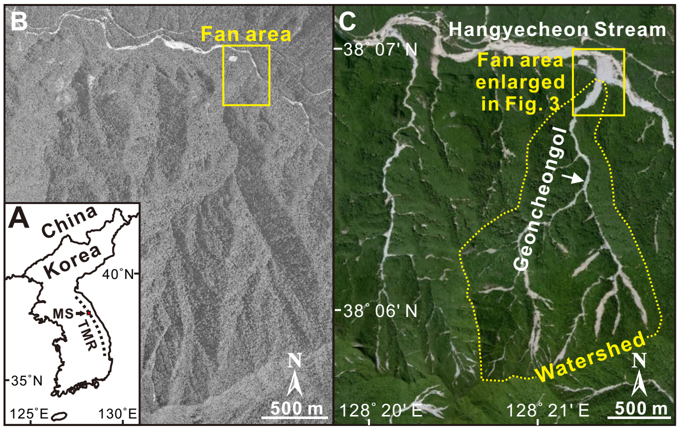

Figure 1: Location of the study area. **A:** Location of Mt. Seoraksan (MS) and the Taebaeksan Mountain Range (TMR). **B:** The study area, located in the southwestern sector of the national park area, was well-vegetated from crests to valley floors in 2005. **C:** The light-colored granitic bedrocks are exposed along the trunk and tributary valleys in 2008 (Photographs B and C are available at http://www.ngii.go.kr and http://map.kakao.com, respectively).

zoic granites (Kee et al., 2010), which are inferred to have been uplifted at a rate of ca. 0.1 mm/yr since the Cretaceous (Cho, 1994). Five earthquakes have been recorded since 1978, the largest of which had a magnitude of 2.3, according to Korea Meteorological Administration data (https://www.kma.go.kr). The height difference between crest lines and valley floors reaches over 1,000 m over a few km, resulting in extremely steep slopes in excess of 30–50° (Migoń et al., 2019). Annual precipitation ranges between 800 and 1700 mm (Fig. 2A), most of which falls as heavy summer rains between June and September with daily intensities of precipitation commonly exceeding 100 mm (Fig. 2B). When hit by occasional typhoons, hourly intensities of precipitation can be above 100 mm. No clear correlation is found by visual comparison between the annual precipitation and the El Niño index (Fig. 2C) or the Western Pacific Monsoon index (Fig. 2D). The mean annual temperature difference is very large (~20°C) with severe snowfall from October to May. Because of these climatic and topographic conditions, physical weathering and soil loss are severe. Bedrock outcrops thus occupy the majority of the Seoraksan area. In the rest of the area, effective soil depth is only about 20 cm (Seoraksan National Park Service, 2008). Poor development of herbaceous plants on the soil, composed mainly of sandy loam, is also one of the important causes of severe soil loss. Mass wasting, dominated by rockfalls, and torrential streamflows have thus been regarded to be the main agents of geomorphic changes (Migoń et al., 2019). No alluvial fan has been reported in the Seoraksan area before 2006, although old bajada-like pediment surfaces are found locally at mountain fronts outside the study area.

From July 9 to July 18, 2006, 671 mm of rainfall with hourly intensities over 100 mm was recorded in the Seoraksan area. Although the total and the daily precipitations during this period were not particularly high compared with other years (Fig. 2B), the rainfall caused severe valley erosion in dozens of places in the national park. The valley erosion occurred as rainwater and eroded soil on the hillslope rushed down into the valleys. The streamflows uprooted trees and eroded bouldery rockfall debris on the valley floors, exposing the light-colored granitic bedrock along their paths (Fig. 1C). A conspicuous fan-shaped landform was produced at the exit of the Geoncheongol valley, where it joins the Hangyecheon stream. According to eyewitness accounts, which were obtained through direct interviews with local residents, the fan formed in the midnight of the heaviest rain, accompanied by rumbling noises. Comparison of aerial photographs suggests that the fan did not exist before 2006 (Fig. 3A). The fan is 170 m long and 330 m wide and has an area of 0.03 km^2. The catchment area of the fan is 2.0 km^2. The fan area is very small compared to the catchment area (cf. Kochel and Johnson, 1984) because of the limited space in which the fan could be made, bounded by the Hangyecheon stream. The area of exposed bedrock after the rainfall in the catchment area is 0.25 km^2. About 50,000 m^3 of soil and an unmeasurable amount of rockfall debris on the valley floors are estimated to have been eroded by this rainfall-induced event. The slope of the fan surface is 6.8°, and the average slope of the main valley in the catchment area is 14°. The topographic analysis was made on 1:5,000 digital topographic maps, which were produced in 2017 by the National Geographic Information Institute of Korea (https://www.ngii.go.kr/eng/main.do).

