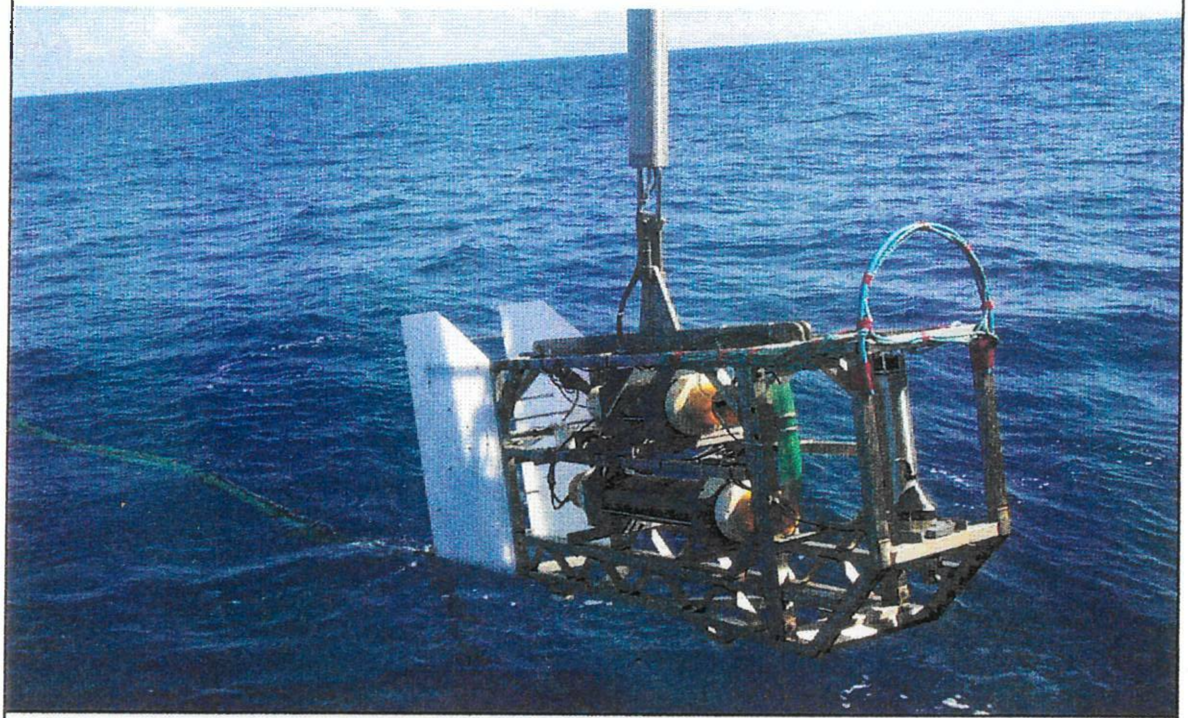
Cruise Report



Madrigals

RRS *Charles Darwin*
Cruise 120

Southampton-Southampton
21 September-19 October 1999

ISO-3D

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'Mid-Atlantic Deep-towed Resistivity and Induction Geophysics at Lucky Strike'

21 September-19 October 1999

Southampton-Southampton

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European Union, MAST-III

Natural Environment Research Council

Contents

Summary

This report describes a geophysical cruise to the 'Lucky Strike' segment of the Mid-Atlantic Ridge - an area which lies to the SW of the Azores archipelago, and within the EEZ of Portugal. The scientific objective was to carry out a controlled-source electromagnetic (CSEM) sounding study of the upper and middle crust beneath the central volcano of the segment, in order to determine crustal electrical resistivity structure and hence to constrain the physical properties of the crust beneath a region of very active recent volcanism and current high- and low-temperature hydrothermal venting. The technological and methodological objective was to demonstrate a capability for collecting and analysing CSEM survey data from a highly 3-dimensional area of the ocean floor.

The cruise was a collaboration between the University of Cambridge, UK; the Universities of Lisbon and Algarve, Portugal; and HALO Ltd, Reykjavik, Iceland. Basic ship time was funded by NERC (UK), and other research costs were funded by the European Union MAST-3 programme. The cruise, designated *'Madrigals'* (Mid-Atlantic Deep-towed Resistivity and Induction Geophysics At Lucky Strike), is a major component of the MAST-3 project *'ISO-3D'* - Applications of Three-Dimensional Electromagnetic Induction by Sources in the Ocean.

The vessel sailed from Southampton on Tuesday 21/09/99. Additional scientists were embarked by boat transfer at Ponta Delgada on 27/09/99, and - after a brief test deployment of the DASI deep tow system on the Princesa Alice Bank - the vessel arrived at the work area during the evening of 28/09/99. Following completion of some wire tests and a sound velocity profile, 10 LEMUR instruments were deployed on the sea floor together with 6 acoustic navigation beacons and 4 near-bottom current meter moorings.

Over the following 9 days, the DASI deeptow system was used to carry out 95 hours of CSEM transmissions at 0.25, 1 and 4 Hz along 212 km of tow track - a greater quantity of CSEM transmission time and line-km than had been achieved by any previous study. Only relatively minor delays were experienced during this period of the cruise.

On completion of the DASI tows, six of the LEMURs and all acoustic navigation beacons and current meters were safely recovered. However four of the LEMURs were lost. One loss was due to the instrument surfacing at night with a failed light. The other three LEMURs all appear to have suffered failures of their acoustic systems some time between deployment and attempts at recovery. We suspect that there may be a systematic fault in the commercially-built releases that we used, although further investigation is required.

The vessel left the work area at the end of 12/10/99; disembarked part of the scientific party in Ponta Delgada by boat transfer on 14/10/99; and returned to Southampton, arriving on 19/10/99.

Despite the serious loss of equipment, a large quantity of data was collected by the other LEMURs. Preliminary assessments from these instruments indicate excellent data quality. The success of the DASI system in providing many hours and line km of transmissions also partly offsets the loss of receivers, and we anticipate that despite the instrument losses we should be able to produce a good determination of crustal resistivity structure and physical properties.

In summary, the cruise was successful in terms of data acquired. The DASI system in particular functioned well, and the cruise has demonstrated the viability of routine and high quality CSEM data acquisition, including in 3-D, even in areas of rugged and volcanically/hydrothermally active ocean bottom terrain. However the loss of four LEMUR instruments is a substantial blow to both Cambridge and Lisbon.

1. Scientific Background and Cruise Objectives

1.1 Scientific Background

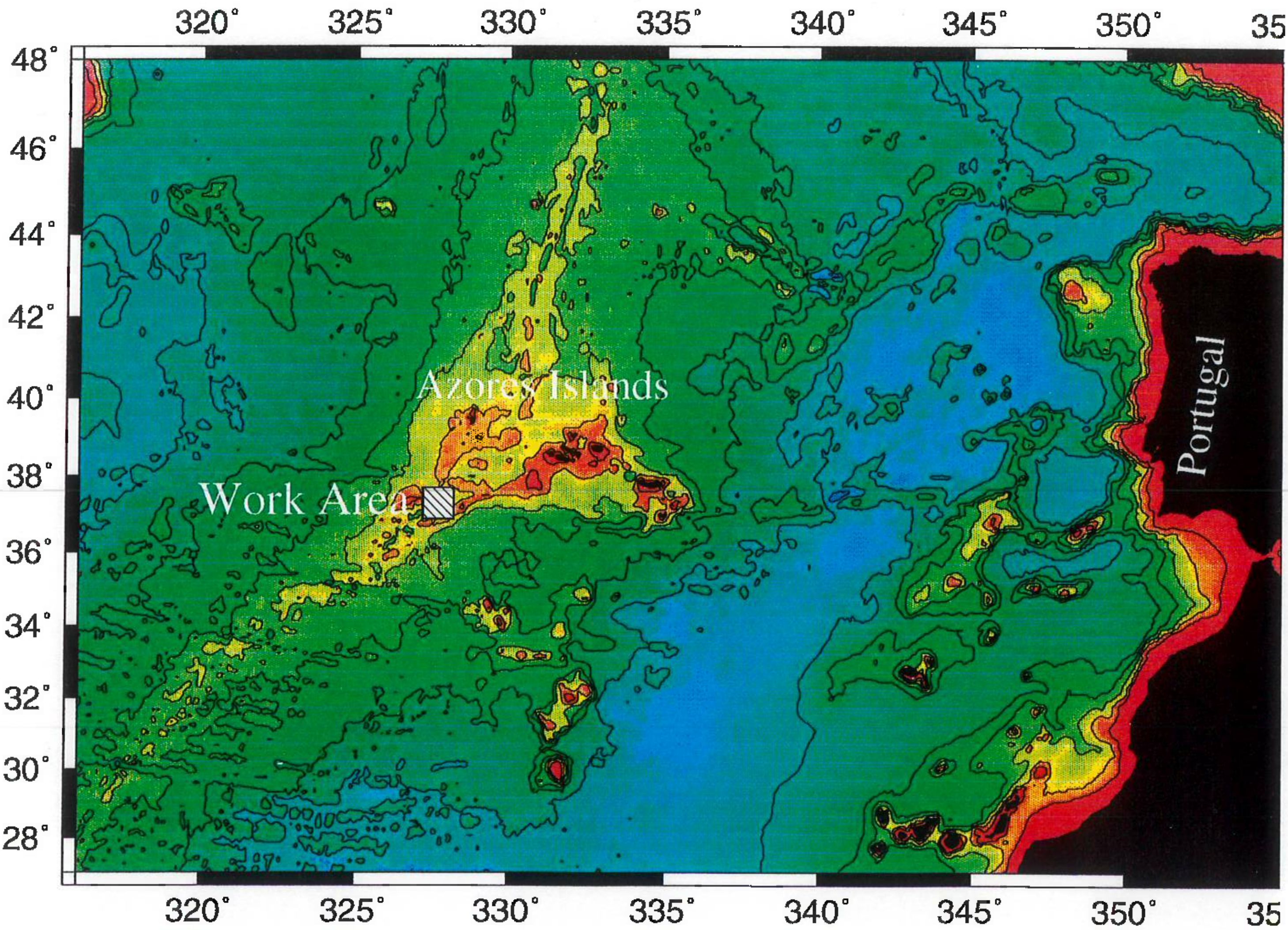
Fluid phases play a crucial role in crustal construction at spreading ridges. In addition to the obvious (though complex) role of magma, the penetration of hydrothermal fluids exerts controlling influences on the thermal structure, and hence rheology, of the crust; on the level to which melt can ascend before ponding to form magma bodies; on heat advection, which accounts for a high proportion of the earth's total heat flow; on high and low temperature alteration and mineralization in the crust and possibly in the upper mantle; and on the residence time of melt bodies in the crust, on the dimensions of crustal melt bodies, and on the nature of tectono-magmatic cycles. Thus the processes by which all oceanic crust is created are driven by the invasion of the axial lithosphere by seawater from above, and by magma from below. Ridges are the sites of vigourous fluxes of energy and material between the earth's interior, the lithosphere and the water column – a process which has a major global impact on the chemical budget of the ocean. The resultant hydrothermal vent fields on the ocean floor provide oases for abundant and productive benthic ecosystems, in which the base of the food chain is inferred to be chemosynthetic (via chemolithoautotrophy), rather than photosynthetic. Modern hydrothermal circulation systems at ridges are believed to be the sites of construction of massive polymetallic sulphide ore bodies. They therefore provide the modern analogues of many ancient ore bodies, now exposed on land, which are of great economic importance. Improved understanding of the mechanisms of formation of these bodies, and of their structure at the time of formation, is likely to benefit relevant sectors of the mining and mineral extraction industries.

Despite the global importance of hydrothermal circulation systems, and many investigations based on chemical analysis of the emerging fluids, there have been few investigations targeted at the large scale physical properties of the cracked and fractured oceanic crust through which the fluids flow. Ocean drilling (Leg 158 – Humphris, Herzig, Miller *et al.*, 1996) has revealed the shallow (< 150 m below the sea floor) structure of the TAG hydrothermal system. Other than this, though, remarkably little attention has been paid to the quantitative characterisation of the physical regime within the most important part of the hydrothermal system – that is, between the seafloor and the base of the hydrothermal reaction zone, which lies several kilometres deeper. Numerous geophysical studies have provided constraints on the seismic properties (P wave velocity and to a lesser extent S wave velocity and seismic anisotropy) of young, upper oceanic crust (Layer 2), but there are serious ambiguities in interpreting these seismic constraints alone in terms of the geometry and distribution of pore spaces and the properties of the invading fluid. An especially valuable set of constraints can, in contrast, be provided by a detailed knowledge of the electrical resistivity structure of the crust, since resistivity is highly sensitive to porosity, to the temperature and salinity of the fluid, and to the degree of interconnection between adjacent pore spaces.

Our objective during Cruise CD 120 was to carry out a 3-dimensional, controlled-source electromagnetic (CSEM) study of the upper- and mid-crustal resistivity structure of the Lucky Strike segment of the Mid-Atlantic Ridge (Figure 1). This segment is the site of known high and low temperature venting, and has been extensively investigated by diving, sampling and geophysical studies which have provided excellent background data on the geological and geochemical characteristics of the hydrothermal regime.

Since 1991, the Mid-Atlantic Ridge SW of the Azores triple junction has been extensively surveyed by six cruises [Fouquet *et al.* 1994, 1995; German *et al.* 1996; Langmuir *et al.* 1993; Wilson *et al.* 1995]. Three volcanic segments have been identified. The Lucky Strike segment is the most northerly of these. All three have been surveyed by multibeam echo sounder, giving 100% swath bathymetric

Figure 1. Location map of the *'Madrigals'* work area in the central North Atlantic, on the Mid-Atlantic Ridge axis SW of the Azores archipelago.



coverage. In 1992, sulphides were dredged from the top of the prominent axial volcano in the Lucky Strike segment. Six dives were carried out there by Alvin in 1993, and these discovered the hydrothermal site. Eight discrete active vents were found and rock, fluid and biological samples were collected. Nineteen further dives were completed by Nautile on the three ridge segments during 1994. The Lucky Strike segment is therefore an area where hydrothermal activity and its associated biological productivity and metalliferous sulphide ore deposition have been well documented. The site was the subject of intensive investigation by another MAST III project, 'AMORES'.

The Lucky Strike segment has an axial valley 15 km wide and up to 950 m deep (Figure 2). In the centre of the rift valley and approximately mid way between the offsets that bound the segment to the north and south lies a composite volcano 13 km long, 7 km wide, and 430 m high, and divided into two parts separated by a N-S trending graben. The western bathymetric high is an elongated narrow ridge, while the eastern side has a semi-circular shape with three volcanic cones at its summit. The high temperature hydrothermal site is located in a depression between these cones. In the central depression there is a drained lava lake. Active vents surround the lava lake, with the most active venting present on the western side. Inactive sulphide deposits cover almost 80% of the surface area of the lava lake. The annular distribution of the sulphide deposits suggests that major upwelling cells are radially distributed, and are controlled by high-permeability margins of the lava lake and the collapsed caldera. Hydrothermal discharge occurs through high temperature, active black smokers at temperatures of up to 324^{0} C.

