A comparative study on suspended sediment discharge initiated by snow- or glacier-melting

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Abstract The physical mechanism on suspended sediment discharge in rivers is examined by comparing observational results from a snow-covered drainage basin (Ikushunbetsu River, Hokkaido, Japan) with those in a glacier-covered one (Peyto Creek, Alberta, Canada). Ikushunbetsu River discharges a considerable amount of sediment into Katsurazawa Reservoir during the snowmelt period of March-May, while Peyto Creek produces the dominant sediment input to Peyto Lake during the glacier-melt period of June-September. Common to the two rivers is the condition that the suspended sediment consists of more than 90% of silt and clay, and the sediment concentration of water varies diurnally in phase with water discharge. In the Ikushunbetsu River basin, the fine sediment originated from weathered soil produced from Cretaceous bedrock, whereas in the Peyto Creek basin, it is yielded from the erosion of dolomitic bedrock due to the downslope movement of Peyto Glacier. The sediment discharge is probably caused by the fluvial entrainment of the yielded sediment which is accumulated on the riverbank (Ikushunbetsu) or around subglacial channels (Peyto).

INTRODUCTION

The yield and fluvial transport of fine sediment such as silt and clay ($d < 63$ μm) in a drainage basin is important for sedimentation in lakes and reservoirs, because the slow settling provides the opportunity for extensive redistribution by wind-driven currents, and density currents (e.g. Chikita *et al.*, 1991; Chikita, 1992; Gilbert, 1975; Smith *et al.*, 1960). For example, more than 90% of the deposits in Katsurazawa Reservoir, Hokkaido, Japan consists of silt and clay (Chikita, 1977), while in Peyto Lake, Alberta, Canada, 68% of the deposits are explained by sedimentation from density currents suspending silt- and clay-sized grains (Chikita, 1992). Kurashige (1992) classified a variety of suspended sediment discharges observed over the world into three types, each characterized by a different mechanism depending on the land surface condition. The physics of the discharge processes, however, is not yet satisfactorily examined. In this study, the origin of fine sediment produced in the two drainage basins is identified, and the mechanism of suspended sediment discharge initiated from the snow- or glacier-melting is discussed together with processes of sediment yield.

STUDY AREAS AND METHODS

The hydrological and meteorological measurements in the Ikushunbetsu River basin (43°11'N, 142°03'E) were conducted at and near A during the snowmelt period of March-May 1984 (Fig. 1; Chikita, 1989, 1990; Chikita & Okumura, 1990). Water level and the temperature were continuously measured with a stage recorder of gas-purging type (accuracy, ± 2 cm) and a platinum thermometer (± 0.05°C), respectively. Rainfall and air temperature were measured using a tipping bucket raingauge and a platinum thermometer. Frequent measurements of river discharge produced a stage-discharge relationship to obtain temporal variations in river discharge. In order to evaluate the suspended sediment concentration and its grain size, the river water was sampled at least twice a day, using an automatic sampler. River-bed materials and riverbank sediment at the foot of gorges were sampled in order to identify the origin of suspended sediment by comparison of grain size. The basin area is 60.0 km^2 upstream of A at 187 m a.m.s.l. (above mean sea level). The gorges of bedrock with slopes of 40-55° occur alternately along the river channels, and topographically the "riverbank" is equivalent to the foot of the steep slopes. The basin geology is Cretaceous mudstone, sandstone, conglomerate, shale and tuff. The precipitation in 1984 amounted to 1134 mm, 60% of which comprised snowfall in January-March and November-December.

Similarly, the hydrological measurement in Peyto Creek (51°44'N, 116°31'W) was performed at A during the glacier-melt period of July-August 1987 (Fig. 2; Chikita *et al.*, 1991; Chikita, 1992). Station A is located at the upstream head of a braided

