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Turbidity Currents and Submarine Channel Formation in Rupert Inlet, British Columbia
1. Surge Observations

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Acoustic backscatter images obtained at 107 and 200 kHz of surge-type turbidity currents resulting from mine tailing discharge are presented. Excess densities in the head of the order of 100 kg m^{-3} are estimated from differences in acoustic backscatter intensity and in the amplitude of the bottom-reflected signal. These excess densities are comparable to estimates based on surge height and speed, the speed being determined by assuming a universal head shape. Unlike gravity current surges from an impulsively started steady source, the surge-type turbidity flows consist of a high concentration slug of short duration followed by a longer-lived wake in which sediment concentrations are lower by 2–3 orders of magnitude. The profile of the high concentration slug resembles those for density slugs on small bottom slopes obtained in laboratory experiments. Discrete scatterers, probably fish, are observed to avoid the surges.

1. INTRODUCTION

Turbidity currents are an important sediment transport mechanism in aqueous environments. They are generally thought to be responsible for one of the major features of the seafloor: the submarine fan and fan valley systems issuing from the mouths of submarine canyons. They also represent a hazard which in appropriate conditions can place man's underwater activities at considerable risk. Testimony to their destructive power and the potential damage to seabed structures is provided by instances of submarine cable breakage [e.g., *Heezen and Ewing*, 1952] and the bending of steel rods and the loss of instruments [*Inman et al.*, 1976].

Few direct observations of turbidity currents have been obtained in the field, however. This is particularly true of surge-type flows. The lack of observations is attributable partly to the intermittent occurrence of these events and partly to the high probability that conventional instrumentation would be lost. The purpose of this article is to present the results of a field investigation of surge-type flows using a technique for which there is no risk of loss or damage. The surges are of considerably larger scale than is normally achievable in the laboratory, and the results are relevant to the problem of sediment transport by turbidity currents in general.

The results consist of acoustic backscatter observations at 107 and 200 kHz. It is shown that estimates of surge properties, including probable speeds and excess density, can be extracted from the acoustic records. These quantities are used in the companion paper [*Hay*, this issue] to estimate the excess mass transported per surge and the surge recurrence frequency in Rupert Inlet. The surge shapes in vertical section are compared with those which have often been assumed in the literature and are found to be quite different.

The experiments were conducted in Rupert Inlet, British Columbia, which serves as the receiving basin for tailing discharged by Island Copper Mine. Submarine channel systems were formed in the tailing deposit both by the continuous flow turbidity current associated with the discharge and by surge-type turbidity currents (see *Hay et al.* [1983*a*] and *Hay* [this issue]). The surge-type flows are believed to result from the failure of the submarine channel banks and levees [*Hay et al.*, 1983*b*].

2. ACOUSTIC OBSERVATIONS

The channelization of the tailing deposit in Rupert Inlet underwent a succession of several phases. The observations discussed here were made during the so-called meander and apron phases. These phases are discussed briefly by *Hay* [this issue], but the reader is referred to *Hay et al.* [1983*a*] for details.

Only a single surge was observed during the meandering channel phase. This is the August 1976 event discussed by *Hay et al.* [1982]. The event was detected for a 1.5-hour period in successive acoustic sounding transects across the straight lower reach. Initially characterized by a sharp upper interface, weakened bottom echo, and minimal overspill onto the adjacent levees, the upper interface was observed to become more diffuse, the bottom echo to regain strength, and the overspilled material to spread laterally with time. In addition, a second cloud of sediment was observed to the south of the channel and was ascribed to overspill from an upstream meander.

During the apron phase, three events were detected at 2344, 0225, and 0525 PST, on September 12, 13, and 15, respectively, at station 2 (Figure 1). The 107- and 200-kHz records for the first two of these events are shown in Figures 2 and 3. The third was less distinct and is not discussed here. Figure 2 shows the head regions for the two events in detail. The records are characterized by intense backscatter from the surge. Note that the most intense backscatter is indicated by light gray shading, like that from the bottom immediately ahead of the nose. This arises from the Fineline feature of the receiver, through which signals above a threshold setting are represented by a uniform light gray shading. Following each surge is a lower-amplitude echo from a diffuse wake, the thickness of which tends to increase with time. During the passage of the thicker event (Figures 2*a*, 3*a*, and 3*b*) the amplitude of the bottom echo is attenuated. Peak surge thicknesses are 2–5 m. The surges pass the observation point in 4–6 min, and the

