Chapter 3

3 Multibeam Swath Sonar

3.1 INTRODUCTION

3.1.1 The Arun Palaeovalley Multibeam Survey

3.1.1.1 Background

The archaeological significance of the English Channel Shelf, and in particular the Palaeo-Arun, has been described in chapter 1; here we detail and discuss the methodology used for exploring the submerged landscape and present our results and interpretations. The only tool available for investigating the palaeo land surface (now the seafloor) at very high resolution is multibeam sonar. Multibeam sonars are used to collect vast numbers of soundings (depth measurements); a full introduction to the technique is given in chapter 3.1.2.

The benefits of using multibeam as part of an integrated site investigation on the Palaeo-Arun are similar to those gained through topographic mapping on land; it gives an excellent appreciation of the spatial variability of the environment and can be used to quantitatively and qualitatively examine the terrain.

Multibeam mapping in the marine environment goes far beyond its onshore analogy, however. Firstly, the seabed is a surface largely unaltered by anthropogenic, ecological, or atmospheric processes. The geological expression is therefore far clearer on the seabed than on land, and in many cases the palaeo-environment is better preserved. Secondly, the resolution of modern multibeam sonar systems is far higher than all nearly all remotely sensed land-mapping techniques. The level of detail that we can now attain from multibeam surveys and new computerised visualisation techniques allow us to see the seabed as if it was land.

An area of 86 km² of sea floor was mapped using multibeam sonar during a period of 13 days in late March 2003. In addition to depth measurements, the amplitude of the acoustic seabed echo was also logged; this gives an impression of the type and texture of material present on the seabed (see Acoustic Backscatter Imaging, Section 3.1.3). To supplement mutibeam acoustic data, a separate side-scan sonar system was also used to collect backscatter measurements.
Additional bathymetry data was provided by the United Kingdom Hydrographic Office. Although the resolution of this singlebeam data is significantly lower than multibeam, it provides an excellent overview of the entire study area including the near-shore sections.

### 3.1.1.2 Aims and Objectives

Multibeam bathymetry is required as a key element in understanding the palaeo-landscapes of the Arun. This is because it is the only sensor capable of providing total seabed depth measurement coverage and a level of resolution capable of discriminating subtle texture changes and features required to reconstruct the palaeo-environmental conditions. The precise aims of the multibeam survey are as follows:

- Confirm the location of the “topographic reaches” of the Palaeo-Arun as predicted from existing data sources
- Define the topographic valley limits and geometry
- Explore the detailed morphology of the valley and adjacent seafloor
- Provide a reference map on which to base the other geophysical and geotechnical datasets
- Explain the spatial variability of the valley terrain with relation to the underlying geology
- Enable the modelling and visualisation of the Arun Palaeo-Valley as a continuous three-dimensional surface.

An important part of the project is the integration of datasets as described in Chapter 2. This will allow the reconstruction of the palaeo-geography of the River Arun.

### 3.1.1.3 Regional Setting

Figure 3.1 shows the location of the study area in relation to the English Channel and Southern Britain. The General study area encompasses the entire Arun Palaeovalley system from the coastline to the deeper east-west oriented submarine valley known as the Northern Paleovalley as depicted on BGS sheet 50N 02W (Wight – Sea Bed Sediments & Quaternery). In Figure 3-1 the detailed study area” shows the limits of the area surveyed using high-resolution multibeam sonar. This corresponds to the “topographic reaches” of the Palaeo-Arun where the system is known from Admiralty Chart 2450 (Anvil Point to Beachy Head) to have a bathymetric expression of a valley.
Figure 3-1. Location map showing the general study area, and the high resolution multibeam study area in the English Channel.
3.1.2 Introduction to Multibeam Swath Sonar Surveying Techniques

3.1.2.1 Background

Multibeam or swath sonar is a technique for acoustically measuring water depths over a wide angular sector (swath) of seafloor from a survey vessel. Traditionally, soundings have been collected using singlebeam echosounders that acquire a profile of soundings along the line of the ship’s track. Where a singlebeam echosounder would have achieved just one sounding per sonar signal, a multibeam collects up to 250 over a width of seabed seven times the depth of water. Multibeam sonars have enabled the progression from two dimensional to three dimensional mapping of the seabed.

The first multibeam sounding system, known as the Sonar Array Sounding System (SASS), was installed on the U.S. Navy Ship Compass Island in 1963 (Goff and Kleinrock, 1991). Driven by military aims, the mainstream usage of multibeam systems by civilian did not occur until the 1990’s. The development of multibeam as an acoustic instrument has progressed rapidly, but constraints have been imposed by two other technologies that required further development in order for multibeam sonars to work successfully; positioning and computing.

The advent of the Global Positioning System (GPS) in 1978 has lead to massive improvements in offshore positioning. For many years since, the positional accuracy of the soundings with relation to the survey vessel has been far higher than the positional accuracy of the vessel with relation to the Earth. An improvement in GPS technology and the decision by the US government to turn off selective availability (deliberate downgrading of the signal for civilians) in 2000 has now reversed this trend. Further, the availability to receive differential GPS where base stations transmit corrections to compensate for factors such as local atmospheric conditions has also increased accuracy (Iliffe, 1989).

The increased volume of data collected by multibeam is 10 000 times higher than singlebeam (1 Gigabyte/hr vs. 10 Kilobytes/hr) and requires a large amount of processing to turn it into useful information. This requires fast processors, large hard-drives and rapid data transfer connections.

In the last three years, the cost and size of multibeam sonars has decreased sufficiently that they can be used by the academic community on small vessels of opportunity.

3.1.2.2 Aims and Objectives

Acquiring multibeam bathymetry data of suitable quality to meet the aims detailed in chapter 2.1.1.2 requires several specific objectives related to the marine survey:

- Obtain and interpret all available pre-existing information on the area
- Acquire a suitable survey vessel on which to mount the sensors
Successfully operate the sensors whilst in the field
Effectively manage and process the data collected

The complexity of multibeam data acquisition and processing, as described in the following sections, makes meeting the objectives a challenging task.

### 3.1.2.3 Operating Principles

Simple echosounders are acoustic devices for measuring the time for sound to travel from the sensor to the seabed and back to the sensor. With knowledge of the velocity of sound in water, the time measurement can be converted to a distance and thus a depth measurement. Multibeam echosounders use the same principle, but use many measurements over a “swath” (wide angular sector) of sea floor. This is achieved by forming an emit beam which is very wide, but narrow in the fore-aft direction; from the returning echo, arrays of transducers (acoustic sensors) measure the arrival times at precise angles. This process is known as “beam forming”, the narrower the beam, the smaller the ensonified area (“footprint”) on the seabed and the higher the resolution. The method by which the sonar detects the seafloor with the footprint area is either by measuring the maximum amplitude (for central beams), or measuring where the phase of the returning pulse is zero (for outer beams). For each pulse of sound a number (usually in the range of 40 – 250) of angle and two-way time measurements are recorded. It is then possible to covert the times to ranges (distances) in the same way as for a simple echosounder described above. An illustration of a hull-mounted multibeam in operation is shown in Figure 3-2.

The complexity lies with converting distance measurements at known angles from the sonar to positions on the seafloor. This is because the orientation of the vessel is continually changing as it moves on the waves. It is therefore critical to measure very accurately both the position and motion of the vessel in order to compute the sounding locations. This is achieved using gyros, accelerometers and GPS.

Other factors affecting the position of multibeam soundings on the sea floor include refraction of the acoustic beams due to changes in sound velocity in the water column (due to changes in temperature, salinity or depth) and the calibration of the sensors (Mitchell, 1996).

Further details of how the data is collected and processed is described in chapters 3.2 and 3.3.
Figure 3-2. Illustration showing the concept of beam forming from a hull mounted multibeam sonar.
3.1.3 Introduction to Acoustic Backscatter Imaging

3.1.3.1 Background

When the seafloor is ensonified by a sonar system, a proportion of the acoustic energy is “backscattered” or returned to the instrument both from the surface and sub-surface of the seafloor (Figure 3-3). The timing of the return signal gives a sounding or range measurement (see bathymetry above) and the amplitude of the signal can be used to determine physical properties of the seafloor. An acoustic backscatter image is a map of the amplitude of the backscatter response of the seafloor, which can be used to determine seafloor geology and locate objects at the surface. Quantitative interpretations of acoustic backscatter imagery (or sonograms) rely on empirical relationships tested in the field since the physical processes responsible for scattering are complex their origins are not fully understood (Jackson et al., 1986). However, a rule-of-thumb relationship between acoustic backscatter and seafloor properties has been established: hard and rough surfaces (e.g. coarse gravels and exposed rock) give a high intensity response whereas soft and smooth surfaces (e.g. silts and fine sands) give a low intensity response.

![Figure 3-3. Acoustic scattering from the seafloor surface (roughness scattering) and sub-surface (volume scattering). (From Jackson et al., 1986 p. 1411).](image1)

3.1.3.2 Mulibeam Swath Sonar Backscatter Imaging

The primary purpose of multibeam swath sonar systems (see Section 3.1.2) is to collect depth sounding data to determine water depth. However, during acquisition, the amplitude of the depth sounding can also be logged and then used. Full information on processing acoustic backscatter data from the multibeam swath sonar is given in Section 3.3.2.

3.1.3.3 Side-scan Sonar Imaging

Side-scan sonar has achieved popularity by being relatively straightforward to use, covering large areas rapidly and giving the user practical information in terms of seafloor shape, surface texture and
object identification. The technique was developed for submarine and mine detection in World War II, however, the suitability of the technique as a seafloor mapping tool has long been recognised (Somers and Stubbs, 1984). The earliest published studies using this equipment date from the late 1950's, and by the 1960's side-scan sonar data was being used to map large scale geomorphological features and sedimentation patterns in the deep oceans (Edgerton, 1986). Initially, the side-scan sonar systems were analogue in design and the output was recorded in real-time onto paper rolls. With the advancement of computer hardware, digital recording capabilities were added to side-scan systems and the development of higher resolution equipment allowed for detailed mapping of smaller, shallower areas.

The side-scan sonar technique measures the seafloor's response to acoustic pulses (or “pings”) transmitted from a submerged instrument (or “fish”), usually towed behind a survey vessel (Figure 3-4). After emitting a pulse, the transducer switches to a listening state and records returned sound energy resulting from the interaction of the pulse with obstructions in its path (Somers and Stubbs, 1984). The transducer array is aligned parallel to the ship's heading, which orients the sound beam in a perpendicular direction (hence side-scan sonar). Transducer arrays are mounted on each side of the fish to give coverage to port and starboard.
Figure 3-4. The process of generating image pixels from a sonar “ping”. The top cartoon shows a ping being emitted by a sonar fish and ensonifying the seafloor. The middle cartoon shows the analogue time series recording of the pulse, with backscatter intensity as the voltage response of the transducers. The lower cartoon shows how a raw digital sonogram is formed, with time in the X direction and ping number in the Y direction. (Johnson and Helferty, 1990 p. 360).

Side-scan sonar systems image a continuous swath of the seafloor following the survey ship's course. Pings are transmitted at regular intervals in time, progressively illuminating or “scanning” the seafloor as the instrument moves forward (Figure 3-5). The resulting acoustic image of the seafloor -- a “sonogram” -- is a visual representation of backscatter variation with ping number along the Y axis and time along the X axis. Raw sonograms can look, at first glance, like an aerial photograph taken at early morning or evening when the rays of the sun cast long shadows and enhance textural detail. However, side-scan sonar imaging geometry differs substantially from conventional photography: 1) acoustic radiation is used as opposed to electromagnetic radiation, 2) both the source of illumination and the viewpoint are in the same location and are restricted to narrow apertures and 3) the image is formed by scanning rather than capturing a single frame. A diagram of side-scan sonar imaging geometry is shown in figure 3.5.
Figure 3-5. Side-scan sonar imaging geometry showing slant range, ground range, grazing angle, altitude and the nadir point. From (Blondel and Murton, 1997).
3.2 DATA ACQUISITION

3.2.1 Survey Planning

3.2.1.1 Review of Existing Survey data

Planning of the survey was aided through the use of existing bathymetric data from the area. Deciding on the position of the survey lines as well as planning how far apart to space the lines was made simpler by the following data sources:

- Single-beam lines from industry surveys of aggregate licence blocks. See Figure 3-6
- British Geological Survey Sheet 50°N 02°W showing solid geology. See Figure 3-7
- C-Map Electonic Nautical Chart based on the British Admiralty Chart. See Figure 3-8

3.2.1.2 Survey Vessel Selection

The “Xplorer of Portsmouth”, a 12 metre twin engine catamaran workboat was chartered for a period of 50 days from 9th March to 24th April 2003. A selection of photographs of the vessel are shown on figure 3.6. The multibeam was installed for the first 20 days of the charter with the boomer seismic system used for the remainder of the time. The vessel was chosen for the following reasons:

- Suitable for carrying all equipment and personnel for day time only survey operations
- High transiting speed of 20 knots maximised the amount of time spent at the survey site
- Specifically fitted out for carrying a multibeam on an over-the-side pole mounting
- Spacious wheelhouse for recording and monitoring data acquisition
- Dual AC power supplies
- Ancillary wheelhouse navigation equipment
- Cost

The skipper Dave Burden is an experienced coxswain on marine geophysical surveys and provided an excellent service throughout.

