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Records of riverborne turbidity currents and indications of slope failures in the Rhone delta of Lake Geneva

Abstract—The sublacustrine topography of the Rhone delta in Lake Geneva is characterized by a channel that can be traced about 9 km beyond the mouth of the river. Two instrumented moorings were deployed from June to August 1985 in the channel axis at depths of 150 and 201 m to detect underflows of dense, sediment-laden river water. Each array consisted of three current meters and a thermistor chain. Data were recorded every 15 min (currents) or 30 min (temperatures). During 78 d of effective measurement, 31 well-defined downslope events were recorded, five with speeds >50 cm s^{-1}. Major events correlate with discharge peaks of the Rhone, and current activity is characterized by single pulses lasting a few hours. Some flow events were accompanied by temperature increases of up to 3°C, suggesting two different current origins: the first is intrusion of sediment-laden, warm river water into the cold bottom water of the lake as a dense turbidity underflow, and the second is turbidity-current flow triggered by sliding or slumping of delta deposits. Damage caused to instruments and breakage of mooring links suggests sliding of large amounts of deltaic sediments or avalanchelike turbidity currents.

The alpine Rhone River is the main tributary and by far the most important source of solid matter to Lake Geneva, where it has built a large delta covering ~100 km^2, or about a sixth of the lake surface (Houbolt and Jonker 1968). For most of the year, the cold, sediment-laden Rhone—as a result of its higher density—plunges below the lake surface. This process has been described by Forel (1885), whose classic work includes many basic observations and theoretical considerations concerning the sinking-river phenomenon. He also attributed the origin of the channels and levees in the Rhone delta to the underflow of dense, sediment-laden alpine meltwater. Surprisingly, Forel's scientific conclusions have never been tested by direct current measurements in Lake Geneva itself, although his description of the "cascading river" is often quoted as one of the earliest scientific treatises on turbidity-underflow phenomena. Several studies in different alpine lakes (Lambert et al. 1976) as well as in glaciolacustrine environments (*see* Weirich 1986) and in reservoirs (Bruk 1985) have indicated that density-current activity is a common process in lakes with sediment-laden tributaries. Maximum velocities of 120 cm s^{-1} have been measured in the Rhine delta area of Lake Constance (Lambert 1982).

Two different modes of river water inflow occur in thermally stratified lakes: under normal flow conditions, the river water will be injected at the interface between the warm, upper layer (epilimnion) and the cold, lower layer (hypolimnion); the river water will form an *interflow* close to the thermocline. During flood surges the concentration of suspended sediments in the tributary may increase markedly. As a consequence, the river water can become denser than the deepest water layers of the lake and therefore continue as a turbid *underflow* following the slopes of the delta. The possible limnological impacts of these density-driven bottom currents have been discussed briefly by Lambert et al. (1984) and recently by Wüest and Imboden (1987).

A different kind of turbidity current is generated by avalanches of unstable sediments which are fluidized and suspended by sliding or slumping (Kelts and Hsü 1980; Lüthi 1980). Although these single-pulse or avalanche-type turbidity currents are not bound to river inflow areas, they are likely to occur in river deltas.

A cooperative research project was initiated in 1983 between the Laboratory of Hydraulics, Hydrology, and Glaciology (ETH Zurich) and the Institut F.-A. Forel (University of Geneva) to study these phenomena in Lake Geneva. An initial attempt in August 1983 to measure interflows of the Rhone used an ultrasonic current meter; the interflows occurred close to the thermocline (at depths of 10–30 m) during the period of stratification and moderate sediment influx. The results of this study (Giovanoli and Lambert 1985) showed that currents caused by the momentum of the inflowing river water were clearly discernible up to a distance of about 1 km from the river mouth (max velocities of 40 cm s^{-1}).

At that time the question remained: would short-term increases of river water density (e.g. by intensified transport of suspended sediment) be sufficient to initiate underflows plunging along the lake bottom instead of being trapped at the thermocline? Therefore, the second experiment (June–August 1985) aimed to monitor some physical parameters (flow velocity, direction, and temperature) for the first time within the Rhone delta channel in order to detect channelized turbid underflows. We here summarize the main results of this study.

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The Rhone River drainage area is 5,220 km^2 in extent; it covers almost the entire area of the canton du Valais and a small part of canton de Vaud. About 16% of the catchment is glaciated. The mean annual runoff at the entrance to the lake is 180 m^3 s^{-1} or 5.7×10^9 m^3 yr^{-1}. The discharge of the Rhone is considerably influenced by storage and release of water at 14 reservoirs for power plants that have a total storage capacity of $\sim 1{,}150 \times 10^6$ m^3. Estimates of annual sediment load carried by the Rhone into the lake vary between 2 and 9×10^6 t yr^{-1} (Burrus 1984); bedload transport is reduced to negligible quantities because of intense dredging and flood control measures in tributary torrents. For the period 1968–1983 the mean monthly temperature of the Rhone was 9.6°C (June), 9.9°C (July), and 9.7°C (August). Short-term variations do not exceed ±2°C.

