ISTITUTO PER LA GEOLOGIA MARINA - CNR
BOLOGNA

TECHNICAL REPORT N. 53

TECTONIC AND PRESSURE CONTROLS ON THE GROWTH OF GIANT VOLCANIC RIDGES IN THE AZORES REGION (ATLANTIC OCEAN). REPORT ON TOBI SIDE-SCAN SONAR, SWATH BATHYMETRY, SBP PROFILING, AND MAGNETIC INVESTIGATIONS DURING CRUISE AZ99.

THE IGM-CNR, OXFORD, TOBI-SOC AND PORTUGUESE TEAMS

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AZ99 Cruise Technical Report / by G.Bortoluzzi, G.Carrara, F.Gamberi, M.Marani, M.Ligi, D.Penitenti, R.Portaro, G.Centorami, M.Rovere, N.Mitchell, C.Jacobs, I.Rouse, C.Flewellen, S.Whittle, J.Freyre Luis, N.Lourenco, P.Terrinha

Includes bibliographical reference and index.
1. Azores 2. TOBI 3. Geophysics

Abstract

A summary of the ship-board activities of a side scan sonar and swath bathymetry (TOBI) and magnetics survey around the Azores I. (AZ99, july 1999) is presented. The survey used R/V Urania of CNR for 35 days, inclusive of transits from and to Civitavecchia. Along with a description of technical details of the equipment employed, we discuss problems regarding data acquisition and quality.

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1 SCIENTIFIC PARTY AND INSTITUTIONS

NAME	INSTITUTE	TITLE	CONTACT
Marco Ligi	IGM-CNR	Chief Expedition	+39-0516398903 marcol@boigm2.igm.bo.cnr.it
Giovanni Bortoluzzi	IGM-CNR	Technician	+39-0516398882 gb@igm.bo.cnr.it
Gabriela Carrara	IGM-CNR	scientist	gabriela.carrara@igm.bo.cnr.it
Fabiano Gamberi	IGM-CNR	scientist	fabiano.gamberi@igm.bo.cnr.it
Michael Marani	IGM-CNR	co-chief scientist	+39-0516398887 michael.marani@igm.bo.cnr.it
Daniela Penitenti	IGM-CNR	Technician	+39-0516398882 daniela@igm.bo.cnr.it
Rosana Portaro	IGM-CNR	scientist	rosana.portaro@igm.bo.cnr.it
Gabriella Centorami	IGM-CNR	student	
Marzia Rovere	IGM-CNR	student	marzia.rovere@igm.bo.cnr.it
Neil Mitchell	UNIOXF	co-chief scientist	+44-1865282122 neilm@earth.ox.ac.uk
Colin Jacobs	SOC	TOBI	+44-1703596576 clj@soc.soton.ac.uk
Ian Rouse	SOC	TOBI	+44-1703596158 ianr@soc.soton.ac.uk
Chris Flewellen	SOC	TOBI	+44-1703596073 cfg@soc.soton.ac.uk
Steve Whittle	SOC	TOBI	+44-1703596307 spwh@soc.soton.ac.uk
Pedro Terrinha	UNILIS	scientist	pagt@fc.ul.pt
Joaquim Freyre Luis	UNIALG	scientist	jluis@ualg.pt
Nino Lourenco	UNIALG	scientist	nlouren@ualg.pt
Carlo Papucci	ENEA		+39-0187-978267 papucci@estosf.santateresa.enea.it
Roberta Delfanti	ENEA		delfanti@ estosf.santateresa.enea.it
Catalina Gascó	CIEMAT		cata@ciemat.es
Marco laganante	SHIP	Ship Technician	
Scotto	SHIP	Ship.Techniciam	
Ist.Geologia Marina CNR	IGM-CNR	www.igm.bo.cnr.it	Bologna Italy
Dep.Earth Sciences,Univ.	UNIOXF	www.earth.ox.ac.uk	Oxford UK
Southampton Ocean.Centre	SOC	www.soc.soton.ac.uk/OTD/instruments/tobi.html	Southampton UK
Univ.Lisboa	UNILIS		Lisboa Portugal
Univ. Algarve	UNIALG		Faro Portugal
Centro Ric. Amb. Marino	ENEA		La Spezia Italy
Dep.Imp. Amb. Energia	CIEMAT		Madrid España

Table 1: Scientific Party

AKNOWLEDGMENTS - We wish to thank the Captain V.Lubrano, officers and crew of R/V Urania for the efforts and professionalism during the cruise. Tim Le Bas of SOC at Southampton is warmly aknowledged for assistance and for making available the software PRISM. We thank the Italian Embassy in Portugal, in particular Dr. G.P.Calabresi and Mrs. Puppo, for their assistance in having the permissions for the cruise. Mr. Carmine Capua and Mr. Viezzoli of SO.PRO.MAR were valuably helpful in the general organization of the Cruise and in the setting of the HPR positioning system. In addition, we would also thank Dr.M.Astraldi, Dr. G.P.Gasparini and Ing. C.Galli of IOF-CNR at La Spezia for having provided us with the equipment for XBT launching. The research was funded by a grant from the EEC under the EASSS (European Access to Sea Floor Survey System) scheme. The National Research Council of Italy (CNR) funded the expedition by providing the R/V Urania. Participation of Neil Mitchell was funded by The Royal Society, UK

2 CRUISE SUMMARY

SHIP: URANIA START: 1999-06-31 PORT DEPARTURE: CIVITAVECCHIA
END: 1999-08-04 PORT ARRIVAL: CIVITAVECCHIA
SEA/OCEAN:

1. Atlantic Ocean
2. Azores Islands
3. Gibraltar Strait

LIMITS: NORTH: 39 SOUTH: 37.5 WEST: -29.5 EAST: -36.5
OBJECTIF:
STUDY OF THE TECTONIC AND PRESSURE CONTROLS ON THE GROWTH OF GIANT VOLCANIC RIDGES IN THE AZORES REGION (ATLANTIC OCEAN)
COORDINATING BODY: IGM CNR BOLOGNA (ITALY)
CHIEF SCIENTIST(S):

1. Dr. Marco Ligi IGM-CNR

PARTICIPATING BODIES:

1. DEPT. EARTH SC.- UNIVERSITY OF OXFORD
2. SOUTHAMPTON OCEANOGRAPHY CENTRE
3. UNIVERSITY LISBON
4. UNIVERSITY ALGARVE
5. CENTRO RICERCHE MARINE AMBIENTE - ENEA
6. CIEMAT - MADRID

DISCIPLINES:

1. Earth Sciences

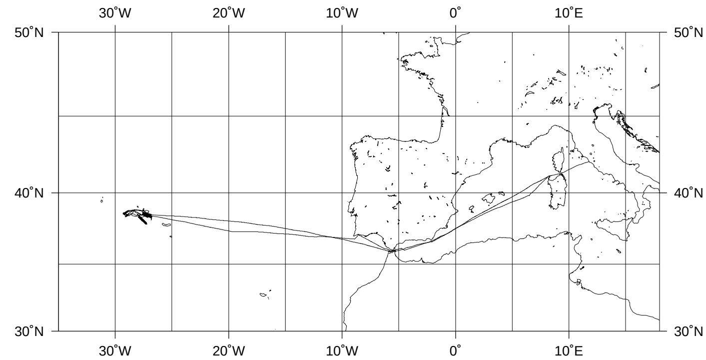
DATA TYPES:

