marily on the areas of overlap with other species in the present study and also on data in (*16*).
16. N. J. Shackleton, in *The Fate of Fossil Fuel CO_2 in the Oceans*, N. R. Andersen and A. Malahoff Eds. (Plenum, New York, 1977), p. 401.
17. Especially cores V 19-29 and *Meteor* 12392 (*13*).
18. The mean number of individuals counted at each level is 103. Counts for five levels are less than 50; these are greatly diluted by ice-rafted material.
19. The data (261 core tops) from which this section was prepared were generated by S.S.S. in cooperation with N. Kipp (Brown University) and supplemented with data from Lohmann (*6*) for the area of the Rio Grande Rise (30°S). A full discussion is in preparation.
20. Dissolved oxygen is negatively correlated with other constituents, notably phosphate and nitrate. Possibly oxygen is not the ecologically limiting variable, but we single it out because its distribution is well described in the literature.
21. G. Wüst, *Wissenschaftliche Ergebnisse der Deutschen Atlantische Expedition auf dem Forschungs- und Vermessungschiff*, Meteor, *1925-1927* (de Gruyther, Berlin, 1936), vol. 6, especially plates 23 through 28.
22. L. V. Worthington, *Deep-Sea Res.* **17**, 77 (1970).
23. T. B. Kellogg, J. C. Duplessy, N. J. Shackleton, *Boreas* **7**, 61 (1978).
24. CLIMAP Project Members, *Science* **191**, 1131 (1976); W. F. Ruddiman and A. McIntrye, *J. Geophys. Res.* **82**, 3877 (1977).
25. W. S. Broecker and Y. H. Li, *J. Geophys. Res.* **75**, 3545 (1970).
26. We thank S. Lavery for the considerable effort involved in preparing and picking the samples for benthic foraminifera and M. A. Hall for operating the mass spectrometer. We thank W. S. Broecker, A. L. Gordon, A. McIntyre, and W. F. Ruddiman for helpful discussions and criticism of the manuscript. S.S.S. was supported by NSF grant OCE-77-19447 and by CLIMAP (Climate: Long-Range Investigation, Mapping, and Prediction). CLIMAP studies are jointly fundec by the NSF Office of Climate Dynamics and the International Decade of Ocean Exploration, under grant OCE-75-19627. We thank the curating staff of Lamont-Doherty; grants NSF-OCE-76-18049 and ONR-N00014-75-C-0210 support the collection. N.J.S. was supported by grant GR-3/1762 from the Natural Environment Research Council. Lamont-Doherty Geological Observatory contribution No. 2767.

23 June 1978; revised 21 August 1978

Wear of Unsound Pebbles in River Headwaters

Abstract. *Pebbles that are initially weathered, inhomogeneous, angular, or fractured ("unsound") become sound with transport. The Sternberg law describes well the wear of sound pebbles found in large rivers, but describes poorly that of unsound pebbles in river headwaters. For unsound pebbles the Sternberg coefficient (which is assumed to be a constant) decreases appreciably downstream. An alternative to the Sternberg law is derived in which the coefficient is proportional to the reciprocal of the downstream distance traveled. The laws are compared by using data from the Clutha basin in New Zealand.*

The change in weight or length of pebbles of a particular lithology as they move has often been described by the empirical Sternberg law (*1*)

$$W = W_0 \exp(-\alpha_W Z) \quad (1a)$$

$$D = D_0 \exp(-\alpha_D Z) \quad (1b)$$

$$\alpha_D = -\frac{\Delta \log_e(\text{diameter})}{\Delta(\text{distance})} \quad (1c)$$

where W and W_0 are the final and initial weights; D and D_0 are the final and initial diameters; Z is the distance traveled (kilometers); α_W and α_D are coefficients per kilometer for weight and length, respectively; and $\alpha_W = 3\alpha_D$.