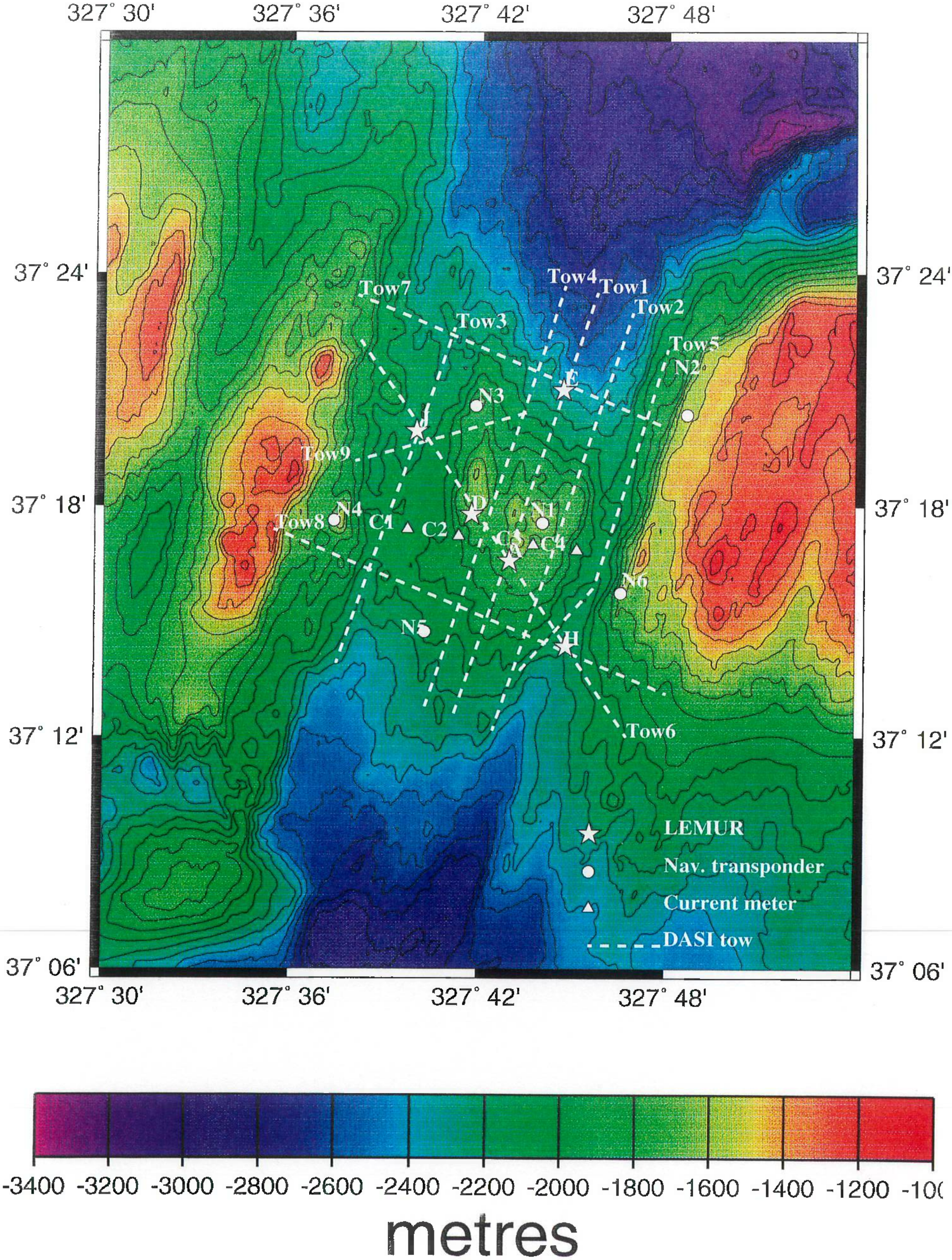
1.2 Technological/methodological background

Marine controlled-source electromagnetic (CSEM) sounding is a powerful, but until recently relatively little used, geophysical technique. It involves the use of an artificial electromagnetic source at or close to the sea floor, and an array of sea bottom recording instruments that measure the resulting fields (Figure 3). It has been successfully applied in several studies of mid-ocean ridges [e.g. Evans *et al.*, 1992, 1994; Sinha *et al.* 1997, 1998; MacGregor et al., 1998; Peirce *et al.*, 1996], and has many potential applications in marine geophysics. Since it is a means of determining the distribution of electrical resistivity within the crust, it is a particularly powerful geophysical technique for studies of conductive fluid phases within a relatively resistive silicate matrix. The bulk resistivity of the oceanic crust is primarily controlled by the presence of fluids (predominantly seawater, but also high temperature hydrothermal fluids and even magma in the ridge areas), and varies both with the volume and connectedness of the fluid passages and with the properties (composition and temperature) of the pore fluid.

The CSEM method has been shown to be capable of constraining resistivity structure to depths of at least 10 km beneath the ocean floor, even in tectonically active regions such as ridges [Constable *et al.* 1996; Sinha *et al.* 1997]. Use of an artificial source allows both the frequency and the experimental geometry to be chosen to suit the application. As a result, studies of relatively shallow structure are possible using frequencies of up to 40 Hz [*e.g.* Peirce *et al.* 1996], and this allows considerably greater structural resolution than has previously been possible from marine EM methods.

All CSEM experiments to date have been conducted over targets carefully chosen to approximate as closely as possible to either a 1-dimensional or 2-dimensional earth structure. This is partly because the technique has been at a developmental stage, and partly because until now the interpretational tools for 3-dimensional structures did not exist. However many of the most interesting and significant structures beneath the sea floor are undoubtedly 3-D in character. The principal, initial objective of the ISO-3D project, to develop a 3-D modelling code,

Figure 2. Swath bathymetric chart of the Lucky Strike segment of the Mid-Atlantic Ridge. Contour interval is 100 m. Also shown are the approximate locations of the DASI tow lines; and the deployment positions of ocean bottom instruments that provided data.



was an indispensable first step towards more effective applications of the technique. However a further objective of ISO-3D is to carry out, analyse and interpret the results from a demonstration CSEM experiment on a 3-Dimensional target of major geological and environmental interest - an active, high temperature, hydrothermal site on the Mid-Atlantic Ridge.

1.3 Specific objectives

The specific purpose of Cruise CD120 was to determine the electrical resistivity structure beneath the Lucky Strike segment of the Mid-Atlantic Ridge, south of the Azores. The 3-D CSEM experiment was aimed at characterising the electrical resistivity structure of a volume of young oceanic crust within the median valley and underlying the axial volcano. The volume extends for approximately 12 km x 12 km along and across the MAR axis (Figure 2), and to a depth of 3 to 5 km beneath the sea floor, and is centred on the high temperature hydrothermal site on the eastern summit of the axial volcano.

Crustal resistivity at a ridge depends primarily on three factors. The first is the porosity of the crust. The second is the geometry of the pore spaces: i.e. whether the pore spaces are predominantly isolated from each other (as is the case for low porosities and pore aspect ratios close to 1), or form an interconnected network (as is the case at higher porosities, and for cracks and fractures with small aspect ratios). The third is the conductivity of the pore fluid – controlled by its temperature and its ionic content. A fourth factor is the presence of other materials with conductivities very much higher than that of the basaltic matrix. These could include conductive sulphide minerals, and accumulations of basaltic melt. Crustal resistivity is thus intimately related to the physical parameters which control the invasion of the newly formed lithosphere by circulating hydrothermal fluids.

Specifically, the aims of the cruise were to investigate:

- Are there systematic variations in resistivity structure within the upper 2 to 3 km of the crust within the segment, that are associated with changes in permeability structure that influence the siting of the hydrothermal system?
- Is the axial volcano underlain by a hydrothermal plumbing system dominated by high temperature fluids, or do fluids at or close to ambient sea water temperatures predominate - and if so, to what depths?
- Is there a deep magmatic heat source still present beneath the centre of the segment, or is the segment magmatically quiescent at the present time?

Although the CSEM data alone cannot unambiguously resolve these questions, we shall apply a multi-disciplinary approach to the analysis, making use of independent constraints provided by the resistivity structure; the known seismic properties of young Atlantic oceanic crust; the pre-existing, segment-scale geophysical data (which include gravity and magnetic field measurements) from Lucky Strike; the chemistry of both high- and low-temperature samples of hydrothermal fluids; and estimates of thermal and fluid fluxes.

2. Methodology, Instrumentation and Work Carried Out

2.1 CSEM data

2.1.1 CSEM method

In a CSEM experiment, an alternating current electromagnetic signal is injected into the oceanic crust and detected by electric field receivers placed on the seafloor at various ranges (up to 10-15 kilometers) extending outward from the

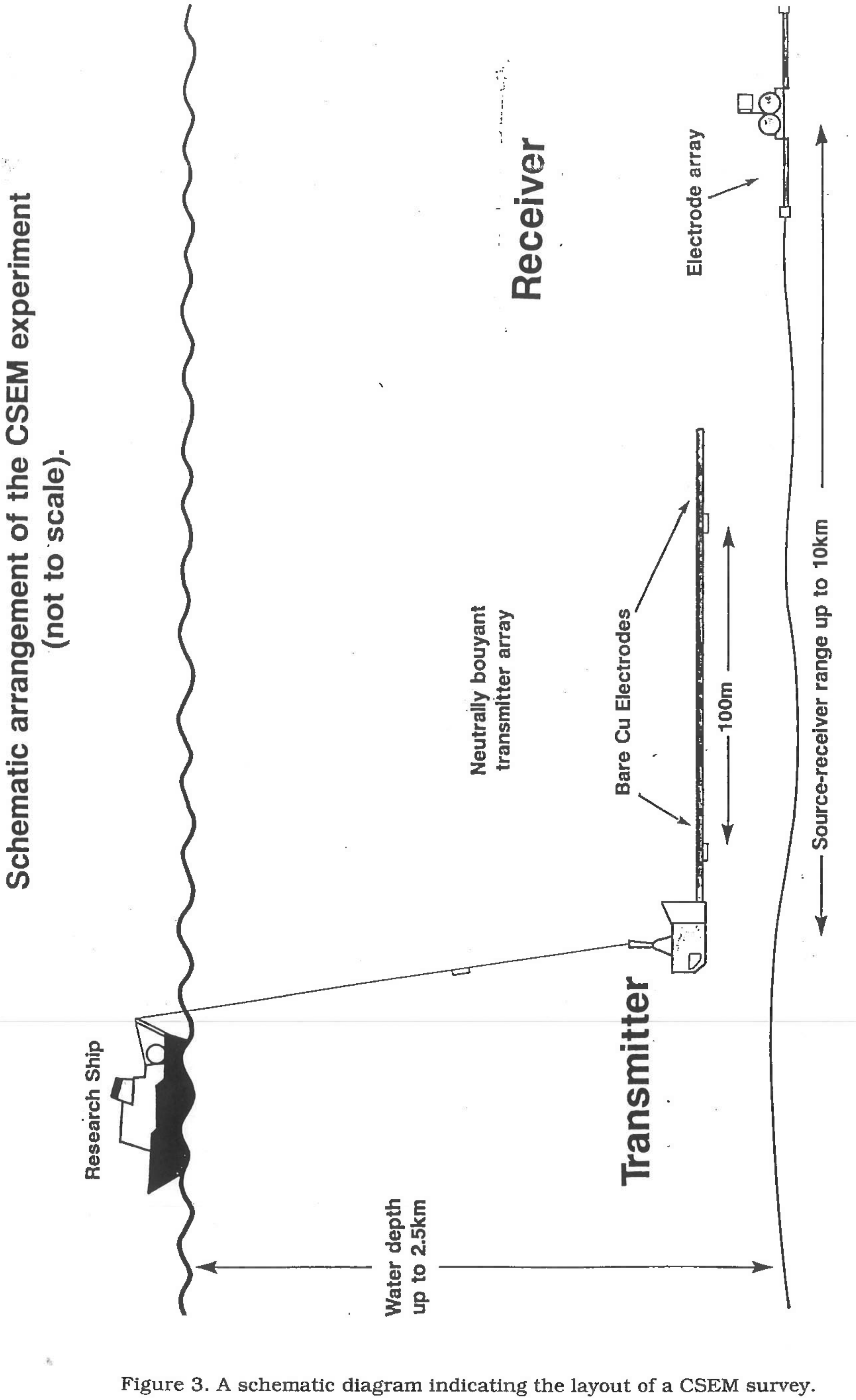


Figure 3. A schematic diagram indicating the layout of a CSEM survey.

source. The part of the signal which has diffused through the lithosphere, rather than the water column, remains detectable by instruments placed on the sea bed because of leakage of electromagnetic energy back up into the ocean. The distribution of electrical resistivity of the rocks below the sea bed is determined by measuring the spatial character of the attenuation and phase shift of the transmitter signals over a range of frequencies and source-receiver geometries.

In practice the most commonly used experimental geometry – and that used for the CD120 study - consists of a horizontal electric dipole (HED) source and a series of horizontal electric field receivers, all deployed on the seafloor (Figure 3). The depth of penetration into the sea floor is typically up to half the maximum source-receiver range, depending on the resistivity structure. Two important factors make the sea floor controlled source method different from land EM measurements in ways which improve its sensitivity to sub-sea floor structure:

(i) Because the conductivity of seawater is much larger than that of the crust, the portion of the source signal propagating through the water is attenuated rapidly with range. Any signal which is observed at ranges exceeding a few skin depths in seawater (typically a few hundred metres in CSEM experiments) is diffusing through the underlying rocks, and its behaviour with range and frequency depends solely on the resistivity structure beneath the sea floor.

(ii) The natural noise level at the sea floor at frequencies of 0.05 to 100 Hz is extremely low, allowing very weak signals to be detected at substantial ranges.

During CD 120, we deployed an array of ten 'LEMUR' ocean-bottom electric field recorders on the sea floor, on and around the central volcano at Lucky Strike. These instruments acted as the receivers for the CSEM experiment. We then used the 'DASI' deep towed transmitter, equipped with a neutrally buoyant horizontal electric dipole antenna streamer, to transmit signals over a range of frequencies into the array of receivers. The experimental geometry was chosen to provide good coverage of both source receiver ranges and receiver azimuths over a zone approximately 12 km by 12 km centred on the hydrothermal site (Figures 4, 5 and 6). The experiment provides data at ranges up to 12 to 15 km, providing some resolution at depths to at least 4 to 5 km; however the bulk of the data are at ranges between 0 and 6 km, providing maximum resolution in the 0 to 2 km depth range. The greatest concentration of data is close to the hydrothermal site itself, again providing maximum spatial resolution here. We used transmission frequencies of 0.25, 1 and 4 Hz. Since the source signal is a square wave, significant amounts of signal are emitted at the third and fifth harmonics: so that it should also be possible to analyze signals at frequencies of 0.75, 1.25, 3, 5, 12 and 20 Hz. The pattern of receivers and DASI tows employed provides for data acquisition in directions both parallel and orthogonal to the axis of the transmitting dipole, as this has been shown to improve resolution substantially (Sinha, 1999; MacGregor, 1999; MacGregor & Sinha, 1999).

2.1.2 the DASI transmitting system

The DASI system (Sinha *et al.*, 1990; Figure 7) underwent considerable development and improvements during preparations for this cruise. The new system uses fibre optic communications between the ship and the towed vehicle. This has greatly improved the reliability of the DASI system, while simplifying the engineering required to provide the vehicle with both power (~10kW) and communications. Because of this it was essential to use RRS *Charles Darwin* for this project, since she is the only European research vessel equipped with a suitable, electro-mechanical plus optical fibre deep tow cable and winch system.

As used during CD120, DASI is equipped with a Simrad 120 kHz acoustic altimeter, with a range of 0 – 500 m, to allow the vehicle's height above the sea floor to be monitored from the ship. Flying height is controlled using the deep-tow

Figure 4. The DASI tow line completed at a transmission frequency of 0.25 Hz.

