The 2005 Chicxulub Impact Crater Seismic Experiment

Cruise: R/V Maurice Ewing, EW0501 funded by NSF and NERC

Port of Origin: Colon, Panama - January 5th, 2005

Port of Terminus: Progreso, Mexico - February 19th, 2005

Co-chief scientists: Dr Sean Gulick, University of Texas, USA & Dr Penny Barton, University of Cambridge, UK

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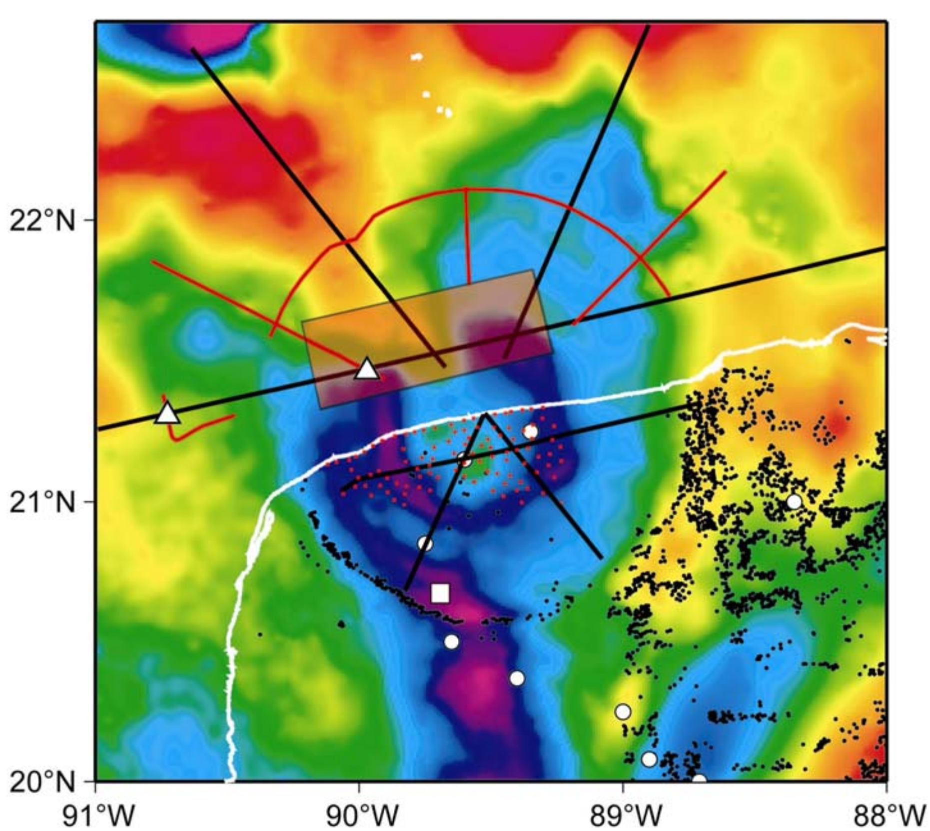

Figure 1. Location figure. Color image is Bouguer gravity anomaly (reds and yellows are high gravity values; blues and purples are low gravity values). White line is coastline of the Yucatan peninsula. Black points indicate cenote locations. Black lines indicate location of 1996 seismic survey. Red lines and shaded region indicates offshore 2005 seismic survey and red points shows seismometers. White points are existing or planned drill sites.

Introduction

Sixty-five million years ago a ~10 km diameter meteor crashed into the Yucatan Peninsula of Mexico leaving behind the 195 km wide Chicxulub crater (Figure 1) which is one of only three known impact craters on Earth with diameters larger than 150 km. Seventy percent of the species on the Earth including the dinosaurs became extinct at the Cretaceous-Tertiary (K-T) boundary, which appears to have been caused, at least in part, by this impact. In addition to being the cause of the K-T extinction event, Chicxulub is the only one of the three large craters on Earth that is well preserved due to a cover of ~1 km of Tertiary (post-impact) limestones. The Chicxulub crater is uniquely suited for a seismic investigation into the way large diameter impacts deform the Earth and what the specific environmental effects of the Chicxulub impact were at the KT boundary.

The goals of our combined reflection-refraction seismic experiment are: 1) We seek to determine the direction of approach and angle of the Chicxulub impact as modeling has shown that a 15-20 time greater amount of airborne particles are produced by low-angle impacts; 2) We will map the deformation (faults and broken rock) recorded in the upper crust near the crater center that may explain the way the surface of the Earth is damaged by large meteor or comet impacts; 3) By imaging the key features in the northwest portion of the crater we can further understand the Chicxulub impact structure and prepare for possible future sampling to examine the melted and shattered rocks deep within the crater; 4) We intend to model the 3-D collapse of the crater to examine both the deformation and the environmental effects of the impact to better understand how such an impact can cause worldwide mass extinctions.

Activities Realized

The operations that occurred on the cruise included deployments and recoveries of towed and seafloor scientific equipment and the firing of an array of 20 airguns totaling 6970 cubic inches during allowed windows. Equipment deployment and recovery took place on 15th-19th January, 3rd-4th February, 14th February, 16th February and 18th-19th February. Airgun operations occurred on the following dates: January 20th – February 2nd, February 5th-February 14th, and February 17th. Within those days the time windows when airgun operations were allowed were highly constrained dependent on daylight (operations only allowed between 0630 and 1800 local time), weather (operations only allowed in sea conditions less than Beaufort 5), lack of marine mammal or turtle sightings within the safety radius of 3.5 km from the ship, and being a safe radius from fishing or diving activities. Additionally, the research vessel collected underway 2.25-6.25 kHz bathymetric sonar data, along-track gravity measurements, and wind/weather data throughout the period from January 15th to February 19th, 2005.

SUMMARY	MCS profiling with streamer - number of shots		Shooting into seabed instruments only - number of shots		TOTAL number of shots
	partial gun array	full gun array	partial gun array	full gun array	
TOTALS	3393	26807	4131	2229	36560

MCS profiling with streamer - line length in km		Shooting into seabed instruments only - line length in km		TOTAL line length in km
partial gun array	full gun array	Partial gun array	full gun array	
168.35	1338.75	204.85	110.90	1822.85

Table 1: Summary of the total shots recorded by the hydrophone streamer and the ocean bottom seismometers and the total line-kilometers of data acquired.

The airgun data were recorded using the towed hydrophone streamer, seafloor seismometers (ocean bottom seismometers) and land seismometers. Airgun shots can be divided into partial array shots recorded on the hydrophone streamer and seismometers, partial array shots recorded only on the seismometers, full array shots recorded on the streamer and seismometers, and full array shots recorded just on the seismometers. Times when the seismic vessel was shooting during turns are included in those shots recorded only on the seismometers. Partial array shots occurred due to the need to ramp up the seismic array from one airgun to full power at the start of each window of operation. In total there were 3393 partial array shots and 26807 full array shots recorded by both hydrophone streamer and seismometers for a total of 168.35 line-kilometers and 1338.75 line-km, respectively. Additionally, there were 4131 partial array shots and 2229 full array shots recorded only by the seismometers, which is equivalent to 204.85 and 110.90 line-kilometers. The total survey therefore included 36560 shots and 1822.85 line-km of seismic data (Table 1).

EW05-01								
Air gun position	Vol. Cu.In.	output db	0 min.	5 min.	10 min.	15 min.	20 min.	25 min.
1	145	226			145	145	145	145
2	350	233					350	350
3	235	230.5					235	235
4	305	232					305	305
5	80	223	80	80	80	80	80	80
6	640	235						640
7	466	235					466	466
8	875	239.5						875
9	145	226		145	145	145	145	145
10	200	229				200	200	200
11	250	231					250	250
12	200	229			200	200	200	200
13	850	239.5						850
14	235	230.5				235	235	235
15	500	236						500
16	466	235					466	466
17	350	233					350	350
18	260	231					260	260
19	250	231				250	250	250
20	145	226				145	145	145
Number on			1	2	4	8	16	20
added Vol cu.in.			80	145	345	830	2682	2865
total Vol cu.in.			80	225	570	1400	4082	6947
total db peak			223	230	236	242.5	249	253.5
							16 gun	20 gun
							chicx6HR	chicx6
Guns added:			5	9	1 and 12	10,14,19	2,3,4,7,11	6,8.13,15
						and 20	16,17,18	
Guns on:			5	5,9	1,5,9,12	1,5,9,10,	1,2,3,4,5	All 20
						12,14,19.	7,9,10,12	
						20	14,16,17,	
							18,19,20	

Table2: Ramp-up pattern for EW0501 array.

