NATIONAL OCEANOGRAPHY CENTRE, SOUTHAMPTON

CRUISE REPORT NO. 03

R.R.S. CHARLES DARWIN CRUISE 178

14th MARCH -11th APRIL, 2006

3D seismic acquisition over mud volcanoes in the Gulf of Cadiz and submarine landslides in the Eivissa Channel, western Mediterranean Sea

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Abstract

The major aims of Charles Darwin cruise 178 were to obtain (i) 3D seismic imagery, video transects and swath bathymetry maps of mud volcanoes in the southern Gulf of Cadiz, (ii) video transects across suspected cold water coral reefs in the Alboran Sea and (iii) 3D seismic imagery of submarine landslides in the Eivissa Channel, immediately east of the Balearic Islands in the western Mediterranean Sea. The cruise was in support of the EU Framework 6 'HERMES' project (Hotspot Ecosystem Research on the Margins of European Seas). A total of four 3D seismic cubes and 10 successful video transects were completed. Live chemosynthetic communities found on one mud volcano in the Gulf of Cadiz appear to indicate active methane seepage. Images of gas-charged sediments in areas of submarine landsliding in the Eivissa Channel appear to indicate a direct linkage between landsliding and fluid escape.

Key Words

Charles Darwin, cruise 178, HERMES, Gulf of Cadiz, Moroccan continental margin, Alboran Sea, Eivissa Channel, mud volcanoes, coldwater corals, submarine landslides, 3D seismic profiling, video transects, swath bathymetry.

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<u>Leg1</u>		
Departed	Avonmouth	14th March, 2006
Arrived:	Algeciras	3rd April, 2006
<u>Leg 2</u>		
Departed	Algeciras	3rd April, 2006
Arrived	Cartagena	11th April, 2006

CRUISE OBJECTIVES

The major objective of the EU-funded FP6 Integrated Project HERMES (Hotspot Ecosystem Research on the Margins of European Seas), coordinated by Southampton Oceanography Centre, is to understand how environmental variables affect the biodiversity, structure, function and dynamics of faunal communities on the continental slope. The overall aim is to provide the scientific context for the management for European margin systems.

Mud volcanoes and areas of active fluid escape at the seafloor are among the 'hotspots' to be targeted by HERMES. Improving our understanding of the processes involved in transporting organic-rich fluids from the geosphere into the biosphere is an important HERMES goal, because these fluids have a profound impact both on benthic ecosystems and the deep biosphere. Flux rates within passive margin fluid flow systems vary by several orders of magnitude from small, episodically active cold seeps to continuously active mud volcanoes. However, little is known of the subsurface processes that control fluid flow or about the impact of these processes on benthic ecosystems.

Gulf of Cadiz/Moroccan continental margin

<u>Geological Setting</u>

The Gulf of Cadiz is located west of the Gibraltar Strait, bounded by the Iberian Peninsula and Morocco (Fig. 1). Its geological setting is complex, and some aspects, such as the nature of deep underlying structures and a possible subduction zone (e.g. Gutscher et al., 2002), are still under debate. In general, an accretionary wedge has formed by the westward motion of the Betic-Rif front (Maldonado et al., 1999). This is the westernmost Alpine deformation zone and obtained its arcuate shape through the westward motion of the Alboran Domain. The accretionary wedge was formed during middle Miocene times. Basin deepening towards the end of the Miocene led to gravitational instability and the formation of large mass wasting nappes ('olistostromes') in the

Tortonian; these now cover the main part of the Gulf of Cadiz seafloor (Maestro et al., 2003), extending towards the Horseshoe and Seine abyssal planes. The chaotic nature of this body complicates its interpretation, although many thrusts are recognized at the foot of the structures (Medialdea et al., 2004). Recent reactivation of normal faults has led to diapirism in the north of the Gulf of Cadiz (Somoza et al., 2003), and the escape of overpressured fluids and gas has fuelled mud volcanoes (Gardner, 2001; Pinheiro et al., 2003). Other fluid-escape related structures such as authigenic carbonate precipitation (Diaz-del Rio et al., 2003) and pockmarks (Baraza and Ercilla, 1996) also occur.

The northwest Moroccan margin is characterized by tectonically distinct areas (Flinch, 1993). The northernmost part of the margin, west of Tanger, is part of the fold-and-thrust belt of the External Rif. These external zones contain thrust sheets that formed during an overall foreland-progressing Alpine deformation (Morley, 1992). Further southward, off the city of Larache in an area characterized by extensional tectonics, deep Plio-Pleistocene basins that cover rotated blocks offsetting the top of the accretionary wedge have been created. This area is likely to be a NW continuation of the onshore Rharb Basin where similar structures are present. Further south, strike-slip and compressive tectonics and mass wasting occur (Flinch, 1993). The south edge of the Rharb Valley, north of Rabat, coincides with the toe of the accretionary wedge.

On the Moroccan continental margin, a great number of mud volcanoes have been discovered and studied in the recent years. In 1999, the first mud volcanoes where discovered at a water depth of about 1000 m (Kenyon, 2000). In 2002, a mud volcano field was discovered in the extensional area off Larache (Van Rensbergen et al., 2005). One of the mud volcanoes received much attention after the observation of a potential gas hydrate related subseafloor bottom simulating reflector (BSR) (Depreiter et al., 2005), fluid venting on the mud volcano slope (Van Rooij et al., 2005); gas bubbling in the crater (Blinova et al., 2006) was discovered more recently. Imaging this mud volcano with 3D seismic data will further define the nature and structure of this mud volcano, aspects of fluid migration within it, and its feeder system. Further southwards, one mud volcano (Meknes MV) has been discovered so far. The sparse seismic data already collected proves that the area has a very complex geological setting and will need further investigation.

Young fossil carbonate mounds are also widespread on the Moroccan margin. The Pen Duick Escarpment is a fault-bounded cliff topped by tens of small (up to 50 m high) carbonate mounds. Live coral is sparse and most mounds are covered by muddy sediments. Other ridge structures often host small dead coral patches. In the framework of the HERMES project, this area will be further studied to unveil the influence of Mediterranean outflow from the north and seasonal upwelling from the south on the growth of these mounds in the past.

Specific Objectives

To address the objectives outlined above, it was intended to undertake:

(i) multibeam bathymetry surveys of the mud volcano field in the Gulf of Cadiz,

(ii) a high-resolution 3D seismic survey over a mud volcano or group of mud volcanoes in the Gulf of Cadiz, and

(iii) a preliminary photographic reconnaissance study of mud volcanoes to get an inventory of morphological and ecosystem diversity.

The mud volcanoes in the Gulf of Cadiz are more active and more numerous than anywhere else on the European Atlantic margins because they are located in a compressional tectonic province. The survey work undertaken during this cruise is an essential prerequisite for the HERMES ROV cruise planned for 2006 and will result in much more efficient use of the ROV.

The following scientific questions will be addressed by the cruise:

1. How variable is the seabed expression of mud volcanoes and can this be related to variation in sub-surface structure?
2. What is the relationship between the location of active mud volcanoes and tectonic structures?
3. Is there a continuous transport of material from the source region to the surface, or is there evidence for buffer zones (mud chambers) in which the material can differentiate?
4. Is it possible to constrain the mechanism for the Great Lisbon Earthquake (Gutscher, 2004) by improving our understanding of the fluid flow systems in the Gulf of Cadiz?
5. How does fluid venting influence the biology and geochemistry of the seabed near mud volcanoes?

Methods

Several multibeam surveys have already been carried out in the Gulf of Cadiz mud volcano province. Data from these will be collated to identify gaps that remain to be surveyed and key areas for detailed study. A high-resolution 3D seismic experiment above one active mud volcano (or preferably a group of mud volcanoes showing differences in recent activity) will be carried out to image the internal structure of these geological features. The NOC's high-resolution system is suitable for high-resolution imaging in water depths up to 2000 m. The system will be deployed to cover an area of 25 km^2. The resulting 3D seismic cube should image the upper 500-1000 m of the mud volcano and should allow a detailed structural analysis to constrain its governing processes. Finally, we will take video transects across the mud volcanoes to identify suitable ROV sites for subsequent HERMES cruises.

Alboran Sea and Eivissa Channel

Geological setting

The Alboran Sea is the basin connecting the Mediterranean Sea and the Atlantic Ocean immediately to the east of the Strait of Gibraltar (Fig. 1) and is, therefore, strongly influenced by the entering of Atlantic surface waters forming two mesoscale gyres in the Alboran Sea. The intermediate and deep-water layers form the Mediterranean Outflow that moves westwards and spreads along the Portuguese and North African margins after crossing the Strait of Gibraltar. This hydrological setting favours the upwelling of deep, nutrient-rich waters along the edges of the mesoscale gyres to the point that the Alboran Sea is one of the areas with the highest primary productivity in the Mediterranean Sea.

The seafloor of the Alboran Sea has a rough topography with ridges and seamounts of volcanic origin hundreds of meters high. The most prominent of these ridges is the one connecting the Xauen Bank to the south with the Alboran Islet ridge to the north along a SW-NE direction. The 1500 m deep Western Alboran Basin develops between the Gibraltar sill and the Xauen-Alboran ridge while the 1900 m deep Eastern Alboran Basin develops to the east. The 1500 m deep northern Alboran Passage is a narrowing opening between the Xauen-Alboran Islet ridge and a parallel ridge to the north. This passage favours deep-water exchange between the Eastern and the Western Alboran basins.

Such an intricate morphology reflects the active tectonic setting of the Alboran Sea between the northwards moving African plate and the Iberia microplate. Some authors claim the existence of an Alboran microplate. Faulting has clear expressions on the seafloor of the Alboran Sea as shown by a recent multibeam map (Instituto Español de Oceanografía –IEO-, pers. comm.) of the Spanish margin and deep basins. SW-NE and SSW-NNE oriented faults are clearly distinguishable on the IEO multibeam map. One of the most prominent faults, the Carboneras Fault that can also be traced on land in Almeria, shifts by 90° the direction of some of the northern tributaries of the Almeria Canyon. Seismic activity associated to the faults in the Alboran Sea region has led to destructive earthquakes in historical times. About 15 historical tsunamis have been reported in the Alboran Sea by the Spanish Instituto Geográfico Nacional.