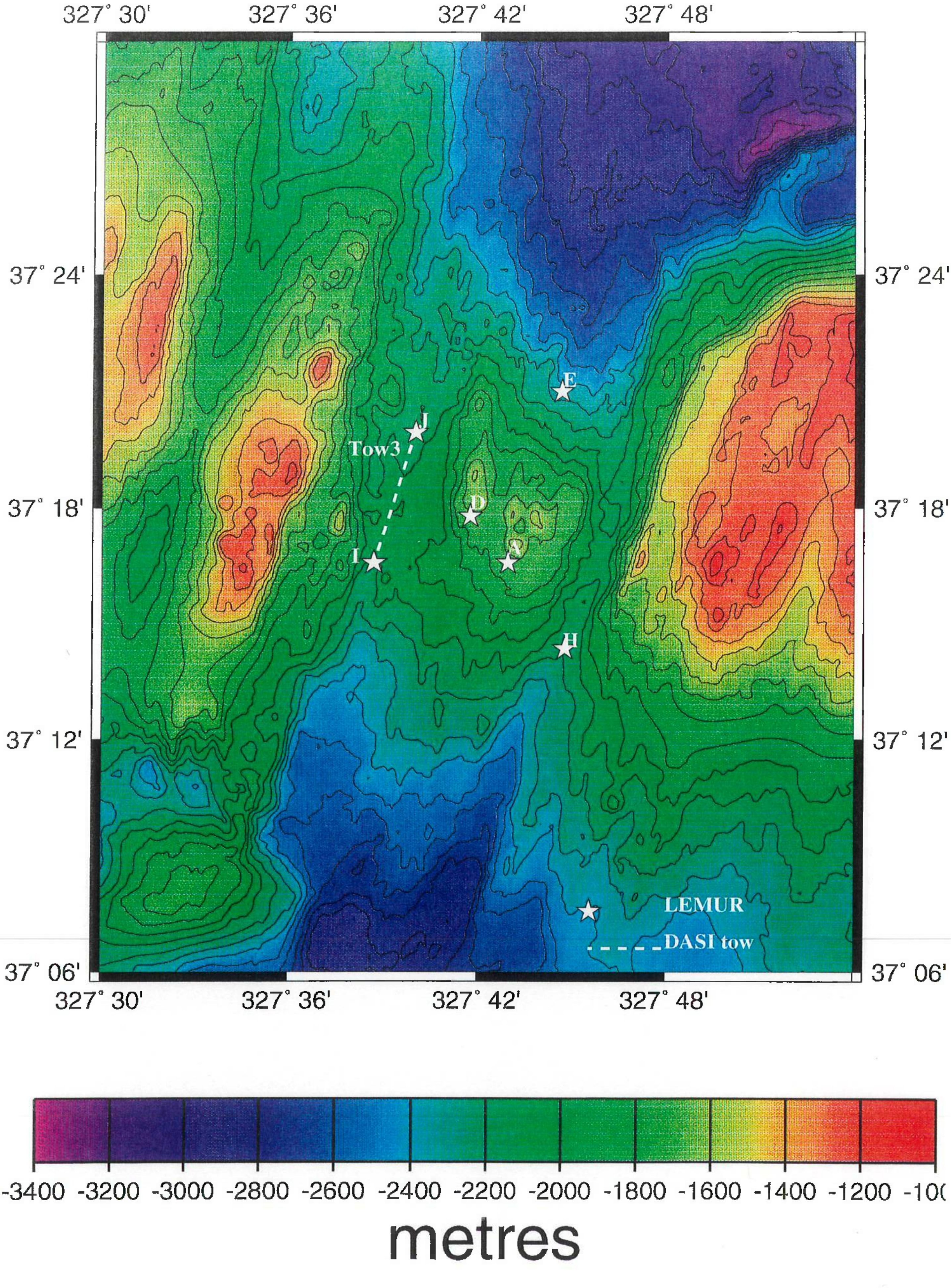
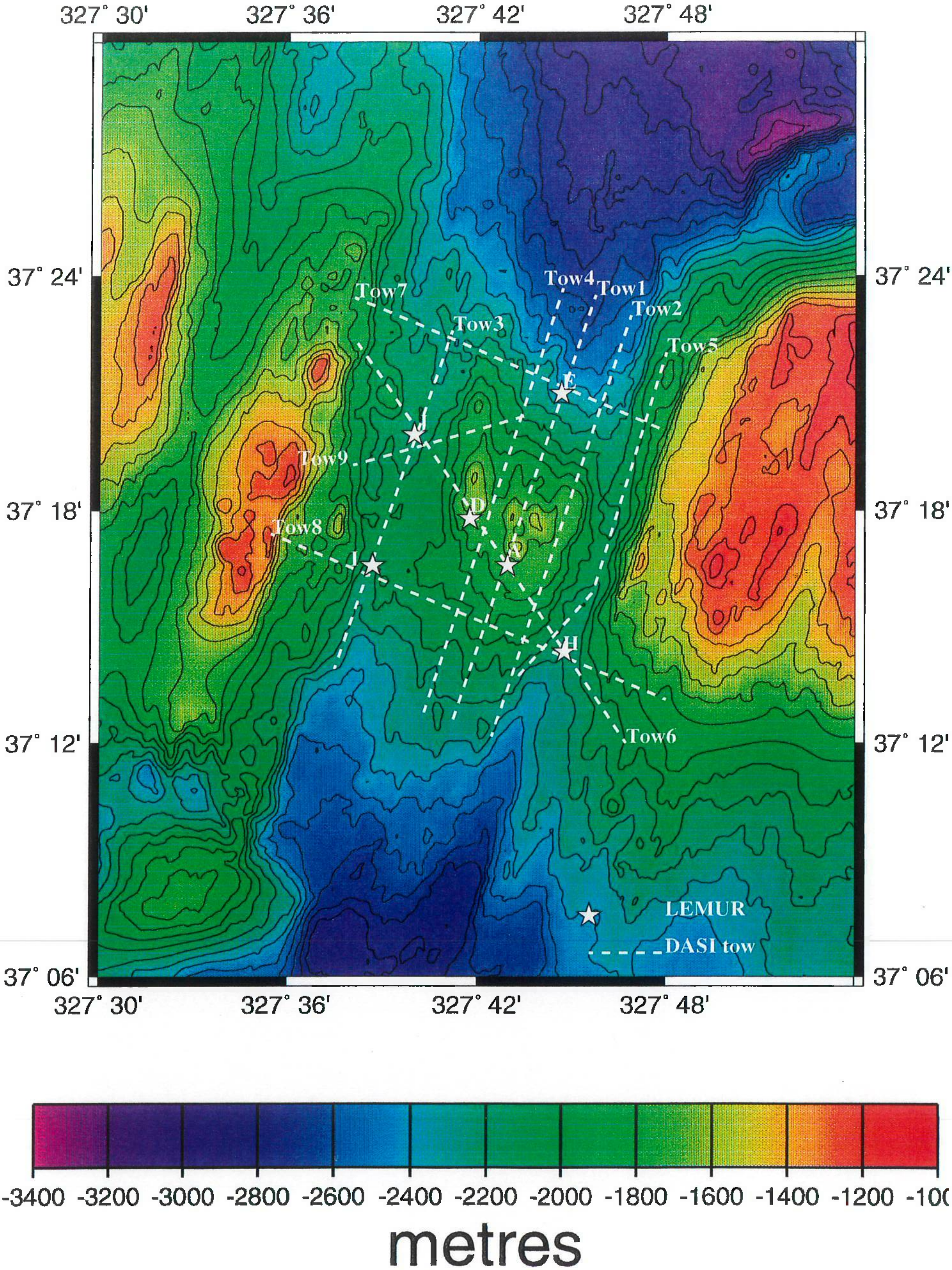


Figure 5. DASI tow lines completed at a transmission frequency of 1 Hz.



winch. For most of the cruise, DASI was flown 70 to 80 m above the seafloor; but during the last phase of transmissions, when the transmission frequency was increased to 40 Hz, a flying height of approximately 40 m was maintained.

The transmitting antenna is a 100 m, neutrally buoyant, horizontal electric dipole streamed behind the DASI vehicle. The antenna is earthed into seawater at both ends using copper welding cable electrodes, placed at 30 m and 130 m behind the vehicle. The output current consisted of a pseudo-square-wave made up of rectified and switched half-cycles of the 256 Hz power supplied to the deep-tow from the ship. All transmissions were made with a peak-to-peak current of approximately 300 A; constituting a source dipole moment of approximately 1.5 x 10^4 Am.

2.1.3 the LEMUR instruments

Ten LEMURs were used for this study (Figure 8). Each was equipped with an orthogonal pair of horizontal electric dipole sensors, using low noise Ag-AgCl electrodes (Figure 9); and 24-bit digital recording systems. Four of them were pre-existing Cambridge instruments, constructed in 1995 for use in a survey on the axis of the Valu Fa Ridge, Lau Basin (Peirce et al., 1996). These LEMUR '95 instruments were fitted with 340 MByte hard disk drives for data storage, and collected 24-bit data from two electric field channels at 128 samples per second per channel. This gave them a total recording time of approximately 5 days 6 hours.

Six new LEMURs were constructed using ISO-3D funding – three each for Lisbon and Cambridge. The new instruments (LEMUR '99s) used a newer version of the 24-bit ADC and digital signal processing chips; and were fitted with 1.2 GByte disk drives, giving them extended recording times in excess of 15 days. All ten LEMURs were fitted with electronic compass; biaxial tilt meter; and temperature sensor, with values from all of these being logged every 40 minutes. The low-noise electrodes were arranged to form two orthogonal horizontal electric dipoles of length 13 m. The LEMURs were fitted with Marine Acoustics Ltd acoustic release units, electrolytic burn-wire actuators and releasable bottom weights.

2.1.4 Acoustic Navigation

We used long baseline acoustic navigation during the experiment to accurately locate both DASI and the LEMURs with respect to each other and to the bathymetric base map. For this purpose, we deployed an array of six Morrs RT661 acoustic navigation transponders within the survey area (Figure 10). An RT161 relay transponder was fitted to the DASI vehicle, allowing 3-D fixes of the deep tow with respect to the fixed transponders. The acoustic navigation system was provided under sub-contract by NERC Research Vessel Services (RVS).

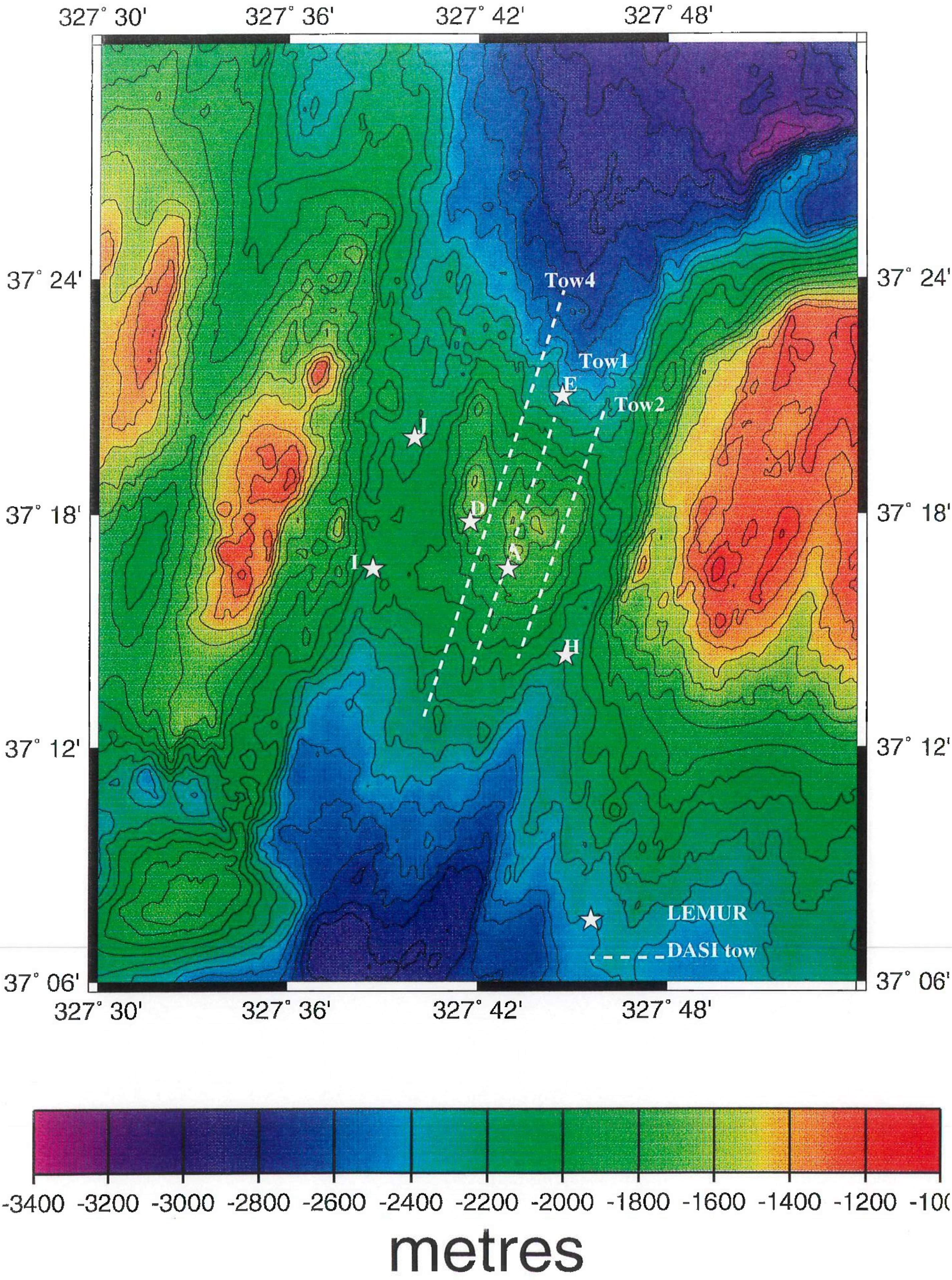
2.2 Other data collected

A number of other data types were collected during CD120, in addition to the CSEM study.

An array of 4 Aanderaa Model RCM7 recording current meters was deployed across the narrowest part of the axial valley and the volcano (Figure 11). All meters were deployed at a height of 50 m above the sea floor. Data from these will allow us to monitor near bottom water mass velocity, temperature and electrical conductivity. This will provide important additional information for the CSEM survey – for which a knowledge of the transmitting dipole streamer orientation and seawater conductivity is required.

Additional data on water column physical properties was obtained by launching a series of expendable bathythermographs (XBTs) at intervals along the current meter profile. At the start of the cruise we also lowered a sound velocity meter through the water column to close to the sea floor. As well as complementing

Figure 6. DASI tow lines completed at a transmission frequency of 4 Hz.



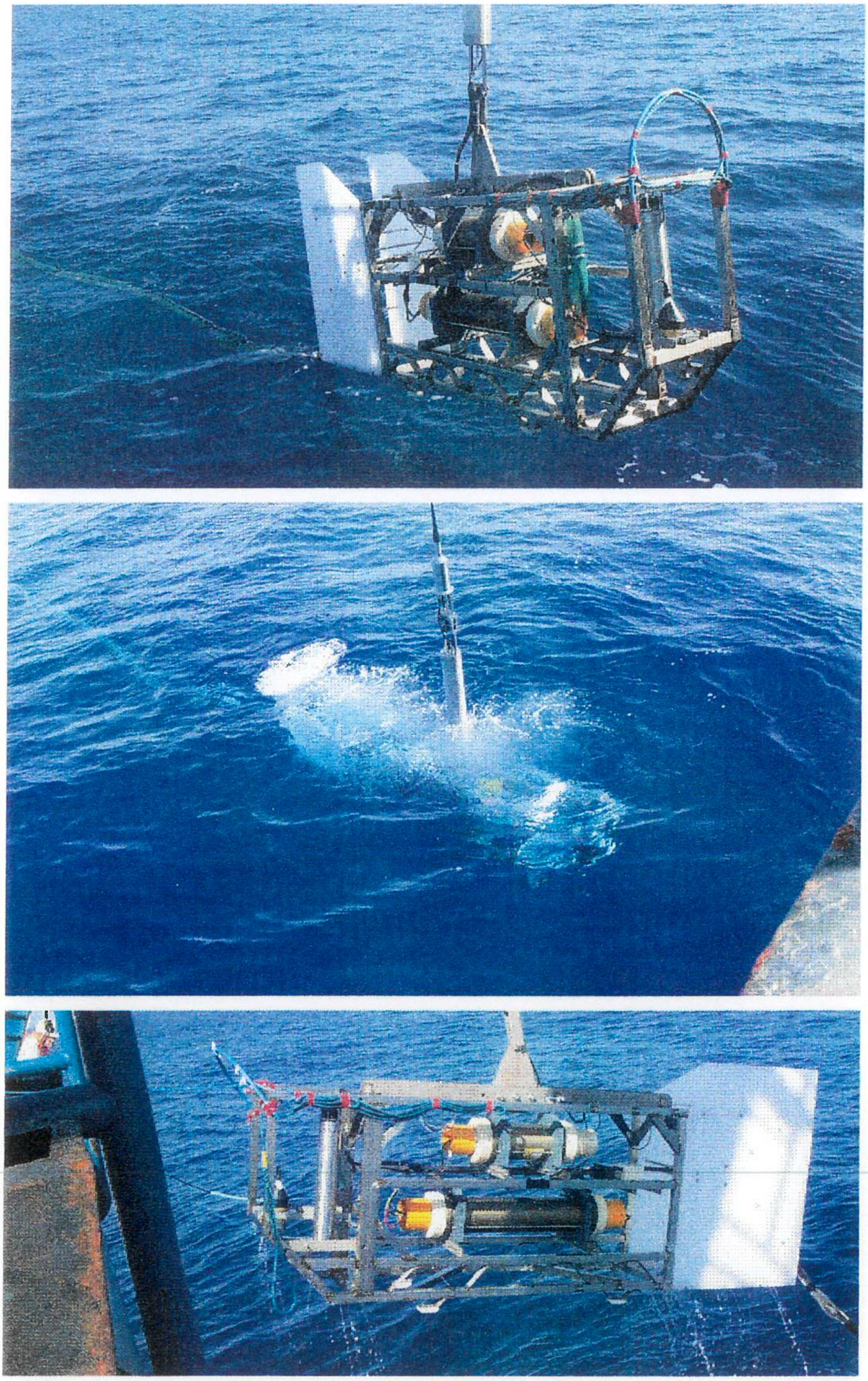
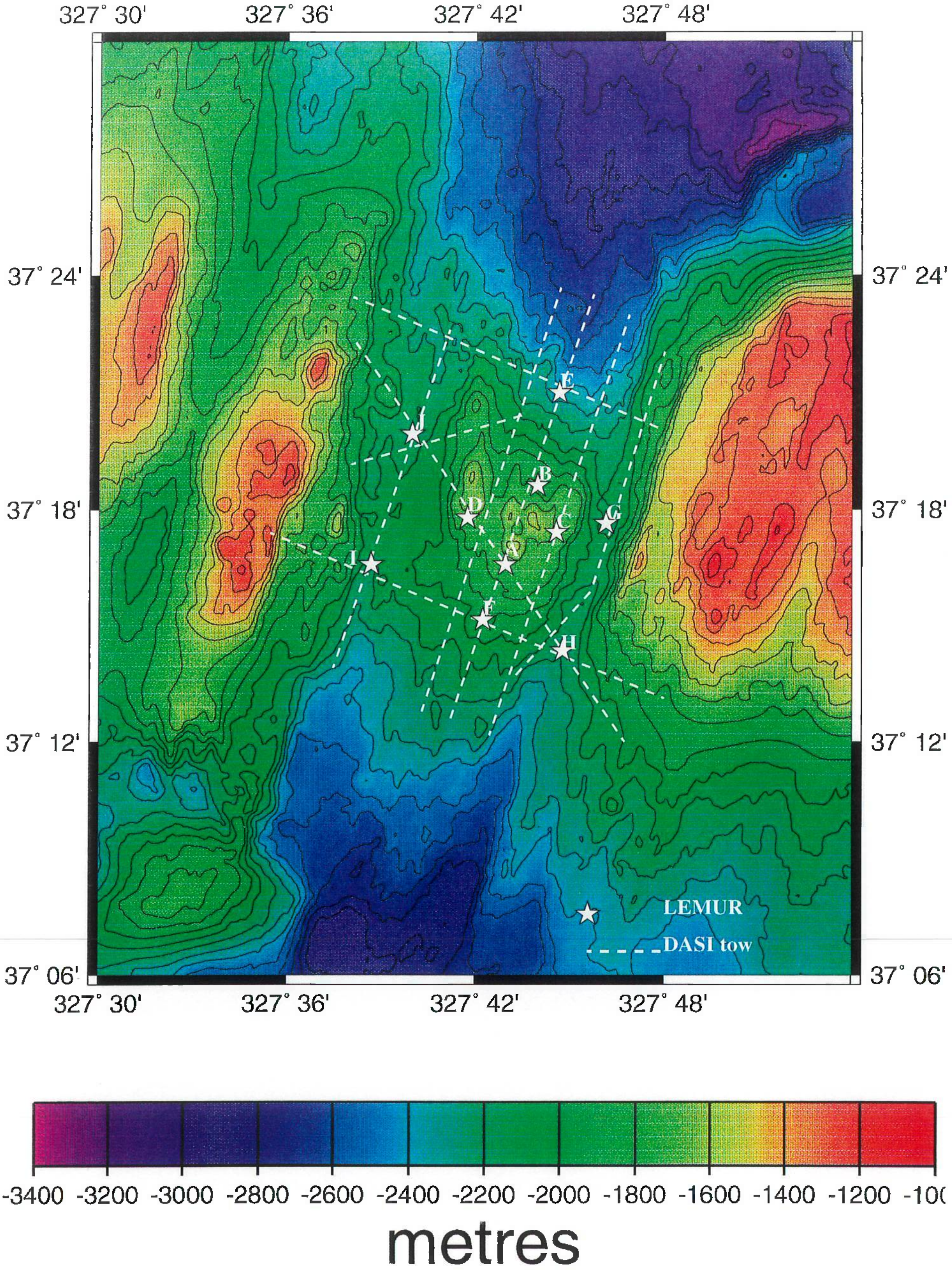


