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Remotely sensed sedimentology of Plymouth Sound

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As part of the Plymouth Sound research project, remotely sensed data are used to evaluate the present day estuarine hydrography of the Sound. Re-examination of 1983 Thermal Linescan images shows a series of small tidal water bodies in the Hamoaze and Drake Channel area. In July 1989 an Airborne Thematic Mapper was flown over Plymouth Sound and concurrent *in situ* surface samples were taken to analyse the suspended sediment, % organics, temperature and salinity. Secchi disc depths were measured to compare with spectral response. A direct correlation is found between surface currents and tidal bodies, and the present day sea-bed deposits.

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Introduction

The Plymouth Sound project was initiated in 1984 by the Department of Geological Sciences at Polytechnic South West. This project initially ran a series of high resolution seismic traverses to study the Quaternary buried channels in Plymouth Sound (McCallum and Reynolds 1987; Reynolds 1987). In 1988 a jack-up rig provided two continuous sediment cores which showed a good correlation between sediment and seismic signatures (Eddies and Reynolds 1988).

The history of the sedimentary fill of the nested buried channels and the rise in sea level from 12,000 to 4,000 years B.P. was largely established by foraminiferal analyses (Eddies and Hart 1989). In 1989 the survey was extended to include investigations of the actual hydrodynamics of Plymouth Sound as a tidal inlet, and the response of the sedimentary patterns to the changing sea level during the last 9,000 years.

In order to study and evaluate the control exerted by the prevailing hydrodynamics of the inlet on the sediment textures and distributions, it is necessary to obtain information about the lateral and vertical changes in the depositional environment. In recent years the use of remotely sensed data from space and airborne platforms has provided an additional source of information for coastal investigations. However, little work has been done on estuarine-inlet hydrography. Re-investigation of the 1983 Thermal Linescan survey of the Hamoaze showed a series of distinct water bodies of different temperatures (Roxburgh 1983) and this was used to propose that an Airborne Thematic Mapper (ATM) should be flown over Plymouth Sound. This flight, on July 17th 1989, was planned to provide an instantaneous picture of the surface characteristics of the inlet. The purpose of this paper is to provide a preliminary comparison between the seabed sonographs and Channel 11 of the ATM images in order to demonstrate any correlation between these apparently different features. The bathymetry of Plymouth Sound and locations referred to in the text are shown in Fig. 1.

Side-scan sonar survey

The bed sediment distribution of Plymouth Sound has been mapped by side-scan sonar. Analogue data were collected using a Waverley 3000 side-scan sonar towed aft of the Polytechnic catamaran *R.V. Catfish.* The sonograph response (Fig. 2) was calibrated against sea bed samples collected during various diving expeditions, and a distinction was made between fluvial and marine gravels.

Use of remote sensing

The analysis of multispectral data in the interpretation of oceanographic and coastal surveys has been widely used since the launch of LANDSAT in 1972. One of the most recent sensors is the Daedalus AADS 1268 Airborne Thematic Mapper. This is a passive remote sensor which collects and records electromagnetic radiation from an airborne platform. It is a linescan system which can record digital image data in 11 spectral bands (and channel 12 at half-gain) spread across the spectrum from the visible blue to the thermal infrared (Table 1). The scanner provides spectral data similar to LANDSAT MSS, LANDSAT TM, SPOT and other Earth Observing Satellites. Since the initial Thematic Mapper simulation work, the AADS 1268 has found increasing usage as an airborne system in its own right and has been put to a variety of other remote sensing research and development applications, including oceanographic monitoring (Collins and Pattiaratchi 1984; Purdie and Garcia 1988).