The downstream decrease of the coefficient for unsound pebbles can be shown in rivers with rocks having very different coefficients. The best example in New Zealand is the Clutha River (45°S, 169.5°E), where most of the bedrock is quartz-veined chlorite schist, and where my measurements in road cuttings indicate that on average the quartz veins make up 5 percent of the bedrock. There is a general downstream increase in the proportion of the quartz (a relatively strong rock) to the schist (a relatively weak rock). The ratio by weight of the quartz to the schist and the average size of the five largest pebbles of each lithology were measured at most of 53 sites. For each site the downstream distance, x, is taken as the channel distance to its furthermost headwater, although few pebbles will have traveled the full distance.

As pebbles become sound with transport, their size change can be described by a law in which the coefficient decreases downstream according to the reciprocal of the distance. In Figs. 1 and 2, I compare the Sternberg law with the one proposed here, using data from the Clutha catchment. The data are linearized in Fig. 2 by plotting $Y = \log_{10}$ (size) against $X = \log_{10}$ (distance) and then fitting the straight line

$$Y = mX + c$$

Then

$$\alpha_D = -\frac{1}{0.4343}\frac{dY}{dx} = -\frac{m}{x} \quad (2)$$

gives the coefficient at each point. The point coefficient given by Eq. 2 is proportional to the reciprocal of the distance from the headwaters and decreases more and more slowly downstream, finally becoming the Sternberg coefficient. Unlike the Sternberg law, the one proposed here cannot be extrapolated to the source to give an initial pebble size. However for an interval (x_1 to x_2) not including the source, the interval coefficient is given by

$$\bar{\alpha}_D = \frac{-\int_{x_1}^{x_2} \frac{m}{x}\,dx}{x_2 - x_1} = \frac{-m \log_e(x_2/x_1)}{x_2 - x_1} \quad (3)$$

which gives the same value that is found by applying the Sternberg law to the change in size between the end points x_1 and x_2. A coefficient of proportional weight change, α_P, expresses the change in proportion of two lithologies downstream. If lithologies A and B decrease downstream according to the law above, their weight ratio R over the short distance Z changes according to

$$A = A_0 \exp(-3\alpha_{DA}Z)$$

$$B = B_0 \exp(-3\alpha_{DB}Z)$$

$$A/B = A_0/B_0 \exp[-3(\alpha_{DA} - \alpha_{DB})Z]$$

$$R = R_0 \exp(-\alpha_P Z) \quad (4)$$

where $\alpha_P = 3(\alpha_{DA} - \alpha_{DB})$.

The point and interval coefficients for the quartz and schist sizes for the interval 2 to 294 km are calculated from the slope of the lines on Fig. 2 by use of Eqs. 2 and 3; for quartz

$$\alpha_{Dq} = \frac{0.171}{x}\ \text{km}^{-1} \qquad \bar{\alpha}_{Dq} = 0.00288\ \text{km}^{-1}$$

and for schist

$$\alpha_{Ds} = \frac{0.574}{x}\ \text{km}^{-1} \qquad \bar{\alpha}_{Ds} = 0.00965\ \text{km}^{-1}$$

The curved lines corresponding the size changes predicted by applying the Sternberg law have also been plotted on Fig. 2 for comparison with the data. The observations indicate that most pebbles in the upstream reaches are unsound and that Sternberg's law is inapplicable.

