9. Bukry, D. in *The Black Sea-Geology, Chemistry and Biology* (eds Degens, E. & Ross, D.) 253–263 (Mem. No 20, Am. Ass. Petrol. Geol., Tulsa, Oklahoma, 1974).
10. Hay, B. J., Arthur, M. A., Dean, W. E., Neff, E. D. & Honjo, S. *Deep Sea Res.* (*Suppl.* 2) **38**, S1211–S1235 (1991).
11. Tugrul, S., Basturk, O., Saydam, C. & Yilmaz, A. *Nature* **359**, 137–139 (1992).
12. Bryantsev, D. A., Fashchuk, D. Ya., Ayzatullin, A., Bagotskiy, S. V. & Leonov, A. V. *Oceanology* **28**, 180–185 (1988).
13. Kempe, S., Liebezeit, G., Diercks, A.-R. & Asper, V. *Nature* **346**, 419 (1990).
14. Overmann, J., Cypionka, H. & Pfennig, N. *Limnol. Oceanogr.* **37**, 150–155 (1992).
15. Brassell, S. C., Lewis, C. A., de Leeuw, J. W., de Lange, F. & Sinninghe Damsté, J. S. *Nature* **320**, 160–162 (1986).
16. Kohnen, M. E. L., Sinninghe Damsté, J. S. & de Leeuw, J. W. *Nature* **349**, 775–778 (1991).
17. Kohnen, M. E. L. *et al. Science* **256**, 358–362 (1992).
18. Kohnen, M. E. L. *et al. Geochim. cosmochim. Acta* **54**, 3053–3063 (1990).
19. Quandt, I., Gottschalk, G., Ziegler, H. & Stichler, W. *FEMS Microbiol. Lett.* **1**, 125–128 (1977).
20. Sirevag, R., Buchanan, B. B., Berry, J. A. & Troughton, J. H. *Arch. Microbiol.* **112**, 35–38 (1977).
21. Summons, R. E. & Powell, T. G. *Nature* **319**, 763–765 (1986).
22. Fry, B. D., Jannasch, H. W. & Molyneaux, L. M. *Deep-Sea Res.* A**38**, S1003–S1010 (1992).
23. Goyet, C. & Bradshaw, P. W. *Deep-Sea Res.* A**38**, S1049–S1058 (1992).
24. Buesseler, K. O., Livingston, H. D., Ivanov, L. & Romanov, A. *Deep-Sea Res.* (in the press).
25. Calvert, S. E. in *Facets of Modern Biogeochemistry* (eds Ittekot, V. *et al.*) 326–352 (Springer, Berlin, 1990).
26. Tyson, R. V., Wilson, R. C. L. & Downie, C. *Nature* **277**, 377–380 (1979).
27. Dickman, M. & Artuz, I. *Nature* **275**, 191–195 (1978).
28. Hay, B. J. et al. *Deep-Sea Res.* **6**, 911–928 (1990).
29. Hayes, J. M., Freeman, K. H., Popp, B. N. & Homan, C. H. *Org. Geochem.* **16**, 1115–1128 (1990).
30. Jones, G. A. *Eos* **71**, 152 (1990).
31. Calvert, S. E. *et al. Nature* **350**, 692–695 (1991).

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Entrainment in turbulent gravity currents

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LABORATORY gravity currents are frequently used to model a range of environmental and industrial flows[1]. The manner in which these flows become diluted with distance by the surrounding fluid has important implications for turbidity currents[2], pyroclastic flows[3,4], avalanches[5], accidental dense gas releases[6], fire propagation[7] and emission of industrial pollutants. Here we present an experimental technique for quantifying the entrainment of ambient fluid into the head of a gravity current propagating along a horizontal surface. The technique relies on the neutralization of an alkaline current by entrainment of acidic ambient fluid, and is visualized by using a pH indicator. Dimensional analysis indicates that the proportion of ambient fluid entrained into a gravity current head depends only on the initial volume of the current and distance from the release point, and is independent of the initial value of the density difference. This result is confirmed by the experimental data, which also show that little dilution of the head takes place during the slumping phase[8,9]. Thereafter the dilution increases with the downstream distance, in quantitative agreement with the predictions of a theoretical model which evaluates the volume of entrained fluid. We apply the results to show that sediment slumps of initially high sediment concentrations will become dilute turbidity currents owing to entrainment of sea water before they have propagated extensively over the floors of ocean basins.

