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Depositional features and sedimentary facies of steep-faced fan-delta systems: modern and ancient

현생 및 고기 급경사 선상지-삼각주계 퇴적층의 특성과 퇴적상

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Abstract : Alluvial fan delta often extends into deep water, forming steep-faced delta front. Depositional features of modern steep-faced fan-delta slope and prodelta are characterized by slump scar, chute/channel, swale, lobe, splay and debris fall. These features largely originate from sediment failure or sediment-laden underflows (sediment-gravity flows) off river mouth. Sedimentary facies of equivalent ancient systems comprise sheetlike and/or wedged bodies of gravelstone and sandstones, slump-scar and -fill, chute/channel-fills, and sheetlike, lobate and slump mass on steeply-inclined fan-delta foreset and prodelta.

Key Words : steep-faced fan delta, chute, channel, lobe

요 약

선상지 삼각주는 흔히 깊은 분지로 전진하여 급경사의 전면층을 형성한다. 현생의 급경사 선상지-삼각주는 사태흔적, 츄트/협곡, 스웨일(swale), 로브(lobe), 스플레이(splay). 및 암설낙하(debris fall) 등의 표층 지형에 의해 특징지워진다. 이들은 강하구에서 발생하는 퇴적물 붕괴나 중력류에 의해 생성된다. 고기의 선상지-삼각주 퇴적상은 경사가 급한 전면층과 비교적 경사가 완만한 기저층 및 전삼각주(prodelta) 층을 구성한다. 이는 다시 판상 또는 쐐기 모양의 역암 및 사암, 사태 충진층, 츄트/협곡 충진층, 판상층, 열편층, 사태층 등으로 구성된다.

주요어 : 급경사 선상지-삼각주, 로브, 협곡

INTRODUCTION

A fan delta commonly comprises tripartite depositional elements: lower part of alluvial fan, transitional zone, and subaqueous part. In shallow water environments, fan-delta system commonly forms either Hjulstrom- or Gilbert-type subaqueous delta front and prodelta (Postma, 1990). In steep-faced delta front, however, sediments are transported further basinwards, forming debris cone, Gilbert-type foreset, or ramp/lobe systems (Postma, 1990). In this realm, subaqueous sediment gravity flows are important. These flows originate from either resedimentation of nearshore and steep delta slope sediments (Postma and Roep, 1985; Colella *et al.*, 1987) or riverine floods that form hyperpycnal flows and subaqueous debris flows and turbidity currents (Prior and Bornhold, 1990).

Subaqueous processes of coarse-grained (fan) delta systems attracted little attention compared to those of fine-grained deltas or submarine fans, as they are virtually inaccessible to sedimentological observations. A number of modern steep-faced and fjord deltas have recently been surveyed, revealing seafloor morphology and surface sediment characters (Prior *et al.*, 1981a, b; Kostaschuk and McCann, 1987; Prior and Bornhold, 1988, 1989, 1990; Syvitski and Farrow, 1989; Piper *et al.*, 1990). In this paper, we describe some depositional features and characters of deep-water steep-faced fan-delta systems in the Pohang Basin (Miocene) SE Korea. Some sedimentary facies and geometry mimic those observed and expected in modern systems, but obvious difference in observation scale exists.

DEPOSITIONAL FEATURES (MODERN SYSTEMS)

Erosional/depositional features of sedimentary bodies on steep slope of (fan) delta systems include chutes/channels, swales, lobes/splays and debris falls (Tables 1, 2 and 3).

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Chutes/Channels

Gravel- or sand-filled erosional features, i.e., chutes and/or channels, commonly occur on steep subaqueous slope off river mouth (Fig. 1; Prior and Bornhold, 1989). They range in width from 10 to 100 m (up to 600 m), in incision depth from 2 to 10 m (maximum relief, 500 m) and in length from 500 to 2,500 m (Table 1). The chutes/channels are generally linear or sinuous in shape, and occasionally converge downslope into larger, incised channels. In some cases, chutes continue over delta slope and prodelta into deep basin forming long sinuous channels which are a few tens of kilometers long (up to 70 km long) and a few tens of meters to hundreds of meters deep (Prior and Bornhold, 1990: Soh et al., in press). Within the chute, splays of sand and gravel,

Table 1. Summary of sedimentologic characters of chutes/channels in modern steep-faced fan-delta systems.

Morphology	Dimension	Sediments	Environments	Location & Ref.
1) Linear or sinuous	16 chutes over 2.75 km Width: av. 85 m Length: 0.5~2.5 km Gradient: 2°~15°	Sands	Sand-rich delta slope off braided river system (water depth: <250 m)	Bella Coola (Kostaschuk & McCann, 1987)
2) Large submarine chute	Width: up to 600 m Gradient: 13°	Finger-like, radiating splays of sand & gravel	1) From delta front to lower delta slope	Britannia Beach, Howe Sound (Prior & Bornhold, 1986)
Gully or shallow channel	Gradient: 7.5°	Arcuate scarps	2) Lower delta slope	
3) Sinuous (scoured conduit)	Width: about 10 m	Lined & flanked with gravels & sands	Submarine slope off ephemeral stream	Howe Sound (Prior & Bornhold, 1988)
4) Between elongate ridges of gravel & sand	Width: 20~50 m gradient 15.7° (up to 27.5°)	Gravel	Upper slope	Bear Bay, Bute Inlet (Prior & Bornhold, 1988)
Between unscoured silt & clay	Width: 50~100 m Gradient: 11.3°	Sand with cobbles, displaced sediment	Lower slope	
5) Highly sinuous channel	Length: 40~50 km, Depth: max. 25~30 m (downslope decreasing) Gradient: 3°~5°		Delta slope to prodelta (water depth: 150~430 m)	Homathko & Southgate deltas, Bute Inlet (Prior *et al.*, 1986)
6) Slope-parallel	Width: 200 m Depth: 10 m Gradient: 5°~35°	Mainly sands (distal fining)	On delta slope (foreset)	Alta delta, Norway (Corner *et al.*, 1990)
7) Anastomosing & downslope convergent	Width: 10~40 m	Fine sediments	1) Upper delta slope	Noeick River delta, British Columbia (Bornhold & Prior 1990)
Incised channel	Width: 130~160 m Depth: 5~7 m	Sand & gravel with large flutes	〃	
Downslope parallel abandoned chutes	Width: 30~50 m	Well developed flutes	2) Mid-slope	
8) No levee Upslope: bowl-shaped source region with scarp	Width: av. 10 m Depth: 2~5 m Gradient: 12°~16°		Delta front & upper slope (water depth: 5~30 m)	Longyear delta (Prior *et al.*, 1981a)
Downslope: extensive hummocky zone	Width: 15~30 m Depth: <3 m Gradient: 12°~16°		〃	Adventfjord delta (Prior *et al.*, 1981a)
9) Straight & parallel to elongation of bulge or lobe	Gradient: 5°~25°	Sheets of sand & gravel	All around surface of bulge or lobe	Fujikawa Fan-Delta (Soh *et al.*, in press)
Straight, braided, radiated outward	Gradient: 3.6°~8.0°	Mud & sand	Lower slope	Sakawa Fan-Delta (Soh *et al.*, in press)
10) Extensive channeling intervened by narrow downslope radiating ridges of 200 to 600 m wide	Width: a few hundred meters Relief: 100~500 m Gradient: 9°~11°	Slump body along some steep-sided wall of channel (water depth: 900~1,900 m)	Water depth: 500~1,400 m	Huon Penin. Papua New Guinea (Liu *et al.*, in press)
Converge into a few incised channels			Water depth: 1,000 m	
Meandering	Length: 70		Water depth: (1,500~3,000 m)	