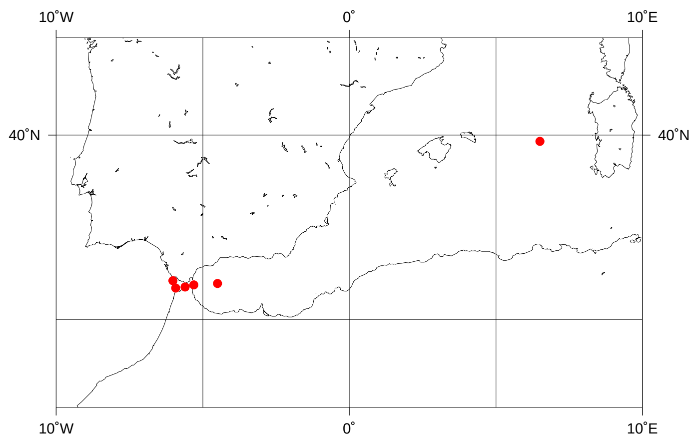
1. SIDE SCAN SONAR
2. MAGNETISM
3. VERTICAL AND SWATH BATHYMETRY
4. OCEANOGRAPHY
5. WATER SAMPLING
6. METEREOLOGY

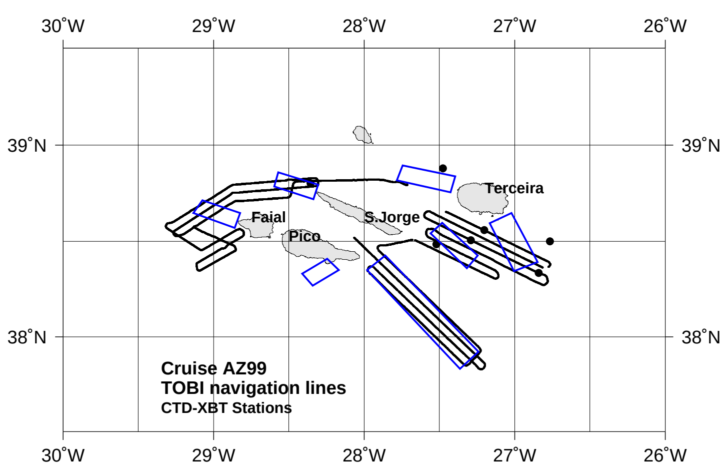
WORK DONE:

1. TOBI RUNS AZORES
2. TOBI SWATH BATHYMETRY
3. CONTINUOUS MAGNETOMETRY BATHYMETRY
4. 1 CTD 5 XBT AZORES
5. 6 CTD/WATER SAMPLING GIBRALTAR
6. CONTINUOUS METEREOLOGICAL DATA

LOCATION MAP(S):







3 INTRODUCTION AND GEOLOGICAL ENVIRONMENT

The Azores archipelago (see Fig.1) lies in the area of the Triple Junction ([1], [2]) between the North-American, Euroasiatic and African tectonic plates. It is characterized by an irregularly shaped volcanic plateau, and is formed by nine islands, divided into three major groups. Volcanism in this region of extension has created giant linear volcanic ridges, notably those forming the Islands of S. Jorge and Pico. These are some of the largest such volcanic ridges actively forming anywhere on earth and represent an important mode of crustal formation, analogous to that observed at mid-ocean ridges. The Azores area is also unique for having so many active volcanic ridges over a wide range of water depth.

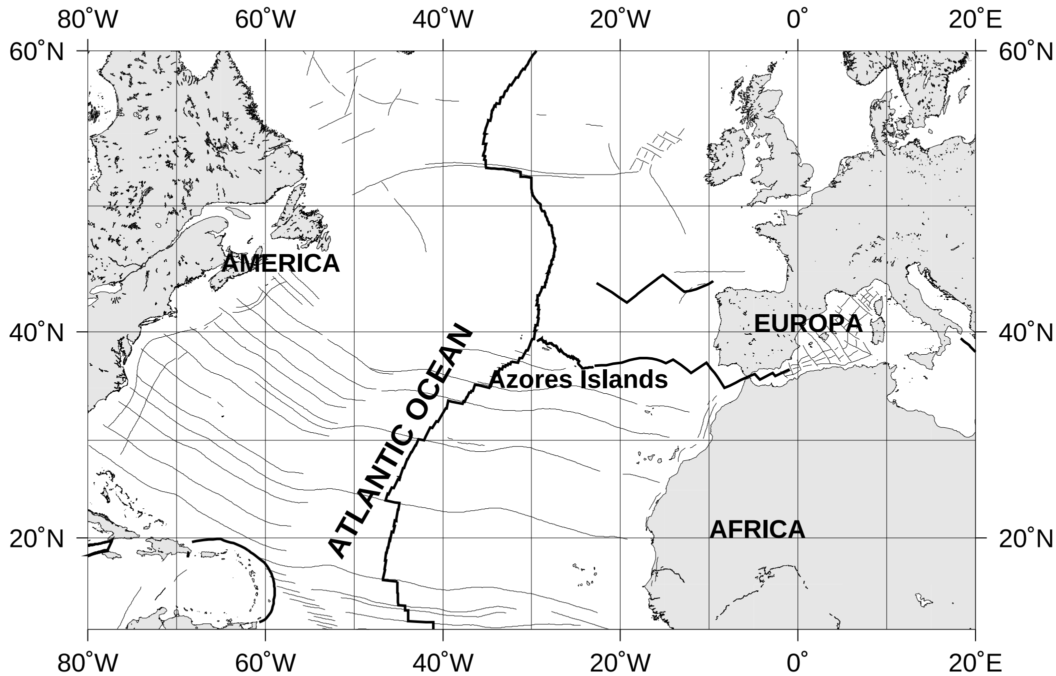


Figure 1: Location of the Azores Islands. Also shown the plate boundaries (heavy lines) and the main fracture zones (data taken from http://www.gsj.go.jp/dMG/free/plates/Intro.html, compiled by NOAA Global Relief Data on CD-ROM (93-MGG-01, original digitizing performed by PLATES project at the University of Texas, edited for plotting with GMT [14] by Kensaku Tamaki, Ocean Research Institute, University of Tokyo).

A joint Italian (CNR) and British (Univ. of Oxford) project was presented during 1998 to study this distribution to test theories for how volcanic morphology varies with pressure, due to effects of variable gas exsolution from the magma, and address the interplay between volcanism and tectonics in the genesis of the ridges. The main practical objective of work at sea was to map the structures with TOBI (the Towed Ocean Bottom Instrument of the SOC, Southampton, UK)([3],[4]), in order to resolve their origin, in particular by resolving relationships between recent volcanism and major faults.

Our other objectives were (a) to locate hydrothermal springs and determine what geological structures favour them in particular their relation to historical submarine eruptions and faults observed in TOBI images, and (b) to contribute to the general understanding of volcanic and submarine land slides hazards in the Azores region.

Figure 2: R/V Urania, CNR, operated by SO.PRO.MAR Spa.

Funding for the TOBI operation and personnel was provided by a grant from the EEC under the EASSS (European Access to Sea Floor Survey System) scheme. Since TOBI had already been deployed on R/V Urania during the 1998 TIVOLI cruise, the Italian research vessel has been considered to be suitable for the installation. A request to CNR for Urania ship-time was submitted and approved, and a cruise of 35 days (AZ99) was scheduled for july 1999. The EEC funding also included travel and subsistance costs for researchers and graduate students involved in post-cruise data processing and training at SOC. In order to allow as wide experience of TOBI surveying as possible, participation of researchers from several European Institutes was planned, including researchers of Portuguese Universities. Participation included all research aspects, from data acquisition to interpretation.

Taking the opportunity of the transit to Gibraltar, as a part of a collaboration agreement with the ENEA (Centro di Ricerche Ambiente Marino of La Spezia, Italy), two days of the cruise time were devoted to water sampling in the Gibraltar Strait within the framework of the EC MAST III Programme CANIGO (Canary Islands Azores Gibraltar Observations). The ocean domain covered by the CANIGO Project includes the sub-tropical North Atlantic gyre and the Mediterranean-Atlantic exchange. The main objective of the oceanographic research was to contribute to the general understanding of water fluxes trough the Strait of Gibraltar, by the analysis of trace metals, metalloids and radionuclides content in the water sampled collected. In addition, the data collected will allow improvements in estimate of exchanges between the Atlantic and the Mediterranean Sea, solving the fine structure of the surficial Atlantic inflow and deep Mediterranean outflow.