Submarine canyons in the Alboran Sea are not particularly well developed with the exception of the Almeria Canyon system to the east. Several landslide scars could be observed as well on the IEO multibeam map. The occurrence of benthic carbonate deposits atop of the ridges (i.e. the Alboran Islet ridge) and seamounts has been known for decades (i.e. Stanley, 1972). This includes the occurrence of death deep-water corals recovered mostly by dredging during previous cruises starting in 1978 with R/V Eastward.

The Eivissa Channel (or Canal de Ibiza) is a relatively shallow gateway connecting the Valencia Trough to the north with the Algerian Basin to the south. The channel opens between the Iberian Peninsula and the islands of Eivissa and Formentera in the Baleares. Water exchanges may occur in both directions depending on the time of year and on general circulation patterns.

The Channel is part of the northeastward prolongation of the external zone of the Betic Ranges from the Iberian Peninsula. Three physiographic elements form the Eivissa Channel: (i) the 100-130 m deep continental shelves of Alacante and Eivissa, (ii) the continental slopes down to 800 m deep, and (iii) a smooth median depression locally exceeding 900 m in depth. This median depression is interrupted by the 200 m high, W-E trending Xabia Seamount. The seamount divides the deep Eivissa Channel in two sectors, one to the north and one to the south. A W-E oriented depression and sediment ridge occupies the base of the southern flank of the Xabia Seamount.

During two surveys in 1995 and 2002, researchers of the University of Barcelona swath mapped and collected very high resolution seismic reflection data over a set of four shallow landslides destabilising the slope to the east of the Channel at water depths ranging from 600 m to 900 m. These slides are up to 50 m thick, < 16 km^2 in area and < 0.4 km^3 in volume. The slip plane is the same for the four slides and they are associated with pockmarks of various sizes (Lastras et al., 2004). It has been interpreted that basal dragging during remobilisation disturbed the in situ sediments underlying the downslope moving sediment mass.

<u>Specific Objectives</u>

The objective for the Alboran Sea site was to investigate possible deep-water coral occurrences on seamounts to the northeastern part of the basin using the SHRIMP video camera system of NOCS.

The main target is the >300 m high, flat-topped Saco de los Olivos seamount to the south of Campo de Dalias in Almeria, with minimum depths of about 70 m. During previous cruises and also during the COBAS cruise onboard R/V Urania in April 2004 dredge samples were collected including dead coral branches amidst a sandy mud matrix, and the aim now is to check how these coral thanotocenoses appear on the seafloor and to check whether there are living colonies.

The first objective in the Eivissa Channel is acquiring a high-resolution 3D seismic reflection box of the Ana Slide with the PCable system. The Ana Slide is the southernmost slide of the four slides found in this area. It has a distinct headwall, stratified tilted blocks in the upper part, and a well developed terminal depositional lobe (Lastras et al., 2004).

NARRATIVE (times in GMT except where otherwise noted)

13th March 2006.

Scientific party embarked. Mobilisation of 3D seismic system.

14th March, 2006.

Completed mobilisation. Ship sailed 1730 local time.

1730-2400. Passage towards first working area west of Portugal.

15th March, 2006

0000-2400. Continued passage towards first working area west of Portugal.

1200. Deployed cetacean monitoring hydrophones

16th March, 2006

0000-2400. Continued passage towards first working area west of Portugal.

17th March, 2006

0800. Weather deteriorating, southerly force 6-7, passage slightly slowed.

0000-2400. Continued passage towards first working area west of Portugal. Speed slowed due to bad weather.

18th March, 2006

0000-0600. Continued passage towards first working area west of Portugal.

0600-0630. Recovered cetacean monitoring hydrophones.

0740. Start SHRIMP run 1.

0800. Power failure on swivel, run terminated.

0815. SHRIMP on deck.

0900-2400. Continue passage south to camera station in Setubal Canyon.

0940. Deploy cetacean monitoring hydrophone.

19th March, 2006

0000-0020. Continue passage south to camera station in Setubal Canyon.

0020-0050. Arrived at SHRIMP station but weather too poor for station keeping with winds reaching 35 kt and a large swell.

0050-2400. Continue passage to the Moroccan margin

20th March, 2006

0000-0240. Continue passage to the Moroccan margin

0140. Recover cetacean monitoring hydrophone

0230-0340. Complete sound velocity probe (SVP) station

0250. 3.5 kHz fish deployed.

0430-1120. Run swath bathymetry line to area of first 3D seismic survey (Mercator mud volcano).

1135-1750. Deployed 3D seismic system.

1750-2100. Tested system and moved to start of first line.

2100-2400. 3D seismic survey of Mercator mud volcano.

21st March, 2006

0005. Seismic signal lost. All outboard 3D seismic equipment lost, apparently after hitting floating debris.

0015-0100. Recovered remnants of tow and power cables of 3D seismic system.

0100-0145. Steamed back along course until paravanes and floatation were found as a single group, still attached to each other by linking cables.

0300-0800. Stood by floating gear until daylight.

0810-0945. Recovered 3D seismic gear. No equipment lost, although all tow and signal cables broken.

1000-2400. Multibeam survey adjacent to mud volcano province while assessing damage to and repairing 3D seismic system.

22nd March, 2006

0000-0900. Multibeam survey adjacent to mud volcano province. Repairs to 3D seismic system continuing.

0900-1000. Passage to SHRIMP station 178/2SH.

1000-1630. SHRIMP station 178/2SH. Good images of carbonate crusts, mud breccia and abundant shells found on crest of newly discovered mud volcano.

1630-1800. Passage to SHRIMP station 178/3SH.

1800-2230. SHRIMP station 178/3SH.

2230-2400. Multibeam survey adjacent to mud volcano province.

23rd March, 2006

0000-0900. Multibeam survey adjacent to mud volcano province.

0900-1420. SHRIMP station 178/4SH.

1445-1800. Multibeam survey and passage to 3D survey area.

1800-2104. Deploy 3D seismic equipment

2104-2400. 3D survey of Mercator mud volcano.

24th March, 2006

0000-2400. 3D survey of Mercator mud volcano.

25th March, 2006

0000-2400. 3D survey of Mercator mud volcano.

26th March, 2006

0000-2400. 3D survey of Mercator mud volcano.

27th March, 2006

0000-1528. 3D survey of Mercator mud volcano.

1320. Problem with starboard paravane on turn at end of line resulted in damage to one signal cable of 3D system, necessitating its recovery.

1502. All recovered. One signal cable broken and cross cable damaged, the latter probably due to wear resulting from towing in the persistent heavy swell.

1530-2400. Continue multibeam survey.

28th March, 2006

0000-1330. Continue multibeam survey as swell too large for SHRIMP.

1330-1437. Deploy 3D seismic system.

1437-2400. Continue 3D seismic survey of Mercator mud volcano.

29th March, 2006

0000-1848. Continue 3D seismic survey of Mercator mud volcano.

1850-1940. Recover 3D seismic equipment.

2010-2045. Complete bathymetry line at right angles to Mercator 3D seismic box for calibration purposes.

2255-0000. SHRIMP station 178/5SH.

30th March, 2006

0000-0013. SHRIMP station 178/5SH.

0013. SHRIMP recovered due to power failure.

0040- 0900. Multibeam survey on passage to next 3D seismic site.

0900-1015. Deploy 3D seismic system.

1100-2400. 3D survey over pull-apart basin on complex strike-slip fault.

31st March, 2006

0000-2400. 3D survey over pull-apart basin on complex strike-slip fault.

1st April, 2006

0000-1030. 3D survey over pull-apart basin on complex strike-slip fault.

1030-1130. Recover 3D seismic equipment.

1130-1330. Run cross line across seismic cube to cross calibrate high resolution bathymetry

1330-1840. SHRIMP station 178/6SH

1840-2150. Passage to next SHRIMP station.

2150-2400. SHRIMP station 178/7SH.

2nd April, 2006

0000-0045. SHRIMP station 178/7SH.

0045-0745. Multibeam survey.

0745-0945. SHRIMP station 178/8SH.

0945-1050. Move to next SHRIMP station

1050-1430. SHRIMP station 178/9SH

1430-1700. Multibeam survey towards Tangier mud volcano.

1700-1915. SHRIMP station 178/10SH

1930-2400. Passage to Algeciras.

3rd April, 2006

0000-0700. Passage to Algeciras

0800. Crew change.

0815-1930 Passage to work area 1 southwest of Almeria

1600. XBT deployment.

1930-2200. Multibeam survey over the coral reef colony SW of Almeria.

4th April, 2006

0135-0605. Shrimp station 178/11SH. Abundant dead corals.

0737-1110. Shrimp station 178/12SH. Abundant dead corals.

1110-2400. Passage to Eivissa Channel.

5th April, 2006

1005. 3D system deployed.

1100. Soft start airguns.

6th April, 2006

0000-2400. 3D survey over Ana Slide.

7th April, 2006

0000-2400. 3D survey over Ana Slide.

8th April, 2006

0830. Finish of Ana Slide survey.

0830-1330. Transit to Formentera study area.

1330-2400. 3D survey south of Formentera.

9th April, 2006

0000-2400. 3D survey south of Formentera.

10th April, 2006

0000-1445. 3D survey south of Formentera.

1445-1530. Recovery of the 3D system.

1530-2400. Passage to Cartagena using multibeam for the first two hours.

11th April, 2006

0730. Docking in Cartagena.

EQUIPMENT REPORTS

3D Seismic acquisition system

The P-Cable is a cost-efficient low-fold high-resolution 3D seismic acquisition system developed by Volcanic Basin Petroleum Research (VBPR) in collaboration with National Oceanography Centre, Southampton (NOCS), University of Tromsø (UiTø), and Fugro Survey AS, Oslo. The technology is covered by Norwegian Patent no 317652, UK Patent GB 2401684 and PCT application no PCT-NO03-00079 (Planke & Berndt, 2002).

The NOCS P-Cable consists of a wire that is towed perpendicular to the ships steaming direction using two specially designed paravanes. Twelve single-channel Teledyne Geophysical Instruments analogue streamers are connected to this wire. The paravanes and a tail buoy keep the cross wire at approximately 1 m depth. The doors are towed behind the ship using reinforced power cables that power the GPS receivers on each paravane. Signal cables to the on-board recording system transmit data from the streamers. The seismic data are digitized on-board using a Geometrics Geode seismic recording system. Logging and quality control of the seismic data are done using the associated PC-based Seismodule Controller software. The navigation data are recorded and calculated using a Kongsberg Seatex GPS tracking system, with a GPS antenna on the ship, on each of the paravanes and on the air gun array.

