m (130 feet). Thermoclines generally correspond to the stratification, with a surface water temperature 5 to 20 K greater than the water temperature 10 to 20 m below the surface. For a typical thermocline temperature difference of 15 K, the equivalent gravitational head is 6.4 km (12×10^4 feet). Therefore, it is apparent that the solar thermal energy stored in freshwater thermoclines substantially exceeds the energy stored in the gravitational potential.

However, not all of the thermal energy can be converted to useful mechanical or electrical energy. The maximum fraction of the thermal energy that can be converted to mechanical energy is given by the Carnot efficiency, and any real heat engine will operate at some fraction, $f < 1$ of the Carnot efficiency. For a ΔT between the warmer surface water temperature and the cooler deeper water, the equivalent head, h', for converted thermal energy is given by

$$Mgh' = MC\Delta T\left(\frac{\Delta T}{T}\right)f \quad (3)$$

or

$$h' = \frac{C}{g}\frac{\Delta T^2}{T}f = 427\frac{\Delta T^2}{T}f \quad (4)$$

where T is the temperature of the warm surface water, and $\Delta T/T$ is the Carnot efficiency.

As an example, for a heat engine that operates at 50 percent of the Carnot efficiency ($f = 0.5$), with a thermocline of 15 K and a surface temperature of 300 K, h' is

$$h' = 427\left(\frac{15^2}{300}\right)0.5 = 160 \text{ m}$$

The h' value is plotted against ΔT in Fig. 1 with the fraction of the Carnot efficiency at which the heat engine operates as a parameter. This convertible head, that is, the portion of the head that can be realized by the use of real thermal energy conversion systems, exceeds the hydropotential for the water in most hydroelectric facilities. Therefore, by adapting heat engines to hydroelectric facilities which possess appreciable thermoclines, it is possible to increase substantially the output power of such plants.

The thermocline application of hydroelectric facilities for heat engines is particularly appealing because power conditioning and transmission equipment are already installed at such sites. Another important consideration is that most modern hydroelectric facilities have water intakes at several reservoir elevations for the express purpose of attaining an output water temperature appropriate to the downstream usage (*1*). It would appear that this configuration would be advantageous for application to heat engines, because the hot and cold water intakes could be directed to the corresponding hot and cold sides of the heat engine and the water outputs could be mixed behind the heat engine.

To illustrate the magnitude and seasonal variations to be anticipated, we obtained thermocline data for three western U.S. reservoirs (Fig. 2). The data for Lake Mead were taken during 1977 (*2*), and the data for Lake Shasta and Clair Engle Lake are 3-year averages for 1973 through 1975 (*3*). As should be expected, the greatest temperature differences occur during the summer months, which also correspond to the times of peak power demand. For these three reservoirs, the temperature difference exceeds 15 K for approximately 3 months and exceeds 10 K for 5 to 6 months.

Our purpose in this report was to identify the thermocline energy source and to demonstrate the benefit to be derived from the utilization of this source at hydroelectric facilities. To properly exploit this thermocline source, effective low-temperature thermal energy conversion systems are required. Although a comprehensive discussion of low-temperature-difference heat engines is beyond the scope of this report, two possible systems for the thermocline application are the vapor-liquid phase Rankine cycle heat engine, currently being considered for Ocean Thermal Energy Conversion (OTEC) power plants (*4*), and the solid-state Nitinol heat engine, which, although in a primitive state of development, shows great technical and economic promise for effective low-temperature thermal energy conversion (*5*). There should be no negative environmental factors associated with power production by this application of heat engines to the thermocline energy resource.

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References and Notes

1. In some cases considerable retrofit expense has been incurred in an effort to provide temperature control of reservoir outlet water [see, for example, *Eng. News Rec.* **199** (No. 4), 18 (1978)].
2. The Lake Mead data were provided by R. D. Mason of the Boulder City office of the U.S. Bureau of Reclamation.
3. Thermocline data for Lake Shasta and for Clair Engle Lake were provided by R. Brown of the California Water Resources Department.
4. W. D. Metz, *Science* **198**, 178 (1977).
5. W. S. Ginell, J. L. McNichols, J. S. Cory, paper presented at the Intersociety Conference on Environmental Systems, San Diego, Calif., 10 to 13 July 1978; J. S. Cory and J. L. McNichols, paper presented at the 13th annual Intersociety Energy Conversion Conference, San Diego, Calif., 21 to 25 August 1978.
6. We thank R. D. Mason and R. Brown for supplying us with reservoir data.