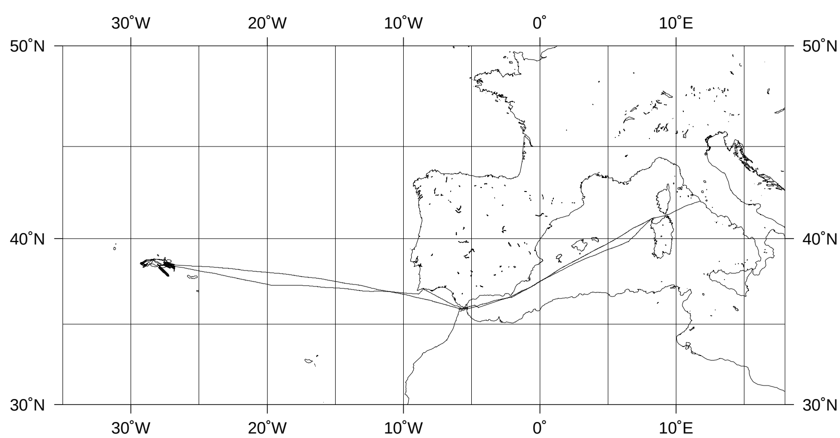


Figure 3: Navigation data.

R/V Urania (Fig.2) left Civitavecchia 30-jun-1999 on schedule. Water samples were collected by the ENEA team in the Mediterranean and Atlantic waters around the strait and on 5 july the team was disembarked in Portimao (Portugal). Ship arrived in the Azores I. 8-jul-1999, and started to work with TOBI after a short bathymetric and CTD survey.

During the first leg, we had 10 days of continuous TOBI, chirp Sonar, bathymetry and magnetics data collection, southeast of Pico, S. Jorge and Terceira Islands. The first leg ended 19-july-1999 with a port call in Horta (Faial I.), where a partial changeover of the scientific crew occured. Weather conditions were good for almost all of the first leg.

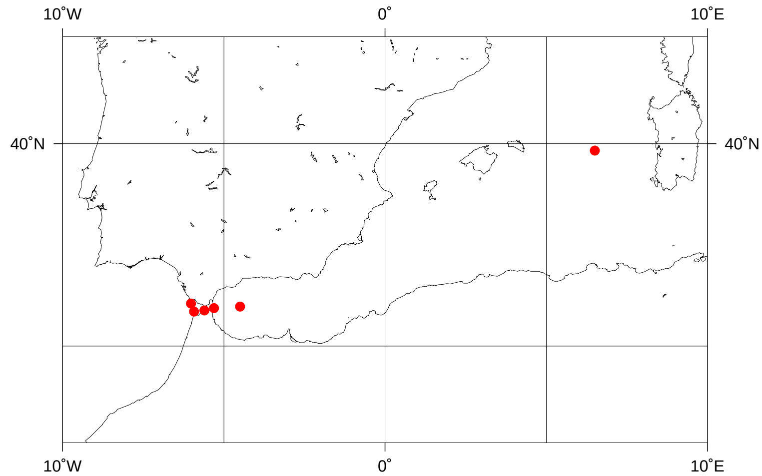


Figure 4: Location of the stations of the CANIGO sampling.

The second leg started 21-jul-1999 and ended late 28-jul-1999, when the ship headed to Civitavecchia, docking 4-aug-1999

Whilst passing Terceira 28-jul-1999, the ship passed close to the eruption of the submarine volcano Cerreta. We observed vapour jets and floating lava blocks.

Fig.3 shows the navigation data including the transits. Fig.4 shows the locations of water samples collected by the CANIGO team. Fig.5 shows the navigation data of the two legs, along with the areas we originally intended to survey with TOBI.

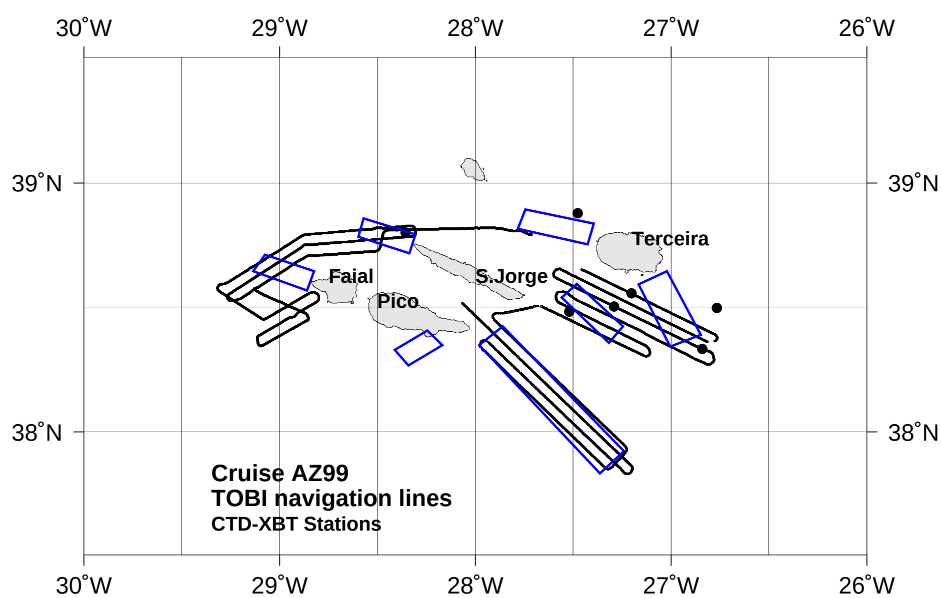


Figure 5: TOBI Planned areas, actual navigation lines and CTD/XBT stations (black circles).

Hereafter, a description of the equipment and of their usage is given, along with details of the general setting, performances and results (Chapter 4). Chapter 5 presents the Oceanographic setting and the problems encountered in the sound velocity data acquisition and processing. Chapter 6 describes the sidescan sonar and swath bathymetry data processing.

4 MATERIALS AND METHODS

A description of the equipment, of the data acquisition and of the processing techniques used can be found hereafter. The cruise was based primarily on the TOBI side scan sonar surveying. The planning of survey lines was based on bathymetric maps created using all available data. Among these were data from Hydrographic Charts (digitized by the Defense Mapping Agency, USA), transits from the NGDC databases, transits from IFREMER cruises (courtesy of Dr. M. Cannat, cruise SUDACORES), and high resolution data from recent surveys (courtesy of the on-board Portuguese Team). GLORIA long-range sonar images originally published by R.Searle [1] were reprocessed at the SOC and were used for planning and navigation of TOBI as well.

Much of our initial efforts were aimed at processing of the navigation data since this would later be required for mosaicking of the sidescan sonar images and swath bathymetry. This led to the merging of all the available instrumental data (except the side-scan sonar data) into a single, self-consistent file. Additional data included the surface magnetometer and the TOBI ancillary data (three component magnetometer, temperature and conductivity data). This file is produced from an integrated procedure of filtering and merging of navigation and TOBI data, jointly with the offset data tables.

4.1 POSITIONING AND NAVIGATION

The ship's NAVPRO 5.4 Navigation Software by Communication Technology of Cesena (Italy) was used ([5]). The primary positioning sensor was the FUGRO DGPS Mod. 3000 SeaStar. The system was used for ship's guidance on the planned lines, and for data logging of various sensors, among them gyrocompass, Atlas DESO 25 echo/sounder, meteo station, magnetometer, HPR transponder. In addition, it exported ship's position data to the Chirp sonar computer.