3.2.1.3 Fieldwork Logistics

The port used for overnight berthing during the survey was Brighton Marina located at 50° 48' 36" N 00° 06' 29" W. This was the closest port that was accessible at all states of the tide and had the necessary power and water supplies. It is 15 miles from the survey site, so it was a major advantage having a vessel that could cover this distance in 50 minutes. A gauge was installed in Brighton Marina so that it could be calibrated against a permanent tide board and accessed easily for downloading data. The survey crew stayed in a local hotel and worked at sea from 7.30 am until 6 pm. Initial data processing for quality assessment purposes was carried out on a laptop PC during the evenings.
Figure 3-6. Industry singlebeam bathymetry data from the dredging licence block areas. Soundings are coloured by depth and overlaid on the C-Map digital chart.
Figure 3-7. Section of the British Geological Survey Solid Geology Sheet 50° N 02° W. Black lines represent boundaries within each sequence, and blue lines represent contours in metres to the tertiary – cretaceous boundary.
Figure 3-8. C-Map Electronic Nautical Chart of the study area showing depths, isobaths, seabed samples, shipwrecks and navigational aids. The information is based on the British Admiralty Chart.
Figure 3-9. The survey vessel “Xplorer of Portsmouth” with multibeam deployed on over-the-side mounted aluminium pole.
3.2.1.4 Survey Plan

A multibeam survey can be performed as a reconnaissance exercise where the tracks of the vessel are chosen in real-time, or it can follow a series of planned survey lines. The Arun survey was planned with the aid of existing data described in 3.2.1.1, but occasionally reconnaissance was carried out when the survey plan required updating in the field. The key components of a survey plan are:

- Positioning the survey “block”
- Line spacing
- Line orientation
- Vessel speed
- Line sequence

The survey block was positioned directly over the topographic low thought to represent the under-filled Palaeo-Arun and was bounded by the coordinates:

0 deg 27' W, 50 deg 40' N
0 deg 27' W, 50 deg 35' N
0 deg 20' W, 50 deg 35' N
0 deg 20' W, 50 deg 40' N

The line spacing is determined by the swath width which for planning purposes is ~ 5 times water depth. The actual swath width is 7.5 times water depth, but as the outer beams often need to be rejected as they are much noisier than the central beams, and the vessel can deviate from the survey line, a 33% overlap was planned. Therefore at 20 m depth the lines were planned 100m apart, increasing to 200m spacing in 40m of water.

The line orientation was selected to run with or against the tidal stream, which was read from the Admiralty Chart to be a bearing of 70°/250°. The ideal vessel speed is a compromise between coverage, data density, data quality and safety. The multibeam pole mounting can vibrate and introduce bubbles into the water above certain speeds which drastically affects data quality. 5 knots was chosen, but in reality this was affected by +/- 2 knots by the strength and direction of the currents.

The sequential order in which lines were completed was planned as block of six adjacent lines, each 11 km long, which theoretically should be completed in one day’s survey. The line plan is shown in figure 1.5 of the Cruise Report.

In practice, the line plan was updated in the field to maximise coverage due to uncertainty over the amount of weather down-time that was anticipated. A map of the lines sailed is shown on Figure 3-10.
Figure 3-10. Plot of lines sailed overlaid on the LandSat satellite image.
3.2.1.5 Side-scan Sonar Survey Plan

The aim of the sidescan sonar survey was to add value to the main geophysical datasets (i.e. bathymetry and sub-bottom profiling) with minimum additional survey cost. The sidescan sonar instrument was deployed concurrently with other instruments; either housed in a dedicated fish during the boomer survey to the north of the survey area or as a chirp/side-scan combination during the multibeam swath sonar to the south of the survey area. Line spacing, length and orientation were dictated by the existing requirements for the higher priority survey instrument.

3.2.2 The Multibeam Survey

A detailed account of the survey can be found in appendix 1 “Cruise Report: Joint multibeam, chirp, sidescan and boomer seismic survey of the Arun palaeo-river system”. A brief overview of data acquisition is given here.

3.2.2.1 Equipment

Five main instruments were used to simultaneously collect data that would be integrated during processing to produce the survey results. These were:

- Reson 8101 Multibeam Sonar
240 kHz (high resolution) multibeam sonar. Acquires 101 soundings per pulse at a rate of ~7 pulses/second over a 150° angular swath. The narrow beams (1.5° x 1.5°) insonify a small area of seafloor providing high spatial resolution. Backscatter intensity is recorded at the same time as the soundings.

- Applanix POS MV 220 Integrated motion and positioning device
Provides highly accurate motion (roll, pitch, yaw and heave) data at a rate of 200 Hz. To prevent “drift” in the inertial sensors, phase GPS measurements to two antennas are used to constrain the external reliability of the motion reference unit.

- CSI MBX-3 Differential GPS Receiver
The MBX-3 records the difference between the known position and the GPS position of a reference station onshore, and feeds this correction into the GPS position measured from the POS MV antennas to improve accuracy to ~ 0.5 m.

- Navtronic SVP-20 Sound Velocity Probe
Used to take twice daily measurements of the sound speed at 1 m depth intervals. The instrument is lowered overboard on a rope until it touches the seabed. Accurate to +/- 0.25 m/s.

- Valeport Tidelog 740
A pressure transducer type tide gauge capable of recording water levels to within 2 cm at a 10 minute sampling rate for up to sixty consecutive days.
The deployment, calibration, and operation of these instruments is described in sections 3.2.2.2 to 3.2.2.9.

### 3.2.2.2 Mobilisation

In multibeam surveying, the accuracy of the final dataset is directly related to the accuracy of the installation. The mobilisation of the multibeam and motion sensor onboard Xpleror involved networking the two systems, and measuring their relative positions. All positions onboard are referenced to a point known as the Vessel Reference Point (VRP). The VRP should theoretically be the vessel’s centre of gravity (CoG) i.e. the point with the least motion. In a catamaran however the CoG is located just above the water line between the two hulls, so the closest point on deck was used instead. The POS MV motion reference unit was secured to the deck using a wooden board located at the VRP. The offsets to the GPS antennas and the sonar head were measured using tapes, spirit levels and an Electronic Distance Measurer (EDM). Tables detailing the offset measurements are in Chapter 3 of the Cruise Report.

The sonar head was installed using a customised aluminium pole designed to pivot alongside the vessel. This enabled the sonar to be recovered out of the water when transiting to and from port. With the sonar deployed the maximum speed was 7 knots (the drag on the pole increased rapidly above this), which was considered impractically slow for the long transit to and from the survey area. With the pole recovered the vessel could transit at 20 knots. It was vital however that each time the pole is deployed, it is located in exactly the same position; otherwise the calibration routine would have needed repeating each time. The use of a rigid locking gate at deck level, and wire stays going fore and aft tensioned using a 4:1 rope purchase meant the pole was repositioned as accurately as possible. Photographs of the pole deployed and recovered are shown in Figure 3-11.

### 3.2.2.3 Sonar Calibration

The calibration of the multibeam is critical for ensuring good survey results. Ideally, the mounting of the sonar head should be “square” to the framework of the vessel, but in reality this is unlikely to be the case. Angular biases in the three directions of rotation (roll, pitch and yaw) therefore all need to be measured so that they can be corrected during processing. The method used for measuring these biases uses real survey data from overlapping swaths, and calculates the amount of “miss-fit” to derive a value for the bias. This procedure is called the patch test. Full details of the patch test with examples can be found in the Cruise Report.
Figure 3-11. The Reson 8101 multibeam sonar head recovered alongside Xplorer (left), and deployed on the pivoting aluminium pole (right). Note the “V” shaped bracket above the waterline used to accurately re-position the system on each deployment.
3.2.2.4 Motion Sensor Calibration

The POS MV integrated GPS and inertial motion sensor must be calibrated in order to lock any changes in heading detected by the GPS to corresponding changes in heading detected by the gyro compasses. This process involves achieving “lock” on at least five GPS satellites and resolving the phase integer ambiguity (the distance to each receiver based on phase measurements of the GPS carrier wave). With the separation of the receivers calculated, any heading variation can now be determined from relative changes in position. To correlate this with the gyro compasses, rapid changes in heading are required; therefore the vessel is turned in a tight figure of eight formation until the GPS Azimuth Measurement Solution (GAMS) has been resolved. This process took around forty minutes to complete.

3.2.2.5 Positioning

Differential GPS positions were logged by the POS MV, with the differential input coming from the MBX-3 reciever. The Trinity House Lighthouse DGPS service broadcasts corrections on 307.5 kHz at 100bps from St. Catherine’s Point of the Isle of Wight 40 miles west of the survey area. As the nearest DGPS station, the MBX-3 automatically picked up the signal from this station. Problems occurred initially with the signal to noise ratio making the DGPS intermittent. GPS accuracy is ~ 0.5 m with DGPS and ~ 5 m without, so it was critical that the DGPS was operational at all times. It was discovered that fixing the antenna at the stern of the vessel improved the signal to noise ratio by separating it from interference from other antennas.

3.2.2.6 Data Logging

The set up and calibration parameters were entered into the Reson 6042 acquisition software to enable data logging and real-time processing. This resulted in raw files (to be used in post-processing) and soundings files used for real-time display. The displays included a “water fall” showing each ping arriving in profile view, and a plan view display of soundings coloured by depth on the navigation screen. The navigation screen also showed the nautical chart, vessel position, and survey lines so a good impression of coverage and data quality could be achieved whilst under way.

3.2.2.7 Multibeam Backscatter

Multibeam backscatter is analogous to sidescan sonar; a method for recording the amplitude of the acoustic seafloor reflection over time. The acoustic pulse used is wide in the across track direction and narrow in the along track direction, this gives high coverage and resolution. The time series can
be converted to distance, thus giving a map of backscatter intensity. In the absence of topography, high intensity generally correlates with reflective seabed types, such as bedrock or course grained sediments. Low intensity correlates with mud or silt. The direct correlation of backscatter intensity with seabed type is not possible because it is influenced by changes in power and gain settings, angle of incidence with the seabed and adsorptions within the water column.

3.2.2.8 Tidal Measurements

Tide data was acquired from several sources so that the quality could be checked and compared:

- Observed tides using Valeport tide gauge in Brighton Marina.
- Observed tides from the National Tide Network station at Newhaven
- Predicted tides for Brighton
- Predicted tides for Shoreham

The predicted tides for Shoreham were used for real-time processing of data, whilst the observed tide at Brighton Marina was used for post-processing and checked against the predicted tides for Brighton. Variations occurred due to changes in atmospheric pressure. The installation, calibration, and results from the tide gauge are described in chapter 3.6 of the Cruise Report (Appendix 1). The tide gauge observations were referenced to Chart Datum.

3.2.2.9 Sound Velocity Measurements

Sound velocity measurements were taken twice daily, before and after surveying, at the survey site. The sound velocity data was immediately uploaded onto the 6042 acquisition computer so that the real-time processing used the mornings SVP results. The positions and profiles from the SVPs are shown in chapter 4.5 of the Cruise Report. A general trend was observed for sound velocity to increase with depth, due to increasing temperature, and during the survey period the velocities increased from ~1480 m/s to ~1485 m/s as the waters became progressively warmer in the good weather.

3.2.2.10 The Arun Survey

Thirteen days were spent in the field area, with only half a day lost due to bad weather. The total length of all the survey lines was 595 km and the area mapped was 86 square km. A total of 72 hours worth of data was acquired which came to 48 gigabytes. The data was recorded onto DVD RAM media and backed up onto DVD-R discs. A full break down of the fieldwork and daily summaries can be found in the Cruise Report (Appendix A).
3.2.3 The Side-scan Sonar Survey

3.2.3.1 Equipment Specification

The side-scan sonar system used is the GeoAcoustics dual frequency model 196D. The side-scan sonar system consists of a port and starboard transducer array that were deployed in two configurations: either combined with a chirp sub bottom profiler system or using a dedicated side-scan sonar fish (Figure 3-12). The advantage to the combined chirp/side-scan configuration is that two different datasets can be collected simultaneously, increasing productivity. However, the dedicated sonar fish has a more hydrodynamic torpedo shape for better ‘flying’ through the water, which improves the potential data quality. In addition, the smaller size and reduced weight of the dedicated fish means that it is easier to deploy and recover.

![Figure 3-12. Photos of side-scan sonar instruments. The dedicated sonar fish is shown on the left with the acoustic transducers in the black section towards the front of the fish. The larger combined chirp/side-scan fish is shown on the right with chirp electronics housed in the orange head section and side-scan transducers running along the side.](image)

The side-scan sonar instrumentation is a dual frequency (100/500kHz) system providing the capability for both low coverage, higher resolution studies (using the high frequency setting) and high coverage, lower resolution studies (using the low frequency setting). The instrument characteristics are detailed in Table 3-1. Side-scan sonar instrument characteristics. To illustrate the theoretical resolution difference between the two frequency settings, at 75m range, the beam width measures 1.3m at 100kHz and 0.4m at 500kHz.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [kHz]</th>
<th>Maximum range</th>
<th>Beam width</th>
<th>Pulse width [μs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kHz</td>
<td>114 +/- 50</td>
<td>1000m at 50m altitude</td>
<td>50° x 1°</td>
<td>166</td>
</tr>
<tr>
<td>500 kHz</td>
<td>410 +/- 50</td>
<td>200m at 20m altitude</td>
<td>40° x 0.3°</td>
<td>88</td>
</tr>
</tbody>
</table>
Instrument frequency, range and data sampling rates were chosen to acquire high spatial resolution imagery. All data were recorded at the 500kHz frequency setting. Instrument range is variable and can be set by the operator: during the surveys this range varied from 183-214m for chirp/side-scan instrument and 92-183m for the dedicated side-scan instrument. The number of samples used to record each ping varied from 1024-4096 giving an across-track sample spacing of between 4 and 10cm. Full instrument settings are given in Section D of the survey cruise report (Appendix 1).

### 3.2.3.2 Towing

Both side-scan instruments were towed using an armoured power/data transmission cable. The chirp/side-scan instrument was towed from the stern of the Xplorer during the swath bathymetry work and the dedicated side-scan fish was towed from the bow section between the two hulls, underneath the ship during the boomer work. Towing leads to an offset between the instrument location and the navigation reference point (GPS antenna) known as layback. For the chirp/sidescan fish the layback varied from 15-25m; for the dedicated sidescan, the fish location was estimated to be at the same position as the navigation reference point with zero layback.