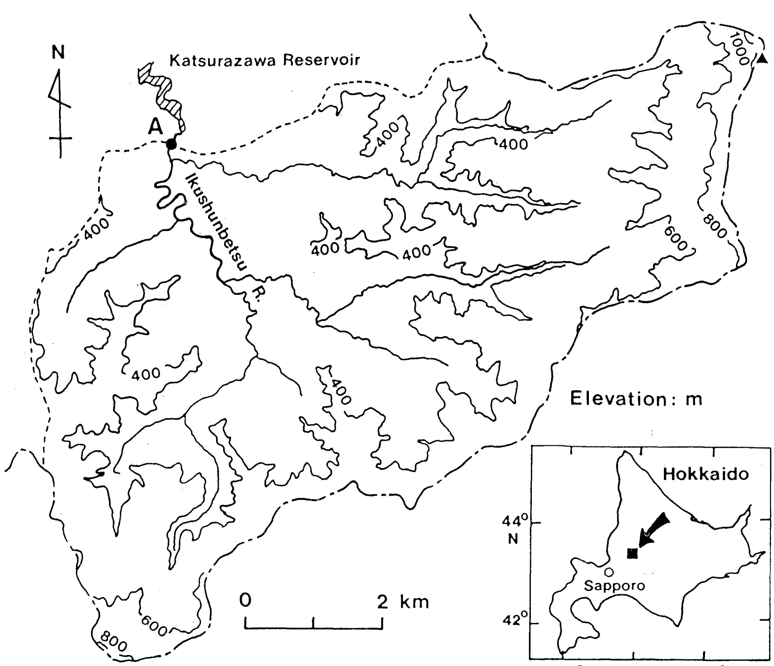

Fig. 1 Location and drainage basin of Ikushunbetsu River, Hokkaido, Japan. The river is a main one flowing into Katsurazawa Reservoir. The study site is indicated (A).

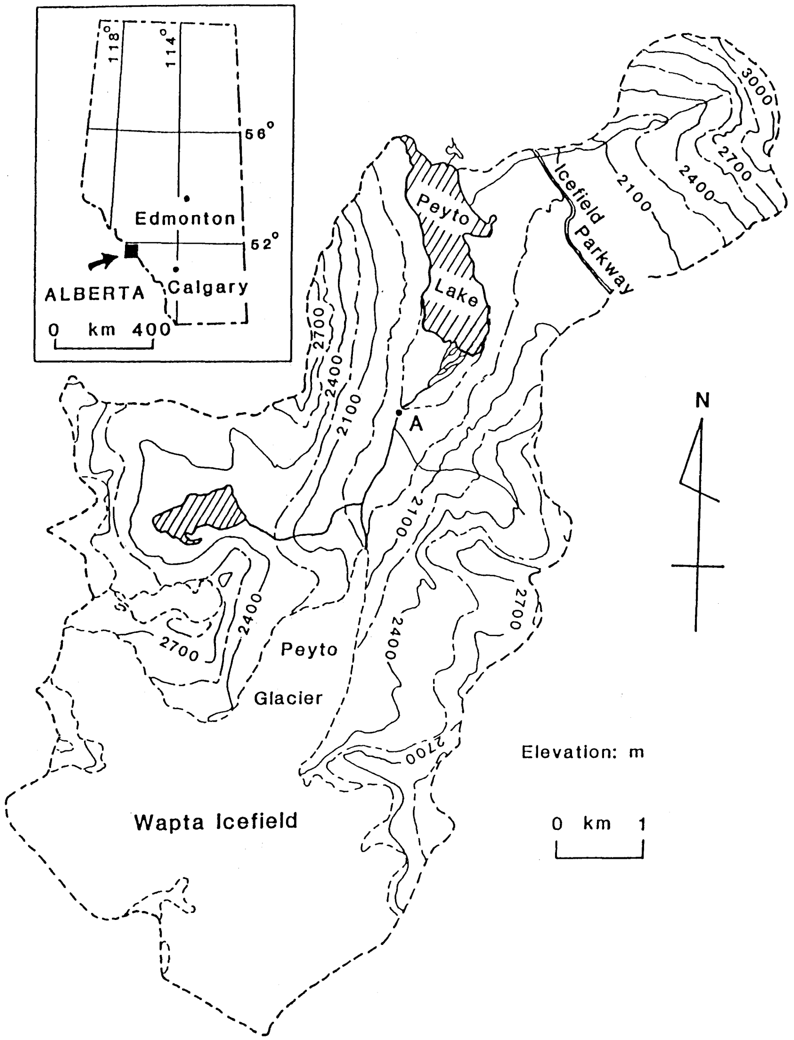

Fig. 2 Location and drainage basin of Peyto Creek, Alberta, Canada.