DEPOSIT FEATURES

The sediments on the fan are divided into three facies based on grain size, depositional morphology, and relief: boulder mounds, cobble bars/sheets, and channels. Spatial distribution of the facies before 2020 was measured from aerial photographs. The facies distribution in 2020 was measured by field surveying and aerial photography using a drone in the spring and fall of that year. The boulder mounds occur from near the fan apex to the toe with a radially elongated shape in plan view (Fig. 3). They are a few tens of meters wide and over a hundred meters long, and composed of clast-supported and mostly openwork boulders with some sand matrix in the interior (Fig. 4A–D). They occupied about 42% of the fan area in 2008, but the area decreased to about 15% in 2020 (Fig. 3E–G). They have a positive relief of over 5 m relative to the surroundings with abrupt margins. The frontal and lateral margins are commonly steeply inclined (Fig. 4A–C), whereas the rear margins have less pronounced relief (Fig. 4D). Clast imbrication is indistinct because of the mostly blocky and equant form of the gravel clasts. Very crude and laterally impersistent stratification is locally recognized by subtle variations of clast sizes. Downfan variations in clast sizes are not obvious between proximal and distal localities.

The cobble bars/sheets occupy the majority of the fan surface (Fig. 4E). Comparison of aerial photographs shows that their area has increased steadily since the fan formation (Fig. 3E–H). Their surface is incised by shallow channels that are less than a meter deep, radiate generally from the fan apex, and overall have a braided distributary channel pattern (Fig. 4E). They are composed mainly of clast-supported and commonly openwork cobbles with minor amounts of pebbles and boulders on the surface (Fig. 4C–D). However, their interiors, observable at a few eroded channel walls, contain medium to coarse sand matrix, and rarely show crude stratification with locally openwork gravel layers (Fig. 4G). Some cobble deposits show scaled-down morphology of boulder mounds, composed of large boulders at the front with the finer-grained and openwork gravels trapped behind them (Fig. 4F). Channels are a few meters deep and incised into the cobble bars/sheets (Fig. 4H), locally dissecting a nearby boulder mound (Fig. 4A). Large boulders, locally in excess of several meters in diameter, are scattered on the channel floors.

DEPOSITIONAL PROCESSES

The changing facies distribution on the fan (Fig. 3) suggests that the boulder mounds, shrinking in area year by year, were produced by the 2006 rainfall event, whereas the cobble bars/sheets and channels, which increase in area