### 3.2.3.3 Survey Coverage

Side-scan sonar data were collected opportunistically during the principal swath and boomer surveys. Surveys were, therefore, not optimized for side-scan sonar acquisition. Due to instrument down-time and weather conditions, side-scan data were collected in two regions – close off shore (northern area) between the 24th and 29th March 2003 and about the swathed region (southern area) between the 16th and 24th of April 2003 (Figure 3-13). During the northern survey, data was collected along 340km of ship track in 25 hours of ship time, which resulted in 8.2GB of recorded data. For the southern survey, the total ship track length was 300km requiring 23.5 hours of ship time and resulted in a total data volume of 8.7GB.
Figure 3-13. Survey track plots with colours indicating days of acquisition. Blue box shows the northern survey: 16/4/03 purple; 17/4/03 blue; 18/4/03 green; 21/4/03 pink; 22/4/03 brown; 24/4/03 red. Yellow box shows the southern survey red, 24/3/03; green 25/3/03; blue 26/3/03; brown 27/3/03; purple 29/3/03.
3.3 DATA PROCESSING

3.3.1 Multibeam Bathymetry Data Processing

3.3.1.1 Real-Time Processing Procedures

The data logging process in the 6042 online acquisition software results in several copies of the data in different formats. Under normal circumstances the raw data format (*.db) was not processed at all in real-time. This was so that all the data would be preserved for post-processing and there was no risk of losing useful data. Where sea-surface multiple reflections were occurring (indirect returns) the *.db file had depth filters applied to reject soundings shallower than 10 m or deeper than 60 m. The resulting files had the extension *.filt.db.

The data was also processed in real-time so that it could be displayed on screen whilst the data was being acquired. These files were not used for anything other than giving a rough estimate of data coverage and quality whilst in the field.

3.3.1.2 Post Processing Procedures

The raw multibeam dataset must be processed into points that are a best estimate of water depth. There are several types of errors that can occur during data processing, and the objective is therefore to identify and resolve these errors:

- **Systematic Errors** – incorrect values that follow a trend, e.g. applying the wrong tidal correction would result in a systematic vertical error.
- **Gross Errors** – data points that can be statistically identified as “outliers” because they do not correlate with their neighbouring points.
- **Random Errors** – small errors that cancel out when locally averaged.

Described in the next section is a processing flow that applies several corrections to the data and at each stage assesses the quality of the result. The processing was carried out using Caris HIPS (Hydrographic Information Processing System) & SIPS (Sonar Information Processing System). This software was run on a 2.6GHz processor on a laptop PC running Windows XP professional. The PC had 768 MB of RAM, a 1400 x 1050 pixel SXGA screen and a 40 GB hard drive with an additional 40 GB of storage on an external fire-wire hard drive.

3.3.1.3 Vessel Configuration

A Caris HIPS Vessel Configuration File (VCF) contains all of the information about the type, position and orientation of all sensors mounted on the vessel. Chapter 3.2.2 describes how the off-set measurements were taken and how the sonar was calibrated using the patch test; the results were entered into a new VCF called “Xplorer” so they could be applied to the data during processing.
3.3.1.4 Data Conversion

The 6042 data files were exported in a format called XTF because Caris HIPS is unable to read .db files directly. A new project called “Arun Survey” was created and the XTF data was loaded using Xplorer as the VCF into folders for each day of the survey. Initially, the Reson 6042 software applied a variable time correction to the navigation and motion data of 0.4 to 0.9 seconds. This correction was however not required, so a systematic error was introduced to the data resulting in corruption of all soundings that manifested itself as a roll artefact. Reson later wrote a program to remove the time error, but this resulted in considerable delays to the processing schedule.

3.3.1.5 Navigation and Motion Data Cleaning

Once the survey lines had been loaded, it became obvious that some of the survey line plots included occasional gross errors because they jumped several kilometres from the line they were supposed to be on. A search was applied to find all jumps in vessel speed over 8 knots. This isolated the errors which were then deleted and the line was then interpolated from the point before to the point after.

Multibeam data quality is adversely affected where the vessel is turning sharply, this is because the distribution of soundings becomes uneven in the along track direction. These parts of the navigation plots were therefore deleted without interpolation thus making the soundings in these areas obsolete. Figure 3-14 shows an area undergoing navigation data cleaning.

Attitude, or motion data refers to the gyro (yaw), roll, pitch and heave data. This data was acquired using a high quality motion sensor, and because of this it was found that the data required virtually no cleaning, smoothing or filtering. In one instance, the roll, pitch and heave data dropped out altogether leaving just the heading and rendering the data unprocessable; the reason for this outage is unknown. Figure 3-15 shows the attitude data during rough sea conditions.
Figure 3-14. Navigation editing on a selected line (shown by grey points). The erroneous jump in velocity is shown in yellow and is visible on the graphs of speed, distance and course made good.

Figure 3-15. Graphs showing gyro, heave, roll and pitch measurements over time during rough seas.
3.3.1.6  Sound Velocity Correction

The 23 individual SVP files were re-formatted into a single HIPS file, with the time and positions recorded in the file headers. The profiles could be viewed and edited using the SVP editor as shown in Figure 3-16, and may be applied to soundings that are either closest in distance, closest in time, or closest in distance within a certain time. Loading the SVP’s converts the range and angle measurements into distances to port or starboard of the nadir (centre) beam, and depths from the waterline of the vessel. The roll data is applied by Caris HIPS during this process and the roll bias calculated in the patch test is corrected.

3.3.1.7  Tidal Correction

The tidal range in the survey area is 7 metres during spring tides, so the vertical accuracy of the soundings was highly dependant on having accurate tidal data so that all soundings could be reduced to a common level known as Chart Datum (CD). The observed tides from Brighton Marina were formatted in to a Caris Tide File and applied to all lines. In some areas adjacent lines did not align vertically due to small differences between the tidal height in Brighton and at the survey area 15 miles away. For these lines a small correction of up to 40cm was measured from cross profiles and applied to bring the lines to a common level.

The complete tidal record is shown in Figure 3-17, note the transition from spring (high amplitude) tides to neap (low amplitude) tides over the 15 day observation period. A full tidal cycle is just over 14 days.

3.3.1.8  Merging of Soundings

The merge process converts the relative positions of the soundings with respect to the sonar into absolute geo-referenced positions. During this process, the heave, yaw, and pitch corrections are applied. When completed, the merged soundings are ready to be gridded, cleaned or exported.

3.3.1.9  Editing, Filtering and Gridding

The processes described so far will hopefully eliminate systematic errors from the dataset and result in only gross and random errors remaining. With several billion soundings recorded during the survey, it is a major task to effectively identify and remove the gross errors. The rapid removal of outliers from multibeam datasets is a topic of ongoing research activity (Calder and Mayer, 2003). Four tools are used at different stages:
• Filters – remove soundings that fail to meet certain criteria such as depth range, beam to beam slope, cross track distance, or angle.

• Swath editor – Used to manually select and reject or accept soundings in one swath.

• Surface Cleaning – fits a mathematical surface e.g. a curved tilted plane to tiled areas and works out the residuals between the surface and the actual soundings. Soundings with residuals that exceed a set threshold are rejected.

• Sub-Set Editor – A method for visualising in 3D and rejecting soundings from an area that may include overlapping swaths.

Theoretically, the most reliable method for rejecting gross errors would be to examine each swath individually using the swath editor, but this is extremely time consuming. A first pass is therefore achieved using the filters to reject sounding outside the expected depth range, unreliable outer beams and large “spikes”. The rejected soundings are then observed using the swath editor, and the filters may subsequently be refined and re-run.

Surface cleaning is a good technique for removing more subtle gross errors that are not removed by filtering, but it requires that a first pass filter is already applied so that the surface is not affected by too many gross errors. The number of soundings rejected can be displayed for each tile to give an impression of the impact of surface cleaning; the thresholds for sounding rejection can then be altered accordingly.

At different stages during the removal of outliers a grid was interpolated from the soundings to enable the effect on the data to be visualised. Gridding is achieved in Caris HIPS using a slant-range weighted interpolation method; this gives a higher weighting to the more reliable centre beams so that in areas of overlapping data the random errors are reduced. The grid cell size selected is critical as a balance must be reached between retaining detail and minimising random errors that should average out if the grid cell size is large enough. If small holes of no data appear in the grid because the data is too sparse to support the chosen cell size these can be filled by expanding the grid using a 3x3 or 5x5 averaging kernel. A 3m grid was produced over the entire area expanded using a 5x5 cell kernel. The grid can be displayed by depth, grey scale shaded relief, or a composite of the two. It is also possible to view the grid in the 3D Project Window which gives an excellent indication of where cleaning is required.

If after filtering, manual swath editing and cleaning there are still areas of “noise” e.g. where outer beams of adjacent swaths overlap, the final solution is to use the Sub-Set Editor. This allows soundings to be selected from a 3D cube and rejected whilst another window shows the instantly re-gridded resultant surface. The sub-set editor is also useful for areas of very complex bathymetry such as over a ship wreck.
Once the grid looked to have as many errors removed as possible, it was exported as XYZ points so that it could be used in the GIS. Overall, the ratio of time spent processing to data acquisition was about 5:1 i.e. for every hour of data acquisition about 5 hours was spent in the lab to produce the final result.
Figure 3-16. Sound Velocity Profile from 21st March showing a steady increase in velocity with depth due to increasing pressure.

Figure 3-17. Observed tidal heights at Brighton Marina from 15th to 29th March.
Figure 3-18. Caris HIPS Swath Editor views of soundings in a line from the side, rear and in plan view.

Figure 3-19. Caris HIPS Subset Editor. Top window shows the area being processed, left window shows the real-time grid and the right window shows the raw soundings.
Figure 3-20. 3D view of a grid to illustrate the presence of “spikes” that require rejecting.

Figure 3-21. Sun-illuminated processed multibeam slant range weighted grid.
3.3.2 Multibeam Backscatter Data Processing

3.3.2.1 Real-Time Processing Procedures

During acquisition, the backscatter data could be shown on screen as either a raw display (backscatter vs arrival time) or a slant range corrected display (backscatter vs distance). This is useful primarily as a quality control measure, however due to other loads on the acquisition computer it was unable to display the backscatter without the PC crashing whilst surveying, so it was logged to disk and then dealt with only during post-processing.

3.3.2.2 Post Processing Procedures

Compared to the sounding data, backscatter requires very little processing. This is because it is a continuously sampled record of backscatter with time, rather than discrete measurements that can be selected and edited. The main processing steps involve rectifying the sonar “image” of the seafloor so that it is correctly located in space. The software used to process the backscatter data is Caris SIPS (Sonar Information Processing System) and is an integral part of Caris HIPS used to process the soundings.

3.3.2.3 Data Conversion

The backscatter data is included within the 6042 database files and XTF files. When the bathymetry data is loaded into HIPS it is optional as to whether to import the backscatter as well. To reduce the size of the backscatter image, it can be resampled from a 16 bit image to 8 bits during import, this results in a small reduction in data quality so the data was preserved as 16 bit.

3.3.2.4 Slant Range Correction

The slant range correction uses a sound velocity value to convert the time series to distances. To do this it is necessary to know the shape of the seabed as this affects how long the ping will take to return to the sonar. The soundings grid can be used to provide this information, but this tool a very long time to process, instead the seabed was assumed to be flat thus simplifying the computation. The software attempts to automatically identify and digitise the first return (seabed) as part of the slant range correction process, but this normally fails and has to be adjusted manually.

A sound speed of 1483 m/s was used for all lines, and the resolution was set to 0.1 m. The options to “beam pattern correct” and “despeckle” the data were used. The beam pattern correction attempts to equalize the differences in pixel intensity from nadir to the outer ranges of the sonar swath. This beam pattern effect occurs as a result of the inability of the Time Varying Gain amplifier in the sonar to
Figure 3-22. Raw backscatter sonar data over the wreck shown on the bathymetry in the left window.

Figure 3-23. Slant-range corrected backscatter data over the same area as figure 3.21.
adequately compensate for the attenuating acoustic signal. Despeckle attempts to smooth isolated bright spots and streaks in the raw sonar file by averaging the neighbouring pixels. Figure 3-22 and Figure 3-23 show the backscatter before and after slant range correction using an inverted grey scale colour range (shows areas of high backscatter as pale colours and areas of low backscatter as dark colours); this makes the image more intuitive to interpret.

3.3.2.5 Mosaicing

A backscatter mosaic is a series of slant range corrected sonar images that have been geo-referenced and often overlap. The term “mosaic” arises from the method used to merge the overlapping areas.

A pixel resolution of 1 m was used for the mosaic, because although this is lower resolution than the slant range corrected data, it prevents the file being too large and smoothes out some noise. A filter to remove data that exceeded an across track distance to depth ratio of 3.5 was used to remove the outer limits of the data, and fore-aft limits were extrapolated by 5 seconds in an effort to prevent gaps between each file. The mosaic was created using the “auto seam” method that uses the highest weighted pixel from overlapping swaths.

The backscatter mosaic was draped over the bathymetry grid to show correlations between terrain and acoustic properties of the seabed as shown in figure 3.25.
Figure 3-24. Completed backscatter mosaic for the northern section of the survey area. Dark shades represent areas of low backscatter intensity.