The data were acquired in two phases centered on the deployments of the ocean bottom seismometers (OBS). The first deployment of the hydrophone streamer and the 28 OBS occurred from January 15-19th after which the airgun profiling served as the source while the OBS and the hydrophone served as the receivers from January 20th-February 2nd. The multichannel seismic (MCS) lines (those recorded on the hydrophone streamer) recorded during this time interval are shown as red lines on Figure 2 and the positions of the 23 OBS that functioned properly are shown as red dots on Figure 2. The lighter red portions of the MCS lines record when the airgun array was only partially firing as in ramp-ups. The second phase of airgun profiling followed on a recovery of 25 of the 28 OBS including two which did not record any data; the three other OBS self-released early and two of them were later recovered by fishermen and transported to the Ewing via the pilot boat from the port, the other one was lost. The recovery and redeployment of the OBSs occurred on February 3rd-4th. From February 5th-February 14th and again on February 17th profiling continued and the blue lines on Figure 2 show the MCS lines collected during this time (light blue are partial array sourced lines) and the blue dots show the 25 OBS which recorded these shots. Final recovery of the OBS and hydrophone streamer occurred on February 18th and 19th.

The operational limitations placed on this cruise were the most restrictive ever imposed on a seismic cruise. Figure 3 shows a pie chart of how the allotted time was consumed during the cruise and unfortunately more than 50% of the time at sea was not spent on science due to waiting on clearances (21% of the time), shutdown for the night (31%), shutdown due to weather conditions (8%), and shutdowns caused by turtles, marine mammals, or fishing vessels encroaching on their respective safety radii (< 1% each). The night-time restriction was placed on the cruise by SEMARNAT such that the airgun array was only able to operate between the hours of 0630 and 1800 local time, instead of 24 hours a day as normally

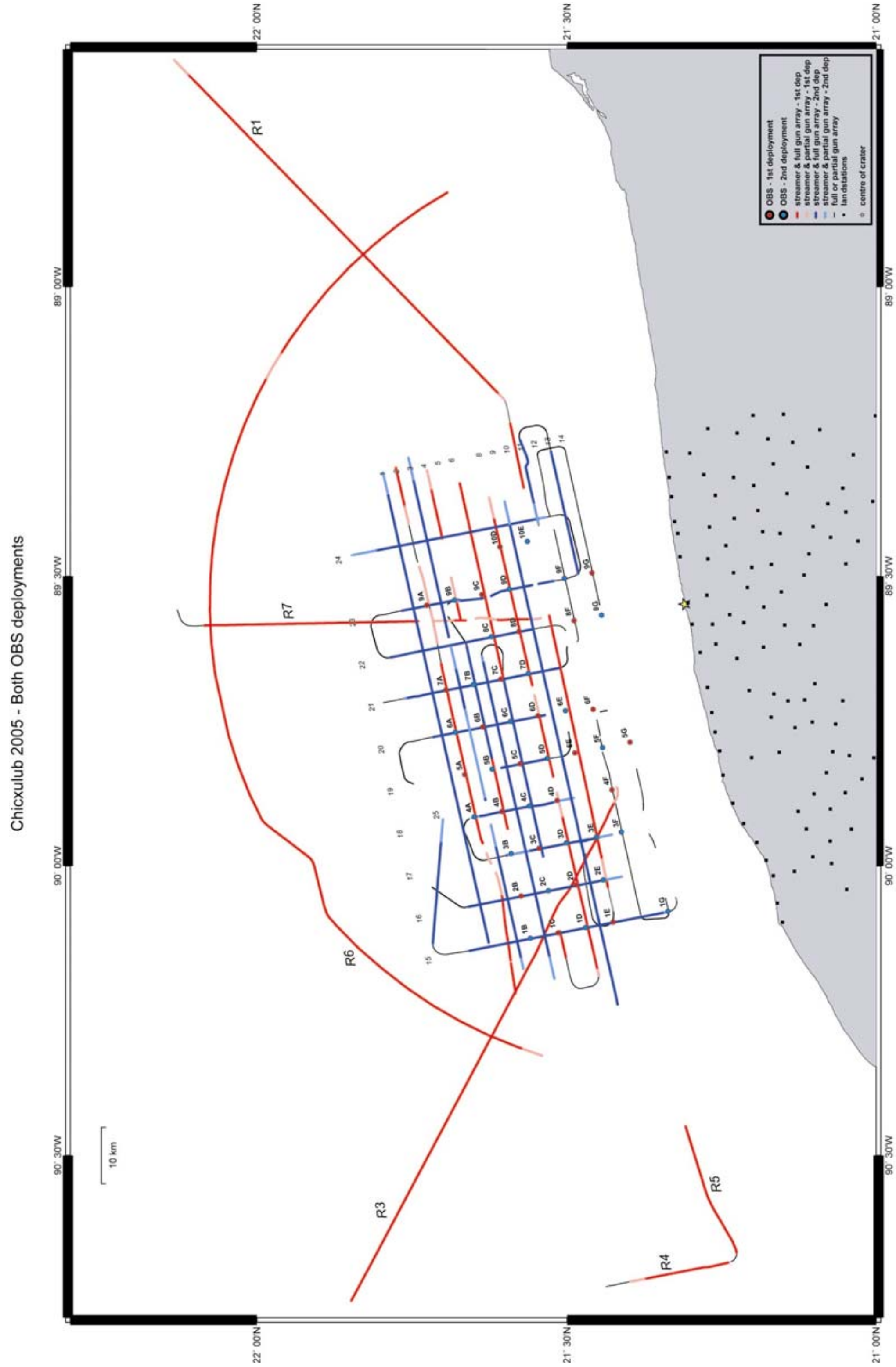

FIGURE 2: The 2005 Chicxulub seismic experiment including 30200 airgun shots recorded on the 6 km, 480 channel hydrophone streamer and 48 ocean bottom seismometers (OBS) in two deployments (shown in red and blue, see legend) and 6360 airgun shots not recorded on the streamer (shown in black, see legend). The 82 land seismometers (black squares) recorded all 36560 shots. Yellow star is the center of the crater.

expected. Due to the need to ramp up the airgun array at no more than 5 dB per 5 minutes the full airgun array was not operational until close to 0700 local time most mornings. The exact ramp-up sequence is shown in Table 2. The best use of night-time was made by processing the already collected data, maneuvering the vessel into position for start of the next day's operations, and conducting maintenance on the hydrophone streamer. During any deployment and recovery operations (OBS or MCS) the ship operated 24 hours a day. The gravimeter, 2.25-6.25 kHz Chirp, and 15 kHz echosounder were also used 24 hours a day either because there were no limitations imposed on these systems or for safety reasons, as the echosounder is the primary indicator on the vessel of water depth.

The weather conditions set on seismic operations at the beginning of the cruise were no airgun use in wind states over Beaufort 2 (7 knots of sustained wind). After much discussion this condition was eased to allow operations in wind states not exceeding Beaufort 4 (17 knots of sustained wind). To determine the level of sustained wind, in order to remain in compliance, a program was written by Kevin Johnson and Anthony Johnson (system administrators for UTIG and LDEO, respectively), which captured the wind measurement every second and then generated a 90 minute running average. Whenever the 90 minute running average went above 17 knots we shutdown operations until the 90 minute running average fell below 17 knots again. Figure 4 shows the graphic user interface for this program. A 90 minute running average was used as winds must consistently blow in the same direction for at least 90 minutes to generate a rougher sea state (see 'The American Practical Navigator, by N. Bowditch, 1995, p527-529). It should be noted that the normal operation of seismic profiling allows successful data collection in sea states up to about Beaufort 5-6 which seldom occurred during the course of this cruise; the weather restrictions imposed here were to allow observation of the safety radius by the marine mammal observers.

