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Stratigraphic evolution of the northern part of the Cretaceous Neungju Basin, South Korea

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ABSTRACT: Several nonmarine basins were formed in SW Korea under an extensional or transtensional tectonic regime during the Cretaceous. The Neungju Basin is one of these basins, filled by alluvial to lacustrine deposits interbedded with thick, amalgamated tuff beds. Facies analysis in the northern part of the basin shows that the basin fill is composed of four facies associations, representing (1) alluvial fan, (2) alluvial plain, (3) sandflat, and (4) marginal playa lake environments. The basin fill can be subdivided into four stratigraphic units by interbedded thick amalgamated tuff beds. The lowermost unit (unit I) is composed of alluvial plain deposits. The lack of any vertical depositional trend indicates a balance between basin subsidence and sediment supply. The middle unit (units II and III) show regional variations. The extensive lake formed in the central to northern parts of the basin, which are later partly filled by proximal sediments from surrounding areas. In contrast, only alluvial plain to sandflat environments occurred in the southern part. The uppermost unit (unit IV) shows a transition from alluvial fan to sandflat, comprising a fining-upward trend that reflects a gradual decrease in sediment supply and slope-gradient during denudation of uplifted source areas. The variations in depositional patterns were possibly caused by the relationship between volcanism-driven sediment supply and basin subsidence. Basin subsidence may have been sufficient to compensate the volcanism-driven sediment supply prior to the deposition of units II and III, resulting in the conformable deposition of lake sediments over thick amalgamated tuff beds. In contrast, volcanism-driven sediment supply may have reduced the generation of accommodation prior to the deposition of unit IV, resulting in the deposition of conglomerates over thick tuff beds. The traditional depositional model composed of syn-eruption aggradation and inter-eruption degradation may not sufficiently explain the development of sedimentary succession, in which the balance between volcanism-driven sediment supply versus basin subsidence coeval to volcanism is variable.

Key words: nonmarine, accommodation space, depositional environments, Neungju Basin, inter-eruption

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1. INTRODUCTION

The distribution of depositional environments and vertical stratigraphic evolution of a sedimentary basin are influenced by variable extrinsic factors. In most inland extensional basins, tectonism tends to be a first-order control on the development of a sedimentary succession (Gawthorpe et al., 1994; Gawthorpe and Leeder, 2000). Rapid subsidence may result in the expansion of distal depositional environments, whereas reduced subsidence may result in the progradation of proximal depositional environments (e.g., Jo, 2003). Climate changes may exert an effect of variable magnitude on a basin. Long-term climate changes may influence large-scale stratigraphic architectures (e.g., Allen et al., 2013), whereas short-term climate changes may produce high-frequency fluctuations of lake-levels (e.g., Mtelela et al., 2016).

Volcanism and basin subsidence may occur coevally in many extensional basins (Acocella, 2010), influencing the development of sedimentary successions (e.g., Ashley and Hay, 2002; D'Elia et al., 2018). Instantaneous input of large amounts of volcaniclastic deposits as floods and debris-flow may facilitate aggradational sedimentation during active periods of volcanism, whereas erosion by normal streamflow channels may generate degradational sedimentation during inactive periods of volcanism (Smith, 1987, 1991). The alternation of syn-eruption and inter-eruption sedimentation, however, may not occur if background tectonics played the primary role in the development of the basin (e.g., Sohn et al., 2013).

The East Asian continental margin including the Korean

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Peninsula was characterized by back-arc to intra-arc settings due to oblique subduction of the Izanagi Plate during the Cretaceous (Lee, 1999). A number of nonmarine basins were formed in the southwestern Korean Peninsula along the NE-SW-trending fault systems under extensional or transtensional tectonic regimes (Ryang, 2013). The Neungju Basin is the largest among these nonmarine basins. Despite the great paleontological interest in the Neungju Basin due to its preservation of various dinosaur track fossils (e.g., Huh et al., 2003; Huh et al., 2006; Paik et al., 2012; Huh et al., 2013), sedimentological analyses have only been performed on limited parts of the basin (e.g., You et al., 1998; Paik et al., 2007) since early geological surveys (Kim and Park, 1966; Son and Kim, 1966). As a result, the stratigraphic evolution of the basin remains poorly understood. The purposes of this study are (1) to describe and interpret sedimentary facies and depositional environments of the northern part of the Neungju Basin fill, (2) to reconstruct temporal and spatial changes of its paleoenvironments, and (3) to evaluate the influences of tectonics, climate, and volcanism on the development of nonmarine successions.

2. GEOLOGICAL SETTINGS

The Neungju Basin is one of the nonmarine basins that developed on the southwestern Korean Peninsula during the Cretaceous (Fig. 1). The basin is located east of Mudeung Mountain, which was formed by volcanic eruptions during the late-stage development of the Neungju Basin (Ahn et al., 2014). The western and eastern basin margins remain unclear because pyroclastic deposits (the Mudeungsan Tuff) associated with the formation of Mudeung Mountain covers most of the basin margins.

The basin fill was deposited in nonmarine environments including alluvial fan, alluvial plain, sandflat, and shallow lacustrine systems, punctuated by intermittent volcanism (Kim and Park, 1966; Son and Kim, 1966; Paik et al., 2007; Roh et al., 2017). Based on lithology, the basin fill is subdivided into the Oyeri Formation, Manwolsan Tuff, Jangdong Formation (Jangdong Tuff), Jeokbyeok Formation (Jeokbyeok Tuff), Mudeungsan Lava, and Ongam Conglomerate in ascending order (Kim and Park, 1966). The terms "*Tuff*" or "*Lava*" were used to represent a sedimentary subdivision (or formation) including a large proportion of volcaniclastic deposits by early researchers (Kim and Park, 1966; Son and Kim, 1966).

The Oyeri Formation is composed of conglomerate, sandstones, and reddish silty mudstones. The Manwolsan Tuff is gray or greenish lapilli-tuff with minor intercalation of dark gray to black silty mudstones. The Jangdong Formation shows regional variations in lithology. It is mainly composed of dark gray to black silty mudstones and fine sandstones in the northern and central parts of the study area, whereas conglomerates, sandstones

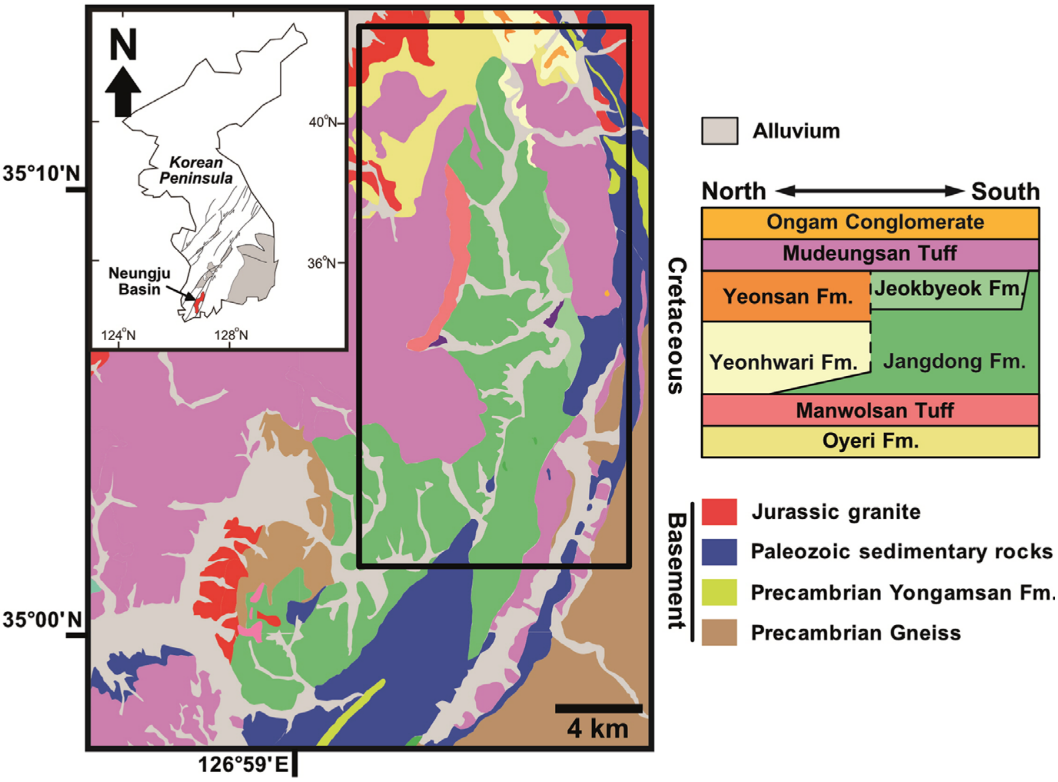

Fig. 1. Geological map and stratigraphy of the Neungju Basin (Kim and Park, 1966; Son and Kim, 1966). The basin fill is bounded by Precambrian gneiss and Paleozoic sedimentary rocks on the east and Jurassic granites on the west. The Mudeungsan Tuff (pink) erupted on the west of the basin during the late stage of basin development, covering most previous deposits. The black square indicates the study area.

