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# Thin-bedded, Fine-grained Lacustrine Turbidite Facies on the Northern Coast of Jindo and the Adjacent Area: Density underflow-induced, Ash-rich Turbidity Current Deposits

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## ABSTRACT

The sedimentary succession on the northern coast of Jindo and the adjacent area comprises the thinly bedded, fine-grained deposits of an epiclastic sandstone, siltstone, black shale/mudstone, and cherty mudstone (ca. 200 m in vertical thickness), which are interpreted as the finely stratified turbidites mainly by density underflow-induced currents.

Most deposits can be divided into eight facies: thin-bedded, ash-rich massive sandstone layer (mS), graded and laminated mudstone layer (glM), graded mudstone layer with ripple lamination (rM), laminated and graded siltstone layer (lgZ), finely laminated black shale layer (lBS), structureless mudstone layer (mM), thin-bedded cherty mudstone layer (lCM), and contorted and laminated mudstone layer (dlM). The thin-bedded, ash-rich sandstone facies is interpreted to be deposited from high-density turbid underflows during a relatively large flooding. Most thinly bedded mudstone facies would be deposited from low-density turbid underflows (turbidity currents) with some different hydrodynamic condition and sediment concentration during the high discharge of river water. Whereas the structureless mudstone facies may result from raining down of suspended sediment intermittently supplied by overflows and interflows.

From the entire succession, graded and laminated mudstone layers interbedded with thin-bedded, ash-rich massive sandstone are dominant in the lower part of the succession, and graded mudstone layers with ripple lamination ripple lamination occur mainly in the middle part of it. On the other hand, laminated/graded siltstone and contorted/laminated mudstone layers prevail in the upper part. The transition of facies association is suggestive of the continuous change of main depositional setting from basin plain to lower slope, which could be due to the movement of depocenter by the increase of sediment supply (volcanic activity).

## INTRODUCTION

Since the occurrence of sediment-laden underflows in Lake Geneva was recognized by Forel (1885), their role as a sediment transport agent in lakes has been discussed by many workers (Kuenen, 1951; Gilbert, 1975; Gustavson, 1975; Sturm and Matter, 1978; Lambert and Hsu, 1979; Weirich, 1986). Most works for turbid underflow deposits have been restricted in the modern glacial-influenced lacustrine environments. The sediment discharge from melt water and the seasonal variation of lake stratification are generally the main controlling factors for the sedimentation of glacial-influenced lakes (Sturm and Matter, 1978; Weirich, 1986a, 1986b). On the other hand, in volcaniclastic lacustrine setting the sediment supply affected by volcanic activities, lake chemistry/stratification and tectonic influence on the margin seem to be much important to understand lake sedimentation. In any lake, the sediment load is transported by the various types of rivers except for the direct supply from slope failure and is deposited mainly by overflows, interflows, and underflows depending on the density difference between river and lake water, especially on the lake slope. Above all, the density underflows play much important role for the sedimentation on basin floor and lower slope environments, especially on the active volcaniclastic lacustrine setting like this area

Although many works for turbidites have been carried out in deep-sea settings, there are a few studies on the ancient lacustrine turbidites. The turbid underflows in the lake slope seemed to be similar hydrodynamically to the classic turbidity current on the deep-sea fan slope. It is therefore expected that the resulting deposits and facies patterns would be analogous each other. Facies models for the deep-sea turbidity current deposits were relatively well known, even if they are not sufficient to explain the lacustrine counterparts (Mutti and Ricci Lucchi, 1972; Piper, 1978; Stow and Piper, 1984; Pickering et al., 1986). The sedimentary deposits on the northern coast of Jindo and adjacent area are good example to compare facies pattern in lacustrine setting with that in deep-sea setting. The purpose of this paper is to understand the characteristics and depositional processes of lacustrine turbidite, influenced commonly by ash-rich volcaniclastic input. Compared with the deep-sea turbidite, lack of sedimentological studies on the lacustrine turbidite warrants for the detailed facies analysis and interpretation of the thinly bedded fine-grained deposits, which are well outcropped along the wave-cut cliffs of study area.

## GEOLOGIC SETTING

The Cretaceous nonmarine sedimentary successions and volcanics in the Korean Peninsula largely occur in the southeastern part (Kyongsang Basin) with subordinate patchy exposures in the southwestern part (Haenam, Neungju, Jinan, Kyokpo, Yongdong, Kongju and Eumsung basins) generally trending NE-SW. These basins are interpreted as extensional basins formed in the overriding continental plate and frontal part of the arc caused by oblique convergence giving rise to strike-slip movement (Chun, 1990; Chun and Chough, 1992).