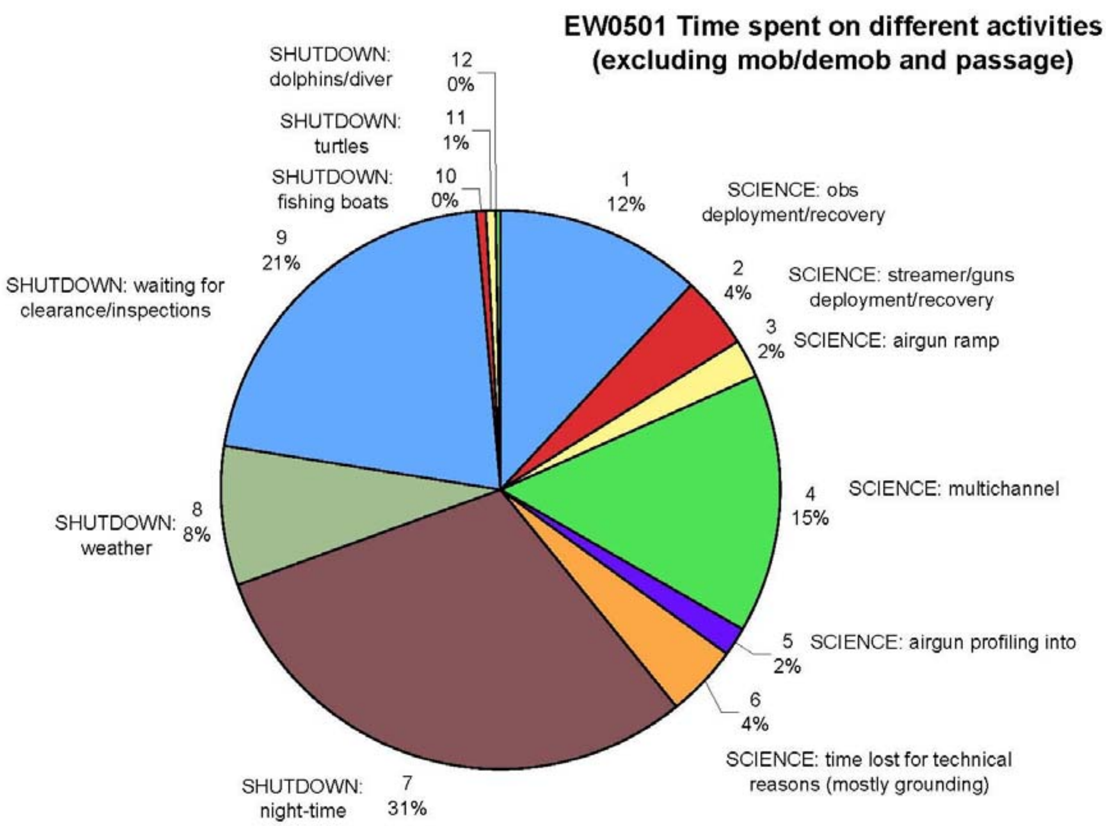

Figure 3. Pie-chart showing time spent on different activities during EW0501. Note that shutdowns due to airgun limitations or clearances/inspections amounted to more than 50% of the time spent at sea.

Despite all the public attention on the issues of marine mammals and turtles in the study area, there were very few sightings of either. Attached to this report, as Appendix 1, is a summary by the U.S. lead marine mammal observer, Meike Holst, of LGL, Inc. This report details all methods used and observations obtained by the joint Mexican-US marine mammal observation team. Additionally, the notes (Bitácora) from the Mexican marine mammal observers were delivered to SEMARNAT shortly after the end of the cruise.

Figure 4. Screen on the *Ewing* that displays the wind data. The bars along the left show the 90 minute running average of the wind and become bright if the 90 minute average exceeds 17 knots. The numbers on the right are the 15 minute and 90 minute running averages. The vertical dashed lines are at 5 knot intervals.

A series of aerial surveys were conducted by Michael Rawson of LDEO in support of this project in accordance with the terms and conditions detailed in document S.G.P.A.-DGIRA.-DDT.-0577/04 that stipulates in Conditions, Section 2, that the project sponsor "will implement air and sea searches for organisms that may be injured as a result of airgun operations and, when detecting animals that are beached or close to the coast, proceed to determine the cause. If that is the case, immediately notify the Federal office of PROFEPA in the state of Yucatan." A total of 19 aerial surveys (e.g. Figure 5) were conducted departing from the commercial airport of Merida, Yucatan during a period of time from Jan 12 through February 19, 2005 when the seismic project was completed. A total of 6,604 nautical miles were covered in survey operations (this does not include the transit from Merida airport to the coast) during 58.45 hours of survey flight time. No turtles were sighted during the aerial survey flights. Two instances of marine mammal sightings were recorded: January 21: 3 dolphins (probably Tursiops truncatus), and February 12: 2 groups dolphins, 3 individuals and 5 individuals (probably Tursiops truncatus). No injured animals or turtles were sighted by aircraft.

The fact that shutdowns from turtles and marine mammals each occurred < 1 % of the time is testament to the rarity of sightings in the shallow Yucatan waters. Whenever a marine mammal or turtle was spotted within the safety radius for this cruise (3.5 km) the guns were either powered down or shut-down depending on the exact distance. Once the biota were no longer observed we waited 15 minutes for turtles and 30 minutes for marine mammals before starting ramp-up procedures again in order to move a safe distance away from the turtles or to allow marine mammals time to exit the safety radius completely.

A larger problem was fishing vessels. The mitigation measure we operated under for fishing vessels was that the airguns had to be shutdown whenever a vessel was engaged in fishing within 0.8 nautical miles (nm) of the *Ewing*. In practice it was often difficult to determine when vessels were actively engaged in fishing and the efforts of our chase boats to warn vessels away from the path of the Ewing were frequently unsuccessful. Therefore, shutdowns for fishing vessels were frequent although sometimes much shorter in duration than shutdowns for turtle or marine mammals. If a fishing vessel exited the 0.8 nm safety radius then airgun operations could resume. If this resumption occurred within 8 minutes then a ramp-up was not required; if longer then 8 minutes, we were required start ramp up procedures again. Nonetheless much of the patchy nature of our final data acquisition in the main grid of the study area (Figure 2) is due to fishing vessels and in order to avoid shutdowns the *Ewing* swerved off its charted course on several occasions to avoid vessels engaged in fishing. Only once during the cruise was a human diver spotted and this diver was treated the same as a marine mammal with a 3.5 km safety radius.