The level of Lake Geneva has been kept at ~372 m asl by outflow regulation in Geneva since 1886. With a surface area of 582 km^2 and a maximum depth of 309 m the lake has a volume of 89 km^3. The delta of the Rhone in Lake Geneva is characterized by a channel (Houbolt and Jonker 1968) that extends about 9 km from the river mouth to a depth of about 250 m (Figs. 1 and 2). This conspicuous structure, discovered in 1885 during a bathymetric survey, is often cited as an example of the erosive power of sediment-laden gravity currents (Shepard et al. 1979), although this suggestion has never been tested by direct measurement. A first visual inspection of the channel was performed in 1982 by J. Piccard and J.-P. Vernet during a dive aboard the submersible *F.-A. Forel.* They found evidence of erosive processes and intense current activity (large amounts of wood and debris transported by the Rhone during floods).

Our measurements were planned for a 3-month period (June–August 1985) that corresponds to the season of most intense runoff and highest probability of flood occurrences. The discharge and the temperature of the Rhone was continuously moni-

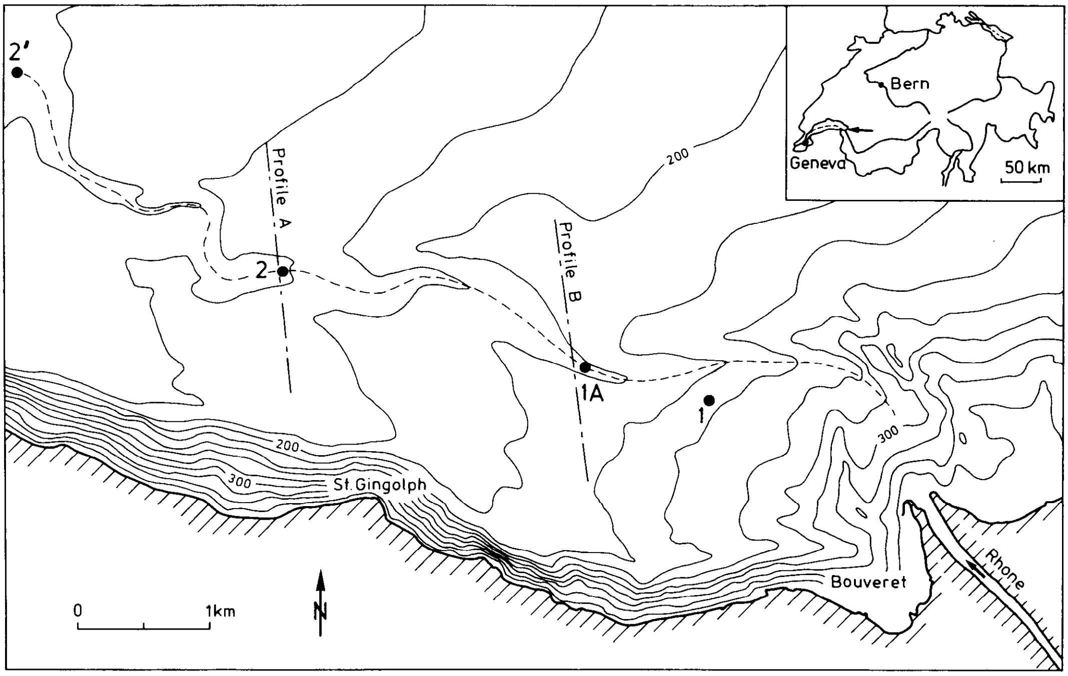

Fig. 1. Index map of the southeastern part of Lake Geneva with mooring positions in the subaqueous channel of the Rhone River delta. Although contour lines (m asl) dating from 1886 give only a rough view of bottom topography, the course of the main channel (broken line) is still approximately correct. Profiles A and B indicate the tracks of the north–south-trending echo-sounder profiles at mooring locations 1A and 2 (*see Fig. 2*). 1 and 2—Original mooring sites; 1A—redeployed moorage site; 2'—recovery site of instruments from mooring 2, displaced by a major gravity current event.

tored about 4.5 km upstream of the river mouth at the Federal Hydrologic Services gauging station near Porte du Scex where suspended sediment concentration is determined three times a week. Deployment and recovery operations on the lake were performed from the 15-m RV *La Licorne* of the F.-A. Forel Institute. Each array (Fig. 3) consisted of three recording current meters [4, 6, and 13 m off the bottom, two of them (4 and 13 m) with temperature sensors] and a 20-m-long thermistor chain (with 11 sensors at 2-m intervals). The current meters were of the Savonius-rotor type (two Aanderaa devices, and one model designed and constructed at the VAW). The recording intervals (15 min for current meters and 30 min for thermistor chains) were determined by the deployment period and the storage capacity of the magnetic tapes. The instruments were suspended vertically between an anchor weight on the lake bottom and four underwater buoys.

The initial threshold speed of the current meters is about 3 cm s^{-1}. The large amounts of sediment carried into the lake caused silt deposits on the instruments, however, and there is some reason to believe that the threshold velocity became higher because of progressive siltation on the rotor bearings.

Mooring 1 was deployed on 3 June 1985 at a water depth of 150 m, about 1.6 km WNW of the Rhone River mouth. Oncoming winds during the deployment operation resulted in the mooring being placed slightly off axis in the channel. Mooring 2, deployed on 4 June 1985 at a water depth of 201 m was perfectly located in the channel axis (Figs. 1 and 2).