Figure 3-25. 3D view of the backscatter draped on the sun-illuminated bathymetry grid.
3.3.3 **Side-scan Sonar (Backscatter) Data Processing**

3.3.3.1 **Real-Time Processing**

Within the sidescan sonar transceiver, Time Varying Gain (TVG) amplification is applied to the recorded data in real-time to compensate for the signal attenuation as the acoustic pulse travels through the water column. In addition to the attenuation TVG amplifier, further signal processing is available including fixed-level amplification, TVG and Automatic Gain Control (AGC). These additional processing steps are used to improve the visual image of the data displayed to the operator during acquisition. However, data was recorded raw, unaffected by these signal processing functions in order to preserve the fidelity of the data for subsequent data interpretation.

3.3.3.2 **Post-Acquisition Processing Scheme**

Side-scan sonar data processing used a set of software tools developed in-house at Imperial College, London (Humber, 2004). The processing strategy follows previous approaches taken for geological seafloor mapping using digital side-scan sonar systems (e.g. Blondel, 1997; Cervenka and DeMoustier, 1993; Chavez, 1986). A flat seafloor is assumed across the width of the imaged swath, which greatly simplifies the subsequent processing calculations. In order to convert side-scan sonar survey data into a continuous map of the acoustic backscatter response of the seafloor, several distinct processing tasks are required (Figure 3-26).
3.3.3.3 Data Preparation

The first stage in pre-processing (after navigation data has been extracted for initial ship track plots) was to determine the altitude of the instrument above the seafloor. Altitude information is contained within the side-scan sonar data as a high amplitude signal caused by the reflection of the sound pulse from the seafloor directly beneath the sonar fish (Figure 3-27). This signal was picked manually and stored for subsequent processing. Raw side-scan sonar data contains a strong across-track amplitude variation caused primarily by the uneven ensonification pattern of the acoustic transducers. The initial stage in removing this effect was too estimate the across-track amplitude function by averaging the sonar data for each day from -90° to 90° grazing angle (covering port and starboard directions) at 0.5° intervals (Figure 3-28). The final stage of pre-processing is to divide survey lines into smaller sections to aid in the practical aspects of file manipulation and transfer in computer systems. To specify a particular section, an ASCII format description file was created that contained the parent data set location, a start time and an end time. For this study, a time-span of approximately 15 minutes was used for each line section resulting in a total of 197 section specification files. For all data processing, the sound velocity in water was set to 1500m/s.
Figure 3-27. Example of a raw sonogram with picked seafloor reflection. The swath example is a selection from the combined chirp/side-scan sonar data acquired on 24th April 2003. More details about the data selection are given in Fig 3-29.
3.3.3.4 Main Data Processing

During the main processing phase, instrument altitude profiles, across-track amplitude functions and section specification files were used to create a geographically registered sonogram mosaic from raw survey data (see Figure 3-29 for an illustration of this process). Firstly the navigation information was smoothed to remove small scale irregularities in either the position or ship heading data. To achieve this, the ship track was resampled with a cubic spline function based on a reduced data set of every 5th navigation point using the time stamp of each point as a reference. The heading was re-calculated from the smoothed ship track. Next, the layback was corrected by removing a fixed geographical fish offset. Layback was specified as the relative heading and range of the fish from ship heading.

The next stage was to remove the across-track intensity function determined in pre-processing by dividing each pixel by the function value according to grazing angle (Figure 3-29b). This operation resulted in a floating point number between 0 – 1, which was then multiplied by a scalar value of 10,000 to reinstate the dynamic range of the data for integer storage. Next, the imaging geometry was corrected by converting the distance from the fish through the water column to the horizontal distance along the seafloor (Figure 3-29c). This correction is the slant-range correction and was calculated using a flat-seafloor assumption then the data re-sampled to give a regular spatial distribution.

Figure 3-28. Example of across track amplitude variation plotted as a function of sonar incidence angle. Data for this figure is from the 24th April 2003 averaged in 0.5° intervals of incidence angle.
After slant-range correction, a 3×1 median filter oriented parallel to the fish direction of travel was used to reduce noise (referred to as ‘speckle noise’) caused by isolated, high intensity data points (Figure 3-29d). Finally, the innermost part of the swath (50 pixels), which is dominated by undesirable reflections of high amplitude was cut to improve overall image appearance (Figure 3-29e).
Figure 3.29. Illustration of the side-scan sonar data processing flow.

Data was acquired on 24/03/2004 at 10:30:00 - 10:57:00. The sonogram is presented before geographical registration with the instrument located at the centre. Direction of travel is from top to bottom; average speed 5.5 knots; total track length 4609m; total width 427m. Dark shades indicate low intensity backscatter.
3.3.3.5 Geographical Registration and Mosaicking

Next, each swath was geographically registered by calculating Geographical Control Points (GCPs) then re-sampling using routines from the commercial remote sensing package, ER-Mapper (Figure 3-30). The Imperial College software automatically generated a mesh of GCPs, linking data values to geographical coordinates. GCPs were located at three points (centre point and extremes) along every 25th ping. A triangulation gridding scheme with cubic re-sampling and a cell size of 75cm was used was specified for the ER-Mapper routine. To produce a final, continuous acoustic image, line sections from common survey areas (i.e. north and south boxes shown in Figure 3-13) were combined or mosaiced. At this stage, sections were omitted if they were of poor data quality and detracted from the overall mosaic appearance. To maintain practical file sizes (i.e. below 300MB), the large mosaics were saved as a series of tiles. In addition, lower resolution 2.25m cell size images were produced of the entire northern and southern areas.

Figure 3-30. Example of a geo-rectified single swath. The swath shown here was used in Error! Reference source not found. to illustrate the data processing sequence. Actual image cell size is 1×1m although display resolution is coarser. A bedrock outcrop is seen in the lower left part of the image as a rough textured area surrounded by sediment cover varying from high to low backscatter intensity.
3.3.4 Singlebeam Bathymetry Data Processing

3.3.4.1 Data Format

The singlebeam bathymetry data was acquired by a naval vessel on contract to the Maritime & Coastguard Agency (MCA) in 2002 and released to Imperial College by the United Kingdom Hydrographic Office (UKHO) in April 2003. The data had been fully processed to remove all errors and reduced to Chart Datum. The data was acquired along transects spaced 65 m apart on a bearing of 80°, the spacing of soundings along each line was ~ 10m.

The format of the data was space delimited lat/lon/depth ascii text files in five blocks. The geodetic coordinate system was WGS84. In total, there were 167,848 soundings covering an area of 588 square kilometres over the Palaeo-Arun and adjacent seabed.

3.3.4.2 Digital Terrain Modelling

The five blocks were merged into one file using Surfer 8, then converted from geodetic coordinates to projected UTM zone 30 N coordinates using Geolcalc. The data was then exported as a point shapefile feature class in ArcGIS and interpolated into a 10 m cell size grid using kriging.

A shaded relief and slope grid were calculated from the depth grid.

3.3.4.3 Verification of Multibeam Dataset

To assess both the internal and external reliability of the multibeam survey against the charted bathymetry for the area, a comparison was performed using ArcGIS. The two bathymetry grids were contoured at 5m intervals and overlaid. Figure 3-31 shows the very close agreement between the positions of the corresponding contours indicating that the horizontal and vertical positioning of the multibeam soundings was very accurate. To obtain a more detailed comparison, the two gridded bathymetry datasets were subtracted from each other to produce the difference grid shown on Figure 3-32. The localised differences of up to 5 m show areas where the multibeam resolved subtle features that were undetected on the singlebeam, or areas of steep gradient that were smoothed out on the singlebeam data. Areas of noise in the multibeam data between swaths were also picked up by this technique; appearing as parallel lines of higher residuals.

The UKHO list of known shipwrecks was added to the GIS, and the size of targets detected on the multibeam and/or singlebeam were compared to the known dimensions of the wrecks. This gave an additional indication of the resolution capabilities of the Reson 8101 multibeam system compared to traditional singlebeam methods. Figure 3-33 shows the results of the respective methods over a 65m long shipwreck in 30 m water depth.
Table 3-2 shows the positions, numbers, water depths and chart symbols for all the wrecks in the general study area.

Table 3-2 Wreck list provided by the UKHO for all wrecks in the general study area. WK = wreck with least depth indicated, SW = least depth determined by wire sweep, OB = obstruction, F = foul.

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Figure 3-31. Comparative contour plots of the multibeam and singlebeam bathymetry datasets showing a strong correlation in position and depth.
Figure 3-32. Grid of residual differences between the singlebeam and multibeam data (positive residuals show the singlebeam is shallower than the multibeam and vice versa).
Figure 3-33. Singlebeam shaded relief topography (top) over two ship wrecks (marked by green flags) and multibeam data (bottom) displayed in the same way. Note the difference in resolution over both the wrecks and geological features.
3.4 DATA DESCRIPTION AND INTERPRETATION

3.4.1 Description of seabed morphology: Singlebeam data

3.4.1.1 Singlebeam Bathymetry – Observations of Seabed Topography

Singlebeam bathymetry data provided by the Marine and Coastguard Agency and the United Kingdom Hydrographic Office provides seafloor coverage from the coastline to 24 km offshore. As discussed in chapter 2.5 the data was processed into grids showing depth, slope and sun-illuminated relief at 10 m cell size.

The singlebeam bathymetry is displayed as colour-filled contours at 5 m intervals in Figure 3-34. Water depths range from less than 5 m up to 2 km offshore to 50 m in the southernmost sector of the study area. This figure illustrates that the bathymetric contours follow an east-west-oriented trend that is sub-parallel to the shoreline up to 6 km offshore. Further south, the topography is much more irregular with embayments less than 5 km in diameter protruding to the north. Figure 3-35 shows a shaded relief map of the singlebeam bathymetry in which the complex details of the topography are clearly visible. Key features are discussed in more detail below. The more irregular, incised topography of the southernmost part of the area (south of 50° 40' 0'”) is apparent from the slope map of Figure 3-36. This figure nicely illustrates where the areas of highest relief are present predominantly at the margins of prominent embayments in the south of the area. Creating slope maps will be a useful tool in determining the margins and orientation of underfilled valley systems.

A set of approximately east-west-oriented topographic profiles across the single beam survey area (located in Figure 3-37) clearly illustrates how the degree of incision of the shelf seabed and the rugosity of the seafloor increase to the south (Figure 3-38). Here the local relief shows variations of up to 20 m. The longitudinal profiles in Figure 3-39 also reveal how the seabed shelves gently from the coastline until 15 km offshore, whereupon it shows much more marked relief variations with amplitudes approaching 20 m.

Perspective views

For each perspective view of the singlebeam data refer to Figure 3-40 for information about the view direction and approximate scale.

Figure 3-41 shows a perspective view of the singlebeam bathymetry looking to the north. The southward increase in seabed topographic relief is clearly visible in this figure. The offshore course of the palaeo-Arun has been traced on this figure and indicates that the valley shows little topographic form in the north, but coincides with a topographic depression in the south. A perspective view of the
northern part of the shelf is illustrated in Figure 3-42. Immediately south of the coastline, regularly spaced ridges of ~0.5 – 1 m amplitude and 200 – 500 m wavelength are visible in water depths up to 12 m extending 8 km offshore. The orientation of the ridge crests is SSW and parallel to the general structural trends of the area. These ridges are interpreted as tilted beds within the Upper Chalk, which are outcropping at the seafloor and dip to the SSW. Identification of Upper Chalk bedrock is important in archaeological assessment of the shelf, as this lithology is the primary source of flint for production of stone tools. Chalk landscapes typically contain high densities of archaeological findspots. An outcropping ridge known as the Bognor Rocks at the coastline extends across the area in an ESE direction at depths of 5 to 12 m. The geometry of the outcrop shows the beds are steeply dipping to the SSW and also show minor folded in the direction of strike (WNW). The maximum relief of the bedrock ridge is 5 m above the surrounding seafloor and it forms a succession of 2-3 parallel ridges. The ridge is very prominent on Figure 3-42 and Figure 3-43. The ridge is not visible on the seafloor over a length of 3 km SSE of the mouth of the Arun River (Figure 3-43). It then reappears and continues eastwards for 6 km before again subcropping beneath sediment deposits at a water depth of 13 m. Inshore of the ridge, small scarps associated with the outcropping chalk beds at the seafloor are not visible for ~1 km. The gap in the seafloor expression of the ridge is interpreted to mark on the offshore course of the River Arun, and the presence of an incised palaeovalley in the subsurface. The bathymetric evidence suggests that the ridge has been eroded away by incision by the Arun flowing perpendicular to the structural trend. Analysis of seismic data shows the presence of a bedrock incised valley oriented NNW-SSE indicating that this interpretation is valid (Figure 5.9).