Figure 7. The DASI deep-towed transmitter system during deployment and recovery. The neutrally buoyant antenna streamer can be seen trailing just below the surface in the upper two pictures.

Figure 8. The deployment positions of all LEMURs during CD120.



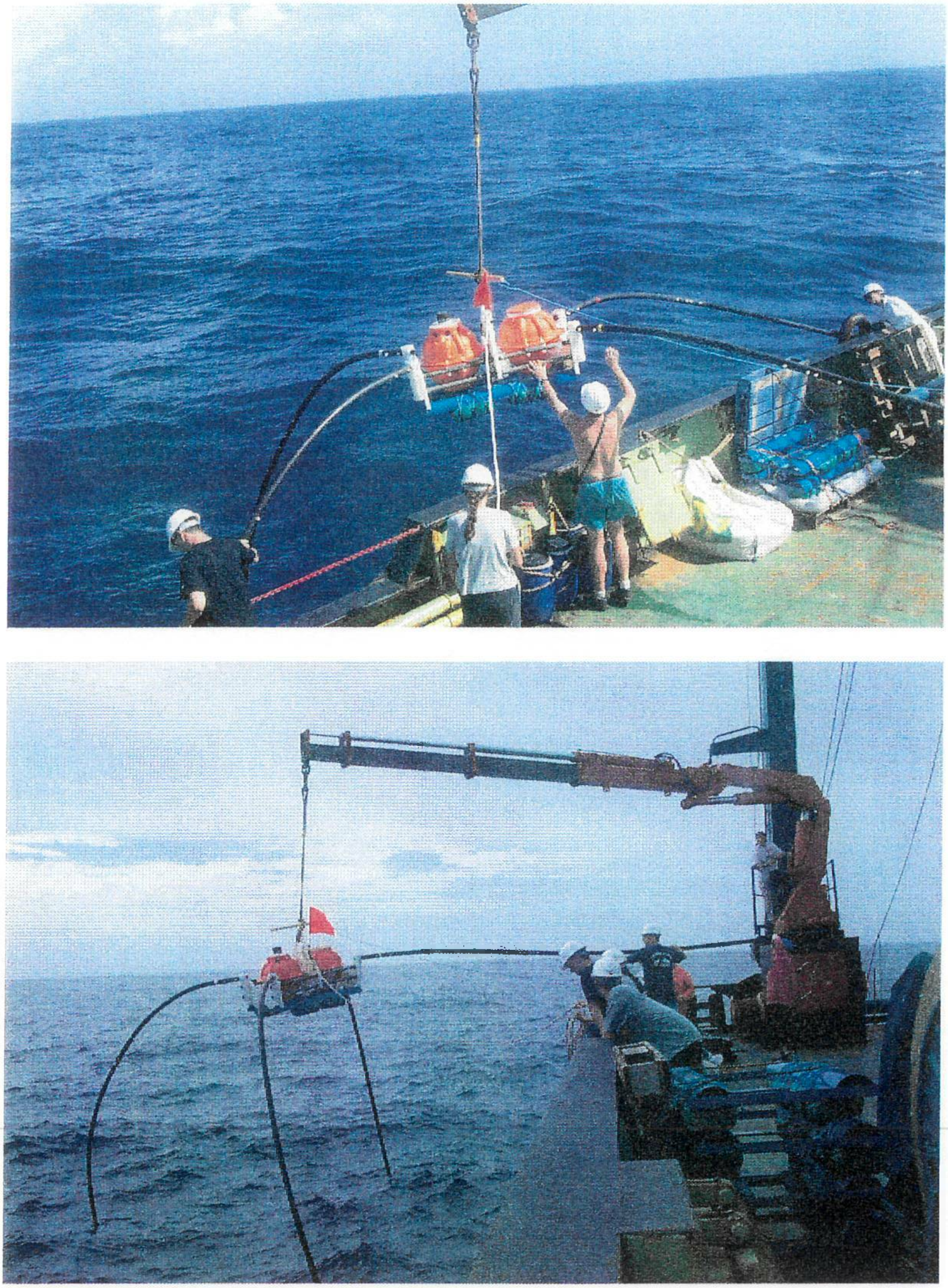


Figure 9. Deploying a LEMUR. The two orange plastic casings contain glass spheres. That on the left houses the recording electronics and acoustic release; while that on the right is for buoyancy only. The electrodes are housed in the ends of the flexible black arms. The black cylinder on top of the left hand sphere is the acoustic transducer. The bottom weight (coloured blue and green) can be seen underneath the instrument frame.

the XBT and current meter data, the sound velocity profile is essential for accurate calibration and use of the long base line acoustic navigation system.

A hull mounted acoustic doppler current profiler (ADCP) was run continuously from the time that the vessel departed from Ponta Delgada until our return to Ponta Delgada.

Throughout most of the cruise, 10 kHz precision echo sounder data were collected. This provided useful real-time information, but since the whole survey area has been previously mapped with swath bathymetry these data will be of limited use post-cruise.

The vessel was fitted with both a Lacoste and Romberg sea gravimeter (meter no. S40) and a total-field proton precession magnetometer. The gravimeter ran throughout the cruise, with base station ties in Southampton at the start and end. The magnetometer was run throughout the DASI towing period, and at some other times when the scientific programme permitted.

All data described in this Section (2.2) were collected using equipment from the RVS oceanographic equipment pool, maintained and operated by RVS Scientific seagoing staff.

3. Cruise narrative

Throughout this narrative times are given in GMT; and dates are given both as dd/mm/yy and as Julian day (ddd).

Monday 20/09/99 Day 263

0800 The scientific party and equipment arrived at the vessel, at the Southampton Oceanography Centre, Empress Dock. The Cambridge and Lisbon equipment was embarked and mobilized. Sinha, MacGregor, Cheng, al Kindi, Pye (U. Cambridge), Flosadottir (HALO) and Soares (U. Lisbon) joined the vessel.

Tuesday 21/09/99 Day 264

0805 The vessel departed Empress Dock, after a few minutes' delay due to fog.

Wednesday 22/09/99 Day 265

0700 At this point, while on passage, we were following a track 6 miles N of, and parallel to, the UK/France median line in readiness for a DASI test deployment. Unfortunately, the Deep Tow cable termination was not usable because of problems with the fibre optic connection.

0900 Attempts to repair the termination proved unsuccessful, so we decided to remake the termination from scratch, and abandoned the DASI test for this morning. We could not postpone the test indefinitely because of the need to carry it out before reaching the shelf edge. The vessel ceased paralleling the median line, and headed direct for Ponta Delgada.

Thursday 23/09/99 Day 266

Forced to reduce passage speed due to adverse head winds.

Friday 24/09/99 Day 267

Weather moderating, passage speed gradually increasing.

Saturday 25/09/99 Day 268

On passage, weather much improved, vessel now making better than 10.5 kts.

PM – carried out successful deck trials of DASI system at full voltage using remade deeptow cable termination.

Sunday 26/09/99 Day 269

Figure 10. The deployment positions of the six acoustic navigation transponders.

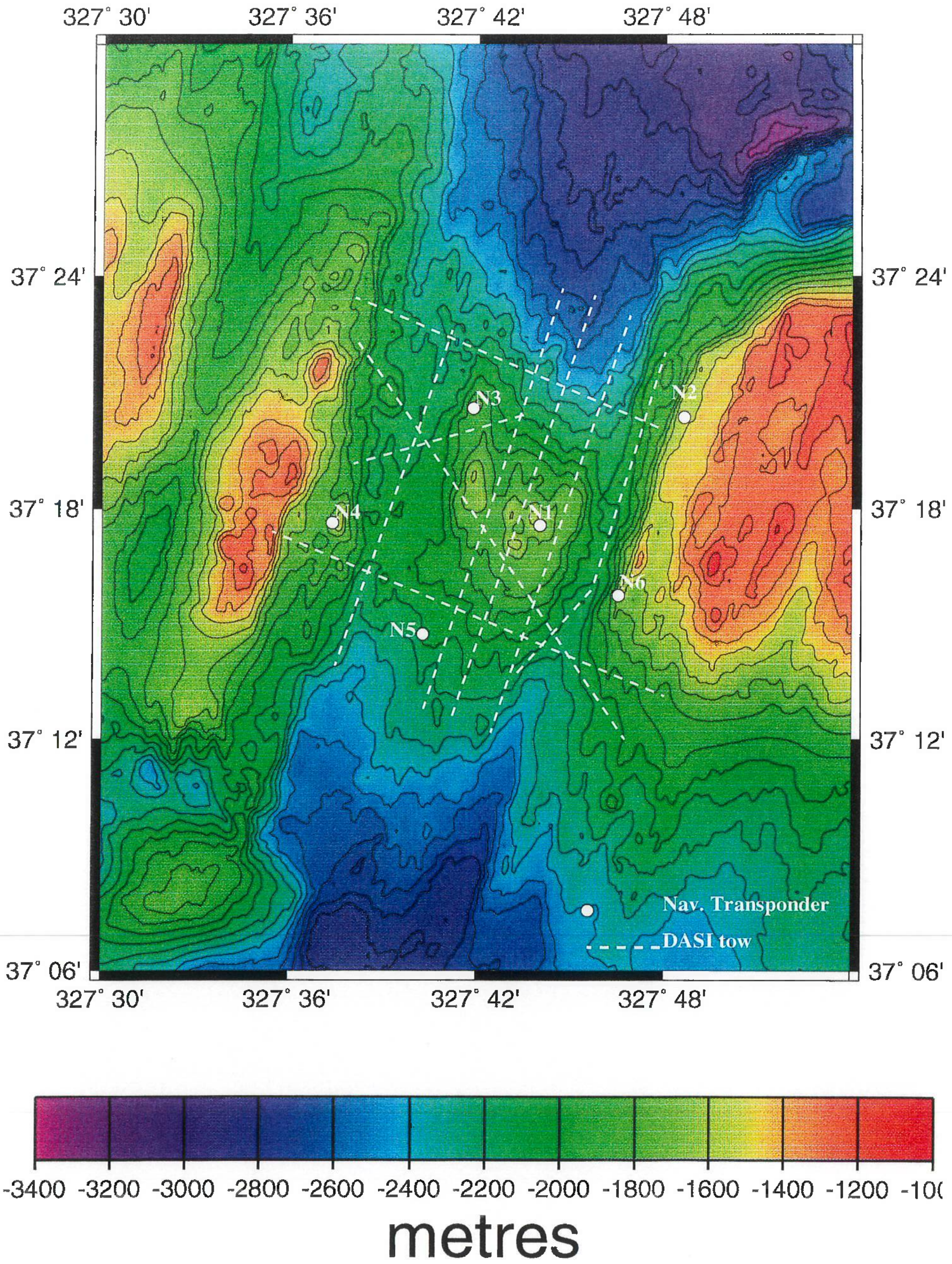
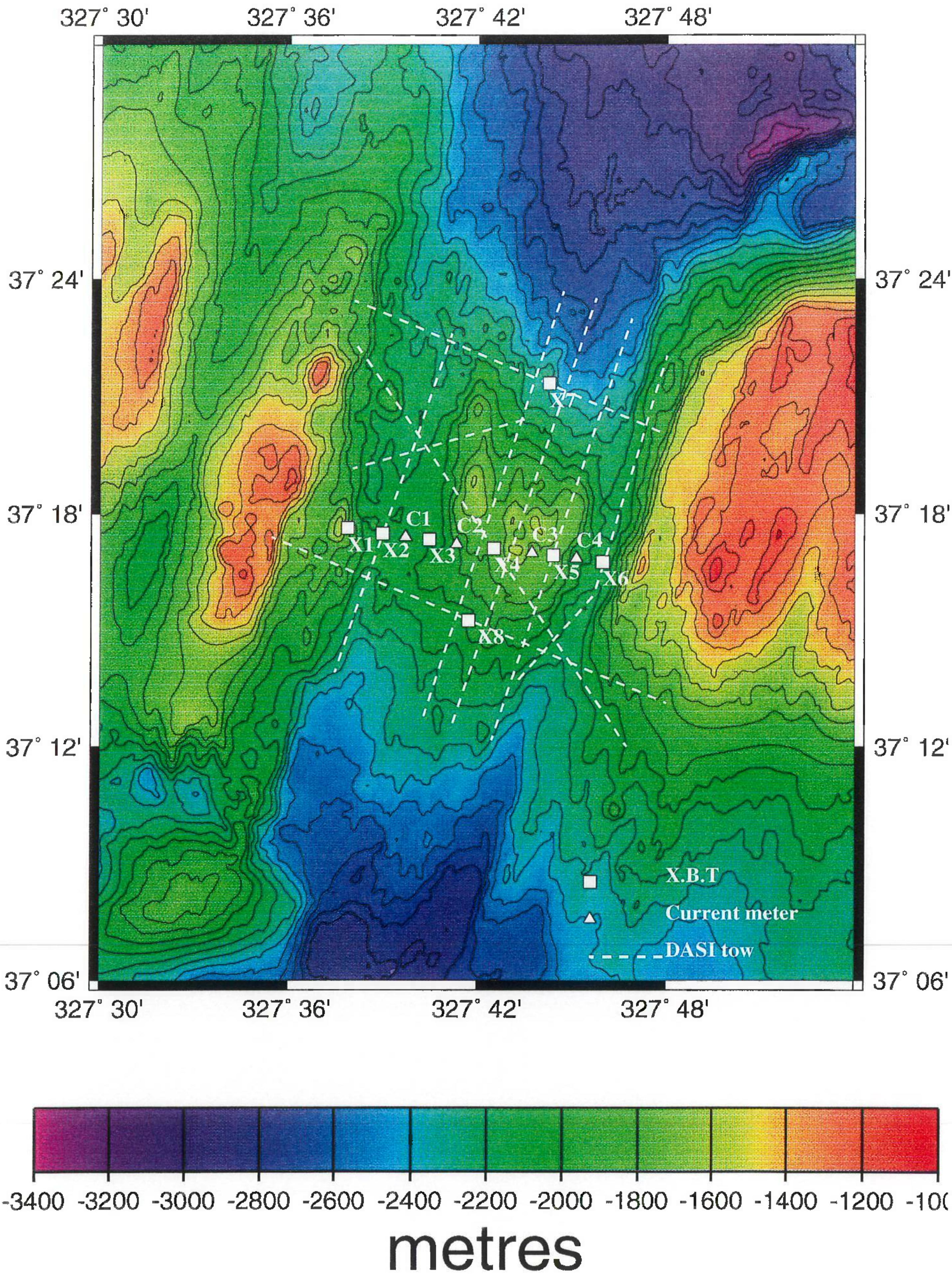


Figure 11. The deployment positions of the four current meters and five successful XBTs.