From Eq. 4 the point coefficient of

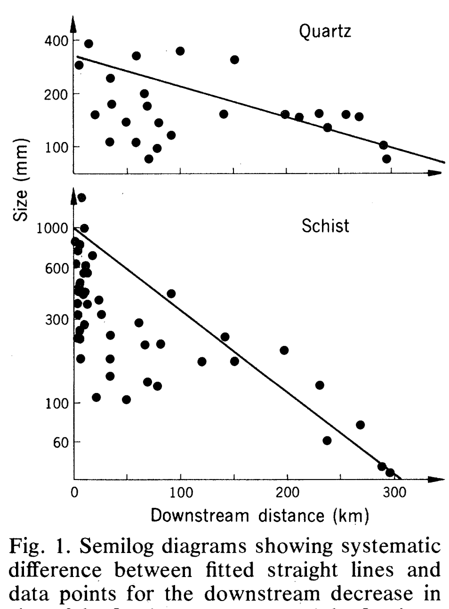
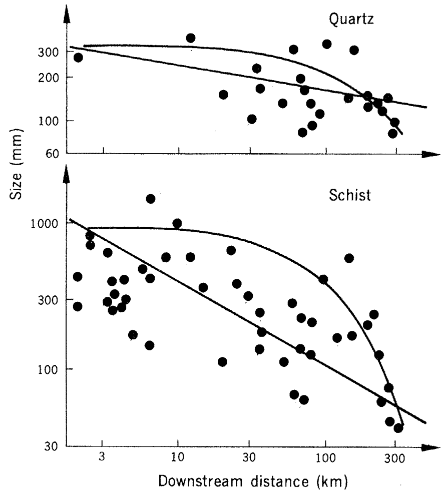


Fig. 1. Semilog diagrams showing systematic difference between fitted straight lines and data points for the downstream decrease in size of the five largest quartz and the five largest schist pebbles for about 40 streams within the Clutha basin.

0036-8075/79/0112-0171$00.50/0



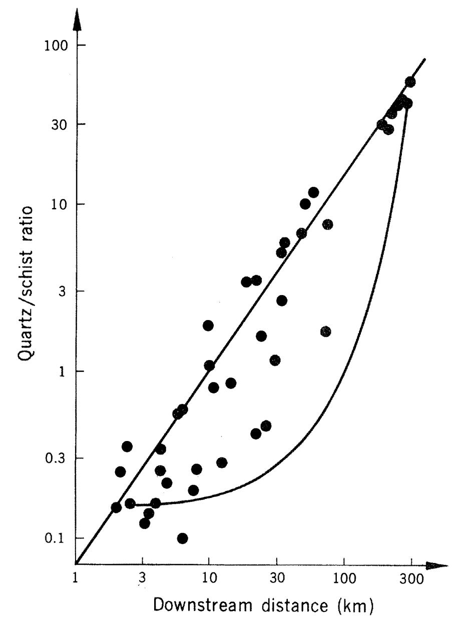


Fig. 2 (left). Log-log diagrams (with normal values) showing same data as in Fig. 1. Curved lines are those that are straight in Fig. 1 and correspond to a constant coefficient for the pebbles; new straight lines, drawn in by eye, represent coefficients that decrease with distance from source. Fig. 3 (right). Log-log diagram with data points and eye-fitted line showing the downstream distance from source increase in the proportion of quartz to schist. About 40 streams and rivers are represented. The curved line corresponds to a constant value for α_P, and the straight line to a coefficient that decreases with distance.

proportional change for quartz and schist can be calculated from their point coefficients

$$\alpha_P = 3(\alpha_{Dq} - \alpha_{Ds})$$

$$\alpha_P = 3\left(\frac{0.171}{x} - \frac{0.574}{x}\right) = -\frac{1.21}{x}\ \text{km}^{-1}$$

Figure 3 shows the downstream increase in the weight ratio of quartz to schist gravel. At source the quartz veins are about 5 percent of the bedrock; at Balclutha, 290 km downstream, quartz gravel is 55 times as abundant as schist gravel. Many of the data points are below the line because not all of the schist comes from the furthermost headwater. From the slope of the straight line in Fig. 3, the point and interval coefficients of proportional change are

$$\alpha_P = -\frac{1.17}{x}\ \text{km}^{-1}$$

$$\bar{\alpha}_P = \frac{-1.17\ \log_e(294/2)}{294 - 2} = -0.020\ \text{km}^{-1}$$

The point coefficient so determined is in excellent agreement (within 4 percent) with the corresponding value calculated from independent data on the change in size of the largest quartz and schist pebbles. A coefficient of proportional change that decreases with distance ($\alpha_P = -1.17/x$ km^{-1}) fits the data points on Fig. 3 much better than the constant value ($\bar{\alpha}_P = -0.020$ km^{-1}) that would be predicted if the size change of the quartz and the schist pebbles fitted the Sternberg law rather than the one proposed here.