Offshore from the ridge the topography become irregular, and is characterised by several subtle scarp features occurring roughly parallel to the coast and along lines of constant depth. The structural control observed to the north is far less apparent as the bedrock lithology changes to the weaker London Clay Formation. The path of the palaeo-Arun is conspicuous by the absence of any surficial feature other than dredging scars denoting its fluvial gravel deposits. At this point 15 km offshore there is no evidence of a topographic valley on the seafloor associated with the River Arun. Two localised shoal areas lie to the west of the area and are likely to be further areas of outcropping bedrock surrounded by London Clay. New erosional depressions become visible to the south, oriented in a N-S direction and are the first topography that can be related to margins of the Arun Palaeovalley (Figure 3-41). From this point onwards the area has been mapped using high-resolution multibeam sonar.
Figure 3-34  Singlebeam bathymetry grid displayed as colour filled contours at 5 m intervals. The entrance to the River Arun can be identified from the single survey line running northward into the estuary. Background imagery is from Landsat.
Figure 3-35 Singlebeam bathymetry grid displayed as a composite depth coloured and shaded relief image. Sun-illumination is from the northwest at an elevation of 45°. Background imagery is from LandSat.
Figure 3-36 Bathymetric slope grid computed from singlebeam bathymetry on a scale of 0° to 10°. Background imagery is from LandSat.
Figure 3.37  Shaded relief singlebeam bathymetry grid with positions of profiles and cross sections plotted in figures 3.37 and 3.38 shown. Background imagery is from LandSat.
Figure 3-38 Cross sectional profiles through the singlebeam bathymetry at lines shown in figure 3.36.
Figure 3-39 Longitudinal profiles through the singlebeam bathymetry at lines shown in figure 3.36.
Figure 3-40 Foreground baselines and view directions for the perspective images shown in figures 3-41 to 3-44.
Figure 3-41 Perspective image of the singlebeam bathymetry viewed at an azimuth of 000°. Vertical exaggeration is x 6 and the sun-illumination is from the NW.
Figure 3-42 Perspective image of the singlebeam bathymetry viewed at an azimuth of 000°. Vertical exaggeration is x 6 and the sun-illumination is from the NW.
Figure 3-43 Perspective image of the singlebeam bathymetry viewed at an azimuth of 300°. Vertical exaggeration is x 6 and the sun-illumination is from the NW.
Figure 3-44 Perspective image of the singlebeam bathymetry viewed at an azimuth of 280°. Vertical exaggeration is x 6 and the sun-illumination is from the NW.
3.4.2  **Description of seabed morphology: Multibeam data**

3.4.2.1  **Multibeam Bathymetry – Overall Topography of Survey Area**

The overall topography of the multibeam survey area is illustrated in Figure 3-45 and Figure 3-46, which show the bathymetry as a contoured grid and as a shaded relief map. Figure 3-47 shows a slope map for the survey area. It is clear that unlike the area to the north, the area covered by the multibeam survey shows complex topography. Water depths range from locally 20 m in the north to between 40-48 m in an ENE-WSW-trending elongate trough at the southern boundary of the survey area. A set of embayments is prominent in the seabed topography. These show water depths of up to 45 m and form north-closing and shallowing indentations in the shelf. The slope map in Figure 3-47 shows that the steepest slopes are present at the margins of these embayments and that the steeper slopes are more prevalent in the southern part of the survey area. The description and interpretation presented in this report will focus on the eastern part of the multibeam survey area, as this is the area that encompasses the course of the palaeo-Arun river.

3.4.2.2  **Morphology of the Arun topographic valley**

**General Description of Valley Morphology**

The most prominent morphological feature on the seabed in the multibeam survey area is a NW-SE-oriented topographic low that extends from 50° 39’ 05” N 000° 25’ 39” W to 50° 37’ 14” N 000° 20’ 43” W. We term this feature the Arun topographic valley to distinguish it from the main Arun palaeovalley or stratigraphic valley. The topographic valley is superimposed upon and incised through deposits of the stratigraphic valley. The bathymetry of the topographic valley is shown in Figure 3-48 as a composite depth coloured and shaded relief image. The valley shows a linear, elongate planform with an azimuth orientation of 320°. Towards the northwest, the valley shows a gradual reduction in degree of incision such that the valley floor merges with the flanks. The southeastern limit of the valley is defined by where it cuts through a prominent east-west trending ridge comprising resistant bedrock layers outcropping at the seafloor. This marks a narrow, 600-m-wide, outlet south of which the valley merges with an approximately east-west-oriented trough, which is the morphological expression of the Northern Palaeovalley (Hamblin et al., 1992).

The depth of the valley floor ranges from 25 m in its northern section to 45 m at its southernmost extent (Figure 3-50 and Figure 3-51). The floor of the valley does not show a smooth downvalley gradient. Figure 3-51 shows that the depth of the valley floor progressively decreases to 3.5 km downvalley, south of which there is an abrupt localised increase in depth of the floor to 40 m. This is likely to be due to enhanced marine erosion in this area. Similar zone of increased erosion is observed
at and downstream of the bedrock outlet of the Arun. Again this might be due to enhanced marine erosion of the seabed due to the narrow geometry of the outlet.

The flanks of the valley lie at between 20 - 25 m water depth (Figure 3-54). Successive valley cross-profiles illustrate the variation in valley relief, width and cross-sectional geometry (Figure 3-49 and Figure 3-50). Traced southeastwards, the valley form shows progressive narrowing and increase in topographic relief (Figure 3-54 and Figure 3-55). Up to 2.5 km wide in its uppermost section, it narrows to less than 200 m at its southern limit. The steep sides of up to 20° abruptly flatten off at the valley floor, which shows little significant variation in topography (Figure 3-56). A thalweg within the main part of the valley cannot be determined due to the absence of any surficial trace of a channel. A graph showing the depth of incision of the valley relative to its flanks shows a progressive downvalley increase until 6 km downvalley, south of which there is a decrease in depth of incision (Figure 3-57). This is suggestive of overdeepening in the central part of the valley, probably by marine erosion processes.

The multibeam backscatter mosaic in Figure 3-52 shows that the valley floor is dominated by low backscatter intensity, which is probably related to fine-grained sediment infill at the surface. Areas of higher backscatter intensity are to be observed on either flank of the valley. Figure 3-53 shows a perspective view looking to 340° in which the backscatter has been draped over the multibeam bathymetry grid. This clearly illustrates he low backscatter on the floor of the topographic valley. A zone of irregular high backscatter is observed on the eastern margin, which corresponds to the presence of gravels at the seafloor.

The interpreted surficial geology of the topographic valley and its flanks is shown in Figure 3-58. The bedrock control on the planform morphology of the valley is apparent.

**Perspective overviews of the topographic valley**
For each perspective view of the overall multibeam data refer to for information about the view direction and approximate scale.

Figure 3-60–3.62 show a series of perspective views of the topographic valley that illustrate our interpretation of the seabed morphology.

A view looking downvalley is shown in Figure 3-60. The narrowing of the valley to the southeast is clear and in the distance the narrow outlet of the Arun where it breaches a bedrock ridge can be observed. The dipping bedrock scarp that forms a prominent cuesta defining the western margin of the valley is clearly shown. On the eastern margin of the topographic valley, the rough seabed texture defines an area of intensive dredging of gravels that form a fill terrace on the valley side. Figure 3-61
shows the main features of the valley topography. The bedrock cuesta at the western margin is well defined and the strike of bedding can be clearly discerned. The margin of the stratigraphic valley on the eastern side can also be observed, where terrace-fill gravels abut against southwest dipping bedrock. The narrowing of the Arun topographic and stratigraphic valley is related to the change in strike of the bedrock cuesta to an E-W orientation. This bedrock ridge defined as a SE-dipping resistant bedrock horizon clearly forms a structural barrier to the valley. The Arun valley cuts across this ridge at a narrow outlet. A set of sediment mounds and ridges is present both landward and seaward of the outlet. These may represent barforms developed during initial transgression through this narrow outlet. A view looking northwest up valley shows the main topographic features discussed above (Figure 3-62). In particular the narrowing of the valley toward the outlet incised I bedrock is obvious.
Figure 3-45 Multibeam bathymetry grid displayed as colour filled contours at 5 m intervals.
Figure 3-46 Multibeam bathymetry grid displayed as a composite depth coloured and shaded relief image. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-47 Bathymetric slope grid computed from multibeam bathymetry on a scale of 0° to 10°.
Figure 3-48 Multibeam bathymetry grid of the topographic valley displayed as a composite depth coloured and shaded relief image. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-49 Shaded relief multibeam bathymetry grid with positions of profiles and cross sections plotted in figures 3-50 and 3-51 shown.
Figure 3-50 Cross sectional profiles across the topographic valley along the lines shown on figure 3.49.
Figure 3-51 Longitudinal sectional profile through the line shown on figure 3.49.
Figure 3-52 Uncalibrated backscatter mosaic acquired from the multibeam sonar. Dark shades correspond to areas of low backscatter intensity. Bathymetry contours at 5 m intervals are overlaid in white.
Figure 3-53 Uncalibrated backscatter mosaic draped on the multibeam bathymetry grid. Dark shades correspond to areas of low backscatter. View azimuth 340°. Vertical exaggeration x 6.
Figure 3-54 Downstream depth profiles for the east and west valley margins and the depth of the deepest corresponding point in the valley.
Figure 3-55 Downstream width profile derived from digitising valley margins.
Figure 3-56 Graph showing maximum slope vs. downstream distance.
Figure 3-57 Incised depth (water depth minus depth to top of valley) v.s downstream distance.
Figure 3-58 Interpreted surficial geology draped on a sun-illuminated multibeam grid. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-59 Foreground baselines and view directions for the perspective images shown in figures 3-60 to 3-62.
Figure 3-60 Perspective image of the topographic valley of the palaeo-Arun imaged using multibeam sonar. View azimuth 110°. Sun-illumination is from the NW and the vertical exaggeration is x 6.
Figure 3-61 Perspective view of the topographic section of the Palaeo-Arun imaged using multibeam sonar. View azimuth 20°. Sun-illumination is from the NW and the vertical exaggeration is x 6.
Figure 3-62 Perspective view of the topographic section of the Palaeo-Arun imaged using multibeam sonar. View azimuth 300°. Sun-illumination is from the NW and the vertical exaggeration is x 6.
Figure 3-63 Location boxes for the close-up areas overlaid on the shaded and depth coloured grid. Sun-illumination is from the northwest at an elevation of 45°.
3.4.2.3 Morphology of the Upper Segment of the Arun Topographic Valley

General Description
The upper segment of the topographic valley is defined as the area extending from the northern limit of the multibeam survey area to where the valley starts to narrow sharply (Figure 3-63). The bounding coordinates are NE 050° 39’ 37" N 000° 22’ 07" W, SE 050° 37’ 34" N 000° 22’ 07" W, SW 050° 37’ 34" N 000° 27’ 05" W, NW 050° 39’ 37" N 000° 27’ 05" W.

The general topography of the seafloor in the upper segment of the topographic valley is shown in Figure 3-64 and Figure 3-65. Figure 3-64 shows that the valley shoulders lie in water depths of between 20-25 m, whereas the valley floor lies between 25-30 m water depth in its northern area and increases downvalley up to between 40-45 m. Figure 3-65 is a shaded relief map that shows the topographic variations along the valley shoulders and floor in considerable detail. Different aspects of the valley topography will be explored below in a series of maps and perspective views linked to graphs of valley cross- and long-profiles.

The upper segment of the valley is oriented NW-SE and is up to 2 km wide, narrowing southeastwards to less than a kilometre. The slope map in Figure 3-65 clearly defines the flanks of the valley and illustrates how valley side slopes increase downvalley from 3-4° in the northwest up to locally greater than 10° in the southeastern area. It is evident from this and the shaded relief figure that valley-side relief increases downvalley. The valley floor, however, shows slopes of <1°, with the general downslope gradient being approximately 0.5°. A distinct change occurs in the southeastern section, where the valley deepens from 35 m to 40 m depth at a break in slope (Figure 3-64 and Figure 3-65).

Valley Cross-sections
Figure 3-69 shows valley cross-profiles averaged for 10 profiles in the northern and central part of the topographic valley; minimum, maximum and mean topography are presented. The locations of the profiles are given in Figure 3-67 and Figure 3-68. Profile 1 in the northern part of the topographic valley shows a symmetrical valley cross-section up to 1.5 km wide and with approximately 10 m of relief on the valley walls. The valley floor is sub-planar with little variation in bathymetry. Profile 2 from a more central section of the topographic valley shows more marked variation in cross-sectional shape and width, narrowing to about 1 km. A resistant bedrock scarp that dips to the southwest creates the distinctive, triangular topographic form of the western margin of the valley.

Backscatter Intensity
Figure 3-70 shows the backscatter intensity derived from the multibeam sonar for the upper segment of the topographic valley. The valley floor is characterised by dark areas indicative of low backscatter, which is suggestive of fine-grained sediment at the seabed. The valley margins are distinguished clearly by showing brighter backscatter, in particular the eastern margin of the valley. Here the higher backscatter is interpreted to be due to the presence of coarser grained sediments on the valley margin.

Interpretation of Surficial Geology
Figure 3-71 shows an interpretation of the surficial geology overlaid on the shaded relief bathymetry. The south-west margin of the topographic valley is clearly defined by a resistant bedrock scarp; whilst the eastern margin is formed by coarse gravely sediments that represent an older valley fill now preserved as a terrace remnant (see Chapter 5). The valley floor shows fine-grained sediment at the seabed.

Perspective Views
The following sections include a number of 3D views of the multibeam bathymetry surface. Figure 3-72 shows the direction and foreground scale of each figure to allow the reader to understand the orientation of each perspective visualisation.

Sand Ridge on Valley Floor
In the northern part of the topographic valley, an elongate, irregular E-W-trending ridge that is 1.5 km long is present on the seabed (Figure 3-73 and Figure 3-74). It shows a convex-up geometry with maximum width of 300 m and height of 6m, which are developed in the central part of the form. The ridge shows symmetric cross-sectional profiles with maximum slopes of 4°. The width and height of the ridge tapers off to the east and west. We interpret this feature as a sand ridge formed by either present day shelf tidal currents or a relict feature formed during the Holocene transgression. The absence of any evidence for bedforms present on the ridge flanks suggests that the latter explanation may have more strength.

Eastern Valley Margin
The eastern margin of the topographic valley is oriented NW-SE and shows an irregular, embayed trace in map view (Figure 3-65). The valley flank descends from 19 m depth on the shoulder to 29 m on the valley floor. The slope has a gradient of ~ 8° over a distance of 50 m. A prominent semi-circular embayment in the central section of the valley is cut approximately 200 m into the valley margin and shows relief of up to 10 m. Longitudinal profiles indicate that the valley shoulder slopes to the south at a lower gradient than the topographic valley floor with the result that valley relief increases to the south-east (Figure 3-69).
Figure 3-75 and Figure 3-76 show perspective views of the valley margin looking to the east-north-east and south-east respectively. The valley sides have gradients of between 5-8° merging westwards into a very gently sloping valley floor. In the foreground, on the valley shoulder, extensive pits up to 8 m in depth and typically 20-30 m in diameter are abundant (Figure 3-75 and Figure 3-76). These represent dredging pits created during an older phase of dredging in the area. Analysis of industry boomer seismic lines and vibrocore data (Chapter 5) indicates that the valley shoulder is comprised of loosely consolidated sands and gravels interpreted as fluvial deposits overlain in places by a marine transgressive horizon. The backscatter mosaic supports this by showing moderate reflectivity in the area (Figure 3-70).