Area under investigation

In this survey, Plymouth Sound is defined as the area north of the Breakwater in a line from Cawsand to Bovisand (Fig. 1). The estuaries of the Tamar and the Laira-Plym join Plymouth Sound from the north. South of the Breakwater the bay extends to a line from Penlee Point in the west to Wembury Point in the east (Fig. 3), separated by a stretch of water 6km wide. Water depths range from 40m in the steep-sided palaeo-Tamar valley, which winds past the Hamoaze and north of Drake's Island, to an average depth of 8m in the body of the Sound. The Sound is connected southwards to the English Channel by two channels, originally separated by two rocky shoals and now by the artificial Breakwater. The Western Channel is 11-12m deep and the Eastern Channel 8- 10m deep. Inside the Breakwater, these two channels shallow to 7m and lose their identity in the main area of the Sound. The Tamar Estuary, tidal to 30km upstream, provides a maximum freshwater inflow of $321.56m^3s^{-1}$ and a minimum of $0.58m^3s^{-1}$. Depending on the freshwater run-off conditions, the estuary does not attain fully marine conditions until it enters the Hamoaze area. The freshwater input into the Sound from the Plym and Laira is low, with a recorded maximum of $31.01m^3s^{-1}$, and a minimum of $0.12m^3s^{-1}$ (Hiscock and Moore 1986). The tidal streams in Plymouth Sound are dominated by the M_2 lunar semi-diurnal component (George 1982) with a mean Spring range of 4.7m, and a mean Neap range of 2.2m. The Mean High Water interval is 5h 20min. The age of the tide is 51h 30min. The general maximum tidal stream in Plymouth Sound is 1.2 knots; the strongest tidal streams occur in the Narrows and across the Bridges (Fig. 1), where velocities of 2.8 knots are recorded on the ebb. Tidal streams in the lower Tamar are quite strong, with 2.6 and 2.2 knots on the Spring ebb and flood respectively (Admiralty Tide Tables 1989).

Methodology

On July 17th 1989, the Plymouth Sound area was overflown by the NERC Piper Navajo Chieftain aircraft deploying the ATM and a Wild-RC aerial camera. The area was scanned in three N-S-N flightlines between 11.49 and 11.59h (BST) at a ground speed of 160 knots and at a height of 2000m, giving a ground resolution of 4m (Fig. 3). Low water (- 1.6m OD) at Devonport was at 11.45h (BST). The surface of the Sound was still and the maximum surface current was 0.5 knots at the Bridges. The prevailing wind was southwesterly at 0.5 knots, the air temperature was 19°C, and the relative humidity was 77%. No cloud cover was present.