outwash plain prograding into Peyto Lake. The water level was measured at A using a stage recorder of Stevens type. No rainfall was observed in the basin, but I otherwise referred to the data of the Lake Louise meteorological station (40 km south-southeast of Peyto Lake). Frequent water sampling was manually carried out. Some sediments were sampled around the river channel and at the glacier toe in order to trace the origin of the suspended sediment. The area of the Peyto Creek basin is 37.0 km^2 upstream of A, 30% of which is covered by a glacier (Peyto Glacier). Peyto Glacier exists over 2100-3200 m a.m.s.l., and is extruded from the Wapta Icefield. The basin geology is Precambrian and Cambrian argillite, limestone and dolomite. The mean annual precipitation in 1951-1980 is 684 mm at Lake Louise, 62.0% of which is due to snowfall from October through May.

The suspended sediment concentration was evaluated by filtering the water sample with a millipore filter (0.45 μm opening) and then drying the filter at 105°C more than

2 hr. The grain size of suspended sediment and river-bed and riverbank sediment was analyzed by a gravitational settling method ($d \leq 44$ μm) and by sieving ($d > 44$ μm). Before analysis, the grain density was obtained with a pycnometer. The mineralogy of suspended sediment was examined for grains of $31 < d < 250$ μm and $d < 2$ μm, using an X-ray diffractometer. As a result, quartz was found to be common to the two rivers. The roundness and surface texture of sand-sized ($88 < d < 125$ μm) quartz grains were thus observed with a polarizing microscope, because these features would be distinguishable between the two basins, depending on a difference in sediment-yielding conditions.

RESULTS AND DISCUSSION

Hydrology and meteorology

Figure 3 shows examples of temporal variations in hydrology and air temperature for (a) Ikushunbetsu River (27 April-6 May 1984) and (b) Peyto Creek (9-15 July 1987). No rainfalls occurred during these periods. In Ikushunbetsu River, the maximum discharge and sediment concentration throughout the snowmelt period were recorded at 20:00 on 28 April, giving 60.1 $m^3 s^{-1}$ and 6680 mg l^{-1}, respectively. The water temperature and discharge diurnally varied with a time lag of 0-1 hr and 6-8 hr, respectively, relative to air temperature. The small time lag between air and water temperatures suggests that the river temperature is determined by the surface heat flux, probably mainly by shortwave and long-wave radiations (Yamada, 1984). The large time lag between air temperature and discharge is generally explained by the time consumption by snowmelt water produced at snow surface, which infiltrates in the snow mass toward bedrock, and then flows down to the river channel (Oura *et al.*, 1967). Discharge is perfectly in phase with suspended sediment concentration. This suggests that an increase of flow shear stress with increasing discharge linearly increases the amount of sediment entrained. Identifying the origin of suspended sediment is thus necessary so as to examine where and how the fluvial entrainment of sediment occurred.

In Peyto Creek, by contrast, a significant time lag did not occur between air temperature and water discharge, though they varied almost diurnally (Fig. 3(b)). Little snow cover was then seen expect on and around the glacier, and thus Peyto Creek was probably occupied by the meltwater from Peyto Glacier and ice-cored moraines around the glacier (Osborn, 1987). Hence, the very small time lag between air temperature and discharge is likely caused by the quick flow of the meltwater over, inside and under the glacier and from its surrounding area (Sugden & John, 1976). Daytime water temperature appears to decrease with increasing discharge and air temperature. This suggests that the river temperature is controlled by the amount of the meltwater discharged rapidly, rather than the heat flux at the water surface. Meanwhile, as typified on 11 and 12 July, sediment concentration also decreased with increasing discharge in a diurnal cycle, though throughout the observation period, it increases on the whole with increasing discharge. Upstream of Station A, the sediment in and around the channel of Peyto Creek is gravelly, and the fine sediment equivalent to river-suspended sediment was not found (Fig. 4). Hence most of the suspended