The planned schedule was, however, interrupted by incidental surfacing of both ar-

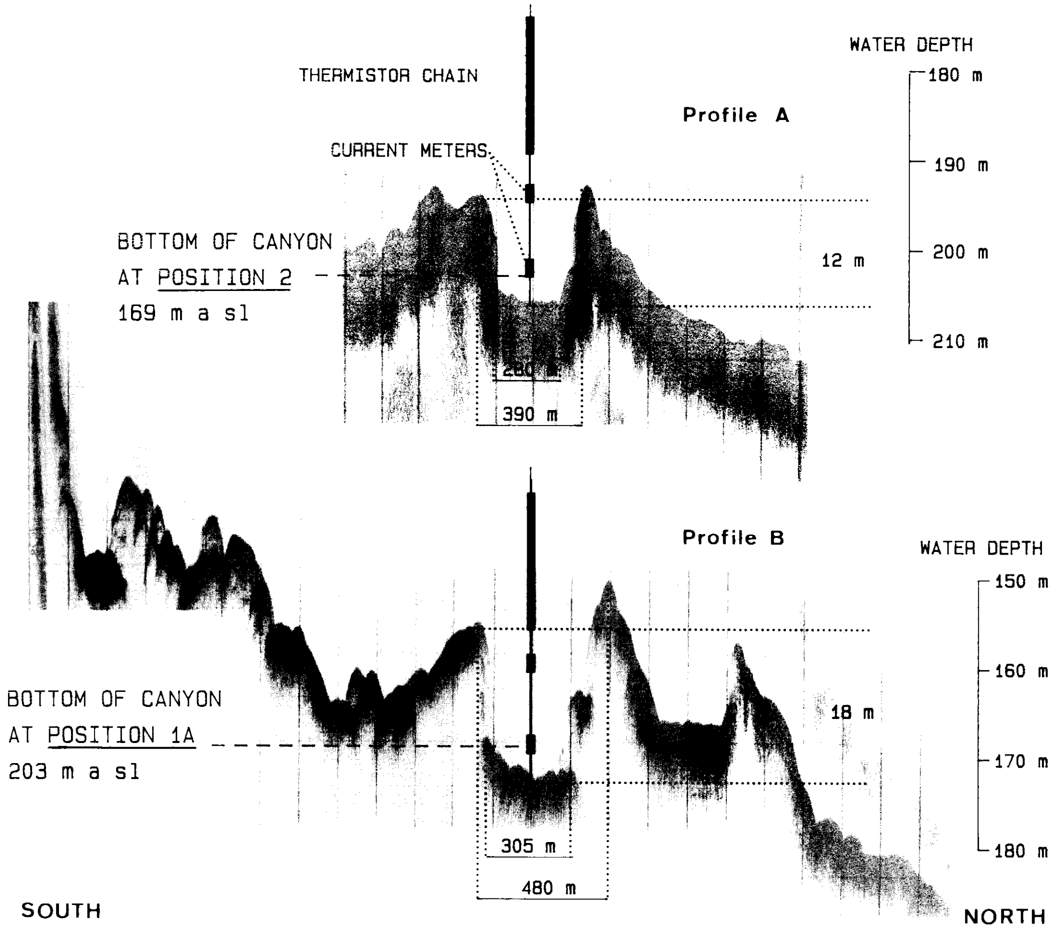

Fig. 2. 33-kHz echo-sounder profiles close to mooring site 2 (top) and 1A (below) with the outlines of the thermistor and current meter arrays in the main Rhone delta channel (downslope view).

rays 4 d after deployment (Fig. 4). Unfortunately, only one mooring could be redeployed for the rest of the period (position 1A in Fig. 1). Mooring 1A was installed from 14 June until 27 August as scheduled (Figs. 1 and 2). Thus, for 74 days the instruments of this array provided almost continuous data.

We concentrate on the data of the lowest and uppermost current meter because the intermediate one yielded virtually the same values as the lowest instrument (immediately subjacent).

The records at moorings 1 and 2 (3–7 June) and 1A (14 June–28 August) cover 84 d (Fig. 5). During this period, 31 well-defined down-channel events were recorded, five with maximum speeds >50 cm s^{-1}, 19 events between 10 and 50 cm s^{-1}, and seven events <10 cm s^{-1}. Eleven of the major events correlate with discharge peaks or with phases of rapidly increasing discharge of the Rhone.

Some general characteristics of the currents are summarized as follows. Events are characterized by single pulses lasting a few hours rather than by longer episodes of more or less intense current activity. The longest event lasted about 14 h (1 July). Currents are predominantly directed down-channel (Fig. 6). A few events are preceded by short and faint up-channel pulses. Between the