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Paleocirculation of the Deep North Atlantic: 150,000-Year Record of Benthic Foraminifera and Oxygen-18

Abstract. *Benthic foraminiferal faunas in a piston core from 3331 meters at 44°N on the Mid-Atlantic Ridge show striking variations in the relative abundance of species.* Uvigerina peregrina, *which is broadly distributed today in the South Atlantic and in the Pacific in water that has been long isolated from the surface, is absent in the North and Equatorial Atlantic at depths occupied by highly oxygenated North Atlantic deep water. This species dominated the fauna at this site for much of the past 150,000 years. It is suggested that North Atlantic deepwater production was much reduced or eliminated at times of* Uvigerina peregrina *abundance, as a result of cooling and stratification of the Norwegian Sea surface, coincident with the times of the southward migration of the polar front in the North Atlantic.*

Studies of deep-sea sediments have shown that the temperature, oxygen isotopic content, and sediment sources (*1*) in the deep ocean have changed on a time scale of millions of years. These changes are due both to the drifting of the lithospheric plates through time and to changes in the thermal structure of the oceans. In particular, gradual cooling of the poles during the last 35 million years has led to a decrease in the temperature of the bottom water of the deep sea (*2*). On a shorter time scale, sediment cores provide the best record of fluctuating surface zooplankton and phytoplankton distribution, revealing the climatic fluctuations of the Pleistocene. Weyl and others (*3*) have proposed that these fluctuations of Pleistocene climate repetitively modified the deep circulation of

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the ocean by altering either the characteristics of deepwater sources or their locations.

Presumably the benthic fauna of the deep sea responded to significant changes in the deep-sea circulation. Foraminifera are the only component of the benthos that can be recovered in sufficient numbers from deep-sea sediment cores to allow a test of this hypothesis. Streeter (*4*), Schnitker (*5*), and Lohmann (*6*) have shown that the relative abundance of benthic foraminiferal taxa varies within the Pleistocene and that striking changes occurred within a few thousand years. Streeter (*7*) has shown that these changes are oceanwide, affecting the whole of the North and Equatorial Atlantic.

We have studied piston core V 29-179 in detail to establish the timing and magnitude of these benthic faunal changes over the last 150,000 years. This core was raised from a water depth of 3331 m on the eastern flank of the Mid-Atlantic Ridge about 600 km north-northeast of the Azores (*8*). The core is composed of planktonic foraminiferal marl throughout its length, and our data show that it has an apparently uniform sedimentation rate of 4.1 cm per 1000 years without detectable hiatuses. A sample 1 cm thick was taken every 5 cm from 5 through 610 cm; the intersample distance represents roughly 1200 years. The samples were shaken in deionized water for 4 hours, wet-sieved through a 63-μm sieve, and dried on the sieve (*9*). Benthic foraminifera were handpicked from a weighed portion of the fraction coarser than 150 μm. Only benthic foraminifera with tests of hyaline carbonate were counted (*10*).

Oxygen isotopic determinations based on the use of well-established procedures were made at the University of Cambridge (*11-13*) with a mass spectrometer (VG Micromass 602C). As it is known that many benthic foraminiferal species do not deposit their calcite tests in isotopic equilibrium with seawater (*14*), only monospecific samples were analyzed. Where possible, we analyzed *Uvigerina peregrina* as Shackleton (*11*) has shown that this species deposits its test in isotopic equilibrium. Three other species were also used; the analyses are plotted with a correction factor of + 0.64 per mil for *Cibicides wuellerstorfi* and + 0.40 for *Melonis barleeanum* and *M. pompilioides* to take account of their respective departures from equilibrium (*15, 16*).

The isotopic record (Fig. 1) is readily correlated with the standard sequence of stages and substages to stage 6 (*17*), and the absolute values obtained are closely comparable with those from the high accumulation rate core, *Meteor* 12392 (*16, 17*), also in the Atlantic. The major signal in this record is believed to result from isotopic changes in the world's ocean water resulting from the locking up of large volumes of isotopically light water in the Northern Hemisphere ice sheets during the major part of Pleistocene time. The changes observed in the deep waters of the Atlantic are not less than, and possibly slightly greater than, those observed in cores of comparable sedimentation rate in the Pacific. This implies that glacial-age deep waters in the North Atlantic must have been cooler than they are today, rather than warmer as was previously suggested (*3-6*).