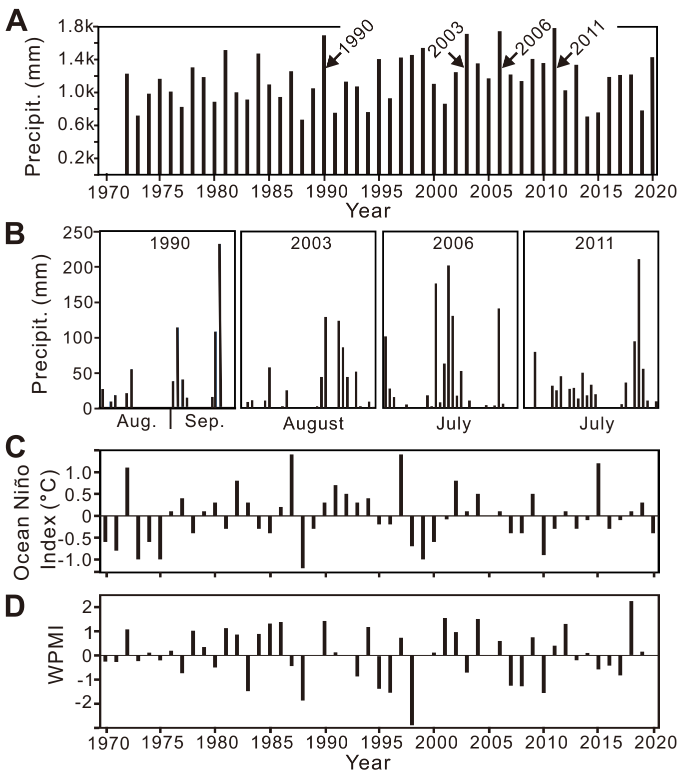

Figure 2: Meteorological data. **A:** Annual precipitation in Seoraksan since 1972 (data available at http://www.weather.go.kr). **B:** Daily precipitation during the months of the heaviest rainfall in 1990, 2003, 2006, and 2011. **C:** The Oceanic Niño Index since 1970 (data available at http://origin.cpc.ncep.noaa.gov). **D:** The Western Pacific Monsoon Index since 1970 (data available at http://apdrc.soest.hawaii.edu).

and gradually cover the boulder mound area, were produced mostly by multiple rainfall events after 2006. Cobble bars/sheets of the 2006 event may be locally present on the surface, but are inferred to have been mostly buried, reworked, or eroded by post-2006 events.

The boulder mounds are interpreted to have formed by torrential sheetfloods, which possibly had the properties of hyperconcentrated flood flows temporarily. Their radially elongated shape and mound-like morphology is clearly distinguished from the deposit geometry of debris flows characterized by levees and lobes (Blair and McPherson, 1998) (Fig. 5). The overall lack of muddy to sandy matrix also negates the role of debris flow processes. The lack of matrix can possibly be due to post-depositional removal by recessional or later sheetfloods. Near absence of pebble- to cobble-size gravel in the interstices between boulder clasts (e.g., Fig. 4D) suggests, however, that the boulder mounds were initially made up of only boulders. Almost complete removal of pebble- to cobble-size gravel in the interstices of bouldery deposits together with muddy to sandy matrix by recessional or later sheetfloods is hardly conceivable. The sand matrix-filled interior of the boulder mound in Figure 4A suggests that both coarse and fine particles could be deposited together at an early stage of mound formation because the flood flow had a high particle concentration, similar to a hyperconcentrated flood flow. However, the flow changed promptly into a water flood, selectively depositing the boulder clasts in the mound and transporting the finer gravel clasts and the liquid component with suspended sand and mud further downfan. Such separation of a flow into solid and liquid components during deposition is an unlikely process in debris flows (Costa, 1988).

The boulder mounds are similar to the transitional-flow deposits of Wells and Harvey (1987) in that they have lobate geometry with steep margins, comprise matrix-free upper zones and matrix-rich lower zones, and show local crude stratification. The boulders are interpreted to have been transported as rolling and sliding bedload, and deposited rapidly as the sheetflood expanded and decelerated. The development of boulder jams that can cause local flow deceleration and flow separation around them might have led to the deposition of boulders (Blair, 1987). The boulders are inferred to have accumulated clast-by-clast in an upfan direction and then by avalanching of clasts on steeply inclined fronts and lateral margins of the mounds (Fig. 5B). The avalanching of clasts resulted in local concentrations of large clasts at the front and margin of the boulder mounds (Fig. 4A–B), which can be confused with megaclast concentrations at the front of a debris-flow lobe produced by frictional freezing of clasts pushed forward by the more fluid and mobile debris-flow body (Pierson, 1980, 1986) (Fig. 5A).