There is little possibility that the size changes discussed here are caused by a hydraulic selection (*2*) mechanism in which the largest pebbles accumulate in the river headwaters. Erosion rates in the headwaters of the Clutha catchment are so rapid that if pebbles of a particular size were to accumulate they would be conspicuous. No such accumulation is observed, many rivers being in bedrock gorges, and all pebbles must therefore be moved downriver. Again, if selection were important, the downstream size changes—schist initially larger than quartz, then vice versa—would preclude any simple relation between their weight ratio such as that shown in Fig. 3.

The downstream size reduction is therefore mainly due to the abrasive processes of wear, chipping, and fracture. In river headwaters abrasion is initially rapid as the weakest parts of the pebble are preferentially abraded, sharp corners are rounded, and fracture occurs along planes of weakness. Eventually all differences in lithology and weaknesses are removed, and the result is a homogenous, sound pebble, the downstream change of which is well described by the Sternberg law. Pebble abrasion, when allowance is made for wear of unsound pebbles, thus accounts for the downstream changes observed in the Clutha catchment.

JOHN ADAMS
Department of Geological Sciences, Cornell University, Ithaca, New York 14853

References and Notes

1. H. Blatt, G. Middleton, R. Murray, *Origin of Sedimentary Rocks* (Prentice-Hall, Englewood Cliffs, N.J., 1972), p. 59.
2. F. J. Pettijohn, *Sedimentary Rocks* (Harper & Row, New York, ed. 3, 1975), pp. 45–48.

3. I thank H. W. Wellman and other members of the Geology Department, Victoria University, Wellington, New Zealand, where this work was done, for their criticism. Department of Geological Sciences, Cornell University, Contribution No. 633.

25 August 1978

Molecular Structure of an Unusual Organoactinide Hydride Complex Determined Solely by Neutron Diffraction

Abstract. *The structure of an unusual organometallic complex,* $\{Th[(CH_3)_5C_5]_2H(\mu\text{-}H)\}_2 \cdot C_6H_5CH_3$, *has been determined from neutron diffraction data, using only the direct-methods program MULTAN. Besides providing accurate metrical information on the first organometallic actinide hydride complex, these results have general and far-reaching implications concerning the complexity and size of crystal structures that can be elucidated solely on the basis of neutron diffraction data.*

A common misconception regarding neutron crystallography is that preliminary structural solutions can only be derived after the tedious collection of redundant x-ray data. In spite of the great recent advances in the use of direct methods for phase determination of x-ray diffraction data (*1*), there has been some question about the general applicability of these techniques to neutron data. In the theory of direct methods, as developed for the x-ray case, it is assumed that the scattering amplitudes all have the same (positive) sign, but for neutron diffraction many atoms have negative coherent scattering lengths (b) (*2*); for example, $b_H = -0.374$, $b_{Li} = -0.214$, $b_{Ti} = -0.34$, and $b_{Mn} = -0.39$ (all in units of 10^{-12} cm). Sikka (*3*) estimated that the negative scattering amplitude of hydrogen would be the major limiting factor in applying the symbolic addition procedure for centrosymmetric crystals (where the sign of the structure factor F_{hkl} is + or −). He predicted that if the quantity $\Sigma b_H^2/\Sigma b^2{}_{all}$ exceeds 25 percent and if there are more than 100 atoms in the unit cell, the structure probably cannot be derived directly from neutron diffraction data. Although