Counts of 59 hyaline taxa were the input to a rotated principal components analysis (*18*); four species groups account for 88 percent of the variance in the data. The most important component is the species *U. peregrina*, which is rarely found below 2000 m in surface sediments from the mid-ocean ridge in the North Atlantic. The second and third components, *Epistominella exigua* and *Cibicides wuellerstorfi*, respectively, have independent distributions in this core; both are common species between 2000 and 4000 m in the North and Equatorial Atlantic today. The fourth component represents *Melonis barleeanum* and *Astrononion* sp. (a deepwater form apparently undescribed); both species presently occur scattered throughout the Atlantic but usually in low abundance. No satisfactory analog for this component has yet been identified in any ocean. The downcore percentage distributions of *U. peregrina* and of *M. barleeanum* and *Astrononion* sp. are shown in Fig. 1. *Cibicides wuellerstorfi* and *E. exigua* (not shown) dominate the fauna whenever the two species groups shown in Fig. 1 are both rare.

Within the last 150,000 years, only during the interval between 127,000 and 115,000 years before the present (B.P.) (substage 5e) was there as little ice on the earth as during the past 12,000 years (stage 1). It is thus scarcely surprising that the benthic foraminiferal faunas of these two warm intervals are similar. The ice volume during substages 5c and 5a was greater than today, although only

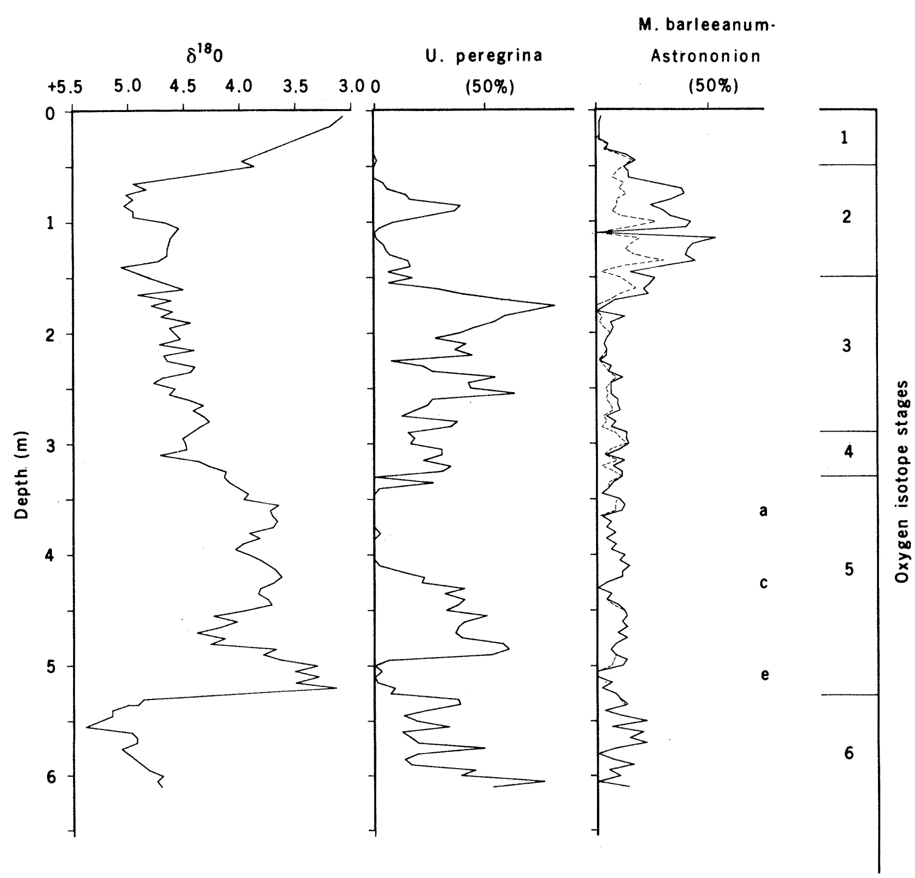

Fig. 1. Oxygen isotopic and faunal curves for core V 29-179. Isotopic values (left column) are derived from benthic species and are per mil deviations from the Pee Dee belemnite standard. Curves for *Uvigerina peregrina* and for *Melonis barleeanum* and *Astrononion* sp. are given as percentages of all hyaline species (the dotted line is the percentage for *M. barleeanum*; the solid line is the sum of this and the percentage for *Astrononion*). The standard oxygen isotope stages as determined for this core are shown at the right.