The cobble bars/sheets are also interpreted to have formed by sheetfloods (Wells and Harvey, 1987), which were generated by both 2006 and post-2006 rainfall events. Year-by-year increase of the area occupied by the cobble deposits (Fig. 3) suggest that the majority of the deposits

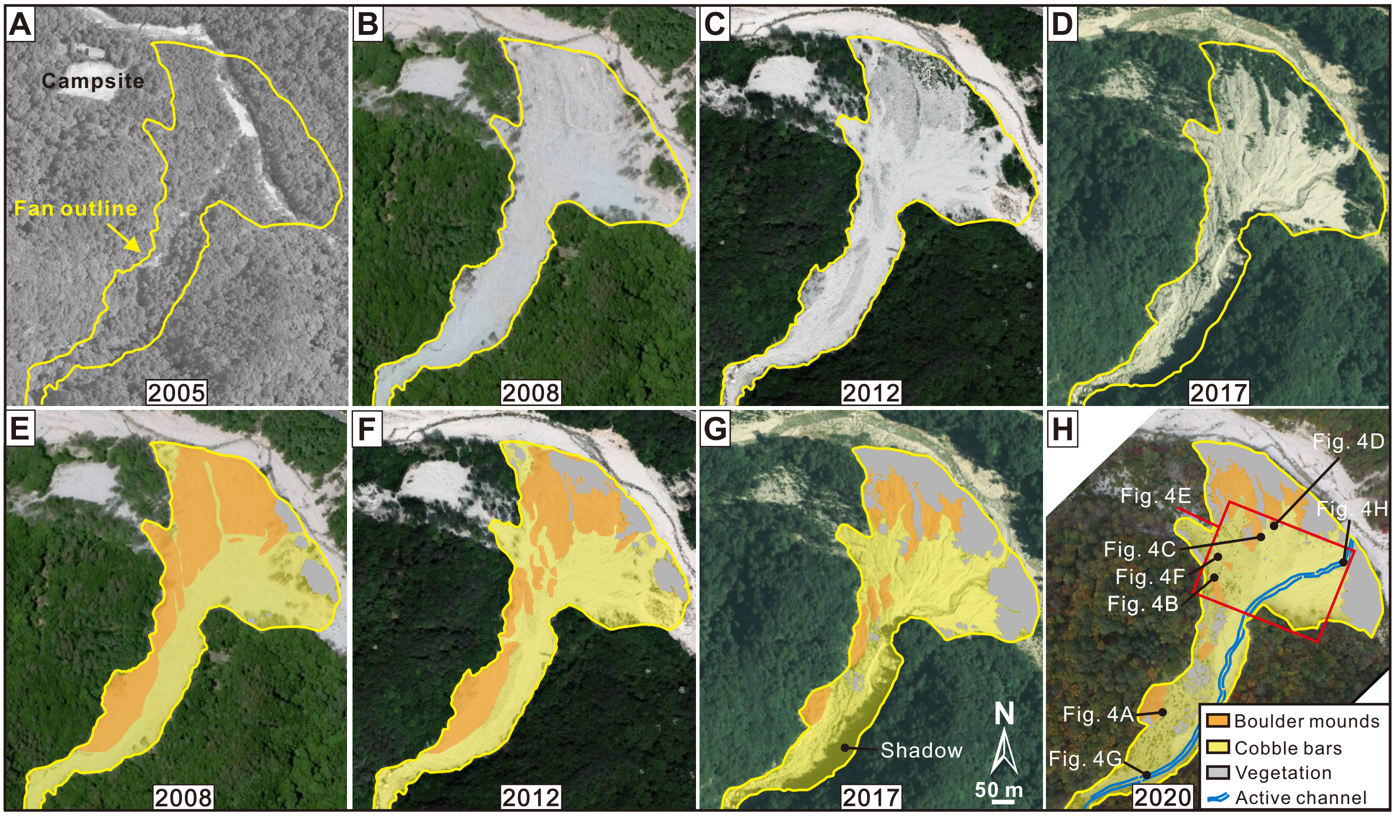

Figure 3: Changes of the fan surface. **A–D:** Aerial photographs taken between 2005 and 2017. **E–H:** Changes of sediment facies on the fan (Photograph A is available at http://www.ngii.go.kr, photographs B to G are available at http://map.kakao.com, and photograph H was taken with an unmanned aerial vehicle by the authors).