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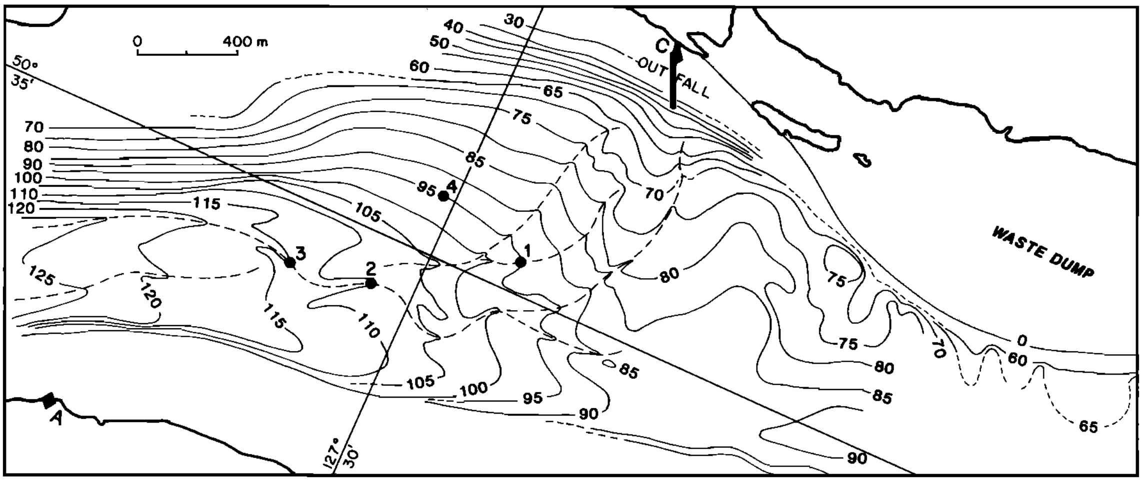

Fig. 1. Tailing deposit bathymetry in September 1978. Contours in meters. Anchor station locations are shown as solid circles.

echo from the wake persists for 0.5–1.5 hours (not shown). These characteristics are similar to those of the August 1976 surge.

A contour plot of the backscattered signal amplitude recorded at 200 kHz during the passage of the September 13 event is presented in Figure 4. The contour levels are in volts. Figure 4 was constructed after analog to digital conversion of the backscattered signal, which was recorded on a Hewlett-Packard model 3960 instrumentation tape recorder. The corresponding echogram (Figure 3*b*) has been discussed previously. This was the only event of the three for which any part of the head region was recorded on tape, and even then the recorder was started after the passage of the nose (compare Figures 3*a* and 3*b*). Figure 5 is a time series of the backscatter amplitude records through the course of the event. The same general features are present in Figures 4 and 5 as in the echogram, and these features may now be discussed quantitatively. The high-amplitude backscatter (>1 V) from the head near time zero at the beginning of the recording, the low-amplitude (<0.25 V) echo from the bottom at the same time, the rapid decrease with time of the backscatter from the shrinking body and wake, and the recovery of the strength of the bottom echo with time are all apparent.

The behavior in relation to the surges of discrete scatterers in the water column is interesting. Both of the acoustic images in Figure 2, particularly Figure 2*b*, give the distinct impression that these scatterers move upward to avoid the surge. It is reasonable to assume that these targets are individual biota, possibly fish. It appears that they sense the oncoming surge and swim out of its path.

3. DISCUSSION

Several properties of surge-type flows can be derived from the preceding results. The thickness of the head is an obvious example. The other properties are the surge speed and excess density and the surge shape, which is discussed first.

Three schematic profiles for surge-type turbidity currents are shown in Figure 6. That in Figure 6*a* is based upon the acoustic images in Figure 2 and consists of a head region of high concentration followed by a body of rapidly decreasing thickness and a low concentration wake. The thickness of the wake increases with distance away from the head because of either sustained vertical turbulent diffusion or the positive buoyancy of the water advected from shallower depths by the surge. This profile of the head and shrinking body region is very similar to those obtained in laboratory experiments by *Shwartz et al.* [1973] and *Beghin et al.* [1981, Figure 2*a*] with density slugs on small slopes ($\leq 5°$). The profiles in Figures 6*b* and 6*c* are adapted from *Middleton and Hampton* [1976] and *Komar* [1977], respectively. Both are based on laboratory experiments in which the discharge at the source was essentially steady. In both, the head is followed by a body region in which excess density and flow thickness are assumed to be sufficiently constant so that uniform flow dynamics may be used in the body. The observations presented here do not support the existence of such a region in naturally occurring turbidity currents. That is not to say that such regions do not exist. Clearly, the shape of a surge must depend critically on conditions at the source and along its path. In actual fact a continuum of surge shapes spanning the range shown in Figures 6*a*–6*c* may be possible.