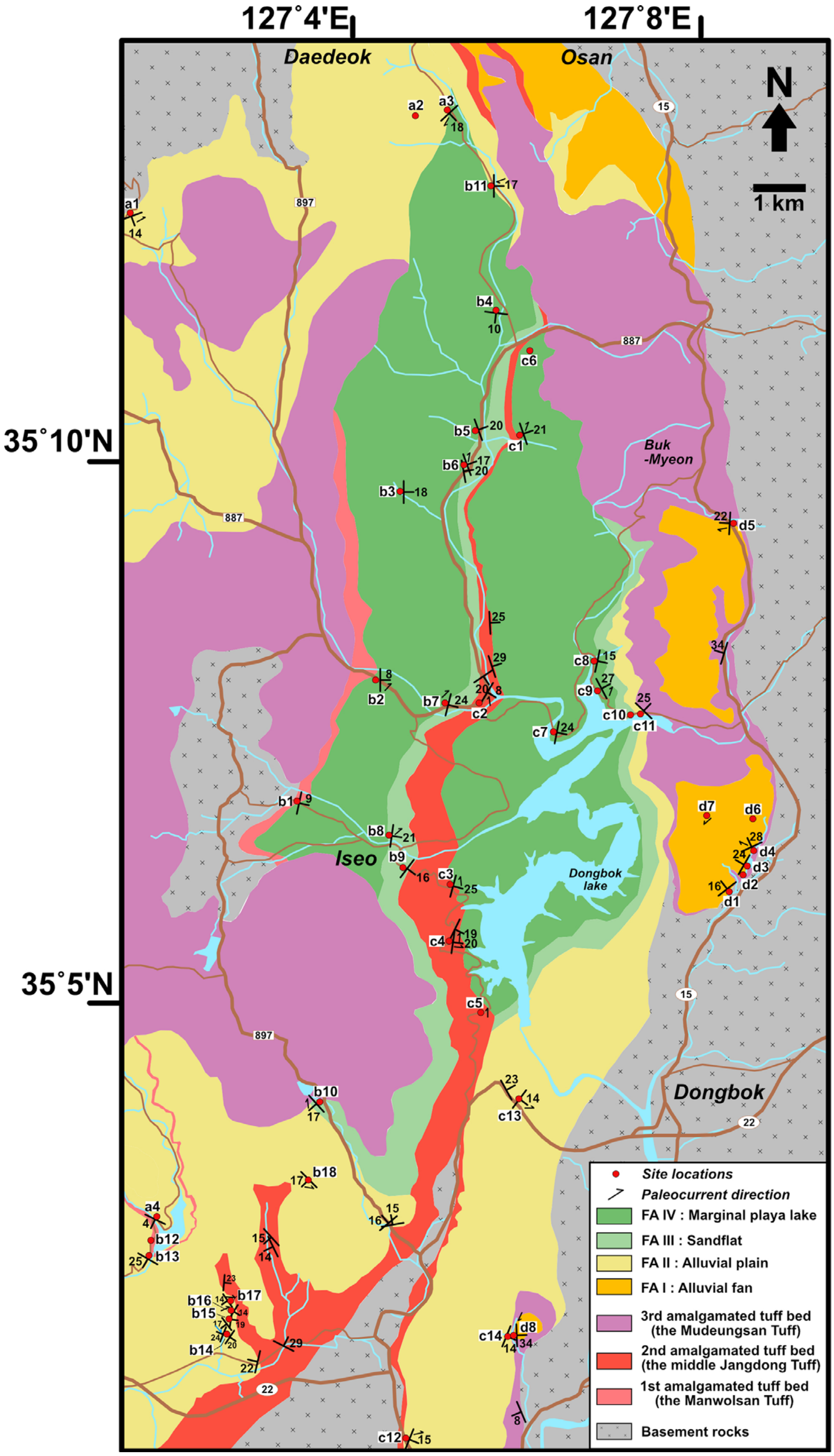

Fig. 2. Location map of the measured sections, showing regional distribution of facies associations (modified after Kim and Park, 1966; Son and Kim, 1966). Decameter- to hectometer-thick amalgamated tuff beds occur three times in some stratigraphic horizons, subdividing the basin fill into four conformable units (I to IV).

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reddish silty mudstones and volcanic breccia in the southern part. The Jeokbyeok Tuff is composed of dark gray to black silty mudstones and fine sandstones and is occasionally interbedded with lapilli-tuff beds. The Mudeungsan Lava was originally considered to be composed of andesitic lava layers. Jung et al. (2014), however, found that they are welded crystal tuffs with dacitic compositions. Thus, the Mudeungsan Lava will be renamed as the Mudeungsan Tuff in this study. The Ongam Conglomerate is mainly composed of conglomerates and subordinately greenish to reddish silty mudstones, unconformably overlying the Mudeungsan Tuff. Near the northern basin margin, the Jeokbyeok Tuff is not present, and the Yeonhwari and Yeonsan Formations composed of conglomerates and sandstones occur between the Jangdong Formation and Mudeungsan Tuff (Son and Kim, 1966). The basin fill is mostly inclined southeast-northeastward (8–29°) in the northern and central part of the basin (Fig. 2). It is inclined west-northwestward near the eastern basin margin, and south-southwestward in the southern part of the study area.

Most of the previous studies focused on dinosaur track-bearing sites in the Jangdong Formation and Jeokbyeok Tuff, suggestive of their deposition in sandflat to mudflat environments (Huh et al., 2003; Huh et al., 2006; Paik et al., 2007; Roh et al., 2017). The Yeonhwari Formation has also been interpreted as an alluvial fan environment (You et al., 1998). Arid to semi-arid climate conditions during the development of the Neungju Basin were suggested based on the occurrence of evaporite casts in mudstones

Table 1. Facies description and interpretation

Facies	Code	Description	Interpretation
Conglomerate facies			
Disorganized conglomerate	Gd (-v)	1–4 m thick; amalgamated up to 23 m thick; clast-supported or matrix-supported; poorly sorted; very coarse to coarse-grained sand matrix or occasionally reddish/greenish silt matrix; angular to subangular pebble to cobble-size extrabasinal clasts, with some boulder-size clasts (e.g., granite, quartzite and schists); (-v) abundant angular to subangular pebble to boulder-size tuff clasts	Debris flow deposits (Nemec & Steel, 1984; Shultz, 1984); hyperconcentrated flow deposits (Pierson & Scott, 1985; Smith, 1986); sheet/longitudinal gravel bars (Steel & Thomson, 1983; Nemec & Steel, 1984; Nemec & Postma, 1993)
Horizontally-stratified gravelly sandstone	GSh	< 1 m thick; occasionally amalgamated at the top of the disorganized conglomerate; crudely stratified or low-angle cross stratified; very coarse to coarse-grained sand matrix; angular to subrounded pebble-size extrabasinal clasts (e.g., granite, quartzite and schists)	Waning flow deposits (Nemec & Steel, 1984); sheetflood deposits (Blair, 1987)
Cross-stratified gravelly sandstone	GSt	Encased in reddish silt to mudstones; 1–3 m thick; sharp, erosional base and flat top; low-angle or trough cross-stratified; alternation of granule- to pebble-size clast-rich layers and very coarse- to coarse-grained sand layers; subangular to subrounded pebble- to cobble-size clast-rich near the bottom (quartzite, schists, reddish mudstone)	Mixed load deposits in gravelly ephemeral braided stream (Reid & Frostick, 1984; Rhee & Chough, 1993); minor channel or scour fills (Miall, 1977; Ryang & Chough, 1997)
Coarse- to fine-grained sandstone facies			
Thick bedded sheet sandstone	Ssh1 (-v)	Decimeter to a few meter thick (0.4–2 m); tabular sheet-like geometry; medium to very coarse-grained; low-angle or trough cross-stratified; low angle lateral-accreted; (-v) tuffaceous	Sandy ephemeral braided stream deposits (Smoot, 1983; Olsen, 1989)
Thin bedded sheet sandstone	Ssh2 (-v)	A few centimeter to decimeter thick; commonly stacked up to a few meter; tabular sheet-like geometry; very fine- to fine-grained; horizontal- or low angle-cross laminated; normal-graded; (-v) tuffaceous	Plane-bed flow deposits under lower or upper flow regime (Bridge & Best, 1988; Best & Bridge, 1992); sheetflood deposits (Smoot, 1983; Olsen, 1989)
Lenticular sandstone	Slc	Decimeter thick; very fine- to medium-grained; lenticular shape; low-angle lateral accretion; trough cross-stratified	Minor crevasse channel deposits (Fielding, 1984, 1986); solitary-channel ephemeral stream deposits (Tunbridge, 1984; Olsen, 1989 and references therein)
Fine grained sandstone to mudstone facies			
Flaser or wavy-bedded fine sandstone to mudstone	MSd	Interlamination of fine sandstone to siltstone and mudstone; dark gray; a few millimeter to centimeter thick; thin flaser or wavy-bedded; occasional presence of mudcracks	Ephemeral stream deposits (Martin, 2000); sheetflood deposits in mudflat environments (Ainsworth et al., 2012; Smoot; 1983; Paik & Kim. 2006)
Reddish siltstone to mudstone	MZr	Siltstone to mudstone; reddish; variable thickness (up to several meters); poorly- or well-sorted; massive or crudely-laminated; occasional inclusion of granule- to sand-size grains	Suspension sedimentation from overflow on floodplain; reddening under oxidizing condition after deposition
Gray siltstone to mudstone	MZg	Siltstone to mudstone; dark gray to greenish gray; a few centimeter to decimeter thick; massive or crudely laminated	Suspension sedimentation from overflow on floodplain or standing water (e.g., pond or lake); graying under waterlogged, reducing condition after deposition
Dark gray siltstone to mudstone	MZd	Siltstone to mudstone; dark gray to black; horizontal or ripple cross-laminations; occasional presence of secondary structures such as mudcracks, gypsum layers, evaporate casts, and dinosaur footprint	Suspension sedimentation in shallow saline water with occasional subaerial exposures (Paik & Kim 2007; Smoot, 2013)