on the surface resulted from post-2006 sheetflood events, which probably eroded and reworked the 2006 deposits. The overall braided bar- and channel-like pattern of the deposits (Fig. 4E), some of them having the scaled-down morphology of the boulder mounds (e.g., Fig. 4F), suggest that they were also produced by the accumulation of gravelly bedload transported by sheetfloods followed by shallow incision of the deposits by recessional water flows. Scour marks on rare tree trunks standing upright (Fig. 4H) also suggest numerous collisions of gravel clasts carried as bedload in the floods. Crude stratification of the deposits with local intercalations of openwork gravel layers (Fig. 4G) suggests multiple depositional events by sheetfloods with intervening erosional or reworking and winnowing events. Almost complete removal of the trees on the fan surface by the 2006 event (Fig. 3B) suggests that the floods had competency that was high enough to knock down trees even at the fan toe. The significant change of the course of the Hangyecheon stream (Fig. 3A–B) is also notable, which is attributed to the encroachment of the bouldery fan into the former stream channel.

Stratigraphic arrangement of the boulder mounds, cobble bars/sheets, and channels is poorly constrained. Continual shrinking of the boulder mound area since 2006 (Fig. 3) suggests that these mounds were produced by the 2006 event only, whereas the ever-increasing area of the cobble bars/sheets indicates their deposition mostly from multiple post-2006 events. Some cobble deposits are, however, apparently overlain by the frontal and lateral parts of the boulder mounds (Fig. 4B–C), suggesting that the formation of the boulder mounds was preceded by the deposition of cobble deposits during the 2006 event. We therefore interpret that the deposition of the boulder mounds occurred during the peak discharge, while the cobble bars/sheets were deposited both before and after the peak discharge during the 2006 rainfall event. It is uncertain whether the cobble deposits overlying the rear part of the boulder mounds (Fig. 4D) were produced by the 2006 event or the post-2006 events. Whatever the case, we interpret that the deposition of cobbles could occur both before and after the boulder mound formation, i.e., before and after the peak discharge.

The unusually high relief of the boulder mounds and the absence of pebble to cobble gravel in the interstices of the bouldery deposits (e.g., Fig. 4C–D) suggest that the boulder mounds were quickly exposed above floodwater after the peak discharge, and could not trap finer gravel clasts that were transported by the waning or recessional flood or by the post-2006 floods. Meter-deep channels with steep walls and scattered boulders on the floor (Fig. 4H) are interpreted to be erosional features produced by confined streamflows, which led to channel incision and drainage

