Report of Cruise 64PE300 (NERC) INDUS, Arabian Sea

R/V PELAGIA

10th December 2008 to 7th January 2009

Muscat to Muscat

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Introduction

The Indus river meets the Arabian Sea, just to the east of the city of Karachi, Pakistan, where it forms the 5th largest delta in the world. The Indus feeds the world's 2nd largest sediment body, the Indus Fan, which lies under the shelf and continental slope of Pakistan and western India, as well as covering the abyssal depths of the northern Arabian Sea, stretching ~1500 km towards the Carlsberg Ridge. Although the outer shelf had previously been surveyed by shallow-penetrating seismic (Parasound) and multibeam swath bathymetry (von Rad and Tahir, 1997), the character of the inner shelf has never been imaged beyond basic plumb line soundings in the 19th and mid 20th centuries (Giosan *et al.*, 2006b). Onshore some knowledge of the Indus terrestrial delta exists as a result of shallow coring of Holocene sediments. Although it had been proposed that the delta migrated to the SW during the Holocene (Kazmi, 1982) this model was questioned following a campaign of coring in 2003–2004 by scientists from Woods Hole Oceanographic Institution, when a 120-m-thick Holocene section (ca. 14 k.y.) was recovered at the village of Keti Bandar, which lies close to the modern mouth of the Indus (Fig. 1).

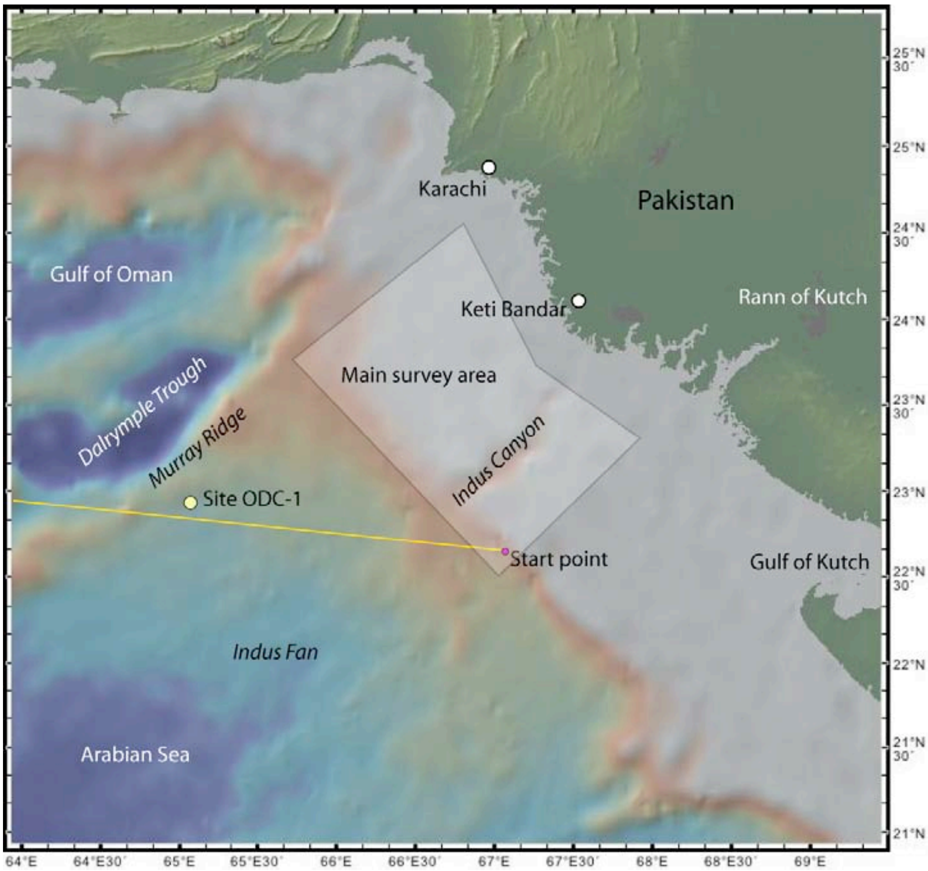


Figure 1. Regional shaded bathymetric map of the Indus delta region showing the general region of operations, the principle submarine topographic features and towns onshore mentioned in this report.

The terrestrial coring showed that the delta had prograded oceanwards even during the Early Holocene (11–8 ka), which was a period of rapid sealevel rise (Camoin *et al.*, 2004). This progradation implied very rapid rise in sediment supply rate at that time (Giosan *et al.*, 2006a). The discovery of fluvial facies throughout the Holocene in most onshore boreholes suggested that the coast may not have been far from the present location during that time, with the exception of a ~40 km retreat of the delta front towards the northeast at ~8.2 ka, as shown by transgression and a reversion to marine conditions at Keti Bandar, at least briefly before renewed delta front coastal progradation.

The primary purpose of Cruise 64PE300 was to map the previously undocumented inner continental shelf of the Indus in order understand how sediment moves from the river to the deep sea Indus submarine fan. Earlier coring had established the fact that sediment delivery to the fan has ceased by 11 ka (Prins and Postma, 2000). This was confirmed by provenance work from core tops within the lower Indus Canyon that show a characteristic glacial (~20 ka) Nd isotope composition that departs sharply from that measured in the modern river (Clift *et al.*, 2008). Although the prograding Indus delta has clearly not reconnected with its deep sea fan, it had been shown that recent sedimentation rates were at a maximum between the head of the canyon and the mouth of the river, despite the sharp drop in sediment supply from the river, following damming in the late 20th century (Milliman *et al.*, 1982). Our objective was to understand how sediment is moved from the river mouth to the canyon and how this has changed since the end of the last ice age (~20 ka), as well as to contrain how the clinoforms on either side of the canyon have been shaped by that sediment supply.

In addition, theoretical considerations based on estimates of the relative importance of wave energy vs. fluvial sediment delivery suggest that the Indus Delta should develop a deep, mid-shelf clinoform (Friedrichs and Wright, 2004). Giosan *et al.* (2006b) compiled existing bathymetry to show that an offshore clinoform composed of three distinct lobes occurs between 30 and 90 m water depth. However, another deltaic clinoform extends along the entire delta coast from the shoreline to the 15–25 m water depth. Unfortunately, the incompleteness of survey coverage for the entire Indus shelf leaves open the possibility that the offshore clinoform lobe on the eastern side of the Indus Canyon, which has built closer to shelf edge, might be entirely or partially relict and no longer active. Resolving this issue is important to understanding what controls clinoform generation in delta settings more generally and how delta stratigraphy is constructed. This is important for general Earth science research, but also to the oil and gas industry’s search for hydrocarbons in channel sands in ancient, as well as modern deltas. In order to accomplish these goals we undertook a programme of seismic surveying and coring of the inner shelf to connect the terrestrial data with the outer shelf surveys.

Figure 2. Edgetech SB-512i “Chirp” seismic system being deployed over the stern of RV Pelagia during cruise 64PE300.

Equipment

Seismic surveys during cruise 64PE300 were conducted using a number of systems. In deeper water and heavier sea conditions that precluded use of our other systems a shallow sub-seafloor image was generated using the shipboard, hull-mounted 3.5 kHz system. More detailed images were derived from towed instruments. We employed an Edgetech SB-512i “Chirp” seismic reflection system (Fig. 2), which was optimized for imaging in the 20–200 m sub-seafloor range. The frequency range was set to 0.7–12.0 kHz for the duration of our operations. During cruise 64PE300 this system was managed and principally operated by Liviu Giosan of the Woods Hole Oceanographic Institution. The data was recorded using EdgeTech Sub-Bottom 3.42 software.

Greater sub-seafloor penetration was achieved using the Boomer and Sparker systems operated by Tim Henstock and John Davis of the National Oceanography Centre, Southampton. Data was recorded over 1540 km of seismic line (318,000 shots) using a hydrophone streamer with a 60-m-long active section consisting of 60 channels at 1 m spacing. The streamer included a 10 m stretch section at each end and a 40-m-long tow lead. Two seismic sources were used, both manufactured by Applied Acoustic Engineering. The Squid 2000 Sparker was powered by a Applied Acoustic Engineering CSP2200 high-voltage power supply (2200J), which was rented from Seatronics Ltd, Aberdeen, UK. This source was typically set to deliver a 2200 J output. The AAE200 Boomer was supplied by an Applied Acoustic Engineering CSP300 power supply delivering a 300 J output. A dedicated sea earth (1 cm diameter) was used for the high-voltage power supplies. The hydrophone was coupled directly to a Geomatrics Strataview R60 seismograph, controlled using Geometrics StrataVisor NX 4.099 software on a PC running Windows NT. The seismic data was logged to dual DDS4 tapes as shot gathers in SEGD 8058 format. Shot instants are derived from the clock on the Strataview, which was automatically synchronized to UTC from a GPS clock at the beginning of each logical line.

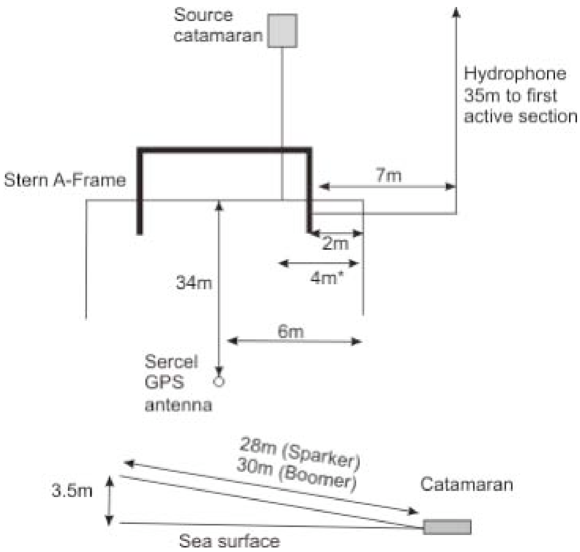


Figure 3. Acquisition and recording geometry of the Boomer and Sparker systems used during cruise 64PE300.

The relationship of the seismic recording geometry to the ship is shown in Figure 3. The streamer was towed from a hoop designed to take the towing strain without pinching the signal cables; this was attached to a pulley on the end of a boom extending to port from the base of the A-frame. Channel 60 was closest to the ship.

Figure 4. View of the Sparker system in the water, with the source catamaran on the left of the picture and the multchannel streamer seen on the right.

The source catamaran was towed from a pin at the stern: From 22 December onward the pin used was 4 m from the port side of the ship; up to the night of 21 December the pin used was 5 m from the port side, but 4 m gave insufficient clearance between the high-voltage cables and Chirp system and the system was reconfigured at that time. Positions from the Sercel GPS antenna are logged by the ship's ABC system at 1 minute intervals. Bathymetric mapping was performed using a multibeam Kongsberg EM302 Swath Mapper using a hull-mounted transducer. These data was recorded and processed shipboard using SIS Konsberg software.

CTD casts were made using a Seabird SBE 9/11 system with a transmissometer, optical backscatter, and fluorimeter mounted on a stainless steel frame with 24 10-liter bottles, although no water sampling was conducted during this expedition.

Coring was achieved using NIOZ's own piston, gravity, box and multicoring systems. Samples from the multicorer were taken from tubes measuring 8 x 60 and 4 x 100 mm. Sub-samples from the box corer were also taken in 4 x 100 mm plastic tubes. Piston and gravity cores were 110 mm in diameter and were split on the ship, described and stored at 4˚C in freezers in the hold prior to shipment to NOC, Southampton.

Figure 5. View of the Sparker and Boomer recording laboratory in the container on the fantail of the vessel. Recording equipment and computer controls are seen on the right on the shelf, while the two source units were placed under the counter on the left of the image.

We adopted a simple numbering system for the cores and samples. All designations are prefixed by "Indus" to show which cruise the materials are derived from. The core sites were then numbered consecutively, starting at one, with a new site number being used if coring deviated more than 200 m from the initial coring location. Each coring deployment was then labelled A, B, C, etc to indicate whether it was the first, second or third coring attempt at each site. Each sample code then has a prefix and an additional label signifying the style of coring employed, whether box core (B), multicorer (M), piston corer (P), gravity corer (G) or the short trigger core (T) from the piston core assemblage. The cores were cut into 1 m sections on deck from the bottom up and numbered consecutively. The core catcher (CC), where this was present represented the lowermost section in any core, followed by Section 1, 2 , 3 etc until the seafloor was reached. A given sample is then further labelled with the depth range it was taken from, with the depth in centimetres from the top of that particular section being used to provide an accurate depth. Most core sections were cut into 1-m lengths, because this was the length the D-Tubes that we had for storage purposes. However, some sections did exceed this value because of the difficulty in cutting core close to the joints in the liner. Similarly, in some cases sections were shorter than 1 m because of lack of recovery, or the location of joints.

Once cut on deck into individual sections cores were either stored at 4˚C or more commonly split vertically into two identical halves soon after recovery. The split core was then described and photographed. Samples were typically taken at this stage, both U-Channels to allow continuous measurements to be made and discrete samples. One half of the core was preserved as archive, with all samples being taken from the working hard. Each half was covered in plastic film to reduce dehydration, and then placed in its own D-tube and labelled with the full sample number, way up and whether it was the working or archive section. Tubes were then sealed with plastic tape and placed in the 4˚C freezers in the hold or in a specially designated container prior to shipment back to National Oceanography Centre, Southampton (UK).

