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Development of a streamflow-dominated alluvial-fan system in the southwestern margin of Gyeongsang Basin (Lower Cretaceous): implications for initial basin-fill history

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ABSTRACT: This paper focuses on the initial basin-fill processes in an extensional nonmarine back-arc basin. Sedimentary facies analysis in the southwestern part of the Gyeongsang Basin (Jinju Subbasin), Hapcheon area reveals that the succession consists of four facies assemblages. The assemblage I mainly consists of disorganized conglomerate deposited by flash floods in a streamflow-dominated alluvial fan. The assemblage II is dominated by stratified conglomerates and massive, stratified, and cross-stratified sandstones, showing architecture of stacked channels and bars. The assemblage III largely comprises massive, stratified to laminated, and trough cross-stratified sandstones, which are organized into channel-fill and bar-accretion structures. It most likely formed in sandy sinuous rivers. The assemblage IV comprises gray mudstone interlayered with fine sandstone, representing water-logged floodplains. Conglomerate and sandstone bodies formed in the fluvial systems appear to be randomly distributed within floodplain fines, displaying a great lateral and vertical lithologic variation. This study helps understand the complexity of basin-fill history, i.e., switching of fluvial networks in time and space, in contrast to the simple notion of margin-parallel stacking of lithostratigraphic units.

Key words: alluvial fan, fluvial system, nonmarine deposit, Gyeongsang Basin, Hapcheon area

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1. INTRODUCTION

In the southwestern margin of the Cretaceous Gyeongsang Basin, i.e., Jinju Subbasin (Fig. 1), sedimentary strata largely comprise conglomerate and sandstone bodies as well as mudstone immediately above igneous and metamorphic basement rocks. Earlier studies (Chang, 1975, 1977; Kim et al., 1998) have shown that the basin fills in this region comprise vertically stacked “formation” units. In practice, however, recognition of the supposed formation boundaries is implausible; each presumed formation unit retains similar lithologic characteristics in which the boundary is drawn at an arbitrary bounding surface (e.g., Kim et al., 2018). These formation units were based on simple notion of stratigraphic stacking order, which caused further ambiguity in regional geological mapping and depositional modeling.

The ill-defined lithostratigraphy of the Gyeongsang Supergroup mainly stems from poor understanding of non-marine depositional processes. Nonmarine deposits exhibit strong lateral facies variability; multiple fluvial systems change their locations across the alluvial plains. In addition, discrete alluvial-fan systems make it more complex in the basin-margin. Depositional systems changes in response to regional tectonics and climate changes, resulting in stratigraphic variations in architecture (Heller and Paola, 1996; Martinsen et al., 1999; Jo, 2003; McLaurin and Steel, 2007; Allen et al., 2013). At high rates of sediment supply with respect to subsidence rates, however, autocyclic processes prevail in depositional systems, blurring allocyclic stratigraphic signatures (Hickson et al., 2005). An understanding of basin-fill history thus requires delineation and characterization of depositional

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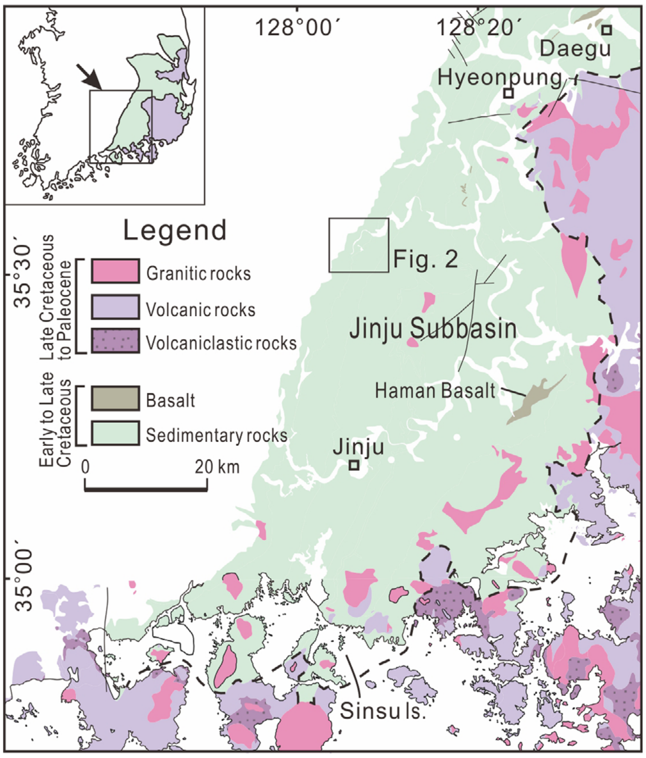

Fig. 1. Simplified geologic map of the southwestern Gyeongsang Basin (Jinju Subbasin) (modified after Chough and Sohn, 2010).

systems, which warrants a detailed sedimentological analysis. Sedimentary facies and their assemblage provide an important criterion for characterization of alluvial and fluvial systems (Miall, 1985, 1996; Jo and Chough, 2001; Jo, 2003).

This study focuses on the depositional systems in the Hapcheon area in order to understand basin-fill history in an unconformable extensional basin margin (Fig. 1). Based on sedimentary facies and architecture of scattered conglomerate and sandstone bodies in various road- and stream-cut sections, the strata are grouped into a number of facies assemblages (or architectural elements). Each assemblage represents a depositional system or part of a system, formed by a suit of depositional processes. The spatial relationships among the assemblages lead to a new avenue for the understanding of complex depositional systems in the western margin of the Jinju Subbasin, which was a passively-subsiding, low-gradient margin and received relatively large amount of sediment. These results also help evaluate the validity of the disguised lithostratigraphic nomenclature which has been used for the past 50 years.