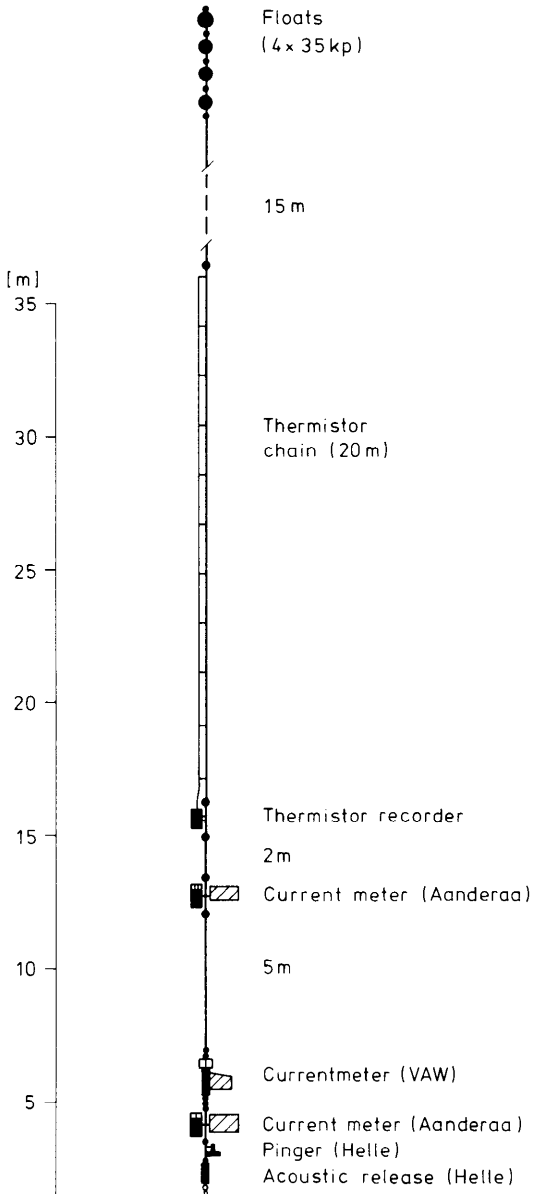

Fig. 3. Configuration of the instrument arrays moored in the Rhone delta channel.

events there are longer periods of apparent inactivity (speed ≤ threshold). Yet, the conformity of current directions recorded simultaneously at different levels suggests the presence of down-channel currents below the threshold velocity of the instrument sensor.

Whereas some current events are accompanied by distinct temperature increases of up to several degrees, others yield only faint increases of this parameter. This fact—suggesting the existence of two different types of currents—is illustrated by the examples of Fig. 7: The event of 1 July 1985 is characterized by a temperature anomaly of nearly 3.5°C beginning at 1630 hours. At least 250 mg liter^{-1} of suspended sediment must have been present in the current to compensate for the density difference to the ambient water ($\Delta\rho = 0.00015$ g cm^{-3}). The concentration in the Rhone River (Porte du Scex) was about 2,600 mg liter^{-1}, the discharge maximum ~471 m^3 s^{-1}. On the basis of the temperature records of the Rhone (10.5°C) and of the underflow (8.6°C) the lake water entrainment can be roughly estimated: the mean temperature of the (stratified) lake along the path of the underflow (from the river mouth to mooring 1A) was about 6°C; assuming a constant entrainment rate, the resulting contribution of lake water was therefore about 40%.

In contrast, the strong event of 4 July 1985 (as well as the event of 27 June) was accompanied by a faint temperature increase of 0.4°C (the temperature of the Rhone being 10.3°C), and neither the discharge (~400 m^3 s^1) nor the sediment concentration (0.3 g liter^{-1}) of the tributary was exceptional. Nevertheless, this event yielded the highest speed (>90 cm s^{-1}) recorded during the experiment. This type of flow probably resulted from a different mechanism than the underflow of dense river water alone.

A comparison of measurements performed simultaneously at different positions in the channel was possible only for the period of 3 d when moorings 1 and 2 were anchored at a distance of 3.6 km from each other.

The first event passing both moorings (5 June) is presented in Fig. 8: Between 0545 and 0600 hours a down-channel movement was recorded at mooring 1 by the lower meter, while a current in the opposite direction (about 30 cm s^{-1}) passed the upper meter. Because the instrument array was moored slightly out of the channel axis, it is possible that this up-channel current resulted from water movements derived from the general

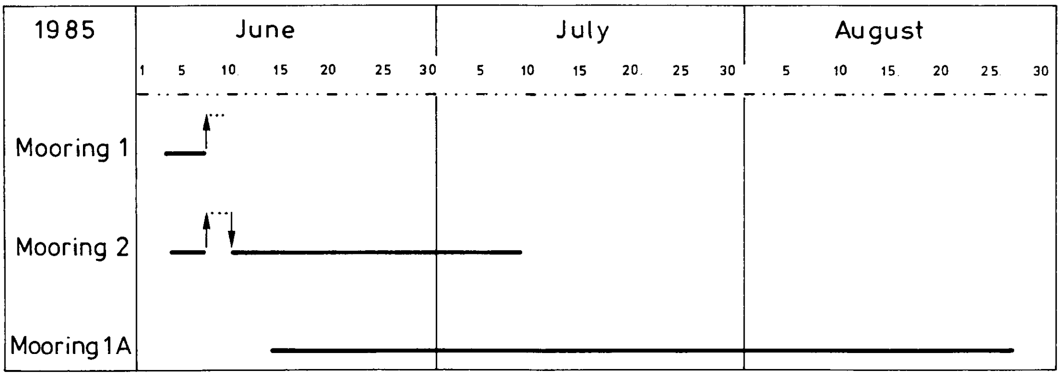

Fig. 4. Time-table of instrument deployment and recovery in the Rhone delta channel. Upward-pointing arrows indicate anchor cable breaks that occurred on 7 June 1985. Mooring 1 was found 2 d later floating at the surface. Mooring 2 sank on 10 June after loss of two floats (arrow pointing down); these instruments were recovered on 9 July 1985 with the help of a remotely controlled underwater TV camera (2′, Fig. 1).

lake circulation. After 0600 hours the current direction in the upper meter also pointed west (down-channel) for the rest of the event, with decreasing current velocities at both levels.

