Journal of Glaciology Vol. 42 No. 140 1996

Instruments and methods

Submersible remotely operated vehicles (ROVs) for investigations of the glacier–ocean–sediment interface

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ABSTRACT. Submersible remotely operated vehicles (ROVs) are valuable research tools for data collection in dangerous or inaccessible environments associated with glaciers terminating in the sea. At tide-water ice cliffs, iceberg calving makes close approaches for extended time periods by manned vessels dangerous. ROVs can be operated from relatively safe distances (hundreds of metres); they can also descend to considerably greater depths (hundreds rather than tens of metres) than scuba diving permits. They can provide data on glacier grounding-line and sea-floor morphology and water-column characteristics (e.g. salinity, turbidity, current velocity). They are also used for diving under floating glacier tongues and ice shelves where no other access is possible. They can be fitted with a variety of oceanographic sensors, imaging sensors, tracking devices and water and sediment samplers, making them versatile research instruments that can supply qualitative and quantitative data for process studies in logistically difficult environments.

INTRODUCTION

The interface between glaciers and ice sheets and the marine environment includes grounded tide-water glaciers together with floating ice shelves and glacier tongues which are dynamically a part of the parent ice mass. In some cases, therefore, the ice–ocean interface is simply the terminal ice cliffs of tide-water glaciers. In others, it includes vertical cliffs together with the base of floating ice shelves and fast-flowing outlet glacier tongues. The interface is an important location for the loss of mass from the glacier system in the form of icebergs, meltwater and sediments. Associated with this transfer of mass are a number of glaciological, oceanographic and sedimentary processes, together with the suite of sedimentary forms and facies that result.

Direct observations of the ice–ocean interface, and of the ice-proximal marine and sedimentary environment, are important in the specification of the morphology and dynamics of the system. Several models of the ice–ocean interface and its oceanographic and sedimentary regime have been proposed (e.g. Powell, 1981, 1990), but detailed direct observations in modern glacier-influenced waters are relatively few (e.g. Oliver and others, 1978; Klepsvik and Fossum, 1980; Stockton, 1983). This is because the nature of the interface imposes severe logistical constraints on our ability to make detailed observations in locations proximal to glacial tide-water cliffs or beneath floating ice shelves. Tide-water glacier termini are usually in longitudinal tension, many transverse crevasses are present as a result, and the calving of icebergs occurs frequently, providing a significant hazard (Fig. 1). The underside of floating ice shelves, and the ocean waters and sediments that lie beneath them, are also inaccessible, but have been instrumented occasionally by drilling through the ice shelf above (e.g. Zotikov and others, 1980; Nicholls and others, 1991).

We have used remotely operated vehicles (ROVs), carrying packages of scientific instruments, as a means of examining tide-water glacier cliffs, and the oceanographic and sedimentary environments proximal to them, in southeast Alaska, Antarctica and East Greenland. We have also deployed ROVs beneath the margins of floating ice shelves and reached the grounding line of floating glacier tongues in Antarctica. In this paper we describe the specifications of ROVs and associated umbilicals used in these investigations, and consider their methods of deployment and operation and the instrument packages carried aboard these vehicles. We also give examples of images we have obtained of the ice–ocean interface and ice-proximal sediments from ROVs, together with records of salinity, temperature and water-turbidity measurements close to tide-water glacier margins.

REMOTELY OPERATED VEHICLES (ROVs)