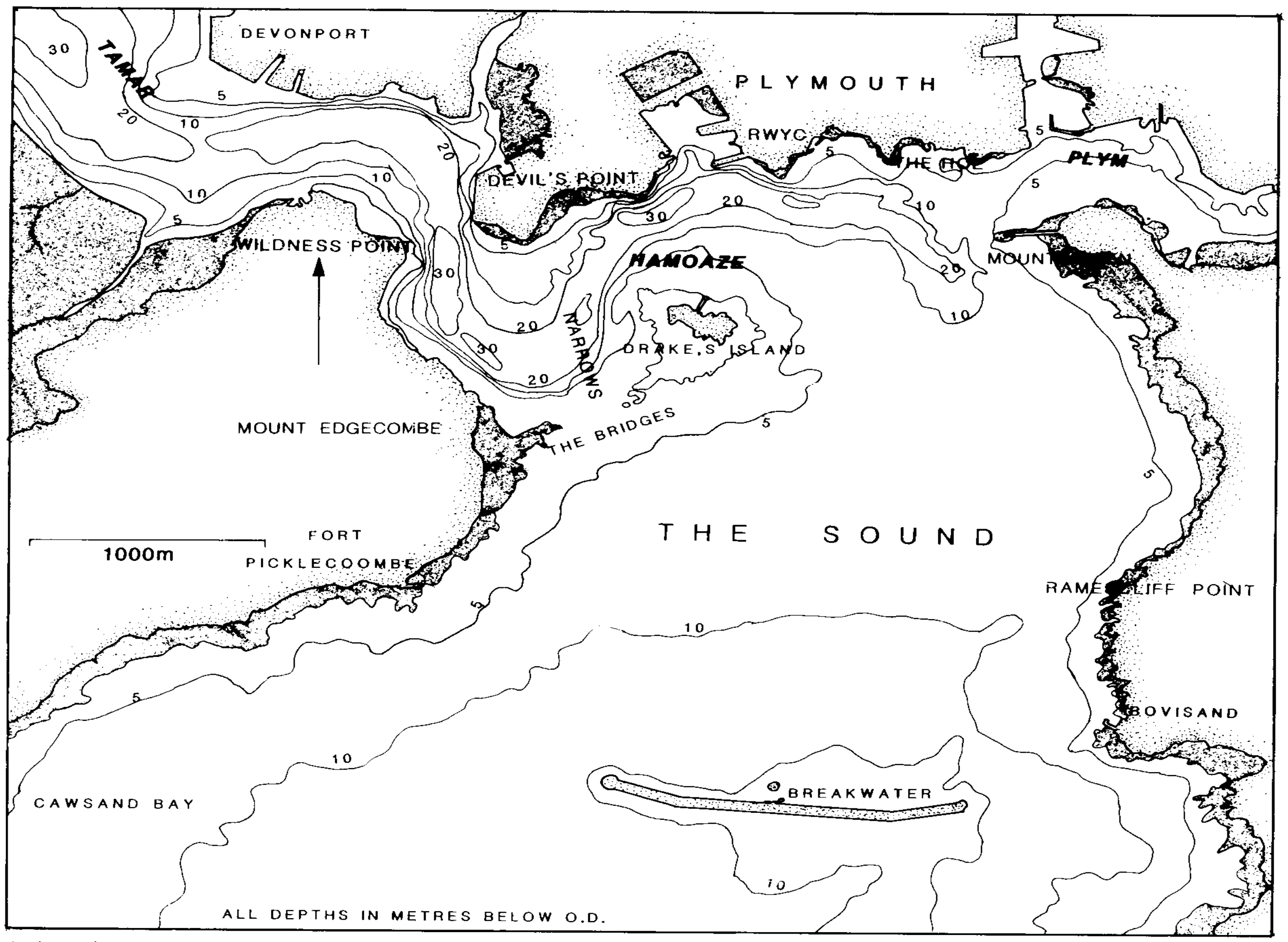

Figure 1. A chart of Plymouth Sound showing the main bathymetric features and locations.

Surface water samples were taken from 35 stations in and around Plymouth Sound, from four vessels: two inflatables, a dive support vessel *Aquatay* and the Marine Biological Association research vessel, the *Squilla.* Unfortunately radio contact was lost between the aircraft and the sea survey; the sampling continued as scheduled, although the aircraft was delayed by an hour. The *in situ* samples were taken between 10.30 and 12.05h, at positions (Fig. 3) designated in advance, using mostly the Admiralty buoyage chain as a guide. Samples taken in the unmarked navigation channels were fixed from *Aquatay* using both hand-held compass bearings and the Decca "mainchain" (Green and Purple lanes). At each site two litres of surface seawater were collected in bottles and covered immediately to inhibit plankton blooming. Salinity and temperature were recorded at 100mm below the surface using MC5 Temperature/ Salinity Bridges. Secchi disc disappearance depths were also taken at each site. The total suspended sediment concentration (SSC) and particulate organic content of each water sample were measured in the laboratory. The suspended sediment concentrations are mapped together with the Secchi disc disappearance depths (Fig. 4); the depths varied from 1 to 8m which is normal for the time of year (D. Pilgrim pers. comm.).

The ATM data were analysed at the NERC Image Analysis Unit at Polytechnic South West using an 1^2S Image Processor. Each image is made up of a series of picture elements (pixels), each with a brightness value on a grey scale ranging from 0 to 255 (Digital Numbers), depending on the amount of radiation reaching the detector from that particular pixel area. The images were subsampled and geometrically corrected. The Digital Numbers of the pixels in each subsampled image were calibrated against the *in situ* temperature measurements.

The radiation from the sea surface is composed of two components: emitted and reflected radiation. During daylight hours the reflected and emitted radiations in the wavebands 3 to 5μm are about equal. This restricts the use of this window for emitted radiation to the hours of darkness and immediately post-dawn. The radiation in the 8 to 13μm window (water temperature signal) is effectively self-emitted and is a function of view angle and wavelength. Surface emissivity is assumed to be a constant and equal to a value of 0.98 (Takashima and Takayama 1981). On a clear day the radiance reaching the scanner in this band from sky radiation is only 1% (Anderson and Collinson 1987). The presence of clouds or haze (Relative Humidity) creates strong absorption. Reflected solar radiation from the sea in the infrared bands is negligible and can be ignored. The infrared images can be analysed without applying any atmospheric correction as the energy measured by the sensor is emitted from the sea surface (Anderson and Collinson 1987).

The images

A composite image of Plymouth Sound has been produced by combining the images from parts of flightlines 1 and 2 which have been geometrically corrected and then joined (Fig. 5). The join is quite distinct and caused by differences in both the look-angle of the sensor and the thickness of the atmosphere. The latter creates an absorption effect governed by the Relative Humidity, which is assumed to be constant over the survey area. An Admiralty frigate steamed into Plymouth Sound 30 minutes before the aircraft passed overhead. The path of this and other ships can be clearly seen where the thermal stratification of the water has been destroyed by turbulent mixing.