The air gun array consists of five 40 in^3 Bolt 600B airguns of which four are used at any one time. The guns are fitted with wave shape kits that emit approximately 10 in^3 of air prior to the main volume to reduce the bubble pulse. The air pressure is 2000 psi. The guns are mounted on a frame with 0.75 m spacing and towed at a nominal depth of 1.5 m approximately 20 m behind the vessel. A British Geological Survey gun controller triggers the guns to fire every 7 s.

In spite of the initial problems with the seismic acquisition system caused by the collision with floating debris, the system performed very well, delivering data of high quality. Partly this is due to the fact that RRS Charles Darwin is better suited for towing the system than previous ships. It was possible to produce preliminary 3D seismic cubes already during the cruise (Fig. 6). The effort of Henrique Duarte in writing new navigation software should be particularly emphasised here.

SHRIMP (Seabed High Resolution Imaging Platform)

The SHRIMP vehicle is used for video imaging of sea floor features up to a depth of 6000 m. The active camera systems provide 3 independent video feeds via a fibre optic multiplexer to ship side recording equipment. The deck unit consists of a fibre optic de-multiplexer system and DVD video recording equipment to store colour video images. The third monochrome video signal is not recorded and is used for operator guidance only. Telemetry in the form of magnetic heading, echo sounder height above seabed and CTD information is also transmitted to the main deck computer for storage. Lighting for the two colour camera systems comprises of two 400 W High Intensity Discharge (HID) Daylight lamps. Three red laser pointers provide scaling for the vertically mounted camera as well as acting as a guide for visual depth perception.

EM12 multibeam echosounder

The EM12 is a multibeam echosounder system manufactured by SIMRAD. It has two operating modes: in the deep mode it gives a coverage of four times the water depth, whereas the shallow mode gives a coverage of twice the water depth, but at a higher resolution. The resolution is dependent on cruise speed, water depth, and water velocity variations. During the 3D seismic surveys the swath was used in shallow mode to maximize the detail. Here the lateral resolution is better than 10 m because of the large number of sounding due to the short line spacing and the slow vessel speed (Fig. 4). A sound velocity profile was taking on reaching the first survey area and the profile was updated within the swath system manually. For the second leg of the cruise the sound velocity was manually updated during the two XBT stations to account for local variations.

3.5 kHz and Octopus 360+ System

The 3.5 kHz sub-bottom echosounder system consists of 4 transducers mounted in a fish towed from points port or starboard the vessel. Best results are obtained when the vessel speed is limited to less than 5 kt. The entire system comprises a Recorder (Octopus 360+), Transceiver (PTR105B), Correlator (all pass filter system to delay low frequency signals so as the high frequencies can catch up), and the tow fish assembly. The shipboard equipment consists of a Raytheon PTR105B unit that outputs a signal to the fish transducers when triggered by a signal pulse from the Octopus 360+ data acquisition unit. This is networked to the ships internal computer system for data storage.

Cetacean monitoring

Acoustic monitoring for cetaceans was carried out during the cruise using a towed streamer and passive acoustic monitoring (PAM) software. Douglas Gillespie and Paul Redmond were on board for leg 1 of the cruise. David McLaren and Jane Griffiths for leg 2. The primary objectives of the cetacean monitoring were:

1. To provide a mitigation service during gun start up periods in order to conform to JNCC "guidelines for minimising acoustic disturbance to marine mammals from Seismic surveys"
2. To provide a platform for developers of new PAM software to test the new 'Pamguard' software in an operational environment in order to guide future developments in this field
3. To contribute to a program of long term data collection on cetacean distribution using passive acoustic systems deployed from platforms of opportunity.

The streamer was designed primarily for the detection of odontocetes cetacean species, having a useful bandwidth from 2 kHz to 200 kHz. It was therefore unable to detect low frequency vocalisations from baleen whales (e.g. fin whales).

The streamer was deployed during the passage from Avonmouth to the Gulf of Cadiz and at all times during scientific work apart from when vessel was near stationary during SHRIMP sea floor camera work. The streamer was recovered while the 3-D seismic array was deployed and redeployed immediately after the 3-D array was in the water to monitor pre-gun start up periods.

The JNCC guidelines require monitoring for a 20 minute period prior to gun start up. If cetaceans are detected within 500 m of the guns during that period start up should be delayed until the animals have had time to move out of the area. If cetaceans move into the area after guns have started, the guidelines do not require any action to be taken.

Sound from the airgun array was gated out of the acoustic data stream and did not seriously affect data collection. However, acoustic data were seriously compromised by a number of active sonar devices operating on the Charles Darwin. These were a 10 kHz single beam echo sounder, 13 kHz multi beam echo sounder and a 3-4 kHz shallow sediment profiler. This made aural monitoring of the system for sustained periods uncomfortable. Therefore the system was monitored ‘intensively’ during pre-gun start up periods. At other times, it was left to collect data automatically for tasks 2 and 3 above.

Monitoring took place during all gun start up periods apart from the first on 20 March when the guns were started as soon as they were deployed. No cetaceans were detected at any distance during other pre-gun start up periods (up to 30 March).

A preliminary analysis of data collected up to 30th March indicates that sperm whales were detected on a number of occasions during the passage. Perpendicular distances to 21 individually tracked whales indicated that the Darwin is quiet enough for the collection of useful passive acoustic data (the 3.5 kHz was not operational during the passage). No sperm whales were detected during seismic and Swath surveys, but dolphin click trains (of unknown species) were detected on 26 occasions. It is difficult to assess from these data the distance at which animals were detected but it does indicate that acoustic monitoring was still at least partially effective despite the noisy environment. Fin whales were observed on a number of occasions from the bridge and deck. If they had vocalised, the sounds would have been too low frequency to be picked up by system in use.

SUMMARY OF RESULTS

Gulf of Cadiz/Moroccan continental margin

3D seismic profiling

3D seismic acquisition during the cruise had three main objectives: (i) Understanding the dynamics of mud volcanoes and their role in fluid escape, which in turn controls the spatial and temporal variability of chemosynthetic ecosystems, (ii) Imaging of the internal geometry of submarine landslides, and (iii) provision of site survey data for the IODP-MMV pre-proposal (Depreiter et al., 2006). In addition, we intended to collect 3D data in an area with strong lateral velocity contrasts for a quality assessment of the 3D seismic data acquisition.

As 3D seismic data acquisition requires specialised software that was not available onboard and because it is time consuming, it is not possible to obtain the final data products during the cruise. We were, however, able to build 3D seismic cubes during the cruise and visualise them in 3D seismic interpretation software (KingdomSuite). This implies that all initial interpretations are derived from low-resolution (20 m) un-migrated 3D data.

The cube from the Mercator Mud Volcano shows the mud volcano (Fig. 6) with its central feeder system on the southern flank of an anticline. It is accompanied to the northeast by a smaller mud diapir that penetrates the hemipelagic sediments almost to the seabed. The data clearly image the bottom simulating event discussed by Depreiter et al. (2005), and confirm its reverse phase for the lower frequency band provided by our data corroborating that it is caused by trapped gas and may be the seismic expression of gas hydrates in the upper 50 m of the mud volcano. Concentric normal faults are associated with a moat south of the mud volcano indicating a structural origin of the moat. Possibly it is caused by subsidence of the area covered by the mud volcano either due to loading of the sediments by the extruded mud, but more likely because of subsidence as a result of a mud chamber emptying and subsequent caldera-like collapse as described for the Caspian Sea mud volcanoes (Davies et al., 2005). This would indicate at least that the Mercator mud volcano is controlled by similar processes to the Caspian Sea mud volcanoes and that it is different from the Håkon Mosby mud volcano. The Mercator mud volcano 3D cube covers all the proposed IODP drilling sites providing an ideal data set for the drilling safety assessment for the IODP proposal. The seismic data quality of the Mercator 3D cube is very good, because of the favourable weather conditions during the acquisition. However, the data shows two lateral offsets of approximately 90 m. So far the origin of these navigation artefacts could not be determined, but they can be corrected by appropriate processing.

The cube acquired over the pull-apart basin is of even better quality as it does not suffer from the navigation problems mentioned above, because the sea was even calmer, and because sail line coverage was more regular. The pull-apart basin is approximately 1.5 by 0.5 km in size and extends in WNW-ESE direction. The data show many normal faults in its vicinity demonstrating the complex structural deformation of this area. The two objectives for acquiring this data set are to investigate whether the pull-apart basins in the Gulf of Cadiz are sites of preferential fluid venting, and to provide a test data set to test different 3D migrations for the PCable data. The data show many strong diffraction hyperbolae extending down from the seabed. It will be an ideal dataset to test how well different migration algorithms perform in such complex environments. Indicators for fluid venting associated with the pull-apart basin will not be visible before the migration is applied.

SHRIMP video transects

Video transects were carried out over 5 mud volcanoes, 2 areas of coral patches/ridges, and a fault-bounded pull-apart basin associated with a strike-slip fault related to the Neogene tectonic deformation of the area. The locations are shown in Figs. 2, 3a.

The first video line (CD178/2SH) was carried out across a newly discovered mud volcano (named the Darwin mud volcano) (about 40 m high) and pockmark structure south of it (about 35 m deep), both southwest of Yuma and Ginsburg mud volcanoes at a depth of about 1100-1200 m. The sedimentary environment showed bioturbated muddy silts, with many shrimp and/or worm burrows and sponges. The slopes of the mud volcano (angled at about 10°) were covered by sediments, and were equally bioturbated. At different places, reduced greyish sediment was brought to the surface by burrowing organisms. The crater area contained mud breccia, rock clasts and metric carbonate slabs and crusts that were not buried by sediments. Highly abundant seep-related bivalves were observed on and between the cracks of the carbonate slaps, of which some in the cracks were living and thus gave a sign of recent methane seepage (Fig. 3b). However, no ongoing seepage (bubble or fluid escape) was observed. Carbonate cemented shells were also observed. From these observations, we can conclude that the Darwin mud volcano is active, or has recently been active.

The seafloor in the pockmark south of the mud volcano showed no differences from the surrounding seafloor, except for a slightly higher occurrence of reduced sediments brought to the surface by burrowing organisms. No special fauna or activity was observed.

A single video transect over a patch of rough terrain west of Renard Ridge suggestive of small coral mounds found only evidence for dead corals (CD178/3SH). On seismic and high-resolution sub-bottom profiles, the patches were recognized by a chaotic facies, and appeared as small elevations on swath bathymetry. The sedimentary environment was muddy to silty and very bioturbated. On ridge-like elevations (a couple of meter high) with steep slopes, the dead coral patches were more abundant.

