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HYDRAULIC CONDITIONS OF TURBIDITY CURRENTS ESTIMATED BY INVERSE ANALYSIS

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Sediment-laden density flows called turbidity currents occur in delta foresets or submarine canyons, transporting sediments form shallow to deeper regions and forming turbidite deposits. Actual hydraulic conditions of turbidity currents such as flow velocity or sediment concentration has been hardly clarified because the flows are subaqueous so that it is quite difficult to observe directly. Here, we attempted to establish the method to estimate hydraulic conditions of turbidity currents by inverse analysis of ancient turbidite deposits. We calculated turbidite bed profiles with arbitrary initial conditions, and then quantify the degree of difference of thickness profiles between the calculated bed thickness and the actual turbidite bed thickness, which is subject to analyze, as a model evaluation function. We find the combination of initial conditions $\boldsymbol{x}$ that minimize the model-evaluate function, and we consider the discovered parameters as a condition that actualize deposition of the natural turbidite deposits. To test our method, we examined the deposit of river-generated turbidity (hyperpycnal) currents in the Panther Tongue Sandstone, Utah, USA. The investigated hyperpycnl beds were inferred to have deposited on the foreset of the delta. Using of inverse analysis, we estimated that the river-generated turbidity current that formed a hyperpycnal bed in the Panther Tongue Sandstone had around 3 to 9 vol. % in concentration and 2 to 5 m/s in flow velocity. Calculated flow conditions seem to be reasonable, but it is necessary to evaluate the range of values of our estimations against modern systems, and progress both of the forward model and the evaluation function in the future development of the method.

Key Words : *delta front, density current, genetic algorithm, hyperpycnal flow*

1. INTRODUCTION

Sediment-laden density flows called turbidity currents constitute one of main processes transporting sediments from shallow to deep regions in the dams and submarine environment[1)]. River water containing suspensions has higher density than clear water of dams and can occasionally exceeds density of sea-water, so that they intermittently occur from turbid river water at delta foresets of dams or oceans during river floods. As a result, they form very large body of sandy deposits called turbidites. Turbidites can be good reservoir of petroleum or gas-hydrates, and therefore prediction of behavior of turbidity currents is significant issue both for maintaining dams and for resource geology. However, actual hydraulic conditions of turbidity currents such as flow velocity or sediment concentration has been hardly clarified especially in coastal environment because the flows are subaqueous so that it is quite difficult to observe directly.

Here, we attempted to establish the method to estimate hydraulic conditions of turbidity currents by inverse analysis of ancient turbidite deposits. It is known that numerical simulation using layer-averaged one-dimensional model can successfully predict longitudinal thickness profile of turbidite beds with prescribed initial conditions such as slope inclination, flow velocity, flow thickness, sediment concentration, and so on[2]. Therefore, we calculated turbidite bed profiles with arbitrary initial conditions using the simple model, and then quantify the degree of difference of thickness profiles between the calculated bed thickness and the actual turbidite bed thickness, which is subject to analyze, as a model evaluation function. We find the combination of initial conditions $\boldsymbol{x}$ that minimize the model evaluation function $W(\boldsymbol{x})$, and we consider the discovered parameters $\boldsymbol{x}$ as a condition that actualize deposition of the natural turbidite deposits.

2. OBJECTIVE OF ANALYSIS

We examined the deposit of river-generated turbidity (hyperpycnal) currents in ancient strata called the Panther Tongue Sandstone, Utah, USA. The Panther Tongue crops out on the eastern side of the Wasatch Plateau and on the western side of the Book Cliffs. Coarsening-upward deposits of the Panther Tongue form vertical sandstone cliffs with a maximum thickness of 30 meters. The Panther Tongue Sandstone is Campanian in age (ca. 80 millions years ago). The Panther Tongue sandstone was specifically interpreted as deltaic by Newman and Chan[3]. A detailed ichnological study of the Panther Tongue suggested environmental facies intermediate between offshore and nearshore[4]. In a sequence stratigraphic framework, Panther Tongue deposits have been interpreted to be a lowstand delta, formed during a forced regression[5].

The investigated hyperpycnl beds were inferred to have deposited on the foreset of the delta. The hyperpycnal facies links with deposits of the channel-moth bar complex at their upstream end, and pinch out basinward at the base of the distal delta front. More detail information is available in Olariu and Bhattacharya[6].

Thickness distribution and slope inclination of sand beds are measured by ground-based LIDAR (LIght Detection and Ranging) system[7]. Ranges of measurements were about 200-400 m because of limitation of the outcrop exposure. In addition, grain-size distribution of sand comprising measured beds was determined by image analysis of microscopic photographs of deposits.

3. METHODOLOGY

It is known that most hyperpycnal flows (river-generated turbidity currents) are regarded as quasi-steady flows[8], so that we approximated the turbidity currents of analysis objective as steady-state flows. In this case the equations of water mass balance, momentum balance, suspended sediment mass balance, and washload sediment mass balance can be written in the respective forms:

$$\frac{dUh}{dx} = e_w U \qquad (1)$$

$$\frac{dU^2 h}{dx} = -\frac{1}{2}\frac{Rg\partial Ch^2}{\partial x} + RgCS - u_*^2 \qquad (2)$$

$$\frac{dUC_s h}{dx} = v_s(e_s - r_o C_s) \qquad (3)$$

$$\frac{dUC_w h}{dx} = 0 \qquad (4)$$

where U denotes layer-averaged flow velocity, h is flow thickness, and C_s and C_w are layer-averaged concentration of suspension and washloads respectively. S is slope inclination, v_s is settling velocity of suspended sediments, e_s is non-dimensional rate of sediment entrainment[9], e_w is non-dimensional rate of ambient water entrainment[10], g is gravity acceleration, r_o is ratio of near-bed concentration of suspension against C_s, and u_* is shear velocity. Details on model formulation and parameter determination are provided in Kostic and Parker[11].