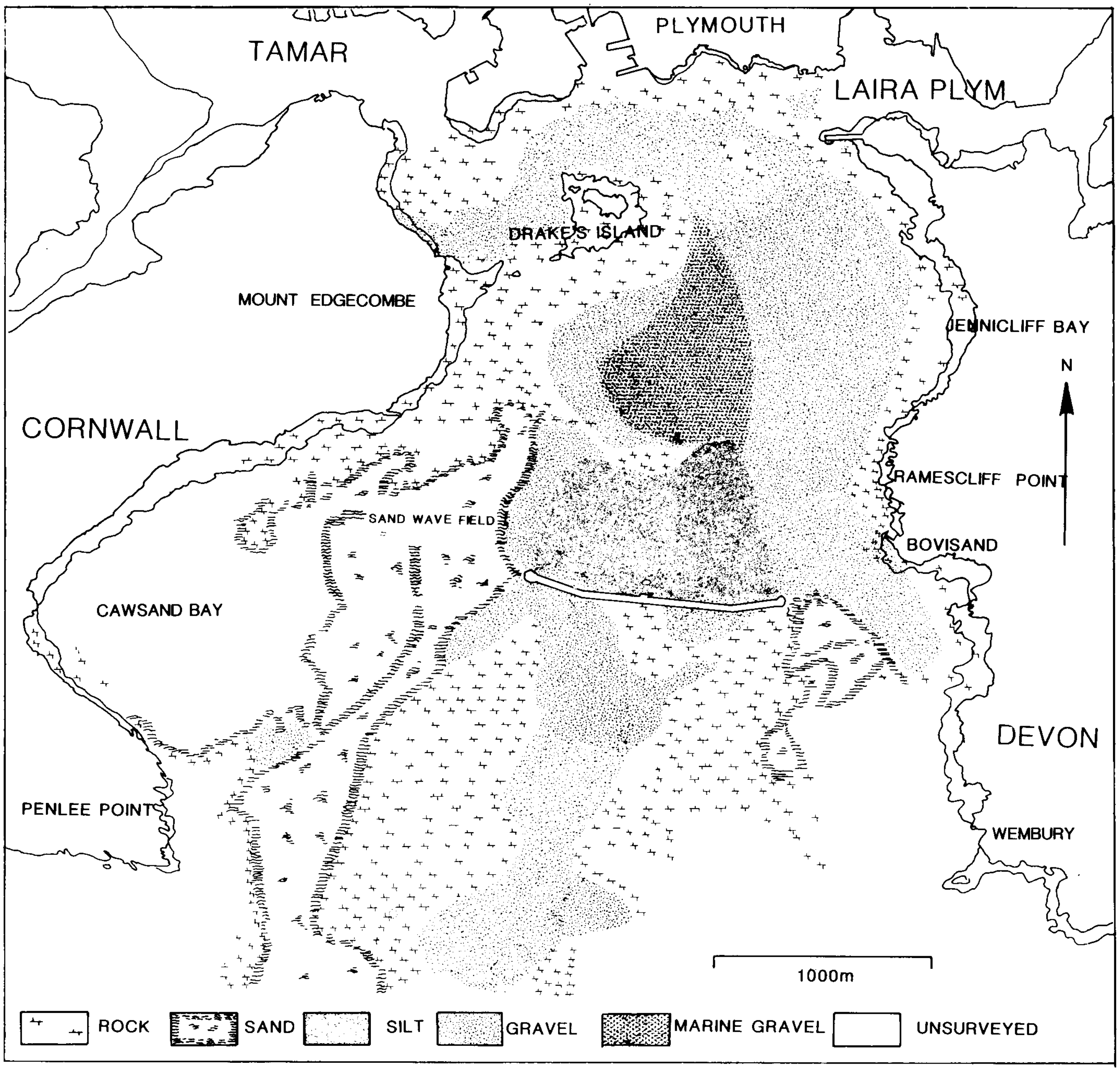

Figure 2. A seabed sediment chart of Plymouth Sound.

Drake's Island upwelling

An area of cooler estuarine water can be seen upwelling from 30m depth from the Hamoaze channel and passing into the Sound through the Bridges. The darker upwelled water shows a parallel streaking pattern, caused by the concrete blocks and reefs of the Bridges where the current is 0.5 knots (Admiralty Tide Tables 1989). The area of cooler water extends around the southern part of Drake's Island. When compared with the sonograph (Fig. 2), it can be seen that the seabed in this location is swept clean of sediment by this current. The rocks and kelp beds surrounding the island can be clearly distinguished as warmer patches in the surrounding water.