A video transect across TTR mud volcano (CD178/4SH) showed that its base and lower to middle slopes are covered by bioturbated mud. Several fields of cold water corals were observed along the upper slope. Towards the rim of the mud volcano the terrain became rougher with outcrops of mud breccia and large boulders on the seafloor. Possible carbonate crusts were noticed at one location. The deepest portion within the crater of the mud volcano appeared to be covered by bioturbated mud possibly due to ponding of the fine-grained material. No evidence of recent activity of the mud volcano was observed along the run.

A video transect on the Lazarillo de Tormes mud volcano (CD178/5SH) had to be aborted after 10 minutes due to a power failure of the SHRIMP. At that moment, only the sedimentary environment NE of the Lazarillo de Tormes mud volcano was imaged and showed moderately bioturbated muddy sediments and current-induced sediment ripples. Trawlmarks were observed. The very high turbidity of the near bottom water was notable. The second run across the mud volcano (CD178/7SH) was more successful and fields of rocky outcrops and mud breccia were observed near the summit of the mud volcano. The area appear to be an active site for fishing activities as the base of the volcano was extensively trawled and numerous bit of fishing gear were noticed caught on the rocky terrain.

The video transect over the pull-apart basin CD178/6SH traversed the basin from north to south passing both over the northern and southern strike slip faults. The seabed is muddy with occasional sponges and lobsters. Judging from shrimp induced resuspension the basin floor seems to be a very quiet environment possibly with finer sediments than the surrounding seabed. There was no seabed expression of the two faults suggesting that they have not been active in the recent past. We did not find evidence for fluid seepage along the transect.

A video transect (CD178/8SH) across newly discovered structure, Challenger mud volcano, at the north of the swath coverage showed that its northeastern flank has a much higher diversity the seabed features than the south western one. Fields of mud breccia, boulders were observed along the slope from the base and up to the top of the edifice. Several small fields of chemosynthetic bivalve shells were found at the top of the volcano indicating its possible active status.

Video transect CD178/ 9SH targeted a crest of an anticline outcropping at the north of the swath coverage. The transect also crossed a conical structure suspected to be a mud volcano on the anticline's western closure. Most of the run was along bioturbated muddy seafloor. Fields of cold water corals, mostly dead, were encountered on the northern slopes of the ridge and the conical structure. No evidence of recent activity was found on the structure itself. A small area where reduced sediments expelled on the surface by burrowing organisms were noticed is the only indication of possible presence of gas-charged sediments.

The last video transect in the Gulf of Cadiz (CD178/10SH) was run across Tanger mud volcano. It showed the structure is completely draped by bioturbated muddy sediment and is not active at the present day.

<u>Swath mapping</u>

Swath bathymetry data was acquired to the south and west of the main mud volcano province, covering a gap in the data coverage from previous research cruises (Fig. 2). The area covered is about 2500 km^2 and images Yuma, Ginsburg and Darwin mud volcanoes and the deeper extension of the Vernadsky and Renard ridges. In front of the ridges at a depth of about 800-900 m, large areas are covered by hilly structures that were object of one of the video lines (CD178/3SH, see above). In the area west and northwest of Meknes mud volcano up to a depth of about 1450 m, large thrust faults and strike slip faults with associated pull-apart basins were imaged.

Swath mapping during seismic acquisition over Mercator mud volcano (Fig. 4), and a pull-apart basin (Fig. 7), has yielded high resolution bathymetry of these structures.

Alboran Sea and Eivissa Channel

<u>Shrimp Video Surveys</u>

Two SHRIMP deployments were performed on the eastern flank of Seco de los Olivos seamount and on a nearby lower elevation ridge to the east in the Eastern Alboran Basin (Fig. 8). A detailed multibeam survey was conducted in order to obtain a good morphological map of the proposed SHRIMP tracks. The swath bathymetry survey cross the seamount from W-E and partly covers its top and eastern flank along proven coral occurrences (HERMES COBAS cruise). The SHRIMP tracks started in a relatively flat area at about 460 m water depth and went upslope towards the summit of the bank at about 100 m water depth. The first dive crossed the main eastern flank, which is characterised on the upper flank by steep ramps (up to 20°). The second transect crossed a small associated ridge on the eastern flank of unknown origin (volcanic or sedimentary) and the steep eastern flank of the seamount.

The flat seabed area consists of heavily bioturbated muddy sediments. At the foot of the seamount, darker spots have been observed, which represent outcropping rocks and (dead) coral fragments. On the steepest flanks of the seamount, pebbles and boulders are colonised by a variety of benthic species including cold water corals. The fossil cold water coral density is highest on the steep upper flanks of the seamount. Dead corals are observed on outcropping rocks along the steep flank. The second dive showed the same pattern of bioturbated muddy sediments in the relatively flat areas and with increasing slope gradient pebbles and coral fragments are more common in the muddy sediments. At the steepest ramps and at one escarpment high concentrations of cold water corals have been identified in water depths around 250-300 m. The corals have a reddish-brownish appearance of Fe- Mn coating. This colour and coating is commonly found on cold water corals in the Mediterranean Sea. From the first observations it is not obvious whether framework building corals are alive in this area. In the coral zone sponges exist. Some of these may be glass sponges. This type of sponge is often found in cold-water coral ecosystems. The ridge located at the eastern side of the seamount is characterised by steep flanks. The steepest slope along the transect display rocky seabed and high concentrations of coral fragments and giant oysters.

During the second dive, the SHRIMP system hit the flank of steep slopes along the eastern ridge at about 410 m water depth and, as a consequence, fragments of the outcropping materials fell on top of the SHRIMP frame where they were retained by the protecting metallic net. Once the SHRIMP was on deck we could observe that these flank fragments are composed of giant fossil oysters colonised by *Lophelia sp*., *Madrepora sp*., *Desmophyllum sp*. and *Caryophyllia smithi* corals. The dominant corals on the recovered oyster shells are the ahermatypic (solitary) corals *Desmophyllum sp*. and *Caryophyllia smithi*. The corals are small in size and seem to be juvenile, though most of them look dead. Only a few of them may be alive. The oysters and corals are colonised by epifauna. The samples have been dried and bagged for further analysis at the lab.

Throughout the survey several trawl marks and or dredging marks were observed. At a few locations, lines and other fishing gear was observed.

3D seismic profiling

During the second leg of the cruise we collected two 3D seismic cubes along with EM12 multibeam bathymetry (Fig. 9). The first cube is 2.2 by 7 km in size and includes the Ana Slide in the Eivissa Channel (Lastras et al., 2004). The slide has an up to 20 m high headwall to the east and a westward run-out distance of approximately 3 km. The new data (multibeam and 3D seismics) show that the run-out of the Ana Slide is somewhat less than measured by Lastras et al. (2004). The 3D data show that it consists of a source region that is almost completely deprived of mobilised material, a chute that is characterised by chaotic internal reflectivity, and an accumulation area with thrust faults and compressional ridges (Fig. 10). The Ana Slide is underlain by a similar though bigger slide that originated in the same place as the Ana Slide, but had approximately 5 km run-out distance. Therefore, slope destabilisation events seem to be recurrent in the same source area. The Ana Slide stopped at the beginning of the accumulation area of this second, previous slide, possibly as a result of buttressing due to the seabed topography created by the depositional lobe of the earlier slide. Pockmark-like elongated features have been identified to the west of the block, over the buried earlier slide. Both slides are within the Plio-Pleistocene sediments that overlie the acoustic basement, which most likely consists of Cenozoic and/or Mesozoic limestones that were eroded during the Messinian desiccation of the Mediterranean Sea, 5 My ago. The Messinian erosional surface is clearly distinguishable in the 3D cube, and marks the onset of the Plio- Pleistocene sedimentation after the early Pliocene re-flooding of the basin. The thickness of the Plio-Pleistocene succession reaches from 150 m in the east to 350 m in the west of the cube. In the sediments tentatively attributed to the Pliocene several strong reverse-polarity reflections exist, which may indicate the presence of free gas. This observation is corroborated by seismic disturbance zones emanating from these high-amplitude reflections. This interpretation has to be confirmed by further processing of the seismic data.

We collected a second 3D seismic cube 20 nautical miles southwest of Eivissa and Formentera islands (Fig. 9). The size of the cube as initially planned was similar to the former one. This cube includes several 300-500 m wide seabed depressions of more than 20 m relief, which we initially interpreted as pockmarks. The 3D seismic data over these structures show, however, no disturbance between the acoustic basement and the 50-100 m of overlying sediments. Instead the seafloor depressions coincide with depressions in the basement (the Messinian erosional surface and the pre-Plio-Pleistocene rocks below) suggesting that they are related to a geological process that affects the basement. As the basement most likely consists of limestones affected by karst development, a possible scenario is differential compaction of sediments that fill either pre-existing or still developing dolinas. Several previously unknown, much smaller, pockmark-like depressions have been also evidenced by the multibeam data. At the slope break to the southeast of the cube several 100 m wide sediment packages exist that have the same geometry as the sediment waves of the Humboldt feature offshore Oregon or the sedimentary structures offshore Ortona in the Adriatic Sea. As with these other examples it is difficult to distinguish between gravitational slope movement and sediment deposition in the presence of bottom currents as the origin of these structures. The multibeam bathymetry data show that the structures are curvilinear in plan view, which may suggest gravitational sediment deformation as the dominant process. However, the curved shape may also be caused by current deviations caused by the complex margin topography. During a survey (SBAL-DEEP cruise) onboard R/V Explora in October 2005 evidences of landslide lobes were identified downslope of the area investigated in the current survey.

The preliminary examination of the two 3D cubes west and southwest of Eivissa-Formentera shows that the thickness of the Plio-Pleistocene sediment cover on the islands submarine flanks is very limited (up to 350 m) thus pointing to low sedimentation rates. Notwithstanding, this was enough to trigger shallow submarine landslides in the Eivissa Channel and could be also related to the current seafloor expression of hundreds of meter in diameter and tens of meters in depth basement depressions, of possible karstic origin, southwest of the Eivissa-Formentera archipelago.