Photographs of a two-dimensional gravity current formed by the sudden release of a fixed volume of dense fluid behind a lock gate into less dense ambient fluid are shown in Fig. 1. Three distinct flow regimes are seen[1]: a slumping phase[8,9], during which the gravity current head moves at a roughly constant velocity (Fig. 1*a*); an inertia-buoyancy regime, during which the length of the current increases like the two-thirds power of time[10] (Fig. 1*b*); and a final regime during which viscous forces dominate over inertial forces[11]. The point of transition from the slumping phase to the inertia-buoyancy regime has been experimentally related to the fractional depth of the denser fluid initially behind the lock gate[9]. Beyond this point a gravity current has a characteristic form with a roughly hemispherical, lobate head, which entrains ambient fluid by shear instabilities at its trailing edge and by overriding and engulfing ambient fluid at the nose. The volume of the head decreases with distance as fluid is left behind in a thin tail beneath a diffuse mixed zone.

We have determined the proportion of ambient fluid entrained as a function of distance by using a simple neutralization technique. A known amount of sodium hydroxide and some universal pH indicator were mixed into saline solution behind a lock gate placed near one end of a horizontal rectangular channel. The final alkaline solution was purple (pH > 10). The water ahead of the gate was acidified with hydrochloric acid to achieve a value of pH ≤ 4. On release, the dense, alkaline gravity current advanced over the base of the channel, entraining acidic ambient fluid. Turbulence within the head rendered the mixing virtually instantaneous. At a distance from the source which depended on the initial excess concentration of alkali, enough ambient fluid had been entrained to neutralize the gravity current head. At this point an abrupt, homogeneous change in the colour of

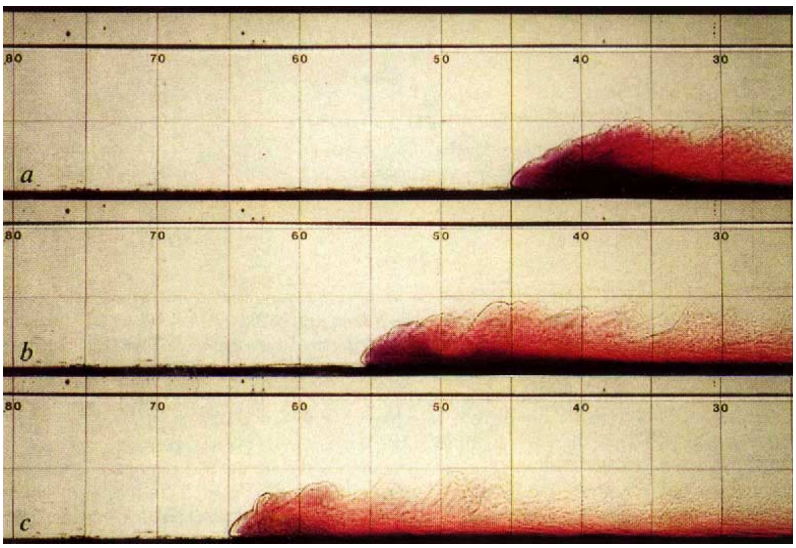

FIG. 1 Photographs of a two-dimensional gravity current formed from the sudden release of a 65 cm^3 saline solution with $x_0 = 5.0$ cm, $h_0 = H = 11.3$ cm and $g' = 20$ cm s^{-2}. *a*, Slumping phase; *b*, inertia-buoyancy regime; *c*, current just at the position at which the head changes colour.

the pH indicator from purple to red was observed throughout the whole head. The fluid composition within the gravity current head at neutrality was determined by prior titration of the initial ambient and dense fluid. Experiments using different initial concentrations of alkali, but otherwise identical initial conditions, mapped out the volumetric proportion of ambient fluid entrained into the gravity current head as a function of distance from the source.

A typical experimental run is shown in Fig. 1. In Fig. 1*c* the gravity current head has just attained neutrality. The whole gravity current head changes colour rapidly, over less than 2 cm, indicating that it is well mixed. With distance from the lock, the head decreases in volume as fluid is laid down to form the tail of the gravity current. The subsequent velocities in the tail are very much less than that of the head. This contrasts with a current maintained by a continuous flux, for which fluid from the body feeds into the head.

