

## CORRESPONDENCE

The Editor,  
*Journal of Glaciology*

SIR,  
*Discharge of debris by Glaciar Hatunraju, Cordillera Blanca, Peru*

I have news about work at Laguna Paron from Ing° César Portocarrero, who has replaced Dr Benjamin Morales, and from Alcides Ames, who stayed for 6 months in Grenoble with Dr Louis Reynaud. The debouchment of the tunnel into this lake was completed at the end of 1983 by large-diameter boring instead of blasting as initially planned (Llibouty and others, 1977, p. 252).

Prior to undertaking the engineering work, six corings were made under the direction of Ing° Andrés Huamán, which now allow further interpretation and discussion of the information given by Llibouty (1977). The floor of the valley, where it dams the lake, was found to consist of strata of fine material, gravel, and "blocks" (cobbles or boulders). There is no correlation between the sequences in the different bore holes, 50 m apart from each other. One coring, 75 m deep, was done on Glaciar Hatunraju, at 4300 m a.s.l., where I had calculated that the glacier should reach its lowest altitude. Here, under 62 m of ice, there are 4 m of fine material, beneath which are 3 m of "blocks", and 6 m of gravel. This substantiates the statement that the huge moraine creeps without any interstitial ice.

The glacier thickness at this site is less than predicted. In the published longitudinal section (Llibouty, 1977, fig. 10, p. 265), the dashed line (corresponding to an annual negative balance  $b = 0.8$  m/year) should be adopted and, between the calculated positions of the bottom under points (41) and (38), it should be replaced by a straight line. With  $b = 0.8$ , the discharge of Glaciar Hatunraju across its upper cross-section should be  $110\,000\text{ m}^3$  of ice per year.

Cores showed a mixture of ice (60% by weight), quartzose sand (25%), and pebbles 1–3 cm in size (15%). By volume, these figures become 81.8, 11.4, and 6.8%, respectively. This finding contradicts the statement (Llibouty, 1977, p. 257) that a small ice cliff showed no morainic inclusions. Nevertheless, this exposure was in the upper part of the covered glacier; the ice found at the surface there was formed in the lower part of the accumulation zone, which is probably not reached by debris falling from the surrounding rock walls.

Thus, my previous estimate of the amount of debris carried by the glacier has to be revised. At point (38), the discharge is  $24\,800\text{ m}^3$  of ice per year, including 18.2% of debris, i.e.  $4520\text{ m}^3$  per year. The thickness of the ablation moraine there can be estimated at 1.2 m (corresponding to the ablation of debris-laden ice over 80 years, on the 600 m up-stream). Thus, about  $560\text{ m}^3$ /year of ablation moraine has to be added. The discharge of debris into the valley should be about  $5080\text{ m}^3$ /year, instead of  $3000\text{ m}^3$ /year. The Hatunraju moraine ( $92 \times 10^6\text{ m}^3$ ) could have been built up in 18 000 years under the present conditions, without assuming that there is soft material beneath the glacier in its upper part, and that this is carried into the valley. If the latter assumption is made, the time necessary might be halved.

A tentative estimate of the amount of cirque erosion during the Holocene can be inferred. The rock wall with hanging patches of ice, which surrounds the accumulation zone of Glaciar Hatunraju, is about 2700 m long and 800 m high. To deliver  $5080\text{ m}^3$  of debris per year, it has to recede, due to frost shattering, at a mean rate of

$2.4\text{ mm/year}$ , which is only 24 m during 10 000 years of the Holocene. Although this estimate is conservative, it shows that it took the whole of the Pleistocene to form the cirque.

Université de Grenoble I,  
and  
Laboratoire de Glaciologie du C.N.R.S.,  
B.P. 96, 38402 St-Martin d'Hères Cedex, France

L. LLIBOUTY

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SIR,

*Spatial and temporal variation of electrical conductivity, pH, and water temperature in the Gornera, Switzerland*

Gurnell and Fenn (1985) have provided a valuable description of the spatial and temporal variations of electrical conductivity in the pro-glacial stream of the glacier de Tsidjiore Nouve, Switzerland. Comparison of their measurements of the spatial variation of pro-glacial stream conductivity with some I took in the same month (July 1981) at the nearby Gornergletscher shows several points which may be of value in future work.