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TABLES

Table 1. Summary of cruise activities

Date	Mobilisation (hr)	Multibeam survey (hr)	3D Seismic survey (hr)	SHRIMP video (hr)	Downtime (hr)	Passage (hr)
14/03/06	18					6
15/03/06						24
16/03/06						24
17/03/06						24
18/03/06				2		22
19/03/06					1	23
20/03/06		8	13			3
21/03/06		14			10	
22/03/06		10.5		9		2.5
23/03/06		12	6	6		
24/03/06			24			
25/03/06			24			
26/03/06			24			
27/03/06		8.5	15.5			
28/03/06		13.5	10.5			
29/03/06		3.5	19.5	1		
30/03/06		9	15			
31/03/06			24			
01/04/06		2	11.5	10.5		
02/04/06		9.5		10		4.5
03/04/06	1	2.5			2	18.5
04/04/06				8	3	13
05/04/06			14			10
06/04/06			24			
07/04/06			24			
08/04/06			24			
09/04/06			24			
10/04/06		2	15			7
11/04/06						8
Totals (days)	**19 hr (0.8)**	**95 hr (4)**	**312 hr (13)**	**46.5 hr (2)**	**16 hr (0.7)**	**189.5 hr (7.9)**

Table 2. SHRIMP camera stations

Station number	**Start position**	**Start time**	**End position**	**End Time**	**Comments**
178/1SH	39° 35.5'N 9° 24.1'W	0742/77 (18/3/06)	39° 35.5'N 9° 24.1'W	0815/77 (18/3/06)	Swivel failure, station abandoned
178/2SH	35° 16.3'N, 07° 10.5'W	1023/81 (22/3/06)	35° 22.2'N 07°11.9'W	1628/81 (22/3/06)	Darwin mud volcano (active seepage) and adjacent pock mark
178/3SH	35° 21.9°N 06° 59.8'W	1827/81 (22/3/06)	35° 20.0'N 07° 00.4'W	2261/81 (22/3/06)	Ridges with corals (mainly dead)
178/4SH	35° 22.9'N 06° 56.5'W	0928/82 (23/3/06)	35° 22.1'N 06°55.3'W	1420/82 (23/3/06)	TTR mud volcano (not active?)
178/5SH	35° 19.8'N, 06° 45.4'W	2255/88 (29/3/06)	35° 19.5'N, 06° 45.8'W	0013/89 (30/3/06)	Swivel power lead failure, station abandoned.
178/6SH	35° 18.1'N 07° 20.4'W	1333/91 (01/4/06)	35° 15.4'N 07° 19.2'W	1840/91 (01/4/06)	Small pull-apart basin on strike-slip fault. All muddy seafloor
178/7SH	35° 19.4'N 06° 46.2'W	2150/91 (01/4/06	35° 18.9'N 06° 46.7'W	0045/92 (02/4/06)	Small mud volcano, some 'fresh' breccia, no active seeps?
178/8SH	35° 26.9'N, 06° 57.9'W	0745/92 (02/4/06)	35° 26.3'N 06° 58.5'W	O944/92 (02/4/06)	'Challenger' mud volcano. Patches of dead shells. Active?
178/9SH	35° 24.7'N 06° 58.5'W	1050/92 (02/4/06)	35°23.7'N 06° 59.5'W	1430/92 (02/4/06)	Coral ridge. Large areas of coral almost entirely dead
178/10SH	35° 33.8'N 06° 48.0'W	1700/92 (02/4/06)	35° 33.0'N 06° 48.3'W	1915/92 (02/4/06)	Tangier mud volcano. No evidence for activity
178/11SH	36° 30.7'N 02° 48.3'W	0135/94 (04/4/06)	36° 31.1'N 02° 50.4'W	0605/94 (04/4/06)	Coral reefs on volcanic outcrop SW of Almeria
178/12SH	36° 31.2'N 02° 50.0'W	0737/94 (04/4/06)	36° 31.0'N 02° 48.3'W	1110/94 (04/4/94	Coral reefs on volcanic outcrop SW of Almeria

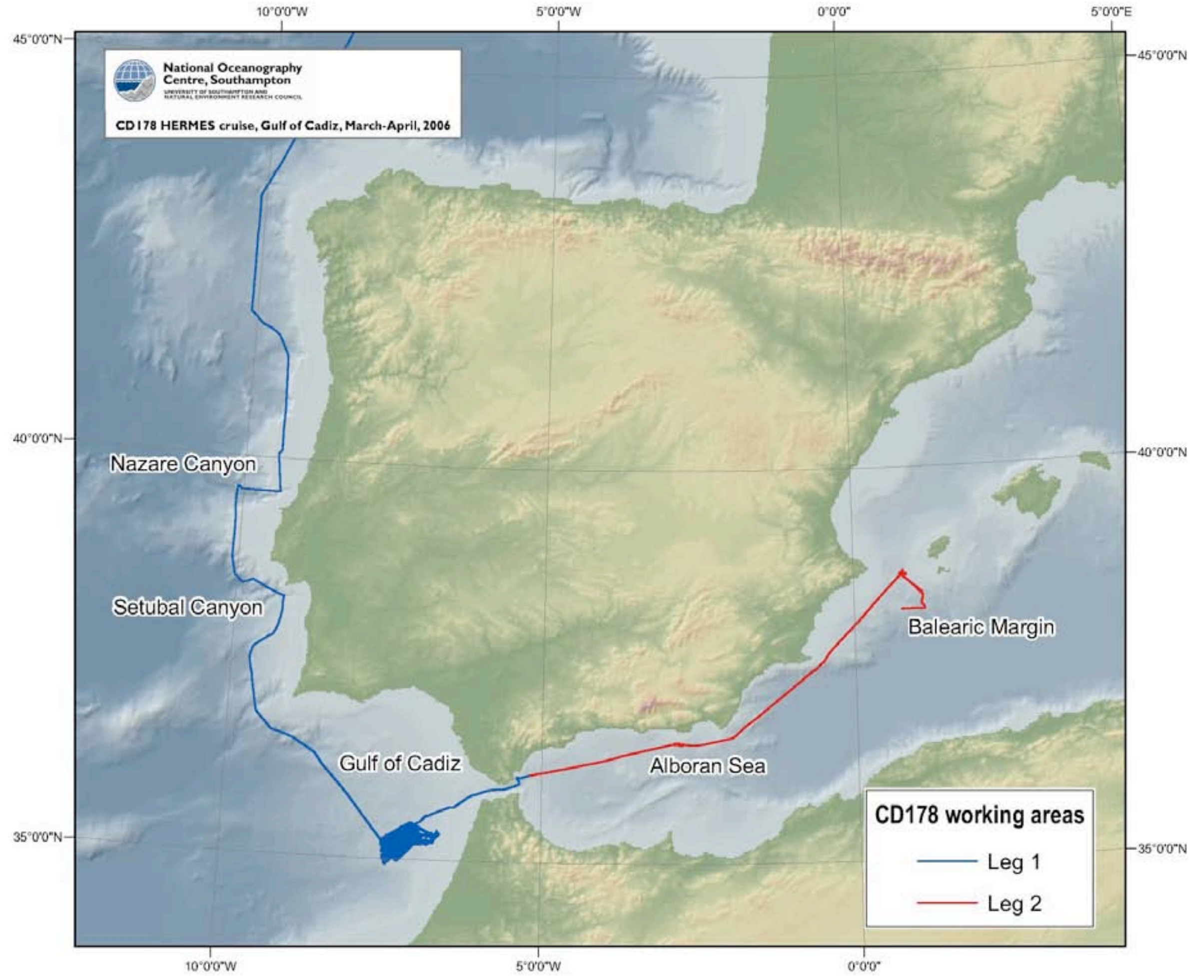


Figure 1. Location of study areas west of Portugal, in the Gulf of Cadiz and in the western Mediterranean Sea.

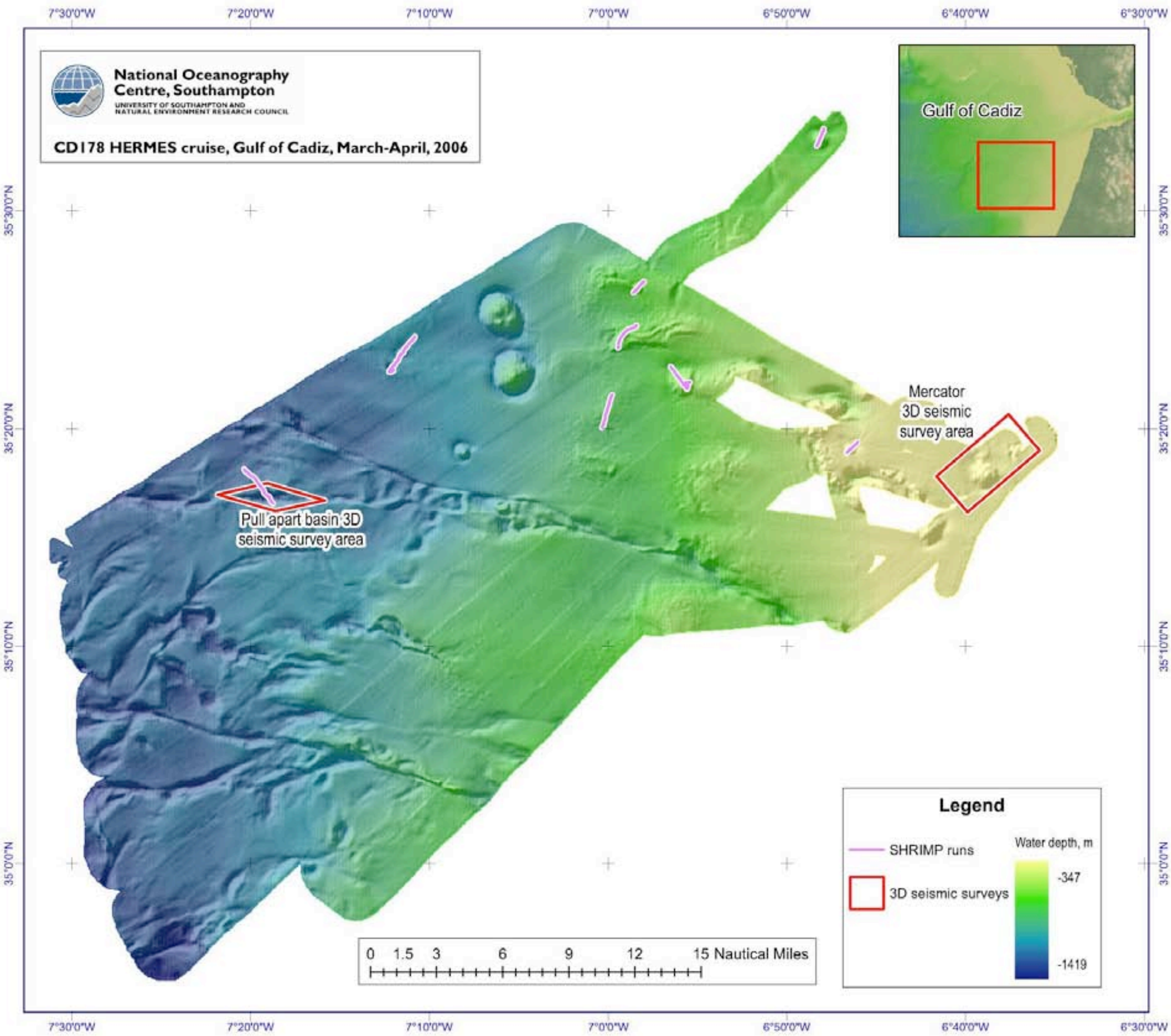


Figure 2. Multibeam bathymetry data collected in the Gulf of Cadiz with locations of 3D seismic surveys and SHRIMP video stations superimposed.