ROV specifications

We have used several types of Phantom ROV (manuf-

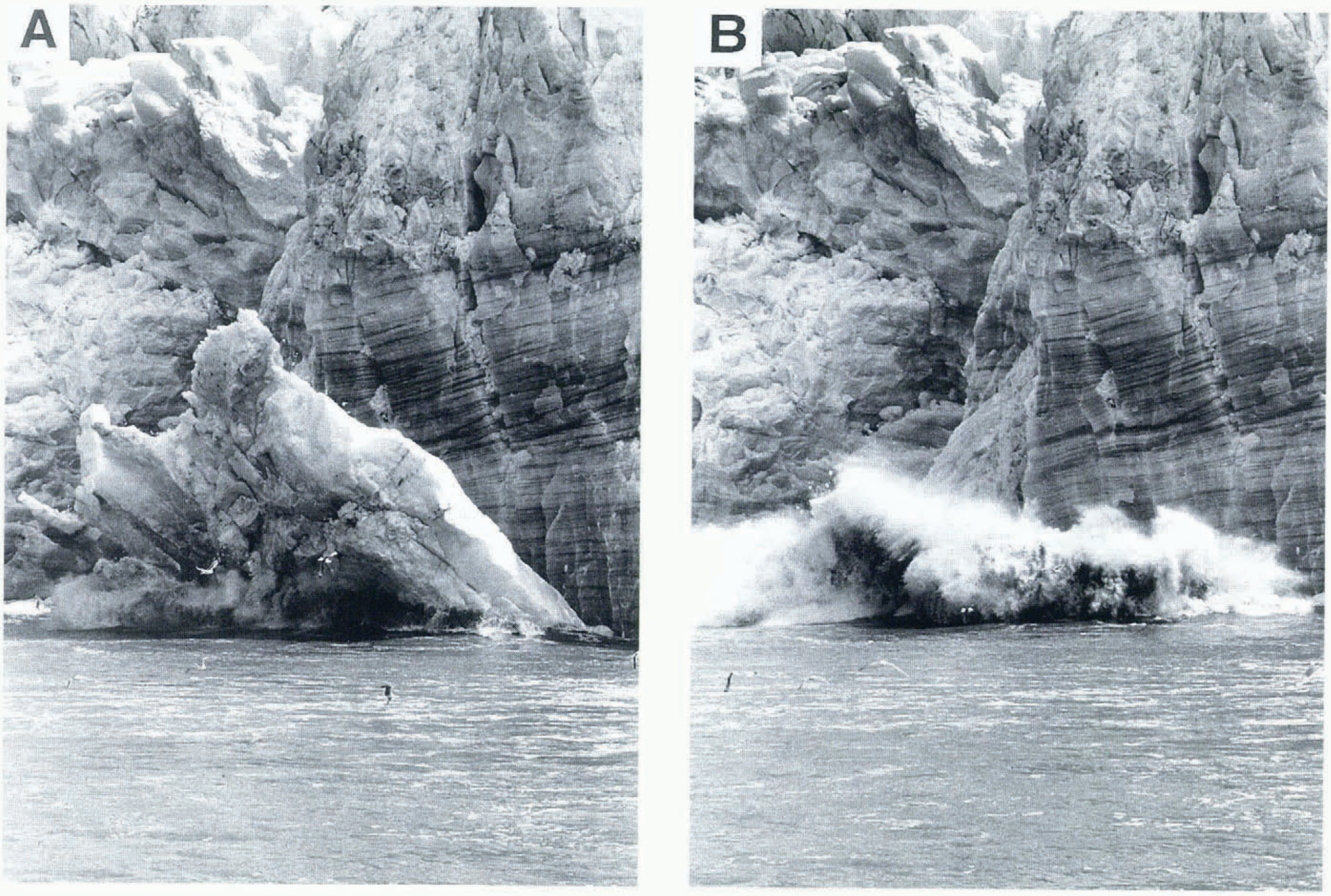

Fig. 1. (a) The tide-water ice cliff of a temperate valley glacier in southeast Alaska. (b) Ice-slab calving event. The iceberg is about 40 m high and 100 m across.

acturer Deep Ocean Engineering) during operations around the ice–ocean interface (Fig. 2). The ROV is mounted within a crash frame and is approximately 0.65 m high, 1.5 m long and 0.85 m wide. Weight is dependent on the modifications made to individual ROVs and the instrument packages mounted on them. We have deployed various ROVs weighing between about 60 and 100 kg, with instrument packages of a further 20–60 kg. Flotation can be added to the ROV frame as required to provide neutral buoyancy in water, and to balance any asymmetry in the positioning of scientific instruments about the frame. Readjustment is then made after trial immersion. The number and power of the counter-rotating, torque-balanced thrusters which propel the ROV are dependent on individual ROV configuration. A typical configuration would be two to four forward thrusters and two vertical/transverse (vertrans) thrusters, yielding 50–75 kg of forward thrust and 15–20 kg of lateral and vertical thrust. This configuration would give a maximum speed of about 4 knots. Power requirements are 115 or 220 V AC at 50–60 Hz and 6 kVA. Maximum operating depth is about 500 m.

The ROV is controlled by joystick(s), which adjust the balance between forward and vertrans thrusters. Read-outs of heading and depth are available to the pilot, in addition to video camera output when visual contact is made with underwater objects. Transponder ranging systems may also be used as a navigational aid. The flying of an ROV requires considerable experience, and professional ROV pilots from companies servicing the offshore oil and gas industries can be hired, if needed. The pilot and control centre are normally located in the parent vessel in dry, heated accommodation. We have also operated ROVs from sea-ice platforms using vehicles with hydraulic arms for deployment. The control centre for sea-ice operations is housed in a heated cabin or trailer.

Umbilicals

The umbilical connecting an ROV to its control centre has several functions: (i) for piloting signals and the supply of power; (ii) for the transfer of data from the ROV to the control centre in real time; and (iii) as a means of vehicle recovery. Some ROVs can be radio-controlled without an umbilical; however, during dives in glacimarine environments the ROV may travel behind ice walls or other large objects which can block communication signals. The ROV can also become so positioned that recovery by hauling on the umbilical is the best safety precaution. Length and internal configuration of the umbilical are dependent on the operational and scientific requirements in any specific study. However, the following configuration would be typical of our ROV investigations of tide-water ice cliffs, the margins of ice shelves and the ice-proximal marine environment.