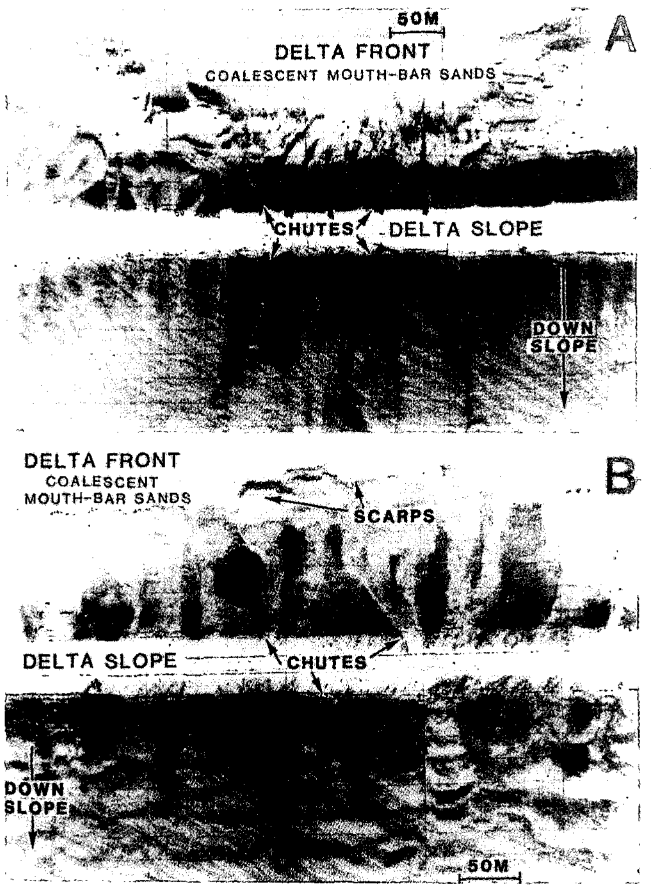

Fig. 1. Side-scan sonograph mosaic of subaqueous fan delta showing gravel and sandy chutes, hummocky lobes and distal sandy splays. Example from Bear Bay, Bute Inlet, British Columbia, Canada (after Prior and Bornhold, 1988).

slumps from steep side wall of channel, and displaced sediment blocks occur (Fig. 1). Flute marks occur on the chute floor, which are indicative of powerful flows.

The chutes/channels are largely due to the sediment failure of delta front and slope as well as to erosion of continuing hyperpycnal flow from rivers. The chutes generally serve as efficient conduit for the transport of coarse-grained sediment from delta to deep water.

Swales

Gravels and sands commonly occur in divergent and anastomosing patterns away from the river mouths over the steep, cone-shaped fan apex (Prior and Bornhold, 1990). These shallow, smooth-floored linear depressions (swales) are separated by low, rounded elongate ridges with a relief of up to 20 m (Fig. 2). The swales are usually filled with undulating sheets of sand and gravel (Prior and Bornhold, 1990). Further downslope, the swales terminate as indistinct splays of fine sand and gravel (Fig. 2). In some cases, swales

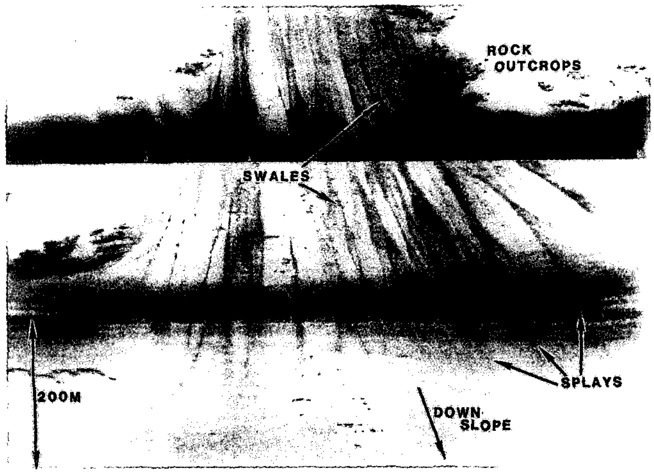

Fig. 2. Side-scan sonar swath of gravel and sand swales on a small fan delta. Example from South Bentinck Arm fjord, British Columbia, Canada (after Prior and Bornhold, 1990).

converge into incised, steep-walled chutes (Prior and Bornhold, 1989).

Coarse-grained sediments in the swales are transported during river floods upstream. During floods, high-energy, hyperpycnal flows continue across the (fan) delta apex with scour of mouth bar (Prior and Bornhold, 1990). The swales are commonly filled with high-concentration turbidite sands and gravelly sands (Prior and Bornhold, 1990).

Lobes/Splays

Depositional features such as lobes and/or splays commonly develop downslope of chutes on the gentle lower (or distal) slope of fan delta (av. gradient: <10°) (Table 2; Fig. 2). The lobes are irregular, hummocky or lobate in shape, forming low-relief depositional area several km wide (Table 2). They consist of splays of sand and gravel, scattered blocks of displaced sediment and discontinuous ridge, rotational slide and hummocks (Table 2).

The lobes mainly form by unconfined sediment-gravity flows at the end of chute. Decrease in slope gradient and flow spreading off chute result in rapid depostion of suspended sediments.

Debris falls

The steep (fan)delta slopes are also characterized by debris fall deposits such as isolated blocks and pebbles and boulders (Table 3; Prior and Bornhold, 1990). The debris may fall as a single particle, or small- to large-volume assemblages of strongly dispersed particles forming isolated block or linear debris stream to broad debris zone. Slump scars and slide blocks commonly occur upslope.

Table 2. Summary of sedimentologic characters of lobes in modern steep-faced fan-delta systems.