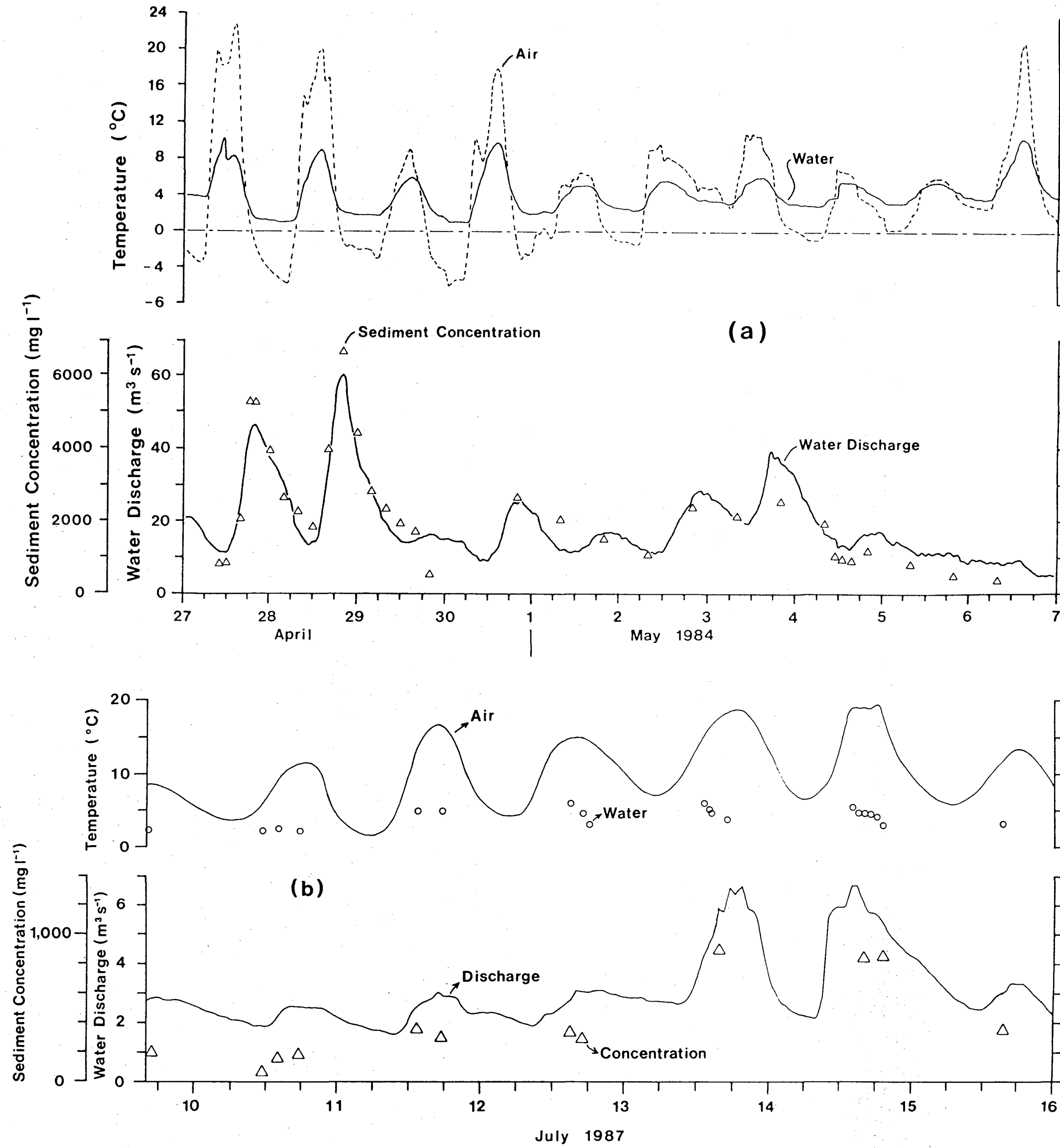

Fig. 3 Temporal variations of air and water temperatures, suspended sediment concentration and water discharge (a) in Ikushunbetsu River and (b) in Peyto Creek.

sediment is likely derived from the glacier toe through a subglacial channel. The decrease of sediment concentration in a diurnal cycle, therefore, is possibly due to the increased supply of relatively clear meltwater from the other places, e.g., ice-cored moraines.