Table I shows the longitudinal profile of Gornera water quality I measured from the glacier portal to the Grande Dixence Prise d'Eau on the afternoon of 19 July 1981 in a rather severe snowstorm (air temperature =  $3.5$ – $5.6^\circ\text{C}$ , barometric pressure = 0.790 bar at portal). The observed conductivity is neither constant, nor slowly increasing, as would be expected during down-stream solute acquisition. Instead, both the conductivity and water temperature vary in an approximately random fashion. This is caused by sampling different parcels of water as they travel down-stream.

A "water parcel" is used here as an operational approximation to a "water particle", which is an infinitesimally small volume of water used to describe fluid flow by particle mechanics (Halliday and Resnick, 1966, p. 440). Water parcels examined during the present work were  $0.25\text{ dm}^3$ , removed from the flow in a plastic beaker, and completely measured within 10–20 s. In the general case, a water parcel should represent the minimum water volume necessary to measure a chemical, or physical, water property in the field at a given time, using a given method. The uniformity of properties for several water parcels varying in length, width, or depth along a stream should be confirmed by measurements, not assumed.

TABLE I. 19 JULY 1981 LONGITUDINAL PROFILE OF GORNERA WATER QUALITY

Distance from portal m	pH	Conductivity $\mu\text{S cm}^{-1}$	Water temperature $^{\circ}\text{C}$	Local time h
0	8.01	35.0	1.4	14.09
50	8.02	29.7	1.3	14.17
100	7.86	31.0	1.4	14.23
150	7.80	30.4	1.2	14.31
200	7.82	30.4	0.9	14.39
300	7.70	30.1	1.5	14.45
400	7.74	30.4	1.3	14.53
500	7.64	29.7	1.3	15.02
600	7.69	34.3	1.3	15.11
900	7.55	31.7	1.9	15.24

Sampling an individual water parcel as it progresses down-stream uses the coordinate system developed by J.L. Lagrange, varying the spatial coordinates of the particle ( $x, y, z$ ) as a function of time ( $t$ ). Common Lagrangian current indicators are "drift poles", marker floats, sheets of paper, or patches of dye (Pickard, 1963, p. 81). Marker floats were used in this study.

The traditional approach of measuring fluid particle properties at a fixed location of the stream uses the coordinate system of L. Euler, holding the spatial coordinates of the measuring site for different fluid particles constant as a function of time. Eulerian sampling is more commonly used because there is less effort involved.

The Lagrangian sampling perspective allows direct measurement of solute changes to a water parcel as they occur. The Eulerian approach allows estimates of solute transport through time at a given location, but it fails to delineate the chemical evolution of a water particle with time. Direct measurements of the chemical evolution of a water parcel during its passage down-stream are the primary data needed to define reaction rates and understand the mechanisms of chemical weathering in the stream.

The Eulerian sampling of fluid velocity and chemistry produces time series which can be calculated into frequency and wavelength information using spectral analysis. To date, such analyses have not been used to derive chemical reaction rates or weathering mechanisms in a stream. Sometimes Eulerian sampling is combined with Lagrangian descriptions of fluid-flow equations to predict down-stream chemical property changes; for instance, the longitudinal dispersion of a chemical point-source input (Fischer, 1968). Unfortunately, longitudinal dispersion theory yields invalid predictions for the measured down-stream evolution of chemical tracers in natural streams, due to undetected sampling errors (Chatwin, 1971), or fundamental errors in the theory (Day, 1975). Day's (1975) exhaustive field conductivity measurements of the longitudinal dispersion of salt in the mountain streams of New Zealand show that stream conductivity varies longitudinally in presently unpredictable ways, after a point-source chemical injection up-stream. It is assumed here that the flow characteristics of Day's (1975) mountain streams are similar to many pro-glacial streams, and that chemical erosion of a several square metres area of bedrock in a glacial stream is analogous to a point-source injection. For the above reasons, this study attempted to sample one water parcel as it moved down-stream by Lagrangian sampling.

Ambach and Jochum (1973) pioneered the calculation of longitudinal dispersion coefficients with Lagrangian equations in pro-glacial streams with an excellent study of dye-fluorescence measurements versus time at Eulerian sampling stations. Day's (1975) field measurements show that accurate prediction of down-stream chemical concentration changes in mountain streams is not possible with present methods.

Until predictive methods are developed further, the only available way to determine chemical reaction rates in a pro-glacial stream is by direct measurement. Directly measured reaction rates will always be the standard that any field predictive method is compared against. I failed to

obtain the needed direct measurements in this study. The point of this letter is to let others learn from my observations and errors, without having to repeat them.