Morphology	Dimension	Sediments	Environments	Location & Ref.
1) Irregular		Blocks & spreads	Lower end of chute	Longyear Delta (Prior *et al.*, 1981a)
2) Hummocky		Hummock, block, scarp	Downsolpe of chute	Adventfyord delta (Prior *et al.*, 1981a)
3) Low-relief splay (<5 m in thickness)		Sand & gravel	Submarine slope associated with ephemeral stream	Howe Sound (Prior & Bornhold, 1988)
4) Low-relief hummocky with crenulate pressure ridge	gradient: 1.6°		distal delta	Bear Bay, Bute Inlet (Prior & Bornhold, 1988)
Radiating thin sand splay	gradient: 1.1°	Sand	Downslope end of chute	
Lobate		Scattered blocks of Displaced sediment & discont. ridge	Downslope end of delta	
5) Spillover		Sand with flute marks	Sides of channel (water depth: >430 m)	Homathko & Southgate deltas, Bute Inlet (Prior *et al.*, 1986)
Overlapping, low relief & abandoned, partially fielld channel remnants			Further downslope (water depth:530~600 m)	
Distal splay		Sand with debris & displaced sediment blocks	Further downslope (water depth: 600~700 m)	
6) Elongate convex-upward	Width: 2~3 km Length: 4~6 km Gradient: 5°~25°	Gravel & sand	Lower delta slope	Fujikawa Fan-Delta (Soh *et al.*, in press)
7) Smooth & minor	Area: 4×1 km^2 Gradient: 3.6°~8.0°		Lower delta slope	Sakawa Fan-Delta (Soh *et al.*, in press)
8) Lobate	Gradient 7.5°	Scattered blocks of displaced sediment & discont. ridge	Lower delta slope	Britannia Beach, Howe Sound (Prior & Bornhold, 1986)
9) Broad, overlapping splays	Gradient: 0.5°~2.2°	Sand with debris lobes & displaced sediment blocks	Distal end of chute	Bella Coola (Kostaschuk & McCann, 1987)
Large-scale deformation		Rotational slide	Prodelta (water depth: 250~550 m)	
10) Slump	Area: 5~12 km Gradient: 5°~8°		Toe of delta (water depth: 500~1,400 m)	Huon Peninsula, Papua New Guinea (Liu *et al.*, in press)

SEDIMENTARY FACIES AND GEOMETRY (ANCIENT SYSTEMS)

Sedimentary facies that are indicative of steep-faced fan delta systems can be grouped into a few distinct architectures (Table 4): sheet-like or wedged bodies on steeply-inclined foreset, slump-scar and -fill, channel fill, lobe sequence, sheet sequence, slump mass and debris fall deposit. These elements can be outlined by observations of sediment bodies on 2-dimensional outcrop sections with subsequent three-dimensional interpretation (e.g. Bridge, 1993). These architectural elements occur in steeply inclined foreset and prodelta environments.

Sheet-like or wedged bodies on steeply-inclined foreset

Sheet-like bodies of gravelstone and sandstone extend laterally (or downslope) for some distances (width/thickness ratio, more than 15°) and retain similar grain size and sedimentary structures over a few tens of meters (Fig. 3). Whereas wedged gravelstone and sandstone bodies are characterized by rapid downslope decrease both in bed thickness and in grain size. These bodies form steeply-inclined (>20°, up to 40°) foreset sequence of steep-faced fan delta and comprise disorganized, (crudely) stratified, normally graded gravelstone and inversely or inverse-to-normally graded gravelstone with some intercalating sandstone layers (Table 4). Individual depositional units range in thickness from a few centimeters to several meters (Fig. 3). Gravel clasts are either matrix- or clast-supported in a very poorly-sorted sand matrix (Fig. 3).

The sheet-like or wedged bodies form on initially steeply-inclined surface by gravity slides, debris (or grain) fall, cohesionless debris flows and high-density turbidity curre-

Table 3. Summary of sedimentologic characters of debris fall on modern steep-faced fan-delta systems.

Morphology	Dimension	Component	Environment	Location & Ref
1) Broad coarse talus debris zone	Width: up to several meters Gradient: 24°	Very large subrounded boulders with rock debris of av. 0.5 m long	Submarine slopes off alluvial fans	(Prior & Bornhold, 1988)
2) Linear debris stream		matrix-free debris		〃
3) Isolated block		1~2 m long block outrun 10~50 m		〃

Table 4. Architectural elements, bed geometry, sedimentary facies, and processes of ancient steep-faced fan-delta system.

Architectural Elements	Bed geometry	Facies	Processes
Steeply inclined foreset	Sheet-like/Wedged	Gravelstone: disorganized, crudely stratified, stratifed, normally graded, inversely or inverse-to-normally graded Sandstone: massive, laminated, graded	Small-scale slides (gravity slides), debris fall (or grain falls), cohesionless debris flow (or grain flow, density-modified grain flow) with slight influence of gravelly high-density turbidity current, frictional freezing of avalanching of gravels and sands
Slump scar	Scar-fill	Gravelstone: Proximal: disorganized, crudely-stratified Distal: normally or inversely graded	Proximal: cohesive debris flow, retrogressive slide/slump Distal: cohesionless debris flow, high-density turbidity current
Chute/channel	Channellized	Gravelstone: disorganized, crudely stratified, normally graded, inversely or inverse-to-normally graded Sandstone: massive, laminated, graded	Various sediment gravity flows
Lobe	Lobate	Gravelstone: disorganized, normally graded, inversely graded Sandstone: massive, laminated, narmally graded	Cohesionless debris flow, gravelly high-density turbidity current Sandy high-density turbidity current
Interchannel/interlobe	Sheet-like	Thick homogeneous muddy sandstone with intercalations with intercalations of disorganized or graded gravelstone & massive, laminated or graded sandstone layers	Particle-by-particle settling from turbid clouds with intermittent sediment gravity flows
Slide block/slump mass	Chaotic	Disrupted beds of gravelstone, sandstone and mudstone	Slide/slump

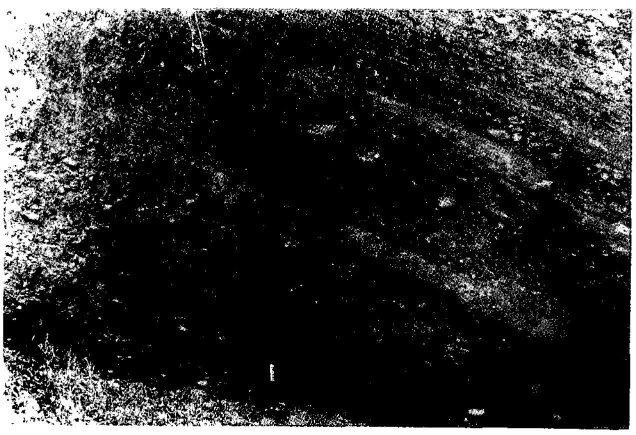

Fig. 3. Sheet-like bodies of gravelstone and gravelly sandstone on steeply-inclined foreset. The gravelstone units are partly openwork, indicative of deposition by small-scale gravity sliding and/or grain flow on inclined surface. Scale is 20 cm long. Example from a Miocene fan delta, Pohang Basin, SE Korea (after Hwang and Chough, 1990).

nts (Postma, 1983, 1984a, b; Postma and Roep, 1985; Colella *et al.*, 1987; Colella, 1988; Chough *et al.*, 1990; Hwang and Chough, 1990). Frictional freezing of avalanching gravels and sands or cohesionless debris flows plays more important role in deposition of wedged bodies (Postma and Cruickshank, 1988; Massari and Parea, 1990). Sediments are fed by high-energy alluvial fans and ephemeral streams in fjord deltas (e.g. Prior and Bornhold, 1988, 1989, 1990).