The diameter of an ROV's footprint on the sea floor is dependent on umbilical length, water depth and current conditions (Fig. 3). For example, a 640 m umbilical would have an operating footprint of 400–500 m diameter

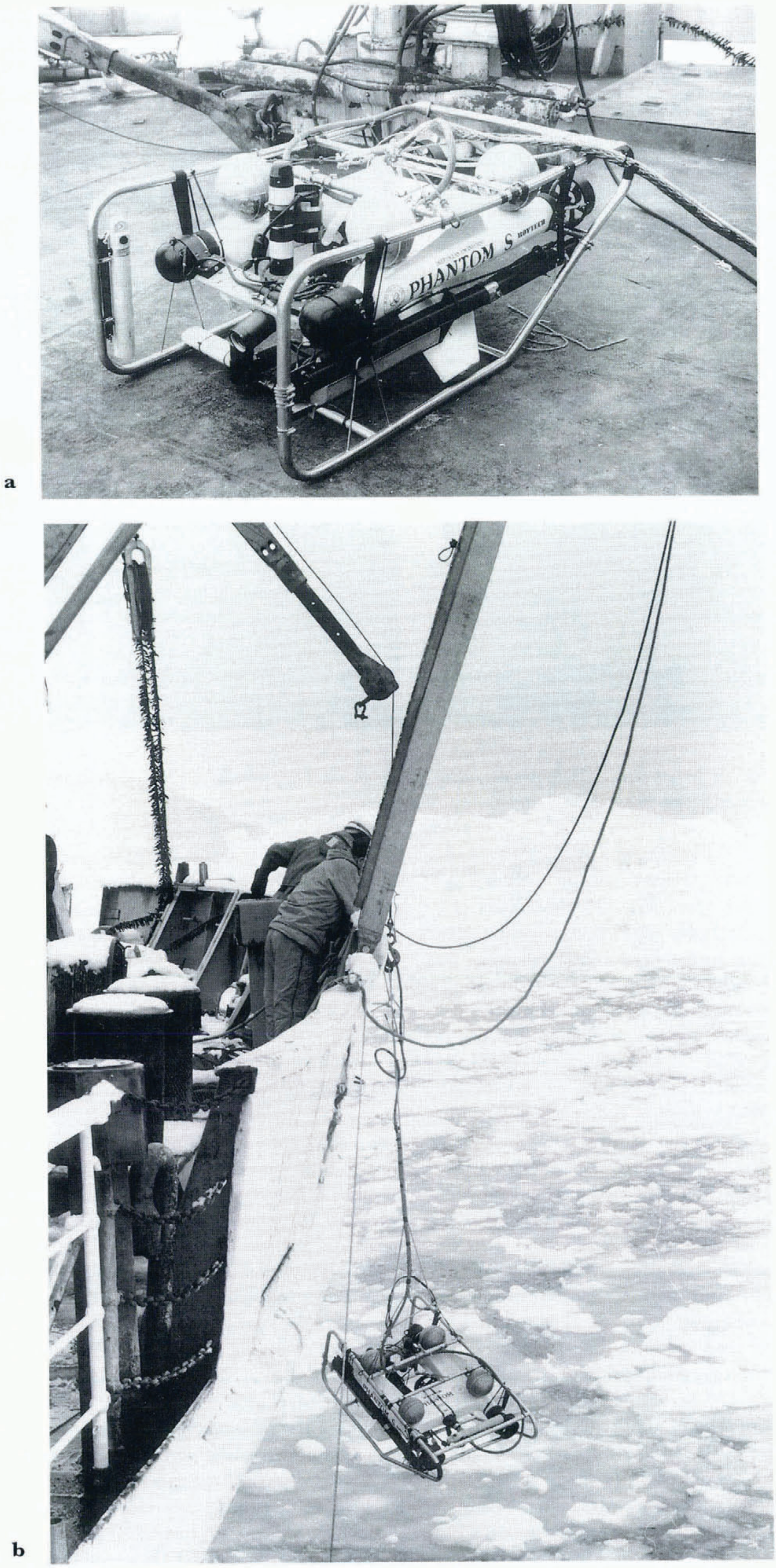

Fig. 2. (a) Configured submersible ROV prior to launch, with side-scan sonar fish, CTD meter and camera systems mounted on its external frame. (b) ROV deployment through sea ice from the deck of CSS Hudson in Kangerdlugssuaq Fjord, East Greenland.

in 100 m of water. The umbilical weighs about 30 kg per 100 m in air. It is usually neutrally or positively buoyant in water, which helps avoid tangles on the sea floor, especially around boulder fields which are relatively common in ice-proximal environments. However, a buoyant umbilical may tangle on underside protuberances of sea ice, icebergs, ice shelves and floating glacier tongues, and care is needed during descents and ascents. The weight and diameter of the umbilical, together with the current regime, define the amount of drag that will be caused. As drag on the umbilical increases, the ROV operating footprint decreases as the umbilical becomes progressively more curved (Fig. 3). An alternative method of ROV deployment, especially in strong currents and/or where the sea floor is a principal object of interest, is to deploy the umbilical vertically downward to the sea floor, and then to fly the ROV horizontally outward from this position.

The configuration of the umbilical varies with the nature of each operation, but unarmoured umbilicals, which are most useful for operation from smaller vessels and ship's launches (< 20 m long), are typically designed with a breaking strain of about 8 t. Inside a watertight sheath the umbilical has cables for power, control of the ROV thrusters, and any links between instruments and data-logging facilities on the parent vessel. The number of cables, especially shielded twisted pairs, will usually be the limiting criterion for the number of sensors operating on the ROV at one time for real-time displays of data. A video or photographic camera and associated light connection is supplied as standard in most umbilicals, and connections for manipulator arms are also common. When "off-the-shelf" umbilicals are used, the simplest configuration is to deploy scientific instruments which log internally on the ROV and, therefore, require no separate cable within the umbilical. However, for scientific operations there are considerable advantages in having real-time information on the variation of environmental parameters such as water salinity, turbidity and temperature, and from imaging systems such as side-scan sonar. Real-time displays allow instant evaluation of conditions in process studies and facilitate adjustment of flight strategies during a dive. All cables for real-time data logging at the surface require appropriate terminations and watertight seals for connection to the umbilical, and the umbilical to have both coaxial and, increasingly, fibre-optic cables available for ROV-to-surface data transfer.