The Hamoaze, the Hoe and the Plym

The Hamoaze channel shows a diffuse wake pattern caused by the frigate, indicating stratification of the water. This is in conformity with the deep slow-moving water mass of the deep-water channel. A plume of warmer water from the Plym estuary is clearly distinguished (Fig. 5). This plume has a suspended sediment concentration of >100mg l^{-1} (100% Particulate Organic Carbon) and a salinity of 32.4‰. The water is warmed on the shallow mud banks of the upper Plym and Laira estuary. The plume has been heavily dissected by ships wakes, again indicating stratification. The Plym plume, once it reaches the Sound, can be seen deflecting past the Mountbatten breakwater.

Along the Hoe, cold water discharges can be seen issuing from submerged springs in the limestone (Fig. 6). Their temperature is 6°C below the ambient seawater. These are the so-called "Millbay Blue Holes" and were identified by Roxburgh (1983, 1985a, b). The springs have also been identified by side-scan sonar. The plumes would be best seen in early winter when the contrast in temperatures is greatest. The freshwater is cooler during the summer and sinks below the warmer seawater, due to the different densities and temperatures. Roxburgh (1984) estimated that the mean temperature difference would be between 4.1 and 4.2°C in July. On the Thermal Linescan survey of 4th July 1983, the average temperature in Plymouth Sound was 14.2°C while the average temperature on the 17th July 1989 was 17.8°C. The largest thermal anomaly coincides with a major sewer outfall at Ash buoy. The Particulate Organic Carbon content (100%) of that area further confirms the nature of the