Slump scar and fill

Large-scale slump scar and fill commonly occur on the steeply-inclined fine-grained foreset environment. The scar is bounded by sharp scour surfaces with the underlying beds (Fig. 4A), whereas the floor is flat-lying (Fig. 4A). The scar ranges in depth from a few tens to hundreds of meters and is several hundred meters wide.

The scar is commonly filled with thick (up to several tens of meters) disorganized (clast- or matrix-supported) gravelstones and sandstones (Table 4). Some gravelstone bodies can be traced for more than hundreds of meters across the chute axis and more than several kilometers along the chute axis, revealing a large-scale tongue-like geometry in the foreset, bottomset and prodelta slope environments. In the foreset, the gravel bodies are generally disorganized and crudely stratified in which gravel clasts are either clast- or matrix-supported in poorly-sorted sand or muddy sand matrices (Fig. 4A). They contain large-scale rip-up mud clasts, calcite-cemented sandstone blocks and distorted sandstone and muddy sandstone blocks as well as armored mudstone balls. Some units are bounded by sharp erosional surface with the underlying muddy sandstone (Fig. 4A).

The gravel bodies filling the slump-scar are most probably deposited by cohesive debris flows as evidenced by disorganized and crudely-stratified nature, poorly-sorted sand and muddy sand matrices (Curry, 1966; Winn and Dott, 1977; Lowe, 1982; Postma, 1986). Large-scale rip-up mud clasts and distorted sandstone and muddy sandstone blocks suggest that the debris flows were triggered by slide/slump in the upslope part of the foreset, forming downslope-running scour surfaces or troughs which commonly occur on modern steep-faced slopes or foreset (e.g. Postma, 1983, 1984a, b; Prior and Bornhold, 1988, 1989, 1990). Retrogressive slide and slump are generally responsible for the thick stacked units of gravelstone (commonly upto 50 m in thickness). Some sequences are penecontemporaneously deformed with slump folds, faults and large-scale flame structures.

In the prodelta slope, however, the gravel clasts are either matrix- or clast-supported in a well-sorted sand matrix and are horizontally stratified (Fig. 4B). Here, thin units of graded gravelstone and inversely graded gravelstone are partly intercalated. The well-sorted sand matrix, relatively well-defined flow units as well as thin layers of graded gravelstone and inversely graded gravelstone may represent deposition by cohesionless debris flows and high-density turbidity currents (e.g. Lowe, 1982). Downslope variations in matrix content, fabric and sedimentary structures suggest transformation of sediment gravity flows from slide/slump to cohesive debris flows and, finally, into cohesionless debris flows and high-density turbidity currents (Middleton and Hampton, 1973).

Channelized bodies (channel fills) of gravelstone and sandstone

The channelized body of gravelstone and sandstone is commonly bounded by sharp, concave-up or step-wise scour surfaces encased within fine-grained deposits. The channels range in depth from 1 m up to several tens of meters and are more than several tens of meters wide. The channels are filled with lenticular bodies of disorganized, crudely-stratified, normally or inversely graded, and cross-bedded gravelstone and massive, laminated and normally graded sandstones (Table 4; Postma and Roep, 1985; Choe, 1990; Hwang, 1993).

Channel fills in steep slope environment are characterized by abrupt channel margin and deeply scoured (about 2~3 m in relief) channel base (Fig. 5). Channel fills in prodelta environment can be divided into two types: gravelstone-filled and sandstone-filled channel fills. The former occurs in the proximal area (Fig. 6), whereas the latter occurs further basinward (Fig. 7)

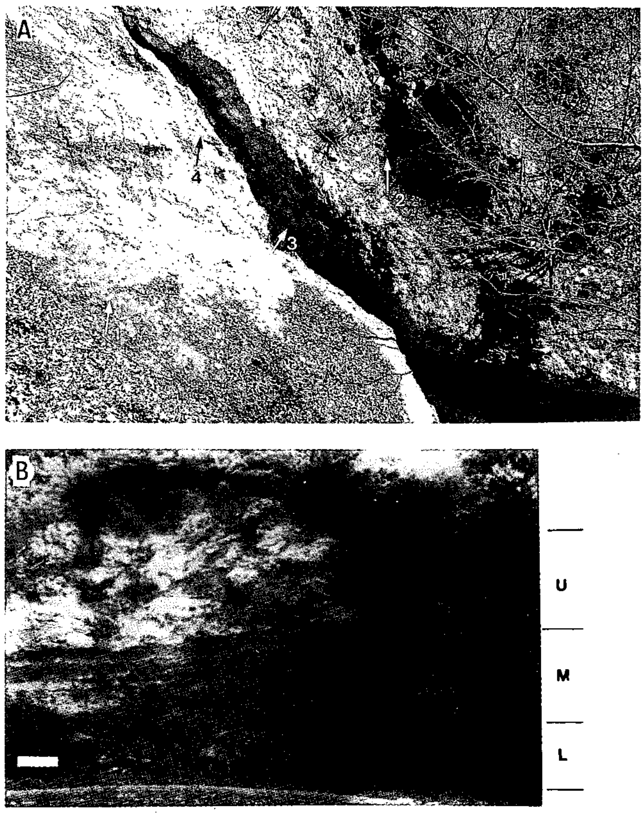

Fig. 4. Slump-scar and fill in steeply-inclined fine-grained foreset (A) and gravelstone bodies in prodelta (B). Example from a Miocene fan delta, Pohang Basin, SE Korea. (A) A large-scale slump scar with lower flat boundary (arrow 3) occurs on the steep-faced fine-grained foreset (arrow 1), which is subsequently filled with disorganized and crudely stratified gravel deposits (arrow 2). The deposits are either clast- or matrix-supported in poorly-sorted sand and muddy sand matrices. Large-scale mudstone clasts also occur. The underlying sandstone layers are deformed in part (arrow 4). The gravel body is up to 50 m thick, about 500 m wide and 1~2 km long. The gravel body formed as a fill of a large-scale slump scar (or chute) on the foreset (slope), whereas the underlying muddy sandstone and sandstone was deposited in the interchute areas. (B) The gravelstone bodies in prodelta slope are disorganized (L) and stratified (M) showing flat lower boundaries. The upper part (U) represents slump deposits of disrupted sandstone and mudstone layers with large boulders. Bar is about 2 m long.