The main difficulty encountered is that the pro-glacial stream often flows faster than one person can sample with Lagrangian stations. The ideal solution would be to deploy a floating, telemetering sensor which monitors chemical changes as the stream flows. If traditional Eulerian stations must be used, more equipment must be purchased, and marker floats should be used to identify water to be sampled. Field tests at sampling stations are necessary to determine if instantaneous Eulerian velocity measurements may be used to estimate accurately float-travel times. The 49.7% variation in observed Gornera float-travel times in 11.53 min on 2 August 1981, during constant discharge, is not encouraging in this regard.

The time to measure the profile given in Table I was 4500 s. The mean water-parcel travel time for this section of the Gornera was 390 s ( $n=9$ ), based on measurements of 474 and 495 s on 29 July; 427 s on 1 August; and 433, 401, 332, 296, 312, and 329 s on 2 August 1981 for  $Q$  from 18 to 22  $\text{m}^3 \text{s}^{-1}$ . Travel time was determined by timing neutral buoyancy oranges tied to empty 1  $\text{dm}^3$  plastic sample bottles by fluorescent orange surveyor's tape, using two synchronized digital watches to within 1 s accuracy. The straight-line distance between the terminus portal and the Prize was surveyed as 731  $\pm$  19 m, but the actual stream course was paced at 885  $\pm$  80 m.

Although Gurnell and Fenn (1985, p. 109) found a maximum difference of 0.5  $\mu\text{S cm}^{-1}$  over about 200 m in the main pro-glacial stream, Table I shows a change of 15%, 4.6  $\mu\text{S cm}^{-1}$ , in 9 min from the sites 500–600 m down-stream in the Gornera. I have also observed such significant conductivity changes in a few minutes in the pro-glacial streams of Coleman and Nisqually Glaciers in the U.S.A. It follows that steady-state stream conductivity cannot be assumed to hold generally during the brief time period required for sampling the spatial variations of pro-glacial streams by one observer.

Table I shows pH values progressively decrease down-stream, as re-aeration apparently supplies  $\text{CO}_2$  across the air-water interface faster than weathering reactions proceed. Often at Gornergletscher and Nisqually Glacier, this is not the case, and pH increases down-stream, as weathering proceeds faster than re-aeration. The relatively smooth decrease of pH in Table I implies a nearly steady-state pH profile during the 75 min sampling traverse. For any one site in the Gornera, pH was observed to vary out of phase with both water discharge and conductivity, suggesting its possible future worth in sorting out solute sources in the glacial hydrologic system.

Unfiltered, *in-situ* pH measurements are from 10 000 to 100 000 times more sensitive than conductivity in detecting acid-driven rock weathering reactions in the Gornera. This is because *in-situ* Gornera pH is generally in the range of 7–8 (Table I), corresponding approximately to a hydrogen-ion concentration of  $10^{-7}$  to  $10^{-8}$   $\text{E dm}^{-3}$ . For a Gornera conductivity of 30  $\mu\text{S cm}^{-1}$  at 0–2  $^{\circ}\text{C}$ , the total ionic content is about  $10^{-3}$   $\text{E dm}^{-3}$ . Since the Gornera has been shown to have a linear correlation between electrical conductivity and major cationic content of filtered samples (Metcalf, unpublished), the stream conductivity is linearly proportional to total ionic content.

Since the hydration of  $\text{CO}_2$  supplies acid for rock weathering in the Gornera, pH is a very sensitive indicator of this weathering process. To ensure that  $\text{CO}_2$  exchange does not alter pH from *in-situ* values, no pressure or vacuum filtration must be used prior to the measurement. I explained this poorly in Metcalf (1984). Unfiltered samples yield *in-situ* pH (or an approximation from  $\text{CO}_2$  transfer effects), if no rock weathering occurs during the measurement. Filtered samples suspend non-volatile ionic species concentrations at *in-situ* values, and allow determination of the pH when the sample is in equilibrium with atmospheric  $\text{pCO}_2$ . Although the method of Metcalf (1984) is precise, it contains unknown systematic errors of 0.2–0.5 pH units without independent standardization, due to calibration with concentrated buffers. Dilute standards must be used for accurate pH measurements of pro-glacial streams (Metcalf, *in press*).