Now consider the question of surge speed and excess density and how to extract information on these quantities from the acoustic data. Several methods are used, and because each involves the use of some approximation, the degree of success will be judged from the extent to which the estimates are mutually consistent. Speed and excess density are, of course, linked dynamically, so we begin with a brief discussion of the form that this link takes for slug-shaped surges.

The problem of gravity currents of finite length on a sloping bottom has been discussed by *Hay* [1983*a*], who obtained an expression for the nose speed U_0 of the form

$$U_0 = (g'H_0/2)^{1/2}[1 + C \sin \beta] \tag{1}$$

where H_0 is the maximum thickness of the head and $g' = (\Delta\rho/\rho_0)g$, g being the acceleration due to gravity, ρ_0 the density of the ambient fluid, and $\Delta\rho$ the excess density in the surge. C is a constant of order unity. Equation (1) was shown to apply to gravity currents driven both by a steady source and to slugs of dense fluid of finite length and to be consistent with laboratory experiments. Because C is of order 1, the effect of bottom slope is weak, and for small slopes there is little difference between the nose velocities for gravity surges driven either by a continuous source or by a source of finite duration. For slopes less than 5°, (1) differs little from the usual relation [e.g., *Middleton*, 1966; *Benjamin*, 1968; *Komar*, 1977]:

$$U_0 = 0.75[g'H_0]^{1/2} \tag{2}$$

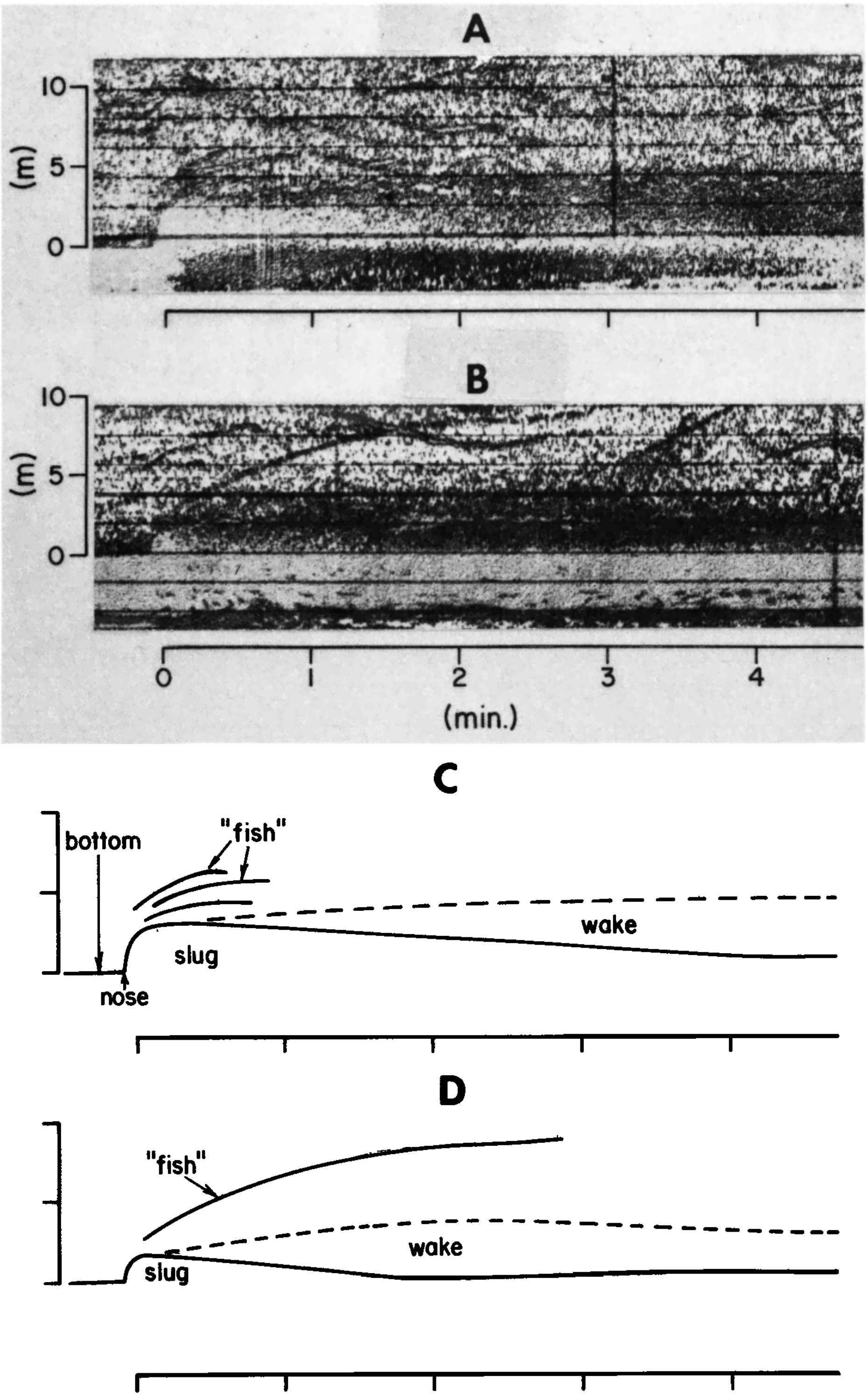

Fig. 2. Acoustic images at 107 kHz of the head regions of two surge-type turbidity currents on (*a*) September 13, 1978, and (*b*) September 12, 1978. (*c*) and (*d*) The location of the bottom echo and discrete scatterers (probably fish) evading the surges in Figures 2*a* and 2*b*. The vertical scale (in meters) and horizontal scale (in minutes) are shown.

and therefore (2) will be used for the order of magnitude estimates required here.

Estimates of the surge speed may be made directly from the acoustic records if a universal shape for the head is assumed. A universal shape for the head of a density surge has been suggested on the basis of laboratory experiments [*Keulegan*, 1957, 1958; *Middleton*, 1966; *Simpson*, 1969]. This shape is such that the ratio x/H_0, x being the horizontal distance between the leading edge and the point of maximum thickness (Figure 6*a*), is about 1.5. Should this relation hold in the present instance, the nose velocity would be given by

$$U_0 = 1.5H_0/\Delta t \tag{3}$$

where Δt is the elapsed time between the leading edge of the surge and its crest on the acoustic record (5–10 s). This implies