OPERATIONS

Transit and Equipment Testing

RV Pelagia arrived at the buoy offshore Mutrah harbour (Muscat, Oman) at 15:00 (all times in UTC) on 10th December 2008. After loading and bunkering, the vessel departed Muscat at 15:00 hrs on 11th December 2008 and began transit to the Indus offshore operational area, making a direct line to the initial proposed start point east of the Indus Canyon and close to the India-Pakistan border (22˚ 39.0'N, 67˚ 3.0'E)(Fig. 6). During 12th December the science party decided to perform a test of the equipment by running a survey across a proposed Integrated Ocean Drilling Program (IODP) site located on the Murray

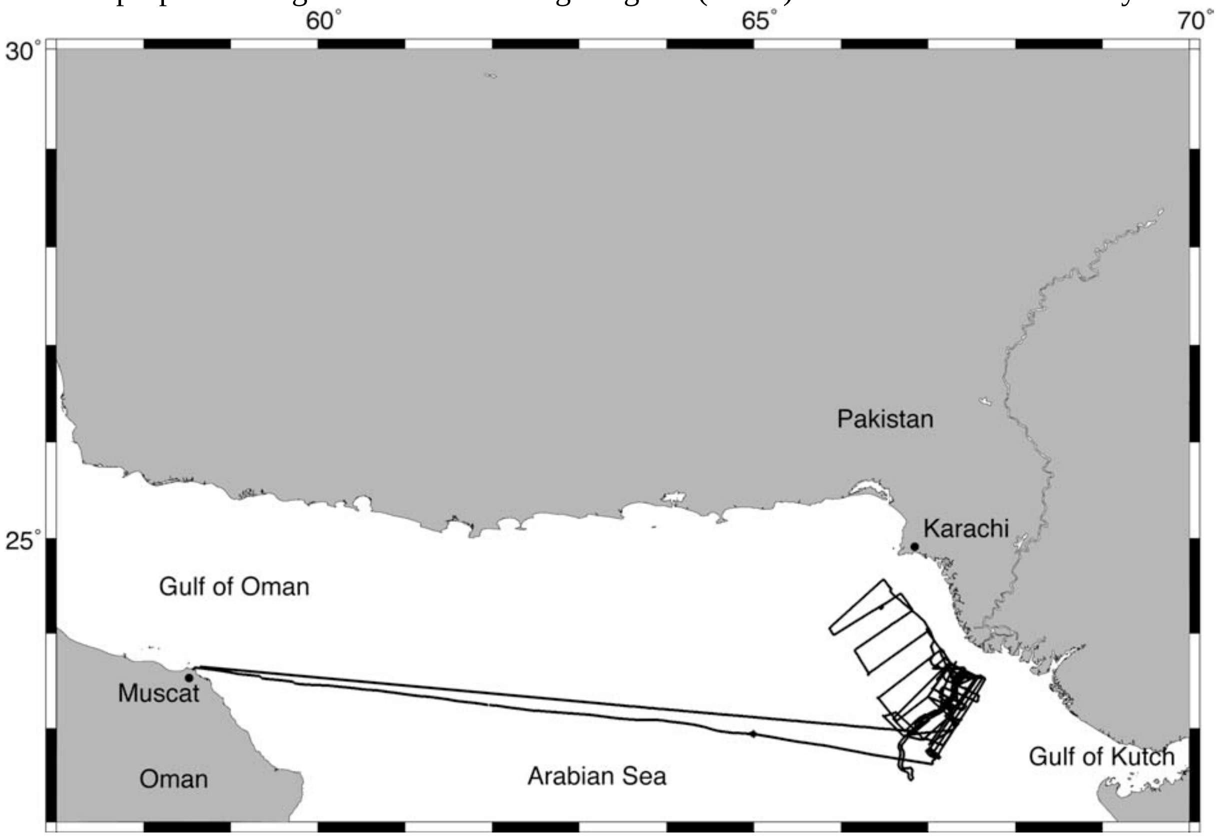


Figure 6. Track chart of the entire cruise showing the transit route from Muscat to the operating region and the general coverage of the Indus delta offshore area.

Ridge at 22˚ 56.2'N, 64˚ 59.6'E. *RV Pelagia* arrived at 22˚ 56.45'N, 64˚ 56.0'E at 07:00 on 13th December and the Chirp seismic system was deployed at 04:10. The system operated well until 05:00 when it was retrieved. Because of the water depths, which exceeded 2000 m no good Chirp data was acquired. At 05:13 a CTD cast was made in order to provide a salinity-seismic velocity profile for the accurate operation of the multibeam bathymetry system (Table 1). The CTD was returned to the deck at 06:30. Although good data was collected there was a software fault in the multibeam system that prevented immediate callibration and recording of accurate water depth information at that time. Following the CTD cast the vessel returned ~3 nm to the west to allow deployed of the Sparker seismic system. The streamer was initially deployed over the stern with no problems at 07:53, followed by the Sparker source at 08:10. By 08:40 the system was operational and collecting data ~1.3 nm west of the proposed IODP site (our Site Indus-1; Table 2), with the vessel on a course running due east. After completing a south to north transect through the site the seismic gear was pulled at 10:35 and the ship was repositioned over the site for piston coring.

A 5.87 m long piston core was recovered, together with a 66-cm-long trigger core, with core arriving on deck at 13:22. The ship was then repositioned for a multibeam bathymetry survey and 3.5 kHz seismic record. A three transect survey was run over the core site, commencing at 14:03 and completing at 16:15. Several shallow slumps and possible shallow gas vents were noted on the 3.5 kHz record. The vessel then resumed transit to the start of the main survey area. During the night the 3.5 kHz system recorded passage over a number of significant channel levee complexes (Fig. 8).

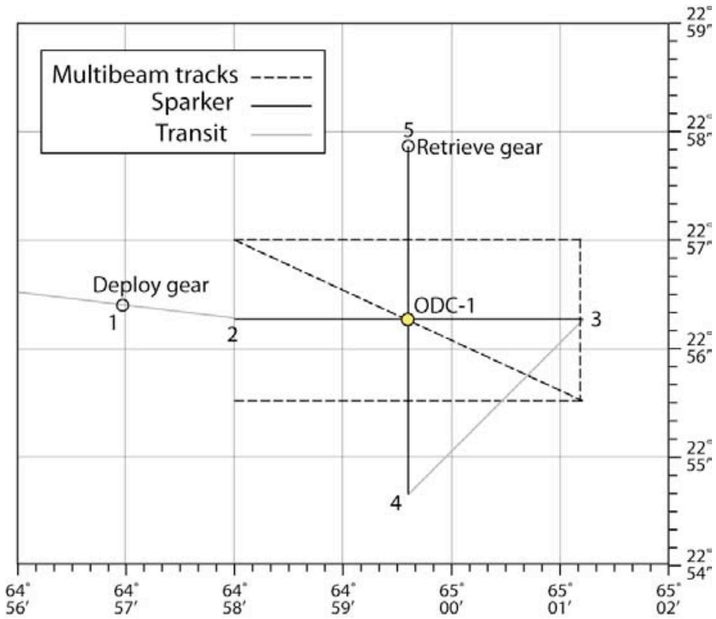
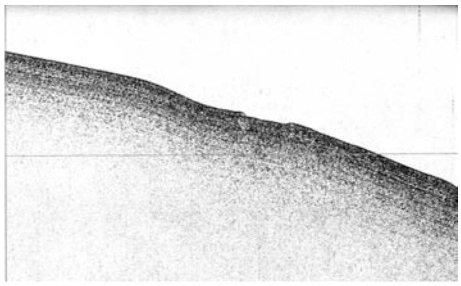


Figure 7. Left. Close-up map showing the survey run around proposed IODP Site. Surveying involved an initial cross of Sparker data (way points, 2, 3, 4 and 5) followed by swath multibeam and 3.5 kHz profiling along the dashed line tracks. Below, example of data between 4 and 5.



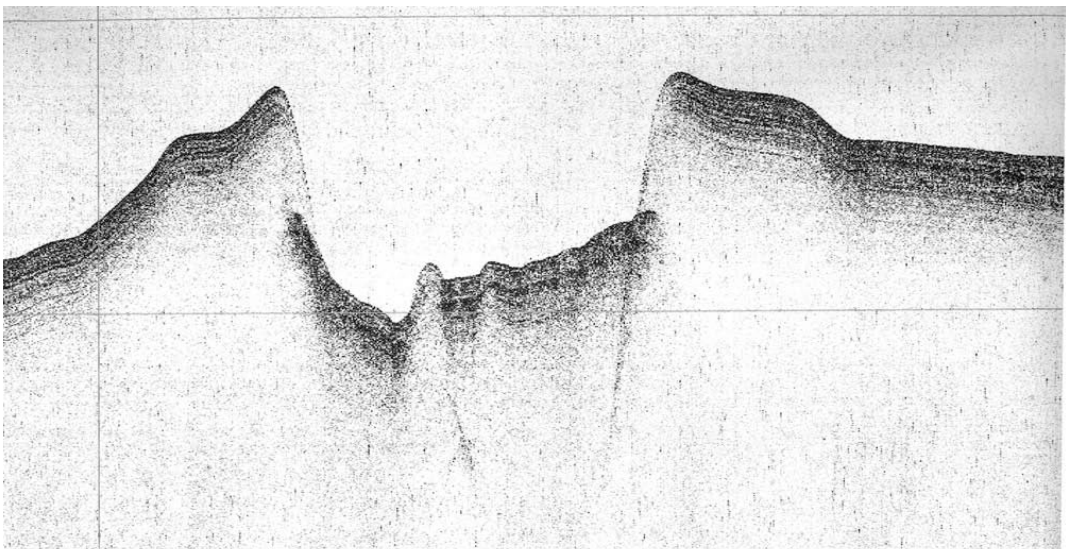


Figure 8. West-East oriented 3.5 kHz image across channel-levee on upper Indus slope.

Geophysical Operations East of the Indus Canyon

RV Pelagia arrived 2 nm south of the survey start point (22˚ 39.0’N, 67˚ 3.0’E) at 04:00 on 14th December 2008 (Fig. 9). A CTD cast was made, being completed at 5:00 hr. Water depths were close to 1200 m. The weather was then judged to be too rough to undertake useful Sparker surveys. Consequently the Chirp was deployed over the stern and the ship set on a course towards 22˚43’N, 67˚7’E collecting multibeam bathymetry and Chirp data. The intention was to produce a map in an area of the upper slope which could be used to select coring locations within the Oxygen Minimum Zone (OMZ). At 07:20 the ship was brought to a halt following problems with the Chirp instrument and a new strategy was adopted that involved mapping of the outer shelf and slope using the multibeam bathymetry and the 3.5 kHz system over an area directly southeast of the earlier survey published by von Rad and Tahir (1997). Several dramatic bowl-shaped slump scars feeding into canyons were revealed, as well as meandering channels incised into the shelf top. The heavily incised character of the shelf edge strongly suggests that the shelf is not actively building at this point, but is erosive.

Surveying continued until 18:00 on 14th December when the Chirp was again deployed over the stern. We returned to our start point of the morning (22˚39'N, 67˚3'E) and began a survey transect heading NNE towards a point at 23˚31'N, 67˚39'E, close to the 12 mile terretorial limit of Pakistan, paralleling the long axis of the canyon. Our aim was to image the subsurface of the wide shallow shelf on the east side of the Indus Canyon. Unfortunately, the sea state was too rough to deploy the sparker. During the night sea conditions continued to improve and the Chirp was able to image 10–15 m sub seafloor. A number of sand-filled channel systems were observed, as well as a steep clinoform shallowing up to ~40 m water depth, but surprisingly located far south of the predicted position from von Rad and the earlier BGR surveys. The 3.5 kHz system was switched off because of stong echoes eliminating all sub-surface stratigraphic details and interference from the Chirp.

The vessel completed the SSW to NNE multibeam and Chirp profile at 23˚31'N, 67˚39'E at 06:30. At this point RV Pelagia held stationary position and a CTD cast was made at 06:40 on 15th December 2008. The CTD, including transmissometer, was recovered on deck at 07:00. The multicorer was then prepared, deployed and then recovered on deck at 07:50 with 27–30 cm of sediment in the tubes (Site Indus-2). The ship was then prepared for a return transect to the SW. The Sparker was deployed at 08:15 at 23˚ 31.3'N, 67˚ 39.0'E (27 m water depth), followed by the Chirp at 08.25 with the vessel headed towards the NW at 2 knt. At 09:25 the vessel came about and started the long geophysical-bathymetric transect SW towards 22˚48'N, 67˚2'E at a speed of 5.5 knt. At 21:00 UTC the ship made the turn and resumed a course to the NE subparallel with the line already run. Interference between the Chirp and the Boomer was still significant and data quality from the Chirp was poor. On the outer shelf little below the seafloor was visible.

Coring the Eastern Clinoform

At 03:10 on 16th December 2008 both Chirp and Boomer systems were retrieved and the vessel was put in transit NE towards 23˚ 5.4'N, 67˚ 22.2'E, located on the top of the major clinoform to the east of the Indus Canyon in order to core the stratigraphy we had seismically imaged. The vessel deployed the multicorer at 05:14 at Site Indus-3 but penetration and recovery were low. As a result the box corer was made ready and collected at 05:55 at 23˚ 5.40'N, 67˚ 22.28'E (32.7 m water). A section 32-cm-thick was recovered. The piston core was then prepared for a 12 m penetration and the device was recovered at 06:49, but disappointingly with no sediment inside and with the lower half of the core barrel severely bent. In order to choose a better location for coring the ship was then used to shoot a six line 3.5 kHz survey around the proposed core area. The core appeared to have impacted into a zone of dense silty clay that the Chirp suggested lay under an unconformity surface on the top of the Holocene clinoform. The 3.5 kHz survey identified a number of small basins above the surface which promised better coring opportunities. A piston core was deployed at Site Indus-4 (23˚ 5.64'N, 67˚22.75'E) at 11:15 but recovery was still only 40 cm of stiff clay. As a result coring operations were abandoned at Indus-4.