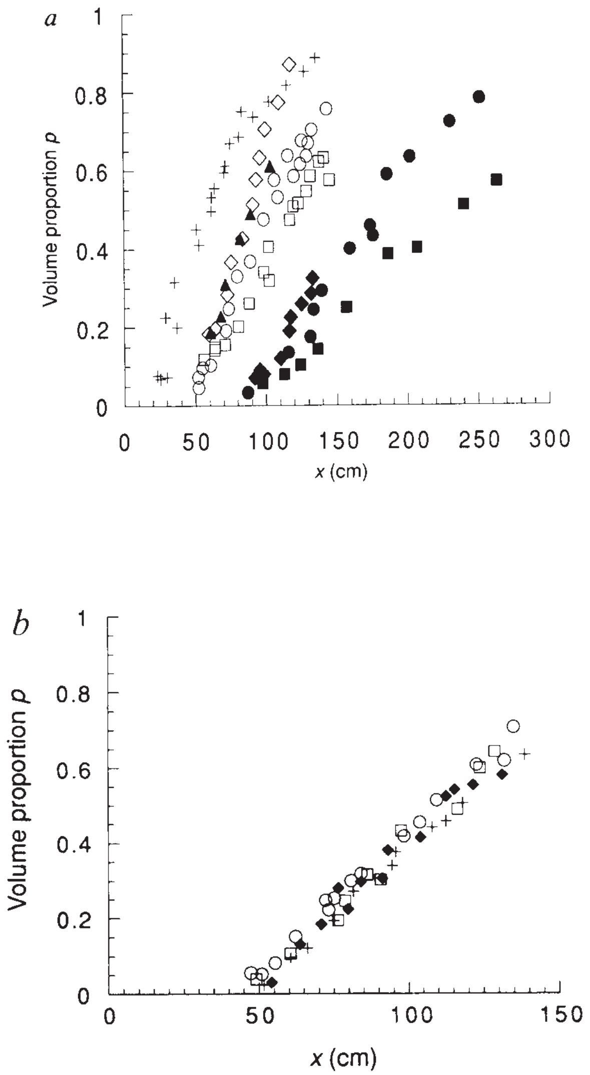

FIG. 2 Measured volume proportion of ambient fluid entrained into the head of a gravity current, *p*, as a function of the distance from the lock. Each experimental point corresponds to a different run, with conditions as follows: *a*, + $x_0=2.5$ cm, $h_0=H=9.3$ cm; ◇ $x_0=5.0$ cm, $h_0=H=6.0$ cm; ○ $x_0=5.0$ cm, $h_0=H=9.3$ cm; □ $x_0=5.0$ cm, $h_0=H=13.0$; ◆ $x_0=10$ cm, $h_0=H=6.5$ cm; ● $x_0=10$ cm, $h_0=H=13.0$; ■ $x_0=10$ cm, $h_0=H=23.0$; ▲ $x_0=10$ cm, $h_0=5.0$ cm, $H=35.0$ cm. For all experiments $g'=20$ cm s^{-2} except for the last (▲), for which $g'=37$ cm s^{-2}. *b*, $x_0=5.3$ cm, $h_0=H_0=10$ cm for different values of g': ○ $g'=10$ cm s^{-2}; + $g'=20$ cm s^{-2}; ◆ $g'=40$ cm s^{-2}; and □ $g'=80$ cm s^{-2}.

To quantify the experimental results, we denote by p the fraction of ambient fluid entrained into the gravity current head as defined by

$$p = V_a/(V_a + V_b) \tag{1}$$

where V_a and V_b are the volumes of ambient and original fluid per unit width in the head respectively. The value of p will initially be 0 (no entrainment) and will approach 1 at large distances from the lock, reflecting the high proportion of entrained fluid. Figure 2 presents our measurements of p as a function of x, the distance downstream from the position of the gate, for a range of different initial conditions including three different lock lengths, x_0. For some distance there is little entrainment into the head. Beyond this distance, p increases significantly downstream. We can identify the beginning of the significant mixing phase with the slumping distance, x_s, empirically determined[9] as

$$x_s/x_0 = 3 + 7.4h_0/H \tag{2}$$

where h_0 is the height of the dense fluid initially behind the lock gate and H is the total depth of the ambient fluid. For experiments with the same lock length, x_0, the value of p at a fixed value of x decreases monotonically with increasing volume of initial fluid behind the gate.