about one-quarter of that which accumulated during full-glacial conditions such as stages 2 and 6. During substage 5a and part of substage 5b, the benthic faunas were again similar to those of the present. The dominance of *M. barleeanum* and *Astrononion* sp. in stage 2 is obviously associated with a worldwide glacial climate; we have no explanation for the low abundance of these taxa in stage 6, which seems to have been as severe a glacial. *Uvigerina peregrina* is a conspicuous and important element in stages 6 and 3. In addition, it characterizes substage 5d and part of substage 5c. During most of this time, the world was in neither a full glacial nor a full interglacial mode. This faunal pattern is repeated in other cores from 3000 to 4000 m in the North and Equatorial Atlantic (*7*). Rapid changes in the composition of the benthic fauna, such as occurred at the top and bottom of substage 5e and at the boundary between stages 5 and 4, must reflect some fundamental change in the climate of the deep sea.

The present-day distribution of *U. peregrina* in the Atlantic provides a key to the meaning of these downcore faunal shifts. Figure 2 shows schematically the present distribution of this species (*19*). Between 2000 and 4000 m, the distribution of *U. peregrina* is generally congruent with the distribution of dissolved oxygen (*20*); *U. peregrina* becomes an important component of the fauna when the oxygen content falls to below about 5 ml/liter. This species is absent from the well-oxygenated core of North Atlantic deep water (NADW) but is present in circumpolar deep water (CDW), which is derived from the Southern Ocean and is relatively low in dissolved oxygen. In the North and Equatorial Atlantic, *U. peregrina* occurs in an intermediate oxygen minimum (IOM) (*21*); over much of the North Atlantic, Mediterranean outflow water is an important component in this minimum. The NADW is young water, having been formed relatively recently from water flowing out of the Norwegian Sea over the sills of the Denmark Strait and the Iceland-Faeroe Ridge. This outflow water is formed within the Norwegian Sea itself by the cooling and sinking of surface water. Because it has been isolated from the surface for such a short time, this water has a high content of oxygen. Both CDW and IOM have been isolated from the surface for much longer; biologic respiration has resulted in oxygen depletion. In the present-day Atlantic then, *U. peregrina* is most abundant in older waters whereas *C. wuellerstorfi*, *E. exigua*, and other species are characteristic of the younger NADW.

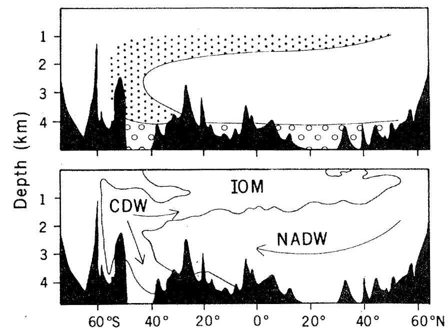

Fig. 2. The distribution of *Uvigerina peregrina* (stippled) in the Atlantic in a section west of the mid-ocean ridge (top) compared with the distribution of dissolved oxygen (bottom). Recent sediment samples from the seafloor at depths equivalent to the stippled area typically contain 5 to 30 percent *U. peregrina*, whereas this species is nearly always absent in Recent sediments north of 40°S and deeper than 2 km. Below 4 km the species *Osangularia umbonifera* (open circles, top) tends to dominate the fauna and does not seem to reflect the oxygen distribution. In the oxygen profile the contour for 5 ml/liter is shown (*21*); circumpolar deep water (*CDW*) and water in the intermediate oxygen minimum (*IOM*) generally contains less than, and North Atlantic deep water (*NADW*) and the southernmost waters more than, this amount of dissolved oxygen.

We suggest that the rapid increases in the abundance of *U. peregrina* result from a significant diminution or cessation of NADW formation. Well-oxygenated water was replaced by older, less oxygenated water. This old water would have been similar to present-day CDW, and it too may have originated in the Southern Ocean. The deepwater circulation of the Atlantic at times of abundant *U. peregrina* in core V 29-179 was similar to the deepwater circulation of the Pacific today.

A simple mechanism exists to limit or cut off production of NADW. As the Norwegian Sea overflows are presently the most important volumetric component of NADW (*22*), cooling in the high-latitude North Atlantic would result in the southward migration of the polar front out of the Norwegian Sea. The Norwegian Sea would develop a stable near-surface stratification and a nearly year-round ice cover and would cease to be a source of overflow water (*23*). The North Atlantic itself would not be a source for deep water until sufficiently dense water could develop in the center of the cyclonic gyre formed north of the polar front (*24*). This may have occurred in stage 2, and the *M. barleeanum*-*Astrononion* sp. fauna may be associated with this configuration.