Grain size and mineralogy

Figure 4 shows grain size distributions of suspended sediment in the two rivers

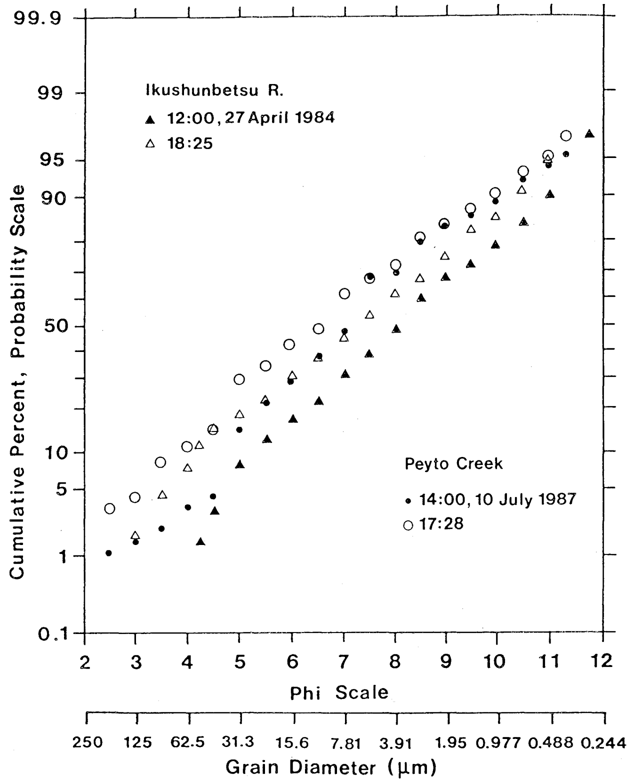

Fig. 4 Grain size distributions of suspended sediment in Ikushunbetsu River and Peyto Creek, plotted on a lognormal probability paper.

described on lognormal probability paper. The phi scale (ϕ) is given by $\phi = -\log_2(10^{-3} \cdot d)$ (d, grain diameter in μm). The suspended sediment commonly exhibits nearly log normal distributions with grain size of silt ($4 < \phi \leq 8$) and clay ($\phi > 8$) more than 90 wt.%. The mean size increases with increasing sediment concentration because of the increased proportion of sand grains.

Table 1 shows the mineralogy of the suspended sediment analyzed with an X-ray diffractometer. For coarse grains ($31 < d < 250$ μm), quartz and plagioclase are dominant in Ikushunbetsu River, and dolomite in Peyto Creek, while clay-sized ($d <$ 2 μm) grains are dominated by quartz, illite and "mixed-layer" clay for the former, and dolomite, and muscovite for the latter. It should be noted that the mineralogy of clay-sized grains differs from the so-called clay mineralogy. The "mixed layer" is a clay mineral peculiar to the Ikushunbetsu River basin. Quartz, the hardest and most stable mineral, is found in both the rivers independent of grain size. The difference in mineralogy between the two rivers evidently results from differences in geology and in processes of sediment yield, which are typified by sand-sized and clay-sized minerals, respectively. It is noted that clay minerals such as Illite and mixed-layer clay are noticeably found in Ikushunbetsu River, whereas little occurs in Peyto Creek except amesite. Furthermore, the sand-sized quartz in Ikushunbetsu River exhibits more roundness in shape than that in Peyto Creek. These suggest that the suspended sediment of Ikushunbetsu River was produced through bedrock weathering under humid climatic

Table 1 Main minerals for grains of $31 < d < 250\ \mu m$ and $d < 2\ \mu m$, contained in suspended sediment of Ikushunbetsu River and Peyto Creek. The peak intensity shows the relative peak height on an X-ray diffraction curve, among the identified minerals.

Ikushunbetsu River						
Minerals	Plagioclase	Quartz	Kaolinite	Illite	Mixed-layer	Chlorite
Lattice spacing, Å	3.2	3.3	7.1	10.0	10.8	14.3
Peak intensity:						
$31 < d < 250\ \mu m$	10	10	1	1	1	1
$d < 2\ \mu m$	1	10	5	10	10	2