Traced eastward it is clear in Figure 3-75 and Figure 3-76 that the dredging pits terminate sharply and an area of seafloor characterised by continuous slightly irregular ridges less than 1 m in amplitude and oriented WNW-ESE is present. These ridges represent SW-dipping bedrock outcropping at the seafloor. The contact between the area of pitted topography formed by dredging of fluvial gravels and the bedrock therefore represents a major erosional unconformity and is interpreted here as the margin to a bedrock-incised valley which subsequently filled with sediments. This contact marks the eastern margin of the palaeo-Arun stratigraphic valley, as distinguished from the Arun topographic valley. Boomer seismic data show that these sediments onlap to the east onto the dipslope of the bedrock (Figure 5.30).

The detail observed in the multibeam topographic data permits accurate mapping of the valley margin because of the difference in erodibility of valley-fill sediments as opposed to bedrock and also the presence of the dredging scars in the gravels. These gravel deposits are interpreted in Chapter 5 as the sedimentary infill of the Arun stratigraphic valley that were later incised by the topographic valley thus preserving them as a fill terrace on the margin of the topographic valley. Thus it is clear that high-resolution multibeam bathymetry data has the capability to distinguish valley margins, where valleys are incised into bedrock. This is of great importance to exploration for archaeological resources as valley margins are excellent localities for potential findspots (see Chapter 6).

Figure 3-77 and Figure 3-78 illustrate in more detail the morphology of the eastern shoulder and in particular the margin of the Arun stratigraphic valley. Figure 3-77 shows the difference between the topographic valley margin and stratigraphic valley margin. On the left side of the view, a NW-SE-oriented elongate zone of subdued topography represents an infilled small palaeo-channel, approximately 500 m wide that is confluent with the main Arun valley further to the southeast (see Figure 5.38).

In Figure 3-78, a detailed view is obtained of the topography of the terrace at the margin of the topographic valley. The dredging pits are developed in an elongate unit that comprises sands and
gravels that form the infill of a small channel that is about 500 m wide. Interpretation of boomer seismic data indicates that the eastern edge of this channel fill is defined by bedrock and the western edge by a succession of fine-grained stratified sediments.

**Western flank of the topographic valley**

Figure 3-79 shows a perspective view of the western margin of the topographic valley looking to the northwest. The valley margin here is sharp and clearly defined. Analysis of the multibeam data when coupled with seismic stratigraphic evidence presented in Chapter 5 indicates that a prominent scarp of resistant bedrock forms the western valley flank. The bedrock lithology is interpreted to be calcareous sandstones of Lutetian age (Hamblin et al., 1992). Evidence that bedrock is exposed at the seafloor is evident in the multibeam bathymetry from the presence of well-defined linear scarps observed on the western margin of the topographic valley. These represent bedrock ledges exposed at the seabed.

Figure 3-79 and Figure 3-80 show that the western flank of the valley forms a well-defined scarp. Depths on the bedrock ridge are 20-25 m, descending to 30-37 m in the valley. The valley margins show gradients of up to 20°. Traced southwestwards, the topography on the valley shoulder decreases steadily. The bedrock horizon dips at 2° to the southwest. Figure 3-81 shows an overview of the western flank looking west. The scarp at the valley margin is clearly apparent, and is interpreted as a cuesta. It is incised by several tributary valleys, which are discussed in detail below. West of the valley side, the dipslope of the cuesta is evident, and several linear minor scarps that strike NW-SE are present on the seafloor. These are bedrock ledges. At the base of the dipslope, a NW-SE-oriented topographic low that deepens to the southeast is observed. Minor linear scarps are observed in the floor of this depression. Seismic stratigraphic data indicate that the depression is floored by bedrock, and no sediment infills this depression. We interpret the topography as being due to enhanced erosion of a less resistant bedrock lithology sandwiched between two resistant units. In the top left hand corner of Figure 3-81, a second distinctive NW-SE oriented scarp formed by a resistant bedrock unit is present forming a second cuesta. Thus a distinctive scarp (or cuesta) and vale topography is present at the seabed that appears to be controlled by variation in bedrock resistance to erosion.

**Tributary valleys**

The presence of tributary valley forms incised into the scarp face of the cuesta is an important observation (Figure 3-80). At least three minor side valleys and a number of indentations are observed (Figure 3-81). The tributaries cut back into the scarp at least 500 m and slope perpendicular to the bedrock strike orientation in a direction opposite to the dipslope.

Figure 3-82-Figure 3-84 illustrate the most northerly and well-developed tributary valley in some detail. Note how the valley margins cut across the strike of southwest dipping bedrock. The valley shows a branching dendritic planform, with side valleys branching off the main segment. V-shaped
valley headwalls are clearly defined. At its mouth the valley is 150 m wide and shows an asymmetric cross profile, with valley wall relief of up to 10 m. Valley width and relief decrease upstream, and the valley cross profiles show a U-shaped form. Figure 3-85 - Figure 3-87 illustrate perspective views of another of these tributary valleys.

The branching dendritic drainage net show by these tributary valleys strongly suggests an origin by fluvial bedrock incision. It is difficult to envisage how these forms could have developed in bedrock by marine erosion processes. It seems likely that spring sapping processes may have been important in their detailed origin. Overall the form of these tributary valleys suggests an origin by subaerial erosion processes, which leads us to interpret the origin of the incised western margin as also a subaerial process driven by bedrock fluvial incision.

We propose that these tributary valleys may be important targets for archaeological resources as they are sheltered bedrock locales with potential for the occurrence of rock shelters (see Chapter 6).

**Topple Blocks**

The perspective view of the western valley wall shown in Figure 3-86 illustrates another possible geomorphic feature that may be of some importance. A linear elongate topographic feature is present adjacent to the western margin of the topographic valley. This feature is up to 400 m in length, and less than 100 m wide with a maximum relief of 7 m. We propose that this feature may represent a topple block formed by undercutting of the base of the bedrock valley margin. Higher resolution bathymetry data is needed to investigate this further. However, these features may also have significance for locating archaeological findspots as similar features in the Weald provide natural rock shelters (see Chapter 6).
Figure 3-64 Multibeam bathymetry for the upper segment of the Arun topographic valley displayed as colour filled contours at 5 m intervals.
Figure 3-65 Multibeam bathymetry for the upper segment of the Arun topographic valley displayed as a composite depth coloured and shaded relief image. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-66 Bathymetric slope grid for the upper segment of the Arun topographic valley displayed on a scale of 0° to 10°.
Figure 3-67 Location of the area used to measure topographic swath profile 1 (parallel profiles spaced 10 apart) shown in figure 3.69 overlaid on the shaded relief bathymetry. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-68 Location of the area used to measure swath topographic profile 2 (parallel profiles spaced 10 apart) shown in figure 3.69 overlaid on the shaded relief bathymetry. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-69 Swath profiles 1 and 2 illustrating the averaged cross-sectional topography of the valley, plus the longitudinal profile. Maximum, minimum and mean depths are shown.
Figure 3-70 Uncalibrated backscatter mosaic for the upper reach with bathymetry contours overlaid at 5m intervals. Dark areas correspond to areas of low backscatter intensity.
Figure 3-71 Interpreted surficial geology overlaid on the shaded relief bathymetry for the upper reach. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-72 Foreground baselines and view directions for the perspective images shown in figures 3-73 to 3-87.
Figure 3-73 Perspective view of the northern area of Upper segment of Arun topographic valley. View azimuth 270°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.

Northwestward (up-valley) decrease in relief of western valley margin

Elongate mound on seafloor - Transgressive ridge complex?

Fluvial gravel infill of Arun stratigraphic valley
Figure 3-74 Perspective view of the transgressive bar deposit. View azimuth 100°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-75 Perspective view of the dredging area. View azimuth 050°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-76 Perspective view of the eastern margin of the Arun topographic valley. View azimuth 150°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-77 Perspective view of the eastern valley shoulder showing margin of the stratigraphic valley with bedrock. View azimuth 270°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-78 Perspective view of the eastern shoulder of Arun topographic valley. View azimuth 300°. Sun-illumination is from the northwest and the vertical exaggeration is x 6. Note the mapped margin of the Arun stratigraphic valley.
Figure 3-79 Perspective view showing the bedrock cuesta defining the western margin of the Arun topographic valley. View azimuth 280°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-80 Perspective view of the western margin of the middle reach. View azimuth 270°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-81 Perspective view of the western margin of the middle reach showing side valley tributaries. View azimuth 280°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-82 Perspective view of an eroded tributary on the western valley margin. View azimuth 200°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3.83 Perspective close-up view of the eroded tributary show on figure 3.76. View azimuth 160°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-84 Perspective view looking down the tributary valley shown on figures 3.81 and 3.82. View azimuth 080°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-85 Perspective view of the cuesta forming the western valley margin with eroded tributaries. View azimuth 210°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-86 Perspective view of the southernmost tributary of the western valley margin. View azimuth 120°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-87 Perspective view looking into the southernmost tributary valley. View azimuth 270°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
3.4.2.4  Morphology of the lower segment of the Arun topographic valley

General Description

The lower segment of the topographic valley is defined as the area between where the valley first begins to narrow at about 50°38′0″N to where it is confluent with the WSW-ENE-oriented trough that marks the margin of the Northern palaeovalley. Figure 3-88 shows the contours of bathymetry and Figure 3-89 shows the bathymetry as a composite depth coloured and shaded relief image. Figure 3-90 shows the slope grid.

The lower segment of the topographic valley shows a marked change in morphology to the upper segment. The slope map in Figure 3-90 shows the occurrence of very steep slopes (>10°) along valley margins. The valley width decreases to less than 200 m downvalley. At its eastern margin the valley opens out into an elongated SW-NE orientated embayment that is up to 40 m deep, and is bounded to the southeast by south-dipping bedrock (Figure 3-94). Analysis of seismic data in Chapter 5 reveals that this embayment is superimposed on a tributary channel to the Arun that enters the depression from the northeast. Figure 3-97 shows a perspective view of this embayment looking to the west, with the course of the tributary marked on.

The western margin of the valley is defined by a continuation of the bedrock cuesta observed to the north (Figure 3-94, Figure 3-96 and Figure 3-98). The minimum depth of the bedrock cuesta decreases from 28 m to 24 m in the lower segment. As the outcrop also rises above the adjacent topography it increases in width from 300 m to 1500 m. The direction of strike indicated by the azimuth of exposed bedding planes on the crest of the cuesta can be seen to change orientation from NW-SE to E-W. This change in strike appears to control a 45° bend in the orientation of the channel (to the ENE) in the lower segment (Figure 3-98). The margin slopes at the outside of the bend are extremely steep, measured at 40° although it is likely the true slopes on the 15-m-high cliff may be significantly steeper. A large linear ridge 600 m in length occurs immediately adjacent to the scarp and may represent a topple block formed by scarp undercutting (Figure 3-98). The valley cross profile shown in Figure 3-91 and Figure 3-92 shows a U-shaped cross-section with a width of approximately 200 m and a vertical relief of 12 m. Large scale bedforms are visible in the channel from the multibeam and backscatter imagery (Figure 3-89 and Figure 3-93) suggesting a fine sandy infill rather than a bedrock substrata.

Perspective Views

The following sections include a number of 3D views of the multibeam bathymetry surface. Figure 3-95 shows the direction and foreground scale of each figure to allow the reader to understand the orientation of each perspective visualisation.
Sediment ridges
A series of irregular elongate sediment ridges that extend from the southern limit of the gravel terrace to the main Arun outlet is present in the lower segment of the topographic valley (Figure 3-99). The ridges are up to ~300m wide and have a relief of 10 m above the adjacent seabed. They appear to show continuity with ridges at the mouth of the outlet. We provisionally interpret these as barforms that formed landward of the outlet during initial marine transgression of the valley. Thus they could represent flood tidal delta sediment bodies formed by tidal reworking of sediments as the tidal flow entered the narrow bedrock outlet. An alternative interpretation is that the ridges represent eroded remnants of the valley-fill sediments.

Valley outlet
The outlet of the Arun is located where the bedrock ridge curves to the ENE creating a structural barrier. The outlet is 600 m wide and opens out to the south into the Northern Palaeovalley. The origin of the outlet is interpreted to be the result of fluvial incision through the bedrock ridge. A perspective view looking to the north shows an overview of the bedrock outlet (Figure 3-99). The bedrock ridge on the east side of the outlet continues for a further 1km before terminating at a NE orientated scarp line that is likely to be fault-controlled (Figure 3-101). As the valley no longer exists to the north of this section of bedrock, the tilted bedding planes can be seen to extend for over 2 km.

South of the outlet, two elongate N-S oriented sediment ridges are observed on either side of a central channel (Figure 3-99). The ridge at the west is 1400 m long and 350 m wide. It forms a convex up sediment body that appears to unconformably overlie bedrock. The ridge flanks slope at up to 6° and the ridge has a sub-horizontal crest. The sediment ridge to the east shows 10 m of relief. These sediment bodies are interpreted as sediment bars formed at an ebb-tidal delta during transgression of the river mouth. At the outlet, an almost circular pool has formed inside the sharply curving bar as the channel turns through 90° to run SSW through the outlet. The pool has a radius of ~60 m and deepens rapidly from 35 to 45 m. The depth here is slightly greater than depths seen further upstream prior to the shallowing and constriction of the valley. This pool is probably the result of erosion due to wave/tidal erosion of the valley entrance.