The rapidity of the shift in benthic fauna is remarkable. At 115,000 years B.P. (the boundary between substages 5e and 5d) the *U. peregrina* abundance increases from 6 to 52 percent in 1200 years. This is very close to the mixing time of the ocean (*25*) and ignores any faunal mixing brought about by bioturbation. The change in fauna at the boundary between stages 5 and 4 is equally rapid but marred by what we presently believe to be burrowing, although no burrow is evident in a photograph of the freshly opened core.

Benthic foraminiferal faunal change in the North Atlantic is thus striking and is clearly related to the climatic cycles of the Pleistocene as documented by the isotopic ice volume signal. The major features of the faunal curves may be explained by a model which postulates that the present deepwater circulation with the production of large volumes of NADW is typical of only a limited portion of the past 150,000 years. For most of this time, little or no deep or bottom water formed in the North Atlantic, and the Atlantic, like the present Pacific, was filled by water characterized by lower oxygen content and perhaps originating in the Southern Ocean. Between 15,000 and 35,000 years B.P., deep water may have been formed in a cyclonic gyre to the north of the full-glacial polar front, but its characteristics must have differed significantly from any water present in the Atlantic today.

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References and Notes

1. T. H. van Andel, G. R. Heath, T. C. Moore, Jr., *Geol. Soc. Am. Mem. 143* (1975); T. H. van Andel, J. Thiede, J. G. Sclater, W. W. Hay, *J. Geol.* **85**, 651 (1977).
2. C. Emiliani, *J. Geol.* **63**, 538 (1955); S. M. Savin, R. G. Douglas, F. G. Stehli, *Geol. Soc. Am. Bull.* **86**, 1499 (1975); R. G. Douglas and S. M. Savin, *Init. Rep. Deep Sea Drill. Proj.* **32**, 509 (1975); N. J. Shackleton and J. P. Kennett, *ibid.* **29**, 743 (1975); *ibid.*, p. 801.
3. P. K. Weyl, *Meteorol. Monogr.* **8**, 37 (1968); R. E. Newell, *Quat. Res (N.Y.)* **4**, 117 (1974).
4. S. S. Streeter, *Quat. Res. (N.Y.)* **3**, 131 (1973).
5. D. Schnitker, *Nature (London)* **248**, 385 (1974).
6. G. P. Lohmann, *J. Foraminiferal Res.* **8**, 6 (1978).
7. S. S. Streeter, *Geol. Soc. Am. Abstr. Programs* **9**, 1192 (1977).
8. Location: 44°00.6'N, 24°32.4'W; core length: 669 cm.
9. In many instances, wet-sieving and drying were repeated to aid disaggregation of the sample.
10. See (*4*), p. 132, for the rationale behind this choice.
11. N. J. Shackleton, *Colloq. Int. C.N.R.S.* **219**, 203 (1973).
12. ——— and N. D. Opdyke, *Quat. Res. (N.Y.)* **3**, 39 (1973).
13. N. J. Shackleton, *Philos. Trans. R. Soc. London Ser. B* **280**, 169 (1977).
14. J. C. Duplessy, C. Lalou, A. C. Vinot, *Science* **168**, 250 (1970).
15. The calibration for *C. wuellerstorfi* was first obtained by Shackleton and Opdyke (*12*) and has subsequently been verified elsewhere. The calibration for the species of *Melonis* is based pri-

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.

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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*)

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

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

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

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

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

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 downsıream, 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

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

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

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

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

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

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

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

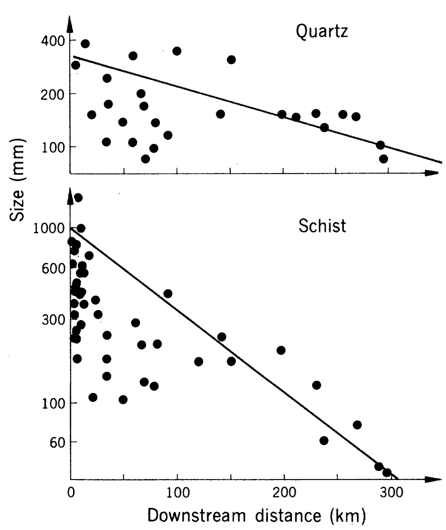

Fig. 1. Semilog diagrams showing systematic difference between fitted straight lines and data points for the downstream decrease in size of the five largest quartz and the five largest schist pebbles for about 40 streams within the Clutha basin.