Peyto Creek						
Minerals	Dolomite	Calcite	Quartz	Aragonite	Amesite	Muscovite
Lattice spacing, Å	2.9	3.0	3.3	3.4	7.1	9.9
Peak intensity:						
$31 < d < 250\ \mu m$	10	1	1	-	-	-
$d < 2\ \mu m$	10	3	2	10	2	6

conditions, whereas that of Peyto Creek was yielded by the direct erosion of bedrock due to the downslope glacier-mass movement, and was supplied through the subsequent rapid fluvial entrainment. Hence the Ikushunbetsu sediment was likely originated from the weathered soil on bedrock. As an analytical result, the bed of Ikushunbetsu River is always gravelly, and in the samples obtained before the snowmelt season, silt- and clay-sized grains were scarce. Furthermore, the grain size distribution of suspended sediment was similar to that of bank sediment on the foot of gorges. After the snowmelt season, I observed that the fine sediment continuously exists downslope from the humus at the top of gorges and the other slopes. Hence, the suspended sediment discharge of Ikushunbetsu River is considered to occur by the fluvial entrainment of the bank sediment.

Sediment discharge

Figure 5 shows relations between river discharge, Q and suspended sediment concentration, C_s for the discharge less than 8 $m^3\ s^{-1}$. Though the sediment concentration from some water samples obtained simultaneously showed the possibility of an error of 10-20% for a given value, there is a nearly linear relationship for each river except one plot (black) of Ikushunbetsu River. The regression lines in Fig. 5(a) are given by $C_s = 200 \cdot Q - 424$ ($r = 0.96$) for Ikushunbetsu River and $C_s = 202 \cdot Q - 277$ ($r = 0.97$) for Peyto Creek. The slope of these regression lines are thus nearly equal. This suggests the analogous mechanism for sediment discharge of the two rivers, supposing that the sediment concentration is proportional to the amount of sediment entrained under a given flow shear stress. The sediment discharge of Peyto Creek seems to be due to the fluvial entrainment of sediment around subglacial channels followed by transport by rough turbulent flow in the meltwater river. Under the order of the magnitude in shear stress evaluated at A of the two rivers (Figs 1 and 2), net

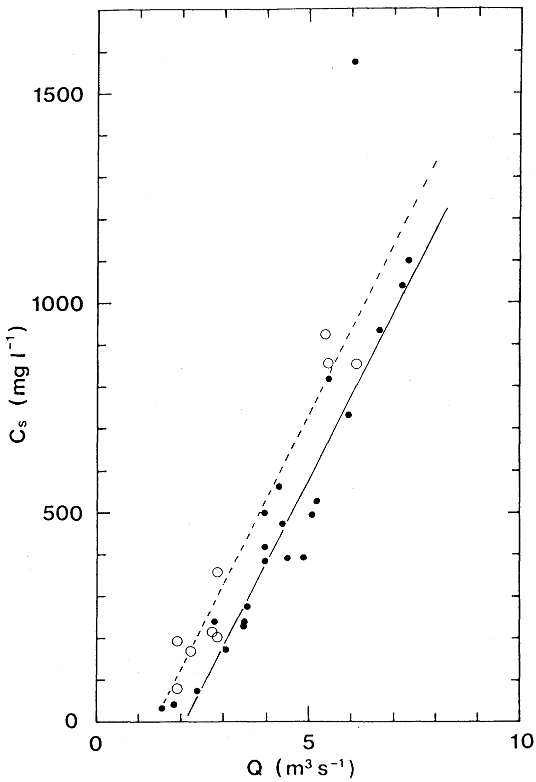

Fig. 5 Relations between water discharge, Q and suspended sediment concentration, C_s for Ikushunbetsu River (black circle) and Peyto Creek (white circle). For Ikushunbetsu River, only the data of 12-21 April are plotted. A regression line is drawn for each of Ikushunbetsu River (solid) and Peyto Creek (dotted).

deposition of fine sediment (silt and clay) probably occurs in either of the channels, since the corresponding plots on the extended Shields diagram are far from the threshold line for erosion (or entrainment) (Mantz, 1977; Chikita, 1990).