From the model described above, thickness of turbidite Dm can be calculated as follows:

$$D_m = \frac{1}{1-\lambda} T v_s (r_o C_s - e_s) \qquad (5)$$

where T is duration of the flow, and λ is porosity of the bed. Then, as a model evaluation function, we employed the square mean of normalized difference of bed thickness between calculated thickness D_m and measured thickness D_o. Thus, model evaluation function $W(\boldsymbol{p})$ is expressed as follows:

$$W(p) = \frac{1}{n}\sum\left(\frac{\|Do_i - Dm_i\|}{\|Do_i\|}\right)^2 \qquad (6)$$

where n is number of measurements, and $\boldsymbol{p}$ denotes parameter set ($U_0, h_0, C_{s0}, C_{w0}, T$) that is required for model calculation.

To find parameter set that minimize the model-evaluation function $W(\boldsymbol{p})$, genetic algorithm with population size 100,000 and 100 generation was used. Then, the modified powell's method was optimized the solution. The optimized parameter set found by the procedures described above can be interpreted as a best explanation of actual bed deposition.

4. RESULTS AND DISCUSSIONS

Totally seven beds were analyzed, and the inverse analysis revealed hydraulic parameters of hyperpycnal turbidity current that deposited Panther Tongue Sandstone. Total sediment concentrations were estimated to range from 3 to 9%, and the ratio between suspension and washloads was 10 to 55 %.

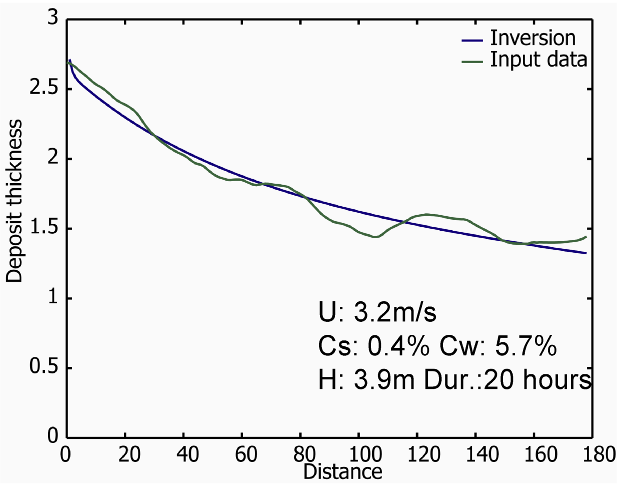

Fig. 1. An example of the result of inverse analysis. Thickness distribution of natural turbidite was well reproduced by model calculation.

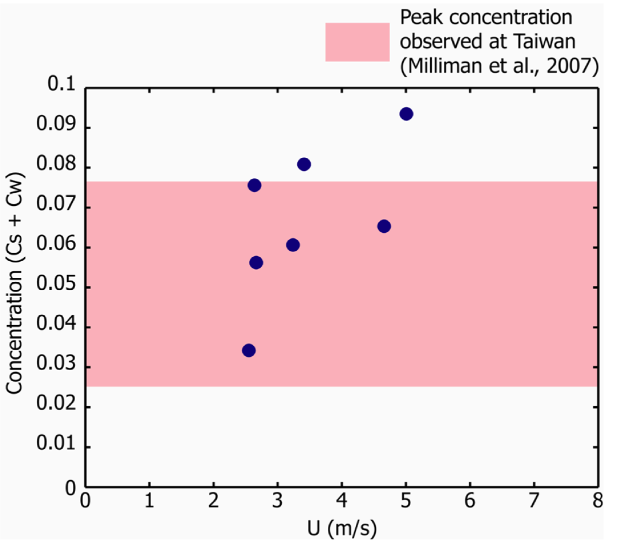

Fig. 2. Summary of results of inverse analysis. Reconstructed values of flow velocity and sediment concentration is consistent with values observed at modern river mouth in Taiwan[12].

Also, layer-averaged flow velocity was about 2-5 m/s. Flow thickness and duration were estimated to be 2-6 m and 1-3 hours respectively (Figs. 1 and 2).

It is difficult to evaluate results of our method because direct measurements of recent hyperpycnal flows are absent. However, at near mouth of flooding turbid river, Milliman et al.[12] measured sediment concentration of river water that is supposed to be producing hyperpycnal flows. Range of their measuremens are almost conformable to our estimation by inverse analysis. Considering Panther Tongue Sandstone deposited quire near the ancient river mouth[6], consistency between their measurements and estimated values suggests that estimation in this study seems plausible.

Also, we predicted the maximum extent of beds using the forward model with reconstructed values. As a result, it is estimated that each bed distributes 1-4 km in maximum. This predicted range is consistent with the actual distribution of the beds contained in Panther Tongue Sandstone, whereas the measurement interval was only 200-400 m. Thus, this consistency between prediction and observation again justifies assumptions employed in this study, and it implies that the method is efficient for prediction of bed extents from limited data sets. In the future development of the method, however, it seems necessary to evaluate the range of values of our estimations against modern systems, and progress both of the forward model and the evaluation function

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