The decision was taken to move south and attempt a core on the foreset of the clinoform at Indus-5 (23˚1.923'N, 67˚19.779'E). A box core was deployed at 12:05 UTC on 16th December 2008 and was recovered full (50 cm thick) from which sub-samples were taken. The piston core was then made ready for deployment, but during lowering the trigger core was activated prematurely causing the piston to drop suddenly and resulting in a severing of the cable and loss of the corer to the seafloor. Fishing operations were then initiated with the intention of finding the corer using a grappling line. However, by 17:00, after around 2.5 hrs of fishing no success had been achieved and the operation was discontinued.

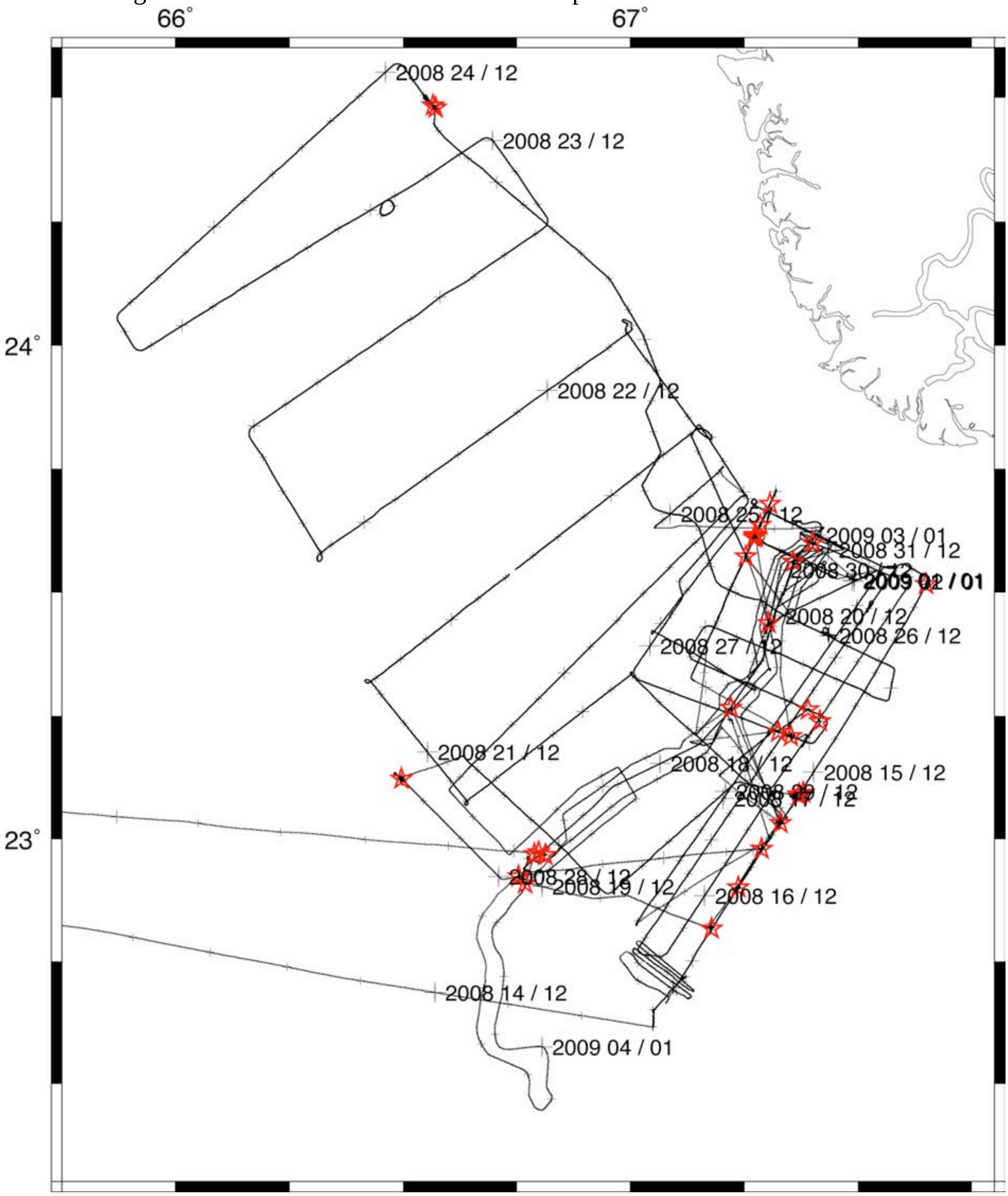


Figure 9. Track chart showing the coverage of geophysical surveys across the Indus Shelf and Canyon acquired during cruise 64PE300. Red stars show the coring locations.

Seismic Surveys over the Eastern Clinoform

After fishing the ship was put underway towards 23˚0.00'N, 67˚18.34'E in 68 m of water, where a tripod of oceanographic instruments was deployed at 17:40. The tripod comprised an ACDP, transmissometer and current meter (Fig. 10). The ship resumed course at full cruising speed (ca. 10 knt) towards 22˚49.98'N, 67˚1.02'E at which point the Chirp was lowered over the stern and a survey conducted running towards the NE, subparallel with but east of the Indus Canyon. The profile was run because the Chirp survey of the previous evening had been compromised in quality by interference from the Boomer and because the area was considered crucial for understanding the origin of the eastern clinoform. The profile was offset towards the west relative to the earlier line in order to derive greater spatial coverage and make some use of the data that had been collected on 15–16 December. A survey was then run, together with multibeam bathymetry towards a way point at 23˚ 33.06'N, 67˚33.36'E, roughly parallel and to the east of the Indus Canyon. The waypoint was reached at 07:30 hr on 17th December 2008. Data quality on the Chirp was good and several erosional, infilled channel systems with very intricate geometries were observed in the shallow subsurface.

Imaging the Indus Canyon

The ship was then turned towards a new way point of 23˚40.56'N, 67˚16.38'E located just west of the head of the canyon. The sea state was too rough to allow deployment of the Sparker as intended and so the survey was continued with Chirp and multibeam bathymetry alone. Dramatic seismic images across the head of the Indus Canyon showed a complicated infill and a number of completely buried channels located west of the modern "Swatch of No Ground". At 11:10 the signal from the Chirp was suddenly interrupted. The vessel was slowed to 2 knts and the instrument was recovered. Deck tests revealed a loose connection, which was readily fixed and the instrument was soon ready to be deployed again. The ship returned to its course and the Chirp was again deployed ~0.5 nm of the SE of the point at which the technical fault had developed so that a continuous profile could be made. The survey resumed at 12:13 hr. The end waypoint was reached at 13:30 hrs at which point the Sparker and streamer were deployed thanks to the wind being from the NE and the calming sea state. However, by 17:30 hrs the sea state had again deteriorated substantially, with swells ~3 m in height so that it became necessary to pull both instruments.

A new plan was then devised for use of the overnight hours involving swath mapping and 3.5 kHz seismic work along the length of the Indus Canyon, particularly following its western flank (Fig. 11). The surveying revealed a number of dramatic meander channels with terraces within the canyon, especially prominent towards the southern end of the survey. Multibeam mapping was terminated at 05:10 hrs when the ship arrived at core location Indus-6 on the eastern clinoform, just south of the active foreset. The box corer was prepared and deployed but returned overfilled, with the surface sediment layer missing. A sub-sample core measuring 39 cm was taken. In order to recover the surface layer we then deployed the multicorer, which sampled the top 35 cm in Core Indus-6B-M, being recovered to the vessel at 11:00 hr on 18th December 2008. Finally a longer core was attempted using the gravity corer. The soft seafloor resulted in an over-penetration and final recovery of 256 cm of sediment. At this time the vessel was returned to nearby core site Indus-5 and a gravity core was taken and recovered on deck at 12:30. The core contained 301 cm of sediment, mostly silty clays with scattered shelly fragments. With night fall we then attempted a further recovery of the missing piston corer with a fishing operation involved four grappling hooks. This procedure was terminated unsuccessfully at 17:00 hrs.

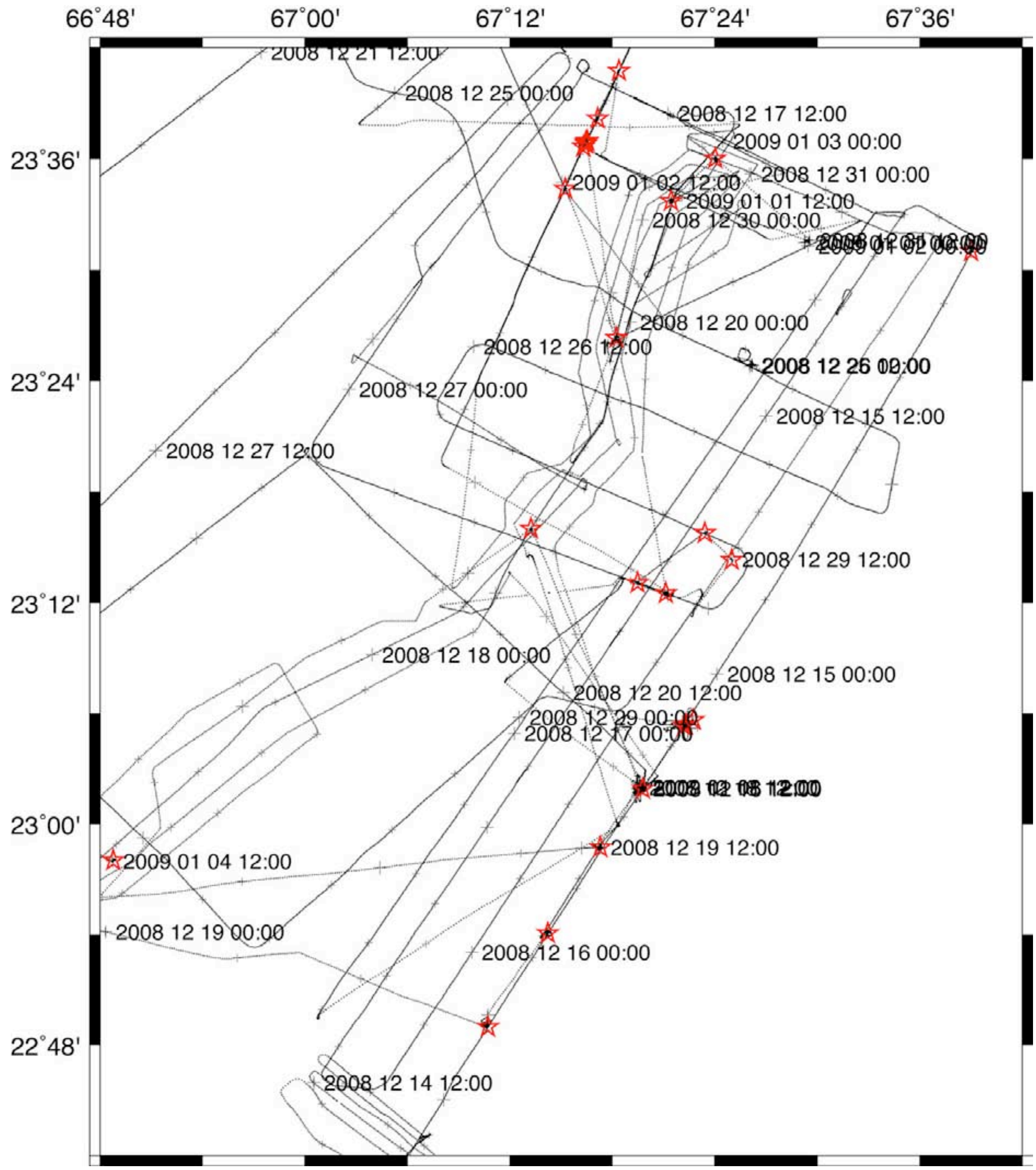


Figure 10. Track chart of the region directly around the Indus Canyon showing the coverage that images most of the canyon with multibeam swath bathymetry and with several along and across canyon profiles with Chirp, Sparker and Boomer seismic systems.

Between 17:00 on 18th December and 03:00 on 19th December the ship performed multibeam swath bathymetric mapping in the southern half of the Indus Canyon (Fig. 11). After departing core location Indus-5 the ship moved to 23˚13.5'N, 67˚12.0'E before starting the survey at 6.5 knt, a speed that was considered the maximum to generate high quality data with the system. The vessel terminated the detailed bathymetric survey at 22˚55.0'N, 66˚45.5'E after shadowing the track of the multibeam swath generated during the previous evening. As before the decision to conduct multibeam mapping was largely a result of a high sea state that precluded use of the Chirp and Sparker systems, and the operational requirement that no coring be undertaken at night. The vessel arrived at core site Indus-7 (22˚49.0’N, 67˚10.71’E, 114 m water) at 03:50 and shortly after this time a multicorer was deployed, recovering 45 cm of sediment on deck at 04:30. This was followed by a gravity core (Indus-7B-G) which was on deck at 05:40. 1.4 m of sediment was recovered from a sotf substrate. The vessel was then offset to a new location (Indus 8, 22˚54.07’N, 67˚14.21’E, 104 m water) where a multicore was taken at 06:45. Although a piston core was desirable the presence of a potential hard unconformity horizon in the shallow sub-surface meant that piston coring at this site was considered risky, As a result the ship was moved to the previously occupied Site Indus-6 on the slope of the eastern clinoform and the piston corer was prepared for a 12 m section while underway, and was deployed shortly after arrival. The piston core was recovered on deck at 12:00, where recovery was measured at 9.37 m.