ROV DEPLOYMENT AND NAVIGATION

Platforms for deployment

The usual platforms for ROV deployment adjacent to tide-water glaciers are fully equipped research ships, their launches, or, where safety considerations permit, a stable winter fast-ice cover. Operations from a large research ship are straightforward. Electrical supplies for the ROV, the control and navigation consoles, and digital data-logging facilities are available. Cranes for ROV deployment and winches for umbilical handling are present (Fig. 2b). An indoor control room can also be set up easily.

A number of our operations have been from small launches (8–20 m long). In this case, electrical power (AC) is produced from petrol generators mounted on the

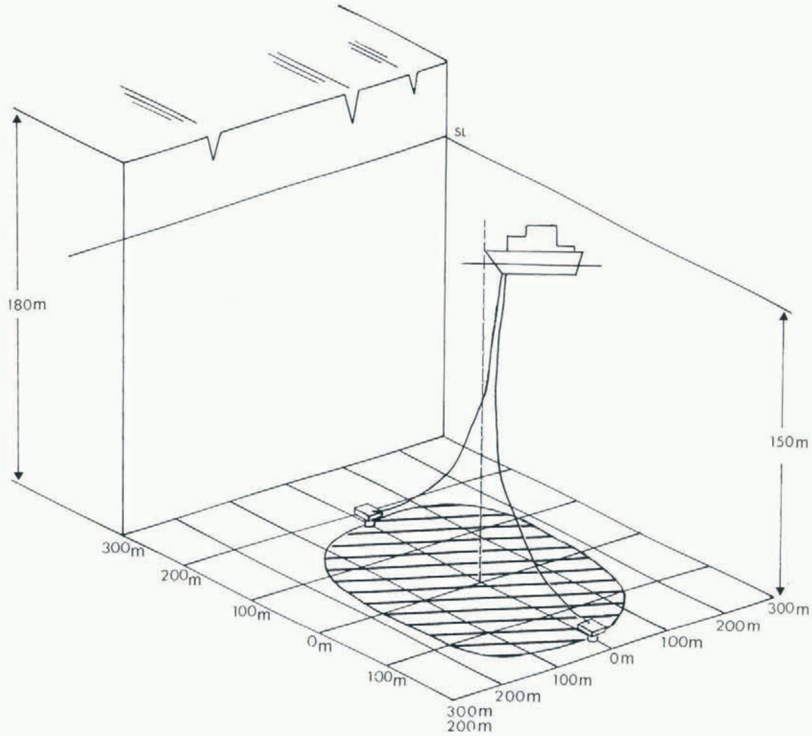

Fig. 3. Schematic diagram of the deployment of a submersible ROV from a parent surface craft close to tide-water ice cliffs. Note that the length of the umbilical constrains the area that can be examined by the ROV. In the example, water depth is 150 m and the shaded area represents the "footprint" on the sea floor which can be examined by the ROV while the parent vessel is stationary.

vessel. We have found a 3.5 kW generator, giving a 110/220 V AC supply at 50 Hz, to be suitable, although attention must be paid to the stability of the power source. On such small vessels, covered and heated space for consoles is also at a minimum, and deployment and recovery of an ROV weighing about 100 kg is difficult. Sufficient open deck space also needs to be available for handling umbilicals up to 640 m long. On sea ice, umbilical handling is simple; it can be strung out across the sea ice in long loops. However, heavy equipment is needed to make an access hole through the sea ice and to deploy the ROV. This type of operation has been successful in Antarctica, but a heated control centre is essential. Considerable care must also be taken with watertight seals on the ROV because, when the vehicle is retrieved, sea water can freeze at low air temperatures, causing seals to be broken. Unless checked and resealed, the ROV may be flooded by sea water on the next dive. Washing the ROV with fresh water and keeping it in a heated space between dives is best for successful operation.

Navigation systems

ROV navigation involves two problems: (i) the absolute location of the parent platform, usually a ship or ship's launch, in which the ROV control consoles are set up; and (ii) the location of the ROV relative to the parent platform. The former is often trivial, in that differential global positioning systems (GPS) and a gyro compass to provide ship heading will normally be part of the routine data acquired by a research vessel. For launch or small-boat operations or on sea ice, a portable GPS system and gyro compass can be used.