2. GEOLOGICAL SETTING

The Gyeongsang Basin consists of thick nonmarine sedimentary and volcanic deposits accumulated during the Cretaceous (Chang, 1975). The basin constitutes a continental back-arc system, formed by an extension of the Japanese Arc in the early Cretaceous (Chough and Sohn, 2010). The basin comprises three subbasins: Jinju Subbasin in the southwest, Uiseong Subbasin in the north, and Yeongyang Subbasin in the northeast (Fig. 1). The occurrence of terrestrial and nonmarine fossils (Yang, 1976, 1982; Choi, 1990; Kim et al., 2008) and calcareous paleosols (Paik and Lee, 1998; Paik et al., 2001, 2007) indicate that the basin developed in a continental area under semiarid climatic conditions. Sedimentary strata in the southwestern part of the basin (Jinju Subbasin) represent initial sedimentation, unconformably overlying the basement, in response to eastward extensional opening of the basin. The strata generally dip eastward to southeastward at low angles. Chang (1975, 1977) and Kim et al. (1998) established seven formations (Nakdong, Hasandong, Jinju, Chilgok, Shilla Conglomerate, Haman, and Jindong formations in ascending order), based on the supposed recognition of varying proportions of conglomerate, sandstone, and mudstone. Numerous studies have followed this scheme for regional mapping of sedimentary strata and constraining depositional models, including those of the volcanic arc region (refer to Chough and Sohn, 2010 for a summary). However, the formation boundaries have been arbitrarily drawn at the changes in varying lithofacies proportion and color (purple to dark gray mudrocks); the established lithostratigraphic column of formations thus resembles tilted layers stacked one after another eastward. These formations were generally interpreted as time-transitional strata of alluvial, fluvial, or lacustrine deposits eastward (Choi, 1986).

The eastward dipping strata (5–10 degrees) are, in fact, discontinuous in outcrop sections a few tens to hundreds of meters distance. The seemingly continuous beds, showing the inclined depositional surface, are thus unmappable. Instead, the strata are wedged in both downstream and lateral directions, in which precise correlation of individual beds is implausible. For these reasons, the traditional lithostratigraphic boundaries, based on assumed bed-by-bed correlation of arbitrary lithologic variations and color change, are invalid and have rather hampered to envision the complexity of lithologic variations in time and space.

3. STUDY METHODS

This study is mainly based on geologic mapping and sedimentary facies analysis of scattered outcrop sections in the Hapcheon area (Fig. 2). It constitutes sedimentological measurements, including sketches of outcrop sections, columnar description of sedimentary characteristics, and measurements of paleoflow directions. These characteristics are commonly grouped as a facies association: a group of sedimentary facies that are genetically related to one another and have some environmental

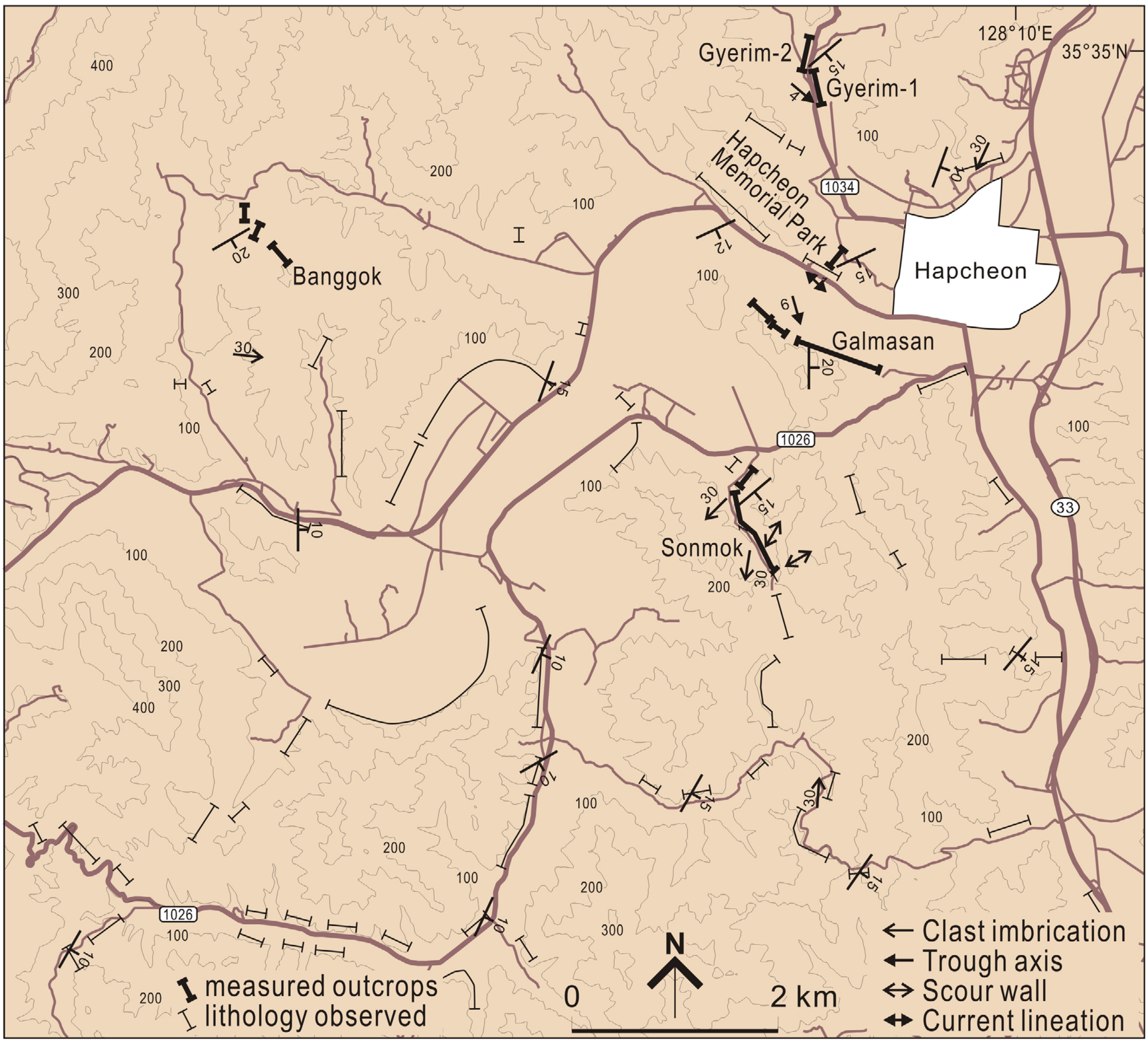

Fig. 2. Simplified map of section locations. Paleoflow directions (arrows), measured from clast imbrication, trough cross-bedding, scour walls, and current lineation, are also marked with measurement numbers.

significance (Collinson, 1969). In addition, on the basis of a distinctive bed geometry and facies assemblage, these attributes are collectively designated as architectural elements, which are related to the main geomorphic elements such as channels, bars, and floodplains of depositional systems (Miall, 1985; Brierley, 1996; Jo, 2003). Based on sedimentary facies and depositional architecture, the outcrop sections in the study area are grouped into four facies assemblages (or architectural elements), each of which is the product of a particular suit of processes in a depositional system.