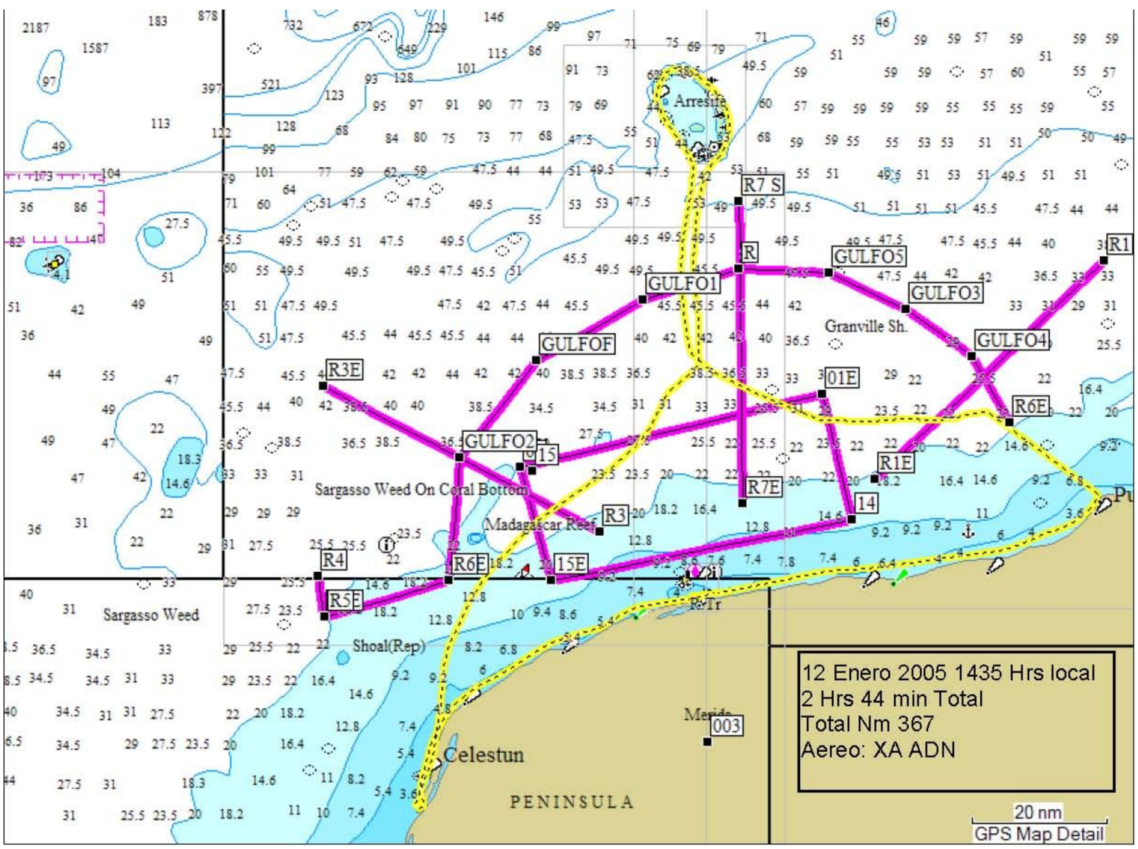

Figure 5: An example aerial survey flight path (dashed yellow line) during EW0501.

A team from PROFEPA visited the R/V *Maurice Ewing* on three separate occasions to inspect our operations and again to deliver legal papers on 18th February due to the grounding. These inspections amounted to the first at-sea inspections of the *Ewing*'s seismic operations ever conducted and were considered by all onboard the vessel, especially the Captain and Mates, to be very dangerous for the visiting personnel and not advisable for the future. Personnel transfer via a boat at sea is done extremely rarely on research vessels due to the inherent dangers and these inspections resulted in more at-sea personnel transfers during cruise EW0501 than were completed the entire preceding year of operations on the *Ewing*. Copies of these inspection reports are filed with PROFEPA, LDEO, and the co-chief scientists.

One notable incident occurred during the cruise on the night of February 14th, while maneuvering to present a lee so that visiting PROFEPA inspectors and a group of visitors that included Senator Erika Larregui and Martha Torrez from the State Department could disembark. The *Ewing* swung wide around the charted position of a rocky reef to the west of our profile Chicx05-9 and then steered farther north to put more distance between the shoal and the vessel, only to scrape the sonar trunk of the ship on the seafloor ~ 1 nm north of the charted position of the rocky reef. Later investigations showed that where the nautical charts reported the rocky reef to exist, the waters are ~17 m deep, while where the reef was really located the charts show the waters to be navigable. The 2.25-6.25 kHz bathymetric sonar (which looks down not forward) showed the seafloor rose from 16 m water depth to < 5 m depth in less that 150 m (the *Ewing* itself is ~75 m long) which given the vessel was traveling at ~5 knots (normal towing speed) and towing ~6 km of gear behind it meant there was no possible way for the ship's crew to detect the presence of the mischarted shoal (the *Ewing* has no forward looking sonars) or to react in time to avoid it. The Seaman's Club found the Captain and Mates not at fault for the incident since the charts were incorrect. No significant damage occurred to the vessel's sonar trunk as was demonstrated by thorough diving inspections of the ship on February 15th and 16th allowing for the resumption of seismic operations on February 17th. Legal papers were served on February 18th requiring the *Ewing* to come to port in Progresso due to the grounding; negotiations with PROFEPA allowed for the complete recovery of the towed and seafloor equipment before coming into port which was completed on February 20th.

Methods Used

EW0501 used a 20 gun airgun array of 6947 cu. in., a 6 km 480 channel hydrophone streamer, 28 OBS of which 25 recorded successfully in two different locations, and 82 land seismometers (Figure 2). The airguns were shot on distance every 50 m along each line (approximately every 20 seconds with our average survey speed of 5 knots). During turns or airgun-only lines the airguns were shot on time every 20 seconds for the majority of the airgun-only surveying but occasionally every 60 seconds. The airgun array was towed at 6 m and the streamer at 7 m depth.

The airgun array used during EW0501 was modified from the standard *Ewing* 20 gun array that totals 8570 cu. in. In order to generate an airgun pulse with a higher peak-to-bubble ratio and a smaller total dB, our modified 20 gun array was better tuned with guns that total 6947 cu.in. Figure 6 shows the array diagram with positions of the different sized airguns and Figure 7 shows what the array looks like when firing. Amplitudes up to 125 Hz should be recordable as shown by Figure 8. The peak-to-bubble ratio for this array is 11.0 as shown by the far field signature in Figure 9.

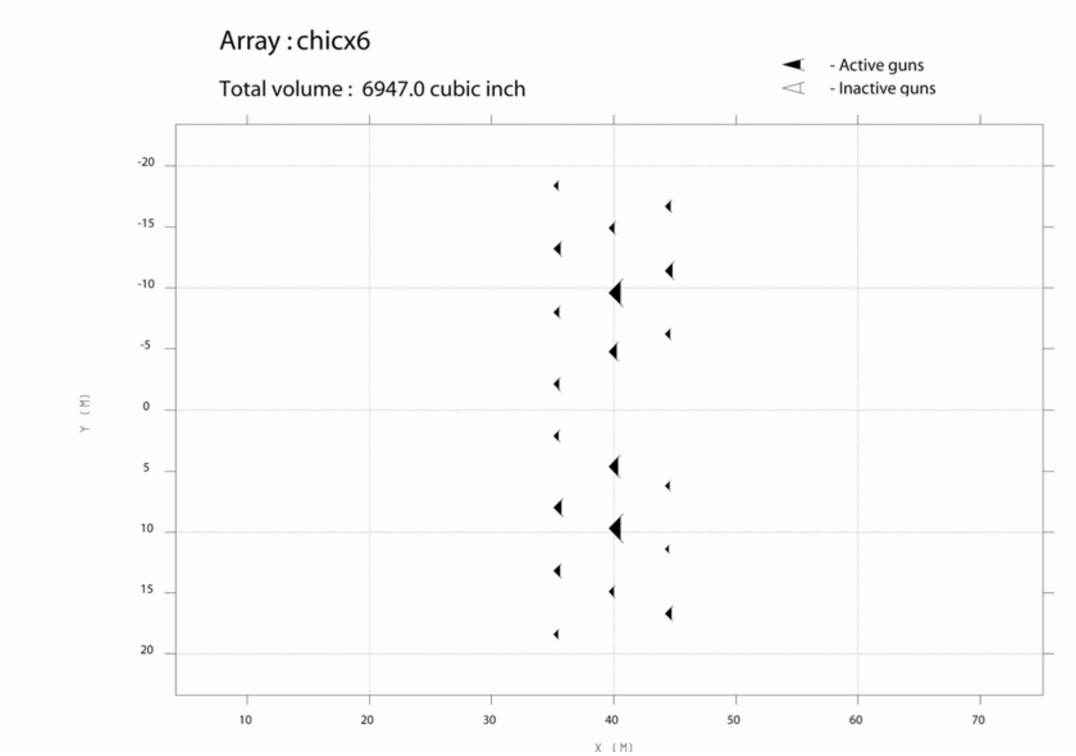

Figure 6. Diagram of the positions of the airguns in the EW0501 array plotted according to their relative size. The total array size was 6947 cu. in. See Figure 13 for details of gun sizes.