Obtaining the x, y and z coordinates of the ROV relative to the parent platform usually requires the use of a high-precision ranging system. We have used the Simrad HPR 300P and the ORE Trackpoint II portable hydroacoustic positioning reference systems for ROV navigation. The calculation of position is based on range and bearing measurements which yield the three-dimensional location of an ROV-mounted transponder relative to the system's transducer (interrogator operating at 20–25 kHz, receiver at 26–32 kHz), which is mounted in a moon pool or rigged over the parent vessel's side. The HPR 300P system has an accuracy better than 2% of slant range, assuming that there is no significant error from ray-bending. Where the water column is strongly density-stratified (as in the meltwater-induced vertical stratification often found proximal to tide-water glaciers) this assumption may not hold, and as a check we have routinely recorded water depth independently, using other instruments mounted on the ROV. The output from these systems can be displayed and logged on a small computer, and plotted in real time as required.

ROV-MOUNTED SENSORS FOR INVESTIGATING ICE, OCEAN AND SEDIMENTS

A first-order constraint on the scientific equipment to be deployed on a basic ROV is its size and weight. The equipment must be capable of being mounted on the ROV frame, and preferably inside the frame for protection against collision. The Phantom is relatively well suited to the attachment of scientific equipment because of its open frame (Fig. 2a). Weight considerations are important to the speed and manoeuvrability of the ROV, and also to deployment and recovery from smaller launches where lifting gear, such as winches, may be unavailable. The power draw of each scientific instrument, and the type of data logging (internal to the sensor or via cable to a remote unit), are further considerations, which are dependent in part on the umbilical configuration, and may constrain the combination of sensors that can be deployed on any single sortie.

For the investigation of glacier ice, and the marine waters and sea-floor sediments located proximal to and beneath tide-water glaciers and ice shelves, a number of types of instrument are appropriate for deployment on ROVs. These can be divided into: (i) imaging systems to view ice and the sea floor (e.g. black-and-white and colour video cameras, still cameras, side-scan sonar, forward-looking sonar); (ii) manipulators for direct sampling of marine waters and sea-floor sediments; (iii) sensors for measuring water-column properties (e.g. salinity, temperature, sediment concentration, dissolved oxygen content, current velocities); and (iv) geophysical equipment for sub-bottom profiling.

Of the imaging systems, the video camera(s) allow the pilot a real-time display forward of the ROV in clear water. The images are usually recorded on VCR continuously. It is also possible, if contrast is sufficient, to digitally reproduce still images from a "frozen" videotape frame. For keeping records of locations and events we use one stereo channel on the videotape to record a digital time-code and the other channel for audio description of images and any other data of note. We commonly use a colour and a low-light black-and-white video camera. The latter is most useful where there is high turbidity in the water column, as occurs in temperate glacier environments with large stream discharges. Still photographs can be taken using underwater cameras (stereo cameras are also available) and synchronised flash units. Because aperture and focus need to be pre-set before diving, it is useful initially to use polaroid slide film that can be processed immediately in the field, so settings can be adjusted. Once favourable settings for a dive site are found, then regular, bulk slide film or print film can be used in the camera.

Where conditions of high turbidity or rapid attenuation of light away from the ROV occur, visual images from the video cameras do not allow long-range viewing. To compensate, it is possible to use a forward-looking sonar, with real-time scanning image displayed in the control centre. The display can also be recorded on a VCR if required. With such images one can determine exact distances from ice faces or grounding lines when they are beyond viewing range. Large boulders or banks on the sea floor can also be detected and avoided while flying the ROV in "blind" conditions of high water-column turbidity. Side-scan sonars can be used to map the sea floor, but care must be taken to fly the ROV at constant height above the sea floor and at a constant speed. Pitch and yaw of the ROV can also be problems. We have experienced problems with side-scan signal interference from the ROV thrusters; shielded twisted pair cables should be used to ensure good analogue records.

Manipulator arms are available commercially for sampling water and bottom sediment. A small bucket dredge has been custom-made for sampling bottom sediment; it can collect samples of about 5–6 cm^3 in volume, which retain primary sedimentary structures. Six samples can be collected on one dive using this instrument.

Water-column properties are critical for process studies, and most types of sensors used for standard oceanographic surveys can be configured into the ROV system. Caution is needed to ensure minimum disturbance from thrusters. Perhaps the most difficult measurements are of current velocity. The ROV must be stationary and its orientation must be known in order to obtain a precise current-velocity vector. It is possible to process the magnetic-compass signal from the ROV with electromagnetic-current meter voltages to produce a real-time current velocity and direction read-out in the control centre. To increase the number of sensors that can be used simultaneously with a finite number of cables in the umbilical, it is also possible to "daisy-chain" data streams up the umbilical and then separate them at the surface.

EXAMPLES OF ROV OBSERVATIONS OF ICE, OCEAN AND SEDIMENTS

Several images digitized from black-and-white video tapes acquired from ROV operations in the cool-temperate glacimarine setting of southeast Alaska are shown in Figure 4. The first image is of sea-floor sediments at the grounding line where the glacier is in contact with the top of a morainal bank (Fig. 4a). Note that the glacier is overriding the sediment, since clasts can be seen under the glacier through the ice. A second image illustrates the submarine ice-cliff face with dispersed englacial debris and gas bubbles (Fig. 4b).