The Cretaceous volcanic and sedimentary succession of the study area are divided into andesitic tuff/andesite, Uhangri Formation, Hwangsan tuff, and rhyolitic tuff/rhyolite in ascending order. The sedimentary succession on the northern coast of Jindo and adjacent area has been referred as part of Uhangri deposits by many earlier workers (Lee and Lee, 1976; Son et al., 1980; Chun, 1990; Koh and Chang, 1996). However, the stratigraphic and lithologic patterns on the study area suggest that this succession seems to be a discrete sediment body, which is intercalated within the Hwangsan tuff, not in the Uhangri Formation.

The sedimentary succession of the study area largely comprises the thinly bedded epiclastic sandstone, siltstone, mudstone/black shale, and cherty mudstone (ca. 200-m-thick). It has many small-scale soft-sediment deformation structures such as microfaults, microfolds, and microflames and load structures, which all suggest the relatively rapid sedimentation on the lake slope.

## FACIES CHARACTERISTICS AND INTERPRETATION

From the detailed measurement and the facies analysis lamina by lamina in the Yangjungri and Jugjeon sections, the fine-grained sediments could be divided into eight types of facies (Fig. 1). Each type is presented by the facies code as proposed by Ghibaudo(1992) with some modifications.

***Thin-bedded, ash-rich massive sandstone (Facies mS)*** consists of fine-to-medium -grained, thin to medium bedded (5 to 20cm thick), and ash-rich sandstone layers with sharp lower boundary. Rip-up clasts are often observed in the lowermost part of some sandstone layers. Rip-up clasts consist mostly of laminated black shales, and parallel to the bedding plane. Most layers show massive or slight normal grading, but some layers show the transition of lower massive to upper crudely stratified structural pattern. These facies are dominant in the lower to middle part of the Yangjungri section. This facies is essentially similar to Ta division and Facies B1.2 described by Bouma(1962) and Pickering et al.(1986), respectively. It suggest the deposition from rapid suspension sedimentation of ash-rich turbidity currents during a relatively large flooding

***Graded and laminated mudstone (Facies glM)*** consists of laminated and normally graded mudstone (1 to 15 cm thick) with sharp upper and lower boundaries. 5 mm to 1 cm thick laminae are also observed in the middle part of the Yangjungri section. It occasionally shows a thinning-upward trend. Microflames and load structures occur sometimes in contacts between laminae. This mudstone facies is predominant in the lower to middle part of the Yangjungri section. This facies is similar to the graded mud facies (E2 and E2.1) described by Piper(1978) and Pickering et al.(1986). Normal grading and sharp base of this facies suggest the deposition from low-density turbidity current. The presence of microflames and load structures suggests rapid deposition.

***Graded mudstone with ripple lamination (Facies rM)*** consists of thin-bedded (5 to 15 cm thick) siltstone, with grading upward into structureless mudstone. Low-amplitude, high-wavelength ripples, fading ripples, and starved ripples are common at the base of these layers. Individual siltstone layer is typically normally graded and characterized by sharp basal contact. These layers occur mainly in the lower part of the Yangjungri section. The well-defined grading and presence of rippled laminae suggest that this facies was deposited from low-density silty turbidity current.

***Laminated and graded siltstone (Facies lgZ)*** consists of siltstone laminae alternating with very fine siltstone, grading upward into normally graded mudstone. Individual laminae are 0.5 to 2 mm thick, and the entire bed thickness ranges 2 to 10 cm thick. Stratified lamination to normal grading is predominant in this facies. The upper and lower boundaries are sharp. This facies prevails in the upper part of the Yangjungri section. This is similar to the laminated silts described by Piper (1978) and Facies D2.1 by Pickering et al.(1986). Parallel lamination, sharp bases, and fine-grain sizes suggest grain-by-grain deposition from suspension, followed by traction transport. Mud-grade tops are deposited from suspension, with no subsequent traction transport.

***Finely laminated black shale (Facies lBS)*** consists of regularly alternating dark and light gray laminae (1-3 mm thick). Sometimes microflames, irregular load structures and synsedimentary reversed microfaults were observed. The individual lamina shows normally graded. The laminated black shale beds prevail in the upper part of the Yangjungri and Jugjeon sections. Alternating dark and light gray laminae of this facies are characteristic of the laminated mudstone (E1), thin regular laminae (T3) and laminated muds and clays (Facies E2.2) described by Piper(1978), Stow and Shanmugam(1980), and Pickering et al(1986), respectively. Microflames and load structures probably resulted from rapid deposition. The abundance of synsedimentary reversed microfaults suggests the presence of depositional slope during the sedimentation and/or rapid sedimentation. This facies is interpreted as the suspension settling by the overflows repeatedly produced due to the seasonal change of river input, or by the fluctuation of sedimentary/chemical events. Low-density turbidity currents may contribute to the formation of some layers.