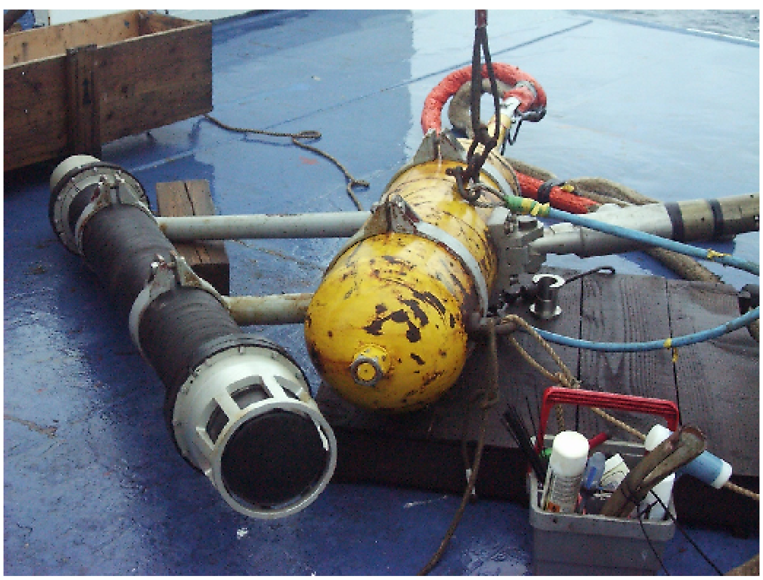


Figure 6: HPR

The system performed quite well within the technical specs, and without any problem to be reported. The availability of differential GPS signals by the FUGRO 3000 receiver ranged from good to excellent, and provided ship's position to metric accuracy for most of the acquisition time (DGPS corrections were unavailable for only short periods). Acoustic positioning of the TOBI vehicle was accomplished by using the ships' Simrad-Konsgberg HPR-1507 system and a long-range (6km) transponder, which was mounted 45 deg. below TOBI's depressor (Fig. 6).

The Navigation and Data Acquisition System had the following major settings:

1. UTC
2. Datum WGS84
3. Projection Direct Mercator on 38 N (for ship's guidance)
4. Output position POS1
5. Acquisition Cycle 10 seconds.
6. Speed of Sound for DEPTH 1 and 2 1500m/sec

Table 2 and Fig. 7 shows the offsets of principal instruments. It is worth to note that the POS 1 position is recorded in multibeam files, as well as in the NAVPRO binary and ASCII files. The final coordinates for every instrument should be recalculated accordingly.

COORDINATES				
POINT	ALONG (Y)	ACROSS (X)	DISTANCE	BEARING
POS1	0.0	0.0	0.0	0.0
GYRO	-2.0	-2.0	-	-
DEPTH 1 12/100 Khz	-0.2	-3.25	3.5	266
DEPTH 2 33/210 Khz	-0.2	0.45	0.5	114
CHIRP SBP	-11.0	-2.35	11	192
HPR1507	-1.7	-2.4	-3	235
STERN	-43.7	-1.4	44	182
TOBI CABLE LAYOUT	-45.9	-1.4	46	182
MAGNETOMETER	-225.7	-10.0	226	183

Table 2: Offsets from primary navigation sensor (POS1)

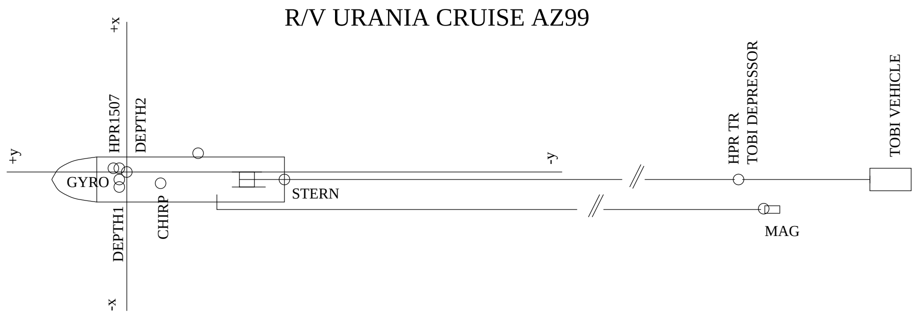


Figure 7: Offsets from primary navigation sensor (POS1)

4.2 TOBI SIDE-SCAN SONAR

Although TOBI's main instrument is a sidescan sonar, a number of other instruments are fitted to make use of the stable platform TOBI provides. For this cruise the instrument complement was:

1. 30kHz sidescan sonar (Built by IOSDL) with swath bathymetry capability 2. 7.5kHz profiler sonar (Built by IOSDL) 3. Three axis fluxgate magnetometer. (Ultra Electronics Magnetics Division MB5L) 4. CTD (Falmouth Scientific Instruments Micro-CTD) 5. Gyrocompass (S.G.Brown SGB 1000U) 6. Pitch & Roll sensor (G + G Technics ag SSY0091)

An AutoHelm ST50 GPS receiver provides the TOBI logging system with navigational and time data. An MPD 1604 9 tonne instrumented sheave provides wire out, load and rate information both to its own instrument box and wire out count signals to the logging system.

The TOBI system uses a two bodied tow system to provide a highly stable platform for the on-board sonars. The vehicle weighs two and a half tonnes in air but is made neutrally buoyant in water using syntactic foam blocks. A neutrally buoyant umbilical connects the vehicle to the 600 kg depressor weight. This in turn is connected via a conducting swivel to the main armoured coaxial tow cable. All signals and power pass through this single conductor.

For this cruise the SOC TOBI winch system, purchased using European funding, was utilised. This system combines tow, launch and umbilical winches onto one container- sized baseplate enabling one driver to control all operations. The winch was secured to the aft deck using the mounting bed frame designed by and manufactured by SO.PRO.MAR. S.p.A. - the ship's owners and used first on the TIVOLI expedition in 1998. During the surveys the winch was controlled by a remote station in the main laboratory.

In order to accurately navigate the TOBI vehicle the ship's Simrad HPR short baseline positioning system was used. The HPR1507 transponder beacon was fitted to the depressor weight in order to reduce any acoustic interference with TOBI. Appendix A presents a detailed report on the TOBI operations.

TOBI is a deep-towed multi-sensor sonar system developed at SOC (Southampton Oceanographic Centre)([3],[4]). The system comprises a two-sided 30kHz sidescan sonar, a 7.5kHz sub-bottom profiling sonar, a set of scientific instruments (magnetometer and CTD), and a range of vehicle attitude sensors (pitch, roll, and heading from a gyro-compass). The underwater vehicle is towed with a 200 m umbilical behind a depressor weight. The depressor is attached to the surface ship via the main 0.68" armoured coax cable. This towing method prevents ship induced heave influencing the vehicle. The vehicle is usually 'flown' at heights of between 200 to 500 m above the seabed. All signals to and from the vehicle are sent via the single coax conductor. Signals are processed on the ship and logged onto magneto-optical disks. The sidescan sonar has a total range of 6km and a has a seabed footprint ranging from about 4 x 7m close to the vehicle track to 42 x 2 at far range. The profiler sonar can penetrate up to 70m into soft sediments and has a vertical resolution of better than 1m.

Although originally designed for acoustically imaging the deep ocean floor, the TOBI system has developed into a highly versatile instrument used by both scientific agencies and commercial companies.

Figure 8: Deployment of the TOBI tow fish

4.2.1 TOBI TECHNICAL SPECIFICATIONS

SYSTEM HIGHLIGHTS

1. 6000m depth capability
2. 30kHz sidescan sonar with 6km swath range
3. Swath bathymetry system uses sidescan transmit signal for a fully co-registered data set.
4. 7.5kHz sub-bottom profiler sonar giving up to 70m penetration into soft sediments
5. Tri-axial fluxgate magnetometer and gyrocompass combine to give local magnetic field measurement and orientation.