Table 2. GPS coordinates of the measured sections

Site no.	Latitude	Longitude	Site no.	Latitude	Longitude
a1	35°12′29.8″N	127°01′28.7″E	c1	35°10′27.0″N	127°06′05.9″E
a2	35°13′29.0″N	127°04′43.5″E	c2	35°07′57.9″N	127°05′34.8″E
a3	35°13′31.2″N	127°05′12.8″E	c3	35°06′13.4″N	127°05′14.1″E
a4	35°03′07.5″N	127°01′53.6″E	c4	35°05′42.8″N	127°05′14.1″E
b1	35°07′01.7″N	127°03′29.8″E	c5	35°05′03.5″N	127°05′36.8″E
b2	35°08′12.5″N	127°04′21.0″E	c6	35°11′16.9″N	127°06′05.7″E
b3	35°09′57.1″N	127°04′37.8″E	c7	35°07′41.8″N	127°06′25.2″E
b4	35°11′35.3″N	127°05′46.9″E	c8	35°08′21.0″N	127°06′53.1″E
b5	35°10′29.9″N	127°05′33.4″E	c9	35°08′04.7″N	127°06′54.0″E
b6	35°10′10.5″N	127°05′24.2″E	c10	35°07′51.2″N	127°07′20.3″E
b7	35°07′55.9″N	127°05′12.4″E	c11	35°07′51.3″N	127°07′32.1″E
b8	35°06′41.7″N	127°04′33.6″E	c12	35°01′05.0″N	127°04′43.6″E
b9	35°06′24.5″N	127°04′41.5″E	c13	35°04′13.4″N	127°06′02.9″E
b10	35°04′12.7″N	127°03′48.0″E	c14	35°02′00.8″N	127°05′51.8″E
b11	35°12′46.3″N	127°05′45.4″E	d1	35°06′10.2″N	127°08′22.8″E
b12	35°02′54.8″N	127°01′49.8″E	d2	35°06′20.1″N	127°08′35.0″E
b13	35°02′49.3″N	127°01′49.6″E	d3	35°06′24.6″N	127°08′36.1″E
b14	35°02′02.7″N	127°02′41.7″E	d4	35°06′33.0″N	127°08′39.8″E
b15	35°02′12.3″N	127°02′44.9″E	d5	35°09′38.6″N	127°08′23.9″E
b16	35°02′15.6″N	127°02′44.9″E	d6	35°06′52.8″N	127°08′40.1″E
b17	35°02′20.8″N	127°02′44.1″E	d7	35°06′52.5″N	127°08′02.7″E
b18	35°03′29.3″N	127°03′38.1″E	d8	35°02′01.8″N	127°05′57.6″E

Table 3. Facies associations and interpretations

Code	Dominant facies	Subordinate facies	Interpretation	Occurrence
FA I	Gd, GSh	MZr, MZg	Alluvial fan	Yeonhwari Fm. (upper part), Yeonsan Fm., Ongam Cg. (lower part)
FA II	GSt, MZr	Slc, MZg	Alluvial plain	Oyeri Fm., Yeonhwari Fm. (lower part), Jangdong Fm.
FA III	Ssh1, Ssh2	Slc, MZg, MZr	Sandflat	Jangdong Fm. (middle and uppermost parts), Jeokbyeok Fm., Ongam Cg. (upper part)
FA IV	MZd, MSd	SSh2	Marginal playa lake	Jangdong Fm.

of the Jangdong Formation (Paik et al., 2007).

The depositional age of the basin fill can be roughly constrained as the Late Cretaceous. Based on K-Ar geochronology for volcanic clasts in the Jangdong Formation, its depositional age was suggested to be between 71 to 66 Ma, corresponding to the Maastrichtian (Kim and Kang, 2012). In contrast, the Manwolsan Tuff and a tuff bed in the middle of the Jangdong Formation have yielded zircon U-Pb age of 96 Ma and 94 Ma, respectively. The Mudeungsan Tuff has yielded zircon U-Pb ages between 87 to 85 Ma, suggesting that most of the basin fill was deposited before the Santonian (Ahn et al., 2014).

3. FACIES ASSOCIATIONS

Based on texture, rock colors, and sedimentary structures, ten sedimentary facies are classified in the study area. Their detailed descriptions and interpretations are presented in Table 1 and Figure 3. Figures 4 and 5 provide the measured stratigraphic sections in the study area. Site locations and their GPS coordinates are presented in Figure 2 and Table 2, respectively. These sedimentary facies are grouped into four facies associations representing (1) alluvial fan, (2) alluvial plain, (3) sandflat, and (4) marginal playa lake environments. The occurrences, characteristics, and interpreted depositional environments of the facies associations are described below and are summarized in Table 3. The regional distribution of the facies associations is presented in Figure 2.

3.1. Facies Association I: Alluvial Fan

Facies association I (FA I) occurs along the eastern margin of the basin, corresponding to the upper part of the Yeonhwari Formation, Yeonsan Formation, and the lower part of the Ongam Conglomerate. FA I is composed of mainly disorganized conglomerates (Gd) and horizontally stratified gravelly sandstones (GSh) (Figs.

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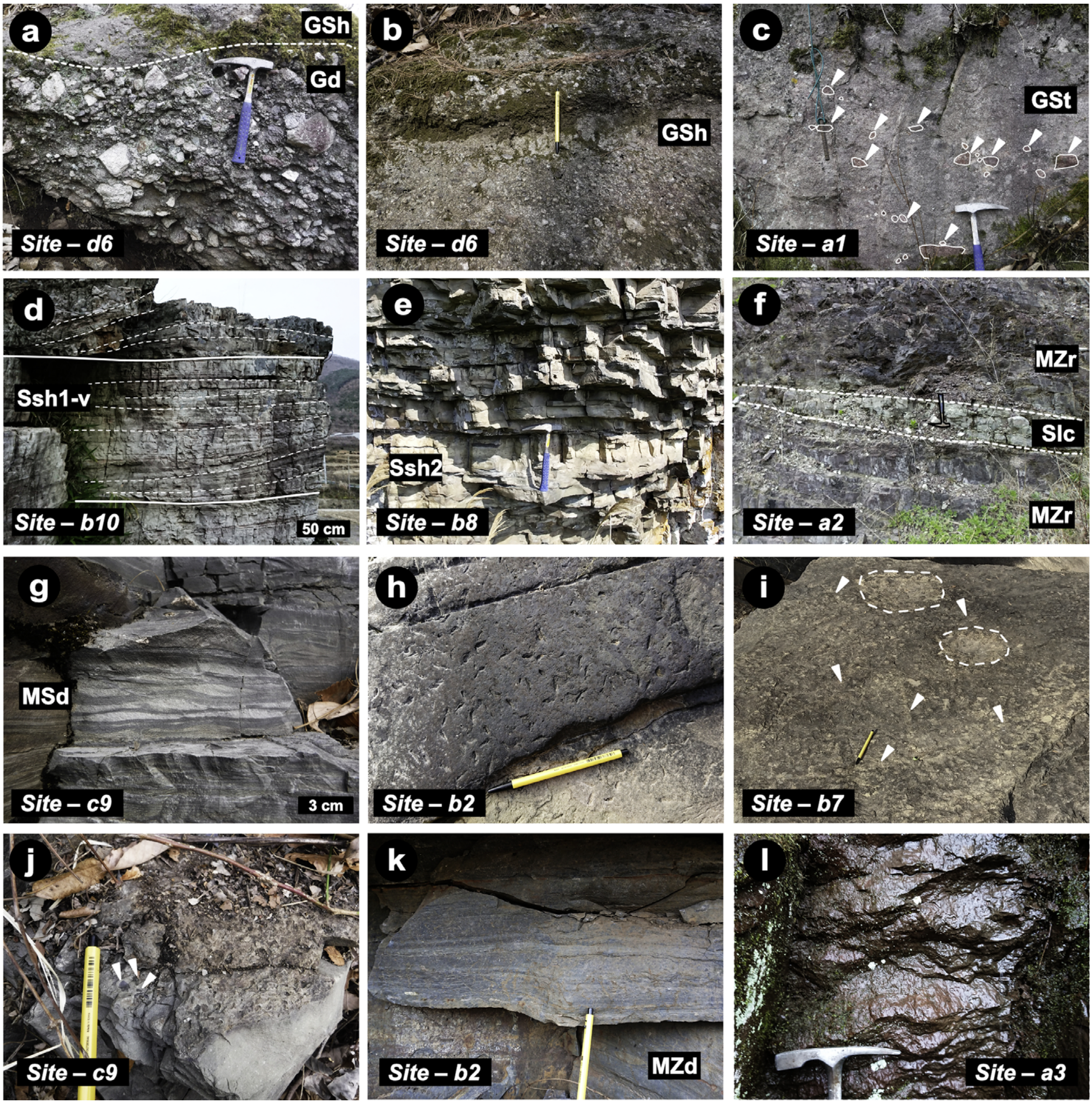