A systematic collapse of all these data can be obtained by dimensional analysis. We denote by A_0 the initial volume per unit width of the heavy fluid of density $\rho_0+\Delta\rho$, where ρ_0 is the density of the ambient. Dimensional arguments then suggest that the proportion of ambient fluid entrained into the gravity current head will depend on: A_0, of dimensions L^2; the initial reduced gravity $g_0'=g\Delta\rho/\rho_0$, of dimensions LT^{-2}; and the length of the gravity current x, of dimensions L. Because p is dimensionless, it must be independent of g_0', the only external parameter dependent on T. This conclusion is verified by the results of experiments at different values of g_0' (Fig. 2*b*).

To collapse the data further, we introduce the entrainment ratio or dilution, r, defined by

$$r = p/(1-p) = V_a/V_b \tag{3}$$

which is the volume ratio of ambient to original fluid in the head, where $r=0$ initially ($x=0$) and tends to infinity for long currents ($x\to\infty$). As both p and $r\approx 0$ for $0<x<x_s$, we introduce the new variable $y=x-x_s$, whereupon dimensional analysis suggests that r is a function of y^2/A_0 only. Replotting all our data in this way, we obtain the satisfactory collapse shown in Fig. 3.

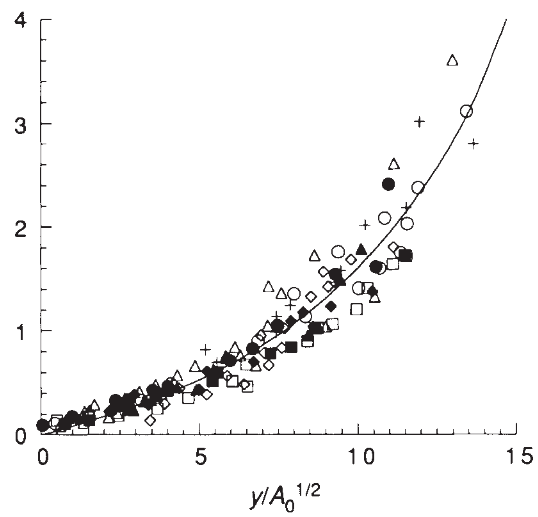

FIG. 3 Entrainment ratio r as a function of $y/A_0^{1/2}$ for all our data, with the best-fit theoretical curve $r=(1-0.0347y/A_0^{1/2})^{-2.236}-1$.

The form taken by the data can be explained as follows. The volume of the head per unit width beyond the slumping phase, V, increases by entrainment of ambient fluid and simultaneously decreases by leaving fluid behind in the tail. These processes can be represented, respectively, by

$$\frac{dV}{dy} = \alpha V^{1/2} - kV^{1/2} \quad (4a)$$

$$V(0) = A_0 \quad (4b)$$

where α is an entrainment constant and the constant k is representative of the ratio of the height of the tail to that of the head. The expression $V^{1/2}$ indicates that the spatial rate of change of volume is proportional to the height of the head; and this is the only form possible from dimensional considerations. The solution to equation (4) is

$$V/A_0 = [1 - \tfrac{1}{2}(k-\alpha)y/A_0^{1/2}]^2 \quad (5)$$

This expression indicates that the head considered as a separate entity runs out of volume at $y = y_c \equiv 2A_0^{1/2}/(k-\alpha)$. Thereafter the fluid must continue to move forward, driven by a horizontal density gradient within the tail. In most (but not all) natural and laboratory situations, viscous effects dominate before the current has reached $y = y_c$.

Keeping account of ambient and original fluid individually, we find that the volume of ambient and original fluid in the head are described by

$$\frac{dV_a}{dy} = \alpha V^{1/2} - kpV^{1/2}, \qquad \frac{dV_b}{dy} = -k(1-p)V^{1/2} \quad (6a, b)$$

$$V_a(0) = 0, \qquad V_b(0) = A_0 \quad (6c, d)$$

Substituting $p = V_a/V$ and $1 - p = V_b/V$, with V represented by equation (5), into equation (6) and integrating the result, we obtain

$$r = [1 - \tfrac{1}{2}(k-\alpha)y/A_0^{1/2}]^{-2\alpha/(k-\alpha)} - 1 \quad (7)$$

which becomes infinite as y approaches y_c. The values of α and k that give a best fit to all our data are $\alpha = 0.078$ and $k = 0.147$ ($k - \alpha = 0.069$), with a computed error of ~3%. Equation (7), incorporating these values, is displayed in Fig. 3 along with all the data. The agreement between the form of the curve and the data is good. The total volume per unit width of entrained plus original fluid left behind in the tail, V_T, is given by

$$V_T = k\int_0^{y_c} V^{1/2}\,dy \quad (8a)$$

$$= k/(k-\alpha)A_0 = 2.12A_0 \quad (8b, c)$$

so the total volume of fluid entrained into the gravity current head is slightly in excess of the original volume. The average dilution is therefore just above one, although the local dilution can be much larger.