4. FACIES ASSEMBLAGES

The facies assemblages in the Hapcheon area are defined on the basis of sedimentary facies and depositional architecture. Individual lithofacies are described and interpreted based on sedimentary structures and texture (Table 1). Depositional processes at channel-bar scale are interpreted from the architecture of strata combined with their sedimentary facies. In the following, the individual assemblages are described in six measured sections (Fig. 2).

4.1. Facies Assemblage I: Alluvial Fan Apex

This assemblage consists of conglomerate and sandstone with minor amount of mudstone (Fig. 3). It occurs in the Banggok-ri area adjacent to the basin margin, overlying unconformably the granitic rocks. The conglomerate is mostly clast-supported and

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Table 1. Description and interpretation of sedimentary facies

Facies	Description	Interpretation
Disorganized conglomerate (Cd)	Clast-supported; pebble to boulder-grade gravels; disorganized to poorly organized gravel fabric; crude stratification in amalgamated beds	Gravel sheets and bars deposited by high-magnitude flood flows
Organized conglomerate (Co)	Clast-supported; pebble to cobble-grade gravels; imbricated gravel fabric; commonly stratified	Gravel sheets and bars formed by grain-by-grain bedload deposition
Crudely cross-stratified conglomerate (Cx)	Crudely stratified	Gravel bars
Massive (gravelly) sandstone (Sm)	Structureless; very fine to very coarse-grained sandstone and pebbly sandstone; mudstone clasts in some units; partly stratified	Rapid suspension settling from heavily sand-laden flows
Stratified (gravelly) sandstone (Ss)	Medium to very coarse-grained sandstone and pebbly sandstone; pebbles at the base and aligned along stratification	Upper plane-bed deposition
Trough cross-stratified sandstone (St)	Medium to very coarse-grained sandstone and pebbly sandstone; occasionally containing mudstone clasts; several to decimeters thick sets	3-D dunes or filling of scour hollows
Planar cross-stratified sandstone (Sp)	Medium to very coarse-grained sandstone pebbly sandstone; pebbles and mudstone clasts in some units; a few decimeters thick sets	2-D dunes or longitudinal and transverse bars with slipface
Parallel-laminated sandstone (Sl)	Very fine to coarse-grained sandstone; parallel to low-angle lamination	Upper or lower plane-bed deposition
Ripple cross-laminated sandstone (Sr)	Very fine to medium-grained sandstone; set thickness of less than a few cm	2-D and 3-D ripples
Gray mudstone (Mg)	Homogeneous or laminated; dark gray and greenish gray; some units, sandy; calcareous nodules; plant debris	Suspension settling from weak currents or standing water; post-depositional carbonate precipitation and graying under reducing condition
Purple mudstone (Mp)	Homogeneous; dark reddish brown and grayish red; calcareous nodules	Suspension settling from weak currents; post-depositional carbonate precipitation and reddening under oxidizing condition

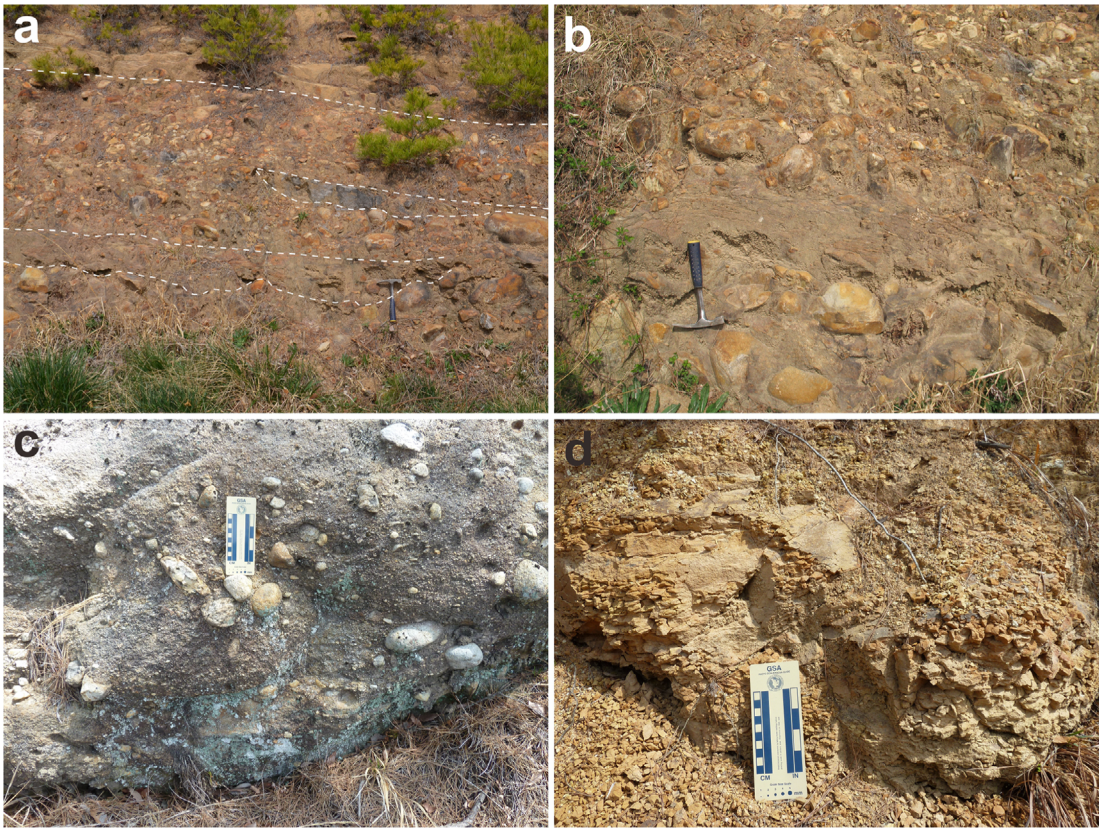

Fig. 3. Photographs of facies assemblage I, Banggok section. (a) Disorganized, bouldery conglomerate beds intervened with lenticular or wedge-shaped sandstone beds (white dashed lines). (b) Close-up view of bouldery conglomerates and an intervening sandstone bed. Hammer (28 cm long) for scale. (c) Massive to crudely stratified, gravelly sandstone. (d) Gray mudstone intercalated within assemblage I.