The ship was then put on a course to measure multibeam swath bathymetry in the northern parts of the Indus Canyon, up to the territorial 12 nm line of our operating area during the night hours of 19-20th December. RV Pelagia returned to core site Indus-5 on the crest of the eastern clinoform on 20th December 2008, arriving at 03:45. The piston core was made up for an 18 m recovery and after deployment was recovered on deck at 05:30 on 20th December 2008. A record 12.43 m of recovery for this cruise was achieved and it was should that collapse of the upper part of the core liner had prevented the recovery from being even greater. After the core had been cut and stored a fnal attempt was made to fish the missing piston core from the seafloor, starting at 08:30 and finishing at 11:00. At this time the Chirp and Sparker seismic systems were deployed from the back of the vessel and a course was set towards 23˚20’N, 67˚00.0’E at 4.5 knt. The aim of this line was to image the sediment deposited in the central parts of the Indus Canyon and to start surveys on the western side of the shelf.

Geophysical Surveys on the Western Shelf

Chirp and Sparker seismic operations continued throughout the night and into the 21st December. Around 05:00 the Sparker in particular was experiencing reduced data quality because of a higher sea state and the change in direction of the track towards the NW, which brought the track of the instruments across the wave transport direction. As a result vessel speed was reduced sligthly to 3.5 knt and was kept at this rate as the track turned back towards the coast along a northeasterly heading. Data quality was then reasonably good but the shelf west of the Indus Canyon itself was largely swept of sediment and only a modest drape of Holocene was identified across most of the transect. Sparker images in particular served better to pick out the structures in the underlying strata.

The lack of major deck operations during the prolonged geophysical survey of the survey west of the canyon allowed servicing of the coring devices and processing and description of the long piston that we had recovered the day before. During the night the Chirp became entangled first with the power cable to the Sparker source and then with the seismic streamer itself, triggered by the higher sea state. At this time (20:10 on 21st December) the decision was taken to recover the Sparker and streamer to the vessel and continue the survey of the western shelf using only the Chirp. Fortunately the morning brought improved conditions and following the turn at 23˚34.80’N, 66˚19.14’E we were able to redeploy the Sparker, which resumed activity at 08:35 on 22nd December (Fig. 12). A close watch was kept on the relative positions of the Sparker and Chirp, but operations were able to continue as the sea state remained relatively favourable. At 08:17 on 23rd December the Sparker source was temporarily deactivated and taken back onboard for simple maintenance operations, before being redeployed. At the same time the Chirp data was backed up as the ship circled to maintain a constant position on the line.

Coring the NW Shelf

Our planned survey finished its NW limit at 00:20 on 24th December 2008. We then turned towards the SE on a bearing of 142˚ because the Chirp had revealed a bare seafloor around the waypoint and proposed coring location at 24˚35'N, 66˚30'E, the northernmost point on our survey. In addition, we adjusted our course to stay within the approved survey limit agreed with the Government of Pakistan and to avoid the track of another geophysical survey vessel the *GeoWave Champion*, which was conducting a 3D commercial survey in the area. At 02:45 the vessel was brought to a halt and the geophysical equipment recovered. A tripod comprising an ACDP, transmissometer and current meter was then deployed at 24˚30.25'N, 66˚32.89'E in 70 m of water and subsequently a CTD cast was made in the same location, being completed at 03:13. The vessel was then offset from this location by ~200 m and a multicorer was taken (Site Indus-9), being recovered on deck at 05:36. The soft seafloor suggested that a gravity core would be effective and one was made up and taken at Indus-9, being recovered on deck at 04:20, with 443 cm of sediment being sampled. Having established that the region identified by Chirp was suitable for coring the piston corer was prepared and the vessel moved again a short distance to Site Indus-10 (24˚29.05'N, 66˚33.96'E). The piston core was shot and brought on deck at 05:35 after recovering 906 cm from a 12 m core barrel, including a spectacular unconformity with a weathering profile, presumed to represent the Last Glacial Maximum.

Return to the Indus Canyon

After processing the core the decision was taken to make full use of the good sea state and continue geophysical surveying back towards the southeast. After setting a course along a line of 140˚ and deploying the Sparker and the Chirp from the stern evasive manouvres had to be made to avoid the *GeoWave Champion* which was advancing towards our position along a parallel track in the opposite direction and with minimal separation calculated. We then proceeded along the NE boundary of our approved survey area towards the southeast, diverting to roughly follow the supposed 60 m isobath, interpreted as the possible crest of the active clinoform. This route brought RV Pelagia close to the western edge of the Indus Canyon around 03:00 on 25th December. We then proceeded towards the southeast transecting the canyon, until 06:10 when the vessel slowed to 2 knt to retrieve the seismic arrays. Once this process was complete we returned towards the northeast to drop anchor is a region of shallow bathymetry ~27 m at 23˚24.8'N, 67˚26.2'E. The ACDP, transmissometer and current meter tripod was deployed at 11:00 at 23˚24.9'N, 67˚26.17'E and the ship's crew and science party spent the rest of the day and overnight enjoying a Christmas Day rest.

At first light on 26th December (02:10) the RV Pelagia retrieved its anchor and shortly after recovered the physical oceanographic tripod to the deck. We then made a wide turn to the northwest of the anchorage, making a speed of 2 knt while the Chirp and Sparker were deployed. The Sparker had a delayed launch because of some maintenance related to new sparker tips. However, by 03:25 we were making 4.5 kts towards the southeast away from the Indus Canyon to complete the transect we had started the day before. The programme for the day then involved a series of four long seismic and swath bathymetric profiles across the canyon in a NW-SE orientation cutting across the long axis of this feature. Data quality was an issue at some points in the deep canyon, especially where the seafloor was rubbly and the number of sub-seafloor reflections that could be seen was modest. Nonetheless, because of the good sea state the data quality on these transects was generally very good. By morning on 27th December the RV Pelagia was on the west side of the canyon and after reaching way point 23˚19.8', 66˚59.8'E we changed course to run to the northeast parallel to the canyon's long axis. We also planned our lines into order to join two shorter, pre-existing lines. After reaching way point 23˚41.0'N, 67˚15.7'E we made a turn towards the west and resumed a long profile, running NE-SW towards the shelf edge. As before Chirp and Sparker seismic data were collected. Pelagia reached the final way point (23˚09.0'N, 66˚39.1'E) at 16:00 hrs, at which point the seismic gear was recovered to the deck and the ship was set on a programme of bathymetic mapping of the southern parts of the Indus Canyon using the hull-mounted multibeam system at a operational speed of 6.5 knts. The objective was to fill holes in the earlier mapping surveys we had done in the area and to occupy the ship usefully in this region prior to day light when coring could begin at the formerly occupied Site SO-90-136 (von Rad and Tahir, 1997).

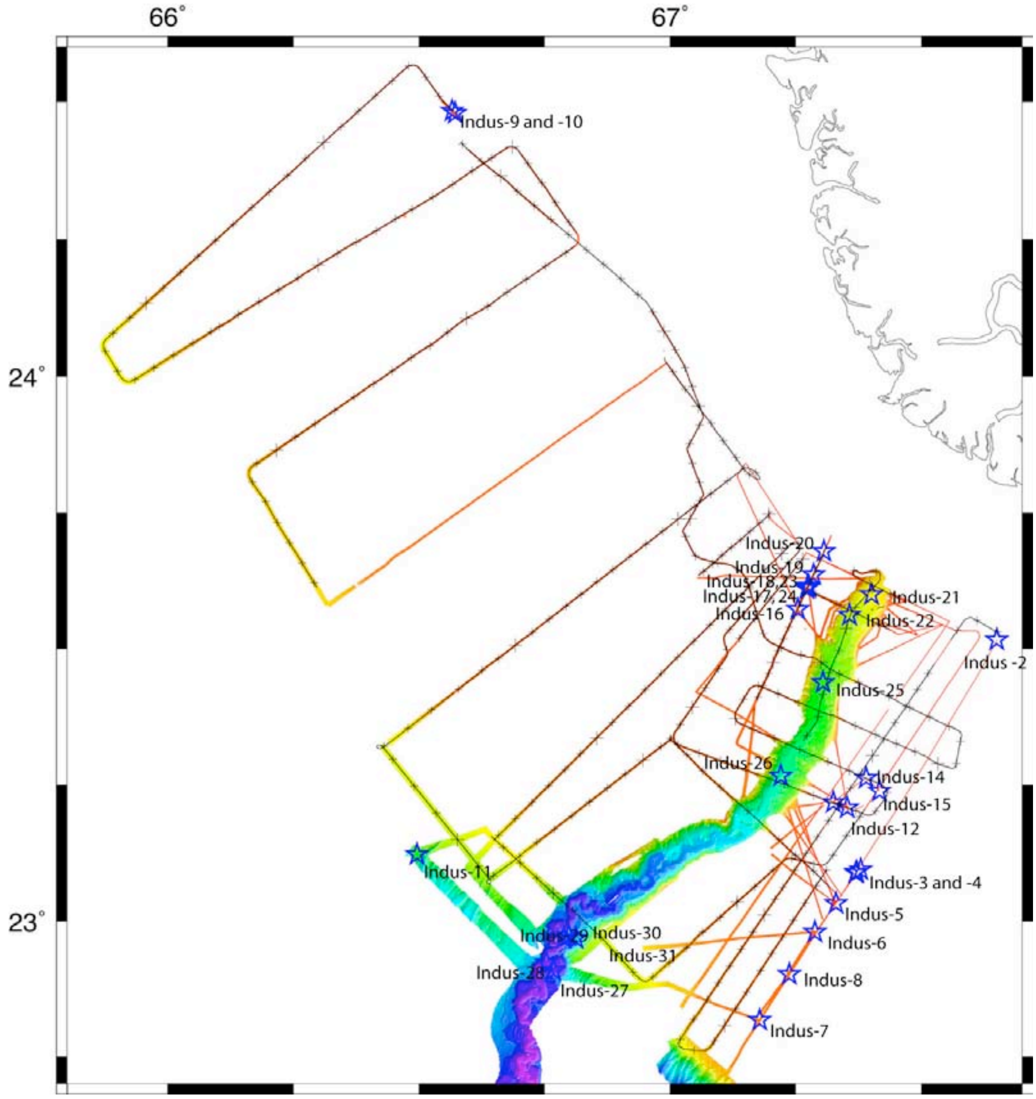


Figure 10. Track chart showing the coverage of multibeam bathymetry over the shelf and Indus Cayon acquired during cruise 64PE300, as well as the location of the core sites.

Coring the Western Continental Slope

Bathymetric mapping was terminated at 02:40 hrs on 28th December on arrival at 23˚07.30'N, 66˚29.80'E, the location of previous coring by the BGR Sonne cruise 90. The ship continued for a short distance over the site to provide full bathymetric and 3.5 kHz seismic coverage over the intended coring locations. At 03:30 a CTD cast was made in 566 m of water. After completion the multicorer was then made up and deployed. The first attempt was unsuccessful because of overpenetration resulting in only two liners having the seafloor sediment in them. A second attempt resulted in eight good cores with 50 cm of sediment in each. The piston was then made ready with an 18 m barrel and was recovered to the deck at 05:55. The core was hard to extract from the barrel because the plastic liner had become concertinaed during firing, so that the bottom 70 cm of sediment in the barrel had no liner. The sediment was nonetheless extruded and stored in liners. However, the decision was taken to attempt a second piston core at this site in order to achieve a good quality core. Consequently a second 18 m piston corer was taken and recovered to deck at 12:18. This core was of good quality and sampled 12.96 m of sediment at the location previously targetted by German SO90. The core was broken down into sections and the ship was put in transit to 22˚53.00'N, 66˚57.0'E, which was the end point for the geophysical profile the previous evening. At this point the ship speed was reduced to 2 knt and the Chirp and Sparker were deployed from the stern at 13:50. Speed was increased to 4.5 knt and a course set towards 23˚07.00'N, 67˚14.0'E, allowing us to transect the lower canyon before running up towards the northeast during the night.