On passage

Monday 27/09/99 Day 270

0815 Arrived off Ponta Delgada, Sao Miguel, Acores.

0830 Luis, Lourenco (U. Algarve) and Nolasco (U. Lisbon) joined by boat transfer.

0930 Departed Ponta Delgada.

Tuesday 28/09/99 Day 271

0030 Arrived at DASI test deployment site on Princesa Alice Bank, in about 270 m of water. Carried out successful test deployment of DASI system (without antenna streamer) to check deep tow cable terminations and insulation; ship-board power supply system; fibre optic communications; and DASI's altimeter and pressure sensor. DASI was tow-yoed to within 50 m of the seafloor. All tests were successful, and the vehicle was recovered safely after less than two hours. On completion, continued passage to Lucky Strike work area.

1905 Arrived on station at Sound Velocity Meter site. After initial problems holding station in strong currents, carried out (i) a wire test of the release acoustics on one of the LEMURs (L11), using the CTD wire; (ii) Sound velocity meter profile to 1800 m water depth, again using the CTD wire, and simultaneous XBT (site X6).

Wednesday 29/09/99 Day 272

0200 Carried out wire tests of all six RT661 acoustic navigation transponders, plus acoustic releases for the current meter moorings, to 1500 m depth.

0600 Began deploying LEMURs in order 11, 13, 14, 15, 17. All were deployed safely in their correct locations. All were observed using acoustics until they had arrived at the sea floor. Acoustic ranges were taken on each LEMUR once it reached the sea floor during passage to the next site, to provide acoustic determinations of their final positions.

2110 Began deploying six acoustic navigation transponders at sites N6 to N1. All transponders were acoustically tracked until they arrived at the seafloor. The acoustic navigation system was found to be providing consistent and reliable ranges both to the navigation transponders and to the LEMURs at slant ranges up to at least 11 km.

Thursday 30/09/99 Day 273

0912 Deployed LEMUR 16 successfully. However the next LEMUR (18) had developed a problem in its acoustic system – consequently LEMUR 1-Lis was deployed next at 1201. Both of these LEMURs were, as previously, observed with acoustics all the way to the seafloor, and then successfully ranged on during passage to the next deployment site.

1540 Deployed LEMUR 18, after opening it up; powering down the acoustic release system; restarting the acoustics; and resealing the pressure case. We had found that the acoustics on all three remaining LEMURs (18, 2-Lis and 3-Lis) had unexpectedly locked up since the instruments had been sealed into their spheres; but the problem appeared to be solved by restarting the acoustics systems, and then leaving the acoustic transducers connected. LEMUR 18 was observed with acoustics all the way to the seafloor, and then successfully ranged on during passage to the next deployment site.

1905 Deployed LEMUR 2-Lis, after applying the same corrective procedure as above. Its acoustic system initially functioned correctly, but we ceased to receive any returns from it after its range exceeded 670 m during its descent.

2005 Started sending the release command on a 2-minute cycle to LEMUR 2-Lis. ETA at surface would be 2120 if the acoustic release is working.

1750 Launched XBT at site X4, successfully. This XBT produced an unexpectedly high temperature profile, so another XBT was launched a few minutes later.

1800 Launched XBT at site X4R, successfully.

1931 Launched XBT at site X6, without success.

2230 By this time we were back on station to restart the second half of Line 9, with the cable termination repaired and DASI successfully deck tested. However there were now increasing winds from the SE with the result that Line 9 looked like an impossible proposition for deep towing, due to wire angle difficulties. So, instead, we continued NE towards the start point of Tow Line 7, and deployed DASI there.

Thursday 7/10/99 Day 280.

0220 Began DASI transmissions at 1 Hz along Tow Line 7 from WNW to ESE.

0835 Successfully completed the 1 Hz tow along line 7, and then hauled DASI in rapidly to 1200 m of wire out, to lift DASI out of the median valley before hitting the valley wall. Then turned to port with the intention of running back along Tow Line 9, but the wind was now on our port beam and the current was behind us, so the wire angle became impossible for working. Consequently we abandoned the attempt to tow along the NE half of Tow 9, and instead made for a start point at the NW end of Tow 6, intending to tow DASI along line 6 from NW to SE at 1 Hz. Happily from this point on, we experienced no further weather conditions that prevented or restricted DASI towing; and DASI worked perfectly until all lines had been completed.

1445 Started DASI transmissions at 1 Hz along Line 6 from NW to SE.

2344 End of DASI transmissions on Line 6. Began turning towards Line 8.

Friday 8/10/99 Day 281

0630 Start of DASI transmissions at 1 Hz along tow line 8, from ESE to WNW.

1145 End of DASI transmissions on Line 8. Began turning towards Line 3.

1604 Start of DASI transmissions at 0.25 Hz along tow line 3, from S to N

2034 End of DASI transmissions on Line 3. Began turning towards Line 1.

Saturday 9/10/99 Day 282

0245 Start of DASI transmissions at 4 Hz along tow line 1, from N to S

0740 End of DASI transmissions on Line 1. Began turning towards Line 2.

0950 Start of DASI transmissions at 4 Hz along tow line 2, from S to N

1550 End of DASI transmissions on Line 2. Began turning towards Line 4.

1900 Start of DASI transmissions at 4 Hz along tow line 4, from N to S

Sunday 10/10/99 Day 283

0230 End of DASI transmissions on Line 4. This marked the completion of all DASI tows. Recovered DASI and magnetometer; ran a final set of deck tests and calibrations; and then recovered the DASI streamer.

0600 Recovery finished. DASI had been in the water and functioning flawlessly since Wednesday evening - 3.5 days of uninterrupted and essentially problem free DASI towing.

0800 Began recovery of acoustic navigation transponders. All were safely recovered in order N5, N4, N3, N2, N1, N6.

1625 Began recovery of LEMUR '95 instruments. Recovered LEMURs 11, 13 and 14 without difficulty.

Monday 11/10/99 Day 284

0030 Began recovery of Lemur 15. This was again completed successfully. All LEMUR '95s were now safely recovered, and 3 out of 4 of these had recorded a full set of data (no. 13 had experienced problems with its ADC.)

0233 Started acoustic positioning survey to collect acoustic ranges on LEMUR '99s, transitting from E via B and G to F.

0506 Started second attempt to communicate with, and release, Lemur 2-Lis. We had no success at all, but nonetheless posted extra lookouts and waited until 30 minutes after daylight in case the instrument had surfaced silently.

0830 Abandoned Lemur 2-Lis. Began recovery of current meters. Recovered C1, C2, C3 and C4 all safely. All had recorded data.

1530 Set course to Lemur 1-Lis to attempt recovery. No acoustic response was heard at all from this instrument.

1604 Began sending release codes continually to LEMUR 1-Lis, and posted lookouts in case it surfaced. ETA at surface would be 1715, if it had heard the release signals.

1705 Stopped sending release signals.

1830 Abandoned LEMUR 1-Lis. We had heard no clear responses from its acoustics; and allowed enough time since sending the last release command for it to have surfaced. Headed for LEMUR 3-Lis.

1906 Arrived on station close to LEMUR 3-Lis. However there was no acoustic response from this instrument either.

1910 Headed instead for LEMUR 17.

1959 Successfully sent release code to LEMUR 17. Ranges were obtained consistently all the way up through the water column, and the instrument surfaced by 2120. However its light was not visible. Either the light was excessively dim, or it had failed to switch on. The instrument was therefore lost on the surface at night, with no moon, and no working light on it, and with surface currents in excess of 0.5 kts.

2218 We started a box search pattern for the missing LEMUR 17, with extra lookouts posted on the bridge wings, using the searchlight to starboard and a signal lamp to port.

Tuesday 12/10/99 Day 285

0600 A small number of possible acoustic ranges suggested that LEMUR 17 may be 2 miles 280° from us, so we set off (still searching) to that location. We stopped ship there and continued searching while waiting for daylight.

0806 At first light we recovered the acoustic navigation fish (damaging its cable connection in the process), so that we could continue the search at full speed. We then commenced a new box search pattern over a wider area to the N, S and W, at 10 kts, with lookouts on the bridge wings and bridge roof. Visibility was occasionally affected by heavy rain showers, but the LEMUR should have been easily visible had it been within the area searched.

1006 Spotted a floating orange object on the extreme edge of visibility to the north. Went to investigate, but it was only a drifting fishing float. The search for LEMUR 17 was reluctantly abandoned at 1028, after more than 13 hours. We then headed for LEMUR 18, making one detour en route for another false alarm which turned out to be another drifting fishing float.

1120 Successfully released LEMUR 18, and recovered it safely and without difficulty. We then investigated yet another floating fishing buoy, before heading for LEMUR 16.

1311 Successfully released LEMUR 16, and recovered it safely and without difficulty. Both LEMURs 16 and 18 had recorded complete datasets.

1431 We began fresh attempts to release LEMUR 1-Lis; manouevring at low speeds and using the full range of available acoustic equipment and transducers. Extra lookouts were posted yet again on the bridge wings in case it surfaced without responding acoustically.

2000 After a further five and a half hours of attempts to communicate with it, LEMUR 1-Lis had still failed to surface or even to respond; and was abandoned. We then began further attempts at recovery of LEMUR 3-Lis, again using all transducers/deck units in rotation, and with lookouts posted on bridge wings.

2400 After four more hours of attempts to communicate with it, LEMUR 3-Lis had also failed to surface or even to respond. The available scientific time for the cruise had now been fully used; and the search was abandoned. We set course for Ponta Delgada, passing over the location of LEMUR 1-Lis again en route, just in case it had surfaced in the meantime.

Wednesday 13/10/99 Day 286

0020 Passed over the location of LEMUR 1-Lis for the last time, with a full complement of lookouts still posted on the bridge wings and bridge roof. There was no sign of any of the missing instruments. This was the end of scientific time for the MADRIGALS cruise, and we continued on course for Ponta Delgada.

Thursday 14/10/99 Day 287

0800 Arrived off Ponta Delgada for the boat transfer. Flosadottir, Luis, Lourenco, Nolasco, Cheng and Beaman (RVS Scientific) disembarked. On completion, set course for Southampton at full speed.

Tuesday 19/10/99 Day 292

2100 Arrived Southampton Oceanography Centre, Empress Dock.

Wednesday 20/10/99 Day 293

am Scientific equipment and remainining scientific party disembarked.

4. Equipment performance

4.1 The DASI system

The modified and improved DASI system worked well on this cruise. All aspects of the system are both easier to operate, and more reliable, than previous versions. The desired antenna output current of 300 A p/p was achieved with a power supply output voltage at the ship of approximately 1150 V rms – well within the rated output of 2000 Vrms. The use of fibre optic communications has greatly simplified the engineering problems associated with the use of the deep tow cable simultaneously for power provision, control and data telemetry. New software on the ship-board operator's computer, including graphical displays of key data relayed from the DASI vehicle, makes operation of the system close to the seafloor both easier and safer.

The 120 kHz Simrad acoustic altimeter used for determining the height of the vehicle above the sea floor is more reliable than the 3.5 kHz deep towed profiler used previously. It has also simplified the data telemetry requirements: all data are now transmitted digitally, and there is no longer any requirement for transmission of analogue data from the deep tow to the ship.

Changes to the mechanical design of the vehicle improved both accessibility to the pressure vessels for maintenance and preparation; and the towing arrangements for the streamer. The new towing arrangements in particular proved important. During the last major DASI survey, in the Lau Basin (Peirce *et al.* 1996), heave of the DASI vehicle transmitted down the tow cable from the ship had resulted in rapid wear and abrasion to the front end of the streamer, and this had caused considerable delays due to the need for repairs. During CD120, despite the length of the deployments, no discernable wear or abrasion was caused to the streamer. The redesign of the towing point, and the incorporation of a cable bend restrictor into the tail fin assembly, have made a major contribution to the overall improvement in DASI's reliability.

Only one failure occurred that was attributable to the DASI system: the pressure-related loss of communications on Day 278. This proved to be due to failure of a connector at depth – either the lead connecting the fibre optic from the swivel to the DASI upper electronics pressure case, or the serial communications lead between the upper and lower pressure cases (both were changed to solve the problem).

Overall the DASI system proved to be both effective and generally reliable. Cruise CD120 thus marks an important milestone in CSEM development, with the transition from a working prototype instrument to a fully developed system suitable for routine operations.

4.2 The deep tow conducting cable, and its winch, slip rings, outboard termination and swivel

Prior to CD120, RVS made a major investment in a new deep tow cable for RRS *Charles Darwin*. The new cable has a conventional armoured external strength member, and coaxial copper conductors. Embedded within the central conductor is an optical fibre for high bandwidth data transmission. CD120 was the first cruise to make full operational use of this facility.

In order to exploit the optical fibre, further investment by RVS was needed. They purchased a new set of slip rings for the inboard end of the cable, and fitted these in the ship's winch room, together with the necessary cable and optical fibre runs to the main laboratory. The new arrangement includes both slip rings for connections to the coaxial copper conductors; and a 'FORJ' (fibre optic rotating joint) assembly for the optical signal. A similar arrangement is needed at the bottom of the cable, where it attaches to the deep tow. A load-bearing swivel, with optical and electrical connections between the deep tow and the cable, is required at this point to relieve torsional stresses in the cable. RVS had their two existing swivels modified by the manufacturers (Nova Scotia Research Foundation of Canada) to include FORJ units, as well as slip rings. At the same time, the electrical connectors on the swivels were completely replaced using a new design; since the old connectors had proved insufficiently reliable, especially at high voltages. Thirdly, it was necessary to obtain fibre optic interface systems for both the ship-board and deep tow ends of the system, that would provide conversion between optical signals and digital electrical signals. This last item is analogous to an extremely high-speed modem pair, operating over the optical fibre. After discussions between Cambridge and RVS, a specific model of interface was agreed upon; and Cambridge purchased the deep tow end, while RVS purchased the shipboard end. Lastly, the termination of the cable at its outboard end – where it is coupled mechanically, electrically and optically to the top end of the swivel – needed to be redesigned and fabricated. All of this ancillary equipment represented large investments by both Cambridge and RVS, although by far the larger share was met by RVS.

In order to test the new, optical fibre based communications system used by DASI, RVS kindly invited Cambridge to participate in an equipment trials cruise in March 1999: RRS *Charles Darwin* Cruise 116. Lucy MacGregor led the Cambridge participation, and was accompanied to sea by Zongfa Cheng. Trials of the DASI system at that time were successful; and gave us considerable confidence ahead of CD120. Nonetheless we were relieved during CD120 that the system again worked extremely well. We experienced two problems (see section 4.1): firstly a failure in a connecting communications lead, and secondly an insulation failure in the cable termination. Both of these were rectified within hours, and without causing damage to any other components. Minor problems of this magnitude are simply part of the learning curve when making a transition to a new technology in the deep ocean; and should not cause either surprise or consternation, provided that the experience gained is fed back into future operating procedures. The new electrical connectors on the swivel were completely reliable. The swivels, which are pressure balanced, appear to have leaked some oil; and this should be investigated, and if necessary rectified by the manufacturer.

The deep tow winch was heavily used for many days during the cruise. For most of the time, rates of hauling and veering were limited to 30 metres per minute, since this is desirable for the DASI streamer. However there were moments when it was necessary to haul in cable much faster than this, as the DASI system approached steep cliffs (fault scarps) on the sea floor. Some of the scarps were significantly higher than DASI's flying height, and close to vertical – so that avoiding a collision required vigilance, rapid reactions, and sometimes rapid hauling. Winch speeds in excess of 120 m/min were used on one or two occasions. Throughout the cruise the winch worked totally reliably – an excellent record for what is by now a very elderly piece of equipment.

This is an appropriate point to note that, from the perspective of the ISO-3D project, the fibre optic cable and its associated equipment represents a significant advance in capabilities for UK research vessels; and has proved highly successful during the first major cruise to rely on it. I also wish to record my appreciation of the effort, financial investment and close technical support and cooperation that RVS put into the project, and for the opportunity to participate in trials during CD116.

4.3 The LEMUR acoustic releases

The most serious equipment problems during the cruise relate to the acoustic release systems in the LEMURs. Failure of releases led to the loss of three new LEMUR '99 instruments, together with the data that they had recorded. A fourth instrument was lost due to the failure of its light. These losses represent two-thirds of the LEMURs constructed for Cambridge and Lisbon using ISO-3D resources, and are a severe blow to both institutions.