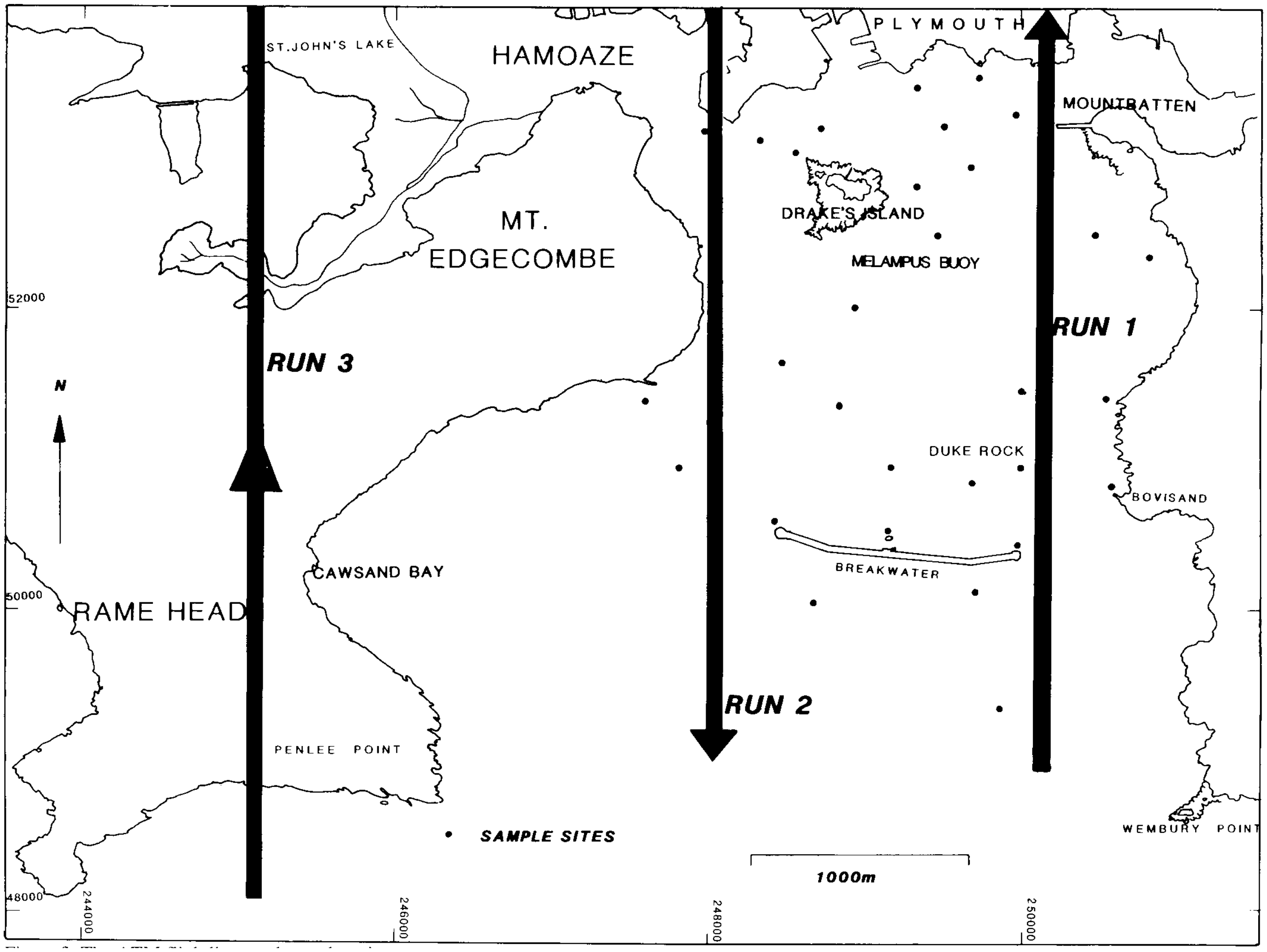

Figure 3. The ATM flightlines and sample points.

discharge. A cooler spring can be seen issuing from the area immediately in front of the Royal Western Yacht Club. This cold stream can be seen to be deflected to the east by the Tamar inflow and is then swept southwards by the Plym discharges.

The Plymouth Breakwater

The Breakwater imagery shows two spin-off turbulent eddies on each side. The eddies are deflecting to the west, illustrating the effect of the Coriolis force, and giving the western eddy a more elliptical structure. The position of the eddies is also reflected in the bottom sediments (Fig. 7, X-X), where a change from mud to gravel is found on the bed. The eddies show turbulent mixing in their margins. There was little surface movement at the time of the overflight. The boat handler in the inflatable working along the Breakwater recalled that, at both ends, the boat did not drift off station during sampling. The eddy at the eastern breakwater shows a temperature division to the southwest (Fig. 7, Y-Y), probably caused by an intensification of the eddy during maximum ebb. The suspended sediment concentrations show similar results.

Plymouth Sound

The main body of Plymouth Sound shows a parallel series of NW-SE trending bodies of water. These are Langmuir rotatory cells built up as a response to the prevailing SW wind. It is interesting to note that the ships' wakes show differences in temperature from 17.2°C in the southern half of Plymouth Sound to 17.8°C in the northern half in a line from Picklecombe to Ramscliff Point. This indicates the relatively stationary aspect of the Plymouth Sound water body.

A major feature in Plymouth Sound is the tidal front to the east of

Table 1. Spectral Characteristics of the Airborne Thematic Mapper.

detectors	Band Edges µm	LANDSAT TM	
Channel 1	0.42 - 0.45		
Channel 2	0.45 - 0.52	Channel 1	0.45 - 0.52
Channel 3	0.52 - 0.60	Channel 2	0.53 - 0.60
Channel 4	0.605 - 0.625		
Channel 5	0.63 - 0.69	Channel 3	0.63 - 0.69
Channel 6	0.695 - 0.75		
Channel 7	0.76 - 0.90	Channel 4	0.76 - 0.90
Channel 8	0.91 - 1.05		
Channel 9	1.55 - 1.75	Channel 5	1.55 - 1.75
Channel 10	2.08 - 2.35	Channel 7	2.08 - 2.35
Channel 11	8.5 - 13.0	Channel 6	10.40 - 12.50

IFOV ....2.5m rad
2.5m at 1,000m AGL
5.0m at 2,000m AGL
Digitised FOV 85.92°
Swathwidth (for a 74° total FOV)
1.5km at 1,000 AGL
3.0km at 2,000 AGL
Scan rate 12.5,25,50 scan sec^{-1}
Roll Correction ..± 15°