Fig. 3. Examples of selected facies and sedimentary structures. (a) Disorganized conglomerate (Gd). Horizontally stratified gravelly sandstone (GSh) are amalgamated with the top of Gd facies. (b) Horizontally stratified gravelly sandstone (GSh). (c) Cross-stratified gravelly sandstone (GSt). White arrows indicate reddish mudstone clasts. (d) Thick-bedded sheet sandstone (Ssh1). Note the sheet-like external geometries with minor lateral accretion. (e) Thin-bedded sheet sandstone (Ssh2). (f) Lenticular sandstone (Slc) encased in reddish siltstone to mudstone (MZr). (g) Flaser or wavy-bedded fine sandstone to mudstone (MSd). (h) Evaporite casts on the surface of MSd facies. (i) One pair of dinosaur footprints on the surface of MSd facies. White arrows indicate mudcracks. (j) Small, dark gray mudstone intraclasts are accumulated in a layer of MSd facies. (k) Dark gray siltstone to mudstone showing horizontal laminations (MZd). (l) Pedogenic slickensides developed in reddish siltstone to mudstone.

3a and b). The disorganized conglomerate beds are 1 to 4 m thick, forming several meter-thick amalgamated conglomerate bodies (< 23 m). They are mostly massive, clast-supported to matrix-supported conglomerate, but some show crude stratifications. The conglomerate clasts are angular to subangular and are composed of pebble to boulders of schist, quartzite and granite originated from the northern and eastern margins. The disorganized conglomerates overlying the Mudeungsan Tuff (corresponding to

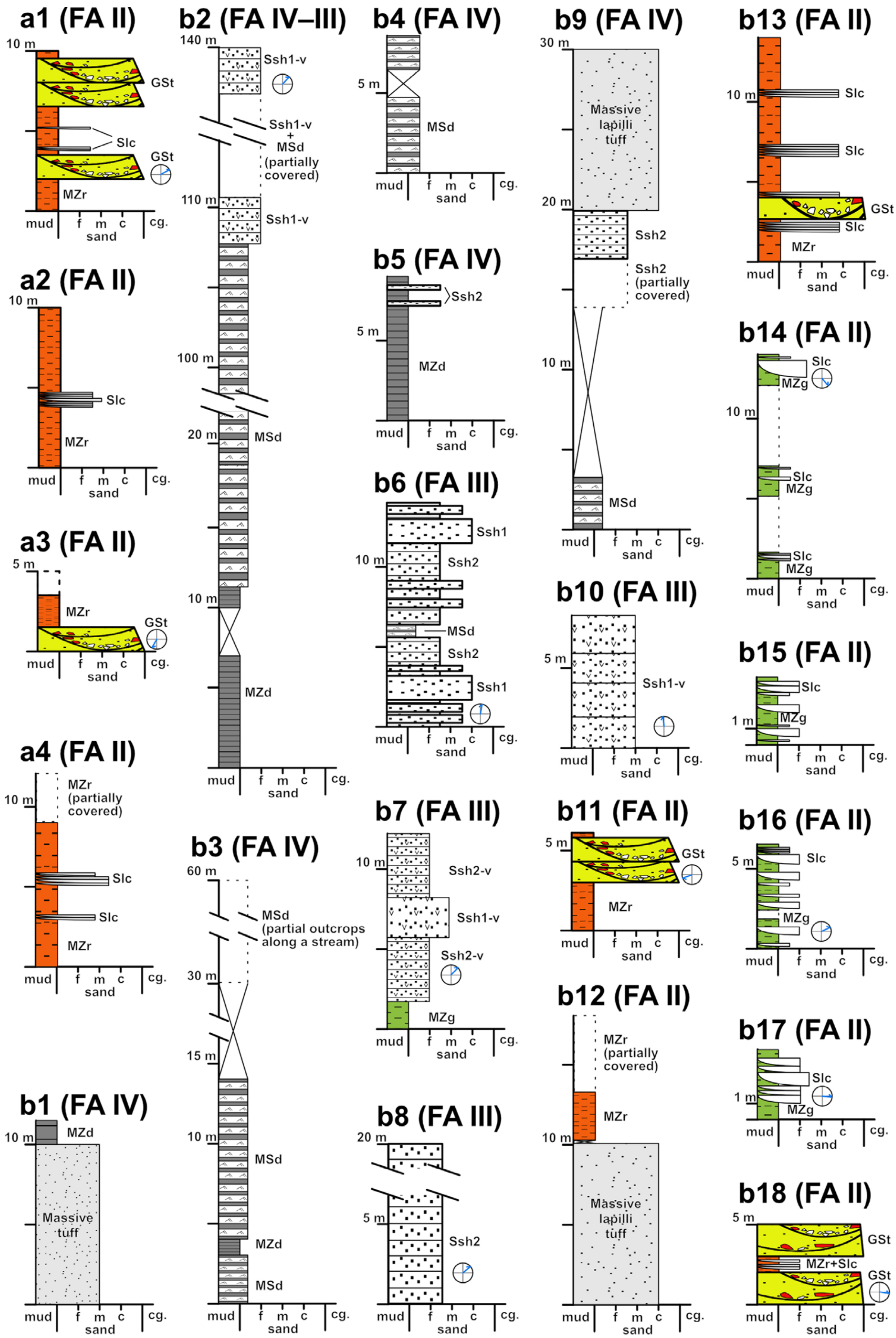

Fig. 4. Measured sections from stratigraphic units I and II. Site locations are shown in Figure 2. Blue arrows indicate trough axes, determined by measuring two sides of a trough. Facies codes are presented in Table 1.

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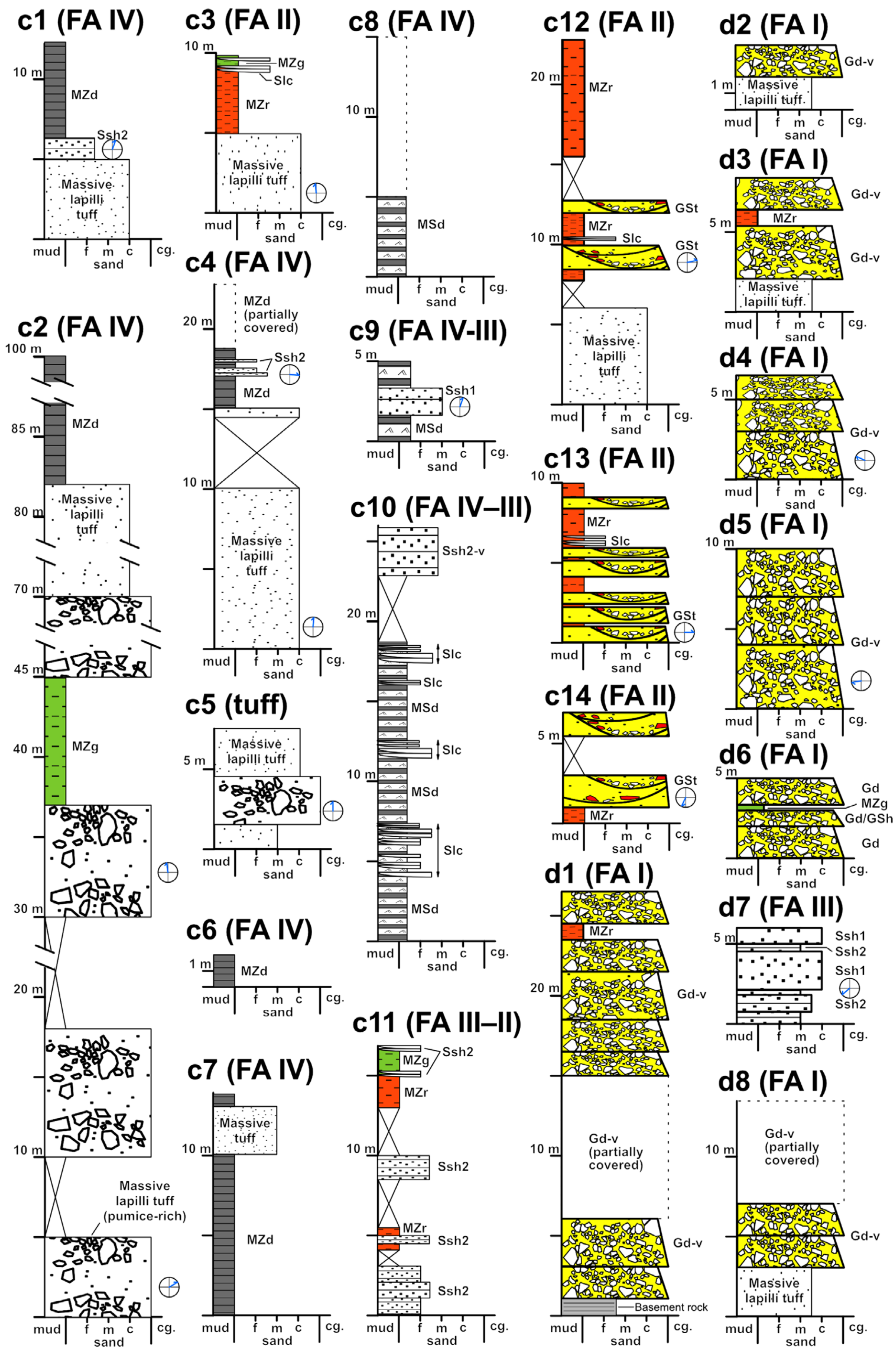