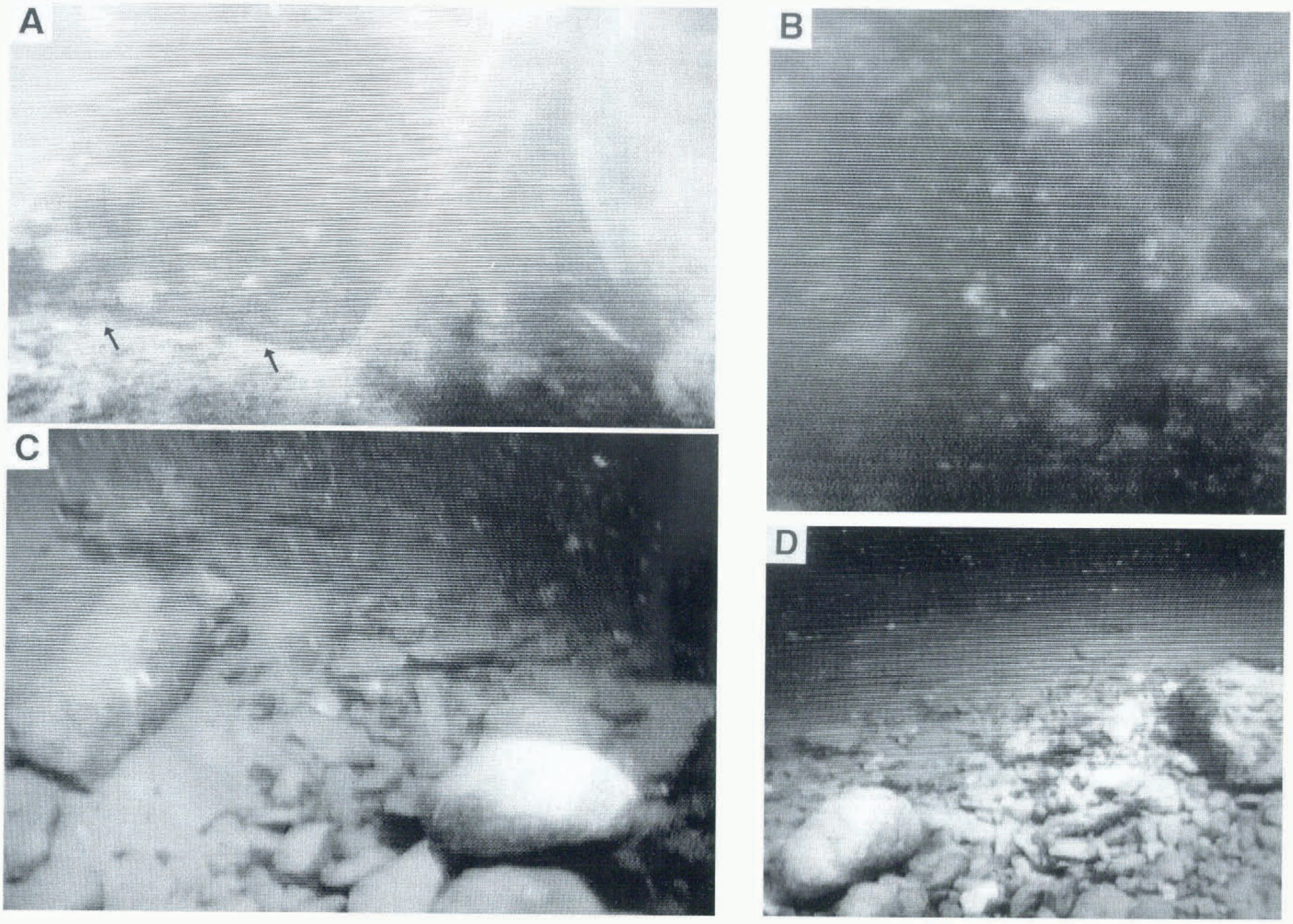

Fig. 4. Images of the grounding-line environment of tide-water glacier termini in Alaska, obtained using pause frames of S-VHS video tapes recorded by a submersible ROV. (a) Close-up of the grounding line (0.6–1.0 m in length on the image) where morainal bank sediment is piled against the ice face. The grounding line is marked by arrows. The ice is also overriding the top of the morainal bank and it is sufficiently clear that overriden sediment (bottom right) can be seen through it. (b) Close-up of the ice face above the grounding line. Objects are englacial debris particles up to 20–30 mm across. (c) Chaotic sediment on the morainal bank front where boulders up to 0.3 m across, and of angular-to-rounded shape, are stacked at the angle of repose. The view is looking obliquely along the bank front. The slope, best illustrated at the top right where the black area is water, is the real foreslope of the bank. (d) Gravel in the area immediately beyond the morainal bank showing boulders (to over 1 m across) that have rolled down the bank front, and other clasts that are from iceberg rafting. The background shows a smoother surface representing glacimarine mud.

The front of the morainal bank has steep slopes at the angle of repose of the open-framework gravel. Boulders have rolled down from the bank to become isolated blocks in pro-bank muds (Fig. 4c and d). It is also possible to obtain images of sediment in the walls of turbidity-current channels to observe the internal nature of sea-floor sediment. These data allow the spatial pattern of debris within ice, and the spatial patterns of ice-proximal sedimentation that result from the release of this sediment, to be observed and modelled in more detail than has been possible previously.