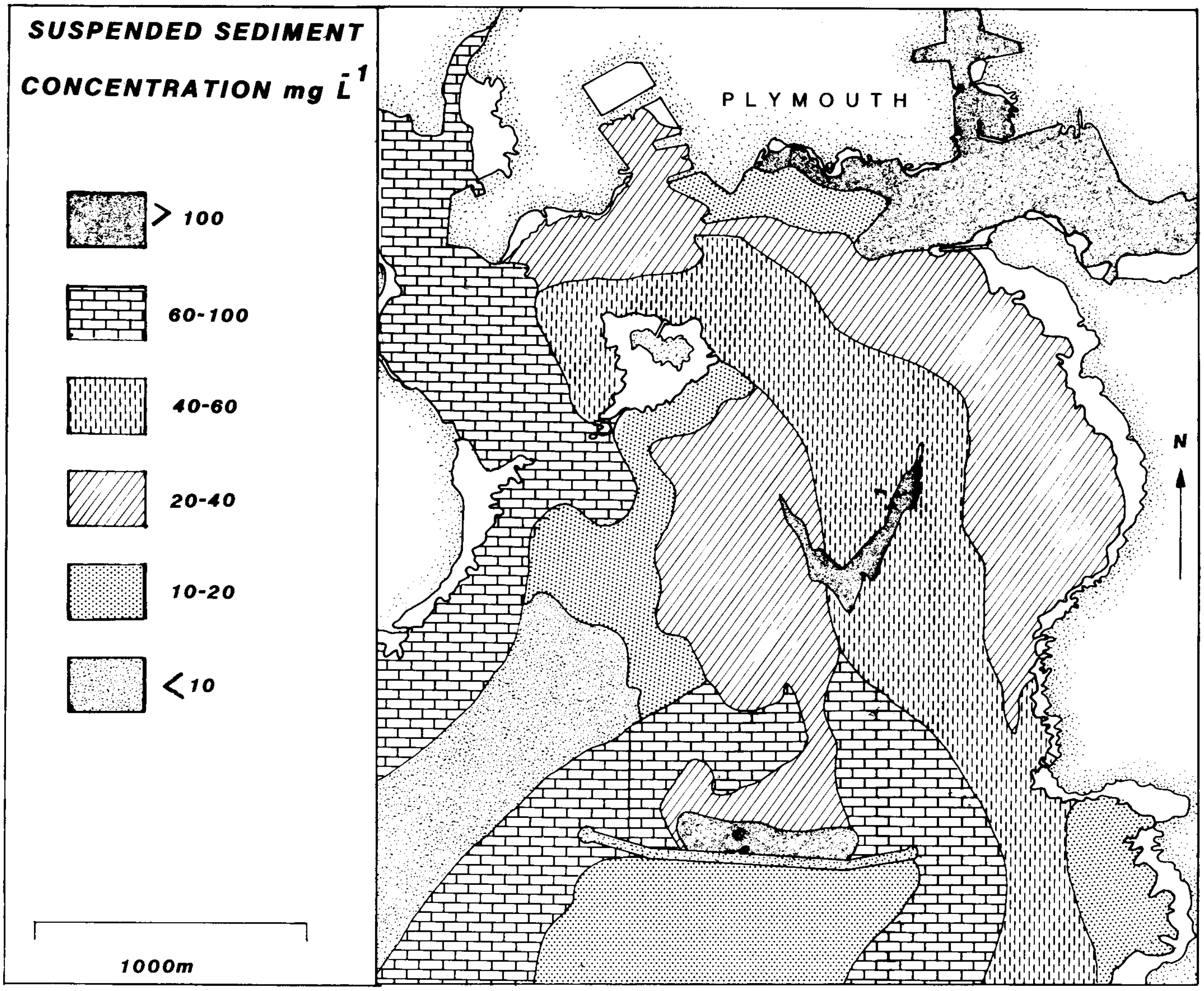

Figure 4. Surface Suspended Sediment Concentrations on 17th July 1989, compiled from Secchi disc depths and *in situ* water samples.

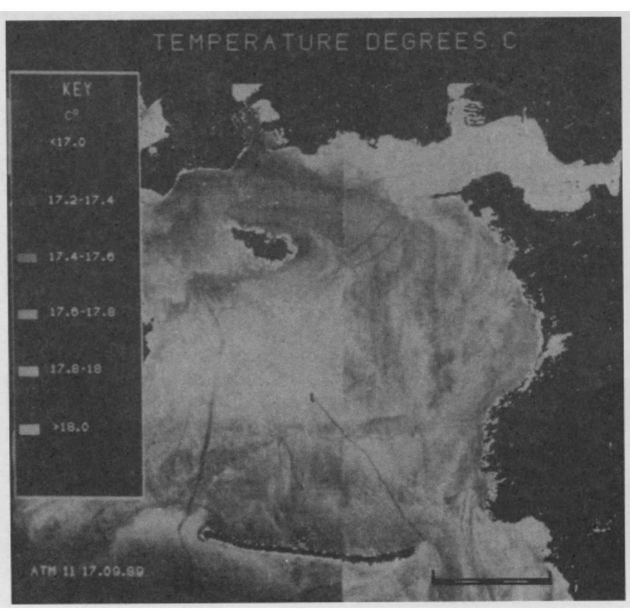

Figure 5. A calibrated composite image of Runs 1 and 2, Band 11 (Scale bar = 1km).