***Structureless mudstone (Facies mM)*** comprises homogeneous mudstone. Individual layers range from 2 cm to 60 cm in thickness and are characterized by sharp basal contact. Petrographic examination of the structureless mudstone interval shows a very subtle normal grading and is also characterized by faintly convoluted laminae in some layers. They occur mainly in the lower to middle part of the Yangjungri section. This facies is analogous to Piper's (1978) ungraded mud (E3) deposits, which are interpreted to have accumulated from mud-rich fine-grained turbidity current. Alternatively, ungraded layers may reflect deposition from stationary sediment clouds by overflows.

***Thin-bedded cherty mudstone (Facies lCM)*** consists of olive gray, normally graded, and thin-bedded (5 to 15 cm thick) cherty mudstone exhibiting sharp upper and lower boundaries. The normally graded thin silt layer (1 cm thick) at the base is observed, grading into cherty mudstone and again laminated chert. Individual chert lamina is 1 to 10 mm thick, and shows progressively thinning upward trend. The cherty mudstone layers occur mainly in the lower part of the Yangjungri section. This facies may result from chemical fluctuation of lake water by episodic riverine inputs, resulting in alternating precipitation under high and low pH conditions (Chun, 1990; Chun and Chough, 1995; Chough et al., 1996).

***Contorted and laminated mudstone (Facies dlM)*** comprises folded and slightly contorted, essentially coherent to semi-coherent strata in irregularly-shaped layers or horizons, ranging from 10 to 150 cm in thickness. Discrete internal glide or shear surfaces may be recognizable. Internal structure, bed thickness and grain size of this facies are highly variable. There may be a consistent sense of overturning in any folded interval, and locally such folds may be of relatively constant wavelength and amplitude. Mud-rich layers tend to deform plastically and may inject microfaults. These folded layers occur mainly in the upper part of Yangjungri and Jugjeon sections. This facies probably results from slides and rotational slumps, either due to depositional overloading of loose sediments or to cyclic or single shocks (earthquakes) on slopes.

The sedimentary successions of the Yangjungri and Jugjeon sections are characterized by planar- and thin-bedded (mostly laminated) and laterally continuous fine-grained mudstones interlayered with thin-bedded ash-rich sandstones. Laminated/graded mudstone, graded mudstone with ripple lamination, and thin-bedded cherty mudstone layers occur predominantly in the lower to middle part of the Yangjungri section. The laminated(stratified)-graded siltstone, finely laminated black shale, and contorted mudstone layers prevail in the upper part of this succession. Finely laminated black shale layers intercalated with thinly massive sandstone are also dominant in the Jugjeon section. Contorted mudstone layers are characteristics of the upper part of the Yangjungri and Jugjeon sections. These change of facies association suggests a transition of basin plain into slope setting.

## DISCUSSION AND CONCLUSION

On the margin of lake, most sediment load is transported/deposited by overflows, interflows, and underflows (low- and high-density turbidity currents). Especially, density underflows play a major role as a sediment transport agent in the siliciclastic lakes of this tectonically active region. Thermohaline stratification is also important factor for the sedimentation in this subtropic nonmarine setting.

The thin-bedded ash-rich sandstone layer, with sharp bases, massive to slightly grading, and some rip-up clasts, is similar to the Ta division of the Bouma succession in its sedimentological characters, suggesting rapid deceleration of turbidity current. These high-density turbidity flows may occur probably as a result of a relatively large flooding during the increasing volcanic activities. Graded and laminated mudstone layers with ripple lamination, which show planar and laterally continuous, are interpreted to have accumulated from low-density turbidity underflows during the high discharge of river water. Paleocurrent direction obtained from ripple lamination is approximately NNE-SSW trend, which indicates the direction of sediment supply, without the possibility of flow deflection. Fine-grained sediments supplied by overflows and interflows rain down continuously to form structureless mudstone layers (Fig. 2).

Graded and laminated mudstone layers with ripple lamination are dominant in the lower to middle part of the Yangjungri section, whereas laminated (stratified) siltstone and contorted mudstone layers occur predominantly in the upper part of this succession. This change of facies association would be attributed to the transition of depocenter from basin plain (distal) to slope setting (proximal) (Fig. 2). Toward the uppermost part of the Yangjungri and Jugjeon sections, the abundance of small-scale deformation structures indicating the presence of depositional slope supports the transition. This uppermost part is also rich in volcanic ash fragments. Such facies transition may be due to the increase of sediment supply from active volcanism, resulting in the movement of depocenter toward the basin center. The laterally continuous and finely laminated black shale layers intercalated with thin sandstones are dominant in the Jugjeon section. In the upper part of this section, slumps and contorted black shale layers are also dominant. These contrasts of facies characteristic and lithology both in the Yangjungri and Jugjeon sections indicate the presence of different source, but the founding of much more evidence will be needed to support it fully.