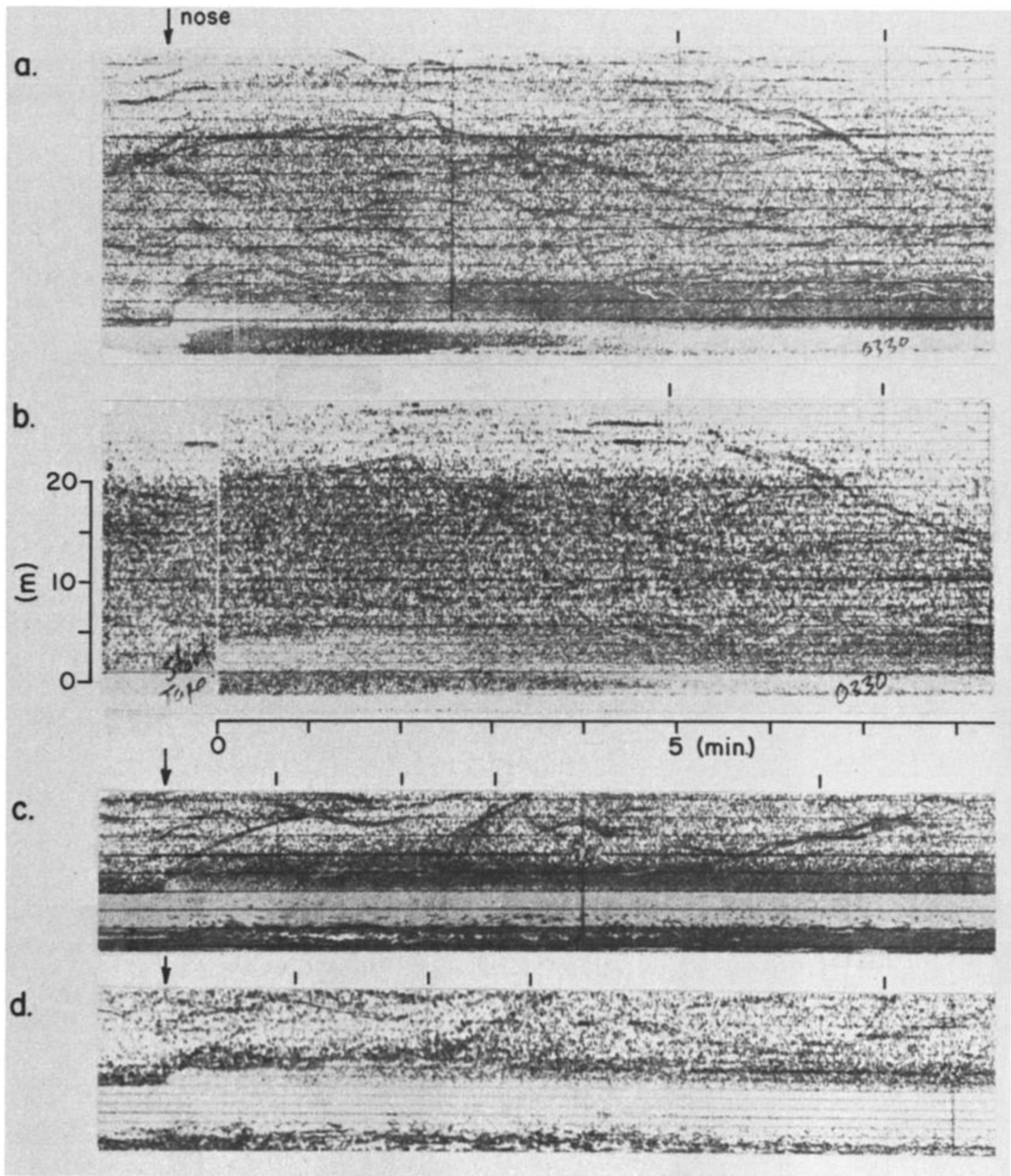

Fig. 3. Acoustic images illustrating head and wake regions of surge-type turbidity currents on September 13, 1978 at (*a*) 107 and (*b*) 200 kHz; and on September 12, 1978 at (*c*) 107 and (*d*) 200 kHz. Figures 3*a* and 3*c* are from the same records as Figures 2*a* and 2*b* but cover longer time intervals. The arrows denote the position of the nose at the left side of each image.

nose velocities ranging from 30 to 120 cm s^{-1} for the surges observed.

Equation (2) and the above estimates of U_0 give values of $\Delta\rho$ ranging from 8 to 50 kg m^{-3} for these events. These values are quite reasonable, being much less than the 10–20% by volume concentrations at which grain-to-grain contact is expected to become important [*Komar*, 1969], and 2–3 orders of magnitude larger than the concentrations measured in the discharge plume at this time [*Hay*, this issue, Figure A2]. Furthermore, as will be seen, these concentration estimates are consistent with that derived from the digitally processed acoustic backscatter data.

(Nevertheless, more recent laboratory work [*Simpson*, 1972] suggests that a universal head shape may not exist. Simpson found that the elevation of the nose above bottom, when nondimensionalized by H_0, exhibited a weak surge Reynolds number dependence ($=0.61Re^{-0.23}$, Re being the surge Reynolds number). Since the nose overhang arises from the no-slip condition at the bottom, the dependence of nose elevation on Reynolds number (i.e., viscosity) is not unexpected. At the same time, U_0 is known to depend on nose elevation [*Benjamin*, 1968], so there may be some variation of x/H_0 with Reynolds number. It is assumed here that such variations are small.)

The data in Figures 4 and 5 suggest that another estimate of the concentration of suspended material might be derived from the changes in amplitude of the bottom echo and of the signal backscattered from the surge. The obvious difficulty with the former method is that the acoustic impedance of the bottom is likely to change during the passage of the event. It is