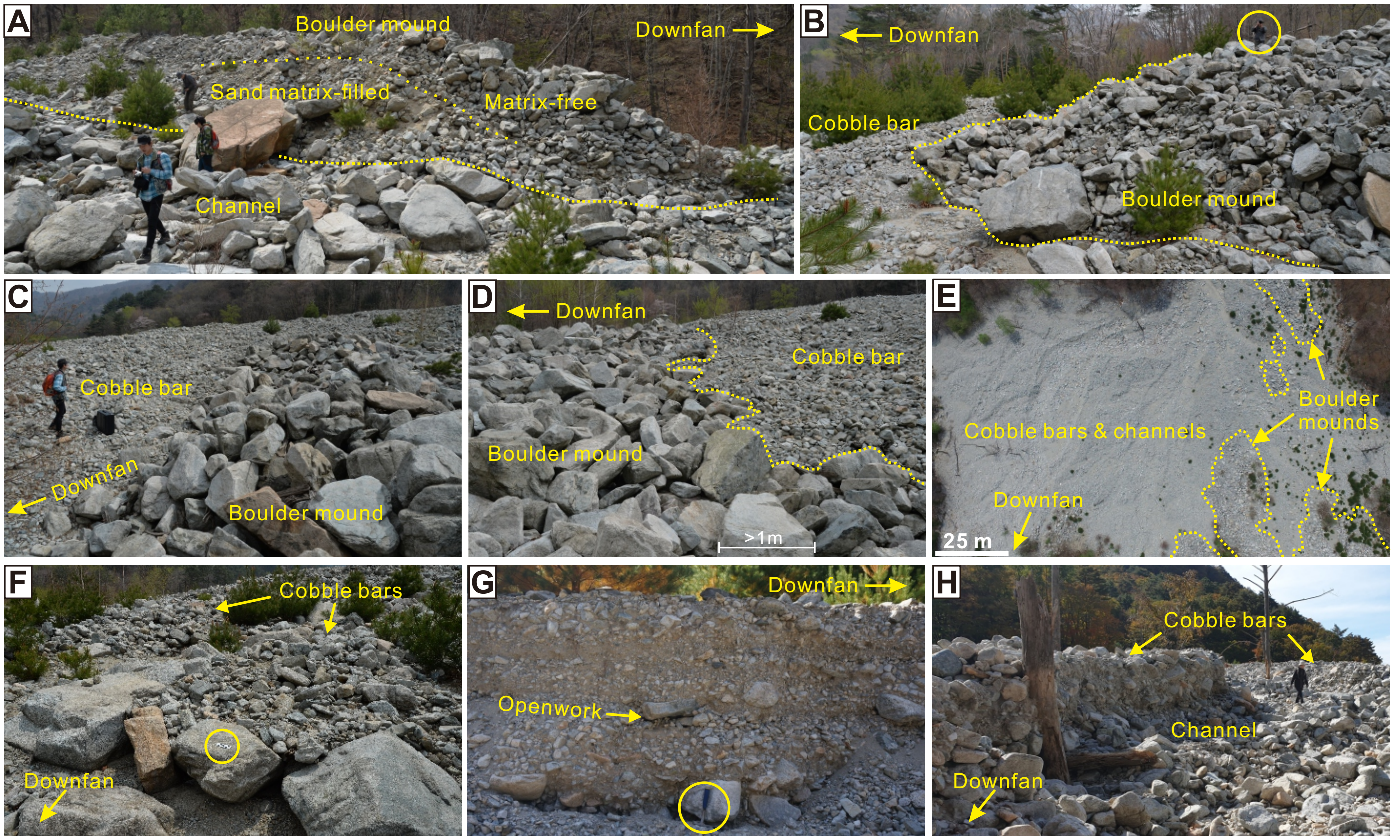

Figure 4: Deposit features. **A:** Longitudinal section of a boulder mound dissected by an abandoned channel in the foreground. **B:** Frontal margin of a boulder mound overlying cobble bar deposit. A figure (circled) gives the scale. **C:** Lateral margin of a boulder mound overlying cobble bar deposit. **D:** Rear margin of a boulder mound partly overlain by cobble bar deposit. **E:** Aerial photograph of the fan surface taken with a drone in 2020. **F:** A cobble bar with a frontal boulder jam. A 10 cm-long photo scale is circled. **G:** Crudely stratified, relatively fine-grained cobble bar deposit with medium to coarse sand matrix and an openwork gravel layer. A hammer (circled) for scale. **H:** An active channel incised into cobble bar deposits. Note the scour marks on the moribund tree trunks. The locations of the photographs are shown in Figure 3H.

network development on the fan surface over a decade. For example, the channel in Figure 4H was eroded by more than a meter after a typhoon-induced rainfall in 2020.

CONTROLS ON ALLUVIAL FAN FORMATION

Climate change and tectonic activity are the main extrinsic controls of alluvial fan formation that operate independently of an alluvial fan system. These two controls probably created the topographic and environmental conditions in the Seoraksan area over a long period of time setting up the conditions for an alluvial fan to be formed. However, the specific timing and location of the alluvial fan formation are not likely to have been determined by these two factors because no significant tectonism or seismicity has been reported in the study area recently, and the episodic fan formation in 2006, but not in 1990, 2003 or 2011 when the precipitation was similar (Fig. 2B), cannot be related to climate changes between these years.