The LEMURs make use of an acoustic release card developed and manufactured by Marine Acoustics Ltd, together with a burn wire actuator and release packaging – which includes the light used for location and recovery at night – manufactured by Carrack Measurement Technology. Both the Marine Acoustics release card and the burn wire actuator had been used fairly extensively during previous cruises, and were expected to be very reliable. In the event, the burn wire system – used previously for many deployments of Cambridge's 'mini-DOBS' ocean bottom seismometers, and for LEMUR tests in 1998 – worked faultlessly on all instruments that responded acoustically. The Marine Acoustics cards had been used previously on a small number of mini-DOBS cruises, and had also previously worked reliably. However on this occasion, problems with the cards were experienced both before deployment and when recovery was attempted.

The pre-deployment problems occurred on three out of ten instruments. Initially, the releases were powered up during LEMUR instrument preparations while on passage between Southampton and Ponta Delgada. The LEMURs were all sealed into their pressure cases (17" glass spheres) during this phase, with both the releases and the recording electronics fully tested, powered up and functioning. The releases were tested again about a week later, immediately before the instruments were deployed. Seven LEMURs were deployed without any problems - the releases were still working correctly. However the releases in three of the LEMURs had ceased working at this point. The instruments were re-opened, and the releases checked. As soon as battery power was removed from the releases and then reapplied, they began functioning normally again. It appeared that the release cards had entered some 'hung up' mode while stored in the wet lab; but had returned to normal operation on being rebooted. As a precaution, when these release cards were being restarted, they were kept connected to their acoustic transducers throughout reassembly of the pressure cases and subsequent deployment.

During deployment of all LEMURs, the ship remained on station at the deployment site and acoustic contact was maintained with the instrument until at least ten minutes after it had landed safely on the sea floor. The only exception was LEMUR 2-Lis, with which we lost contact at a range of 670 m from the ship during descent. All subsequent attempts to communicate with, and recover, LEMUR 2-Lis failed. Prior to loss of communication there had been no indication of any problems, except that this was one of the releases that had needed to be rebooted. At the time that communication was lost, there was no sign of any noise burst on the precision echo sounder record, such as we would have expected to see had a pressure case imploded.

Another of the LEMURs – LEMUR 3-Lis – that had needed to have its release card re-booted prior to deployment also apparently suffered from an acoustic failure after it had arrived safely on the seafloor, and was lost. However the third instrument to need pre-deployment re-booting – LEMUR 18 – was recovered safely and without difficulty at the end of the cruise.

One other LEMUR - LEMUR 1-Lis - suffered from an apparent acoustic failure after it had safely reached the sea floor, and was lost. However it had NOT suffered any release card problems, or needed re-booting, prior to deployment.

LEMUR 17 did not have a failure of its acoustics either in the water, or prior to deployment. At the end of the cruise we were able to communicate with it acoustically and release it normally. However it surfaced at night with its light not working. It remained dark, with no moon, for a further eleven hours; and a surface current of at least 0.5 kts, varying in direction, was running. Despite a prolonged search – during which (to our immense frustration) we located no less than three small, abandoned fishing floats – we were unable to find and recover this instrument. A summary of LEMUR losses and recoveries is presented below in Table 4.1.

Performance of the acoustic system depends on the ship-board command and ranging units, as well as the bottom units. During CD120 we had three different ship board units, and four shipboard transducers. The acoustic command units were the Oceano/Morrs acoustic navigation telecommand unit (RVS); an Oceano/Morrs portable telecommand unit (RVS); and a Marine Acoustics deck unit (Cambridge). Both the Morrs portable unit and the Marine Acoustics unit had their own overside transducers. The acoustic navigation telecommand unit used the transducer in the acoustic navigation fish; and the portable Morrs unit could also use the hull-mounted transducer for the precision echo sounder. All available combinations of these systems were used during our attempts to recover the failed LEMURs; and all worked successfully with the LEMURs that were recovered.

LEMUR number	Type	Release Serial Number	Pre-deployment release problems?	Post-deployment release failure?	Relocation light working?	Recovered or lost?
11	95	B1349	No	No	Yes	Recovered
13	95	B1348	No	No	Yes	Recovered
14	95	B1352	No	No	Yes	Recovered
15	95	B1347	No	No	Yes	Recovered
16	99	B1351	No	No	Yes	Recovered
17	99	B1346	No	No	No	Lost
18	99	B1350	Yes	No	Yes	Recovered
1-Lis	99	A0030	No	Yes	-	Lost
2-Lis	99	A0033	Yes	Yes	-	Lost
3-Lis	99	A0034	Yes	Yes	-	Lost

Table 4.1. LEMUR losses and recoveries, and acoustic release histories

It is not known at the time of writing why so many problems were experienced with the Marine Acoustics Ltd release cards. The only feature of this cruise which differs from previous ones on which the same type of release had been used without problems is that, during CD120, long-baseline acoustic navigation was in operation almost continuously. This means that all of the LEMURs, while on the sea floor, are likely to have been within range of acoustic transmissions from the ship, the deep tow and the sea floor transponders. The releases normally remain in a 'sleeping' mode, in which they consume very little current, while on the sea floor. On receipt of an acoustic ping at the correct frequency and of the right duration, they 'wake up' and decode any succeeding string of pings to determine whether or not this is a command that they should act on. They then 'time out' for a period of about 8 seconds – during which they ignore any other acoustic signals – before returning to the 'sleep' mode. The effect of the acoustic navigation operations is that the releases in the LEMURs may have been waking up, then timing out, more or less continuously while on the sea floor. We observed that, while stored in the lab between being sealed into their spheres and being deployed, some of the releases went through a similar cycle of waking up, timing out and sleeping again due to inductive pick-up of extraneous noise in their transducer leads. It is possible that occasionally the release cards do not complete this cycle successfully, and consequently hang up. At the time of writing, we are attempting to replicate this – and think we have done so - in the laboratory in Cambridge. If this were the case, then operation under a regime where frequent waking-up cycles occurred (either through inductive pick-up in the wet lab, or through extraneous pings in the water column during acoustic navigation) might lead to a proportion of the release cards becoming hung up over a period of days to weeks. This might explain the observed failures both in the wet lab and on the sea floor. In contrast, in the absence of frequent triggering of the wake up - time out - sleep cycle (as would be the case during previous cruises, when no acoustic navigation was used), it is unlikely that the release cards would become hung up and fail.

Once out of its sleep mode, a release card consumes many times more current than when sleeping. This raises the possibility that continuous waking up of the failed release cards may have drained their batteries before recovery was attempted. However the battery packs used should have had enough capacity to prevent this, even if the releases spent their entire time on the sea floor in their wakened state. Battery packs from the releases that were recovered had used only a small fraction of their capacity – they were subsequently able to power their release cards for many days even when the cards were continually cycling from wake to sleep modes.

The other point that should be noted is that the three cards that failed all had similar serial numbers; while the cards from a different run of serial numbers all worked correctly. We are in communication with Marine Acoustics Ltd at the time of writing, over this issue.

4.4 The LEMUR electric field recording systems

The mechanical arrangements, sensors, amplifiers and digital recording systems of the LEMUR instruments in general performed well. Of the six instruments recovered, five had recorded complete sets of data. The one failure was due to the ADC interface hanging up on LEMUR 13, preventing data acquisition and recording. On investigation we could find no faults in LEMUR 13's recording system; however it is possible for the LEMUR '95 instruments to boot up with their ADC interfaces disabled. The problem is normally avoided by booting the recording system with the ADC interface disconnected, and only connecting it once the data logger CPU is up and running. This is a 'known bug' in the LEMUR '95 system, and has been rectified by redesign of the ADC interface card in the LEMUR '99 system; it is however the most probable cause of the failure of LEMUR 13.

Preliminary plots of recorded amplitude at the DASI transmission frequency vs time for the five LEMURs are shown in Figure 12. These show excellent signal to noise ratios during DASI tows, and typical noise levels of around 10^{-10} V m^{-1} at 1 Hz – consistent with the highest quality data recorded in previous surveys.

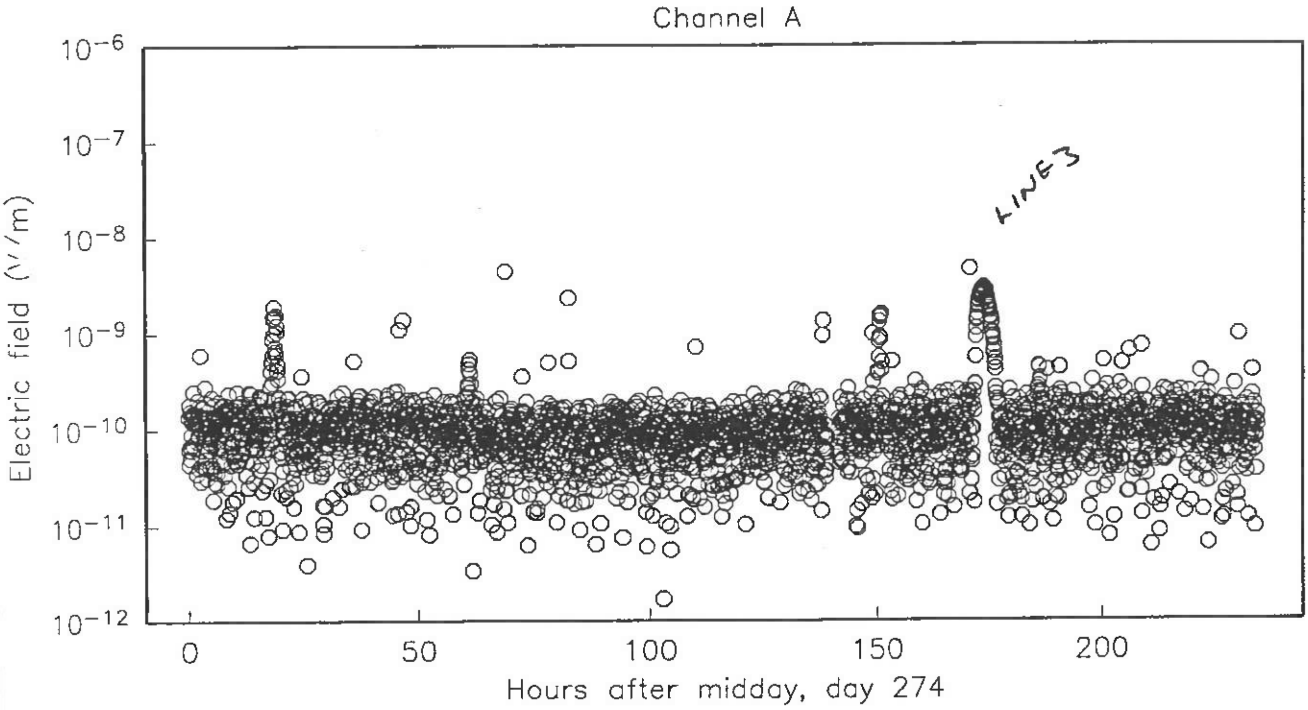
We conclude from this that the LEMUR '95s and '99s are fundamentally reliable and high performance ocean bottom electric field instruments. The known bug in the LEMUR '95 ADC interface cards has been rectified in the LEMUR '99 instruments; and no further bugs in the instruments' sensors or electronics have come to light. The remaining outstanding problem with these instruments is the acoustic release systems. Our intention is either to replace the Marine Acoustics cards with alternative systems; or to have the release cards updated, if Marine Acoustics are able to identify and rectify the apparent problem. One avenue that we shall explore is the use of two independent acoustic release systems in parallell; but this has major cost implications. We shall also seek to fit each instrument with two independent, external flashing lights, since the fixed lights fitted for this cruise as part of the acoustic release package were not completely reliable; and were in any case too dim to allow confidence in seeing them at ranges greater than a few hundred metres. It should be noted that fixed lights are less effective for instrument location at night that strobe lights: they can be easily confused with the lights of distant ships, or even with stars close to the horizon, on a dark night. The most effective lights are the bright strobe devices that flash twice in quick succession.

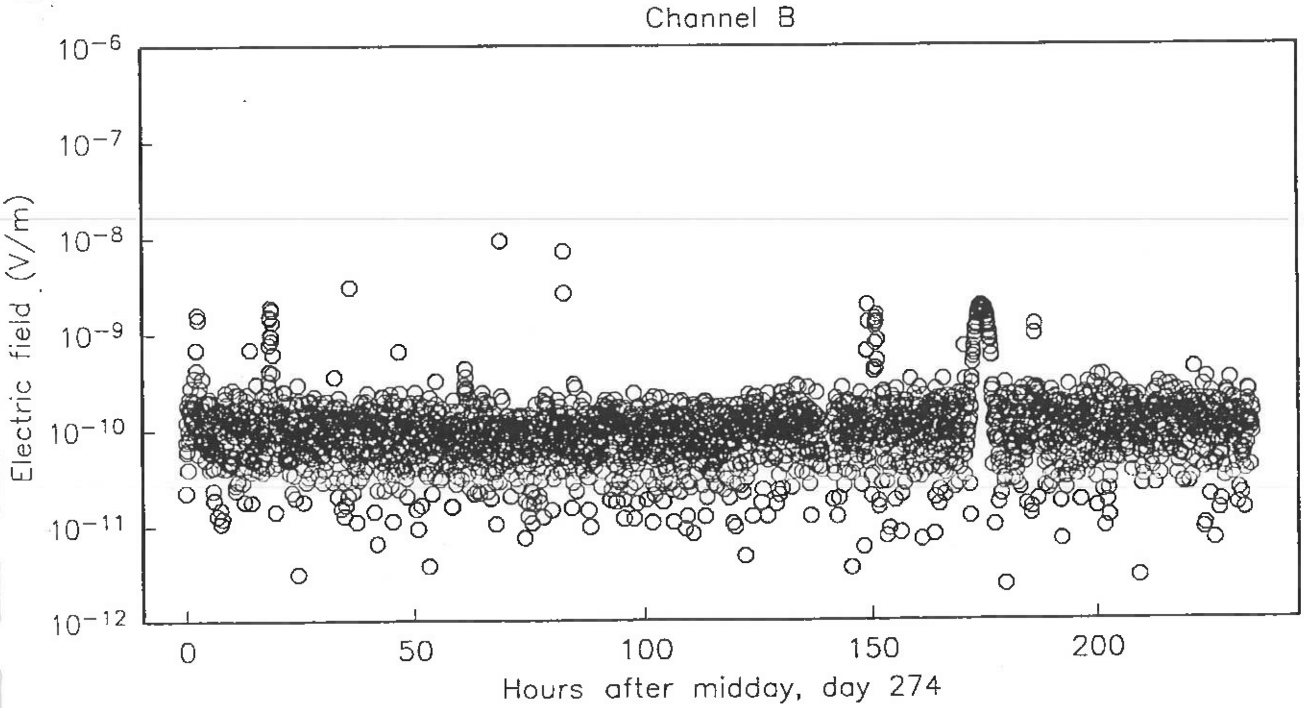
4.5 A frames and sheave wire angle

This cruise made heavy use of both A frame gantries. We experienced a delay of about 2 hours when a hydraulic hose burst on the stern A frame; but this was repaired (although by no means easily) by RVS technical staff.