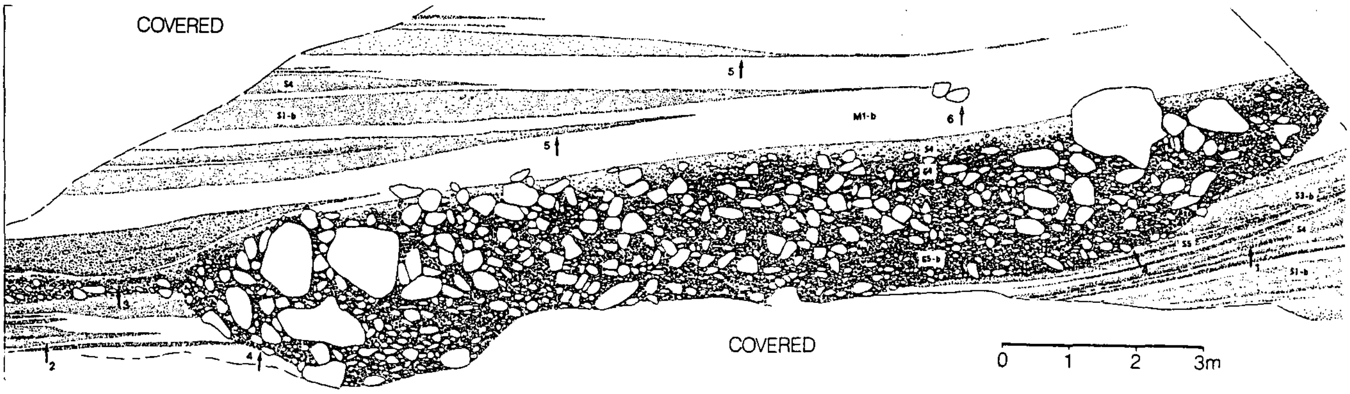

Fig. 5. A detailed sketch of channel-fill deposits in steep-faced slope (Maesan fan delta, Pohang Basin). Gravelstone shows a cross section of a chute-fill with abrupt margins and deeply scoured (about 2 - 3 m in relief, arrow 4) base. The underlying sand beds are discontinuous and either graded or massive (arrows 1, 2). The chute-fill is inverse(-to-normally) graded and large clasts (boulder grade) are concentrated near the chute margins. The gravel body is clast-supported with sandy mud matrix (maximum clast, 130 cm). The flute casts in the sandstone layers and chute walls indicate that the paleoflow was southeastward (into the sheet) with a slope gradient of about 15°. Note a chute wing on the left margin (arrow 3). The chute-fill represents a chute-fill debris flow. The wedged sandstone layers (arrow 5) are indicative of small-scale depositional lobes.

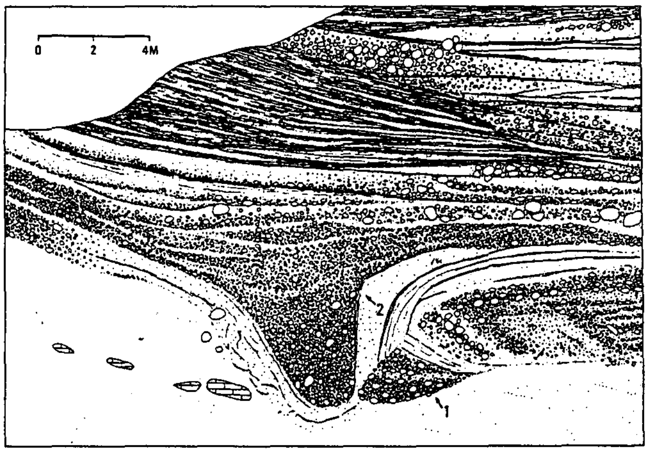

Fig. 6. Detailed sketch of channellized gravelstone bodies (Doumsan fan delta, Pohang Basin). Note three chan nel-fill gravelstone and gravelly sandstone units (Arrow 1, 2 and 3) deposited in the proximal part of mass-flow-dominated prodelta environment off fan-delta slope (foreset).

The dominance of gravel clasts, sand matrix and disorganized nature, normal (and inverse) grading, stratification and cross bedding of gravel and sands are all indicative of high-density turbidity currents and cohesionless debris flows (Table 4).

The channel-fill sequences commonly show thinning-upward trends largely due to progressive channel abandonment. Downchannel decrease in frequency of gravel layers and increase in sand and mud layers are suggestive of basinward decrease of flow competence. The channellized bodies mimic submarine chute deposits that commonly occur on modern fan deltas (Prior *et al.*, 1981a, b; Kostaschuck and McCann, 1987; Prior and Bornhold, 1988, 1989, 1990; Syvitski and Farrow, 1989).

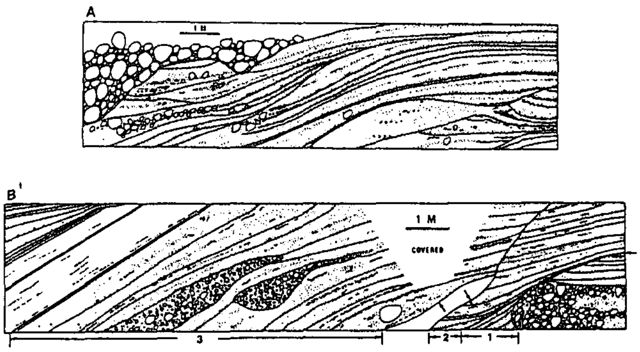

Fig. 7. Detailed sketches of channel fill deposits in mass-flow-dominated prodelta. Example from a Miocene fan delta, Pohang Basin SE Korea. (A) Massive and graded fine sandstone units show cross-cutting geometry, which most probably resulted from scouring by powerful turbulent flows. Note thin draping mudstone layers. The sandstone units commonly contain outsize clasts, lignite fragments and rip-up mud clasts. In upper-left corner, the sandstone layers are scoured by disorganized and clast-supported gravelstone. (B) Three sandstone bodies (indicated by 1, 2 & 3) are bounded by inclined erosional surfaces (Arrows) which represent scouring by powerful, turbulent flows. Very thin mudstone layers are intercalated. The sandstone units commonly contain rip-up mud clasts and lignite fragments. Outsize clasts rarely occur in the sandstone. In the center, laterally discontinuous, disorganized (partly inversely graded) and matrix-supported gravelstone layers incise the sandstone unit.

Lobate gravelstone and sandstone

The lobate bodies commonly consist of disorganized, crudely-stratified, graded, inversely(-to-normally) graded units of gravelstone and sandstone (Table 4). Individual units range in thickness from a few cm to 2 m and commonly shows sheet-like or lobate bed geometry with convex-up upper boundaries and show downslope decrease in bed thickness (Figs. 8 and 9). Some gravelstone units laterally terminate abruptly and are draped by sandstone and muddy sandstone (Fig. 8). The unit boundaries are flat and smooth but some exhibit erosive lower boundaries. The gravelstone and sandstone units are commonly amalgamated, forming thick bed and contain outsized gravels and rip-up mudstone clasts. The gravelstone and gravelly sandstone mainly develop in the proximal part adjacent to the channel or chute, whereas the sandstone occurs further basinward.