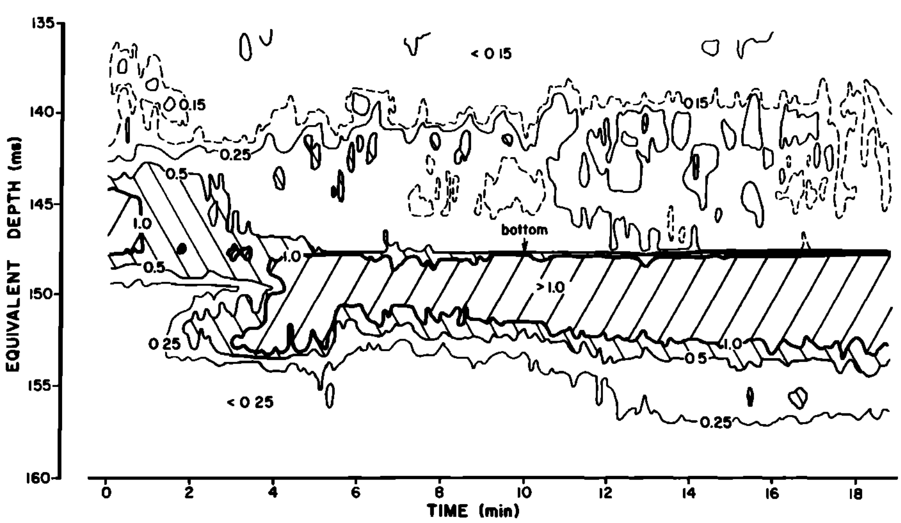

Fig. 4. Contour plot for recorded backscatter amplitude at 200 kHz for the September 13 event (see also Figure 3*b*). Contours are in volts. The bottom echo is indicated. The flow is from right to left, and the trailing part of the head and shrinking body region are on the left between 0 and 5 min and about 143 and 148 ms equivalent depth. (Equivalent depth is the two-way travel time of sound. Actual depth in meters equals equivalent depth times 0.74 m/ms.)

quite possible that the reason for the apparent attenuation of the bottom echo during the surge is simply that the bottom no longer exists as an interface across which there is a marked change in acoustic impedance; that is, the density of the fluid-solid mixture undergoes continuous transition from values within the surge far from the bed to the value for the stationary sediment within the bed. This is most likely to be true during the passage of the nose itself because of upward vertical velocities associated with recirculation in the head [*Simpson*, 1982]. In that part of the surge trailing the head region, however, it is probable that the bottom is again a discrete acoustic interface. The procedure that will be followed therefore is to use the amplitude of the bottom echo to estimate the concentration change in this trailing region and then to use the signal backscattered from the surge to extrapolate this concentration estimate into the head.

Suppose that this is the case and the bottom reflection coefficient is constant by $t = 4$ min (Figures 3*b*, 4, and 5). Let p and p' represent the pressure amplitude of the bottom echo at $t = 4$ and 6 min, respectively. These times correspond to the end of the shrinking body region and the beginning of the longer-lived wake. The ratio p'/p is given by

$$\log (p'/p) = 2(\Delta - \Delta') \tag{4}$$

where Δ represents the vertical integral of the additional attenuation due to the presence of suspended matter [*Hay*, 1983*b*] and is given by $\Delta = 2\alpha H$, H being the thickness of the current and α the linear attenuation coefficient due to the particles in suspension. The magnitude of α depends on the relative sizes of the particles and the acoustic wavelength. At 200 kHz the acoustic wavelength is about 7.5 mm. The particles in suspension are assumed to be no larger on average than those found in the Rupert Inlet turbidites: about 30- to 60-μm diameter [*Hay et al.*, 1983*b*]. The acoustic wavelength therefore greatly exceeds the particle circumference. This means that thermal attenuation and attenuation due to scattering can be ignored [*Hay and Burling*, 1982], leaving only viscous attenuation to be considered. The thickness of the viscous boundary layer at the surface of each grain (about 1.4 μm at 200 kHz) is much less than the particle radius, again, as long as it may be presumed that the particle radii in the surge are comparable to those found in the turbidites. In this case the expression for the viscous attenuation coefficient simplifies to [*Urick*, 1948]

$$\alpha_v = 3.9 \times 10^{-4} \varepsilon / a \tag{5}$$

at 200 kHz, where ε is the volume fraction occupied by solids and a is the particle radius in millimeters and where a speed of sound of 1500 m s^{-1} has been assumed. Making the further assumption that ε and a are constant in the vertical, then

$$2\Delta = 2\alpha_v H \approx 3.9 \times 10^{-3} \varepsilon / a \tag{6}$$

where a flow thickness H of 5 m has been used (Figure 4).

From Figure 5, p and p' at 4 and 6 min are proportional to 2.2 and 4.3 V, respectively, which gives

$$\varepsilon/a - \varepsilon'/a' = 1.7 \times 10^2 \text{ m}^{-1}$$

Further assuming that $a = a' = 30$ μm gives $\varepsilon - \varepsilon' = 5.2 \times 10^{-3}$. The excess density is given by $(\rho_0' - \rho_0)\varepsilon$, where ρ_0' is the grain density of the particles. This change in p therefore corresponds to a change in excess density of about 9 kg m^{-3}.