In mooring 2, both instruments recorded down-channel currents, the lower meter much higher values (max velocity: 31 cm s^1) than the upper meter where 5 cm s^{-1} were not exceeded and a short up-channel pulse

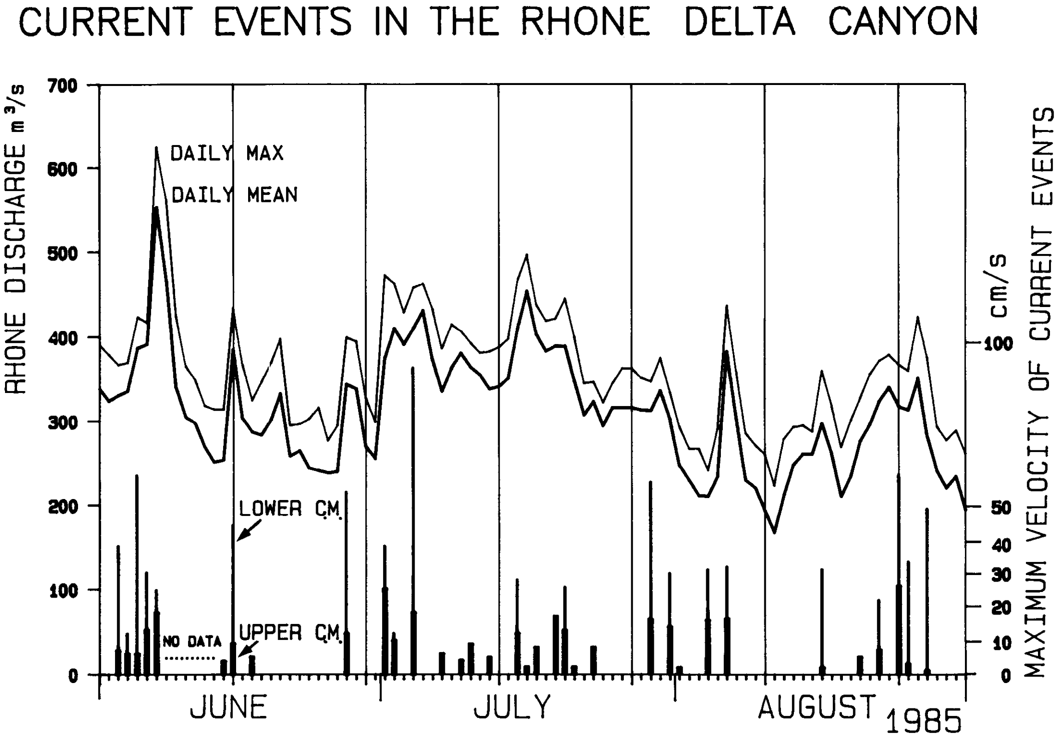

Fig. 5. Discharge of the Rhone River and episodes of downslope current activity (max velocities) recorded in the delta channel (moorings 1 and 1A). Thick bars: upper current meter (13 m off bottom); thin bars: lower current meter (4 m off bottom).

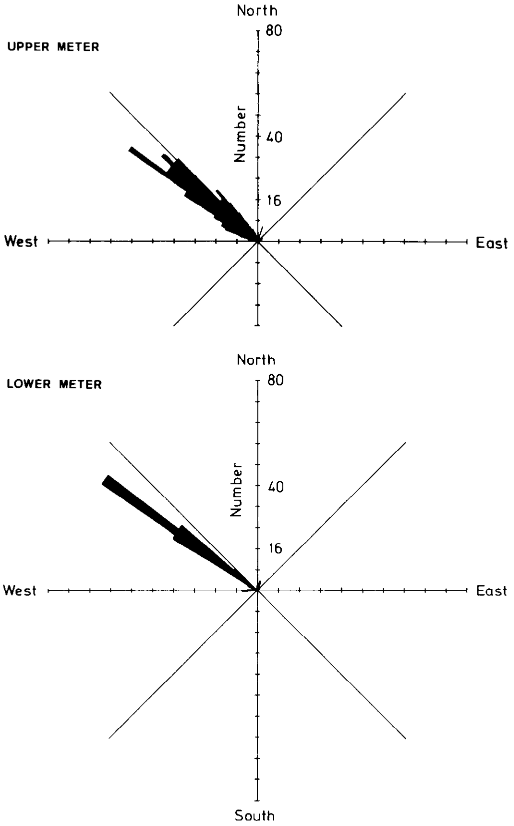

Fig. 6. Frequency of current directions (speed >0.5 cm s^1) measured during 74 d on two levels (4 and 13 m off bottom) every 15 min at mooring 1A (*see Fig. 1 for orientation*). Northwest directions document the dominant downslope movement of water masses within the delta channel.