BRIEF TECHNICAL SPECIFICATIONS

1. Mechanical
   (a) Towing method Two bodied tow system using neutrally buoyant vehicle and 600kg depressor weight.
   (b) Size 4.5m x 1.5m x 1.1m (length x height x width).
   (c) Weight 2200kg in air.
   (d) Tow cable up to 10km armoured coax.
   (e) Umbilical 200m long x 50mm diameter, slightly buoyant.
   (f) Tow speed 1.5 to 3 knots (dependent on tow length).
2. Sonar Systems
   (a) Sidescan Sonar
      i. Frequency 30.37kHz (starboard) 32.15kHz (port).
      ii. Pulse Length 2.8ms.
      iii. Array Length 3m.
      iv. Ouput Power 600W each side.
      v. Range 3000m each side.
      vi. Beam Pattern 0.8 x 45 degree fan.
   (b) Bathymetry Sonar
      i. Transmitter uses sidescan sonar.
      ii. Receiver 6 hydrophone arrays in 2 housings for each side.
      iii. Array Length 3m.
      iv. Detection Single and multi-phase.
      v. Range Up to 3000m each side.
   (c) Profiler Sonar
      i. Frequency 7.5kHz.
      ii. Pulse Length 0.26ms.
      iii. Output Power 500W.
      iv. Range Up to 70m penetration over soft sediment.
      v. Resolution less than 1m.
      vi. Beam Pattern 25 degree cone.
3. Standard Instrumentation
   (a) Magnetometer Ultra Electronics Magnetics Division MB5L.
      i. Range +/- 100,000nT on each axis.

   - ii. Resolution 0.2nT.
   - iii. Noise +/- 0.4nT.

(b) CTD Falmouth Scientific Instruments, Micro CTD.

- i. Conductivity
  - A. Range 0 to 65 mmho/cm.
  - B. Resolution 0.0002 mmho/cm.
  - C. Accuracy +/- 0.005 mmho/cm.
- ii. Temperature
  - A. Range -2 to 32 Celsius.
  - B. Resolution 0.0001 C.
  - C. Accuracy +/- 0.005 C.
- iii. Depth
  - A. Range 0 to 7000 dbar.
  - B. Resolution 0.02 dbar.
  - C. Accuracy +/-0.12
- iv. Heading S.G. Brown SGB 1000U Gyrocompass.
  - A. Resolution 0.1 degrees.
  - B. Accuracy Better than 1, latitude less than 70 degs.
- v. Pitch/Roll Dual Axis Electrolytic Inclinometer.
  - A. Range +/- 20 degrees.
  - B. Resolution 0.2 degrees.
- vi. Altitude Taken from profiler sonar.
  - A. Range 1000m.
  - B. Resolution 1m.

4.3 MAGNETICS

IGM's GEM Systems Mod. GSM-19MD Overhauser Effect Magnetometer was used ([6]). The sensor was towed at a constant offset of 185 m from ship's stern. Data were recorded at the rate of about 0.1 Hz by the NAVPRO navigation system.

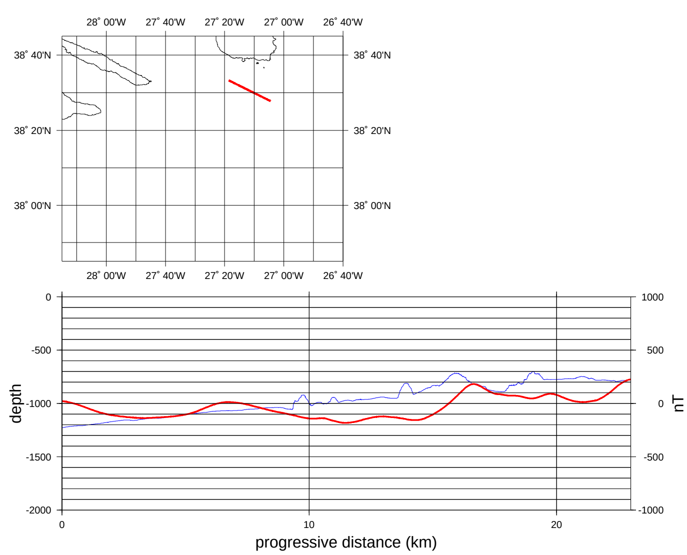


Figure 9: Example of unfiltered magnetic (thick) and bathymetric data

The instrument performed well for the totality of the cruise.

The magnetic data of the survey were collected by the NAVPRO navigation computer, along with date, time (UTC), DGPS coordinates, gyrocompass, bathymetry (DESO 25). A procedure was set to make a first display of the data by means of:

1. positioning of the sensor according to the offset and gyro;
2. computing of the IGRF-95 [7] anomaly
3. display of magnetics and bathymetry along the line;

This served primarily for data inspection. An example can be seen in Fig. 9. The TOBI vehicle carried a 3 component magnetometer, that acquired data at 1/8th of TOBI data (4 seconds). For an initial check we used the data extracted from the header of TOBI data.

4.4 SUBBOTTOM PROFILING

On almost all the survey lines, sediment profiling was carried out using the ship's DATASONIC DSP-661 Chirp 2 Profiler. Trigger rates varied from 2 to 4 seconds, while chirp pulse length was maintained at 120 ms. Data were displayed on an EPC 9600 and recorded on Magneto-optical disks in SEG-Y format, which will be used off-line for post-processing.

4.5 COMPUTING CENTER

With two 10/100 MB Ethernet HUBS we established a star topology network of computers for swath bathymetry and general purpose data processing. Among them, PC's running Linux and Windows OS, two SUN workstations (WS) running Solaris 2.7 OS, SGI O2 running IRIX 6.3. The SUN WS were devoted to TOBI data processing, whilst the LINUX WS were used for NFS disk and printer spooling services. The ship navigation computer was also connected to the network.

During the 60 days cruise, we can report just a few crashes of some machines, which recovered smoothly after the reboot or file system check.

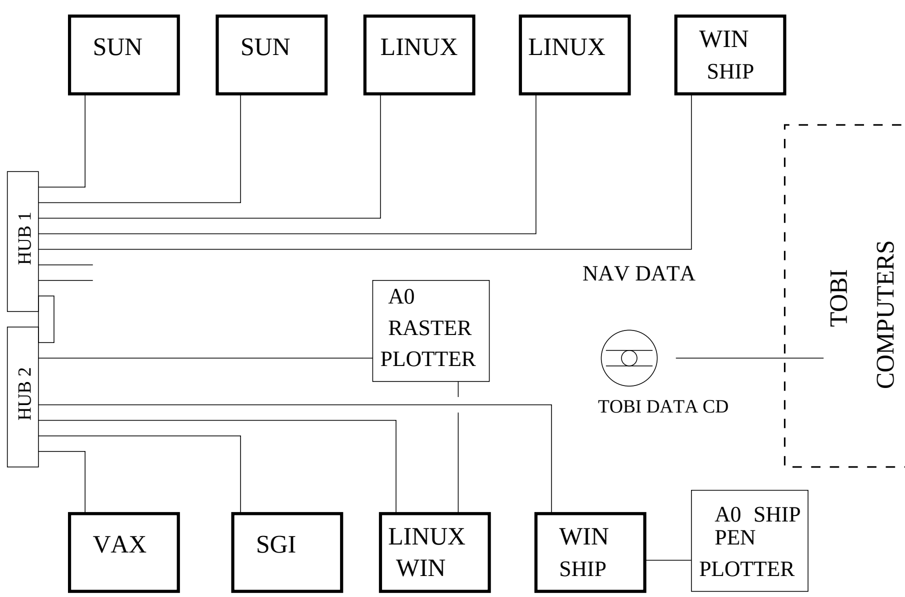


Figure 10: Computing Center and data flow paths

5 OCEANOGRAPHIC SETTING AND SOUND VELOCITY ANALYSIS

At the start of the cruise a CTD station was done SW of Terceira I.. Some Sippican XBT probes were launched South of Terceira and Pico I. and NW of Terceira I. and N of Pico I.