Fig. 5. Measured sections from stratigraphic units III and IV. Site locations are shown in Figure 2, and facies codes are presented in Table 1.

the Ongam Conglomerate) contains abundant angular to subangular tuff clasts. The horizontally stratified gravelly sandstones are occasionally amalgamated at the top of the disorganized conglomerates. They are less than 1 m thick and are characterized by crude stratification or low-angle cross-stratification. Reddish or gray siltstone to mudstone facies (MZr, MZg) is occasionally interbedded with these coarse-grained facies (Gd, GSh).

The disorganized conglomerates are poorly sorted and show no distinct stratification, indicating their deposition as debris flows or hyperconcentrated flows (Nemec and Steel, 1984; Shultz, 1984; Pierson and Scott, 1985; Smith, 1986). The gravelly sandstones are commonly amalgamated with the tops of the disorganized conglomerates and are interpreted as waning-flow deposits (Nemec and Steel, 1984) or sheetflood deposits that developed on the surfaces of alluvial fans during flooding (Wasson, 1977; Nemec and Steel, 1984; Blair, 1987). The disorganized conglomerates include boulder-sized angular clasts produced from the northern and eastern margins, indicating their deposition in medial to proximal parts of an alluvial fan, possibly close to the border fault (Spearing, 1974; Nilsen, 1982). The occurrence of abundant tuff clasts in the disorganized conglomerate overlying the Mudeungsan Tuff indicates that volcanic eruption was intense enough to supply large volume of sediments close to the eastern basin margin, causing significant erosion of volcaniclastic sediments after the volcanism.

3.2. Facies Association II: Alluvial Plain

Facies association II (FA II) is broadly distributed near the northern basin margin, corresponding to the Oyeri Formation and the lower part of the Yeonhwari Formation. In the southern part of the study area, most of the Jangdong Formation is also composed of FA II. FA II is dominated by massive or crudely laminated reddish mudstones (MZr). Cross-stratified gravelly sandstones (GSt), and lenticular sandstones (Slc) are interbedded with the reddish siltstone to mudstones (MZr) (Figs. 3c and f). The gravelly sandstones occur as 1- to 3-m-thick beds and are characterized by the alternation of granule- to pebble-size clast-rich layers and very coarse- to coarse-grained sand layers, showing low-angle to trough cross-stratification. The clasts are composed of quartzite, schist, and reddish silt/mudstones and are abundant at the base of the gravelly sandstone beds. The lenticular sandstones are less than 1 m thick and laterally thin and transit into the reddish siltstone to mudstones. In addition to lenticular geometry, they are also characterized by low-angle lateral-accretion and trough cross-stratification.

The reddish siltstone to mudstones can be interpreted as overbank deposits in the well-drained floodplain (Friend, 1966; Miall, 1996). The unstratified features in the reddish siltstone to mudstones are likely to have been caused by pedogenesis (Fig. 3l). The alternation of gravelly and sandy layers in the gravelly sandstones may be a result of fluctuations in flow velocity during deposition. Similar textures, however, can be produced in gravelly ephemeral streams where gravelly sediments are transported as bed-load and sandy sediments are transported as suspended load (Wasson, 1977; Reid and Frostick, 1984). The concave base and flat top of the lenticular sandstones are suggestive of channel fills. Lateral-accretion also suggests that the channel is sinuous. Based on small grain-size and thickness of the lenticular sandstones relative to the gravelly sandstones, the lenticular sandstones can be interpreted as crevasse channel deposits developed in the floodplain during flooding (Miall, 1985, 1996). Overall, FA II is interpreted as alluvial plain deposits composed of ephemeral streams and well-drained floodplains (e.g., Rhee and Chough, 1993; Ryang and Chough, 1997).

3.3. Facies Association III: Sandflat

Facies association III (FA III) mainly occurs thinly in the central part of the basin, corresponding to the middle part of the Jangdong Formation, and the uppermost part of the Jangdong Formation to the overlying Jeokbyeok Formation. It also occurs in the upper part of the Ongam Conglomerate. FA III is characterized by multiple stacks of thick-bedded (Ssh1), thin-bedded (Ssh2), and lenticular sandstones (Slc). Gray siltstone to mudstones (MZg) are occasionally thinly interbedded with the sandstones (Figs. 3d and e). The thick-bedded sandstones are low-angle to trough cross-stratified, coarse- to medium-grained sandstones that occur as 0.4- to 2-m-thick sheets. Most of them are vertically accreted, but in some beds, low-angle lateral accretion is also shown. Thin-bedded sandstones and lenticular sandstones are identical to those of FA II. In some outcrops, a gradual transition from thin-bedded sandstones or lenticular sandstones to thick-bedded sandstones is observed, forming a coarsening- and thickening-upward trend.

The thick-bedded sandstones are somewhat similar to braided stream deposits (Allen, 1983), showing sheet-like external geometries, multiple stacks of sandstones, and dominance of vertical accretion with a minor lateral accretion (Fig. 3d). In contrast to typical braided stream deposits, however, they are characterized by nonerosive and flat basal and internal surfaces. In braided stream deposits, the basal and internal surfaces tend to be irregular due to episodic erosion and complex development of variable types of bars. Thus, the thick-bedded sandstones may have been deposited in ephemeral braided stream environments where ephemeral run-off and sheetflood generate poorly defined, nonerosive channels (e.g., Miall, 1985; Olsen, 1989). The thin-bedded sandstones can

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be interpreted as sheetflood deposits that developed in alluvial plain areas adjacent to the ephemeral braided stream environments (e.g., Tunbridge, 1984; Miall, 1985; Olsen, 1989). The dominance of sandy sheetflood deposits suggests that FA III is sandflat deposits around shallow playa lake under arid to semi-arid climate conditions (e.g., Smoot, 1983; Paik and Kim, 2006). Although FA III is also similar to the distributary zone deposits of terminal fan environments (cf. Olsen, 1987; Kelly and Olsen, 1993), it is distinguished from terminal fan deposits by the lack of channel bifurcation and interchannel deposits.

3.4. Facies Association IV: Marginal Playa Lake

Facies association IV (FA IV) occurs in the central part of the basin, corresponding to most of the Jangdong Formation. FA IV is mainly composed of flaser- or wavy-bedded fine-grained sandstone to mudstone (MSd) and dark gray siltstone to mudstones (MZd) (Figs. 3g and k). The dark gray siltstone to mudstones are horizontally or ripple-cross laminated and are characterized by the occurrence of sedimentary features such as mudcracks, evaporite casts, and dinosaur footprints (Figs. 3h and i). Laminae including dark gray siltstone to mudstone intraclasts are also rarely observed (Fig. 3j).

The alternation of thin sand and mud layers with flaser or wavy bedding is characteristic of marine tidal flat deposits (Reineck, 1967; Reineck and Wunderlich, 1968). Similar sedimentary structures, however, can be developed in ephemeral streams or mudflat environments where sheetfloods repeatedly generate rapid changes in flow velocity (e.g., Smoot, 1983; Martin, 2000; Paik and Kim, 2006). Thus, the flaser- or wavy-bedded fine sandstone to mudstone may have been deposited in a mudflat environment. The dark gray mudstones may have been deposited in a shallow and stable lake. However, the occurrence of mudcracks, evaporite casts, dinosaur footprints, and intraclast layers indicates that subaerial exposure and minor erosion was common. FA IV is interpreted as a marginal playa lake environment located in the central part of the basin.

4. STRATIGRAPHIC UNITS

4.1. Unit Boundaries

Decameter- to hectometer-thick amalgamated tuff beds occur in some stratigraphic horizons (Fig. 2), aiding correlation across the basin. Using the amalgamated tuff beds as key beds, the basin fill of the Neungju Basin can be subdivided into four conformable stratigraphic units (I to IV; Fig. 6).