The results apply quantitatively only to fixed volume releases of fluid in a constrained channel. However, entrainment rates are likely to be similar in more complex flow geometries or flow conditions. Our results demonstrate that entrainment is substantial and that any natural current will become highly diluted downstream. One application is to turbidity currents where the density difference arises from suspended particles. In ocean basins, large turbidity currents are typically generated by slumps of sediment on the upper continental slope[12-14]. Individual slumps may have volumes ranging from less than 0.1 km^3 to several tens of cubic kilometres. They must initiate as flows with high concentrations of suspended sediments. On the assumption that most currents are erosive in the feeder channels or canyons, entrainment into the flow head once deposition has begun will rapidly cause the head of the current to evolve toward low concentration. For example, with values of a length of 10 km along the axis of the feeder canyon and a height of 100 m, $A_0 = 10^6$ m^2. Inserting this value into equation (7), and extrapolating our concepts to more complex natural situations, we find that the head of a current initiated in water 2 km deep with an initial concentration of 40% would be diluted to ~8% over a distance of 15 km (to 3% over 20 km) beyond a slumping distance of ~33 km, and would cease propagating in the form of a classical gravity current in ~62 km from the source. We would expect the resulting deposits to evolve from those characteristic of high concentration close to the canyon mouth to those characteristic of low concentration further away. This prediction agrees with general observations[2]. Turbidity currents are much more complex than simple laboratory currents because of effects that include lateral spreading, variations in fluid and particle fluxes, sedimentation and erosion. Nevertheless this calculation shows that entrainment is an effective way of evolving an initial high-concentration sediment slump into a dilute turbidity current. □

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1. Simpson, J. E. *Gravity Currents in the Environment and the Laboratory* (Halsted, Chichester, 1987).
2. Allen J. R. L. *Principles of Physical Sedimentology* (Allen & Unwin, London, 1985).
3. Wilson, C. J. N. *Sci. prog. Oxf.* **70**, 171–207 (1986).
4. Sparks, R. S. J. *et al. Earth planet. Sci. Lett.* **114**, 243–257 (1993).
5. Hopfinger, E. J. *A. Rev. Fluid Mech.* **15**, 47–76 (1983).
6. Britter, R. E. *A. Rev. Fluid Mech.* **21**, 317–344 (1989).
7. Emmons, H. W. *Proc. 3rd int. Symp. Fire Safety Science* (eds Cox, G. & Langford, B.) 249–260 (Elsevier, London, 1991).
8. Huppert, H. E. & Simpson, J. E. *J. Fluid Mech.* **99**, 785–799 (1980).
9. Rottman, J. W. & Simpson, J. E. *J. Fluid Mech.* **135**, 95–110 (1983).
10. Hoult, D. P. *A. Rev. Fluid Mech.* **4**, 341–368 (1972).
11. Huppert, H. E. *J. Fluid Mech.* **121**, 43–58 (1982).
12. Piper, D. J. W., Shor, A. N., Farre, J. A., O'Connell, S. & Jacobi, R. *Geology* **13**, 538–541 (1985).
13. Heezen, B. C. & Ewing, M. *Am. J. Sci.* **250**, 849–873 (1952).
14. Heezen, B. C., Erickson, D. B. & Ewing, M. *Deep-Sea Res.* **1**, 193–202 (1954).

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Relationship between eruption volume and neodymium isotopic composition at Unzen volcano

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SILICA-rich lavas, erupted at island-arc or continental volcanoes, are often produced by a complex process involving the assimilation of crust into a crystallizing, mantle-derived basaltic magma[1]. The different strontium, neodymium and oxygen isotopic compositions of mantle-derived magmas and continental crust provide a powerful method for tracing the different contributions to continental silicic magmas, and for understanding the parameters controlling the composition and volume of erupted magma[1-4]. In the large rhyolite eruptive centres of the western United States, the largest-volume, explosive rhyolite eruptions have more mantle-like Nd isotope ratios than other silicic lavas from the same centre[2-4], a relationship that has been interpreted as reflecting increased influx of