3.4.2.5 Morphology of Eastern Margin of Arun Topographic Valley
The area to the east of the Arun palaeovalley consists primarily of fluvial and marine gravel deposits infilling eroded dipping beds of sandstone. The morphology shows localised outcropping of the bedrock, but in general the area has few features and shallow gradients. Bedforms occur on the flanks of both the valley and the depression to the SE of the terrace. The bedforms are regular and approximately 0.5 m high, and occur only in depths of around 25 m. They are ~30 m across and show
steep, 20° slopes on all sides. These bedforms are mounds, as opposed to the dredging scars seen further north, which are pits. Localised fine ripples are evident on the backscatter mosaic (Figure 3-93) showing finer sediments which seem to relate to the location of a small channel detected on seismic profiles. This channel shows continuity with the embayment. At the eastern limit of the multibeam survey a further bedrock unit begins to outcrop. The shallow angle of dip indicates the sediment layer is likely to be thin across this region.

### 3.4.2.6 Morphology of western margin of Arun topographic valley

Bedrock cuestas dominate the landscape to the west of the valley with a succession of vales and scarps. There are two main ridges, one of which defines the western margin of the valley and one that runs parallel and 2 km to the SW (Figure 3-81). A vale between the ridges shows very subtle ridges also parallel to the main ridge, indicating the lack of any infilling sediments. The depth of the vale is ~40 m and the southern ridge has a minimum depth of 25 m. This scarp and vale morphology is the consequence of variability of the bedrock lithology to erosion. The width of the cuestas is 3-4 km, terminating in the east at the margin of the Northern Palaeovalley. In the west, the northern cuesta is disjointed and steps down ~2 m onto a level plateau of subcropping rock. The southern cuesta is intersected by a 38 m deep, 500 m wide short channel which is backed up with sediment. The ridge is seen to continue on the west side of the channel.

### 3.4.2.7 Morphology of the Northern Palaeovalley

The ENE-WSW-oriented trough at the southern limit of the multibeam survey area forms the northern margin of the Northern Palaeovalley (Hamblin et al. 1992) (Figure 3-100 and Figure 3-101). Its northern margin is determined by the bedrock structure. The valley floor shows the development of large 6-m-high tidal sandwaves, with well developed scour pits in their lee and smaller ripples on their stoss slopes.
Figure 3-88  Multibeam bathymetry for the lower segment of the topographic valley displayed as colour filled contours at 5 m intervals.
Figure 3-89  Multibeam bathymetry for the lower segment of the topographic valley displayed as a composite depth coloured and shaded relief image. Sun-illumination is from the northwest at an elevation of $45^\circ$. 
Figure 3-90  Bathymetric slope grid for the lower segment displayed on a scale of 0° to 10°.
Figure 3-91 Location of the area used to measure topographic swath profiles across the lower segment of the Arun topographic valley (parallel profiles spaced 10 apart) shown in figure 3-92 overlaid on the shaded relief bathymetry. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-92 Swath profile illustrating the averaged cross-sectional topography of the lower valley in the area marked on Figure 3-91. Maximum, minimum and mean depths are shown.
Figure 3-93 Uncalibrated backscatter mosaic for the lower segment of the topographic valley with bathymetry contours overlaid at 5m intervals. Dark areas correspond to areas of low backscatter intensity.
Figure 3-94  Interpreted surficial geology overlaid on the shaded relief bathymetry for the lower segment of the topographic valley. Sun-illumination is from the northwest at an elevation of 45°.
Figure 3-95 Foreground baselines and view directions for the perspective images shown in figures 3-96 to 3-101.
Figure 3-96  Perspective view of the lower segment and outlet of the Arun valley. View azimuth 070°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-97 Perspective view of the topographic low east of the Arun topographic valley. View azimuth 260°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-98 Perspective view of the narrow lower segment of the Arun topographic valley. Note the possible topple blocks fallen from the undercut bedrock cuesta. View azimuth 120°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-99  Perspective view looking toward the outlet of the Palaeo-Arun and breached bedrock high. View azimuth 000°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-100 Perspective view of the lower segment of the Arun; note marine sandwaves in foreground. View azimuth 290°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
Figure 3-101 Perspective view of the confluence of the Arun with the Northern Palaeovalley of the English Channel River. View azimuth 300°. Sun-illumination is from the northwest and the vertical exaggeration is x 6.
3.4.3 Acoustic Seafloor Imaging

3.4.3.1 Side-scan Sonar Mosaics

Two side-scan mosaics have been produced covering areas to the north (figure 3.34) and the south (figure 3.35) of the wider survey area, from the dedicated side-scan sonar and combined chirp/side-scan sonar instruments respectively.

The northern side-scan mosaic (Figure 3-102) covers a total area of 100km² with actual data covering 35km² or 35%. In general, the pattern of backscatter intensity variation shows relatively high intensity areas dominating the image with lower intensity backscatter observed in the southwest corner and as a linear feature oriented north-south in the central southern part of the mosaic. In the western half of the mosaic, parts of the mosaic have a more textured appearance, indicative of structural features of the seafloor. These aspects are described in more detail below.

The southern-scan mosaic data (Figure 3-103) covers an area of 34km² out of a total area of 70km² (or 50%). The denser coverage by the combined instrument is a consequence of closer line spacing and using a greater range than the dedicated instrument. The acoustic imagery shows more variation and texture than the dedicated side-scan mosaic. Central parts are of mid to high intensity with low intensity areas at the eastern limit and towards the west. The difference in appearance can be attributed to both greater noise levels in the data set and a difference in seafloor geology.
Figure 3-102. Side-scan sonar mosaic of dedicated side-scan instrument (for location map see Fig.3-13). High intensity backscatter is shown by light shades, low intensity by dark shades.
Figure 3-103. Side-scan sonar mosaic of combined chirp/side-scan instrument (for location map see Fig. 3-13). High intensity backscatter is shown by light shades, low intensity by dark shades.
3.4.3.2 Seafloor Bottom Types

The character of the side-scan sonar mosaics was examined in more detail by selecting 10 locations for closer inspection (Figure 3-104). The side-scan image data at the 10 locations is shown in Figure 3-105. The first six examples are shown with a geological interpretation in terms of seafloor bottom type, determined by eye. The Bedrock outcrop category has a high intensity backscatter signature with a coarse textured, granular appearance on the order of 5-20m (horizontal distance) indicative of a rough, hard, rocky surface. The Dredging spoil category has a high intensity, irregular appearance in a similar way to the Bedrock category. However, characteristic linear markings suggest that, in this case, the seafloor has been mechanically disturbed, possibly by dredging action.

The Ripple category is distinguished by sub-parallel, repetitive linear features varying in separation from hundreds of metres (Ripples 01) to tens of metres (Ripples 02 and 03). These features are interpreted as sedimentary bed forms, created by water currents. Larger scale ripples are seen along the southern border of the complete mosaic (Figure 3-103). The ripple crest orientation is variable, but for smaller scale ripples this is generally northwest-southeast and for the larger scale ripples this is northeast-south-west.

In contrast to the textured appearance of exposed bedrock and sedimentary bed forms, other areas of the seafloor have a smoother, uniform appearance with high or low intensity (Low intensity and High intensity categories). In accord with the known backscatter signature of seafloor types, the Low intensity category would correspond to featureless fine sediments and High intensity category would correspond to featureless coarse sediments.
Figure 3-104. Map of seafloor bottom type example locations displayed as red boxes overlaying side-scan sonar mosaics.
Figure 3-105. Examples of side-scan sonar image data at 10 locations in the mosaics with preliminary interpretations.
To test the validity of the bottom type interpretation, vibrocore sediment samples acquired in 1998 were compared with side-scan sonar data (Figure 3-106). At each vibrocore sample location, the top sediment description determined from core photographs and recorded direct observations was matched to acoustic backscatter, classified by eye as Low intensity, Mid intensity and High intensity. Low and High intensity correlate to examples shown in Figure 3-105. The results of this comparison are shown in Table 3-3. All High intensity backscatter classification correlate with either sand or gravel, Mid intensity backscatter correlates with sand (with additional components of gravel and, in the case of core 51, silt) and Low intensity backscatter correlates with clay, sand and gravely sediment.

Core samples dominated by either gravel (cores 1 and 3) or clay (core 4) are correctly associated with High and Low intensity backscatter respectively. However, the presence of sand introduces a degree of uncertainty into the classification, which sees representation in all three backscatter categories. This analysis defines the limits of using vibrocores for side-scan sonar ground truthing. Sampling techniques targeting the seafloor only combined with detailed particle size distribution analysis of the material and in-situ photographs will provide more suitable comparison data.
1998 vibrocore interpretation

Topmost sediment type
- Red: Gravel
- Orange: Sandy Gravel
- Yellow: Gravelly Sand
- Green: Sand
- Blue: Coastline

Figure 3-106. Location map for correlation of acoustic backscatter with vibrocore data.
Table 3-3. Comparison of vibrocore sediment samples and backscatter classification. Low intensity backscatter is highlighted with red, mid intensity with orange and high intensity with yellow.

<table>
<thead>
<tr>
<th>Core number</th>
<th>Backscatter classification</th>
<th>Sedimentological description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High intensity</td>
<td>Gravel</td>
</tr>
<tr>
<td>3a</td>
<td>High intensity</td>
<td>30cm Gravel over clay</td>
</tr>
<tr>
<td>3b</td>
<td>High intensity</td>
<td>30cm Gravel over clay</td>
</tr>
<tr>
<td>4</td>
<td>Low intensity</td>
<td>Clay</td>
</tr>
<tr>
<td>8a</td>
<td>Mid intensity</td>
<td>20cm gravelly sand over clay</td>
</tr>
<tr>
<td>8b</td>
<td>Mid intensity</td>
<td>20cm gravelly sand over clay</td>
</tr>
<tr>
<td>10</td>
<td>High intensity</td>
<td>70cm sand over gravel</td>
</tr>
<tr>
<td>13</td>
<td>High intensity</td>
<td>20cm gravelly sand over clay</td>
</tr>
<tr>
<td>16</td>
<td>High intensity</td>
<td>20cm gravelly sand over clay</td>
</tr>
<tr>
<td>17</td>
<td>Mid intensity</td>
<td>50cm sandy gravel over clay</td>
</tr>
<tr>
<td>22</td>
<td>High intensity</td>
<td>15cm sand over gravel</td>
</tr>
<tr>
<td>24</td>
<td>Low intensity</td>
<td>60cm slightly gravelly sand over clay</td>
</tr>
<tr>
<td>28</td>
<td>Low intensity</td>
<td>20cm sand over clay</td>
</tr>
<tr>
<td>33a</td>
<td>High intensity</td>
<td>20cm sand over gravel</td>
</tr>
<tr>
<td>33b</td>
<td>High intensity</td>
<td>20cm sand over gravel</td>
</tr>
<tr>
<td>51</td>
<td>Mid intensity</td>
<td>20cm silty sand over clay</td>
</tr>
<tr>
<td>52</td>
<td>Low intensity</td>
<td>15cm sandy gravel over clay</td>
</tr>
<tr>
<td>72</td>
<td>High intensity</td>
<td>3m silty coarse sand</td>
</tr>
</tbody>
</table>

3.4.3.3 Mapping Exposed Bedrock

Following the preliminary interpretation in the previous section, the Exposed bedrock category was mapped across all side-scan sonar data (Figure 3-107). This category was chosen for mapping because its distinctive acoustic signature makes a good candidate for reliable identification and the spatial distribution of bedrock is of key importance to marine archaeological investigations. In particular, resistive rock formations constrain river movement and so their location can be used to infer the location of palaeo river valleys, the potential archaeological site under investigation in this study. Further, bedrock outcrops in themselves would have afforded shelter to ancient peoples and could be a location for primary archaeological finds.
Figure 3-107. Interpreted bedrock outcrop distribution from side-scan sonar data overlayed on merged single and multi-beam bathymetry.

In the northern mosaic, the mapped Exposed Bedrock category covers a small proportion of the total mosaic area and is limited to the southwestern half of the area. Exposed Bedrock is identified on several of the side-scan swaths and, when compared to bathymetry data underlying the interpretation, these outcrops appear to correlate with high relief, linear features on the seafloor. Two of these features can be identified, running in a northwest-southeast orientation. They have a sinuous morphology and are discontinuous with a large gap in the central part of the mosaic area. In the
southwest corner, another high relief feature is correlated with the Exposed Bedrock category. In contrast to the features identified above, this is broader and bends tightly.

In the southern mosaic, the Exposed Bedrock category distribution has an irregular morphology in contrast to the linear morphology to the north. The side-scan sonar interpretation correlates with a high relief feature identified from bathymetry data. This feature is one of several that are oriented northwest - southeast located at the boundary of relatively shallow water to the north and deeper water to the south.

The Exposed Bedrock category correlates well with locally high relief features identified in bathymetry data. This observation is to be expected as hard, resistive outcropping bedrock structures will stand high from the seafloor and have a characteristic acoustic backscatter signature. However, not all high relief features on the seafloor are identified as Exposed Bedrock by side-scan sonar imagery, and this suggests that these are associated with sediment at the seafloor. In this way, side-scan sonar adds to the accuracy of a geological interpretation of bathymetry data by providing an independent confirmation of seafloor character.
3.5 REVIEW OF ARCHAEOLOGICAL RESOURCE ASSESSMENT METHOD

3.5.1 Review of Geophysical Methodologies

3.5.1.1 Contribution by Multibeam Swath Sonar

“It seems apparent that an approach that integrates the best available evidence concerning prehistoric settlement patterns, geological history and landform preservation potential, has the ability to locate buried archaeological deposits on the offshore continental shelf”. (Pearson et al 1986).