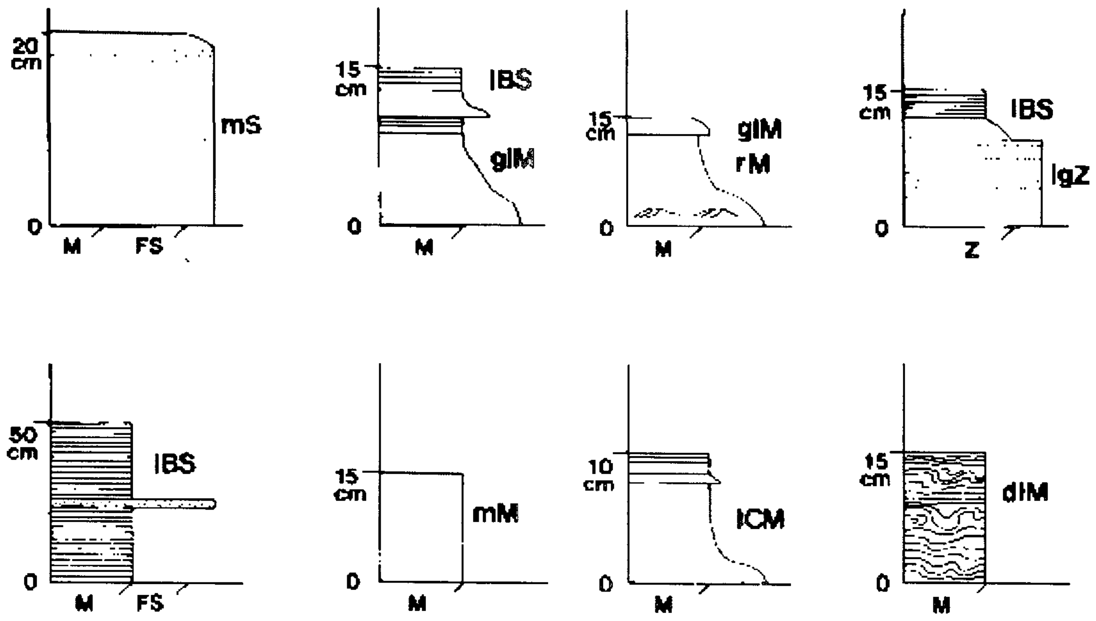

Fig. 1. Sedimentary facies which which occur dominantly in the Yangjungri and Jugjeon sections. FS, Z, and M denote fine sandstone, siltstone, and mudstone, respectively.

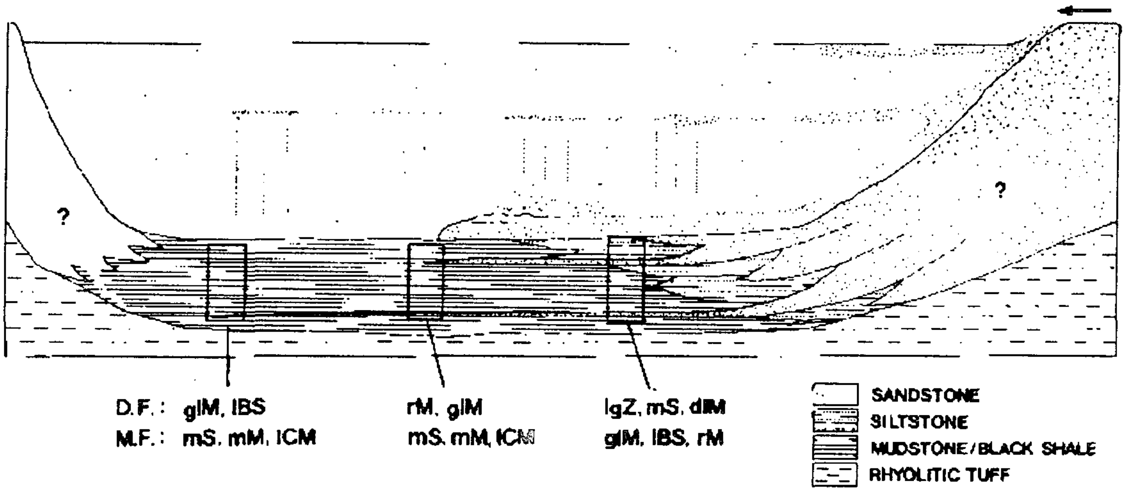

Fig. 2. A schematic feature of a turbid density underflow and the resulting prevalent facies. D.F. and M.F. represent the dominant facies and minor facies which occur in the studied sections, respectively.

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