Coring on the Eastern Clinoform

RV Pelagia arrived at its end way point for the night survey at 23˚12.00'N, 67˚23.0'E at 03:45 hrs on 29th December 2008. We retrieved the Sparker and the Chirp and then made a course towards our targetted coring location, Indus-12 at 23˚12.488'N, 67˚21.122'E. On arrival the physical oceanographic tripod was deployed at 03:30 hrs. At this time the multicorer was prepared and deployed, being recovered to the deck at 04:00 hr. The core revealed a fine sandy seafloor. A piston corer was readied, shot and recovered to the deck at 05:35 hr. Unfortunately there was no recovery and the lower section of the core was severely bent. As result the decision was made to attempt a gravity core (Indus-12C-G). This was deployed at 07:00 hr, but again recovered no sediment, although without damage or loss of the equipment. As a result of our technical problems at Indus-12 the ship was put in transit to nearby site Indus 13 (23˚14.328'N, 67˚24.993'E), still in shallow water depth (34 m) slightly closer to the Indus Canyon. In order to assess the seafloor the multicorer was prepared and sampled the shallow sub-seafloor to a depth of 23 cm, revealing a fine sandy composition. As a result the prospects for piston or graavity coring did not seem good and so the box corer was used to collected 32 cm of shallow sand before the vessel was put in transit to location 23˚15.744'N 67˚23.385'E (Indus-14), again located on the top of the mainly relict eastern clinoform. A multicore deployment again tested a sandy bottom and further coring at this site was therefore terminated. Again RV Pelagia was put underway, the short distance to Indus-15 at 23˚14.32'N, 67˚24.99'E. To assess the nature of the seafloor the multicorer was used and this was deployed and then recovered on deck at 11:45 hr. After successfully recovering 25 cm of sediment by this method we opted to try a 6-m-gravity core, although the seafloor still seemed somewhat sandy. As a result the gravity core returned to the ship at 12:05 hrs but only a handful of sediment was found in the core barrel.

Imaging the Northern Canyon and Western Clinoform

Because of the advanced time and approaching nightfall we chose to abandon coring operations on the east side of the canyon and instead ran a geophysical survey overnight. Arcing problems with the Sparker source ruled out use of this method, so that a transect running SW to NE towards 23˚32’N, 67˚37’E was performed with the Chirp system alone. At this time, 17:00 hr, we opted to take out the Chirp and switched to a purely multibeam bathymetric mapping programme of the central and eastern edges of the upper Indus Canyon over night. The survey was run at 6 knt and aimed to fill in gaps in earlier transects while broadening the image to the east. The survey was terminated at 23˚20.0’N, 67˚19.75’E at 03:45 on 30th December 2008 and the speed was increased to 10 knt. The vessel arrived in the location of the physical oceanographic tripod at 04:45 hr (23˚12.51'N, 67˚21.13'E) at which time the instruments were recovered onboard. Because of transit time considerations we then placed the vessel on a course towards the northwest in order to run a Chirp and Boomer survey across the clinoform on the western side of the canyon and to place the vessel subsequently in a location for coring that region. As a result maximum speed was made towards the start point at 23˚20.00’N, 67˚08.00’E where the Chirp was deployed from the stern and a course set towards 23˚38.00’N, 67˚17.00’E at a speed of 4.5 knts starting at 06:20 hr. After reconsidering the time constraints we then opted to continue our Chirp line north to the limit of the working area at which point the Chirp was recovered and the Boomer deployed. Surveying proceeded towards the SSW in order to image the front face of the western clinoform, but was terminated before the end of line because of poor data quality, whose origin was not clear given the favourable sea state. At this point we opted to start an overnight swath bathymetric survey of the NW edge of the canyon, commencing at 14:45 hrs. RV Pelagia steamed at full speed to the survey start point (23˚13.0’N, 67˚09.0’E) where speed was reduced to 6 knts and logging of the multibeam data commenced. We then followed a meandering track along the western edge of the canyon extending the multibeam survey of the canyon axis that we had already compiled. In particular, our aim was to image the edge of the canyon which had been missed before. The survey wrapped around the northern head of the canyon and returned towards the SSW, ending at 23˚27.0’N, 67˚21.5’E at 01:27 hrs on 31st December 2008.

Coring the Western Clinoform

The ship was then brought to full cruising speed and made a direct passage towards our first coring site on the clinoform west of the canyon, located at 23˚34.38’N, 67˚15.22’E. We arrived at this point (Indus-16) at 03:08 hrs on 31st December 2008 at which time the box corer was deployed with the aim of recovering older sediment from under the major unconformity surface over which the clinoform is prograding. Due to the hard substrate no other coring methods were attempted at this location. After operations were completed the vessel was repositioned at 23˚36.81'N, 67˚16.46'E (Indus-17) where a gravity core was attempted directly, recovering 131 cm of sediment in two sections. Similarly a gravity core was taken at 05:40 hr at 23˚36.95'N, 67˚16.53'E (Indus-18), where 197 cm of sediment were recovered. The ship was then moved to Indus-19 (23˚38.18'N, 67˚17.13'E) where a multicorer sampled the top 28 cm of the sub-seafloor. Although this core revealed a sandy seafloor we still attempted a gravity core, which was recovered to the deck at 06:50 hrs but which yielded no sediment. As a result we moved location to 23˚40.75'N, 67˚18.38'E (Indus-20), where the multicorer was deployed and recovered 25 cm of mostly sandy sediment. An attempt at deeper penetration with the gravity corer was unsuccessful.

After finishing the set of core sites in rapid time we chose to use the rest of the daylight time to run a short Chirp transect across the canyon, towards the ESE. Pelagia steamed south to 23˚36.0’N, 67˚17.5’E at full speed before the Chirp was put in the water and a survey commenced at a speed of 4.5 knt towards 23˚32.5’N, 67˚26.5’E. This track brought the ship directly over the northern part of the canyon thalweg. On reaching the end of the line the Chirp was recovered and the ship returned to full cruising speed towards the east. The ship was brought to a halt at 23˚31.5’N, 67˚29.5’E where the physical oceanographic tripod was deployed in 37 m of water. The vessel was then offset by 500 m from this location and the anchor dropped for the overnight period of observation and celebration of the New Year.

Coring the Head of the Canyon

The tripod was recovered to the deck at 03:10 hr on 1st January 2009. At this point the vessel was put underway to 23˚36.01'N, 67˚24.01'E to begin a series of core locations at the head of the Indus Canyon. The first multicore at Site Indus-21 over penetrated in especially soft muddy sediment, so that a second attempt was made, this time recovered the seafloor and 56 cm of underlying sediment. Because of the soft muddy character of the sediment the piston core was made up for an 18 m penetration. The barrel was recovered to the deck at 07:15 hr and was found to have sampled 1386 cm of sediment. The vessel was then moved to a new coring location towards the south at Site Indus-22, where a multicorer again revealed a soft, muddy seafloor in the canyon thalweg. Once again the 18 m piston corer was prepared and finally sampled 1315 cm of sediment once it was recovered to the deck at 11:08 hr.

Because of the advanced hour we then opted to start a night of geophysical surveys, starting with a Boomer survey across and then along the canyon axis as far south as 23˚20’N. The schedule was planned to bring the ship back to the locality of the western clinoform around breakfast time on 2nd January 2009 and included a Chirp profile across the front of the clinoform east of the canyon, as well as a final Boomer transect across the canyon. Our operations were delayed slightly by problems with the stern A-frame but at 03:45 we pulled the Boomer and were able to offset to the coring location, 23˚36.656’N, 67˚16.307’E, very close to the earlier sampled Indus-17. A 12 m piston core was then made up and deployed at new site Indus-23, being recovered on deck at 04:00 with a recovered length of 767 cm. The vessel was then moved the short distance to Indus-24 (23˚36.904’N, 67˚16.440’E), close to former site Indus-18. As a result there was no need to run a multicorer and instead a 6-m gravity corer was used, recovering 356 cm of sediment. The ship was the put in transit to the next coring site (23˚26.32'N, 67˚18.22'E), Indus-25, located in the centre of the Indus Canyon. Because this was a new location we first sampled the shallow sub-seafloor using the multicorer, which recovered 46 cm of muddy sediment. Consequently the piston corer was made up for an 18-m section, shot and recovered to the deck at 12:20 hr. 11.83 m of sediment were sampled.

Completing the Seismic Surveys

As the cruise was nearing its end a programme of geophysics was designed to complete outstanding gaps in our data sets related to the eastern and western clinoforms, as well as along the axis of the canyon itself. Following coring operations the vessel was set up for a night of geophysical surveying operations. Initially we transitted at full speed northwest to core site Indus 16 at which point the Chirp was deployed over the stern and course set towards 23˚49.00’N, 67˚08.00’E in order to imagine across the top of the clinoform west of the canyon. This 16 nm profile was terminated and return line run back to the southeast, parallel to the boundary of the Pakistan territorial waters. The chirp was recovered at 18:50

before the vessel transited at full speed to 23˚44.5’N, 67˚11.5’E to start a new Boomer transect across the southwest-facing front of the western clinoform. This two hour line was terminated at 23˚38.2’N, 67˚03.50’E when the Boomer and streamer were recovered to the deck at 23:45 hr. The Pelagia transitted at full speed to the head of the Indus Canyon close to the northern edge of the survey box where the Chirp was placed over the stern at 23˚ 34.20’N, 67˚ 21.70’E. The survey was run to follow the canyon thalweg and the earlier Boomer line along the same track, except that the Chirp line extended further to the SSW, ending at 06:45 on 3rd January 2009 at 23˚ 11.70’N, 67˚ 8.20’E.

A short transit brought the vessel to 23˚13.00’N, 67˚18.50’E where the Boomer was deployed for the final time in order to image the frontal slope of the eastern clinoform. This profile was run at at 4.5 knts and finished at 10:05 hr when the streamer and source were recovered to the stern after reaching the end way point at 23˚08.00’N, 67˚12.00’E. At this time we transit at full speed to 23˚1.92'N, 67˚19.78'E (site Indus-5) in order to fish one last time for the missing piston corer. This operation recovered the previously lost grappling hooks but failed to find the original piston corer. Fishing activities were terminated by 13:00 and the ship was then put in transit to a new deep water core site within the thalweg of the Indus Canyon that had been identified during Chirp surveying earlier in the same day. The vessel arrived at 23˚16.00’N, 67˚13.22’E (Indus-26) and a 6 m gravity core was made up and deployed, being recovered on deck at 15:15 hr. On cutting 244 cm of sediment was found within the barrel.

Swath Mapping the Southern End of the Canyon

After terminating these operations the Pelagia transitted at full speed to 23˚ 12.0’N, 67˚7.00’E where the speed was reduced to 7 knt for a multibeam bathymetric survey along the southwestern rim of the canyon, filling in a gap in the coverage we had achieved earlier in the cruise. This survey was completed close to the end of the deep canyon/shelf edge at 19:20 hrs. The ship then transitted rapidly south to pick up a new bathymetric survey for the remaining hours of the night. Our intention was to follow the Indus Canyon south within and beyond the region targetted in 1995 by the BGR on RV Sonne SO90. The canyon was followed south to a latitude of 22˚26.0’N before the vessel had to loop around and follow the track back to the north in order to core during day light hours at the end of the deep canyon.

Coring the Canyon Thalweg and Terraces

RV Pelagia arrived at 22˚55.40’N, 66˚45.23’E (Indus-27) at 05:40 hrs on 4th January 2009. A 6-m-gravity core was made up and deployed, being recovered to the deck at 06:45 hrs after sampling the thalweg of the canyon. Unfortunately only 40 cm of muddy sediment were recovered in this location. The ship was then offset a short distance to 22˚54.51'N, 66˚46.07'E (Indus-28) where the 6-m corer was again employed, this time recovering 573 cm of sediment, including some medium grained sandy turbidites from an abandoned ox bow on the canyon channel. After making the equipment safe we then transitted to 22˚58.10'N, 66˚47.32'E (Indus-29) where the 6 m gravity corer was used to sample the lowermost of three terraces identified from the swath bathymetry, which sits well above the level of the modern canyon channel. The core was recovered to the deck at 10:30 UTC and was shown to contatin 484 cm of sediment from that locality. The vessel was then offset the short distance to Indus-30 (22˚58.34'N, 66˚47.91'E) and again the gravity core was deployed, this time on a shallower terrace than the last, 1108 m versus 1141 m. Once again the core provided a good long section of 489 cm, arriving on deck at 11:45 hr. The last core of Cruise 64PE300 was taken at Indus-31 (22˚58.03'N, 66˚48.75'E) and arrived on deck at 12:50 hr with a recovery of 595 cm. At this point the core barrel was secured and the Pelagia set on a course for Muscat, Sultanate of Oman. Because of the speed we opted not to collect further swath bathymetry, but the 3.5 kHz recorder was activated to image the shallow sub-seafloor en route. The pilot boat met the ship at Muscat harbour entrance at 21:00 hr on 6th January 2009, with the first line ashore at 21;45 hr, bringing cruise 64PE300 to an end.