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disorganized to poorly organized (Fig. 3a). The clasts comprise well-rounded, pebble to boulder-grade gravels (up to 60 cm in diameter) of granite with subordinate amount of quartzite pebbles. The conglomerate beds are decimeters to several meters thick, intervened by thin (20–30 cm thick) lenticular or wedge-shaped sandstone beds. Thick, amalgamated conglomerate beds occasionally show crude stratification by variations in clast-size (Fig. 3b). This assemblage is dominated in the upper part by coarse-grained and gravelly sandstones interbedded with relatively thin conglomerate beds (Fig. 3c). The sandstones are commonly massive and crudely stratified, underlain by thin gravel layers at the base. Thin gray mudstone beds are occasionally interbedded with sandstone beds (Fig. 3d).

The clast-supported, disorganized conglomerate is interpreted as the products of rapid deposition of highly concentrated gravels by flash floods (Todd, 1989, 1996; Jo et al., 1997). The interbedded sandstone lenses and wedges represent the deposits of waning flood flows, preferentially deposited and preserved in low areas among the gravel deposits or bars. The massive structure and crude stratification of sandstones are suggestive of rapid settling and subsequent bedload transport of sand grains during waning flows (Arnott and Hand, 1989; Jo et al., 1997). This assemblage represents a streamflow-dominated alluvial fan, which formed at the major outlet of the drainage basin of the western highland in the Banggok-ri area. Gravel-grade clasts were mostly supplied from the adjacent granite basement rocks. The sandstone-dominated upper part is suggestive of a retreat of gravel deposits, representing long-term decrease in slope gradient of the feeding valleys with increasing drainage area.

4.2. Facies Assemblage II: Gravelly to Sandy Braided Streams

This assemblage comprises stratified conglomerate and sandstone with minor amount of gray mudstone. It occurs in Galmasan and Sonmok sections (Fig. 2). The conglomerate is clast-supported and dominantly pebble-grade with organized gravel fabric (Fig. 4). Some conglomerate layers are pebble to

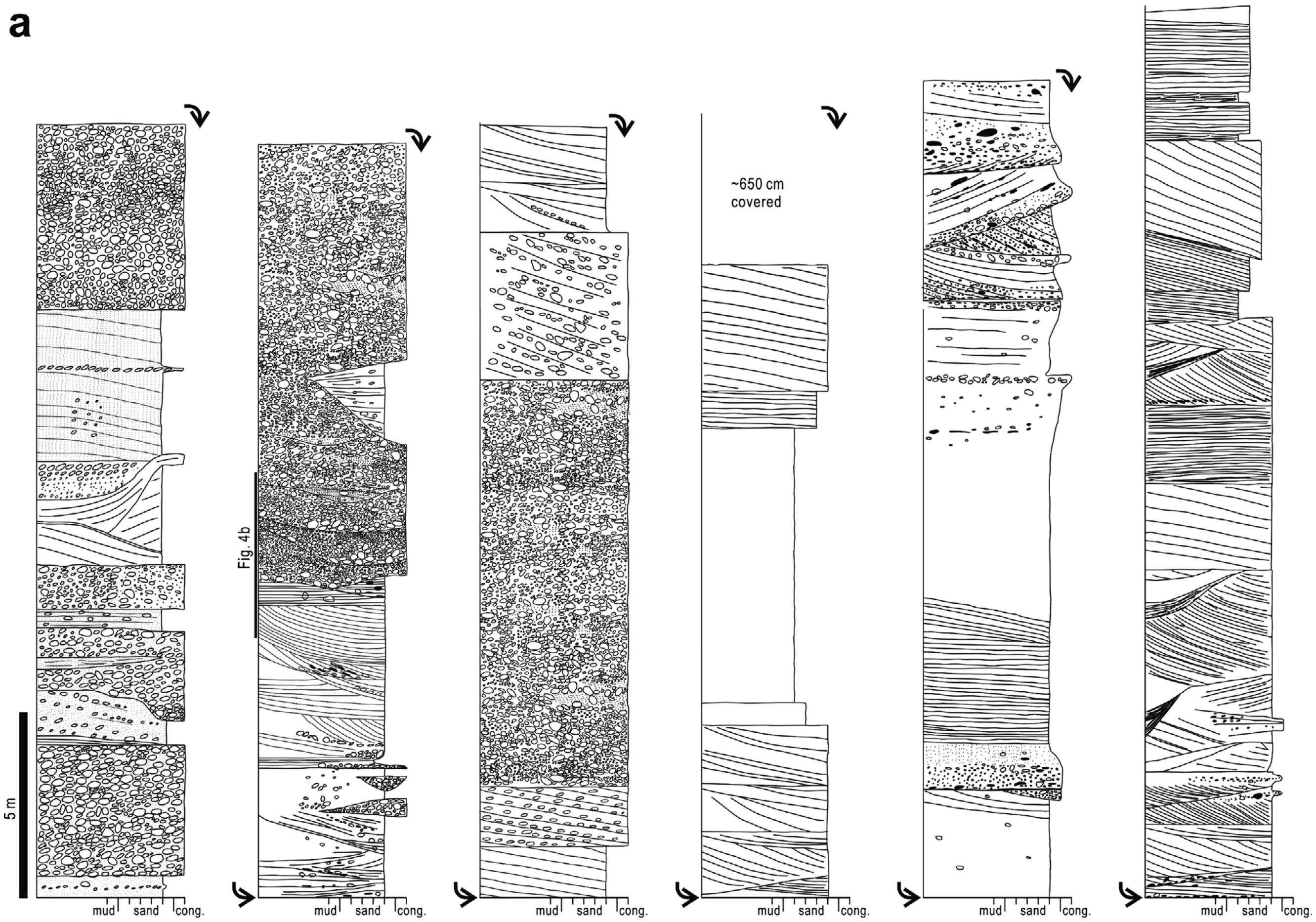

Fig. 4. Facies assemblage II in Sonmok section. (a) Columnar description of assemblages II (lower, conglomeratic) and III (upper, sandy). (b) Line drawing of conglomerate and sandstone bodies. Stacked conglomerate beds are demarcated by erosional surfaces and intervening sandstone wedges and lenses. The sandstone body in the lower part is dominated by trough cross-stratification and scour fills. (c) Close-up view of stratified conglomerate. Hammer (28 cm long) for scale. (d) Trough cross-stratified sandstone interbedded within conglomerate beds.