Unit I is separated from unit II by approximately 50-m-thick amalgamated tuff beds (the Manwolsan Tuff). The 1st amalgamated tuff beds are composed of greenish, massive lapilli-tuff (Fig. 7a). In the central part of the study area, dark gray siltstone to mudstones (MZd) of unit II overlie the 1st amalgamated tuff bed (Fig. 8i). On the other hand, reddish siltstone to mudstone (MZd) of unit II overlie the tuff bed in the southern part. Abundant pebble-size angular tuff clasts in the MZd facies are suggestive of minor erosion (Fig. 8h), although an erosional surface has not been observed. The unit boundary is covered partly by the Mudeungsan Tuff (Fig. 2) and is difficult to specify in the northern part.

The 2nd amalgamated tuff beds are approximately 120 m-thick, and occurs at the middle of the Jangdong Formation (Fig. 2), separating units II and III. In contrast to the 1st amalgamated tuff beds, the 2nd amalgamated tuff beds show variable grain-size (Figs. 7b–d). In the lower part of the 2nd tuff beds, pebble- to cobble-size subangular to subrounded pumices are common (Fig. 7d), whereas in the upper part, the 2nd tuff beds are mainly composed of welded lapilli-tuff (Fig. 7b). In the central to northern parts of the study area, dark gray siltstone to mudstone (MZd) of unit III overlie the 2nd amalgamate tuff beds (Figs. 8e and g), showing no sign of basal erosion. In the southern part, on the other hand, reddish siltstone to mudstone (MZd) of unit III overlie the 2nd amalgamated tuff beds (Figs. 8d and f). The irregular top of the 2nd amalgamated tuff beds is suggestive of minor erosion in the southern part.

The Mudeungsan Tuff (> 300 m in thickness) is the 3rd amalgamated tuff beds, extensively covering unit III. The 3rd amalgamated tuff beds are mainly composed of greenish, massive lapilli-tuff (Figs. 7e and f), and are highly similar to the 1st amalgamated tuff beds. The disorganized conglomerates of unit IV erosively overlie the 3rd amalgamated tuff beds (Figs. 8a–c). The common occurrence of cobble-size tuff clasts in the disorganized conglomerates indicates significant erosion of the underlying 3rd amalgamated tuff beds during their deposition.

The depositional ages of the 1st and 2nd amalgamated tuff beds have been reported to 96 and 94 Ma based on zircon U-Pb data, respectively. The depositional age of the Mudeungsan Tuff was also reported to be between 87 to 85 Ma (Ahn et al., 2014).

4.2. Stratigraphic Unit I

Stratigraphic unit I, the lowest unit, is approximately 150 to 250 m thick and is exposed along the western basin margin. This unit is composed of FA II (Fig. 6), indicating the development of a broad alluvial plain environment along the western basin margin during the earliest stage of basin evolution (Fig. 9). Paleocurrent data indicate eastward flow direction during the deposition of unit I, suggesting alluvial fans may have existed west of the present basin margin.

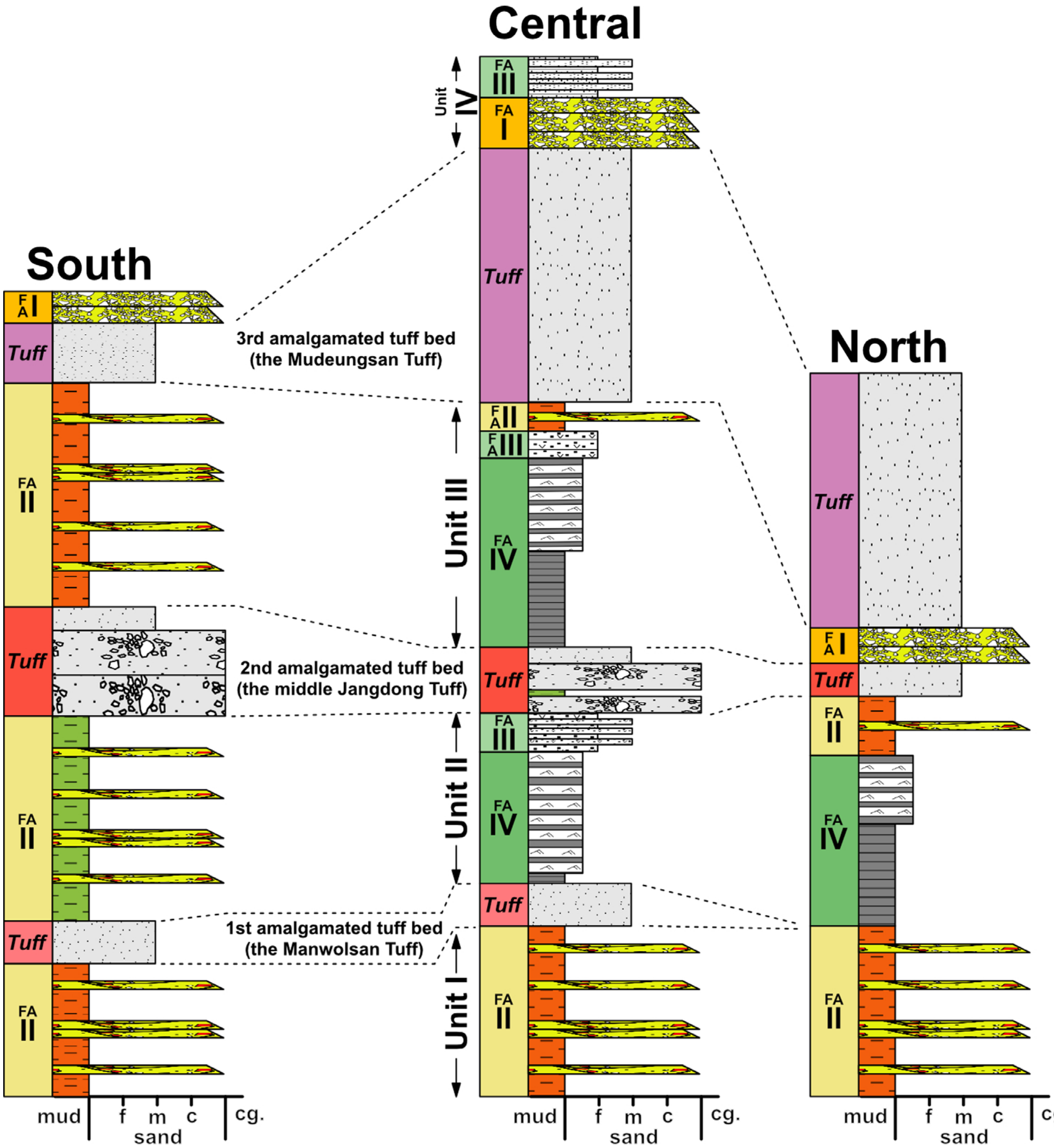

Fig. 6. Schematic composite sections of the southern, central, and northern parts of the study area, highlighting the upsection changes in depositional environments. Vertical thickness is not to scale.

4.3. Stratigraphic Unit II

Stratigraphic unit II (approximately 200 m thick) initiates with an abrupt transition from FA II of unit I to FA IV in the central and northern parts of the study area, indicating a major expansion of the playa lake environment in the basin (Figs. 6 and 9). The occurrence of FA II in the southern part indicates that the lake expansion was limited in the central and northern parts. Although ephemeral braided stream deposits (Ssh1) are characterized by north- to northeastward flow directions and tuffaceous compositions, tuff beds are not observed in the unit, indicating lack of syn-depositional volcanism during its deposition.