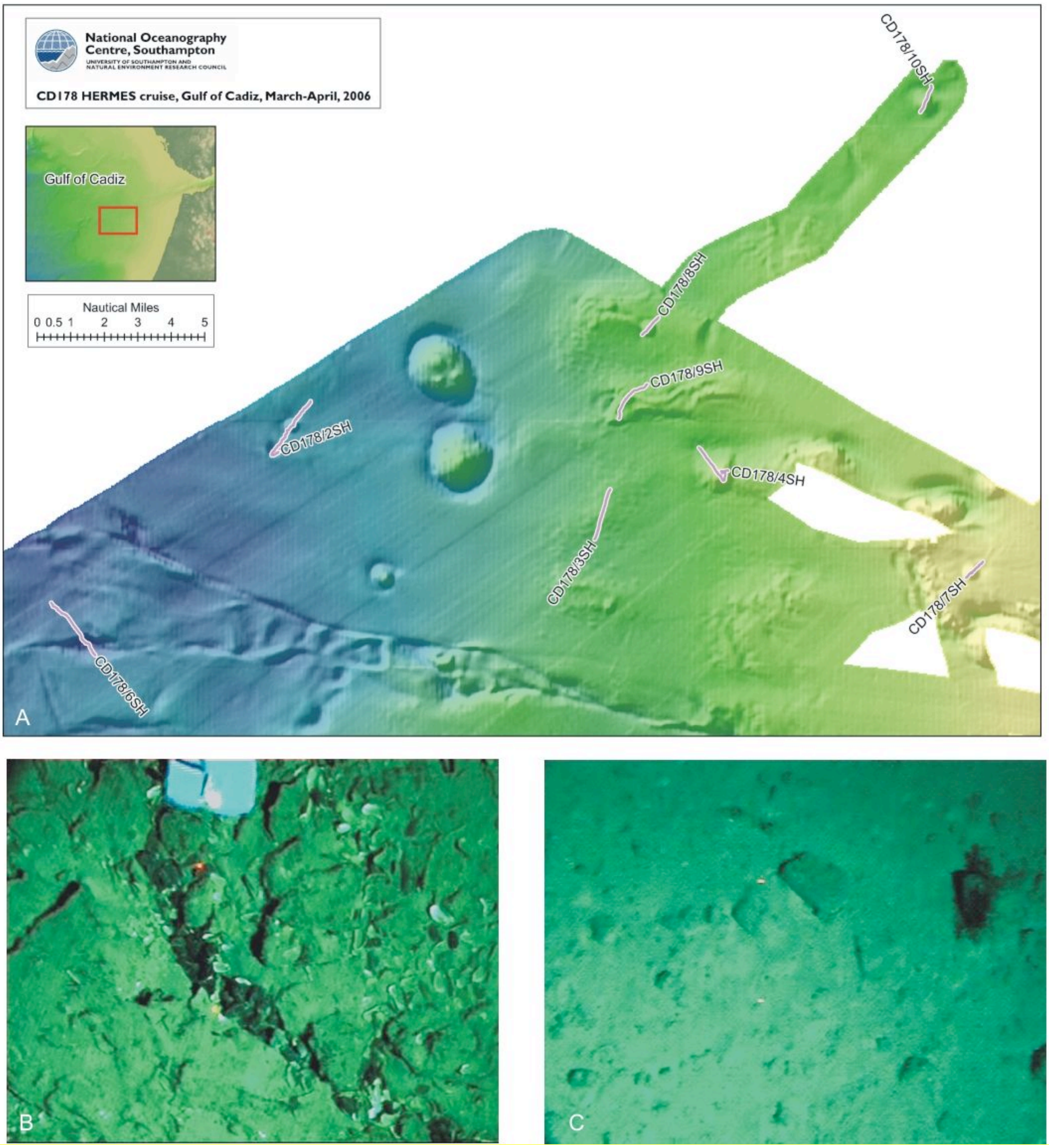


Figure 3. (a) Locations of SHRIMP video stations in the Gulf of Cadiz; (b) seafloor photograph showing chemosynthetic shells from Darwin mud volcano; (c) seafloor photograph showing mud breccia from Challenger mud volcano.

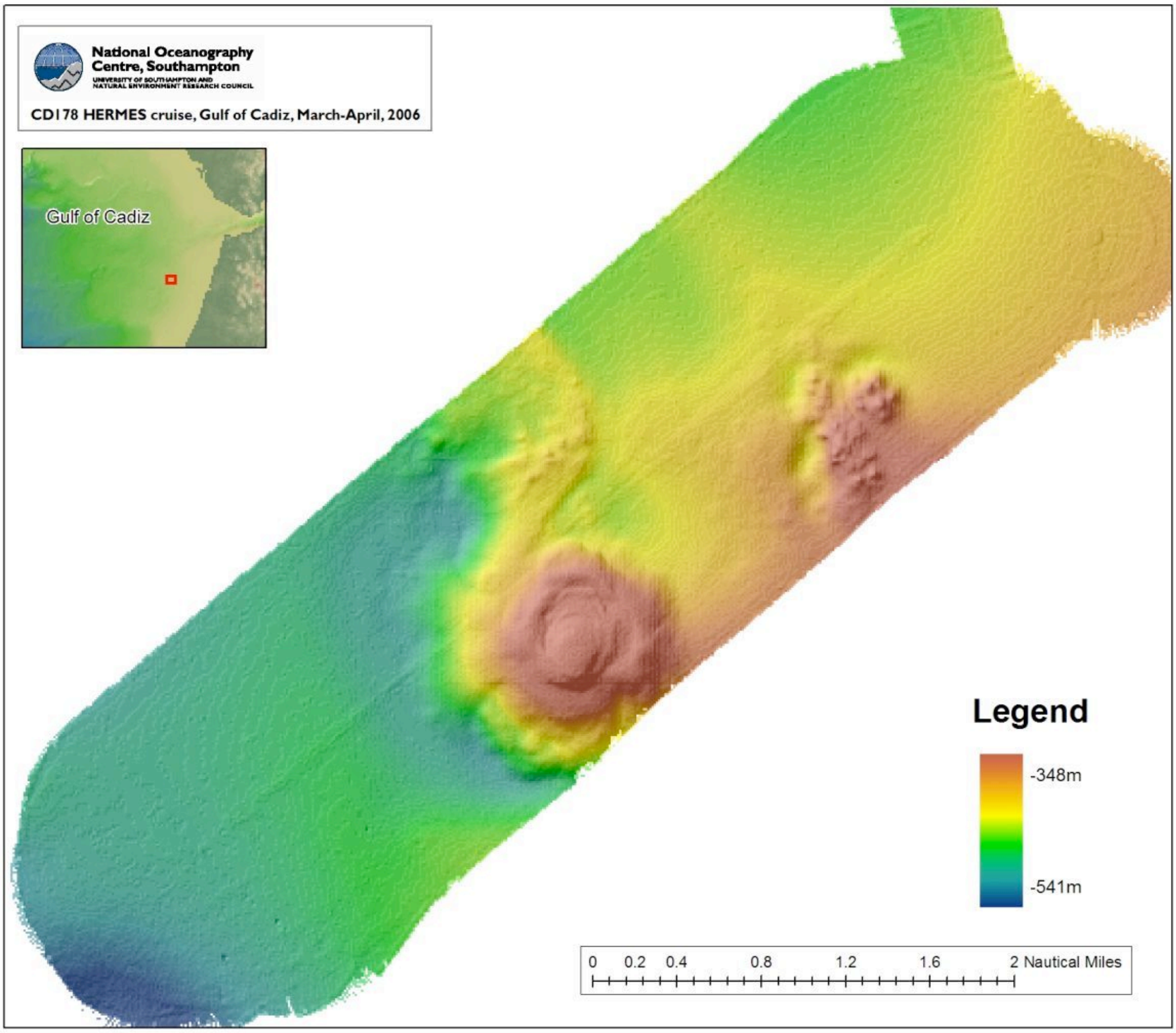


Figure 4. Detailed bathymetry of Mercator mud volcano area.