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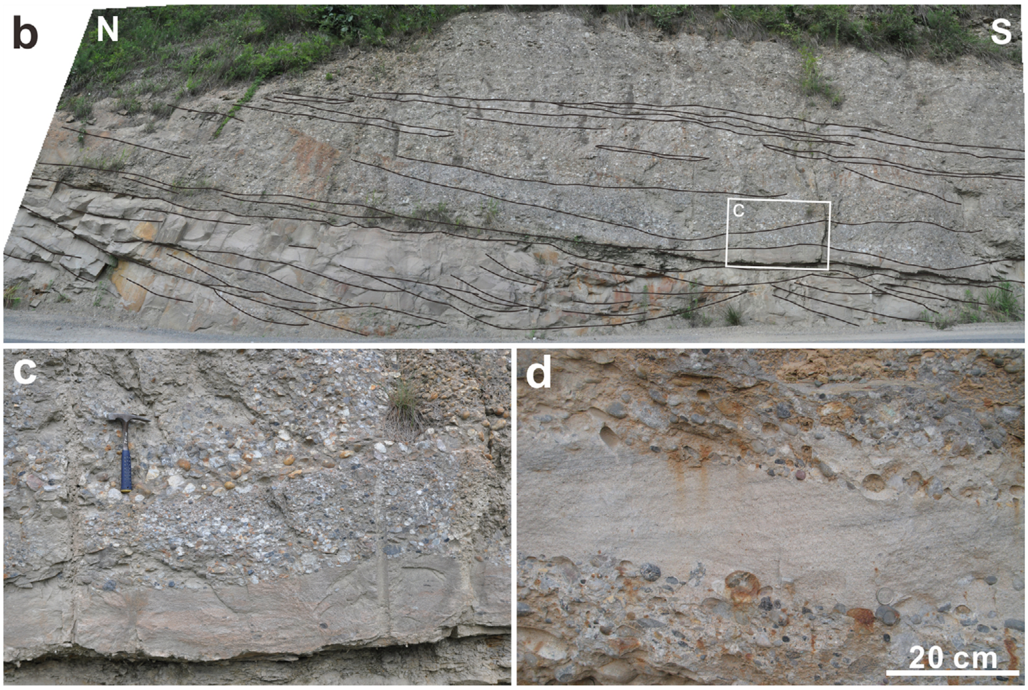

Fig. 4. (continued).

cobble grade. Alternation of pebble and cobble-rich layers gives rise to crude stratification (Fig. 4c). Clasts are mainly composed of well-rounded quartzite with subordinate amount of granite, pelite, and schist. They are commonly imbricated. The matrix consists of medium to coarse-grained sandstone. Sandstone is medium-to-coarse-grained and occasionally contains pebbles. It is either stratified, planar and trough cross-stratified, or massive (Fig. 4d). Sandstone beds are commonly interlayered with conglomerate, thus lenticular or wedge-shaped (Fig. 4b). About 50-m-thick succession consisting of stacked conglomerate interbedded with thin sandstone layers occurs in Sonmok section, showing internal erosional surfaces (Figs. 4a and b). The upper part of this unit is dominated by sandstone. In Galmasan section, ca. 10-m-thick sandstone body with an erosional base overlies gray mudstone (Fig. 5). The lowermost part of this body is characterized by multiple scour fills with E-W axis orientations. The scours are mostly filled with trough cross-stratified, medium-to-coarse-grained sandstone, pebbly sandstone, and mudstone-clast-rich sandstone (Fig. 5b). The middle part comprises stacked sets of planar cross-stratified, pebble-bearing sandstone (Fig. 5c). The upper part of this body consists of horizontally bedded sandstone.

The clast-supported, stratified conglomerate is interpreted as bedload deposits in gravel-bed channels and bars (Boothroyd and Ashley, 1975; Hein and Walker, 1977, Nemec and Postma, 1993). The thin sandstone interbeds are interpreted as the deposits of waning flood flows. The thick conglomeratic succession with internal erosional bounding surfaces most likely represents

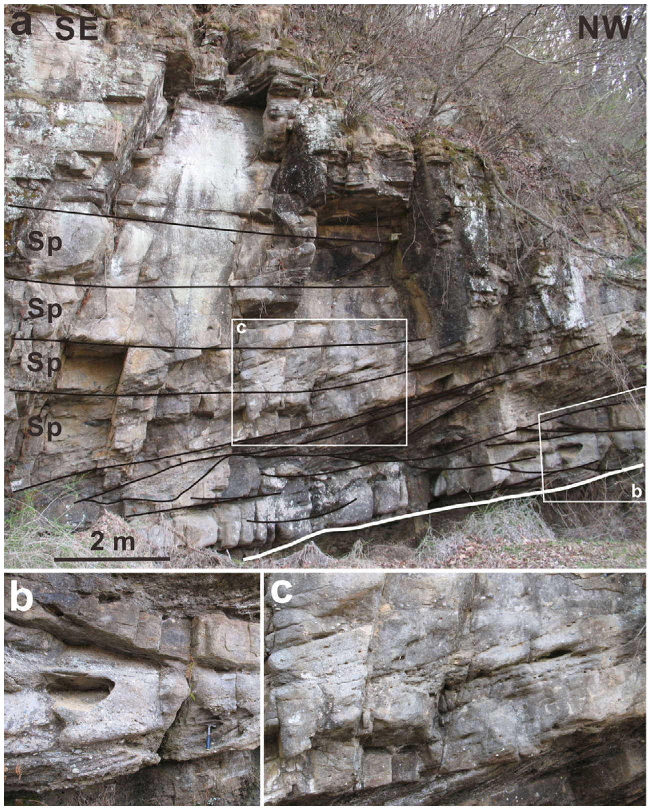

Fig. 5. Facies assemblage II in Galmasan section. (a) Line drawing of a sandstone body (ca. 10 m thick) with an erosional base (thick white line), overlying gray mudstone beds. The sandstone body comprises scour fills and trough cross-stratified sandstone, stacked sets of planar cross-stratified sandstone (Sp), and plane-bedded sandstone in ascending order. (b) A close-up view of trough cross-stratified sandstone and scour-fills in the lower part. Hammer (33 cm long) for scale. (c) A close-up view of planar cross-stratified, pebble-bearing sandstone beds.