A second set of images, taken from an ROV deployed in Antarctic waters, shows the submarine environment close to the grounding line of a small floating ice tongue (Fig. 5). These are among the first images obtained from such an environment. The floating tongue of Mackay Glacier is about 4 km long. Access to the underside of the tongue was from the side, where ice thickness is about 220 m. Using the ROV, we found that water depth at the grounding line ranged from 90 to 130 m. Debris can be seen within the basal ice (Fig. 5a and b). This is an observation of some significance, confirming that sediment can be present at the base of ice shelves close to the grounding line. This englacial debris may then contribute to the sediment load of calved icebergs, or be melted out at the ice-shelf base before calving takes place (cf. Drewry and Cooper, 1981; Dowdeswell and Murray, 1990). Glacimarine diamicton (sandy, pebbly mud of heterogenous grain-size) is also deposited by rockfall and grainfall from the rain-out of glacial debris as it is melted out from the underside of the Mackay Glacier tongue. This diamicton immediately drapes fluted subglacial till that has been exposed by retreat of the grounding line (Fig. 5c). There is also a diverse epifauna close to the grounding line (Fig. 5d).

In addition to images of the ice–ocean–sediment interface, a variety of quantitative oceanographic data can be acquired from the suite of instruments available to be carried aboard ROVs. An example of quantitative oceanographic data obtained using an ROV is given in Figure 6. The ROV obtained these data within 50 m of

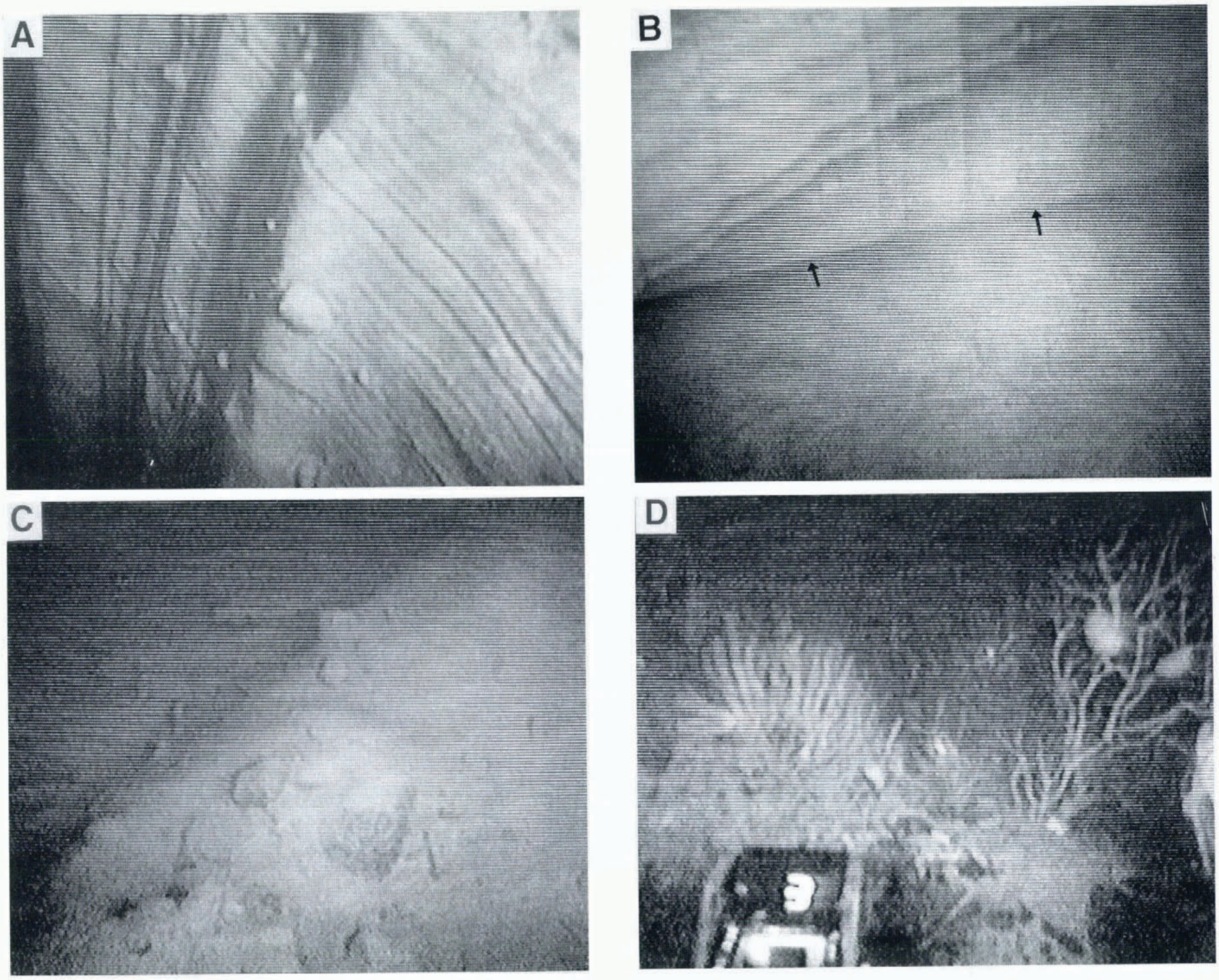

Fig. 5. Images of the grounding-line environment at Mackay Glacier, a floating glacier tongue of an outlet glacier of the East Antarctic ice sheet, acquired from ROV-mounted cameras. (a) Vertical ice face above the grounding line showing basal debris-rich ice with sediment of a heterogeneous, diamictic grain size and individual clasts tens of cm across. Layers are subhorizontal and subparallel with the glacier bed. (b) The grounding line, marked by arrows, showing basal debris-rich layers dipping down to the bed (i.e. to the left). Clasts in the ice are tens of cm across. (c) Fluted subglacial till with marine diamicton (sometimes known as waterlain till) draping its surface. The flute is about 0.5 m high. (d) Diverse epifauna present close to the grounding line, primarily on hard grounds.