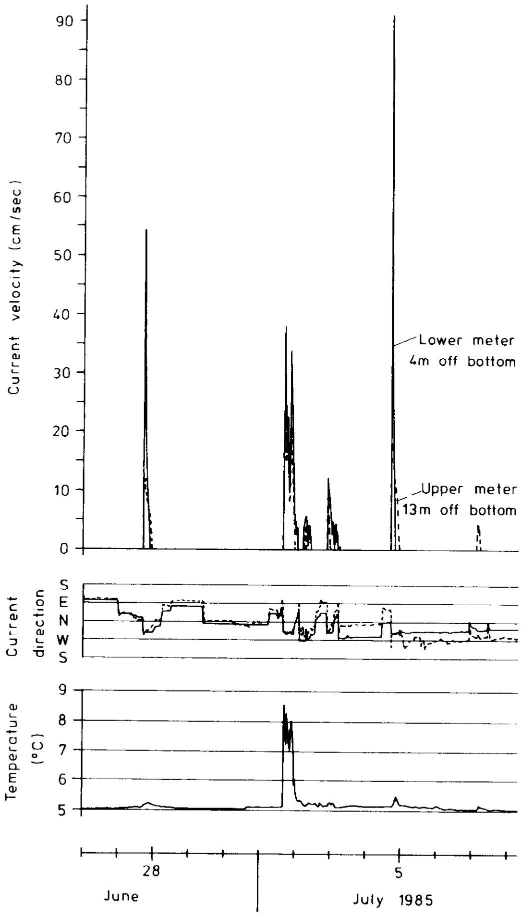

Fig. 7. Section of current meter and temperature records at mooring site 1A. Note the conspicuous positive temperature anomaly of about 3°C during the event of 1 July 1985. In contrast to this "warm" density current attributed to plunging river water, the preceding and following events show only a faint rise in temperature; they probably result from small avalanche-type turbidity currents.

occurred (between 0700 and 0800 hours). The temperature increase is negligible.

The time offset between the current peaks at both moorings is five recording cycles or 75 min. If both moorings observed the same flow event, the mean velocity would be 79 cm s^1 (±13 cm s^1 uncertainty resulting from the measuring interval), much more than the recorded 31 cm s^{-1}. As the recorded velocities are mean values resulting from a 15-min interval, however, they may underestimate stronger pulses. Moreover, temporary siltation of current sensors cannot be excluded.

The second event occurred on 7 June between 0800 and 1030 hours at mooring 1 and between 1030 and 1600 hours at mooring 2 (Fig. 9); it correlates with a discharge peak of the Rhone. On 5 June the discharge had remained fairly constant at about 400 m^3 s^{-1} until midnight (Fig. 5). During the night (5–6 June) heavy rainfall (Le Sepey: 32 mm; Montana: 22 mm; Sion: 19 mm) caused an unusual increase of the discharge from 390 to 615 m^3 s^{-1} within about 10 h, resulting in the annual discharge peak. The underflow passed moorings 1 and 2 with a time offset between 135 and 150 min, resulting in a mean travel velocity of 44±4 cm s^{-1} which is in good agreement with the recorded currents; they indicate an acceleration of the current from mooring 1 to 2.

As already pointed out, the recorded temperatures allow a rough estimate of the amount of mixing between the underflow and lake water. In the event of 7 June (*see above*), the Rhone (9°C) entrained about 36% lake water down to mooring 1 (7.9°C) and 50% down to mooring 2 (6.6°C). The amount of water transported by the density currents is estimated by determining a mean velocity from current meter data and taking the cross section of the channel from echo-sounder profiles (Fig. 2). For example, the event of 5 June, lasting about 7 h at mooring 1 with a mean velocity of 12 cm s^{-1}, transported $\sim$300 m^3 s^{-1} or 7 × 10^6 m^3 through the cross section of about 4,000 m^2. Problems arise if one tries to compare these data with those recorded simultaneously at mooring 2, 3.6 km downslope: although current speed, cross section, and therefore the discharge are of the same order of magnitude, the amount of water transported is much less, simply because the event lasted (at least according to the record) only about 2 h. In addition, such estimates become even more conjectural when temperature anomalies during an event were recorded by the thermistor chains at more than $\sim$25 m off bottom because it indicates an overspill of the channel rim by the density current. In comparison, discharge of the Rhone was >400 m^3 s^{-1} during the events; therefore only about two-thirds of the equivalent volume of river water flowed through the channel—and if lake water entrainment is accounted for, only about one-third. The example of 7 June, in contrast, shows an opposite trend because about five times the amount of water estimated at mooring 1, and therefore much more than the Rhone discharge, flowed through mooring 2. Thus, questions remain concerning the continuity of the density currents along their path through the channel.

As noted previously, measurements at moorings 1 and 2 were unexpectedly interrupted after 4 d by a puzzling incident (Fig. 9). Both arrays surfaced after an almost simultaneous break of the weakest link of the mooring (a steel cable of 3-mm diam). The break occurred between the anchor weight and the acoustic release (that had not been activated). The array of mooring 1 was recovered by chance 36 h after surfacing. The array of mooring 2, which surfaced about