stacked channels and bars, which moved frequently in gravel-bed braided streams. The basal scour fills and the overlying planar cross-stratified sets in the sandstone body are interpreted as channel thalweg and sand bars with distinct slip-faces that prograded into channels, respectively (Boothroyd and Ashley, 1975; Miall, 1977; Cant and Walker, 1978; Todd, 1996; McLaurin and Steel, 2007). The horizontally bedded sandstones in the upper part are interpreted as bar-top deposits (Bristow, 1993). They are suggestive of sandy braided streams (Miall, 1977; Cant and Walker, 1978). These characteristics of assemblage II are collectively indicative of gravelly to sandy braided streams.

4.3. Facies Assemblage III: Sandy Sinuous Rivers

This assemblage mainly consists of thick sandstone bodies alternating with dark gray and greenish gray mudstones. The sandstone bodies comprise medium to very coarse-grained sandstones, occasionally containing pebbles, and are several meters to a few tens of meters thick, overlying an erosion surface. In a sandstone body in Gyerim-1 section, an erosional bounding surface is overlain by mudstone-clast-rich layers (several cm thick), which is, in turn, overlain by trough cross-stratified, medium-grained sandstone beds (ca. 2 m thick) (Fig. 6a). The trough sets are decimeters thick and a few meters wide, with an NW-SE axial orientation, i.e., southeastward paleoflows. The trough cross-stratified sandstones are overlain by and transitional updip to low-angle inclined sandstone beds. In Gyerim-2 section, about 100 m north of Gyerim-1 section, a sandstone body shows inclined beds of medium to coarse-grained sandstone, which are commonly demarcated by thin fine sandstone layers with abundant mica flakes (Fig. 6b).

The thick sandstone bodies are interpreted as main channel deposits, based on the erosional bases, great thickness, sedimentary facies, and internal architecture (Jo and Chough, 2001; Jo, 2003). The inclined sandstone beds represent barforms that accreted laterally and downstream (Miall, 1985, 1994; Bridge, 1993). The southwestward-dipping inclined beds with respect to southeastward paleoflows in Gyerim-1 section are interpreted as lateral-accretion architectural element. In Gyerim-2 Section, the beds formed by either lateral or downstream accretion. The inclined beds inter-

Fig. 6. Line drawings of photomosaics, showing the architecture of thick sandstone bodies of facies assemblage III. (a) Gyerim-1 section. Trough cross-stratified sandstone beds are overlain by inclined sandstone beds. Dashed lines in the lowermost part denote mudstone-clast-rich layers, overlying an erosion surface. Inset shows the section orientation (solid line) and the paleoflow direction (arrow) measured from trough cross-stratification. Hammer (33 cm long) for scale. (b) Gyerim-2 section. A sandstone body shows inclined beds, which are commonly demarcated by fine-grained layers with mica flakes.

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bounded by fine-grained layers most likely represent individual flood events. The trough cross-stratified sandstone beds are interpreted as the deposits of 3-D dunes and scour-fillings in channels. The channel deposits were laterally transitional to and overlain by the bar deposits as the barforms migrated into the channels. The large bar structures showing lateral accretion suggest that the rivers were more or less sinuous. The bar accretion over multiple flood events and lack of significant erosion within bar-accretion deposits are suggestive of relatively perennial discharges.

4.4. Facies Assemblage IV: Water-logged Floodplain

This assemblage consists of grayish mudstone and thin sandstone beds, up to 40 m thick. The mudstone is medium dark gray to black in color. It is largely homogeneous and laminated (Fig. 7). Calcareous nodules and plant debris are commonly present. The mudstone is locally purple in color, especially adjacent to the western basin margin. The sandstone is very fine to medium-grained and mostly grayish (medium light gray). It is massive, laminated, or cross-laminated (Fig. 7b). It occurs as either thin beds (a few cm thick) interbedded with mudstone beds or thin lenticular bodies (< 1 m thick), extending laterally a few tens of meters.

The grayish mudstones are interpreted as the deposits of water-logged floodplains of reducing conditions, where small ponds and lakes might have developed (Mack and James, 1992; Retallack, 1997). The purple mudstones are suggestive of well-drained alluvial plains of oxidizing conditions (Mack and James, 1992; Retallack, 1997). The floodplains in the study area were mostly water-logged and locally well-drained in relatively higher plains on the western margin. The thin sandstone beds and bodies represent sand sheets and crevasse splays and channels on the floodplains (Jo and Chough, 2001; Jo, 2003). Pedogenic modification probably occurred in the floodplain deposits, producing calcareous nodules (Wright and Tucker, 1991; Retallack, 1997).