The lobate bodies can be viewed as submarine depositional lobes that commonly occur in steep-faced slope environments of modern fan deltas (Prior *et al.*, 1981a, b; Kostaschuck and McCann, 1987; Prior and Bornhold, 1988, 1989, 1990; Bornhold and Prior, 1990; Syvitski and Farrow, 1989) and ancient examples (Postma and Cruickshank, 1988; Choe, 1990). The bodies were deposited by various sediment gravity flows such as cohesionless debris flows (or density-modified grain flows) and high- or low-density turbidity currents (Choe, 1990). As the slope gradient gradually decreases downslope at the terminal edge of the submarine channel/chute, the sediment gravity flows decelerate, forming gravelstone and sandstone bodies.

Sheet sandstone body

The sheet sandstone bodies (up to 15 m thick) are laterally extensive (>1 km) (Fig. 10). Outsized clasts commonly occur in the lowermost part of each unit and large mudstone clasts are abundant in the middle and upper parts.

The sheet sandstone bodies are deposited most likely by unconfined high-density turbidity currents which probably originate from slide/slump on steep fan-delta foreset (Postma and Roep, 1985; Choe, 1990), continuation of sheetfloods off alluvial fan (Turnbridge, 1981; Ballance, 1984; Dabrio and Polo, 1988) and resedimentation of nearshore sediments by seismic and storm events (O'Connell *et al.*, 1985; Bouma *et al.*, 1985; Choe, 1990). The thick sheety sandstone bodies mimic distal splays deposited at the downslope end of fjord delta channel (Prior *et al.*, 1986).

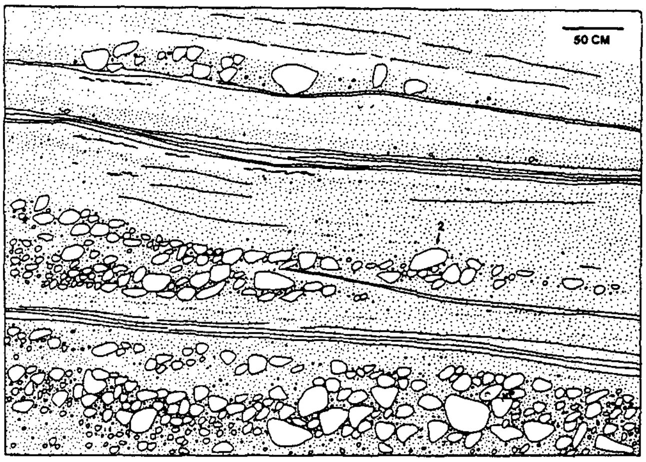

Fig. 8. Detailed sketch of proximal lobe deposits in mass-flow-dominated prodelta (Doumsan fan delta, Pohang Basin). The lobe comprises stacked sequence of gravelstone and sandstone units with very thin mudstone layers. The gravelstone units are laterally discontinuous, disorganized and matrix-supported. Note floating large protruding clasts (Arrow 2). Intercalating very thin mudsotne is incised by overlying massive and normally graded sandstone units.

Fig. 9. Distal lobe deposits in mass-flow-dominated prodelta (Doumsan fan delta, Pohang Basin). The lobe comprises mainly massive or normally graded fine to medium sandstone layers with very thin mudstone layers. This section is divided into two sandstone bodies. The lower one (1) shows a rightward decrease in thickness from 1 m (plane-bedded sandstone) to 40 cm (amalgameted sandstone) in 5 m. This body exhibits lower flat and upper convex-up geometry and is overlain by about 2 m thick upper sandstone body.

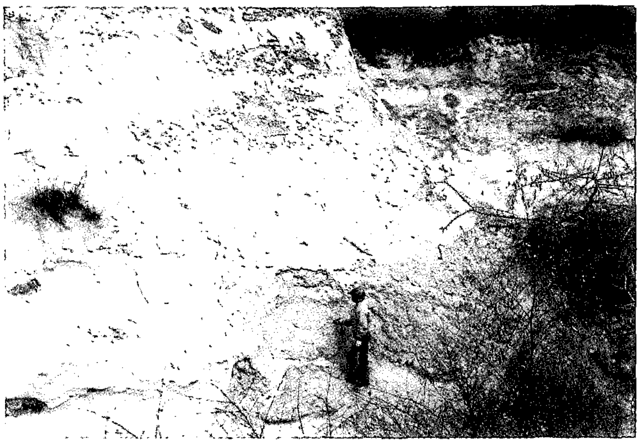

Fig. 10. Sheet sandstone body in mass-flow-dominated prodelta slope is dominated by very thick (over 15 m) normally graded gravelstone-sandstone bed with extensive lateral continuity (traceable for up to 1 km). The sandstone body was deposited by unconfined high-density turbidity currents. Note abundant large mud clasts. Man for scale. Example from a Miocene fan delta, Pohang Basin, SE Korea.

Sheet-like mudstone and sandstone

It mainly comprises thick homogeneous mudstone and thin massive fine sandstone (Table 4). Wedges of disorganized, graded gravelstone and massive, graded gravelly sandstone units are rarely intercalated (Table 4). These deposits represent low-energy setting, characterized by sedimentation from hemipelagic suspension and low-density turbidity currents (Table 4), adjacent to the channels and depositional lobes (Mutti and Ricci-Lucchi, 1975).

Chaotic deposits of gravelstone, sandstone and muddy sandstone

The chaotic bodies are represented by disrupted beds of gravelstone, sandstone and muddy sandstone, and shear zones due to rotational slumps, folds, faults and loading and shearing by moving flow (Fig. 11). Small-scale chaotic units such as slide blocks of calcite-cemented sandstone, armored mudstone balls and outsized boulders also occur (Fig. 4B). The chaotic bodies are interpreted as large-scale slide and slump deposits (Prior *et al.*, 1987; Prior and Bornhold, 1988, 1989, 1990; Bornhold and Prior, 1990).

COMPARISON AND DEPOSITIONAL PROCESSES

Superficial depositional features of modern steep-faced slopes off fan-delta systems are commonly surveyed by high-resolution instruments whose resolved dimension is in the order of several hundreds of meters or more. In out crops, however, observations are made on tens of meters scale and large-scale festures such as channel (or chute) margins are scarcely measured. Most descriptions on out crop sections are thus scale-dependent and are interpreted for the third dimension.

Fig. 11. Chaotic deposits showing slide/slump structure (or growth fault). Note slump fold on the right part of slump (or slide) plane. Over- and underlying sequences of slumped unit are laterally continuous. Example from the Miocene Pohang Basin, southeast Korea (after Choe and Chough, 1988).

Coarse-grained sediments on Gilbert-type foresets and steep slopes commonly form inclined beds. Here, depositional processes are largely controlled by the grain size of sediments (Orton and Reading, 1993) which is also related to the fluvial discharge rate and resultant variation in sediment supply rate (or bed-load/suspended-load ratio) from the alluvial feeder system (e.g. Syvitski *et al.*, 1988). When observed in outcrop sections, sequences are planar and inclined at an angle of repose or more (over 35°) (Kauzanci, 1990; Mastalerz, 1990). Coarse-grained sediments are clast- (or matrix-) supported; individual beds are either continuous, wedged and isolated or chaotic.