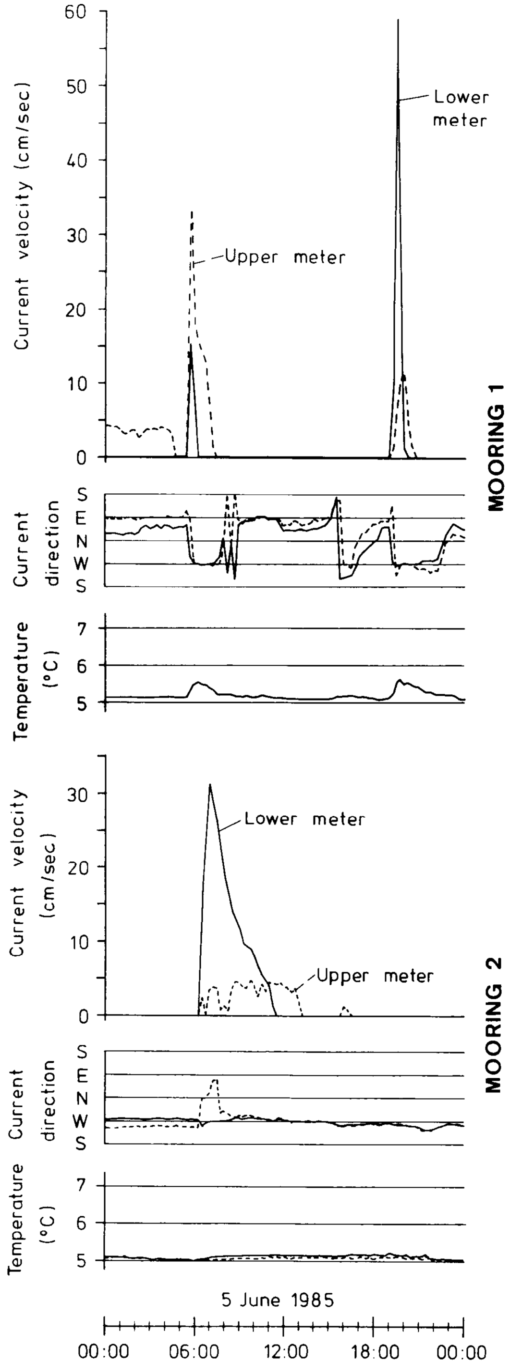

Fig. 8. Current meter data of 5 June 1985 at moorings 1 and 2. Note the higher velocities measured by the upper meter at mooring 1 (0600 hours) and the (weak) backflow recorded by the upper meter at mooring 2 (0600–0800 hours), indicating a maximum flow height around 10 m. The flow recorded between 1900 and 2000 hours at mooring 1 lost its identity before reaching mooring 2.

3.6 km west, was not discovered, and the four floats with the array hanging underneath remained at the surface until 10 June (Fig. 4) when two floats were lost as a result of wave action, and the array sank. Although it remained within the range of the transducer (2.5 km west of the initial position: 2′, Fig. 1), it was not possible to recall the array by activating the release because of the lost floats. The instruments were recovered by means of a remote underwater TV camera on 9 July 1985.

The causes of the incident have not yet been elucidated, but there is reason to believe that the preceding flood discharge of the Rhone led to the release of the moorings (Fig. 9). After the underflow event of 0800–1500 hours on 7 June, the recorded data are difficult to interpret: velocity data were no longer recorded at mooring 1 (later recovery showed that all Savonius rotors had been damaged); the current direction plot of the lower meter at mooring 1 suggests that the direction vane was stuck at one heading; and, the temperature record of the lower current meter (mooring 1) also remained at a level of about 7.5°C, although slightly decreasing. Around 2300 hours, the link breakages occurred and the arrays rose to the surface (arrows in Fig. 9); this process is documented by a sudden decrease of temperature at the lower current meter of mooring 1, increase of temperature recorded by all sensors at mooring 2, and decrease of water pressure (depth) recorded by one sensor at mooring 1 (not shown in Fig. 9).

This sequence of recordings is interpreted as follows. The virtually simultaneous rupture of the cables of *both* moorings within the same recording interval (15 min) and damage to the instruments strongly suggest that the moorings had been exposed to a sudden, exceptional stress. Similar incidents have led to technical problems such