Figure 6 shows the overall relation in Ikushunbetsu River between water discharge and sediment concentration. The data are plotted for four parts of the observation period partitioned by the degrees of snow cover around A. For the time period of 12-21 April, 27-29 April, and 29 April-12 May, the snow cover was observed in more than 50%, 20-50%, and less than 20% of the land area, respectively. These are here called the first stage, the middle stage and the last stage of a thaw, respectively. At the first stage (black circles), the more effective entrainment of sediment occurs as shown by the steep slope of the regression line (Fig. 5), whereas at the middle stage (white circles) of discharge more than 8 m^3 s^{-1}, the entrainment efficiency decreases. This is possibly because the amount of sediment accumulated on the riverbank decreases upslope in cross section, due to an increase of the valley wall slope angle from 20-30° to 40-50° at the water level of discharge ~ 8 m^3 s^{-1}. The slope angle of 40-50° is comparable to or more than a repose angle (~ 40°) of the wet fine sediment. The weathered soil on the top of gorges and the other lateral slope is supplied to the riverbank, likely through the erosion and subsequent transport by the downslope

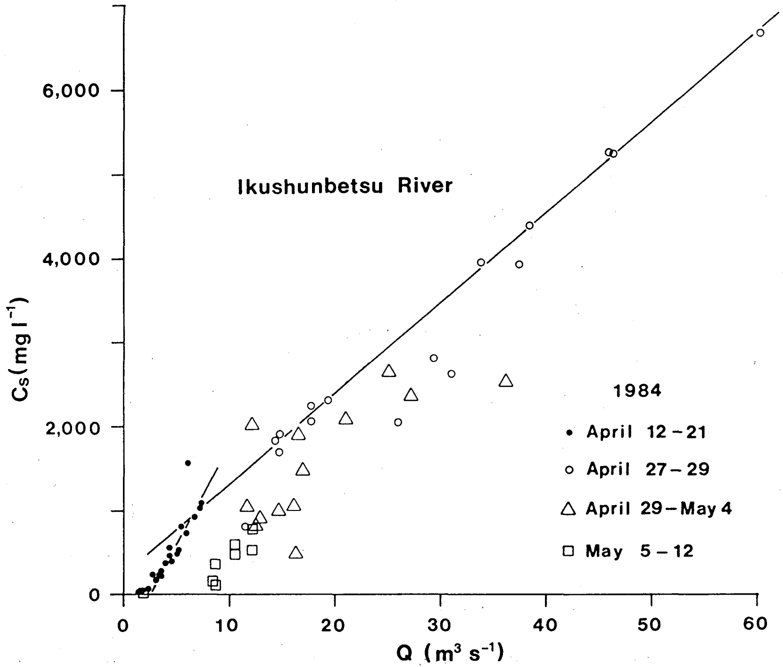

Fig. 6 Total relation between water discharge, Q and sediment concentration, C_s for Ikushunbetsu River. The regression line for black circles is the same as in Fig. 5. The line passing through some white circles indicates the possible upper limit of C_s for give Q.

movement of snow mass during the snowmelt period. The high efficiency in sediment entrainment at the first stage is thus considered to be due to the relatively stable location of bank sediment and its stable supply. At the latter half of the last stage (squares), all the plots are far below the upper limit (solid line) at the middle stage. This is probably due to a great decrease in the amount of available bank sediment after the peak discharge of 28 April, and a decrease or a cessation of the bank- sediment supply by the depleting snow mass.

Figure 7 shows relations at first and middle snowmelt stages of the Ikushunbetsu River between the fluvial force per unit length, T acting on the increment of wetted perimeter p and sediment concentration, C_s. T is given by the product of two times the flow kinetic energy (ρV^2, where ρ is water density and V is the mean velocity in cross section) and the incremented wetted perimeter (P). The ratio, $\tau_b/(\rho V^2/8)$ is known as the Darcy-Weisbach coefficient, f (e.g. Yalin, 1977), where τ_b is the bottom shear stress. ρV^2 is then proportional to τ_b, assuming f constant for the rough turbulent flow over gravel beds. P was given as an increment from the wetted perimeter (P = 8.2 m) at the lowest stage ($Q = 0.37$ m^3 s^{-1}, $C_s \sim 1$ mg l^{-1}) of Ikushunbetsu River observed in the preceding winter. The quantity T thus corresponds to the total fluvial shear force acting on the perimeter increased during the snowmelt period. It is noted that at the first stage (12-21 April), there is a definite, linear relationship shown by a regression line passing through the origin. At the middle stage, there is another linear relationship but with the decreased efficiency as shown in Fig. 7. These suggest that sediment concentration C_s is proportional to the amount of sediment entrained on the