TABLE II. 9 AUGUST 1981 LONGITUDINAL PROFILE OF GORNERA WATER QUALITY

Distance from portal m	pH	Conductivity $\mu\text{S cm}^{-1}$	Water temperature $^{\circ}\text{C}$	Local time h
0	7.20	12.4	1.1	16.14
100	7.48	9.9	1.3	16.25
200	7.36	10.4	1.4	16.33
300	7.35	9.8	1.4	16.40
400	7.40	9.1	1.5	16.46
500	7.39	9.9	1.5	16.54
600	7.45	9.4	0.9	17.02
700	7.25	9.2	1.3	17.08
900	7.20	10.2	1.4	17.16

Table II is interpreted to show the pro-glacial stream is already equilibrated with atmospheric  $\text{CO}_2$  before reaching the glacier portal. This profile was measured as before, on 9 August 1981 ( $Q = 15\text{--}17 \text{ m}^3 \text{ s}^{-1}$ , air temperature =  $8\text{--}9^{\circ}\text{C}$ , barometric pressure = 0.792 bar), a partly sunny afternoon. Conductivity and pH are relatively constant throughout the profile. The water appears to warm generally down-stream during re-aeration, but not in a continuous manner, due to sampling different water parcels. All variables exhibit some scatter attributable to sampling different parcels of water.

I conducted the 9 August 1981 traverse by running and jumping over the boulders between sampling locations. In summer, it is unlikely one individual will be able to sample the same water parcel at many down-stream locations on a swiftly flowing, pro-glacial stream, such as the Gornera. In winter, such sampling is just possible in a steep valley by skiing. Although an inept skier, I was able to sample this way at Nisqually Glacier in 1977 and 1984. An easier approach is to use field assistants or recording instruments, if the resources are available.

I gratefully acknowledge the extensive data on longitudinal dispersion in glacial streams furnished by Professor Dr W. Ambach, prior to planning field sampling strategies.

MCR Scientific,  
227 Ravenhead,  
Houston,  
Texas 77034, U.S.A.

RICHARD C. METCALF

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SIR,

*The faces of ice*

In spending a few months working at the Scott Polar Research Institute, I had the pleasure of meeting Charles Swithinbank and Hilda Richardson. In the course of explaining my purpose in Cambridge, which was to write a book on the growth and decay of ice, I took pains to disqualify myself as a glaciologist. This declaration immediately produced wistful and knowing smiles from both of them, for reasons I have since discovered. Despite some 20 years of working on various ice problems, I still had a narrow view of the glaciologist and it is evidently a widely held view. In this letter, I have been bold enough to suggest a possible remedy to this perennial perception problem.

The four main chapters of my book each deal with ice in a particular context which, upon reflection, suggests to me that the glaciological community at large may admit to a useful contextual taxonomy. Given the Society's general definition of glaciology as "the study of snow and ice", I suggest the following contextual sub-divisions:

*Geo-glaciology*, dealing with ice in and on the Earth: snow and glacier ice; avalanches; ice caps and ice sheets; *aufeis* and needle ice; permafrost; ice lenses, wedges, and other forms of ground ice.

*Hydro-glaciology*, dealing with ice in and on water: sea ice, icebergs; lake and river ice; ice shelves; frazil, anchor, slush, and pancake ice; ice in channels and conduits.

*Aero-glaciology*, dealing with ice in the air: snow, sleet, and hail; ice crystals, frost, hoar, and rain; accretion on land-, sea-, and airborne structures.

*Bio-glaciology*, dealing with ice in and on bio-organisms: snow and frost coatings; ice in biofluids; ice in unicellular organisms; ice in plants; ice in animals; ice in foods.

It is not difficult to construct other contexts such as astro-glaciology and eco-glaciology.

If such terms were adopted, their common use would do much to identify glaciological specialists who may then possess a greater sense of their particular community. Reticence to acknowledge the glaciological label might then evaporate, as it evidently has in radio-glaciology, which is not a contextual division but an aspectual one. Again, it is not difficult to imagine other aspects: chemo-glaciology, electro-glaciology, thermo-glaciology, rheo-glaciology, and so on.

I know of no attempt to develop a taxonomy of glaciology on contextual and aspectual lines. May I suggest that an attempt to do so, through international discussion, would be more than an academic exercise. It would tell us more about ourselves, about each other, and may flood the membership department with the names of people who, like me, suddenly realize that they have been glaciologists all along.

Department of Mechanical Engineering,  
University of Alberta,  
Edmonton,  
Alberta T6G 2G8,  
Canada

G.S.H. LOCK

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