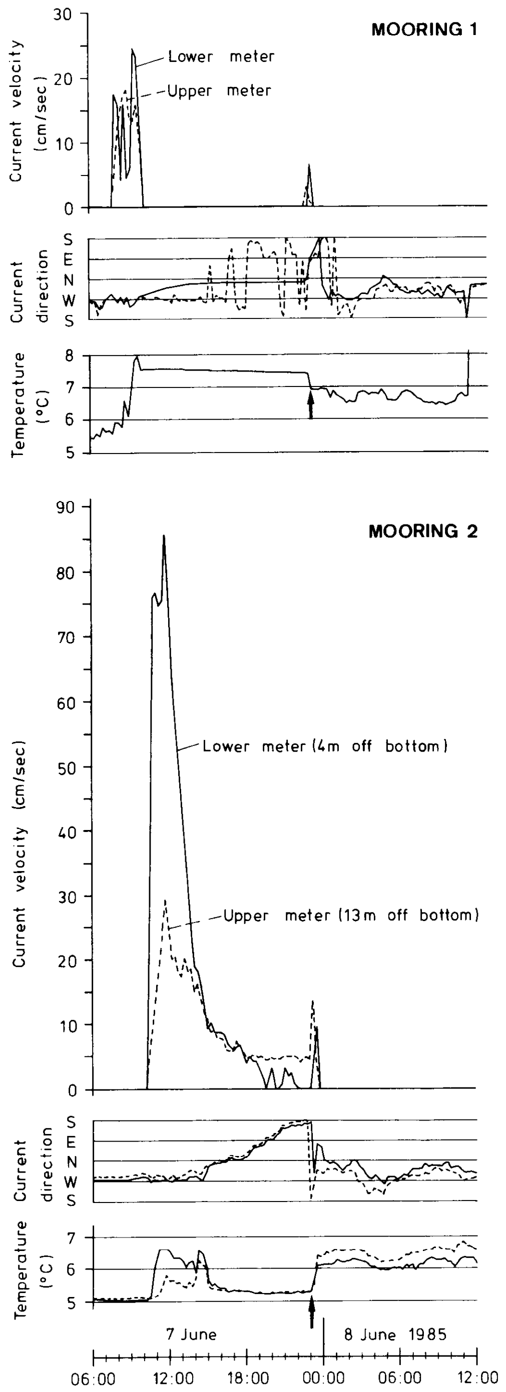

Fig. 9. Current meter records at moorings 1 and 2 documenting the events that led to the almost simultaneous break of both mooring anchor cables (7 June 1985 about 2300 hours, arrows). This event was preceded by an underflow episode (0800–1030 hours at

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mooring 1; 1030–1500 hours at mooring 2) which correlates with the exceptional discharge peak of the Rhone (*see Fig. 5*). Note the temperature anomaly caused by this event.

as instrument losses in marine deltaic and shelf environments (Dunlap et al. 1979; Dengler et al. 1984). In one particular case, current-meter moorings, comparable to those used in our study, were moved downslope over a distance of 2.4 km before they surfaced after cable breaks. All events reported in the literature occurred in connection with mass movements of unconsolidated sediments. Such mass movements are well documented from various environments, but especially in marine deltaic areas, where high sedimentation rates increase the pore-water pressures, resulting in undercompaction of sediment until the angle of repose (for noncohesive sediment) is exceeded or failure (of cohesive sediment) takes place. A further reason for reduced sediment strength is the presence of biogenic gas bubbles. Such bubbles are commonly observed rising to the surface of Lake Geneva on the entire Rhone delta area.

There is conclusive sedimentological and morphological evidence that subaqueous sliding occurs frequently in lake deltas (Gilbert 1975; Lambert 1987). Similar mass movements could consequently affect moorings by moving them or by inducing avalanche-type turbidity currents strong enough to damage instruments or even mooring links. Such an event probably occurred in the Rhone delta, causing premature release. The mass movement could have been triggered by unstable deposits from the preceding flood discharge of the Rhone or by bed shear stress exerted by the dense bottom current.

Although the break of the cable links occurred within the same recording interval of the Aanderaa current meters (15 min), there is perhaps an indication of the "event velocity" coming from the VAW current meters (which had a recording interval of 10 min): the data show a unique recording error from the instruments at both moorings immediately preceding the breaks. The most likely explanation our engineers could find for these errors was a shocklike impact which must have disturbed the mechanics of the cassette tape-recording units during one recording interval. The recording errors at the two moorings occurred with a time difference of 20±1 min. If these errors resulted from the impact of a mass movement, the event velocity must have been around 3 m s^{-1} ($\sim$10 km h^{-1}) over a total travel distance of nearly 3.6 km. Comparable velocities have been reported in connection with slope failure and instrument loss in the ocean (Dengler et al. 1984).

Sixteen major underflow events with velocities >30 cm s^{-1} were recorded during 78 d of measurements in the Rhone delta channel. Although the occurrence of flows does not necessarily correlate with discharge peaks, temperature increases indicate that river water (entraining more or less lake water from the surface) moves along the channel as density underflows. This temperature anomaly implies short-term increases of suspended sediment concentration in order to attain the required excess density. There also seems to be a different type of flow yielding only faint or no temperature variations. It is attributed to turbidity currents triggered by sliding or slumping of delta deposits and entraining only relatively cold lake water. Damage caused to instruments and breakage of mooring links suggest sliding of large amounts of deltaic deposits or avalanche-like turbidity currents as possible reasons. Reports of similar problems in oceanic environments, doubtlessly related to sediment mass movements, support this hypothesis.

At present, no statement concerning the frequency of such catastrophic events is possible. As far as the activity of density underflows under normal discharge conditions is concerned, there is no doubt that this type of transport mechanism is important in the eastern part of the lake. Ongoing studies that pay careful attention to short-term variations of suspended sediment concentration aim to evaluate the impact of density current activity on overall lake-water quality. Such effects could result either from direct transport of dissolved matter (oxygen, silica, etc.) or from "sealing" reduced lake deposits with the rapid sedimentation of riverborne solid load, thus inhibiting the reflux of soluble matter from the lake bottom. The quantitative extent of these processes is still not well understood, but may represent a hitherto underestimated limnological phenomenon.

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Inorganic nitrogen uptake by marine picoplankton: Evidence for size partitioning

Abstract—A series of size-fractionation experiments was carried out in coastal waters around Georges Bank and in the oligotrophic NW Atlantic to assess the relative importance of picoplankton (<1 μm) to community nitrogen utilization and to determine if there is a partitioning of the form of nitrogen used (NO_3^- or NH_4^+) based on organism size. Results indicate that picoplankton nitrogen uptake was substantial in coastal and oceanic waters, averaging >30% of the combined nitrate and ammonium uptake by the intact communities; the picoplankton portion of total community N uptake increased offshore. Of the summed nitrate and ammonium used across all sizes, ammonium was favored disproportionately by the picoplankton fraction. On average, however, the differences in preference for nitrogen form were relatively small. The size partitioning of photosynthetic activity and nitrogen uptake was similar.