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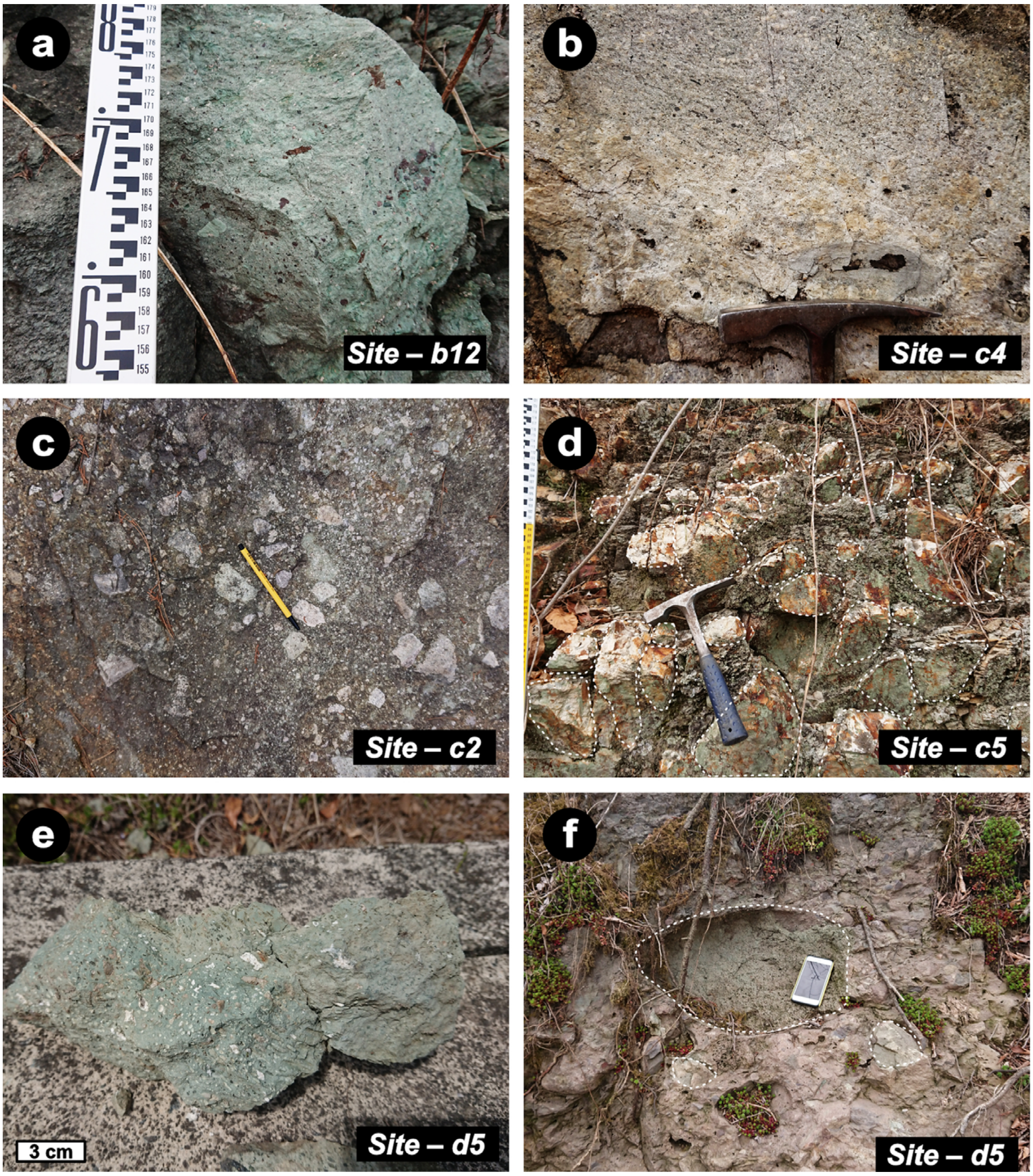

Fig. 7. Examples of the thickly amalgamated tuff beds. (a) Massive, greenish lapilli-tuff from the 1st amalgamated tuff beds (the Manwolsan Tuff). (b) Welded lapilli-tuff from the upper part of the 2nd amalgamated tuff beds (the middle Jangdong Tuff). (c) Pebble-size pumice-rich tuff from the middle of the 2nd amalgamated tuff beds. (d) Pebble- to cobble-size pumice-rich tuff from the lower part of the 2nd amalgamated tuff beds. (e) Massive, greenish lapilli-tuff from the 3rd amalgamated tuff beds (the Mudeungsan Tuff). (f) Lapilli-tuff clasts in the disorganized conglomerate of unit IV.

Pyroclastic alluvial plain, thus, might be developed on the south of the studied areas, and the braided streams parallel to the basin axis might transport the reworked tuffaceous sediments from the south. The upsection transitions of the facies association from FA IV to FA III in the central part and from IV to FA II in the northern part indicates that the playa lake environment was gradually contracted during the deposition of the upper part of unit II, with progradation of proximal facies from the north and south.

4.4. Stratigraphic Unit III

Stratigraphic unit III is approximately 200 m thick and shows similar depositional patterns to those of unit II (Figs. 6 and 9). In the central part of the study area, this unit initiates with FA II and show gradual transitions into FA III, indicating another expansion and subsequent contraction of playa lake environments during the deposition. Alluvial fans (FA I) and alluvial plains

(FA II) developed in the northern and southern parts of the study area, respectively. It is interpreted that Unit III sediments were supplied from the north and east.

4.5. Stratigraphic Unit IV

Stratigraphic unit IV occurs in an area adjacent to the eastern basin margin, overlying the thick, extensively distributed tuff beds (the Mudeungsan Tuff). Erosive boundaries at the bottom of unit IV and boulder-size tuff clasts in its conglomerate deposits indicate significant erosion of the underlying amalgamated tuff beds. The upsection transition from the alluvial fan (FA I) to sandflat (FA III) environments (Fig. 6) indicates retrogradation of proximal facies. Paleocurrent data indicate sediment derivation from the east.

5. DISCUSSION

5.1. Basin Development of the Neungju Basin

According to the stratigraphic changes in unit development of the Neungju Basin, the basin evolution can be subdivided into early (unit I), middle (unit II & III), and late (unit IV) stages. During the early stage of basin evolution (unit I), alluvial plain (FA II) deposits accumulated with no major transition in depositional environments or sandbody thickness. This unit may have been deposited under consistency of accommodation generation (Paola et al., 1992; Fidolini et al., 2013) after initial basin formation, with no significant changes in extrinsic factors including tectonics and climate.

During the middle stage, two coarsening-upward sequences (units II & III) were deposited mainly in the central part of the basin, each representing an early expansion of the playa lake environment and later contraction with the progradation of proximal facies from surrounding areas. If the playa lake of the Neungju Basin was under balanced-filled or underfilled conditions (sensu stricto in Carroll and Bohacs, 1999) due to the prevalence of semi-arid climate conditions in the Korean Peninsula during the late Cretaceous (Paik et al., 2012), the expansion and contraction of the playa lake could be mainly due to climatic fluctuations. The abrupt expansion of lacustrine environments at the bases of stratigraphic units II and III, however, are more likely to be caused by rapid basin subsidence rather than a gradual transition from dry to wet climate conditions. The deposition of fine-grained, distal facies during the early stage and the subsequent, gradual coarsening with progradation of proximal facies are highly similar to tectonically induced stratigraphic units (or sequences) in extensional basins (e.g., Frostick and Steel, 1993; Martins-Neto and Catuneanu, 2010), suggesting that each of these units represents a tectonic pulse comprising an early stage of rapid generation of accommodation space due to basin subsidence and a later stage of gradual filling. Basin subsidence may have been focused on the central and northern parts of the study area, resulting in the preferential development of playa lake environments in these regions. With possible increased sediment supply from the southern pyroclastic alluvial plain, the playa lake environments may not have expanded to the southern part of the study area. The deposition of thick amalgamated tuff beds before the two lake expansion events suggests that volcanism was closely associated with basin subsidence during the development of the Neungju Basin. Basin subsidence may have been sufficiently intensified coincidently with volcanism to compensate the abrupt input of volcanism-driven sediments.

In the later stage (unit IV), the depositional environments changed from the alluvial fan (FA I) to sandflat (FA III) environments. Such stratigraphic variation is common in proximal alluvial environments where source area uplift is the primary control on the development of sedimentary successions (e.g., Hadlari and Rainbird, 2006). Such a fining-upward, retrograding trend would have been produced by a gradual decrease in sediment supply and slope-gradient during denudation of uplifted source areas (Paola et al., 1992; Catuneanu and Elango, 2001). The hectometer-thick amalgamated tuff beds (the Mudeungsan Tuff) below unit IV indicate that a significant amount of volcanogenic sediments was supplied to the basin. The accommodation space generated by basin subsidence related to volcanism might be significantly reduced, resulting in the deposition of unit IV primarily controlled by source area uplift in contrast to the unit II & III.

5.2. Syn-eruption Versus Inter-eruption Sedimentation

The characteristics of sedimentary environments near active volcanoes were reviewed by Smith (1991). Two different conditions of sedimentation may occur in response to volcanism. During the syn-eruption period, a large amount of volcaniclastic debris is supplied as floods and debris-flows, resulting in vertical aggradation of laterally extensive sheet-like volcaniclastic deposits. During the inter-eruption period, in contrast, volcaniclastic input is significantly diminished, and normal streamflow channels are developed, resulting in incision and deposition of channel conglomerates. Erosional surfaces and paleosols are developed during this period, bounding the top of previous syn-eruption deposits. The facies geometry may also differ in response to basin subsidence (Smith, 1991). If basin subsidence is not sufficient to compensate the volcaniclastic sediment supply, deeply incised valleys will develop along the erosional surface during the inter-eruption period, with no or minor deposition of inter-eruption deposits (type 1). If basin subsidence matches or exceeds