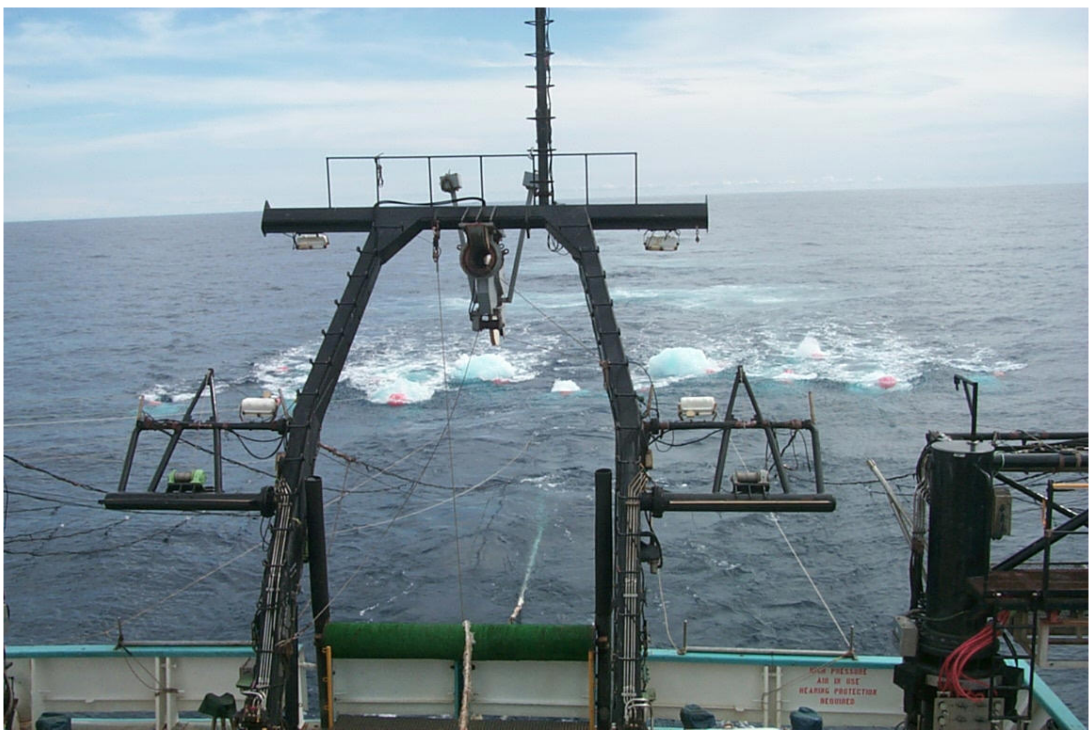
Figure 7. The EW0501 airgun array being fired during the experiment.

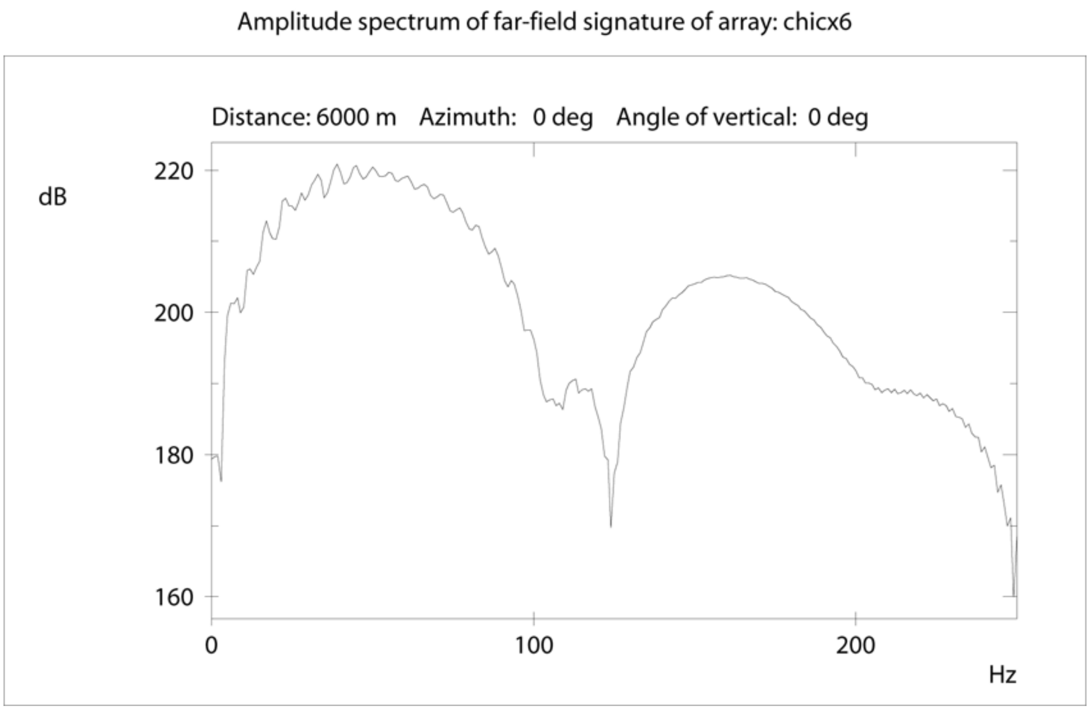

Figure 8. The amplitude spectrum in frequency space of the EW0501 array with energy up to 125 Hz (Nyquist Frequency) being available to record.

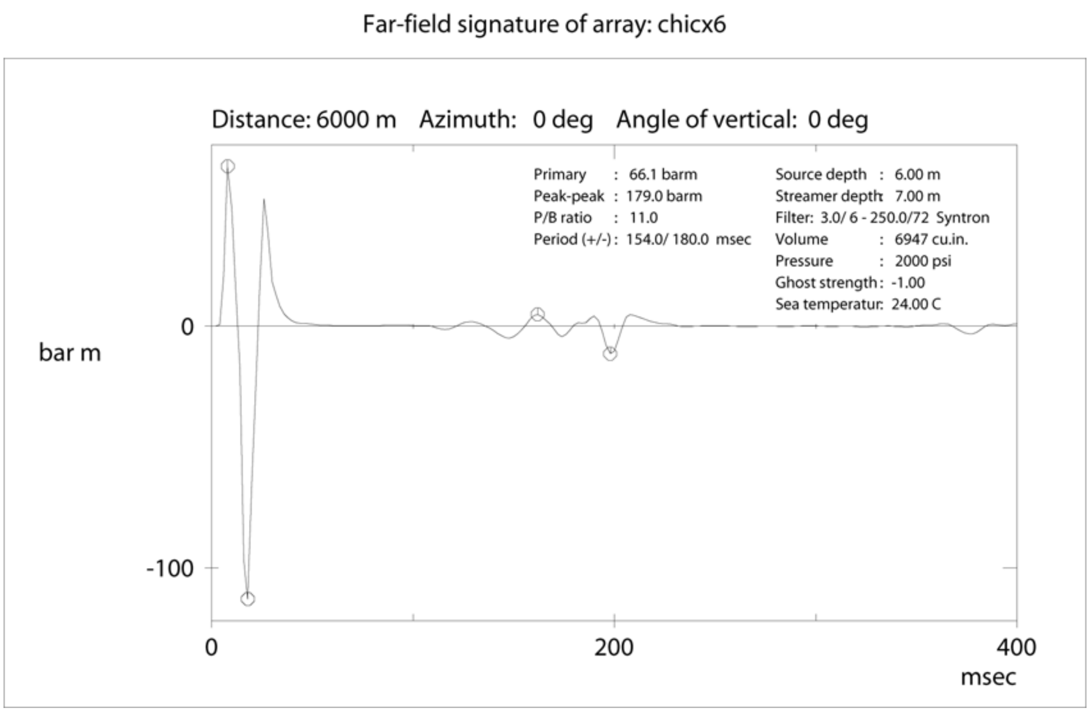

Figure 9. The far-field signature of the EW0501 array showing a peak-to-bubble ratio of 11.0 and a primary output of 66.1 bar m. The standard *Ewing* array has a ratio of 5.8 and an output of 71.4 bar m.