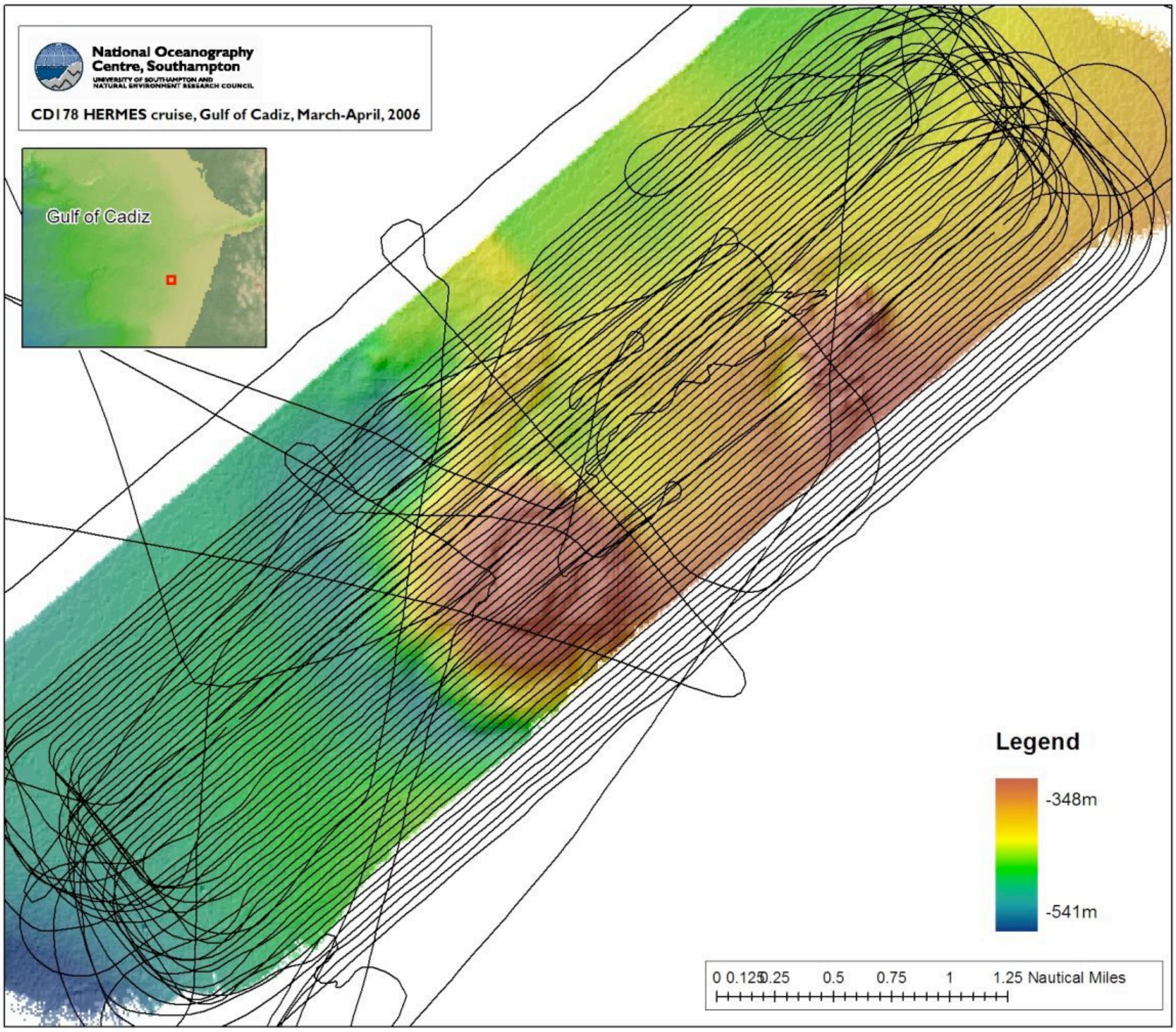


Figure 5. 3D seismic coverage of Mercator mud volcano area.

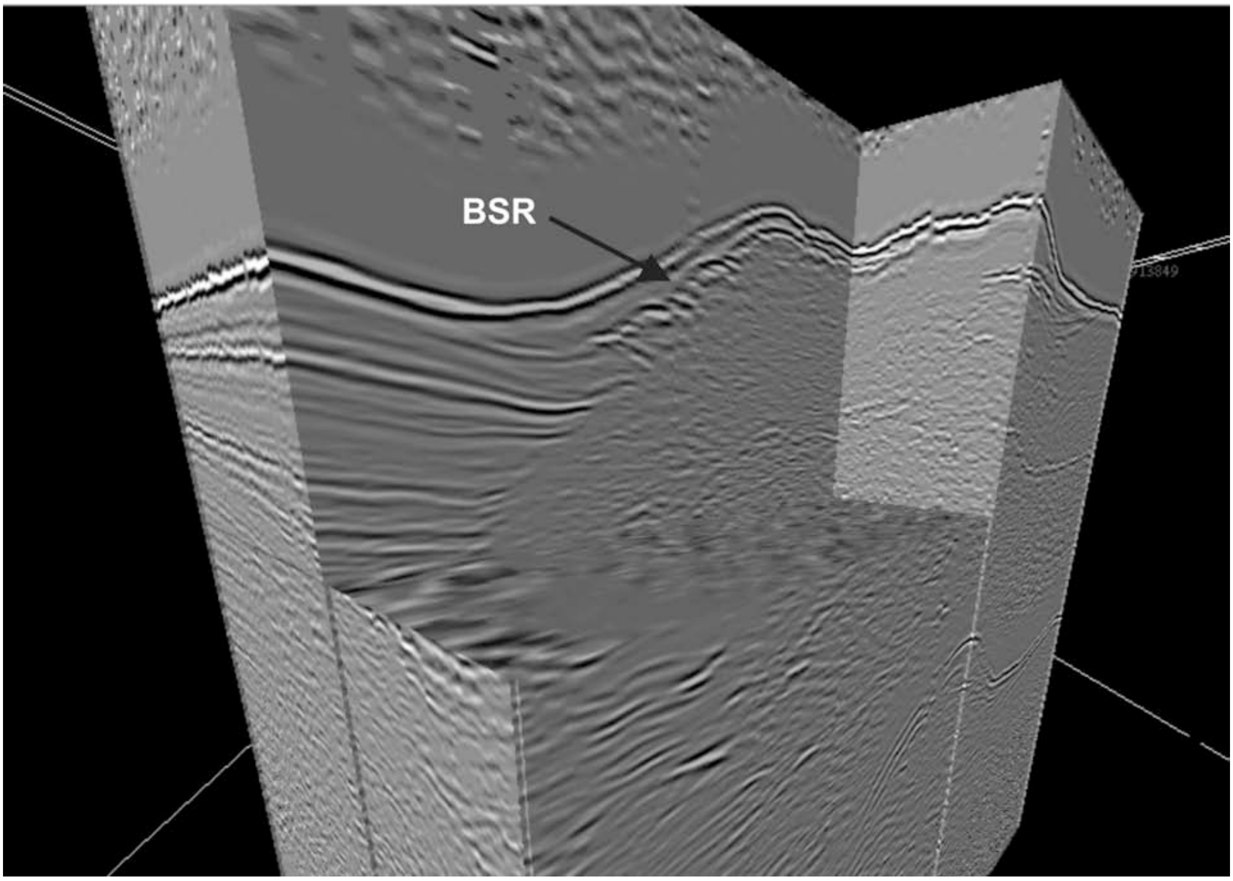


Figure 6. Example of the 3D seismic cube over Mercator mud volcano.

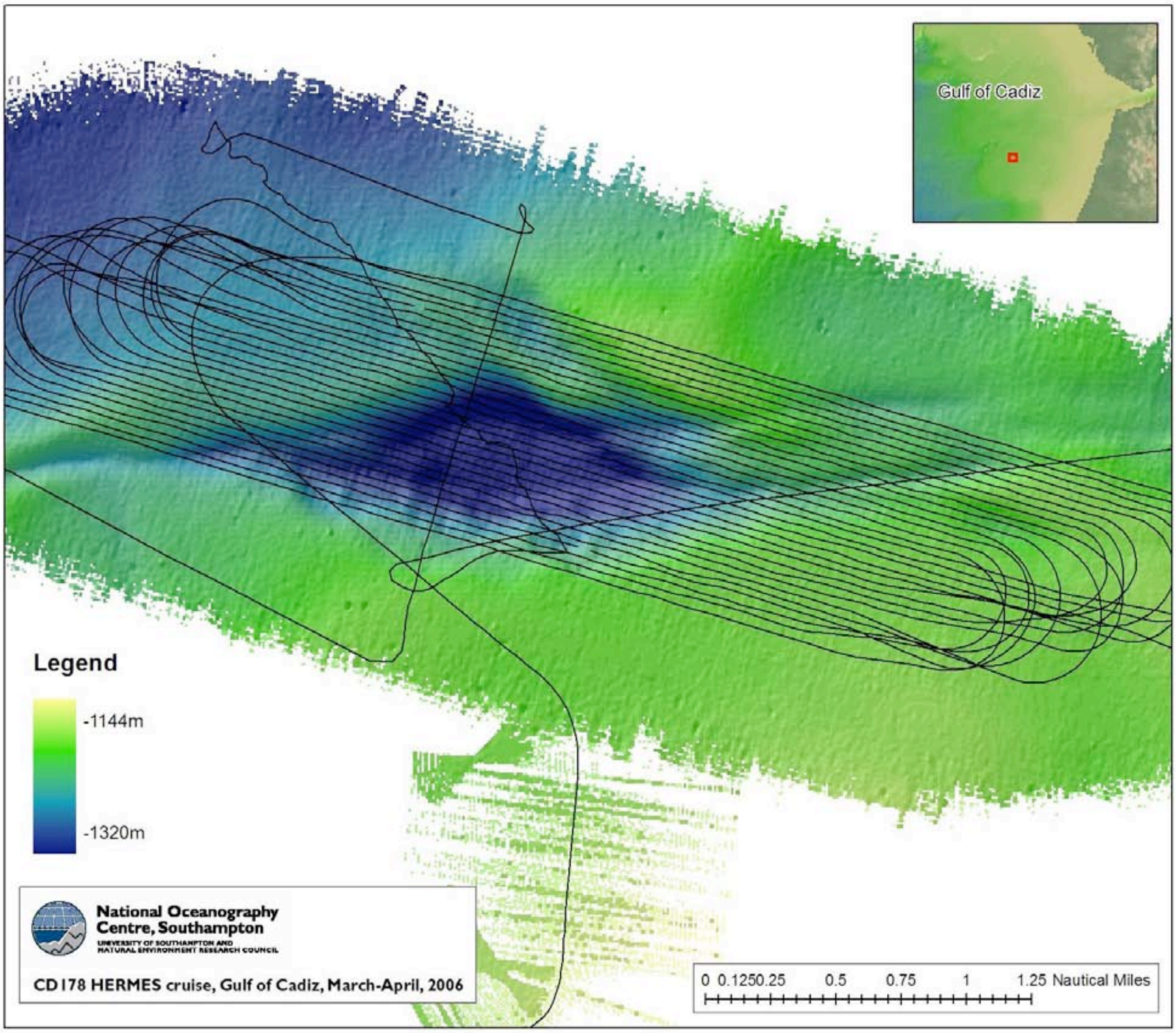
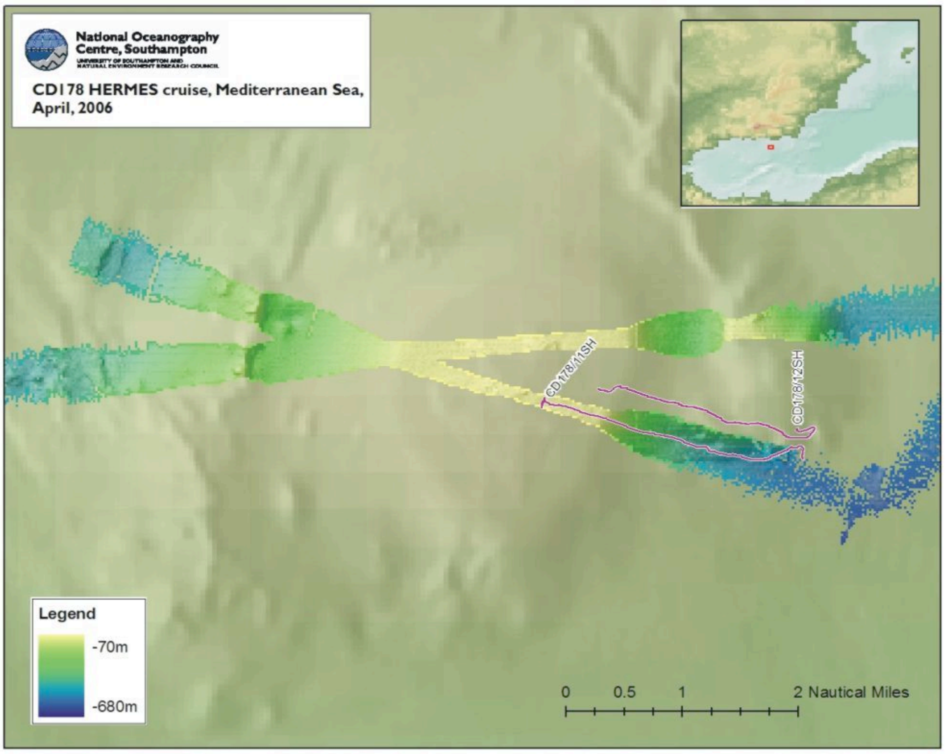