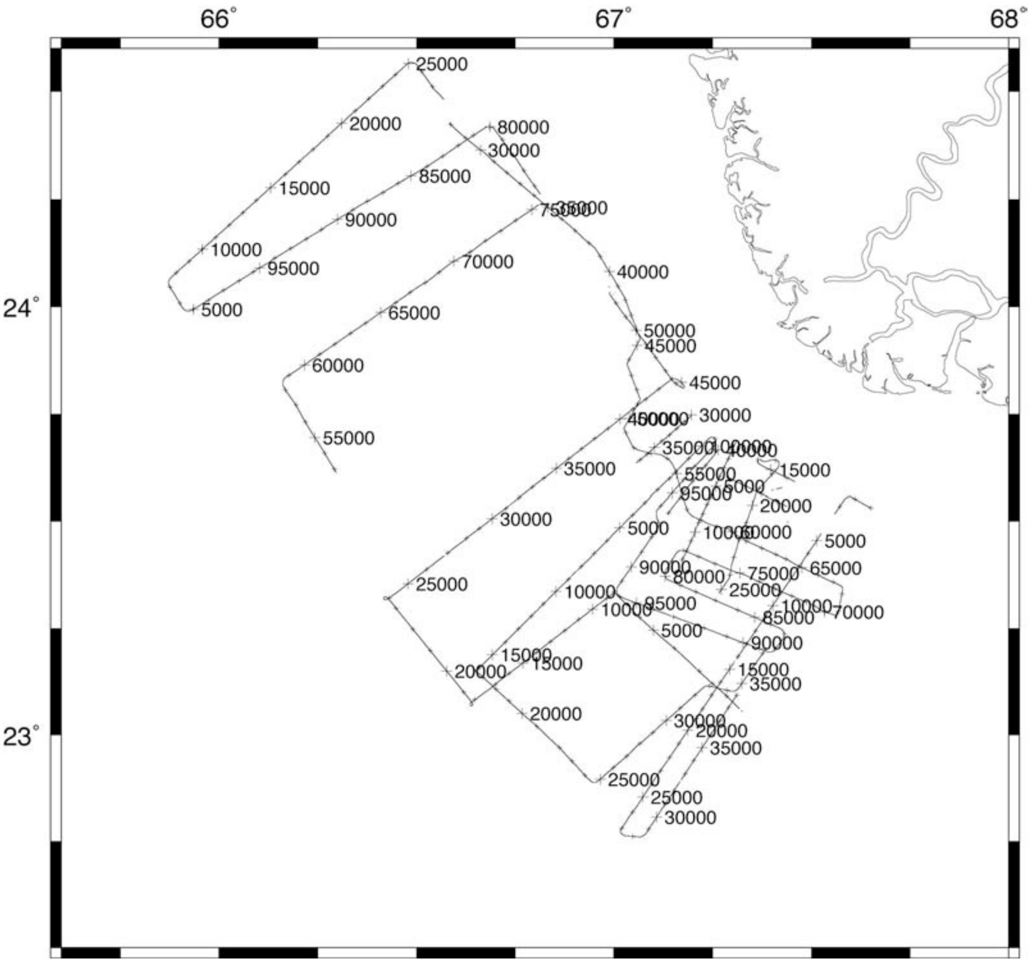


Figure 12. Track chart showing the coverage of Boomer and Sparker data across the Indus Shelf completed during cruise 64PE300.

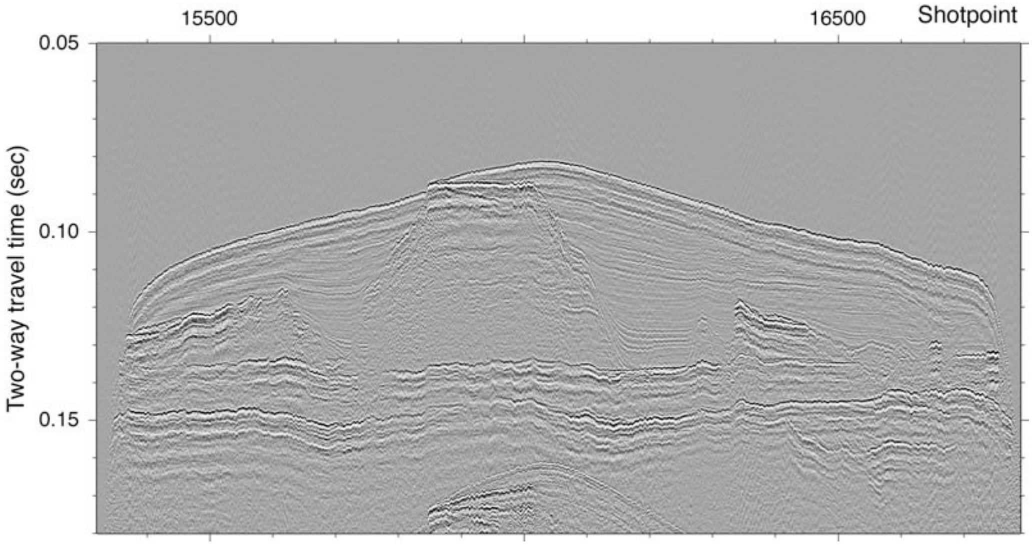


Figure 13. Example of Boomer data from the head of the Indus Canyon. Line includes a 180˚ turn in the ship track in the centre so that the sharp drop off into the cabyon can be seen at either end of the line. Note the strong erosion channeled survey in the sub-surface now infilled by presumably Holocene sediments.

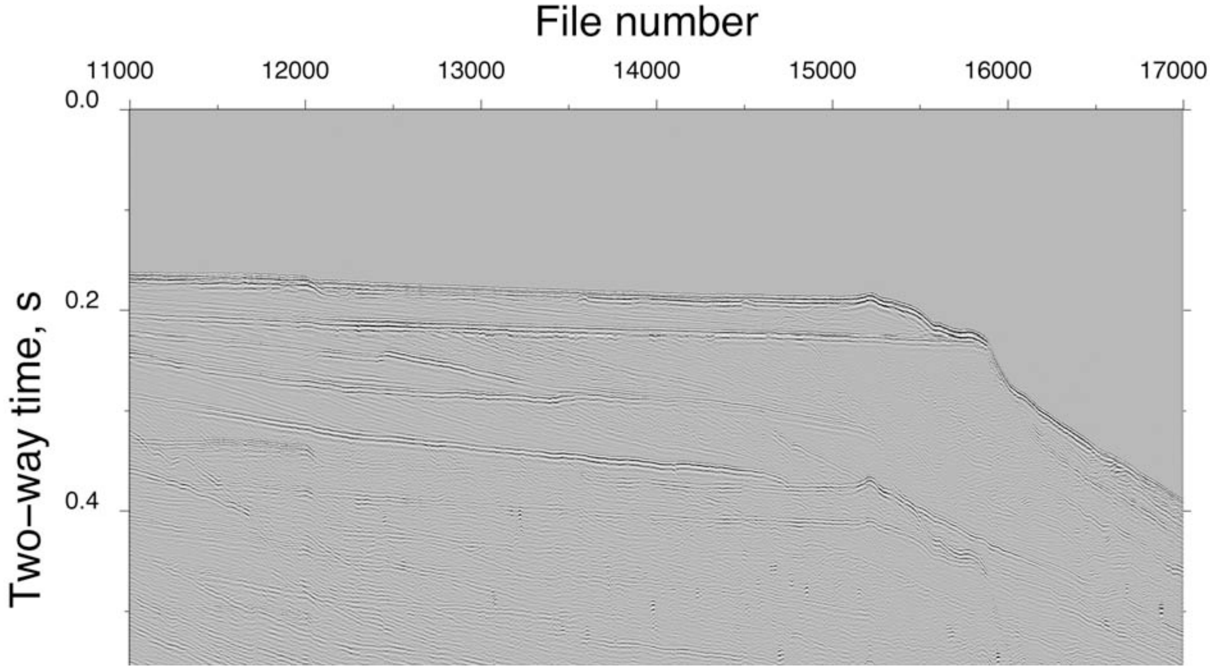


Figure 14. Example of Sparker data from the edge of the continental shelf east of the Indus Canyon. Line shows several stacked delta sequences prograding out to sea. Note the slumping along the outer steep slope and the fact that the most recent foreset sequence has not yet reached the shelf edge.

HYDROGRAPHY OF THE INDUS SHELF

Introduction

The primary objective of cruise 64PE300 was to conduct a geological and geophysical investigation to understand how sediment is moved from the Indus river mouth to the canyon and how this has changed since the end of the last ice age (~20 ka). However, physical characteristics of the shelf were also observed using Physical Oceanographic instrumentation (CTD and ADCP). The Indus Fan is part of the Arabian Sea and of an active region of air-sea interactions, which is recognized as an important driver of the monsoon system over the Indian subcontinent (Nuzhdin, 1982). The Arabian Sea is characterized by a pronounced summer cooling (Wyrtki et al., 1971), and an increase in Sea Surface Temperature (SST) with the advance of the summer. The amplitude of the cooling varies from region to region. Off the coast of Somalia, it has been found to be as high as 10˚C or more between May and July, while off the west coast of India, it is about 2.3˚C. There exists a region of minimum cooling around 70˚E, separating the regions of cooling in the eastern and western Arabian Sea. Like other tropical oceans, a major portion of the Arabian Sea undergoes winter cooling. Thus, the Arabian Sea exhibits a unique bimodal variation in the annual evolution of surface layer temperature and heat storage (Colborn, 1976).

The objective of this report is to present the meteorological and hydrographical data recorded with the Pelagia's instrument and ADCP of Texas A&M University.

Meteorology of the Indus Shelf

Meteorological data for the parameters of air pressure, air temperature, humidity, total radiation, along with wind speed and direction was continuously recorded at an interval of one minute by ship mounted meteorological instruments. The data recorded during the period spent over the Indus Shelf is shown in Figures 15 and 16.

A preliminary analyses of the data show that as atmospheric pressure increased, air temperature dropped (Fig. 15A and C). It is further noted that during relatively low pressure periods the wind blew from the south (Fig. 15B). The wind rose (Fig. 16) plotted for the entire data recorded over Indus Shelf revealed that about 80% of the time direction of wind remained between northeast and northwest and maximum speeds were close to 14 m/sec.

Sea surface water quality data was recorded by ship mounted SeaBird's SBE Thermosalinometer synchronized with meteorological data. The analysis of the data for the seawater surface temperature, salinity and turbidity as presented in Figure 17 and show that there is a diurnal signature in the seawater temperature reflecting the influence of day/night heating and cooling (Fig. 17a).

Vertical profiles of temperature and salinity were taken with the help of SeaBird's SBE 9/11 plus at six different locations marked in Figures 18A and 19A as deep water and shallow water stations, respectively. The CTD data of deep water sampling sites (Stations 1, 2, and 6) was plotted as a T-S plot (Fig. 18B) to characterize the water mass at the respective locations, along with temperature (Fig. 18C) and salinity (Fig. 18D) profiles. T-S plot (Fig. 18B) show that Stations 2 and 6, which are relatively coastward, have higher saline surface water, with a density of about 24.5 kg/m^3. However, Station 6 has a sub-surface salinity maximum with a density of 25.5 kg/m^3 a water mass which is very prominent in the North Arabian Sea. Although similar patterns of subsurface upper salinity maxima are visible in the data recorded at Station 1, salinity is lower than the salinity obtained Station 6. Subsurface

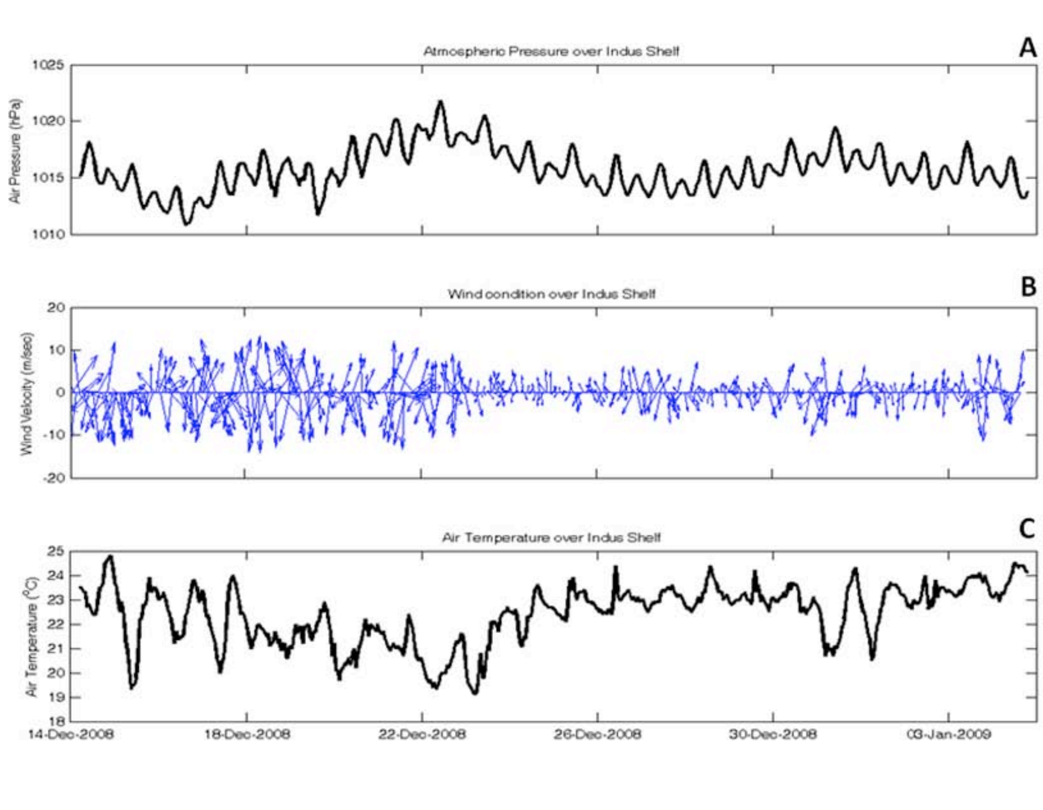


Figure 15. Time series plots of meteorological parameters recorded during the programme by ship mounted instruments. A. Atomospheric pressure, B. Wind condition and C. Air temperature.