Fig.5 shows the position of the sampling stations. The data are plotted in Fig.11 whereas Table 3 shown time, date and position information.

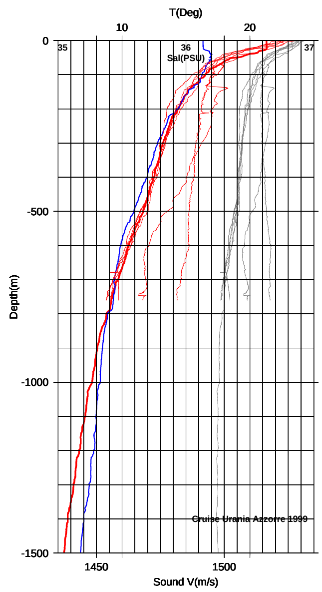


Figure 11: CTD and XBT data. Temperature red, Salinity blue, Sound Velocity gray

STATION	DATE	TIME	LAT	LON
CTD_01	1999-07-09	02:40:50	3829.10	-2731.175
T7_01	1999-07-16	15:50:24	3820.1	-2650.4
T7_02	1999-07-17	02:12:27	3830.33	-2717.53
T7_03	1999-07-18	16:14:00	3833.42	-2712.18
T7_04	1999-07-19	02:47:00	3852.76	-2728.60
T7_05	1999-07-19	10:23:43	3852.76	-2821.3396
T7_06	1999-07-27	23:28:32	3830.1477	-2645.9419

Table 3: Date and Position information of CTD and XBT stations.

Once collected, the XBT data were edited to update file headers and to remove bad and suspicious data and immediately put into the database. The depth readings were corrected according to [8]. A few procedures were then prepared for the browsing and plotting of the data, along with the procedures for the creation of the velocity profiles for the sonar reprocessing. These last accounted primarily for the present cruise data for the upper layer down to 700-800 m. After this depth the profiles were integrated with the best available data found in the historical databases.

Two of the XBT launched SE of Terceira presented an anomalous temperature profile. These data will be further analysed and compared with the TOBI CTD data to check this temperature anomaly.

6 TOBI SIDE-SCAN IMAGERY AND SWATH BATHYMETRY - DATA ORGANIZATION AND PRE-PROCESSING

The processing on board was mainly aimed at (a) verifying the positioning data of the tow-fish, and (b) picking the phase wraps (swath bathymetry) from the TOBI data. Once magneto-otical cartridges were filled, they were immediately copied onto CD-ROM, which could then be ported to the SUN WS for merging with navigation data. The merged files were then used for pre-processing of TOBI images. The navigation data were used to produce navigation maps which were then used as base-maps for mosaicking printouts of the sidescan sonar images by hand (for preliminary interpretation aboard ship).

6.1 NAVIGATION PROCESSING

The tow fish was positioned by the merging and filtering of a) ship's POS1 data , b) HPR Acoustic positioning data on the tow-fish depressor (range, depth from POS1, bearing from ship's heading), and c) cable length, tow-fish depth and azimuth as measured and recorded by the TOBI data loggers. To do so we developed a model of the cable. The attitude data data were used applied in the following sequence:

1. analyze the catenary problem and develop the cable model (2nd order aproximation of the catenary equation)
2. merge the nav data (ship and tow-fish) into a single file
3. smooth the tow-fish nav data (5 min moving average) (wire out, depth and heading)
4. smooth the ship's heading (5 min moving average)
5. median filter the HPR data (bearing and depth) based on the discrepency between observed value and the model's predicted value
6. resample at 1 min rate
7. smooth the HPR's range, bearing (11 min window)
8. calculate the best tow-fish position using ship position, filtered HPR range and bearing (in case of lack of HPR data the model prediction is used)

6.2 THE CABLE MODEL - RANGE PREDICTION USING VEHICLE DEPTH AND CABLE LENGTH

When towing the sensor, the cable may assume a shape which can be described by the well known catenary formula ([9]).

Herafter we will describe the procedure for calculating the best tow-fish position by the wire-out length and depth of the sensor.

In Fig.12 the analytical sketch of the problem is presented.

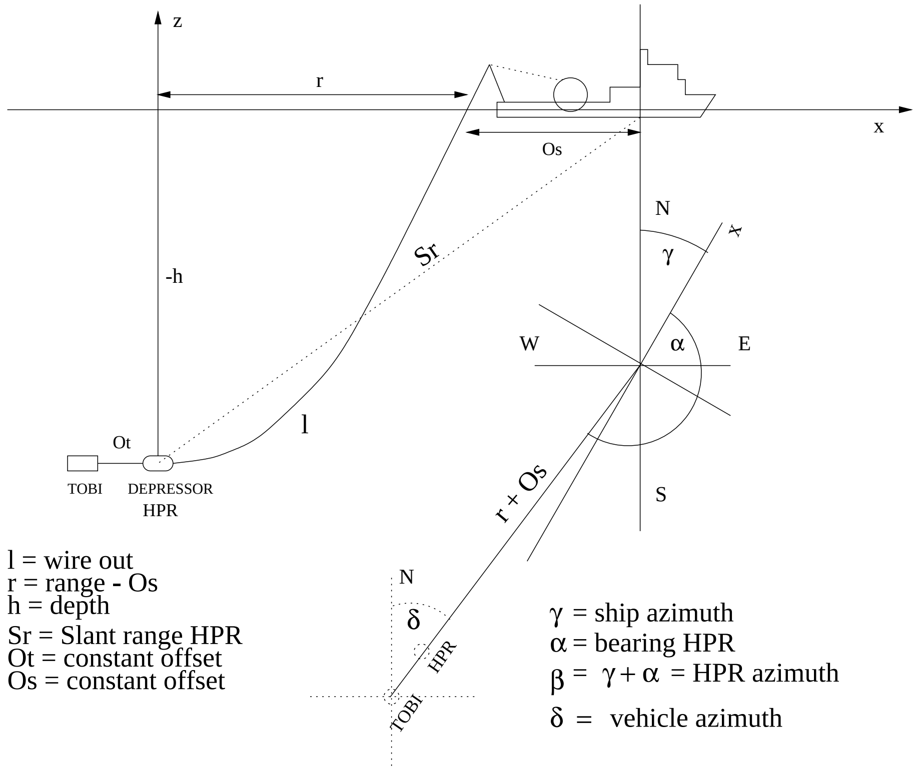


Figure 12: Analytical sketch of the tow-fish position problem. Note that the the catenary is schematic only and not to scale.Note also that acoustic variability and refraction of ray paths leads to errors in range (Sr) and depth derived by the Simrad HPR system.

The catenary equation can be written as:

$$z(x) = \frac{ah}{2}\left[e^{x/h} + e^{-x/h}\right] + b = ah\cosh\left(\frac{x}{h}\right) + b \tag{1}$$

where h is the vehicle depth, a and b are parameters to be determined according to the boundary conditions. We assume that:

$$\begin{cases} z(x) = -h & \text{with } x = 0 \\ z(x) = 0 & \text{with } x = r \end{cases} \tag{2}$$

The cable length is :

$$l(r) = \int_0^r \sqrt{1 + [z'(x)]^2}\,dx \tag{3}$$

In order to obtain an analitycal expression of Eq.3, we approximate the function $z(x)$ of Eq.1 by a 2^{nd} order Taylor expansion:

$$z(x) \cong \tilde{z}(x) = z(0) + \frac{1}{2!}\frac{\partial^2 z}{\partial x^2}\bigg|_{x=0} x^2 = (ah + b) + \frac{1}{2}\frac{ax^2}{h} \tag{4}$$

Given the boundary conditions in (2) we obtain:

$$\begin{cases} a = \frac{2h^2}{r^2} \\ b = -h(1 + \frac{2h^2}{r^2}) \end{cases} \Rightarrow \tilde{z}(x) = \frac{h}{r^2}(x^2 - r^2) \tag{5}$$

Given the Eq.3 the length of the cable is

$$l(r) = \int_0^r \sqrt{1 + \left[\frac{2hx}{r^2}\right]^2} dx = \frac{2h}{r^2} \int_0^r \sqrt{\left(\frac{r^2}{2h}\right)^2 + x^2} dx \tag{6}$$

Let $a = \frac{r^2}{2h}$, therefore Eq.6 becomes:

$$l(r) = \frac{1}{a} \int_0^r \sqrt{a^2 + x^2} dx = \frac{1}{2} \left\{ \sqrt{r^2 + 4h^2} + \frac{r^2}{2h} \ln \left[\frac{2h + \sqrt{r^2 + 4h^2}}{r} \right] \right\} \tag{7}$$

Using Eq. 7 we are able to calculate the cable length given the range distance r and the vehicle depth h.