It remains to estimate the excess density in the head. This may be done roughly if it is assumed initially that the excess density at $t = 6$ min is much less than the 9 kg m^{-3} change calculated above. We use the known proportionality of the mean backscattered voltage to the square root of suspended solids concentration [e.g., *Hay*, 1983*b*]. The mean amplitude of the backscatter at $t = 0$ is about 3 times that at $t = 4$ min (Figure 5). The excess density in the head is roughly 9 times that at $t = 4$ min, or 80 kg m^{-3}. Using (2) with $H_0 = 4$ m, this corresponds to a nose velocity of 1.3 m s^{-1}, which is in reasonable agreement with the value of 1.2 m s^{-1} estimated for this surge on the basis of an assumed universal head shape. This agreement supports the assumption that the excess density at $t = 6$ min is much less than 9 kg m^{-3} and leads us to conclude that in the wake the maximum suspended sediment concentrations are likely to be at least 2 orders of magnitude lower than those in the head.

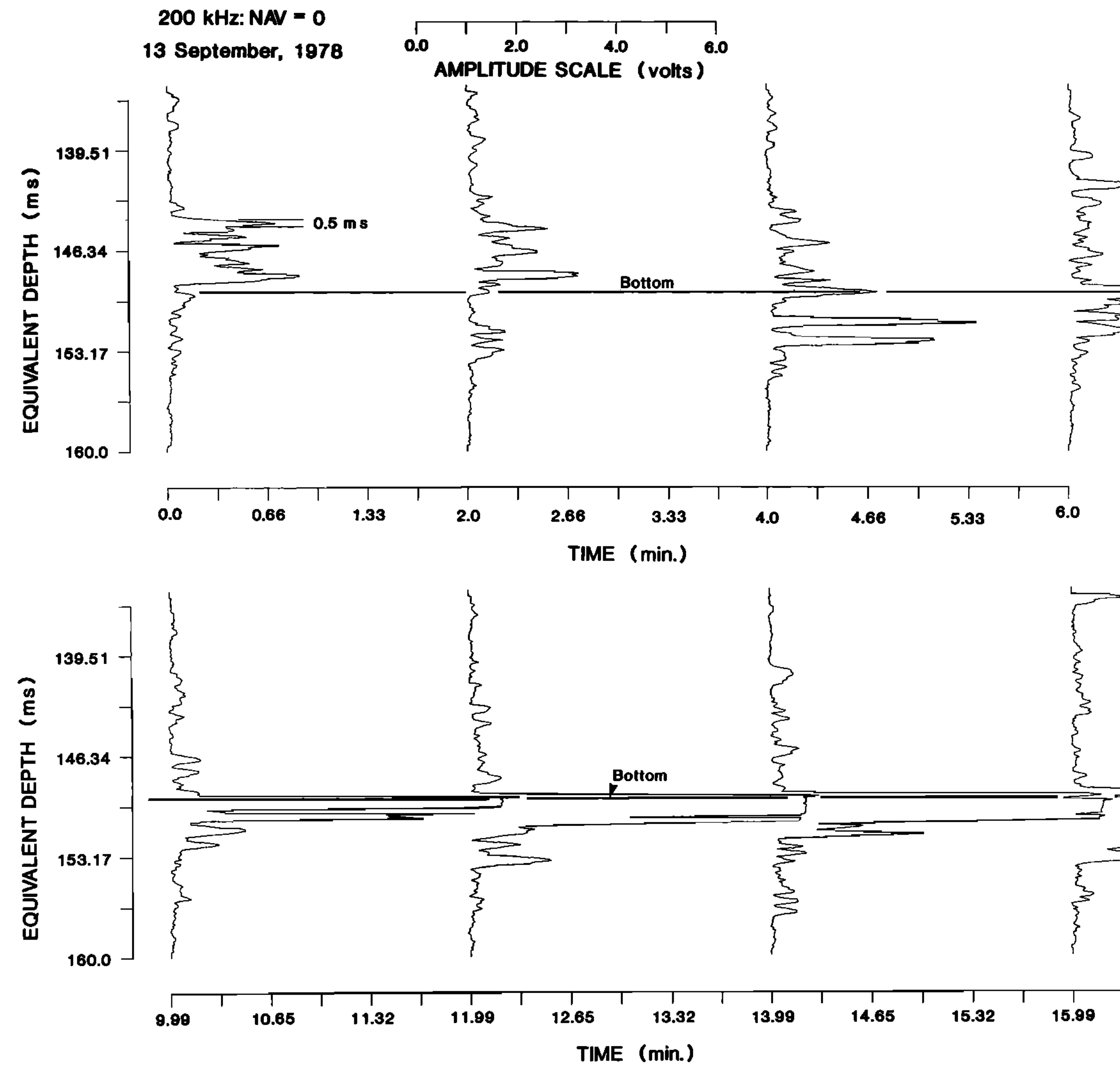

Fig. 5. Time series of 200 kHz backscatter amplitude for the September 13 event. See also Figures 3 and 4. Each vertical trace represents backscatter amplitude as a function of two-way travel time (equivalent depth). Zero backscatter is indicated by the short vertical line at the top and bottom of each trace, and this zero level is positioned along the horizontal axis at the point in time at which the trace was acquired. The receiver output saturated at about 6 V.