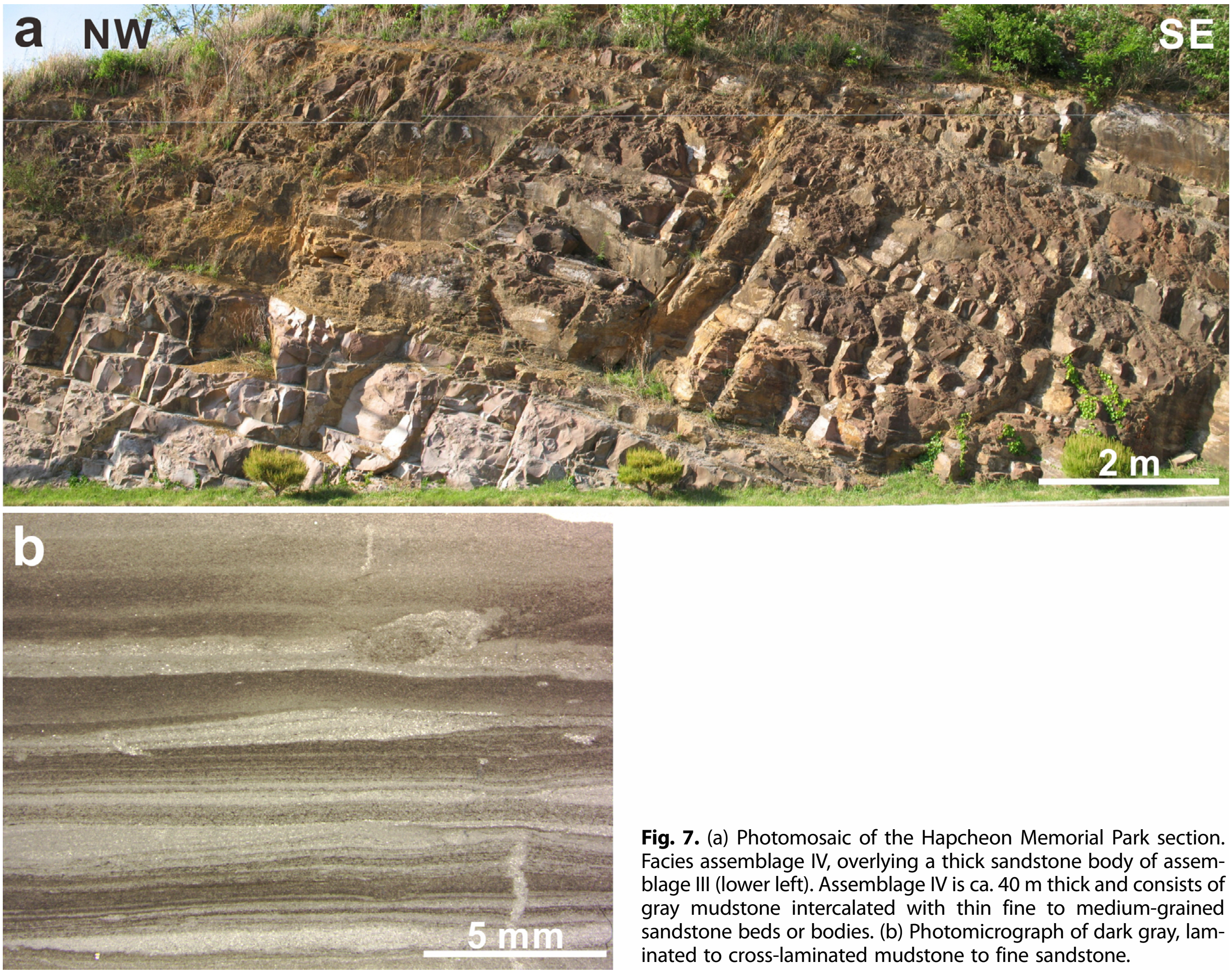

Fig. 7. (a) Photomosaic of the Hapcheon Memorial Park section. Facies assemblage IV, overlying a thick sandstone body of assemblage III (lower left). Assemblage IV is ca. 40 m thick and consists of gray mudstone intercalated with thin fine to medium-grained sandstone beds or bodies. (b) Photomicrograph of dark gray, laminated to cross-laminated mudstone to fine sandstone.

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5. DEVELOPMENT OF DEPOSITIONAL SYSTEM

The facies assemblage I suggests that a streamflow-dominated alluvial fan initiated in the early Cretaceous in response to extensional subsidence of the basin. The fan originated from an outlet (Banggok-ri area) of a large drainage basin in the western highlands, including Precambrian gneiss and quartzite as well as granites (mainly Jurassic) (Fig. 8). It formed a generally radial pattern, delivering large amounts of sediments across the basin with ensued subsidence. Bouldery conglomerates formed by rapid deposition from flash floods, interlayered with gravelly sandstone and gray mudstone layers in the waning stages. The alluvial fan, here named the Hapcheon Alluvial Fan, would have been one of the most important depositional systems for the supply of sediments in the western margin of the subbasin for a few to tens of millions of years. Further eastwards, assemblages II and III are suggestive of downstream fluvial systems including gravelly braided streams and more sinuous sandy rivers. These