The hydrophone streamer used on EW0501 is the standard, full length *Ewing* streamer with 480 channels formed by groups of hydrophones centered every 12.5 m along its length.

Figure 10 shows the streamer on the reel. The streamer's depth was controlled using 28 compass navigation birds (e.g. Figure 11).

The geometry during the survey changed due to the electronic failure of our initial tow leader (section connecting the streamer to the vessel). From January 20th-26th, the near offset (distance between the array and the first receiver) was 180m, during the tow leader maintenance one short line was shot with a 13 m near offset, and the rest of the survey from January 26th-February 17th was shot with a 112.5 m near offset. A diagram of the geometry is shown in Figure 12.

The R/V *Maurice Ewing* is equipped with four GPS antennas. The ship was navigated based on the Trimble for the majority of the survey while the exact position of the vessel for use in determination of the source and receiver locations was calculated by SPECTRA, the seismic navigation software. SPECTRA took in all four GPS positions and calculated a best fit to the data to write out the shot position and then using the information on bearing from the compass birds, also calculated the receiver positions to be reported in UKOOA format. At UTIG these UKOOA format files were merged with the seismic data for interpretation purposes. Figure 13 shows the positions of the GPS receivers with respect to the gun array and streamer for EW0501 (only the 112.5 m near offset case is shown).

Figure 10. The *Ewing*'s 480 channel hydrophone streamer on the reel on the fantail. Replacement sections can be seen in the background and digitizing cans can be seen spaced along the streamer (these sum the acoustic signals and send them up the streamer to the recording systems on the vessel).

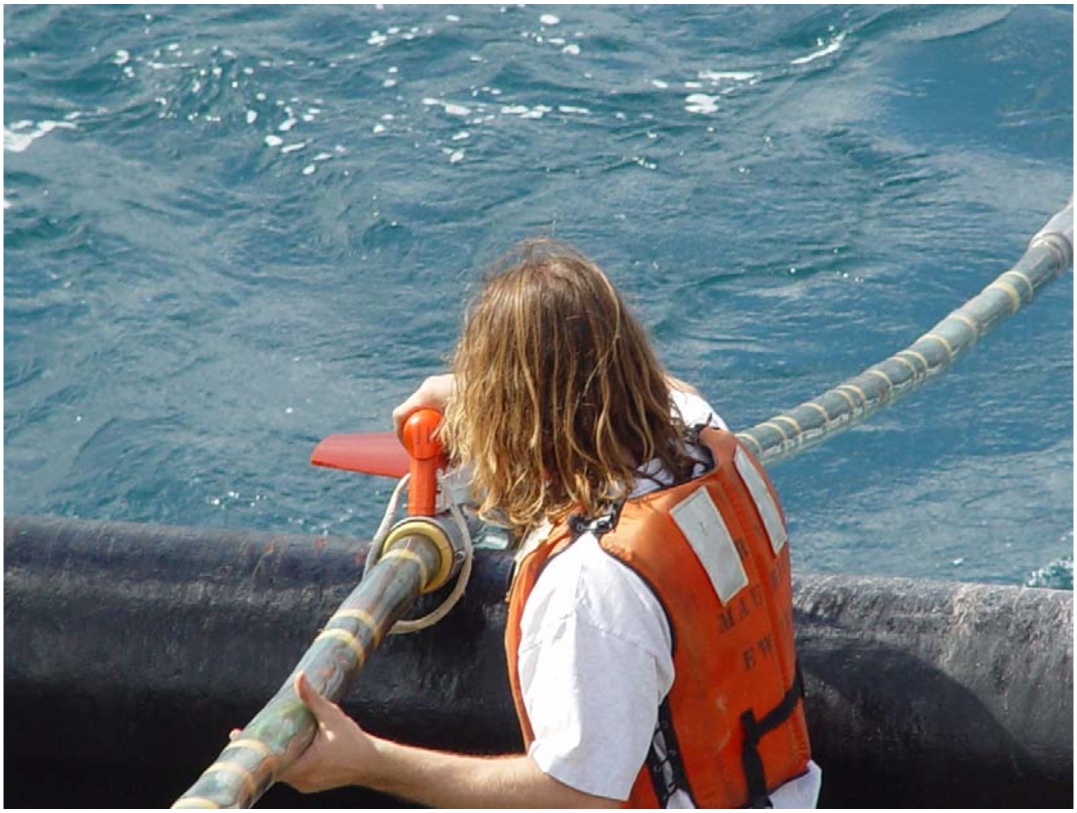

Figure 11. Compass bird being clipped on the streamer during deployment.

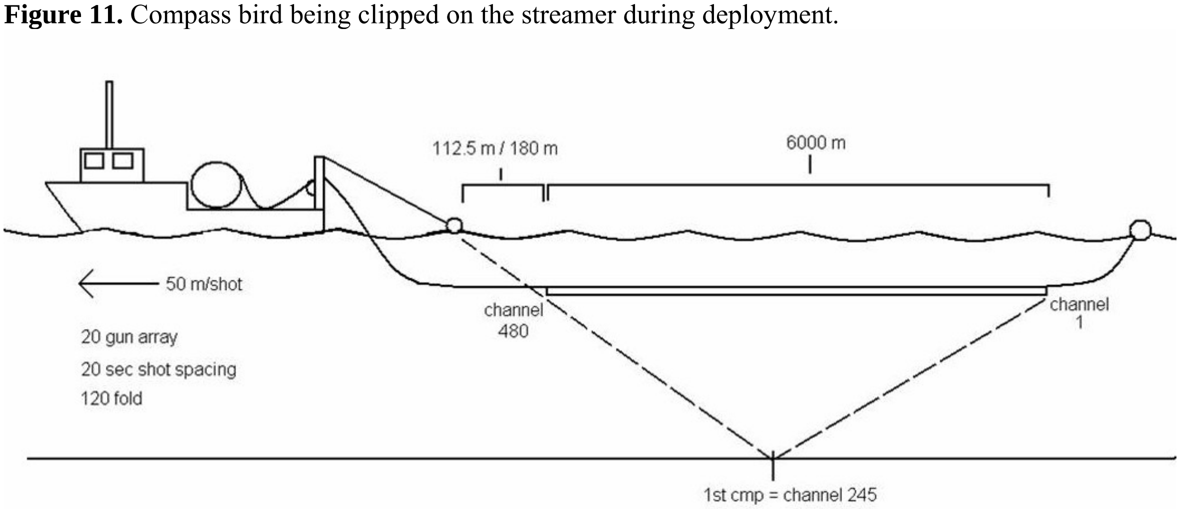

Figure 12. Survey geometry for EW0501 showing near offset that changed during the cruise.

The ocean bottom seismometers (OBS) used were from the UK and were of two different design specifications. There were 18 units of the LC design (Figure 14) which each carried a hydrophone and a vertical component geophone, and ten units of the DOBS design (Figure 15), which recorded hydrophone and 3-component geophone. Each instrument is dropped to the sea bed before the start of seismic profiling (Figures 14 and 15) and there records digital seismic data continuously until called back to the surface using an acoustic command signal, and picked up by the ship. The OBS were recovered from the sea bed in the middle of the cruise and replaced in different positions (shown by red and blue dots in Figure 2) in order to maximize the number of sites sampled. Both types of OBS are sealed autonomous devices which are passive in the environment. During the first deployment three OBS (one LC and two DOBS) broke free from their moorings and during the second deployment one LC broke free. Three of these four instruments were recovered by local fishermen and handed to the Port Captain, and the fourth was lost. We are grateful to the fishermen for their help in recovering these instruments.