Considerably more time was lost during DASI towing due to the wire angle at the sheave on the stern A frame. This occurred when winds and surface currents caused the ship to make a large amount of leeway. As a result, the ship's heading

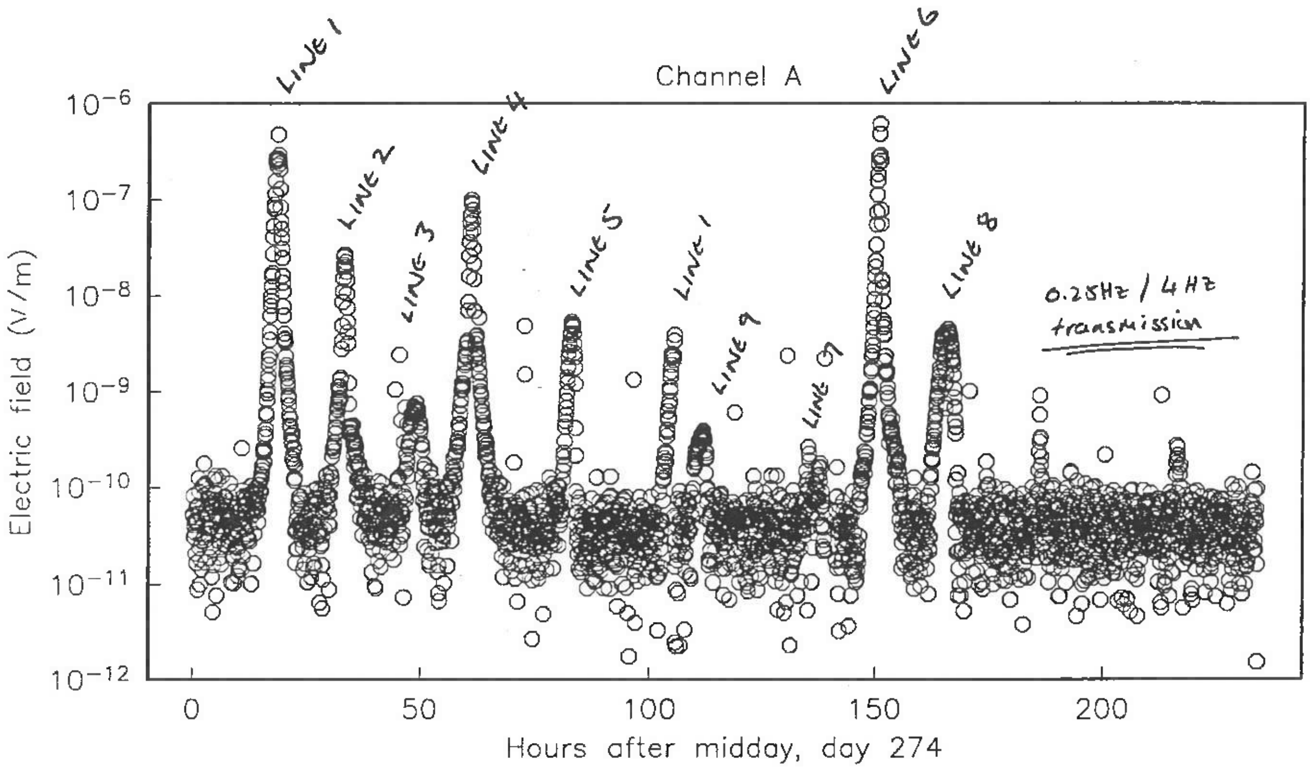
Figure 12(a). Amplitude versus elapsed time plots for the data recorded by the two orthogonal electric field channels of LEMUR 16. The graph shows the amplitude of a single frequency component at 0.25 Hz, obtained by Fast Fourier Transforms of segments of time series data. The large peak in the graph at about 175 hours occurred when DASI was transmitting along tow line 3, at 0.25 Hz.





LEMUR 16 1Hz

Figure 12(b). As for Figure 12(a), but the frequency component shown is 1 Hz.



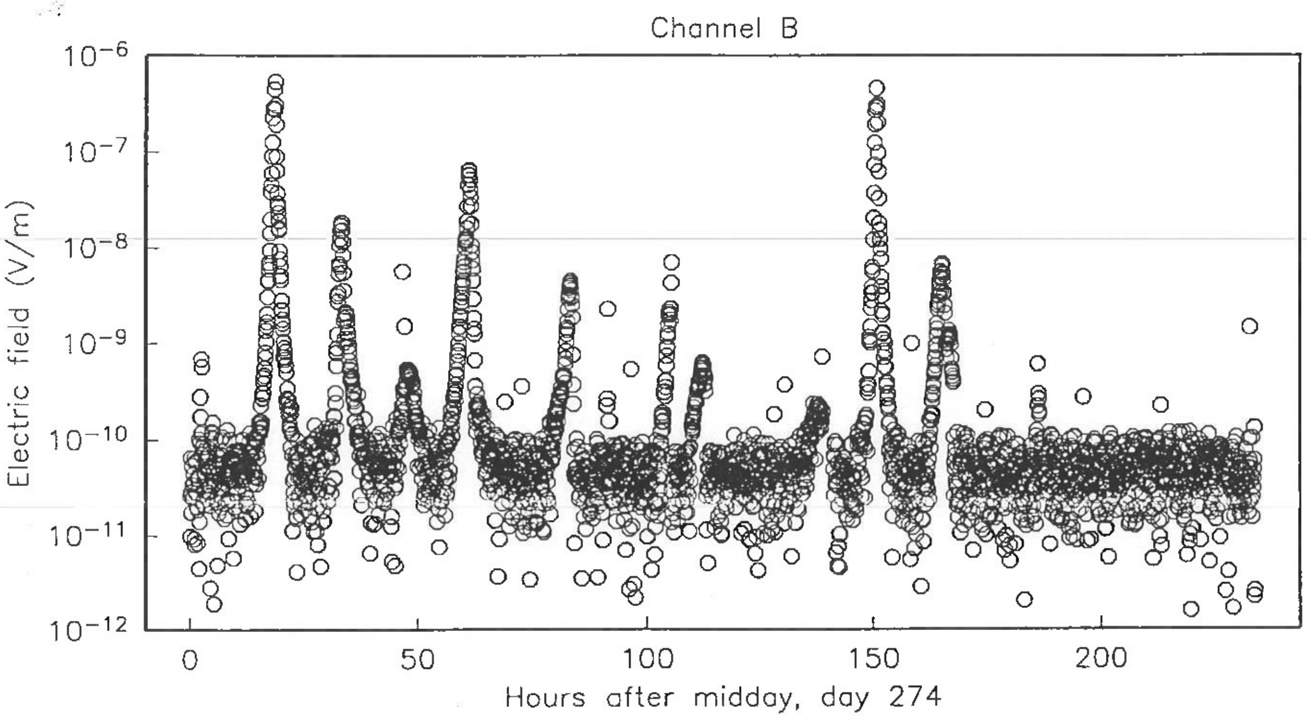
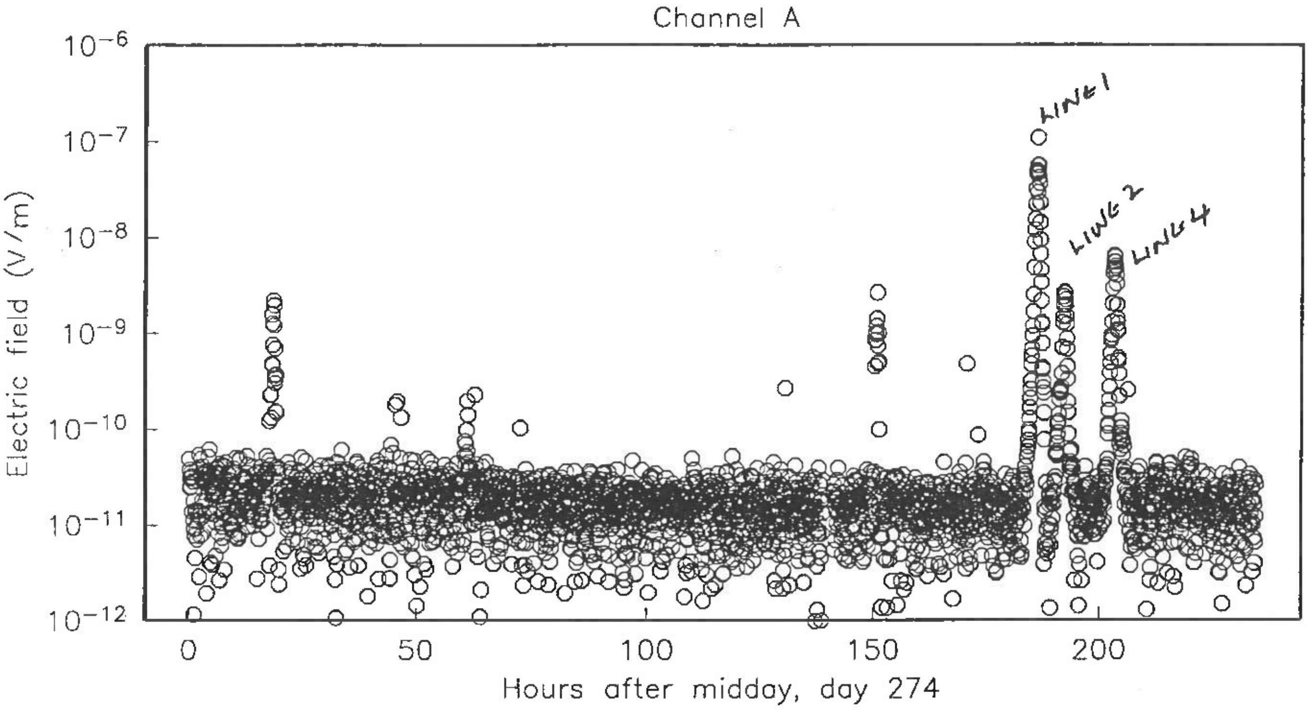
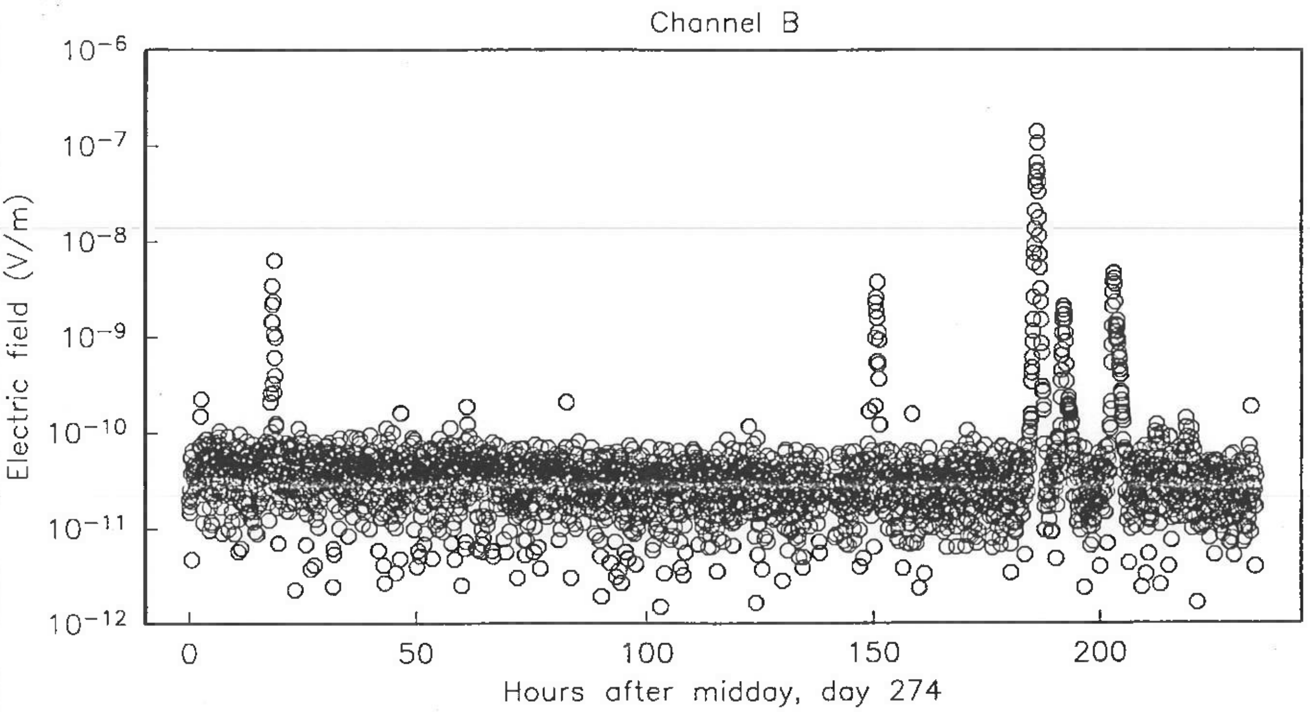


Figure 12(c). As for Figure 12(a), but the frequency component shown is 4 Hz.





differed by up to 60° from the course made good over the ground. Since the angle of the deep tow cable was controlled mainly by its movement through deeper parts of the water coulumn – where current speeds are much lower in this area – the result was that the tow cable led away and downwards from the ship in a plane that made a large angle with the ship's heading. In these conditions, the existing sheave is unable to reorientate itself into the plane of the cable – so that the cable tends to ride up over the cheeks of the sheave, creating dangerous conditions and rapid cable wear.

At no time during the cruise were weather conditions bad enough to make working impossible, or to prevent the ship from progressing along the desired track at an appropriate speed over the ground (although the low speed manoeuvring did make heavy demands on the skills of the bridge watch keepers). However the problems with the sheave did cause substantial loss of time. It would be desirable to replace the existing sheave with a new device that is able to more easily orientate itself into the plane of the cable, over a much wider range of wire angles. It seems likely that developing trends in ocean science will lead to increasing demand for use of deep towed vehicles, tethered landers, remotely operated vehicles and similar systems which require either low speed manoeuvring or precision station keeping coupled with use of a heavy, armoured, electro-optical cable; and so solving this particular problem should be given some priority. However it is not immediately obvious how a solution to it is to be found!

4.6 Acoustic navigation

Long base line acoustic navigation is essential for CSEM studies, since it is necessary to record the locations of both the transmitter and the receivers to a precision of the order of 10 to 20 metres. This is not achievable by surface GPS alone. We used the RVS Oceano/Morrs long base line system, with six sea floor transponders, one relay transponder on the DASI vehicle, and shipboard acoustic interrogation, logging and computing systems. The RVS system has a mixed record – on one or two previous cruises it had worked well, but on several other cruises it had performed so badly as to be virtually useless. For this cruise, we made two changes to the operating procedures. Firstly the relay transponder was attached to the DASI vehicle, instead of to the tow cable. This was because there was some evidence that strumming of the cable during towing had caused random triggering of the relay transponder on previous cruises; and that this had been responsible for much of the poor data quality obtained. Secondly, we moved the towing point of the acoustic navigation transducer fish further forward, away from propellor noise. The fish was streamed about 30 m below the sea surface, on a faired cable, from the Precision Echo Sounder davit on the port side of the fo'c'sle deck. The combination of these two measure resulted in very much better results from the acoustic navigation system that had been obtained on other cruises in recent years.

In general, consistent and reliable ranges were obtained from the sea floor transponders to slant distances of 12 to 15 km. For much of the cruise, acoustic positions for the ship were provided reasonably reliably by the acoustic navigation computer. However, the relay transponder on the DASI vehicle only partially worked: it failed to respond to interrogation at the common frequency. Attempts were made to repair it, but the necessary spares were not on board. It did however respond consistently and reliably to the relay frequency. The result was that the ship-board system received ranges to the deep-tow only on alternate cycles. The navigation software was unable to deal with this situation adequately, and so for much of the time it was not possible to obtain positions for the DASI. However all the data were logged, and as a result it should prove possible to edit and post-process the range files to obtain good positions for the DASI during transmitting periods.

Acoustic navigation frequencies are listed in Appendix 3.

4.7 Current meters

The four Aanderaa current meters were all recovered safely, and had recorded data. Unfortunately, the temperature data from the instrument at C2 (meter no. 12360) were no good, because the thermistor device failed at some time between testing and deployment.

4.8 XBTs

We launched a total of 8 expendable bathythermographs; however only five of these successfully recorded data. Of these, one (X4, file 5) produced an unusual profile, with temperatures of greater than 15 C between 1200 m and 1700 m depth. This may have been due to failure of the XBT probe. Unfortunately, the closest current meter was at C2, and this was the instrument that had a broken temperature sensor.

It would have been beneficial to have had a larger supply of XBT probes on the ship, so that water column anomalies could be more thoroughly investigated. As a general rule, it would be sensible for principal scientists on all cruises of whatever discipline to ensure that they have at least 20 XBT probes available on the vessel.

The failure of the other XBT probes is probably due to them being launched while the DASI streamer was being towed astern of the ship, at the surface: the XBT wires became caught on the streamer. The XBTs were provided free of charge by the Royal Navy Hydrographic Office.

4.9 Gravimeter

The gravimeter (meter no. S40) worked reliably throughout the cruise. Base ties were made in Southampton at the start and end of the cruise. The drift during the cruise was found to be less than 1 mgal; and so no drift correction has been made to the data. Base tie data are include in Appendix 4. Initial inspection of the processed gravity data suggests that they are noisy: this may be due to poor Eotvos corrections, in which case the data can be rectified by post-processing using smoothed navigation data.

4.10 Magnetometer

A proton precession magnetometer was towed whenever practicable: the limitation being that this was impossible during station work or when laying or recovering instruments. For towing at low speeds, during DASI operations, RVS were able to provide a magnetometer sensor and tow cable fitted with floats.

4.11 GPS navigation

Ship positioning was achieved by differential GPS – since the work area is just on the edge of available coverage for DGPS. Early in the cruise it became apparent, though, that while the data logging computers and readouts in the lab spaces were able to use the differential signals, the GPS set being used by the bridge for navigation was not. This caused considerable confusion during early instrument deployments. Subsequently, the differential signal was fed into the bridge's GPS set, and the discrepancies between the two systems were much reduced.

The lack of provision of a properly integrated suite of navigation systems for both bridge and scientific use is one of the more glaring omissions from the *Charles Darwin's* otherwise impressive capabilities as a research vessel. I have never understood why RVS imagine that the scientists do not need equally good, visually accessible and identical navigation data to that being used to manoeuvre the ship from the bridge. As an example, it is absurd that in the age of the internet, scientists when planning or revising track lines have to pick off way points from a paper chart, write them on a piece of paper, and carry them up to the bridge in order to communicate them reliably to the watchkeeping officers.