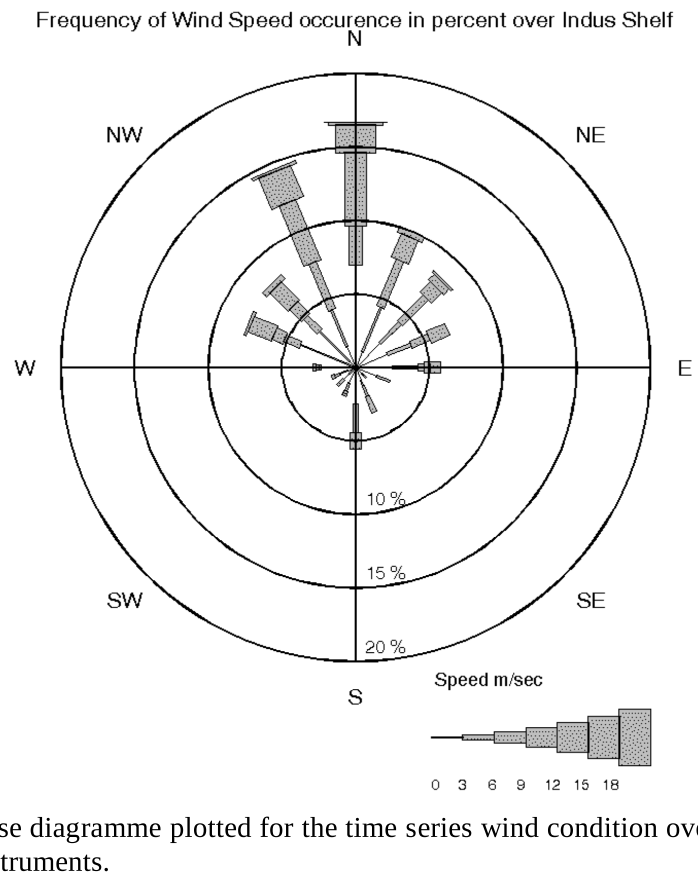


Figure 16. Wind rose diagramme plotted for the time series wind condition over Indus Shelf recorded by ship mounted instruments.

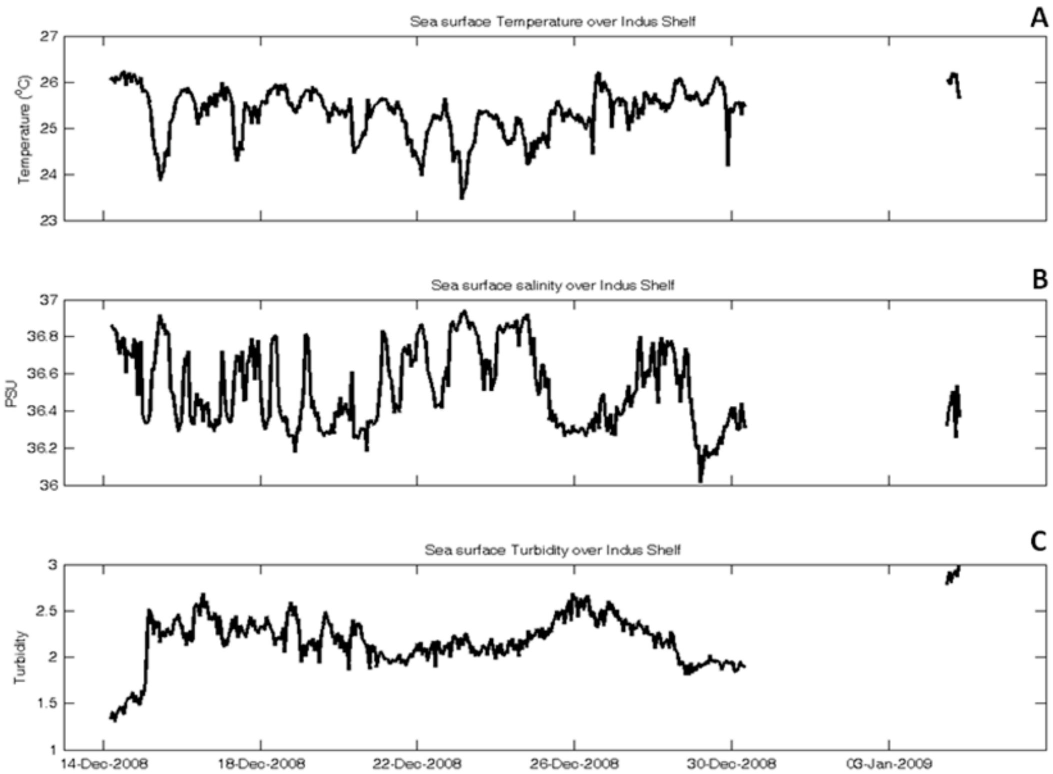


Figure 17. Time series plots of sea surface water quality parameters recorded during the programme over Indus Shelf by ship mounted instruments. A. sea surface water temperature, B. Sea surface salinity and, C. sea surface turbidity.

salinity maxima can be observed in different depths of salinity profile (Fig. 18D). Vertical profiles of temperature and salinity indicate less than an 80 m thick mixed layer (Fig. 18C and D).

The CTD data for the shallow water stations, as marked at Stations 3, 4, and 5, respectively (Fig 5), indicate a different picture of the water quality over the Indus Shelf. The T-S plot of the CTD data (Fig. 19B) shows homogeneous water masses at Station 3 and 4, while at Station 5, (closest to Karachi) there are two water masses. Station 4 has a water mass of 24.5 kg/m^3, whereas Station 3 has a density of 25.3 kg/m^3. The difference in water masses between Station 3 and 4 may result from upwelling from Indus Canyon at Station 3. The water movement recorded by RD Instruments ADCP moored at Locations 1 (23˚00.00’ N, 67˚18.34’ E) on 16th December 2008 and at Location 2 (23˚24.9’ N, 67˚26.17’ E) was plotted in Figures 20 and 21 respectively. The data for the Location 1, collected at a depth just 1.7 m above the sea bed, show that although there is an influence of tidal force (Fig. 20C) but mostly water is moving (Fig. 20A) towards the north (i.e., towards the Indus Canyon).

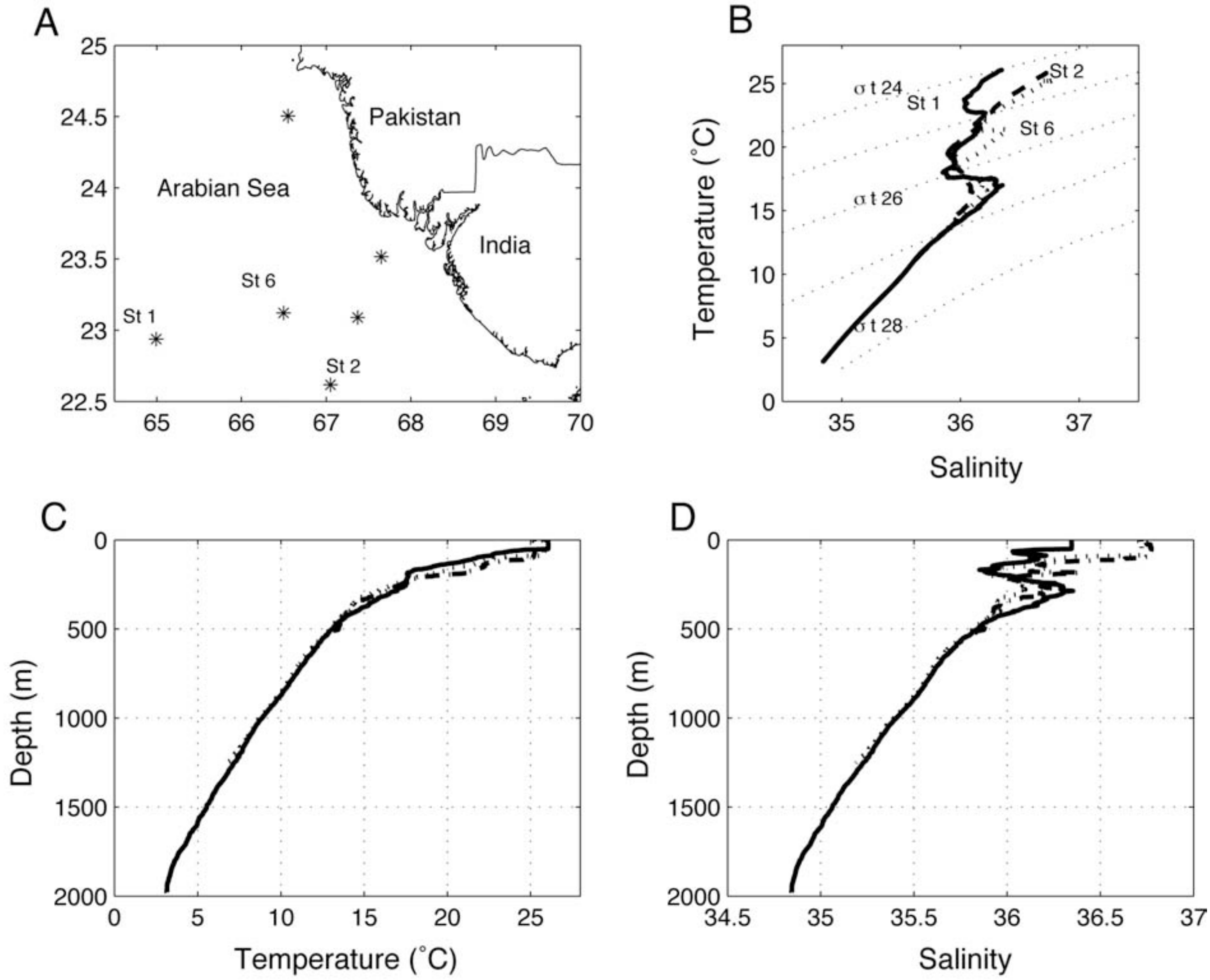


Figure 18. Vertical profiles of CTD data recorded at locations marked as ST. 1, 2, and 6. (From Left to right) Upper A. Location of CDT casts , B. T-S diagramme plotted for the data collected at marked stations at Figure 18A, Bellow, C. Temperature profiles for the same stations. D. Salinity profiles for the same stations

On a more regional scale, both the SST and surface salinity data (Figures 16B and 17) is very spikey from 14th December through 25th December. Graphs from Figures 16 and 17 are reproduced in Figure 21, along with correlation lines. In general, it appears that when the temperature spikes strongly to low values then the salinity spikes high and the wind is blowing towards the south, often as an abrupt wind direction change (e.g., lines labeled A, C, D and F). As the temperature spikes sharply high, the salinity falls sharply low and the wind is blowing out of the north (e.g., lines labeled B and E). The CTD profiles show that in general, there is a thermocline at approximately 40–60 m and below this the water is colder and salinities higher (Figs. 18 and 19). One possible explanation of these general observations is that when the wind blows out of the south, it generates upwelling of colder and higher salinity water towards the surface and when the wind blows out of the north, it drives warmer, lower salinity surface waters from the shelf further offshore. These relationships need to be investigated further and are just general observations at this point.

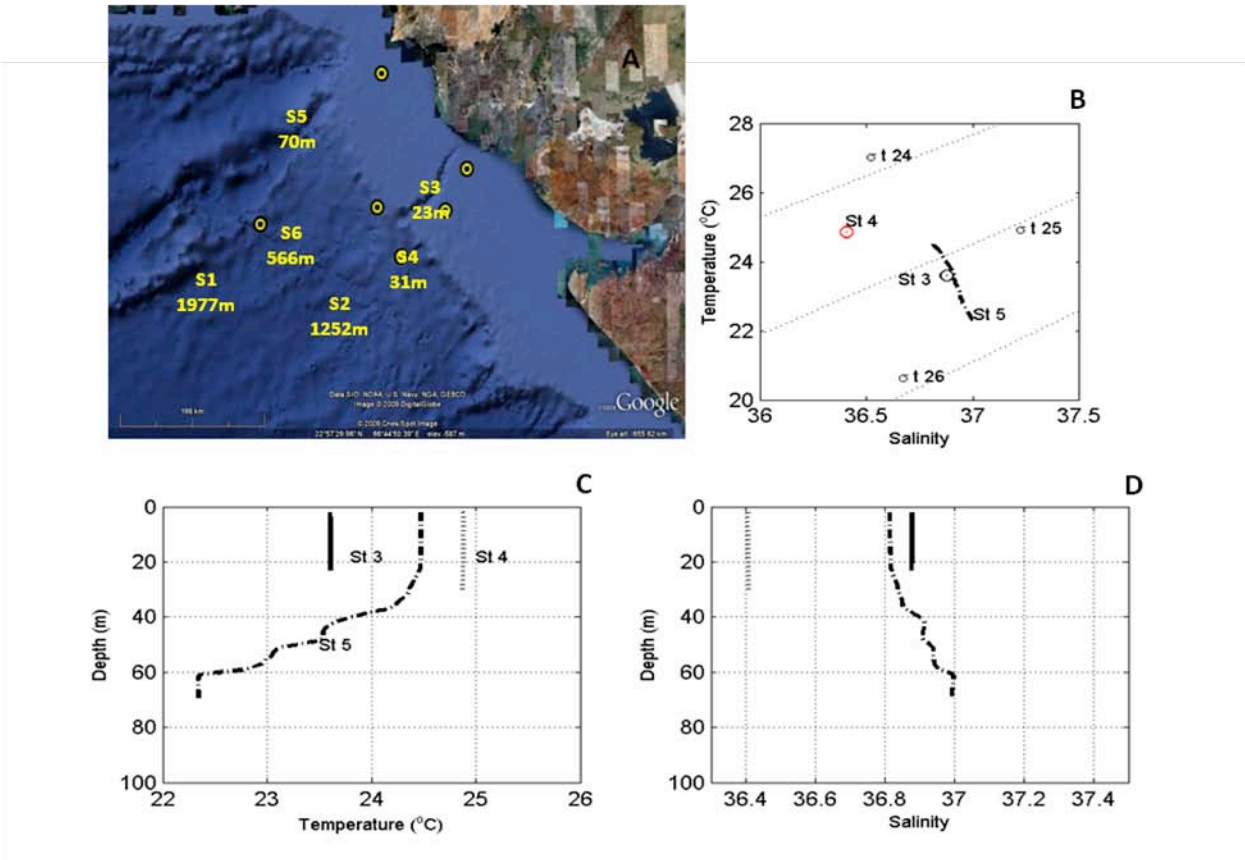


Figure 19. Vertical profiles of CTD data recorded at locations marked as ST. 3, 4, and 5. (From Left to right) Upper A. Location of CDT casts , B. T-S diagramme plotted for the data collected at marked stations at figure 4A, Bellow, C. Temperature profiles for the same stations. D. Salinity profiles for the same stations.