In coarse-grained foreset, sediments are transported by avalanching of loose grains at the brink point between the Gilbert-type topset and foreset. Further downslope, sediments move mainly as small-scale slides (or gravity slides), cohesionless debris flows (or density-modified grain flows) or high-density turbidity currents (e.g. Postma, 1984a, b; Colella *et al.*, 1987; Nemec, 1990). These systems lack large-scale slope failures that commonly occur in fine-grained delta fronts (e.g. Prior and Bornhold, 1988, 1989, 1990).

Fine-grained systems are represented by various sedimentary facies and bed geometries, which show systematic downslope variation in architecture. Fine-grained foreset sequences comprise steeply-inclined (>20°) beds of sheet-like, wedged, and chaotic bodies. The sheet-like units are largely deposited in low-energy settings. The wedged gravelstone and sandstone bodies represent frictional freezing of avalanched gravels and sands. Rapid deposition of fine-grained sediments results in intermittent slope failure, forming long, narrow, downslope-running troughs (Postma,

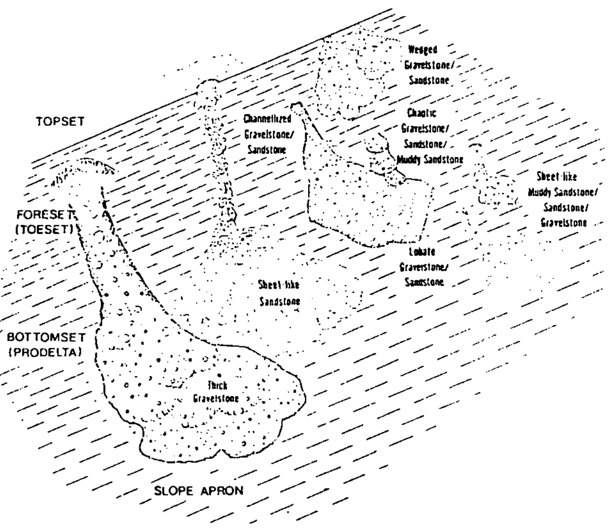

Fig. 12. Simplified depositional model for subaqueous fan-delta system. Note diverse architectures deposited in foreset and prodelta environments.

1983; Prior and Bornhold, 1988, 1989, 1990) (Fig. 12). These deposits are penecontemporaneously deformed largely due to rotational slump and plastic flowage (Postma *et al.*, 1988). The deformation propagates to the bottomset (or prodelta) and slope apron mainly as 'bulldozer' effect, associated with the laminar flowage of the detached foreset strata (Postma *et al.*, 1988).

Slides and slumps result in deposition of channellized gravelstone and sandstone bodies in the upslope part of the prodelta (or bottomset) (e.g. Prior and Bornhold, 1988, 1989, 1990) (Fig. 12). The proximal channels (or chutes) are filled with sandstone units. The channels gradually become shallower and wider downslope, and finally disappear in the distal prodelta where depositional lobes are developed (Fig. 12). Occasionally, large-scale turbidity currents are generated by resedimentation of shallow nearshore sediments during seismic and storm events (Fig. 12). These flows accelerate in the steeply inclined foreset. Abrupt decrease in slope gradient in the bottomset (or prodelta) results in hydraulic jump, during which thick graded sandstone units are deposited (Fig. 12). Interchannel and interlobe areas are dominated by sheet-like muddy sandstone, sandstone and gravelstone. Most of these sequence are penecontemporaneously deformed, resulting from the detached foreset sequence and plastic flowage of the foreset and bottomset strata.

CONCLUSIONS

Modern steep-faced fan-delta system comprises steeply-inclined foreset and prodelta which are characterized by distinct large-scale surface morphology including chute/channel, swale, lobe/splay and debris fall. These features are mainly formed by underflows of riverine processes and sediment-gravity flows originating from sediment failure upslope.

The steeply-inclined foreset sequence of equivalent ancient system comprises sheet-like and/or wedged bodies of gravelstone and sandstone and slump-scar and -fill. Ancient prodelta environment is characterized by channel/chute-fills, depositional lobe sequence, sheet sandstone body interchannel/interlobe sequences and slides/slumps.

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REFERENCES

Bornhold and Prior, 1990. Morphology and sedimentary processes on the subaqueous Noeick River delta, British Columbia, Canada. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. IAS Spec. Publ., 10: 169-181.

Bouma, A.H., Stelting, C.E. and Coleman, J.M., 1985. Mississippi Fan, gulf of Mexico. In: A.H. Bouma, W.R. Normark and N.E. Barnes (Editors), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, pp. 143-150.

Bridge, J.S., 1993. Description and interpretation of fluvial deposits: a critical perspective. Sedimentology, 40: 801-810

Choe, M.Y., 1990. Submarine Depositional Processes of the Doumsan Fan-Delta System, Miocene Pohang Basin, Southeast Korea. Unpubl. Ph. D. Thesis, Seoul National Univ., 287p.

Choe, M.Y. and Chough, S.K., 1988. The Hunghae Formation, SE Korea: Miocene debris aprons in a back-arc intraslope basin. *Sedimentology*, 35:239-255.

Chough, S.K., Hwang, I.G. and Choe, M.Y., 1990. The Miocene Doumsan fan-delta, southeast Korea: a composite fan-delta system in back-arc margin. *J. Sedim. Petrol.*, 60: 445-455.

Colella, A., 1988. Pliocene-Holocene fan deltas and braid deltas in the Crati Basin, southern Italy: a sonsequence of varying tectonic conditions. In: Fan Deltas: Sedimentology and Tectonic Settings. (ed. by W. Nemec and R.J. Steel), pp. 50-74. Blackie and Son, London.

Colella, A., De Boer, P.L. and Nio, S.D., 1987. Sedimentology of a marine intermontane Pleistocene Gilbert-type fan-delta complex in the Crati Basin, southern Italy. *Sedimentology*, v.34, p. 495-519.

Corner, G.D., Nordahl, E., Munch-Ellingsen, K. and Robertsen, K.R., 1990. Morphology and sedimentology of an emergent fjord-head Gilbert-type delta: Alta delta , Norway. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. Int. Assoc. Sediment. Spec. Publ., 10: 155-168.

Curray, R.R., 1966. Observation of Alpine mudflows in the Tenmile Range, central Colorado. Geol. Soc. Am. Bull., 77: 771-776.

Hwang, I.G., 1993. Fan-Delta Systems in the Pohang Basin (Miocene), SE Korea. Unpubl. Ph. D. Thesis. Seoul National Univ., 923p.

Hwang, I.G. and Chough, S.K., 1990. The Miocene Chunbuk Formation, SE Korea: marine Gilbert-type fan-delta system. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. *Int. Assoc. Sediment. Sepc. Publ.*, 10: 235-254.