Given the cable length l_0 and vehicle depth h, in order to solve the inverse problem, we use the Newton-Rapson iterative method, that is:

$$f(r) = l(r) - l_0 = 0 \tag{8}$$

The value of r can be obtained by:

$$r^{\jmath+1} = r^{\jmath} - \frac{f(r^{\jmath})}{f'(r^{\jmath})} \tag{9}$$

where $\jmath$ indicates the $\jmath_{th}$ iteration, and

$$f'(r) = \frac{r}{2} \left\{ \frac{1}{\sqrt{r^2 + 4h^2}} + \frac{1}{h} \ln \left[\frac{2h + \sqrt{r^2 + 4h^2}}{r} \right] + \frac{1}{2h(2h + \sqrt{r^2 + 4h^2})} \left[\frac{r^2}{\sqrt{r^2 + 4h^2}} - 2h - \sqrt{r^2 + 4h^2} \right] \right\} \tag{10}$$

starting with the trial solution $r^{(0)} = h$. The convergence of such aproximation to the desired solution r can be evaluated by the Banach's contraction mapping theorem:

the iteration is terminated when $\frac{|r^{j+1} - r^{j}|}{r^{j+1}}$ is sufficiently small.

6.3 SWATH BATHYMETRY PRE-PROCESSING

TOBI has recently been modified to make measurements of the seafloor bathymetry across the sonar swaths. The system essentially works by trying to resolve the angle at which the sound travels between TOBI and the seafloor, so that we can use that angle, the travel time of the sound and the depth of the vehicle to compute the bathymetry. The backscattered signal from the seafloor is recorded on two horizontal rows of hydrophones (one pair on each side of TOBI) (Fig.13) and the acoustic angle is found from a slight difference in travel time (or phase) of the signal reaching the two rows of hydrophones. One difficulty with this method is that the difference in phase of signals between the two arrays does not represent a unique angle (caused by the two hydrophone arrays being 8 wavelengths apart) and a major part of our work at sea was to resolve the angle corresponding to this phase difference. This was done using software originally written by a student at the University of Leeds, UK, ([10]) based on the MATLAB ©package [11], and further software re-written by Tim LeBas of the SOC to incorporate it into the PRISM software package ([12]). At sea we upgraded the method (including also the software employed by [10]) to allow manual identification of the phase wraps (lines in the data where the measured phase difference changes by 2pi) and produced initial maps of the bathymetry for the eastern survey area (southeast of Pico, S. Jorge and Terceira). These were mosaicked using the same PRISM-based system used for the sidescan sonar imagery. The initial results show that the port side is poor over most part of the survey, while the startboard side has generally high quality measurements over the inner half of the swath. We expect the final data to be incomplete but will have sections of much higher resolution that traditional multibeam sonar data.

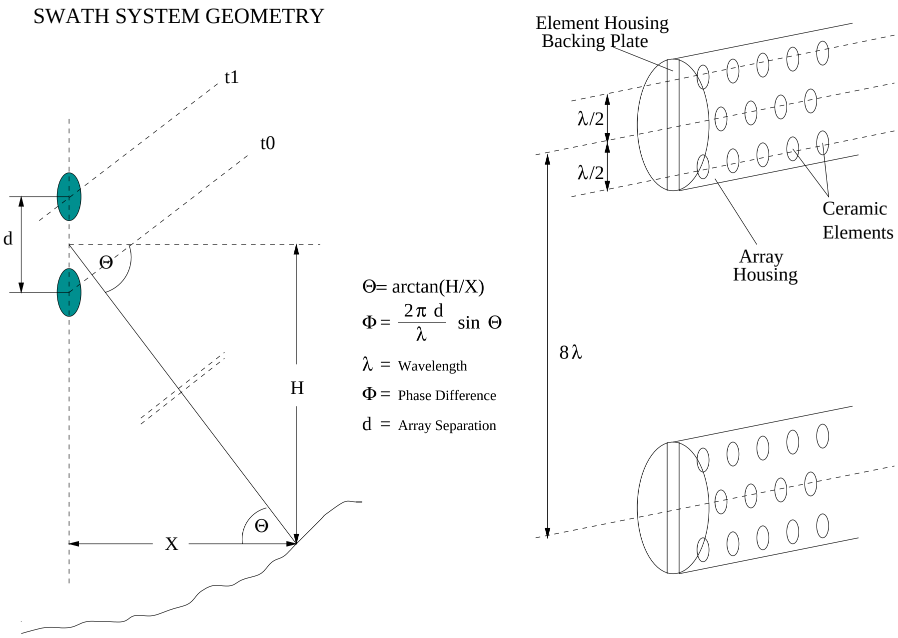


Figure 13: Phase measurement sketch.

6.4 MAPPING AND MOSAICKING

The investigated areas consisted mainly the seaward tips of the Islands of Faial, Pico, S.Jorge and Terceira. The investigated areas were divided into 6 subareas, as shown by Fig.14 to help the navigation and sonar data processing and the procedure for hand mosaicking at the scale 1:60000.

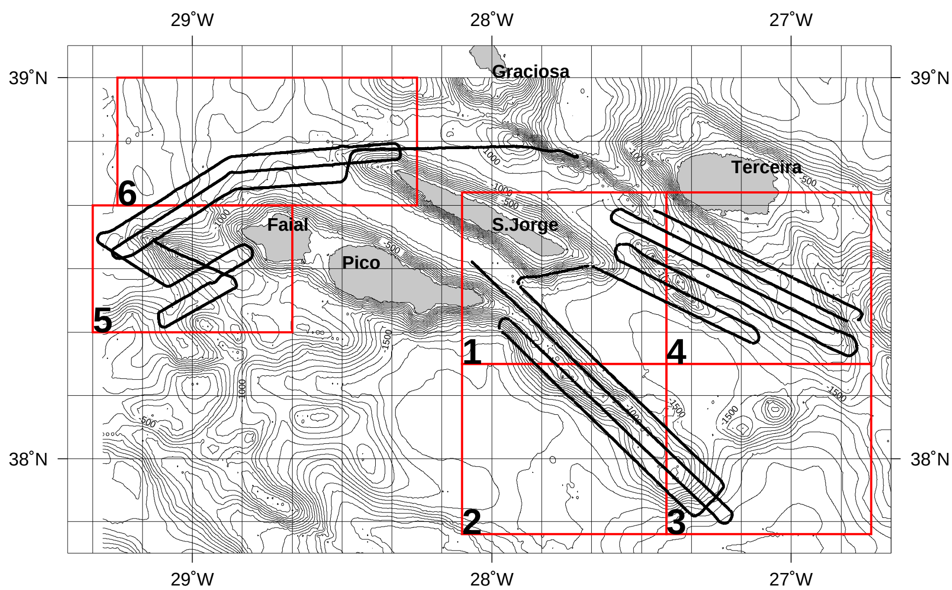


Figure 14: Areas investigated and mosaicked

During the operations on board an attempt was made to process the side-scan sonar data with the PRISM software. This was successful, though at an intermediate level. The LAN files produced by PRISM were used by the ENVI [13] package to make automated mosaicks.