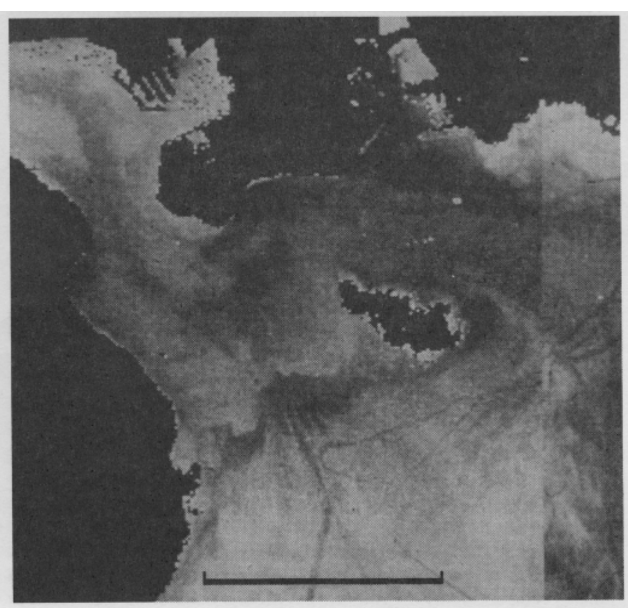

Figure 6. Run 1, Band 11: The Hoe showing the thermal springs (Scale bar = 1km).

Drake's Island (Fig. 5). It has a curvilinear appearance and extends into Plymouth Sound to the east of Melampus buoy for about 1.5km. This frontal system is the confluence of warm Sound water against the colder estuarine outflows. The front is evident on a calm day and can be seen as a line of organics/suspended solids. The side-scan sonar chart illustrates the effect of the front on the underlying sediments as this is where the substrate changes from muddy marine gravel to a clean-washed fluvial gravel.

Concluding remarks

The outcome of the investigation can be assessed in terms of both the ability of ATM to identify thermal fronts and the limitations and advantages of the airborne approach. The main advantage of the overflight is that it allows an almost instantaneous synoptic overview of Plymouth Sound, which would be impossible to obtain from ship measurements. However, it is necessary to have *in situ* measurements in order to calibrate the images. To gain a complete knowledge of the tidal dynamics several overflights are required. A positive correlation between the seabed sediments and the position of tidal fronts and eddies in Plymouth Sound has been established. The level of mud behind the Breakwater appears to be stationary. Lead-line depths, botained in 1889, show a slight increase (1m) since the completion of the Breakwater in 1848. The techniques described above for the identification of tidal fronts and their constraints are applicable to other areas of shallow water.

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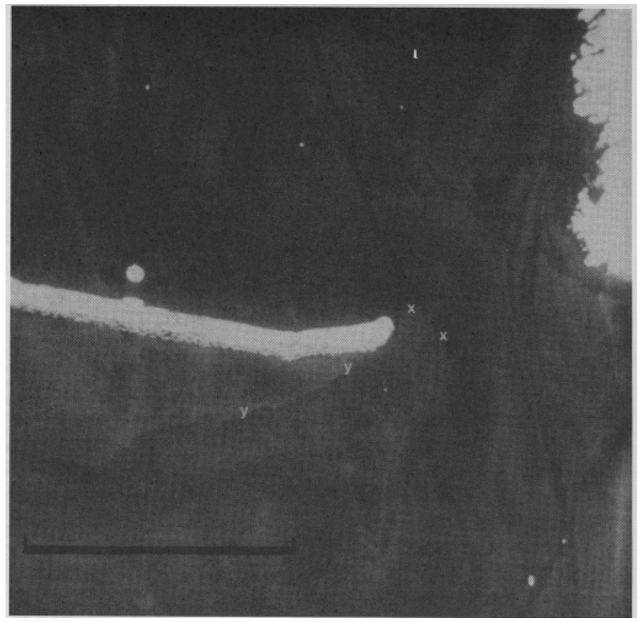

Figure 7. A composite image of Runs 1 and 2, Band 11: The Breakwater eddies (Scale bar = 1km).

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