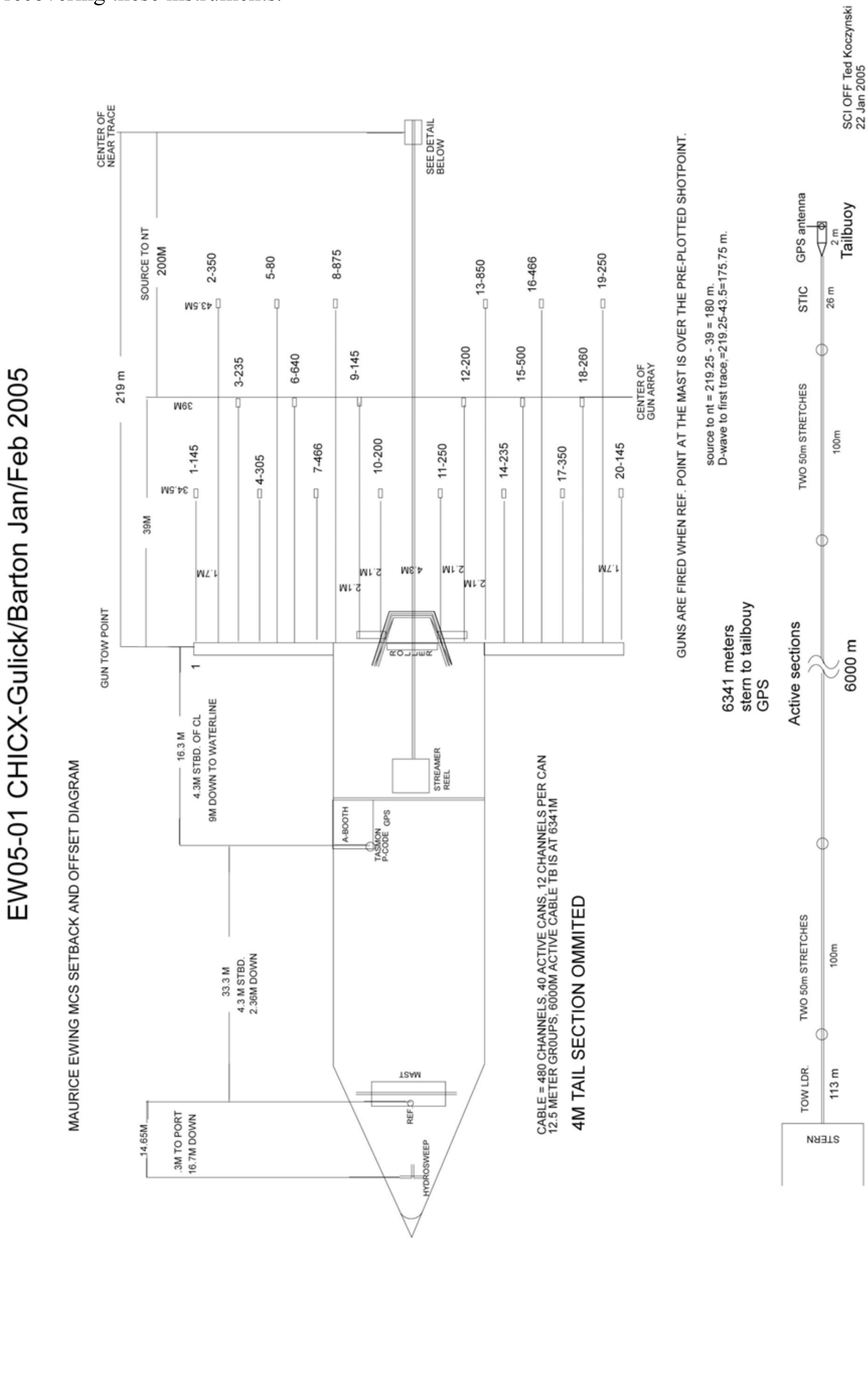

Figure 13. Navigation and position location diagram for EW0501 shown after tow leader replacement.

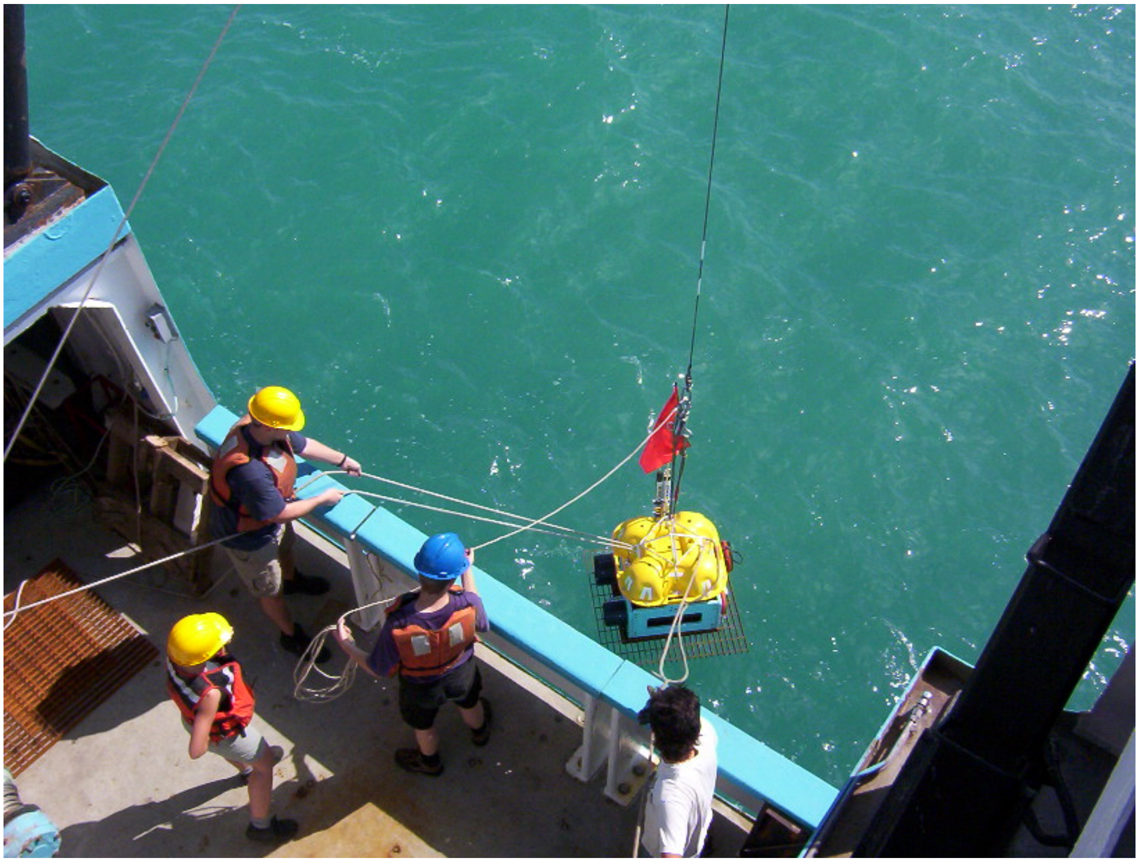

Figure 14: OBS of LC design being launched from the side of the *R/V Ewing* during EW0501.