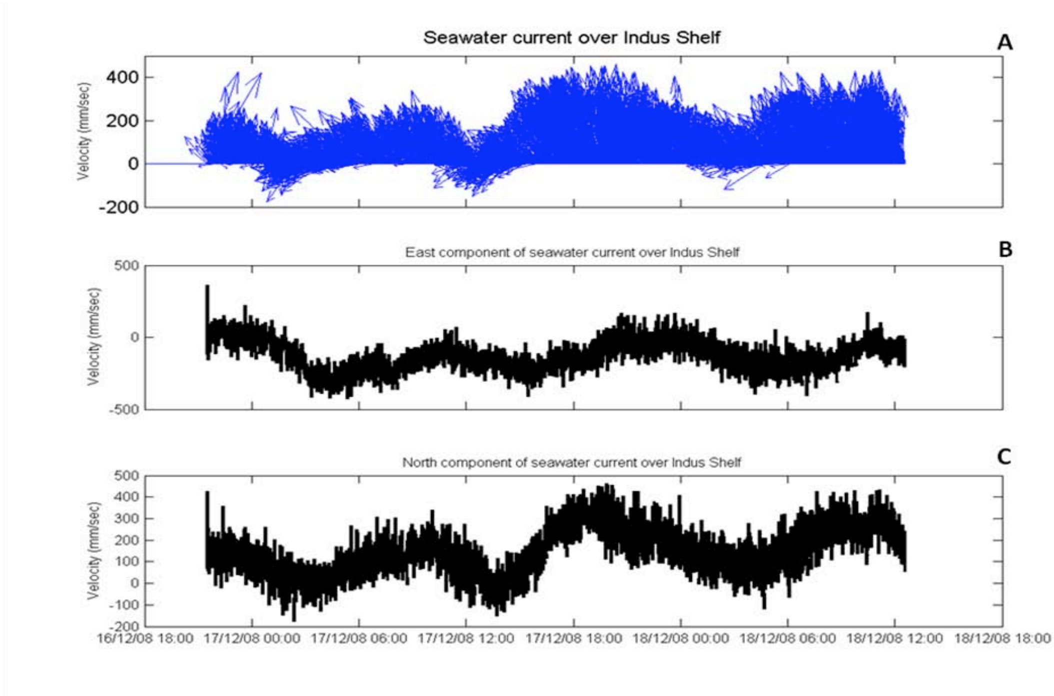


Figure 20. Time series plots of sea water current at location 23° 00.00' N, 67 ° 18.34' E near the bottom of sea (.7m + Hight of ADCP). A. Time series data of sea water movement, B. East component of sea water current and C. North component of sea water current.

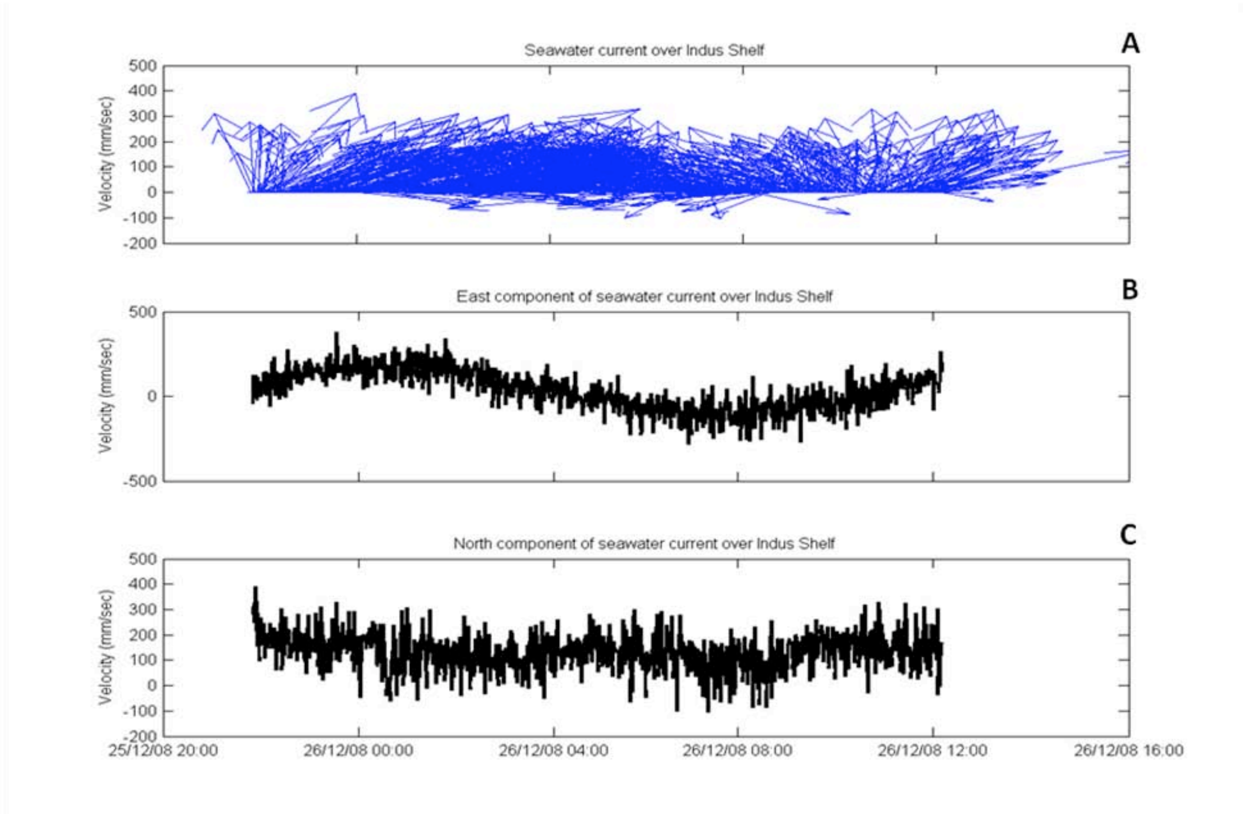


Figure 21. Time series plots of sea water current at location 23 ° 24.9' N, 67 ° 26.17' E near the bottom of sea (.7m + Hight of ADCP). A. Time series data of sea water movement, B. East component of sea water current and C. North component of sea water current.

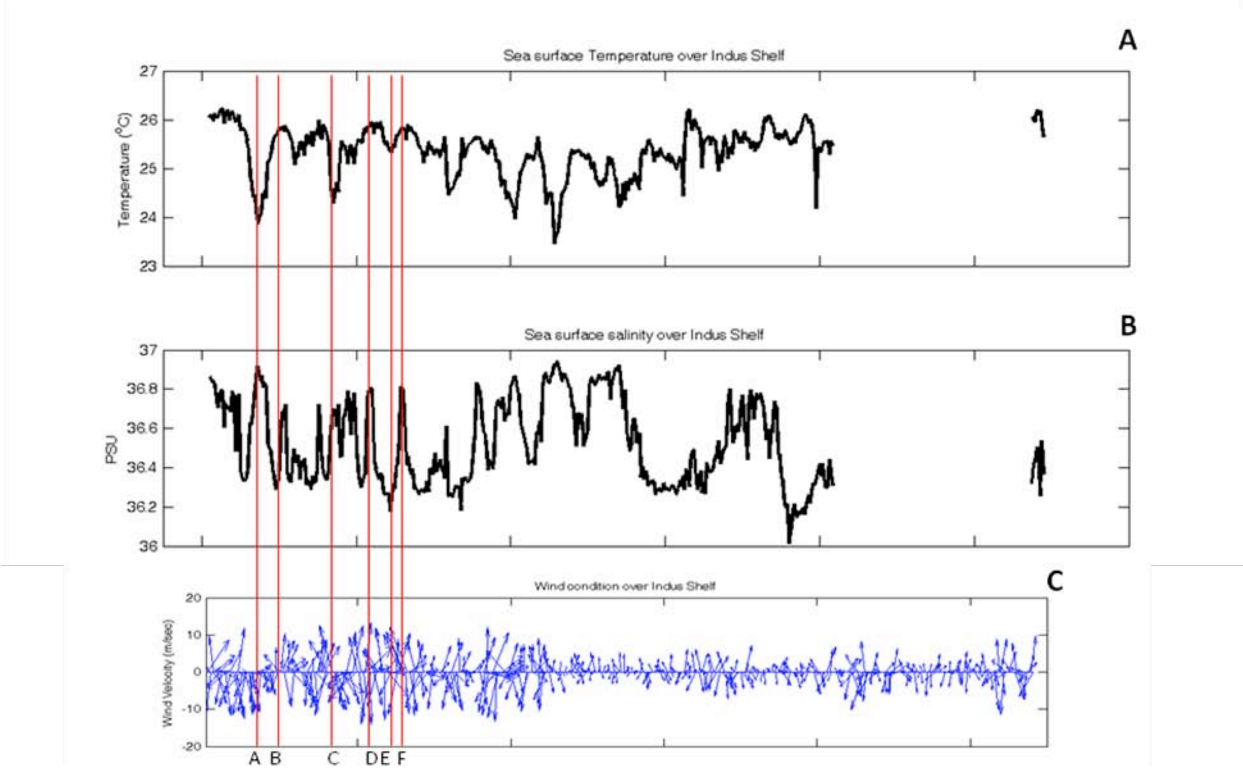


Figure 22. Time series plots of sea surface water quality parameters recorded during the programme over Indus Shelf by ship mounted instruments. A. Sea surface water temperature, B. Sea surface salinity and C. Wind vector and speed over the Indus Shelf. Letter labeled red lines are provided for correlation.

References

Camoin, G. F., Montaggioni, L. F., and Braithwaite, C. J. R., 2004, Late glacial to post glacial sea levels in the western Indian Ocean: Marine Geology, v. 206, no. 1-4, p. 119-146, doi: 10.1016/j.margeo.2004.02.003.

Clift, P., Giosan, L., Blusztajn, J., Campbell, I. H., Allen, C. M., Pringle, M., Tabrez, A., Danish, M., Rabbani, M. M., Carter, A., and Lückge, A., 2008, Holocene erosion of the Lesser Himalaya triggered by intensified summer monsoon: Geology, v. 36, no. 1, p. 79–82, doi: 10.1130/G24315A.1.

Colborn, J., 1976, The thermal structure of Indian Ocean: Honolulu, HI, University of Hawaii Press, 177 p.

Friedrichs, C. T., and Wright, L. D., 2004, Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths: Coastal Engineering, v. 51, no. 8–9, p. 795–811

Giosan, L., Clift, P. D., Blusztajn, J., Tabrez, A., Constantinescu, S., and Filip, F., 2006a, On the control of climate- and human-modulated fluvial sediment delivery on river delta development: The Indus: Eos, Transactions, American Geophysical Union, v. 87, no. 52, p. OS14A-04

Giosan, L., Constantinescu, S., Clift, P. D., Tabrez, A. R., Danish, M., and Inam, A., 2006b, Recent morphodynamics of the Indus delta shore and shelf: Continental Shelf Research, v. 26, p. 1668–1684

Kazmi, A. H., 1982, Geology of the Indus Delta, *in* Haq, B. U., and Milliman, J. D., eds., Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan: New York, Van Nostrand Reinhold, p. 71–84.

Milliman, J. D., Quraishee, G. S., and Beg, M. A. A., 1982, Sediment discharge from the Indus River to the ocean: past, present and future, *in* Haq, B. U., and Milliman, J. D., eds., Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan: New York, Van Nostrand Reinhold, p. 65–70.

Nuzhdin, P. V., 1982, On laws covering fluctuations of the Arabian Sea active layer thermodynamics properties and air-sea energy exchange characteristics during the southwest monsoon, GARP International Conference on the scientific results of the monsoon experiment, Bali: Geneva, ICSU/WMO, p. 724-727.

Prins, M. A., and Postma, G., 2000, Effects of climate, sea level, and tectonics unraveled for last deglaciation turbidite records of the Arabian Sea: Geology, v. 28, no. 4, p. 375-378

von Rad, U., and Tahir, M., 1997, Late Quaternary sedimentation on the outer Indus shelf and slope (Pakistan); evidence from high-resolution seismic data and coring: Marine Geology, v. 138, p. 193–236

Wyrtki, K., Benonett, E. B., and Rochford, D. J., 1971, Oceanographic Atlas of the International Indian ocean Expedition: Washington, D.C., National Science Foundation, 531 p.