Kazanci, N., 1990. Fan-delta sequences in the Pleistocene and Holocene Burdur Basin, turkey: the role of basin-margin configuration in sediment entrapment and differential facies development. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 185-198.

Kostaschuk, R.A. and McCann, S.B., 1987. Subaqueous morphology and slope processes in a fjord delta, Bella Coola. Can. *J. Earth Sci.*, 24: 52-59.

Liu, K., Crook, K.A.W., Hughes-Clarke, J.H. and Whitmore, G.P., (in press). Submarine features of modern open-sea fan deltas, Huon Peninsula, Papua New Guinea. Sedimentary Geology.

Lowe, D.R., 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. *J. Sediment. Petrol.*, 52: 279-297.

Massari, F. and Parea, G.C., 1990. Wave-dominated Gilbert-type gravel deltas in the hinterland of the Gulf of Taranto (Pleistocene, southern Italy). In: A. Colella and D.B. Prior (Editors), Coarse-grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 311-331.

Mastalerz, K., 1990. Diurnally and seasonally controlled sedimentation on a glaciolacustrine foreset slope: an example from the Pleistocene of eastern Poland. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 297-309.

Middleton, G.V. and Hampton, M.A., 1973. Mechanics of flow and deposition. In: G.V. Middleton and A.H. Bouma (Editors), Turbidites and Deep Water Sedimentation. SEPM Pacific Section, Short Coarse Notes, pp. 1-38.

Mutti, E. and Ricci-Lucchi, F., 1975. Turbidites facies and facies associations. In E. Mutti, G.C. Parea and F. Ricci Lucchi (Editors), Examples of Turbidite Facies and Associations from selected Formations of the northern Apennines, Field Trip guidebook A-11, 9th Int. Assoc. Sediment. Congr., Nice, pp. 21-36.

Nemec, W., 1990. Aspects of sediment movement on steep delta slopes. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 3-12.

O'Connell *et al.*, 1985. Drilling results on the lower Mississippi fan. In: A.H. Bouma, W.R. Normark and N.E. Barnes (Editors), Sbumarine Fans and Related Turbidite Systems. Springer-Verlag, New York, pp. 291-298.

Orton, G.J. and Reading, H.G., 1993. Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. *Sedimentology*, 40: 475-512.

Pickering, K.T., 1981. Two types of outer fan lobe sequences, from the Late Precambrian Kongsfjord Formation submarine fan, Finnmark, North Norway. *J. Sediment. Petrol.*, 51:1227-1286.

Piper, D.J.W., Kontopoulos, N., Anagnostou, C., Chronis, G. and Panagos, A.G., 1990. Modern fan deltas in the western Gulf of Corinth, Greech. Geo-Marine Lett., 10: 5-12.

Postma, G., 1983. Water escape structures in the context of a depositional model of a mass flow dominated conglomeratic fan-delta (Abrioja Formation, Pliocene, Almeria Basin SE Spain). *Sedimentology*, 30: 91-103.

Postma, G., 1984a. Mass-flow conglomerates in a submarine canyon: Abrioja Fan-delta, Pliocene, SE Spain. In: E.H. Koster and R.J. Steel (Editors), Sedimentology of Gravels and Conglomerates. Can. Soc. Petrol. Geol., Mem., 10: 237-258.

Postma, 1984b. Slumps and their deposits in fan delta front and slope. *Geology*, 12: 27-30.

Postma, G., 1986. Classification for sediment transport gravity-flow deposits based on flow conditions during sedimentation. *Geology*, 14: 291-294.

Postma, G., 1990. Depositional architecture and facies of river and fan deltas: a systhesis. In: A. Colella and D.B. Prior (Editors), Coarse-grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 13-27.

Postma, G. and Roep, T.B., 1985. Resedimented conglomerates in the bottomset of a Gilbert-type gravel delta. *J. Sediment. Petrol.*, 55: 874-885.

Postma, G. and Cruickshank, C., 1988. Sedimentology of a late Weichselian to Holocene terraced fan delta, Varangerfjord, northern Norway. In: W. Nemec and R.J. Steel (Editors), Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Son Ltd., London, pp. 144-157.

Postma, G., Babic, L.J., Zupanic, J. and Roe, S.L., 1988. Delta-front failure and associated bottomset deformation in a marine, gravelly Gilbert-type (fan) delta. In: W. Nemec and R.J. Steel (Editors), Fan Deltas: Sedimentology and Tectonic Settings. Blakie and Son, London, pp. 91-102.

Prior, D.B. and Bornhold, B.D., 1986. Sediment transport on subaqueous fan delta slopes, Britannia Beach, British Columbia. Geo-Marine Lett., 5: 217-224.

Prior, D.B. and Bornhold, B.D., 1988. Submarine morphology and processes of fjord fan deltas and related high-gradient systems: modern examples from British Columbia. In: W. Nemec and R.J. Steel (Editors), Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Son, London, pp. 125-143.

Prior, D.B. and Bornhold, B.D., 1989. Submarine sedimentation on a developing Holocene fan delta. Sedimentology, 36: 1053-1076.

Prior, D.B. and Bornhold, B.D., 1990. The underwater development of Holocene fan deltas. In: A. Colella and D.B. Prior (Editors), Coarse-Grained Deltas. *Int. Assoc. Sediment. Spec. Publ.*, 10: 75-90.

Prior, D.B., Wiseman, W.J., Jr. and Bryant, W.R., 1981a. Submarine chutes on the slopes of fjord delta. *Nature*, 290: 326-328.

Prior, D.B., Wiseman, W.J. and Gilbert, R., 1981b. Submarine slope processes on a fan delta, Howe Sound, British Columbia. Geo-Marine Lett., 1: 85-90.

Prior, D.B., Bornhold, D.B. and Johns, M.W., 1986. Active sand transport along a fjord-bottom channel, Bute Inlet, British Columbia. Geology, 14: 581-584.

Soh, W., Taira, A. anmd Tanaka, T. (in press) Geomorphology and sedimentary processes on a modern slope-type fan-delta (Fujikawa fan-delta), Suruga Trough, Japan. Sedimentary Geology.

Syvitski, J.P. and Farrow, G.E., 1989. Fjord sedimentation as an analogue for small hydrocarbon-bearing fan deltas. In: M.K.G. Whateley and K.T. Pickering (Editors), Deltas: Sites and Traps for Fossil Fuels. Blackwell Scientific Publications, Oxford. pp. 21-44.

Syvitski, J.P.M., Smith, J.N., Calabrese, E.A. and Boudreau, B.P., 1988. Basin sedimentation and the growth of prograding deltas. *J. Geophys. Resear.*, 3(C-6): 6895-7908.

Winn, R.D. and Dott, R.H., Jr., 1977. Large-scale traction-produced structures in deep-water fan-channel conglomertes in southern Chile. *Geology*, 5: 41-44.

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