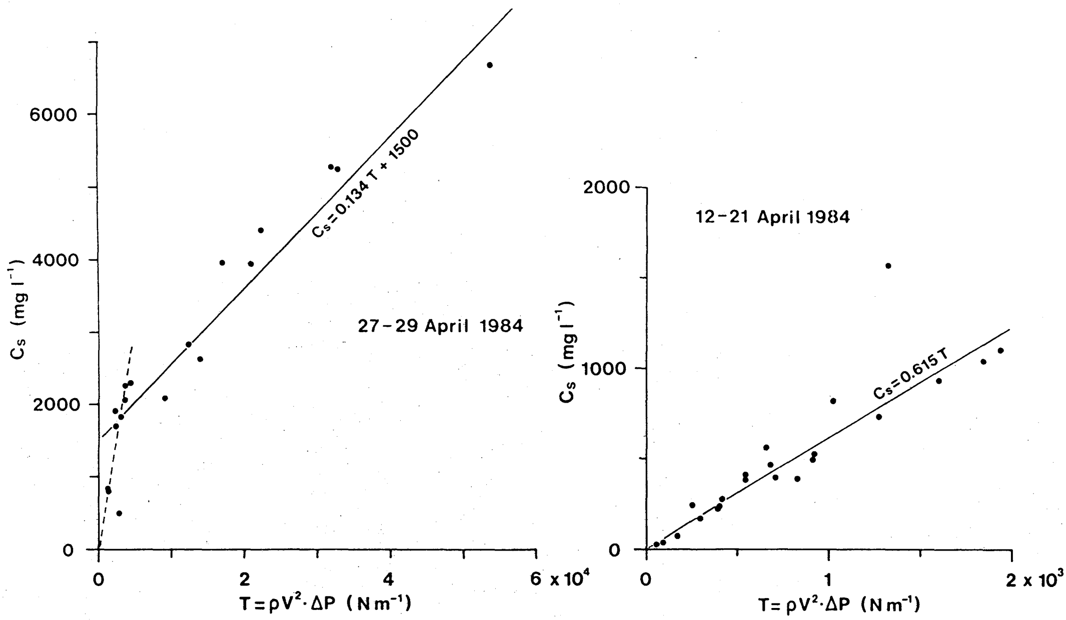

Fig. 7 Relations between the total shear force, T and sediment concentration, C_s at the middle snowmelt stage (left) and the first stage (right) of Ikushunbetsu River. The regression line at the first stage is the same as a dotted one at the middle.

incremented perimeter. As shown in Fig. 5, the remaining discharge at $C_s \sim 0$, possible corresponding to the winter baseflow, appears to be different between the two rivers. This possibly results from the subglacial discharge at the lowest stage, smaller than in Ikushunbetsu River. The lowest subglacial discharge presumably occurs in winter, since Peyto Glacier is a temperate glacier, and thus always has some continuous subglacial melting zone (Ozawa, 1990). The mineralogy of suspended sediment in Ikushunbetsu River indicates mainly cohesive clay minerals such as illite, mixed-layer and kaolinite (Table 1). The equal slope of the two regression lines (Fig. 5) likely indicates that the difference in mineralogy has no effect on the relationship between the entrained-sediment amount and shear force, because of the small amount of clay minerals in the total sediment. If there is any effect, the slope of the regression line may become smaller in Ikushunbetsu River, because the cohesive sediment is relatively resistant to erosion (Task Comm., ASCE, 1968).

FUTURE WORK

The linear relationship between total shear force, T or water discharge, Q and sediment concentration, C_s for Ikushunbetsu River and Peyto Creek (Figs 5 and 7) led to the conclusion that the sediment discharge probably occurs by the fluvial entrainment of fine sediment accumulated around a channel or subglacial channels. This relationship, however, will be true under the condition that the sediment mass entrained at a point is instantaneously determined by a given shear force, and at each observation time, the sediment concentration is already in equilibrium with the shear force, due to turbulent mixing. Actually, some time is needed for the entrained sediment to entirely mix in the turbulent flow. Through future experiments, a relationship between the entrained-sediment amount and flow shear force should be systematically clarified for the mixed sediment of silt and clay. For Peyto Creek, furthermore, the physics of sediment transport following the behavior of glacier-mass and meltwater should be seasonally examined.

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