4.12 Computing and live track plot

The ship's computing systems worked well throughout CD120, and data were provided to the scientific party in the form of a set of CD-ROMs at the end of the cruise. Crucial to the success of the DASI towing operations was the provision by RVS of a live track plot screen on a PC. This showed the position and heading of the ship, overlaid on a base map of swath bathymetry data with planned track lines and instrument positions marked on it. I and other principal scientists have been requesting such a live track plot as routine provision for about the last 15 years; but this was the first time that it had been available to me in useful form on an RVS vessel. This is a great step forward, and I shall certainly be asking for provision of this crucial piece of software in the future. Ideally, it should be developed further to provide the integrated navigation system for both bridge and scientists discussed above.

5. Mobilization and demobilization

Mobilization of the cruise was straightforward. Much of the heavy RVS equipment had been installed before the scientific party arrived. This included the DASI streamers (we took two, in case of damage), on their winch drum. A group of Cambridge scientists had spent a week at SOC earlier in the summer, assembling the arrays and reeling them onto the winch.

There was only one mishap during mobilization - though this was potentially serious. One of the LEMUR instruments (LEMUR 16) was dropped by a forklift truck from a height of about a metre onto the quayside, as it was being unloaded from the lorry. The LEMUR landed upside down, on its release transducer head. Fortunately, it appears that no damage was done – but we are very lucky to have got away with it. My opinion is that this incident was due to carelessness on the part of the fork lift truck driver. This underlines the need for extreme care by all personnel involved in any way in preparations for oceanographic expeditions.

Demobilization was again straightforward. Standards of organization and planning for mob/demob by RVS were good. At the end of the cruise, the DASI system and the five remaining Cambridge LEMURs reamined at SOC, in readiness for Sinha's move there in early 2000. The sixth surviving LEMUR was shipped to Lisbon.

6. Summary of Data Collected

6.1 Data summary

In all, CSEM signals were transmitted along 14 tow tracks; and five LEMURs recorded part or all of these. Due to their shorter recording time, the LEMUR '95 instruments did not record the complete survey. Eight DASI tows were recorded by all five working LEMURs, while a further 6 tows were recorded only by the two recovered LEMUR '99 instruments. Details are provided in the table in Appendix 1.

Gravity, magnetic and ADCP data were collected continuously during DASI tow tracks, and intermittently at other times, between the boat transfers in Ponta Delgada at the start and end of the scientific programme.

Physical oceanographic data were collected by four recording current meters, one sound velocity meter dip, and five deep XBT probes.

feel both welcome and comfortable aboard the vessel.

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Appendix 1: DASI tow lines.

		Cruise CD 120, 'Madrigals'					
		DASI Tow Lines Completed					
Line No.	**Frequency**	**Start Time**	**End Time**	**Hours**	**km**	**Lemur '95s?**	**Comments**
1	1	274/2300	275/1030	11.5	22	No	Whole line
1	1	278/1850	278/2050	2	4	Yes	S end only
2	1	275/1720	276/0250	9.5	21	Yes	Whole line
3	1	276/0810	276/1540	7.5	17	Yes	Whole line
4	1	276/1930	277/0730	12	21	Yes	Whole line
5	1	277/1815	277/2355	5.5	20	Yes	Whole line
6	1	280/1445	280/2344	9	23	Part (18:00)	Whole Line
7	1	280/0220	280/0835	6.2	14	Yes	Whole line
8	1	281/0630	281/11:45	5.25	15	No	Whole Line
9	1	279/0140	279/0500	3.3	8	Yes	SW half only
3	0.25	281/1604	281/2034	4.5	7	No	From I to J
1	4	282/0245	282/0740	5	12	No	Central part
2	4	282/0950	282/1550	6	12	No	Central part
4	4	282/1900	283/0230	7.5	16	No	Almost whole line
	Total Transmission Hours:			**94.75**			
	Total DASI Line km:			**212**			

Appendix 2: Deployment positions of instruments and moorings

Cruise CD 120: ISO-3D: Deployment Positions of Instruments and Moorings

1) **LEMUR Positions:**

			North	West	North		West		Comments
Site	Inst. No	Date/Time	Latitude	Longitude	Lat Deg	Lat Min	Long Deg	Long Min	
A	16	273/0912	37.2762	32.2843	37	16.57	32	17.06	Recovered with data
B	1-Lis	273/1200	37.3100	32.2672	37	18.60	32	16.03	Lost - acoustics failed
C	3-Lis	274/1200	37.2900	32.2573	37	17.40	32	15.44	Lost - acoustics failed
D	18	273/1541	37.2963	32.3045	37	17.78	32	18.27	Recovered with data
E	15	272/1614	37.3498	32.2557	37	20.99	32	15.34	Recovered with data
F	2-Lis	273/1905	37.2525	32.2963	37	15.15	32	17.78	Lost - acoustics failed
G	17	272/1847	37.2938	32.2313	37	17.63	32	13.88	Lost - light failed
H	11	272/0828	37.2392	32.2538	37	14.35	32	15.23	Recovered with data
I	13	272/1110	37.2762	32.3553	37	16.57	32	21.32	Recovered but no data
J	14	272/1343	37.3322	32.3340	37	19.93	32	20.04	Recovered with data

2)		Acoustic Nav Transponder Positions:							
			North	West	North		West		Comments
Site	Inst. No	Date/Time	Latitude	Longitude	Lat Deg	Lat Min	Long Deg	Long Min	
N1	215	273/0724	37.2925	32.2665	37	17.55	32	15.99	Recovered
N2	216	273/0536	37.3393	32.1895	37	20.36	32	11.37	Recovered
N3	439	273/0322	37.3430	32.3023	37	20.58	32	18.14	Recovered
N4	359	273/0125	37.2937	32.3768	37	17.62	32	22.61	Recovered
N5	360	272/2334	37.2455	32.3292	37	14.73	32	19.75	Recovered
N6	370	272/2149	37.2623	32.2245	37	15.74	32	13.47	Recovered

3)		Current Meter Positions:							
			North	West	North		West		Comments
Site	Inst. No	Date/Time	Latitude	Longitude	Lat Deg	Lat Min	Long Deg	Long Min	
C1	11572	274/0318	37.2898	32.3385	37	17.39	32	20.31	Recovered
C2	12360	274/0220	37.2868	32.3112	37	17.21	32	18.67	Recovered
C3	11570	274/0108	37.2830	32.2717	37	16.98	32	16.30	Recovered
C4	6750	273/2357	37.2807	32.2480	37	16.84	32	14.88	Recovered

4)		XBT Positions:							
			North	West	North		West		Comments
Site	File No.	Date/Time	Latitude	Longitude	Lat Deg	Lat Min	Long Deg	Long Min	
X6	2	271/2349	37.2815	32.2375	37	16.89	32	14.25	Successful
X7	(3)	279/1009	37.3548	32.2648	37	21.29	32	15.89	Failed
X1	3	279/1536	37.2937	32.3683	37	17.62	32	22.1	Successful
X2	(4)	279/1606	37.2907	32.3473	37	17.44	32	20.84	Failed
X3	4	279/1622	37.2898	32.3382	37	17.39	32	20.29	Successful
X4	5	279/1750	37.2843	32.2902	37	17.06	32	17.41	Successful
X4-R	6	279/1800	37.2843	32.2855	37	17.06	32	17.13	Successful
X6	(7)	279/1931	37.2792	32.2353	37	16.75	32	14.12	Failed
5)		Sound Velocity Meter Profile Position:							
			North	West	North		West		Comments
Site		Date/Time	Latitude	Longitude	Lat Deg	Lat Min	Long Deg	Long Min	
X6		272/0011	37.2822	32.2378	37	16.93	32	14.27	Recovered

Appendix 3: Frequencies used for acoustic navigation

Transponder	Frequency (kHz)	Channel Number
N1	11.5	7
N2	12.0	8
N3	12.5	9
N4	13.0	10
N5	13.5	11
N6	14.0	12
C2	8.5	1
C4	9.5	3
Common	9.0	2
Relay	11.0	6

Appendix 4: Gravity base tie data

GRAVITY BASE TIE PRE CRUISE 120 'Madrigals'

SHIP LOCATION:	Empress Dock, Southampton
DATE:	263/1999
SHIP:	*RRS CHARLES DARWIN*
SHIPS POSITION:	At Base Station Ref UK-06-03
SHIPBOARD METER:	LACOSTE & ROMBERG S40
POSITION OF BASE STN:	SOC, - UK-06-03
LAND METER FOR TIE:	N/A
OBSERVER:	

0555/293

SHIPBOARD METER CALIBRATION (CALIB):	0.9917mGals per division
LANDMETER CALIBRATION CONSTANT (Calib):	n/a
TEMPERATURE OF METER FOR CALIBRATION:	n/a
SHIPBOARD METER VALUE ALONGSIDE (OBASE):	9439.4
LANDMETER MEAN VALUE ALONGSIDE ($obase_1$):	n/a
MEAN TIME OF OBSERVATIONS (5 TAKEN) t_1:	n/a
LANDMETER MEAN VALUE AT BASE STATION (gbase):	n/a
MEAN TIME OF OBSERVATIONS (5 TAKEN) t:	n/a
LANDMETER MEAN VALUE ALONGSIDE ($obase_2$)	n/a
MEAN TIME OF OBSERVATIONS (5 TAKEN) t_2:	n/a

9439.5

ABSOLUTE GRAVITY VALUE AT BASE STATION: 981114.42mGals

Drift of Landmeter (do/dt) = $(obase_1 - obase_2)(t_2-t_1)^{-1}$
=
= *n/a*

Alongside reading at time t (obase) = $obase_1 + (t_2 - t)(do/dt)$
=
= *n/a*

Gravity difference between base station and the ship = (gbase - obase)(calib)
=
= *n/a*

Absolute value alongside the ship = Abs. base station - Difference base/ship
=
= ***981114.42*** **mGals**

Height difference Land meter to Ship meter = 2.05m   1·70
Free air correction (0.31h) = 0.31 x 2.05   0·31 x 1·70
= ***0.6355***

ABSOLUTE VALUE AT SHIP METER = Value alongside + free air correction
= 981114.42+0.6355
= **981115.0555**

DRIFT CALCULATION

Drift from previous to current station
= (Absolute value at Ship meter previous - Absolute value at Ship meter current)
- (Meter reading previous - Meter reading current) x CALIB
=
= n/a (New installation onboard - No previous data)

Days = day number previous - day number current
=
= n/a

Daily drift = total drift/Days
=
= ***n/a***

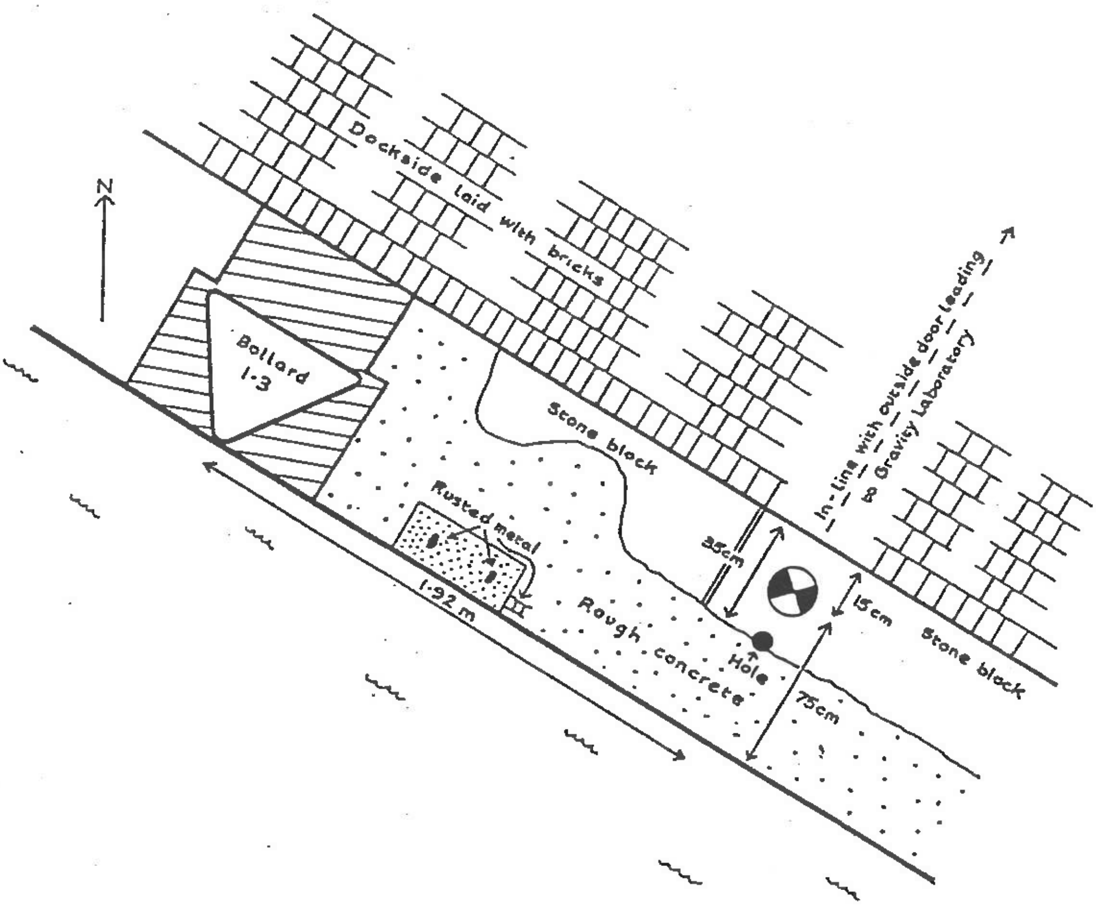
GRAVITY BASE STATION | UK-06-03

Country/State : UK - ENGLAND
City/Town : SOUTHAMPTON
Station Name : SOUTHAMPTON OCEANOGRAPHY CENTRE - SHIP BERTH

Latitude : 50° 53'.5N
Longitude : 001° 23'.6W
(Referred to WGS datum)
Other ref: SOC GBS 1

IGSN 71 g = 981,114.42 ±0.02 mGal

LOCATION DIAGRAM



further diagrams overleaf

Diagram ref: UK Hydrographic Office Dated: December 1996

DESCRIPTION

The station is located on the northern side of Empress Dock as shown in the location diagrams.

Contact: Chris Paulson (01703) 596280 - NERC - Southampton Oceanographic Centre

Description ref: UK Hydrographic Office Dated: December 1996

Appendix 5: Cruise participants

K. O. Avery	Master	
J. D. Noden	Chief officer	
M. H. Graves	Second officer	
J. W. Mitchell	Third officer	
S. A. Moss	Chief engineer	
A. Greenhorn	Second engineer	
C. J. Phillips	Third engineer	
C. J. Cooper	Third engineer	
J. G. L. Baker	E.T.O.	
M. A. Harrison	C.P.O. (Deck)	
T. G. Lewis	P.O. (Deck)	
J. R. Perkins	Seaman	
G. Crabb	Seaman	
R. Dickinson	Seaman	
M. Moore	Seaman	
J.G. Smyth	Motorman	
C. K. Perry	Catering manager	
D. Connelly	Chef	
P.W. Robinson	M/Steward	
J. A. Osborn	Steward	
G. M. Mingay	Steward	
Martin Sinha	Chief scientist	University of Cambridge
Lucy MacGregor	Scientist	University of Cambridge
Jonathan Pye	Scientist	University of Cambridge
Sulaiman Al-Kindi	Scientist	University of Cambridge
Zongfa Cheng	Scientist	University of Cambridge
Agusta Flosadottir	Scientist	HALO
Antonio Soares	Scientist	University of Lisbon
Rita Nolasco	Scientist	University of Lisbon
Nuno Lourenco	Scientist	University of Algarve
Joaquim Luis	Scientist	University of Algarve
Peter Mason	Scientist	NERC RVS
Jason Scott	Scientist	NERC RVS
Martin Beney	Scientist	NERC RVS
Robert Keogh	Scientist	NERC RVS
John Wynar	Scientist	NERC RVS
David Booth	Scientist	NERC RVS
Anthony Beaman	Scientist	NERC RVS
James Sutherland	Scientist	NERC RVS

Appendix 6: ISO-3D Principal Investigators

The principal investigators of the ISO-3D project are:

1. Dr Martin Sinha, Department of Earth Sciences, University of Cambridge, UK (Co-Ordinator).

2. Dr. Agusta Flosadottir, Laboratory of Oceanic and Atmospheric Sciences, Halo Ltd., Reykjavik, Iceland.

3. Prof. Dr. Andreas Junge, Institut für Meteorologie und Geophysik, Johann Wolfgang Goethe-Universität Frankfurt am Main, Germany.

4. Dr Jorge Miguel Miranda, Centro de Geofisica, Instituto de Ciencias da Terra e do Espaço, Universidade de Lisboa, Portugal.