On the other hand, intrinsic geomorphic processes in the source area combined with the role of the geomorphic threshold (Schumm, 1979) are interpreted to have triggered the episodic formation of the Seoraksan alluvial fan. According to the concept of the geomorphic threshold, the formation of the Seoraksan alluvial fan can be regarded as an episodic response of the source area to the stresses applied to that area over a length of time until a threshold is reached. The present catchment area of the alluvial fan is presumed to be near the stage of maximum drainage extension, characterized by tributary valley development to near the watershed (Fig. 1C). Slope erosion is inferred to be at or near its maximum with high production of coarse sediment. The trunk valley and its major tributary valleys might have been, however, reducing their ability to transport coarse sediment and increasing their storage capacity because of the tendency for stages of drainage basin evolution to overlap in time (Schumm, 1979). A threshold condition was probably reached as coarse sediments aggraded valley floors to the point of metastability. A heavy rainfall event in 2006, which would have had no extreme effects before the valleys were substantially aggraded, might have triggered massive remobilization of bouldery sediments on the valley floors and the formation of the bouldery alluvial fan.

Afterwards, only the modification of the fan surface oc-

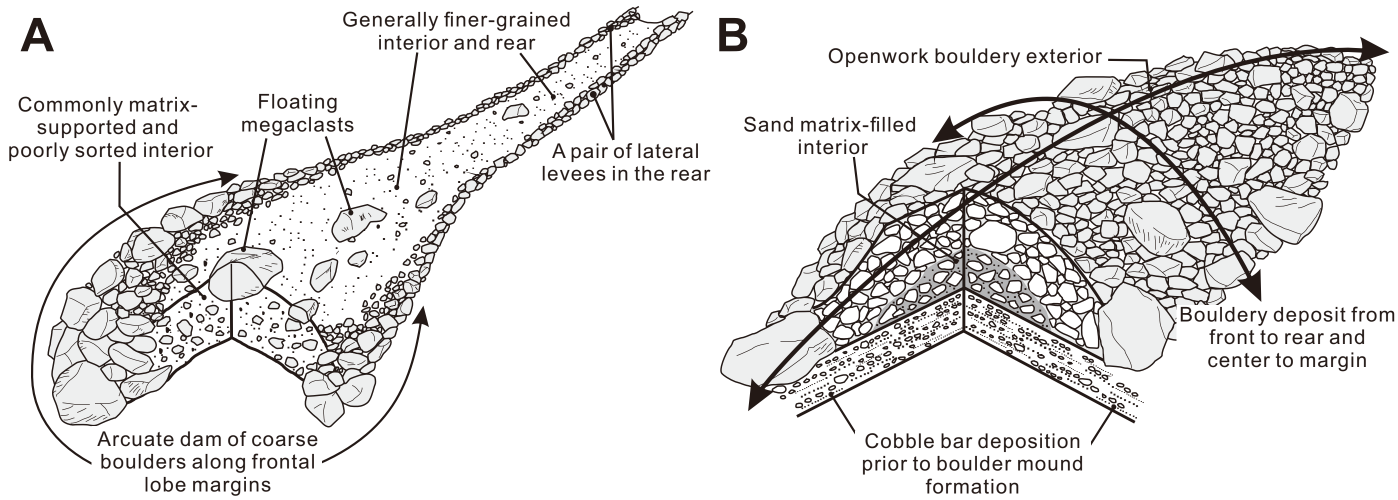

Figure 5: Comparison of debris-flow lobe/levees and boulder mounds of Seoraksan. **A:** Debris flow deposits are characterized by an arcuate dam of boulders along the lobe margins and by parallel levees in the rear. Their interior is composed of commonly matrix-supported and poorly sorted deposits with floating megaclasts (Pierson, 1980, 1986, Blair and McPherson, 1998). **B:** The boulder mounds of Seoraksan are, however, covered by openwork boulders on the entire surface from front to rear and from center to margin. The cobble bar deposit at the base is interpreted to be deposited by sheetfloods before the peak discharge; the sand matrix-filled interior is by hyperconcentrated flood flows; the openwork bouldery exterior is by torrential water flood during the peak discharge. The boulder mounds are up to 5 m high, tens of meters wide, and over a few hundreds of meters long. Debris flow lobe/levees also have similar dimensions.