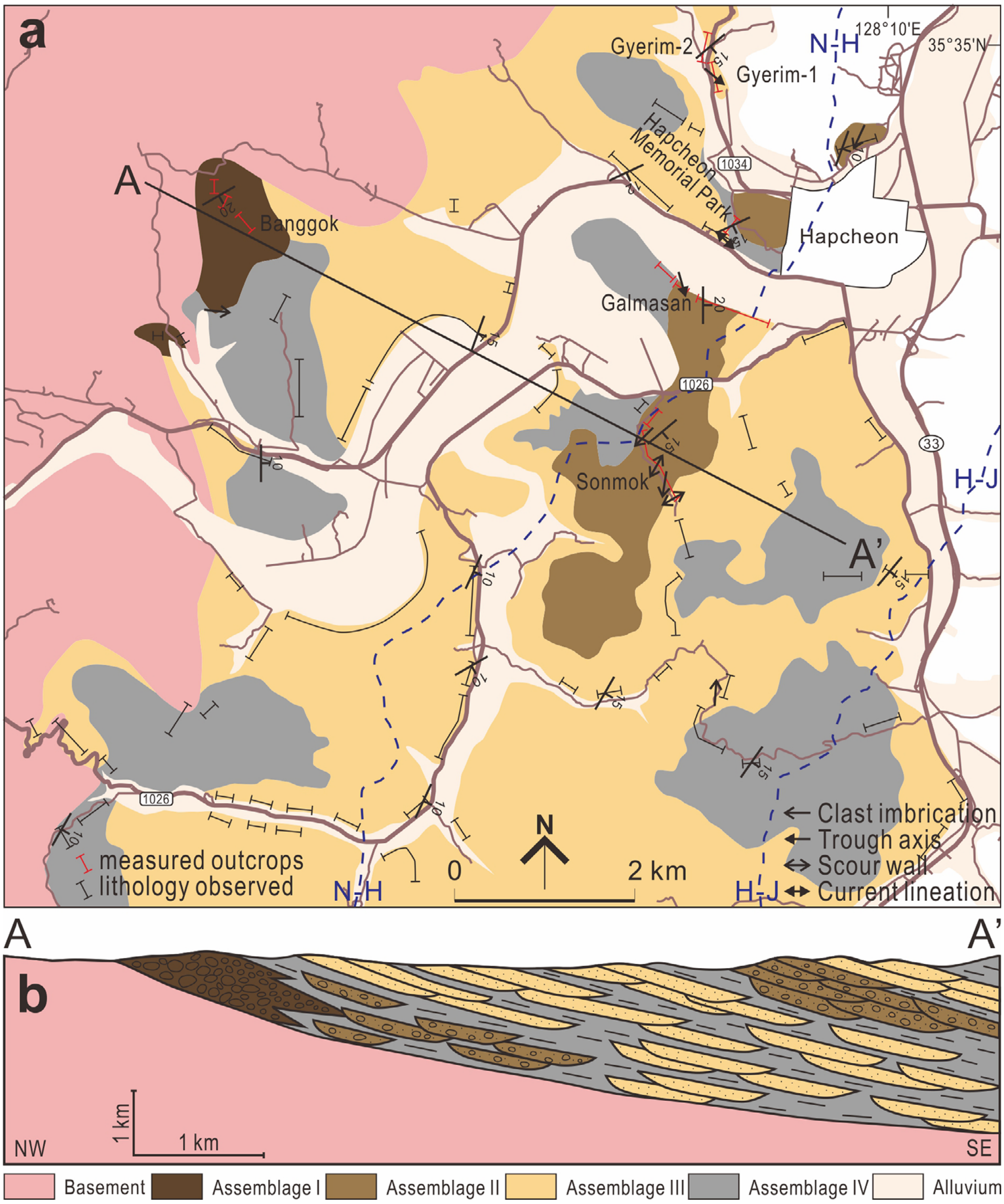

Fig. 8. (a) Distribution of facies assemblages in the Hapcheon area. Note that the supposed formational boundaries (dashed lines) between the Nakdong and Hasandong formations (line N-H) as well as the Hasandong and Jinju formations (line H–J) are not in accordance with lithologic distribution. Arrows denote paleoflow directions. (b) A schematic cross-section with constituent facies assemblages.

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fluvial channels moved across wide alluvial plains and produced randomly distributed, stratified conglomerate and sandstone bodies within background floodplain fines (Fig. 8). The alluvial surface formed generally water-logged floodplains (assemblage IV), as represented by interlayered gray mudstone beds.

6. DISCUSSION

Accommodation in tectonically active basin margin is commonly created by relative magnitude of subsidence by fault movement. Alluvial fans and fan-deltas at the base of the fault are commonly steep in slope gradient and build small-scale depositional systems. Sedimentation rates of sediment-fill depend, however, on the factors such as subsidence rates in the basin area and production of sediments in the drainage area under the prevailing climate conditions. On the other hand, accommodation in tectonically inactive basin margins is created by passive extensional subsidence. On a low-gradient slope, alluvial fans commonly develop into large-scale fluvial systems, depending on drainage-basin area and the caliber of sediment supply from the hinterlands.

The continental back-arc basin of the Gyeongsang Basin was extensional in origin (Chough and Sohn, 2010). It contains depositional systems of both active and inactive basin margins. In the northern margin, the basin was bounded by active faults and formed a series of fault-bounded overlapping alluvial fans and fluvial systems, where sedimentation and resultant stratigraphy were primarily controlled by tectonic movements (Jo et al., 1997; Rhee et al., 1997; Jo, 2003). In the western part of the Gyeongsang Basin, i.e., Jinju Subbasin, however, the basin margin was devoid of bounding faults. The sedimentary strata are generally undeformed, consistently dipping east to southeastward at low angles, unconformably overlying the basement. The general eastward tilting of the basin was due to slow, progressive uplift of the basement in the highlands in concert with denudation as well as relative and progressive subsidence of the basin due to sediment loading (Chough and Sohn, 2010).

New insight into the complexity of lithofacies distribution suggests that individual sandstone bodies are laterally uncorrelated (Fig. 8). The bodies are random in stratigraphic position; the strata are instead characterized by complex array of conglomerate and sandstone bodies with interlayered mudstone beds. The succession in the Jinju Subbasin has long been classified into a number of formation units based on lithology and color and used as criterion for stratigraphic correlation between different subbasins (Chang, 1975, 1977; Kim et al., 1998). However, many workers have had difficulties for the recognition of the supposed formation boundaries and identification of lithosome. A stratigraphic formation is "a body of rock identified by lithologic characteristics and stratigraphic position; it is prevailingly but not necessarily tabular, and is mappable at the Earth's surface or traceable in the subsurface" (Neuendorf et al., 2005). In the Hapcheon area, the two supposed boundaries of the Nakdong, Hasandong, and Jinju formations do not meet the requirement of the definition, where lithologic or color changes are not readily recognized (Fig. 8). For these reasons, the hitherto-used stratigraphic scheme is invalid.

In the passive margins of a continental basin, sediments are delivered by low-gradient streams in the drainage basin and develop low-gradient alluvial fans in the initial stage of basin development. Because of the low connectivity of individual lithofacies units among the outcrop sections, it is virtually implausible to establish facies associations or facies sequences. Instead, we grouped various facies units into facies assemblages. In this scheme, the random occurrence of various conglomerate/sandstone/mudstone can be bracketed, which represents a suit of depositional processes on alluvial plains. Flash floods and stream flows were most likely responsible for the conglomerate and sandstone bodies. In submerged relative lowlands, gray or dark mudstone beds formed, intercalated with sandstone, especially along the basin margin where sediments were least supplied.

7. CONCLUSIONS

A detailed sedimentary facies analysis in the Hapcheon area suggests that the western margin of the Jinju Subbasin was dominated by a streamflow-dominated alluvial fan and fluvial systems, which played a major role for the delivery of large amounts of sediments into the basin during the initial basin-fill stage. The fluvial systems (gravelly braided streams and sandy sinuous rivers), surrounded by water-logged flood plains, resulted in scattered bodies of conglomerate and sandstone within gray mudstone succession. The complex lithofacies distribution in the Hapcheon area invalidates the supposed formation boundaries in the Jinju Subbasin. It warrants a detailed sedimentological study in the Jinju Subbasin and the surrounding volcanic arc region where the previous stratigraphic scheme was applied for geological mapping.

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