Figure 7. 3D seismic coverage of pull-apart basin area, superimposed on high-resolution bathymetry.



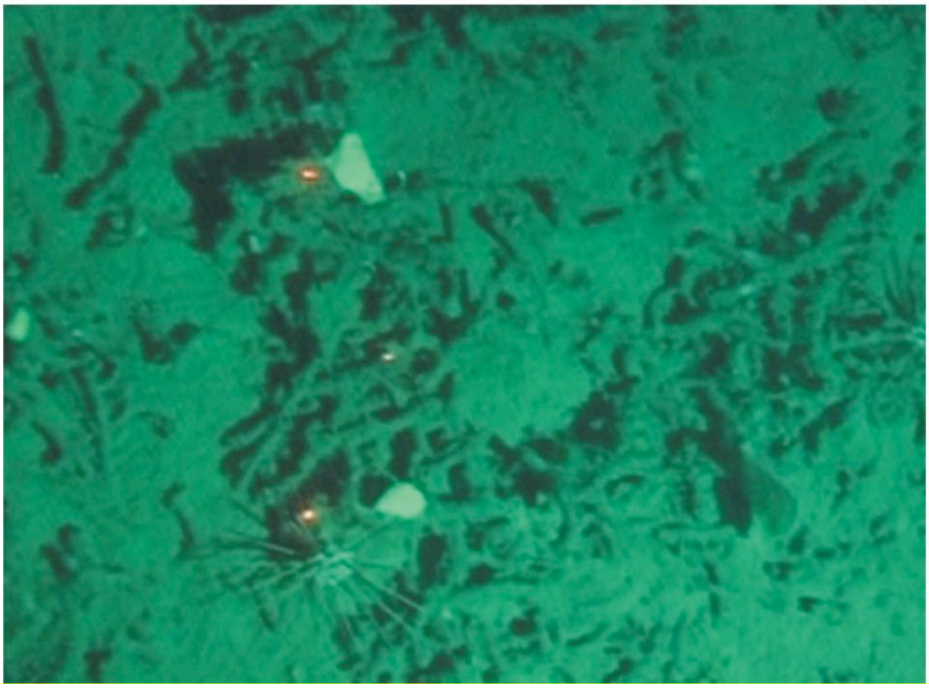


Figure 8. SHRIMP stations in the Alboran Sea (upper). Still image shows abundant coral debris on the eastern slope of the Olive Tree Bank (lower).

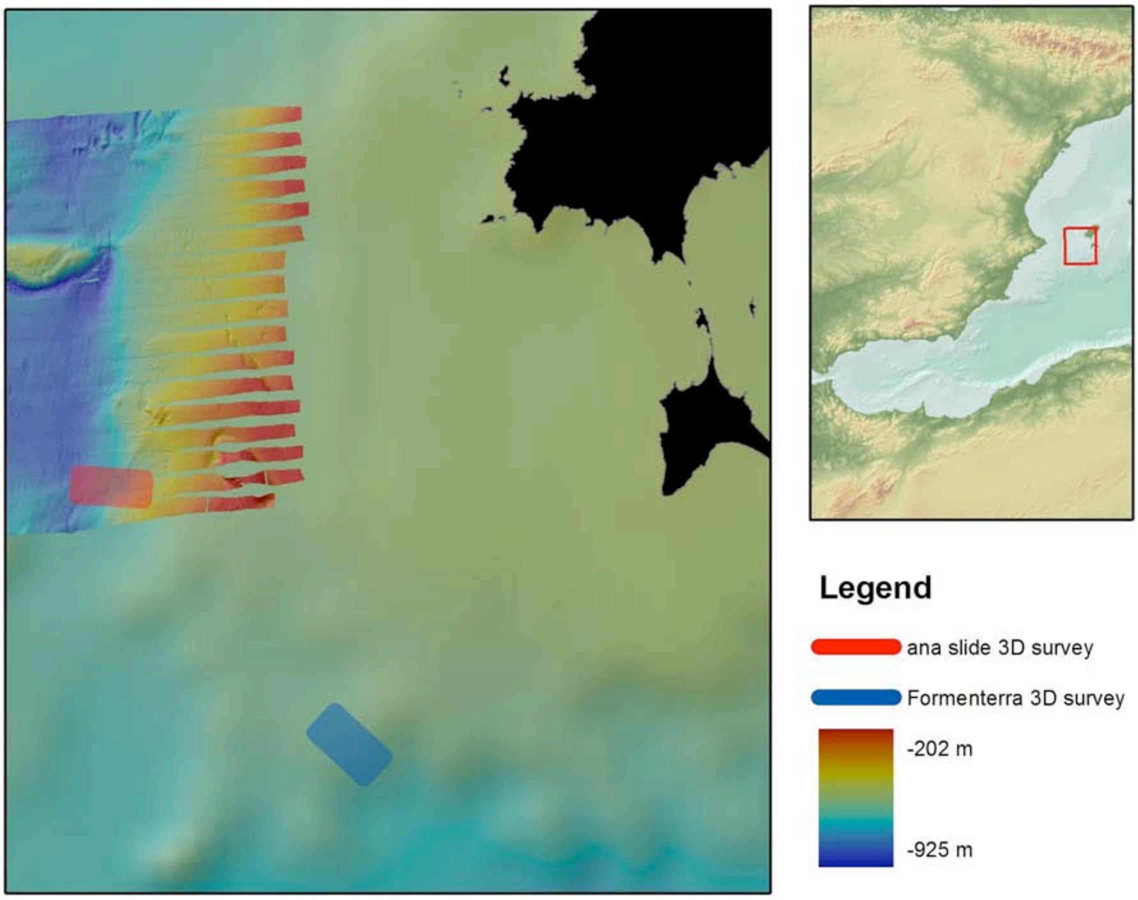


Figure 9. 3D seismic coverage in the Eivissa Channel.

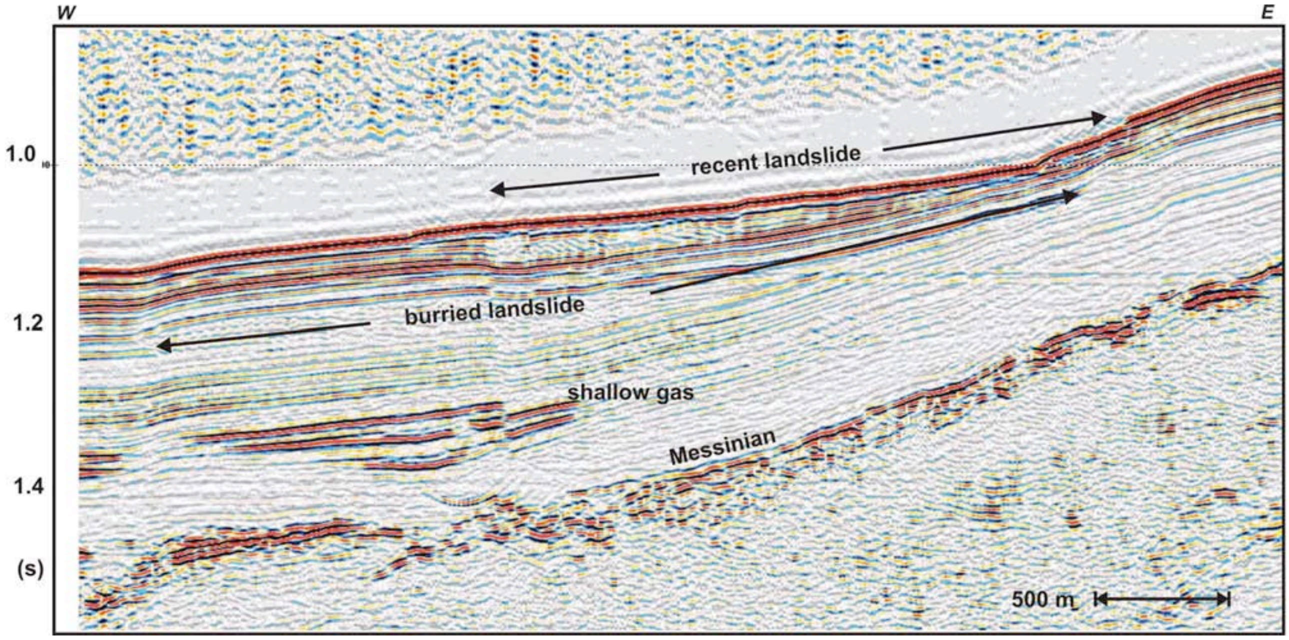


Figure 10. Example of 2D profile across the Ana Slide in the Eivissa Channel.