curred in spite of a few intense rainfall events after 2006 (Fig. 2A–B), probably because the threshold condition was removed in the catchment area. The Seoraksan alluvial fan thus demonstrates that alluvial fans in humid-temperate regions, which have been considered to form by relatively slower and continuous processes, can form in an instant in time, and that the instantaneous fan formation can be triggered by a single, casual hydro-meteorological event if intrinsic geomorphic threshold conditions are met in the source area. The Seoraksan alluvial fan thus highlights the role of geomorphic threshold in causing drastic changes in the hydrologic performance of the watershed.

CONCLUSIONS

Alluvial fans are a type of distributive fluvial system (DFS), which is defined as 'the deposit of a fluvial system which in planform displays a radial distributive channel pattern' (Hartley et al., 2010). Some workers claim that the term 'alluvial fan' is no longer necessary and can be replaced with the term DFS or 'small DFS' because the DFS display the characteristics of alluvial fans at all scales (Weissmann et al., 2010, 2015). However, the term alluvial fan has been widely used for a long time in earth science communities, entrenched in the literature, and appears to be still useful for describing conical, commonly coarse-grained sedimentary bodies formed at the mouths of mountain valleys or in a piedmont setting and for distinguishing them from rivers or river deltas (Blair and McPherson, 1994), even if there is a continuum between fans and rivers.

The Melton ratio, defined as watershed relief divided by the square root of watershed area (Melton, 1957), of the Seoraksan alluvial fan is 0.7, and the watershed length is 2.4 km. According to these watershed morphometrics, the watershed of the Seoraksan alluvial fan is predicted to be prone to debris flows (Wilford et al., 2004). The main depositional processes on the fan are, however, interpreted to be water floods and hyperconcentrated flood flows. The discrepancy between the predicted and the actual depositional processes resulted most likely from the lack of soils on the hillslopes and fine-grained sediments on the valley floors in Seoraksan that could form the matrix of debris flows. This indicates that the use only of topographic factors, without the consideration of field-based datasets, can lead to wrong prediction of hazards in mountainous areas. Defining and interpreting the alluvial fan types and the dominant hydrogeomorphic processes based solely on topographic factors, which are being conducted in some academic circles, can also lead to serious misinterpretation of the nature of alluvial fans.

The Seoraksan alluvial fan is distinguished from either arid-region or humid-region alluvial fans and either debris flow-dominated or streamflow-dominated alluvial fans in that

1. the fan was produced by a single seasonal rainfall, which was not necessarily of a very rare and unusually intense event,
2. the main depositional processes were sheetfloods or hyperconcentrated flood flows, rather than debris flows or constant to seasonal braided streamflows,
3. the deposits are unusually coarse-grained and devoid of mud or muddy sand matrix and fine-grained over-

bank facies, dissimilar to either debris-flow or streamflow deposits, and

4. the streamflows acted mainly as erosional rather than depositional processes after the fan formation (cf. Kochel and Johnson, 1984, Evans, 1991, Nemec and Postma, 1993).

The Seoraksan alluvial fan can more likely be described as a 'sheetflood-dominated alluvial fan', which has long been documented in the literature (e.g., Blair, 1987, Wells and Harvey, 1987, among others) but has largely been ignored or misrepresented in the scientific communities (Blair and McPherson, 1994). The Seoraksan alluvial fan can thus serve to develop sedimentological models for sheetflood-dominated alluvial fans, which are presumed to occur in abundance and in diverse forms in glacial to periglacial, tropical, and temperate environments.

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