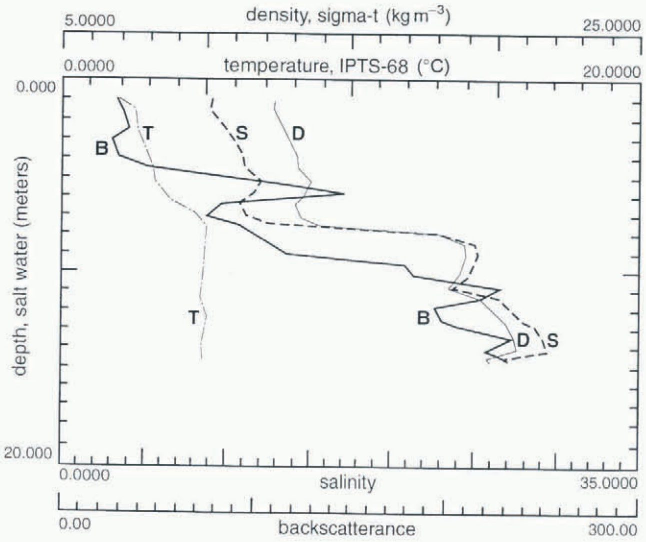

Fig. 6. Oceanographic data collected in front of a small subglacial stream portal from ROV-mounted equipment at about 50 m from a tide-water ice cliff in Alaska. Parameters were measured using CTD and optical back-scatterance instruments on the ROV. Back-scatterance (B) is a measure of relative suspended sediment concentrations in the water column. Water density (D) is a function of salinity (S) and temperature (T). Water depth at the point of sampling is only 17 m because a morainal bank has built up to that level against the ice face from the deeper basin floor.

the mouth of a subglacial stream channel entering marine waters at the grounding line of an Alaskan glacier. The record shows changes in water temperature, salinity, density and back-scatter (relative turbidity) as the ROV dives down. Note the relatively low salinity, temperature and density in the meltwater-derived waters between 0 and 7 m (Fig. 6). The strong temperature and salinity gradient at a depth of about 7–9 m is known as the pycnocline. There is also a spike of increased water turbidity above the pycnocline. The high back-scatter and water salinity and density in the lowest part of the water column probably represent a turbidity current close to the sea floor. These detailed data on the salinity and temperature structure of the water column beneath ice shelves and at tide-water glacier ice cliffs, can be used to constrain and calibrate physical models of ocean circulation and mixing in these environments (e.g. Josberger and Martin, 1981).

CONCLUDING REMARKS

Submersible remotely operated vehicles (ROVs) are valuable research tools for data collection in dangerous or inaccessible environments associated with glaciers terminating in the sea (e.g. at calving tide-water ice cliffs and beneath floating ice tongues and shelves).

ROVs can be operated from relatively safe distances (hundreds of metres); they can also descend to considerably greater depths (hundreds rather than tens of metres) than scuba diving permits. They can provide data on glacier grounding-line and sea-floor morphology and water-column characteristics (e.g. salinity, turbidity, current velocity).

ROVs can be fitted with a variety of oceanographic sensors, imaging sensors, tracking devices, and water and sediment samplers, making them extremely versatile research instruments for obtaining qualitative and quantitative data for investigating glacial sedimentary processes and ice and sea-floor morphology in logistically difficult environments.

ACKNOWLEDGEMENTS

J.A.D. was funded through U.S. Office of Naval Research grant N-00014-93-1-0416 for ROV work in the fjords of East Greenland on the Canadian Scientific Ship *Hudson* (cruise HU93-030, chief scientist Dr J. P. M. Syvitski). R.D.P was supported for ROV studies in Alaska and Antarctica by U.S. National Science Foundation grants DPP-8822098 and OPP-921048. Logistical support in Alaska was provided by the U.S. National Park Service and Capt. J. Luthy of the M/V *Nunatak*. ROV maintenance and technical assistance came from N. Barringer and L. Butler (J.A.D.) and R. Bailey and B. Blake (R.D.P.). Scientific field support was from E. Broughton, P. R. Carlson, J. Cai, E. A. Cowan, M. Dawber, L. E. Hunter, T. S. Hooyer, D. E. Lawson, A. R. Pyne, J. P. M. Syvitski and R. J. Whittington. We also thank the following for their assistance and support of our ROV programmes: P. J. Barrett, S. E. Bograd, R. S. Bradley, H. W. Borns, C. F. Forsberg, J. H. Kravitz, J. M. Palais, H. Smith and H. Zimmerman.

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MS received 27 April 1995 and accepted in revised form 15 August 1995