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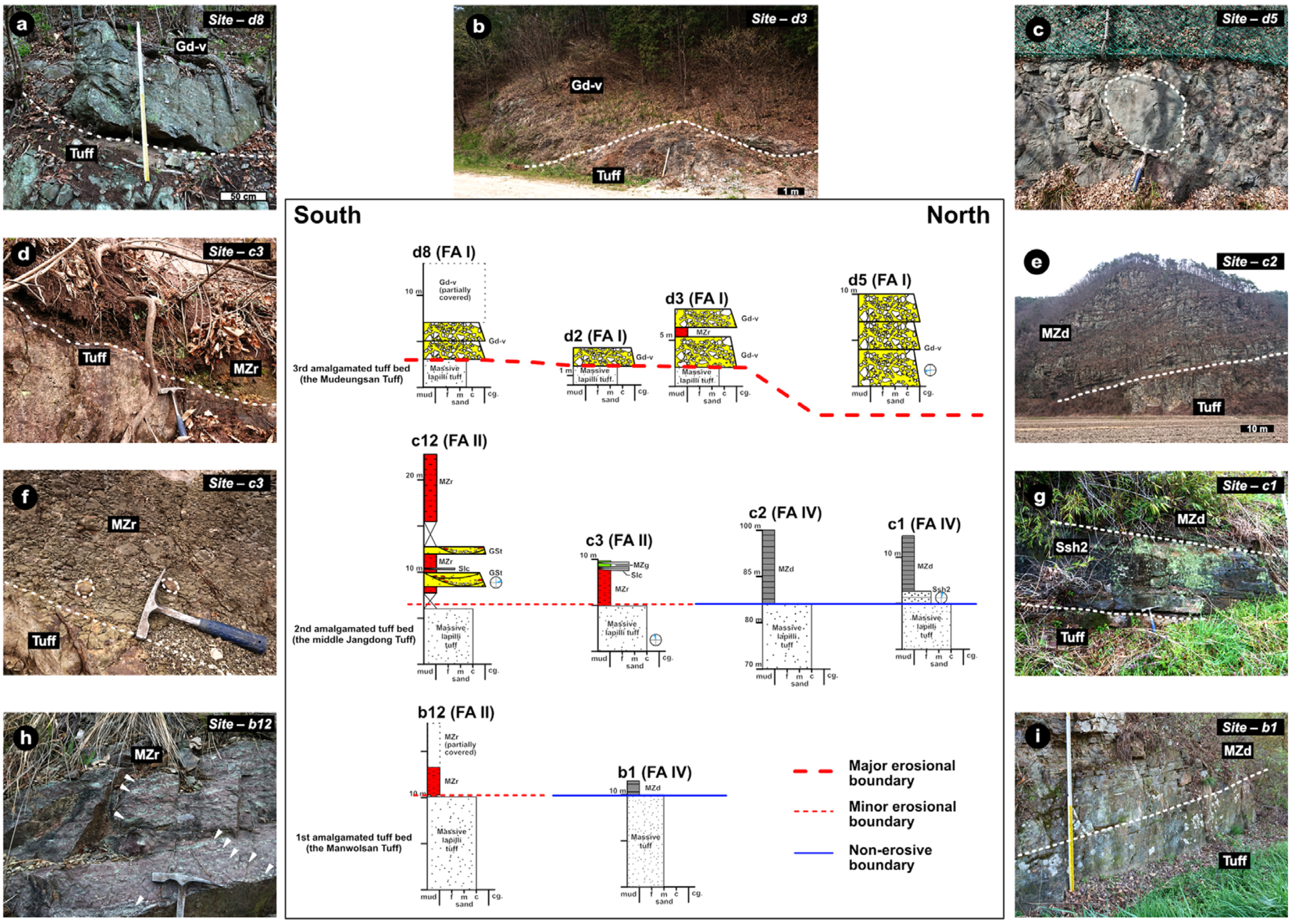

Fig. 8. Characteristics of the top of the thickly amalgamated tuff beds and outcrop photographs. (a and b) The disorganized conglomerate erosively overlying the 3rd amalgamated tuff beds (the Mudeungsan Tuff). (c) Boulder-size clasts of the 3rd amalgamated tuff beds in the overlying disorganized conglomerates, indicating significant erosion of the tuff beds below. (d) Minor erosion at the top of the 2nd amalgamated tuff beds (the middle Jangdong Tuff). (e) Marginal playa lake deposits (MZd facies) non-erosively overlying the 2nd amalgamated tuff beds. (f) Carbonate nodules in reddish siltstone to mudstone facies, few cm above the tuff beds. (g) Non-erosive boundary between Ssh2 facies and the underlying tuff beds. (h) Pebble-size angular tuff clasts (white arrows) in reddish siltstone to mudstones. Approximately 1 m above the underlying tuff beds, indicating minor erosion. (i) Non-erosive boundary between MZd facies and the underlying tuff beds.

volcaniclastic input, inter-eruption channel conglomerates will be partially preserved within incised channels (type 2a) or extend laterally as sheet-like morphologies (type 2b).

The deposition of the stratigraphic units and the amalgamated tuff beds observed in the Neungju Basin may be referred to as inter-eruption and syneruption deposits, respectively. The conglomerates (Gd) of unit IV erosively overlie the amalgamated tuff beds (Figs. 8a–c), resembling the depositional model by Smith (1991). In contrast, units II and III show regional variations in depositional patterns. In the central and northern parts of the study area, units II and III conformably overly the amalgamated tuff beds below. In the southern part, on the other hand, minor erosional surfaces were formed at their bottoms with development of paleosols in some outcrops. As discussed above, significant input of volcanism-driven sediments prior to the deposition of unit IV may have reduced the accommodation space, resulting in the development of an erosional boundary between unit IV and the amalgamated tuff beds, as shown in the depositional model by Smith (1991). The accommodation space, in contrast, might not be fully reduced before the deposition of units II & III, resulting in conformable deposition of distal, inter-eruption deposits over syn-eruption tuff beds in the central to northern parts.

6. CONCLUSIONS

The facies analysis from the northern part of the Neungju Basin reveals that the basin fill is composed of alluvial to lacustrine facies associations. These facies associations represent the deposition of (1) alluvial fan; (2) alluvial plain; (3) sandflat; and (4) marginal playa lake environments. The basin fill can be subdivided into four hectometer-scale stratigraphic units by thickly amalgamated

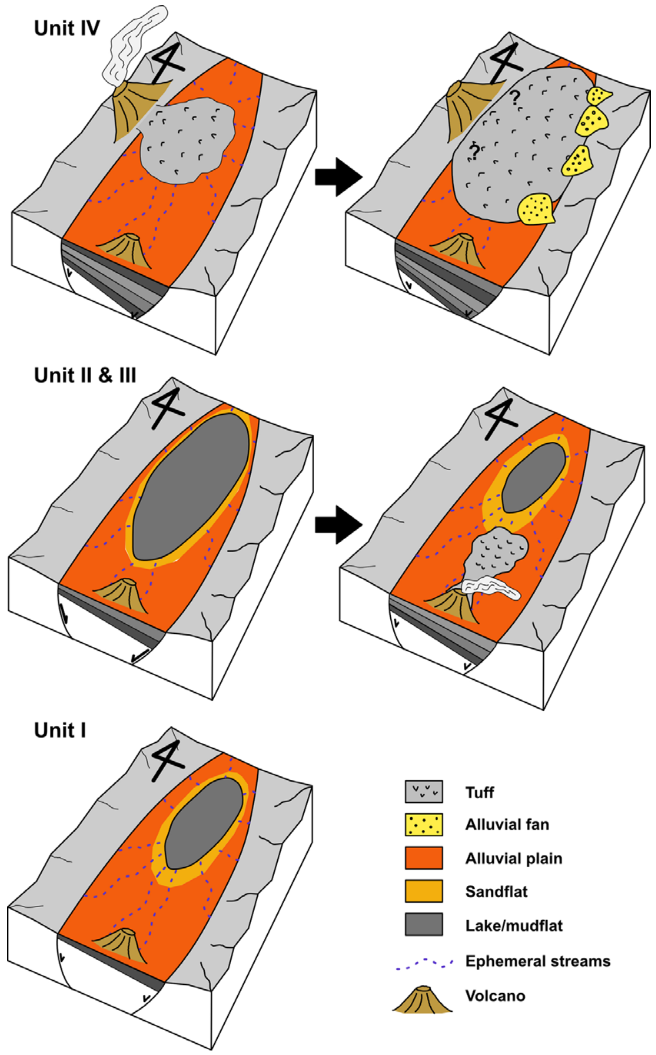

Fig. 9. Depositional model illustrating the paleoenvironmental evolution of the Neungju Basin in the study area.

tuff beds. During the early stage (unit I) of basin development, an alluvial plain developed in the western part of the basin. During the middle stage (unit II & III), two coarsening-upward sequences were deposited mainly in the central part of the basin, each representing earlier expansion of a playa lake environment and later contraction with progradation of proximal facies from surrounding areas. Finally, during the late stage, alluvial fans developed near the eastern basin margin and changed into sandflat environments.

Volcanism and tectonism may have been closely associated, influencing on the development of the Neungju basin. Two lake expansion events were possibly caused by intensified basin subsidence associated with volcanism, leading to the development of two coarsening-upward sequences in the central part of the basin. In contrast, significant input of volcanogenic sediment before the development of unit IV may have reduced the accommodation space that was generated by basin subsidence being coeval with volcanism, resulting in the development of the fining-upward, retrograding depositional trend observed in unit IV.

This study provides insight into a variable relationship between syn-eruptional and inter-eruptional deposits. If volcanism-driven sediment supply during the syn-eruption period is sufficient to reduce the accommodation space, an erosional surface will be formed at the lower boundary of the inter-eruptional deposits, as depicted by the traditional depositional model by Smith (1991). If basin subsidence exceeds the volcanism-driven sediment supply, a conformable surface will be formed at the lower boundary of inter-eruptional deposits.

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