6.4.1 HAND-PRODUCED TOBI MOSAICKING

The reasoning for the production of unprocessed TOBI mosaics is twofold: 1) to use the mosaic as a quality control device, 2) to begin familiarization with the data and, if appropriate begin initial interpretation.

The production of the scaled prints for mosaicking follows a sequential order as detailed below. Prior to production the working scale of the final mosaic should be determined and the width of the 6.0km TOBI swath determined for that scale (in this case, a working scale of 1:60,000 meant that the swath width would be 100.0mm).

1. The MO disk header information, and start and stop times are checked using the program ”REPTEST”.

2. The distance between successive 1/2 hour periods along the TOBI track line at the required scale are determined either by the use of software or direct measurement from the track plots. The processing PC has software that requires the input times for each file to be between full 1/2 hours marks, e.g. if a data file begins at 23:16, the first input value would be the distance between the 1/2 marks at 23:00 and 23:30 hours. This is also the case for the end of file. An ascii data file is created for each of the TOBI MO disks (usually 16.25 hours in length), labeled to match the MO disk number. i.e. MO disk No.197 would have an ascii file created called ”197.ana”

3. The raw sidescan data are downloaded from MO disk to the processing PC and scaled at the same time using the programme ”ERASDISK” and the ”.ana” files for subsequent replaying. A number of parameters are entered such as file name modifier and the offset into the file in minutes, the gamma and gain values (affecting the brightness and contrast of the final print, for this cruise gamma=0.6, gain=1.0), and finally the desired swath width in mm. Scaling is achieved simply by the repetition of lines of sonar data until each 1/2 hour time stamp is the same as in the ”.ana” input file. The output from ERASDISK is written to the PC hard disk as special ”.scl” files. As the programme reads the data from the MO disk and scales it appropriately, the final sonar image is displayed on the PC monitor as a waterfall display.

4. The final scaled sonar data are then replayed through a Raytheon thermal line scan recorder using the programme ”DISCCRAY”.

5. The TOBI 7.5kHz profiler data is replayed using the programme ”PROFRAY”. This software reads directly from the MO disk, and uses the encoded depth and altitude data to correct for variation in tow-cable length. Required inputs include the length of time required to be replayed and a ”decimation factor” (roughness of the seafloor topography).

7 RESULTS AND CONCLUSIONS

The TOBI survey was almost enterely devoted to the central group of islands (Terceira, Pico, Graciosa, Faial and Sao Jorge) where seismotectonic studies show an extensional regime with structures lying parallel to the Terceira Ridge. The Terceira Ridge, originally thought to be the westernmost boundary between the Euroasiatic and African plates, is also considered to act as a slow spreading axis or as a leaky transform fault. For this reason the survey was planned and carried out along the Terceira Ridge, with a WNW-ESE direction, and along other parallel volcanic ridges. The high quality images gained during the Azzorre99 cruise, where submarine volcanoes and associated fault systems were spectacularly revealed, will throw much new light on this poorly known area. Data processing to be performed at the SOC during the next few months will further improve the images of these structures and will make it possible for us to develop an understanding of the relationship between onshore and offshore structures. At this early stage, it seems reasonable to be optimistic that the quality and amount of data acquired will lead to several high quality research publications.

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A TOBI OPERATIONS

This section was prepared by the TOBI team. TOBI was launched and recovered five times during the cruise. The logging times are listed below on Tab.4 along with relevant comments:

The disks used and their relevant times are listed in Table 5.

The Urania is equipped with a stern mounted 5 tonne hydraulic 'A' frame. The frame has three locations for towing blocks. The main sheave was hung from the middle position via a swivel and used for deploying and recovering both the TOBI vehicle and the depressor weight.

The A' frame has been considerably modified since the TIVOLI cruise in 1998. The wider stance and taller cross piece have made the launching and recovery of TOBI much easier tasks, allowing the system to be deployed and recovered in higher sea states than previously. This gives a far greater flexibility to the use of TOBI on the Urania that in turn helps the planning of the scientific survey.

In calm conditions the TOBI vehicle could be launched directly in a fore-aft position. In other conditions and for recovery a normal sideways position was adopted to give maximum control over the vehicle. The only problem encountered was that the stern doors reduce the effective width of the A' frame and make it difficult to position TOBI especially during recovery. Particular care had to be taken to ensure that the umbilical cable was not trapped between the vehicle and the stern doors or undue bending applied. Data Recording and ReplayData from the TOBI vehicle is recorded onto 1.2Gbyte magneto-optical (M-O) disks. One side of each disk gives approximately 16 hours 10 minutes of recording time. All data from the vehicle is recorded along with wire out and ship position taken from the GPS receiver. Data was recorded using TOBI programme LOG.C. The profiler data was corrected for the depth of the vehicle and replayed in programme PROFRAY.C. BLOWUP.C was used to generate large images of areas of interest. Data from the M-O disks were copied onto CD-ROMs for archive and for importation into the on board image processing systems.

During the cruise scaled sidescan images were generated at 1:60000 using the TOBI sidescan data, vehicle positional data from the HPR navigation system and replay programmes ERASDISC.C and DISSCRAY.C. The images were printed out using a Raytheon TDU850 thermal printer and then manually overlaid on track charts to create mosaics of the work area.

TOBI Watchkeeping

TOBI watchkeeping was split into three four-hour watches repeating every 12 hours. Watchkeepers kept the TOBI vehicle flying at a height of between 350 to 400m above the seabed by varying wire out and/or ship speed. Ship speed was usually kept between 2.0 and 2.5knts over the ground, depending on wire out, with fine adjustments carried out by using the winch. As well as flying the vehicle and monitoring the instruments watchkeepers also kept track of disk changes and course alterations.

RUN	START TIME & DATE	END TIME & DATE	COMMENT
0	08.30/190		Launch aborted after open circuit found.
1	21.30/190	02.30/191	Curtailed due to electrical short.
2	14.26/191	22.38/199	End of run1. Noise on record.
3	21.26/202	21.45/202	Curtailed due to open circuit.
4	02.06/203	18.04/208	End of science cruise.

Table 4: TOBI runs.

M-O Number	File Name	time start	time end	comment	profiler roll
690	TOBI.DAT	2130/190	0230/191		1
690	TOBIA.DAT	1426/191	0145/192		2
691	TOBI.DAT	0145/192	1755/192		3
692	TOBI.DAT	1755/192	1004/193		4
693	TOBI.DAT	1004/193	0213/194		5
694	TOBI.DAT	0213/194	1822/194		6
695	TOBI.DAT	1822/194	1031/195		7
696	TOBI.DAT	1031/195	0240/196		8
697	TOBI.DAT	0240/196	1849/196		9
698	TOBI.DAT	1849/196	1058/197		10
699	TOBI.DAT	1058/197	0307/198		11
700	TOBI.DAT	0307/198	1916/198		12
701	TOBI.DAT	1916/198	1126/199		13
702	TOBI.DAT	1126/199	2238/199		14
703	TOBI.DAT	2126/202	2145/202		-
703	TOBIA.DAT	0206/203	1758/203	no-data	15
704	TOBI.DAT	1758/203	1007/204		16
705	TOBI.DAT	1007/204	0216/205		17
706	TOBI.DAT	0216/205	1825/205		18
707	TOBI.DAT	1825/205	1034/206		19
708	TOBI.DAT	1034/206	0243/207		20
709	TOBI.DAT	0243/207	1852/207		21
710	TOBI.DAT	1853/207	1102/208		22
711	TOBI.DAT	1102/208	1804/208		23

Table 5: TOBI MO logs.