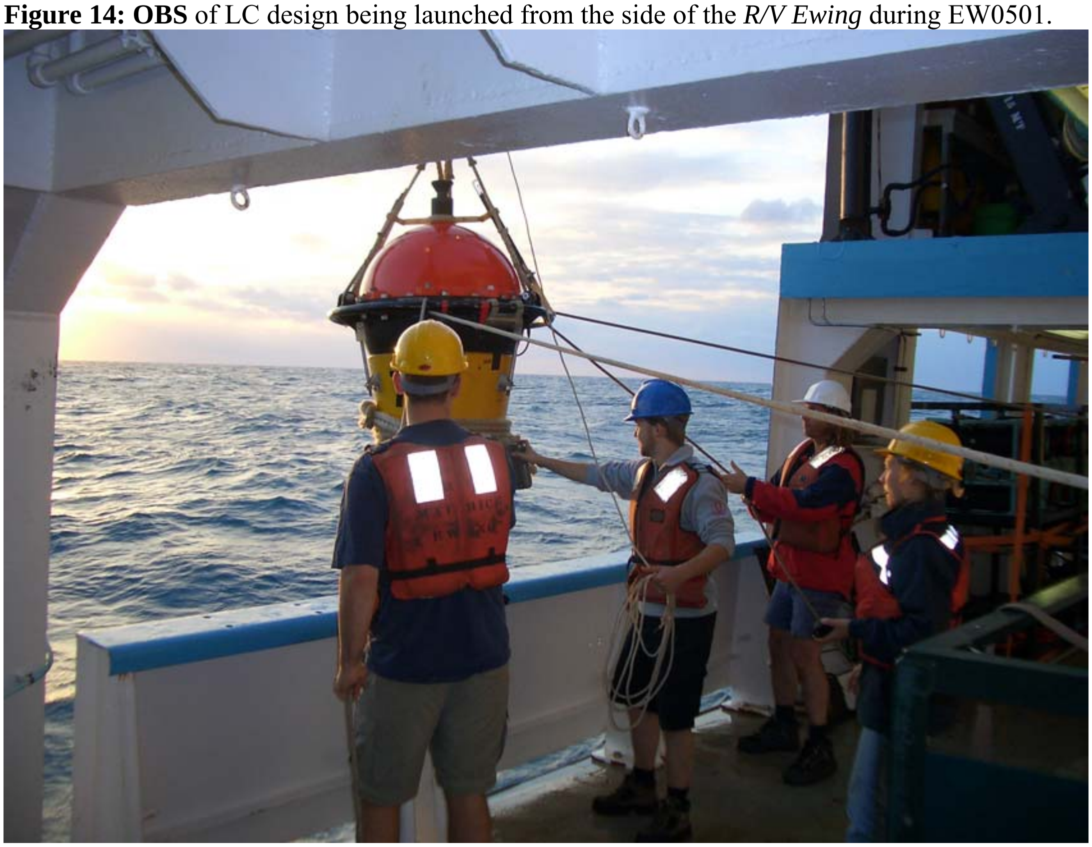

Figure 15: OBS of the DOBS design being launched during cruise EW0501.

Objectives obtained

All the major scientific objectives of the project were met to a greater or lesser extent, and the work programme was modified continuously to achieve the maximum results within the imposed restrictions. The stages of the project may be seen in the map of Figure 2 and are laid out in Table 3, with expected line-km of airgun profiling with and without the streamer and around turns, and the actual line-km collected shown below. Stage 1 was the first pass of the regional tomography grid (red profiles in the grid box, Figure 2), for which the seabed seismometers were in their first (red) positions. This took place approximately as expected, but with more of the profiles collected whilst towing the streamer than originally anticipated, due to the surprising ease of towing the streamer at a constant depth. Stage 2 consisted of a series of long profiles radial to the crater (R1, R3, R4, R5, R7, Figure 2). These profiles were reduced significantly from the original work plan, partly in response to the restricted time available due to no night-time shooting, and partly to avoid approaching the Alacran Reef too closely. Stage 3, a high resolution survey over the proposed IODP drillsite, was dropped due to lack of time, and replaced by a more basic survey which is incorporated into stages 1 and 4. Stage 4 consists of the second pass of the regional tomography grid (blue profiles on Figure 2): the relatively higher number of line-km collected during this stage relative to the expected figure is due to the incorporation of some of the Stage 3 objectives into this stage, though not at the high resolution originally expected. Stage 5 is the arc-shaped regional profile R6 (constant radius profile). Stage 6 consists of operations to relocate ocean bottom seismometers between stages 1 and 4. Stage 7 was a second detailed survey over a second possible IODP drillsite: the objectives of this survey were achieved at a more basic level as part of Stage 2 (profile R4).

Stage	Experiment		Total km with streamer	Total km without streamer	Turns km	Total km
1. Regional tomography grid pass 1	A1	EXPECTED	225	255	144	624
		ACTUAL	318	145	35	498
2. Regional MCS profiles	C1 (R1,R3,R4,R5,R7)	EXPECTED	675	0	-	675
		ACTUAL	286	12	-	298
3. High res survey 1	B1	EXPECTED	-	900	-	900
		ACTUAL	-	-	-	0
4. Regional tomography grid pass 2	A2	EXPECTED	495	-	144	639
		ACTUAL	703	49	76	827
5. Regional MCS profile	C2 R6 (CRP)	EXPECTED	325	-	-	325
		ACTUAL	200	-	-	200
6. OBS operations without airguns		EXPECTED	-	-	-	0

		ACTUAL	-	-	-	0
7. Detailed survey	B2	EXPECTED	150	-	-	150
		ACTUAL	0	-	-	0
TOTAL		EXPECTED	1870	1155	288	3313
		ACTUAL	1506	206	111	1822

Table 3: An attempted categorization of the collected data versus the original stages of work proposed. Note the total allowed line-km with and without the streamer were not exceeded during this experiment.

Our primary imaging targets included the peak ring, the inner and out rings, the tertiary basin, and the underlying slump blocks. All of these targets were successfully imaged. Our primary tomographic goals were to gather 3-D velocity data by recording the airgun sources on the streamer, the OBSs and the land seismometers. These receivers recorded the over 30,000 shots successfully and will allow a good 3-D tomographic model of the velocity structure of the crust. Additionally, the reflection and refraction data serve as a site survey for future sampling of the lithology within the crater at depth.

Results and Conclusions

At this stage our results are a suite of preliminarily processed MCS lines, and the 3-D collection of refracted arrivals on the streamer, OBS, and land stations. We include two versions of each of the reflection section as a jpegs in Appendix 2. The first version shows the entire 14 seconds of data while the second shows just the upper 1 second of data for easier viewing of the Cretaceous-Tertiary boundary, peak-ring, and rings. We also include example shots gathers recorded on the LC and DOBS instruments. Appendix 3 shows all four channels on DOBS 1B shot to on Chicx05-15 and DOBS 5D shot to on Chicx05-9 and both channels on LC 9B shot to on Chicx05-23 and LC 10D shot to on Chicx05-8. The preliminarily processed seismic data, the chirp (Bathy2000) data, weather and wind data, and the gravity data have been sent to the U.S. State Department to be distributed to Mexican officials.

Scientific conclusions would be very premature at this stage however we list some preliminary conclusions that were reported at the American Geophysical Union Joint Meeting in New Orleans, May, 2005. The Chicxulub impact crater is confirmed as a multi-ring basin (Gulick et al., 2005). The topographic peak-ring is observed to be irregular in 3-D but with clear transitions to crater floor inside and outside of the peak-ring (Gulick et al., 2005). Initial analysis of the refraction data showed that the peak ring is characterized by lower seismic velocities than adjacent features (Surendra et al., 2005). There is no evidence for an inner ring in the northeast quadrant of the impact crater raising questions of a possible blow-out feature associated with an oblique impact (Gulick et al., 2005). The concentration of deformation in the terrace zone (slump blocks) to the northeast also suggests the downrange direction of the impact is in that quadrant (McDonald et al., 2005). The slump blocks everywhere in the crater reach to depths beneath the peak-ring suggesting an interaction between the collapsing peak-ring and the lateral gravitational collapse into the transient crater (McDonald et al., 2005). An enigmatic set of inward-dipping set of reflectors are observed beneath the inner ring at lower crustal depths in several azimuths around the crater (Gulick et al., 2005).

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