4. SUMMARY AND CONCLUSIONS

In summary, remote acoustic images have been used to estimate the properties of surge-type turbidity currents. Flow thickness is, of course, obtained directly. Reasonable estimates of suspended sediment concentration in the head region are extracted by using the changes in acoustic backscatter intensity and in the amplitude of the signal reflected from the bottom. A typical excess density estimate is 100 kg m^{-3}, which is roughly consistent with independent estimates based on surge speed and thickness. The surge speeds were determined from the acoustic images, assuming a universal head shape.

No elongate body region of constant thickness was observed. Instead, the head is followed by a rapidly shrinking body (or tail) and a long-lived low concentration wake. Concentrations in the wake are estimated to be 2–3 orders of magnitude below those in the head and shrinking body. The wake persists about 10 times longer and probably transports much finer-grained and much less sediment than the head. It also increases in thickness with time at a fixed point, possibly because of the positive buoyancy of the water advected from shallower depths by the surge.

These acoustic images of surge-type turbidity currents, which are presumed to have been generated by failure of the tailing deposit, are consistent with the results obtained in laboratory experiments with slugs of dense fluid on small slopes, which also consist of a head followed by a rapidly shrinking body. This means that flow in the body region of these surges cannot be described by steady, uniform flow density current theory, as has been commonly assumed for surge-type turbidity currents elsewhere. Because naturally occurring turbidity currents are known to be generated at least in some cases by discontinuous sources such as earthquake-generated sediment failure, these results raise questions about the conditions under which steady flow conditions may be assumed. In addition, surge-type flows with rapidly shrinking bodies and their associated wakes may affect the nature of the deposited turbidite in ways which remain to be explored.

These results represent one of the few instances in which direct observations have been obtained of surge-type turbidity currents in a submarine channel system which is in the process

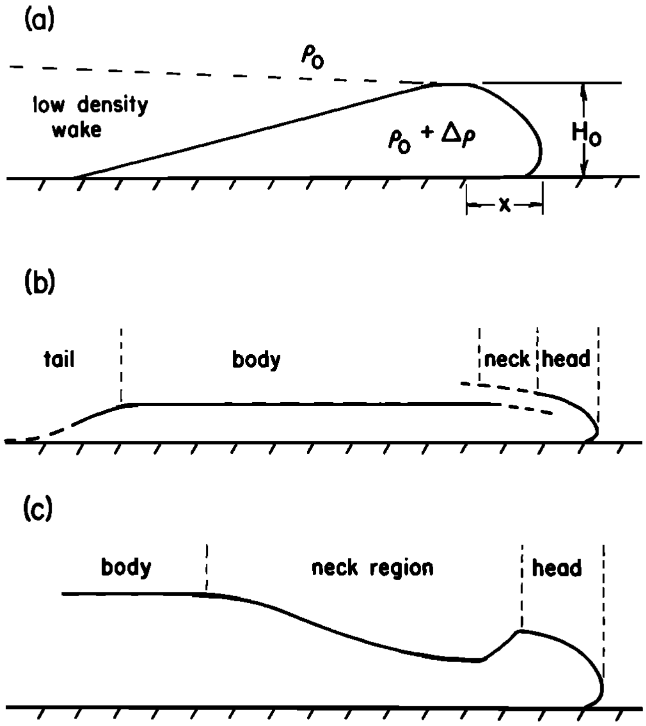

Fig. 6. Schematic profiles of surge-type turbidity currents flowing down an incline (shown here in a horizontal orientation for convenience) based on (*a*) the acoustic images in Figures 2 and 3, (*b*) sketches by *Middleton and Hampton* [1976], and (*c*) *Komar* [1977].

of active development. The quantitative estimates are necessarily approximate but appear to be self-consistent when independent checks are made. Further support for these estimates is provided by *Hay* [this issue], who estimates the surge recurrence frequency from the results presented here and finds that it agrees with the recurrence frequency estimated from the number of turbidites in cores. Finally, it has been demonstrated that acoustic remote sensing has considerable potential for the quantitative study of this potentially destructive phenomenon.

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