Late Quaternary changes in sea level drowned many shelf areas worldwide. Patterns of human habitation are structured by the presence of water. The post-glacial submergence of these coastal plain areas has hidden much of the human record from glacial times. The use of high-resolution multibeam survey methods in archaeological resource assessments is a new and rapidly developing technique. A survey performed off the Queen Charlotte Islands, Western Canada (Fedje & Josenhans, 2000) proved that through mapping and interpreting the palaeolandscape, it is possible to subsequently recover archaeologically significant artefacts, in this case a flint tool. Although this find was perhaps a little exceptional, there are several other studies that have relied on marine geophysical survey techniques to provide the spatial context in which to evaluate the archaeological resources of the area (Pearson et al, 1996).

In the onshore environment, topography defines human habitat. The Arun palaeofluvial system created variability in the terrain that provided locations suitable for shelter, materials, and food harvesting or production. The presence of a topographic palaeovalley complex rather than an infilled system is significant because the possibility of finding archaeological material on the seabed is far higher. Diving or ROV surveys can then be targeted to explore the potential site, thus vastly increasing the chances of recovering artefacts.

The primary technique available for accurately mapping the topography or morphology of the seafloor is multibeam sonar. Multibeam offers complete coverage of the seabed so that within the resolution limits of the system, it is possible to gain a complete understanding of the present submerged topography. Unfortunately, the topography imaged using multibeam has been modified to an extent by terrestrial, transitional and marine processes since the time of possible occupation. The amount of modification is often something that can only be understood by investigating the sub-surface evidence from seismic data, but the identification and interpretation of morphological features can help to solve this problem. In this study, we have identified from the multibeam data features that fit into the following four categories:

- Resistant bedrock morphological that have not been influenced by fluvial or marine processes
- Bedrock morphological features that have been eroded by predominantly fluvial processes
- Sedimentary features that have been formed by fluvial processes
- Sedimentary features that have been formed or modified by marine processes

The spatial distribution of these units is in some cases very clear, e.g., fluvial incision into a bedrock outcrop, and in other cases the distinction is very hard to make, e.g., is a sediment mound a tidal barform or a remnant fluvial terrace? The topographic evidence for these features is something that becomes surprisingly obvious from the multibeam data even without the aid of sub-bottom profiles. The texture, geometry, and distribution of seabed features as mapped by multibeam allows, in many cases, a reasonable assumption to be made about the underlying geology and therefore the likely form of the palaeo-landscape. An accurate reconstruction of the palaeo-landscape based on the above factors is the key to understanding where occupation may have occurred, and where archaeological resources may have been preserved in-situ or deposited.

The palaeotopography of the area of the palaeo-Arun valley mapped using multibeam has been partially preserved during the marine transgression, and this has meant that the multibeam has worked as an important tool in reconstructing the palaeo-landscape. With an accurate model of where the fluvial landscape is preserved, it is possible to locate points of highest archaeological potential.

Potential archaeological sites buried in sediment are harder to predict from multibeam, as a detailed understanding of the stratigraphy is required for this. However, the multibeam survey is still helpful in identifying for example channel margins against bedrock. Singlebeam data from the inshore areas where the palaeo-Arun valley is completely infilled helped locate the valley due to the difference in erodability of the bedrock as compared to the valley fill. A multibeam survey would have helped refine the margins of the palaeovalley more precisely before detailed sub-bottom profiler data is acquired. The seismic data provides little information about the spatial variability of the seabed, but, by imaging the buried stratigraphy, it can prove or disprove the inferred geology, as well as imaging buried features that have no topographic expression. The integration of multibeam data with seismic profiles has been an integral part of the study, and has functioned primarily in the identification of sites which may be buried in sediment. It is therefore essential that the depositional history of a potential study area is understood prior to undertaking a multibeam survey.

The modelling and interpretation methodology is a critical element in extracting maximum benefit from the multibeam data for archaeological evaluation. The ability to artificially sun-illuminate a bathymetric grid gives an excellent perspective of topographic features, and the quantitative analysis of cross profiles supports study and hypothesis testing about the geomorphology. Combining the bathymetric model with backscatter mosaics helps to more accurately discriminate the seabed type, and isolate archaeologically significant boundaries in sedimentary and bedrock units. A more detailed discussion of the contribution of acoustic backscatter is discussed below and the
recommendations for applying the techniques to archaeological investigations are described in chapter 3.4.2.3.

3.5.1.2 Contribution by Acoustic Backscatter Seafloor Imaging

The interpretation of acoustic backscatter images is an established methodology for marine archaeological investigations in the case of nautical finds (ie. ship wrecks) on the seafloor (Quinn et al., 2000). However, rather than nautical artefacts, this study is concerned with former human settlements on the palaeo land surface, now submerged as the seafloor. Here, acoustic imagery is used to map physical characteristics of the seafloor surface, a valuable dataset for assessing potential for primary finds and adding to our overall knowledge of the palaeo landscape.

Distinctive seafloor textures can be readily inferred from acoustic backscatter images: sedimentary bedforms (ripples), dredging activity and exposed rock. Mapping the spatial distribution of exposed bedrock on the seafloor is one of the key results of acoustic image interpretation. In particular, the interpretation acts to confirm, by independent means, that high relief features seen in mutibeam bathymetry images are bedrock ridges. These ridges are of fundamental importance to the archaeological assessment in terms of locating palaeo river valleys and identifying human shelter sites as explained in the previous section. Dredged areas will have been considerably disrupted with a loss of internal structure, possibly reducing their archaeological value. Contemporary sediment ripples provide information on the modern hydrodynamic regime and the seafloor, which may be useful for planning diver surveys or assessing the erosion risk of important sites.

A further result of acoustic image interpretation is the discrimination of sediment type, which is not possible with bathymetry data alone. Sediment type forms a body of evidence to distinguish ambiguous sedimentary features identified in multibeam bathymetry. Initial ground truthing indicates that clay correlates with low intensity backscatter and coarse gravel correlates with high intensity backscatter. However, sand is represented by all backscatter intensity levels. To gain a detailed picture of how sediment type relates to backscatter intensity, more ground truthing by surface sediment sampling and in-situ photography is needed.

Acoustic backscatter imaging as a survey technique is recommended both because of its scientific application and its relative economy. Acoustic backscatter data can be acquired as a secondary dataset simultaneously with other geophysical survey methods. In this study, data was acquired as a bi-product of multibeam bathymetry and from separate side-scan sonar instrumentation. Side-scan sonar equipment was attached to a chirp sub-bottom profiler and in a dedicated fish deployed simultaneously with a boomer sub-bottom profiler. This type of ‘piggy back’ acquisition requires only a minimal incremental cost in equipment hire and configuration time.
3.5.2 **Recommendations for Future Surveys**

### 3.5.2.1 Archaeological Aspects of Multibeam Sonar Surveys

The multibeam survey has proved an outstanding success on the Palaeo-Arun study, giving a unique insight into the complexity of the seabed and interpreted palaeo-landscape. The success can be attributed to several factors related to both the selection of the study area, and the methodology applied in acquiring, processing and presenting the data. The study area chosen for a multibeam survey for prediction of archaeological resources needs to be:

- A site with known links to archaeological evidence – in this case the on-shore Arun and adjacent coastal plains are rich in Palaeolithic artefacts.
- Linked to human occupation and migration patterns such as fluvial or estuarine systems.
- Geologically complex environments with known topography and a local supply of materials such as flints.
- Protected locations, or geomorphic niches, likely to have withstood the marine transgression with a high degree of preservation potential.

Careful analysis of existing data from the English Channel led to the selection of the Arun, but there are several other locations with equal or greater potential off the south coast of England alone. Having the right data to base the site selection on is critical. Shortly after completion of the multibeam survey, the singlebeam data collected by the Maritime & Coastguard Agency for nautical charting purposes was acquired from the United Kingdom Hydrographic Office on a special arrangement. This data covered a broader area spanning from the coastline to the outlet of the Arun, and although it did not have the resolution provided by multibeam, it would have proved extremely useful in locating the area as a prime site. It is recommended therefore that an effort is made to acquire the raw singlebeam sounding datasets digitally from the UKHO as the first method of selecting sites for investigation using high-resolution multibeam.

### 3.5.2.2 Technical Aspects of Multibeam Sonar Surveys

Acquisition of multibeam data on the Arun survey was assisted greatly by having near perfect weather conditions, but there are several factors that are critical to data quality which are the responsibility of the hydrographic surveyor. These are:

- Mobilisation
  - The mountings for all sensors, in particular the pole supporting the sonar head must be extremely rigid to prevent movements that result in corruption of the data. The offsets between the sensors must be measured accurately and applied correctly into the acquisition software.
- Calibration
A full patch test must be performed before, during and after the survey to reliably check the installation biases of the sensors. Suitable seafloor targets (objects or steep slopes) must be located to ensure the calibration can be performed successfully.

- **Positioning**
  - The use of high accuracy (Real-time Kinematic or Differential GPS) must be used to locate the vessel at all times, and the accuracy monitored at ~20 minute intervals. Vertical positioning is also critical and the use of predicted tides should be avoided; a tide gauge or RTK GPS system should be used.

- **Sound Velocity Measurement**
  - In areas of well-mixed coastal waters, at least one SVP dip should be performed per day. In areas of deeper or stratified water this should be increased to 2 or 3 per day.

- **Sonar Operation**
  - The power, gain and range settings of the sonar should be monitored continuously and adjusted for changes in depth, ambient noise and seabed type.

- **Data Logging**
  - The data should be logged in a completely raw state so that all processing can be reversed if necessary, the logging of backscatter data is useful for seabed discrimination, but ideally a towed sidescan sonar should be deployed simultaneously for best results.

- **Coverage**
  - Due to the poor quality of outer beams, swaths should overlap by a minimum of 30%. This gives greater redundancy in the areas of sparse/unreliable data and avoids “artefacts” between swaths. The vessel speed becomes critical to data coverage in deeper water where the ping rate is lower, but in general a survey speed of 5 knots is recommended.

The processing of raw data into soundings, and then a gridded model of the seafloor is as critical to the quality of the end results as the acquisition, and takes considerably longer to do properly than the survey itself. The key considerations are:

- **Software**
  - The use of a specialist multibeam processing package such as Caris HIPS is essential for achieving a high quality result.

- **Applying Motion, SVPs and Tide**
  - After each stage in the processing, the data should be gridded and displayed so that a thorough check on the effect of each processing step is made.

- **Data cleaning**
  - Removing bad data points from a dataset of several billion soundings is a fairly arduous task. The use of statistical filters or cleaning routines is therefore
recommended to speed up the process. Manual editing should only be necessary on areas of complex seafloor, or unusual data.

- **Gridding**
  - The cell-size of the final grid dictates how resolute the data appears, and how much smoothing of random noise takes place. It is recommended that as a rough guide the cell size should be $1/10^{th}$ of the mean water depth.

To interpret the dataset, the use of GIS has proved extremely useful as it allows the manipulation of the dataset into derived layers such as slope maps or shaded relief images. The ability to overlay supporting information such as backscatter mosaics or seismic lines has enabled an integrated approach to data interpretation, as described in chapter 2. The final recommendation would be to explore the data using 3D visualisation software such as IVS Fledermaus from which many of the figures in chapter 3.4 have been taken.

### 3.5.2.3 Side-Scan Sonar Surveys

It is recommended that acoustic backscatter data be acquired as a matter of course during geophysical surveys, particularly with side-scan sonar equipment during the reconnaissance phase. The modest additional cost of this work yields an independent dataset with unique capabilities in determining the physical character of the seafloor. It has been demonstrated that acoustic imagery, particularly when combined with high resolution bathymetry, can provide a valuable insight into palaeo landscapes with real relevance for archaeological investigation. For future surveys specific recommendations are:

- **Equipment choice**
  - Ideally, a dedicated side-scan sonar fish should be used to give the best possible data quality.

- **Configuration**
  - Side-scan sonar instrumentation should be configured according to the primary survey tool’s requirements. Specifically, instrument range should be scaled to survey line separation, with the aim of giving full coverage of the seafloor. With wide line spacing (> 200m) in deeper water (>20m), the low frequency setting could be used to increase the effective range. Ship time should be set aside to test and configure the side-scan sonar instrumentation to give best results with the planned survey geometry. These settings should then be fixed for all subsequent surveys. During this study, instrument settings were changed during surveys, which led to some deterioration in the final side-scan sonar mosaic images.

- **Data logging**
  - It is essential that raw data be recorded for post-acquisition processing.

- **Data processing**
In this study, custom software was used for side-scan sonar data processing, which gave excellent results in the light of variable data quality. For further surveys, the use of a high quality commercial package such as Caris SIPS could be substituted.
3.6 CONCLUSIONS

The Palaeo-Arun is a submerged valley system that despite having been studied in reasonable detail using marine geophysical techniques, has not until recently been fully understood due to the complexity of the morphology and stratigraphy, and the limitations of the mapping techniques employed. The study by Bellamy, 1995 focused primarily on interpreting the sedimentary environment from Industry seismic datasets; the use of multibeam at the time was not widespread and the usefulness of the method was considered questionable. Now however, it is accepted that modern multibeam systems coupled with advances in computer technology, vessel motion sensors, and precise navigation, provide unprecedented data sets with which to investigate the quantitative geomorphology of the seafloor (Gardner et al., 2003). The results from the multibeam survey of the Palaeo-Arun have further proved the usefulness of the technique and demonstrate how little was previously known about the system. The resolution achieved by the multibeam survey of ~20 cm vertically and ~1 m horizontally has surpassed expectation and facilitated a reliable interpretation of the large scale morphology.

Sidescan sonar data has enabled a comprehensive evaluation of the sediment cover, and has yielded some interesting results when merged with bathymetry or vibrocore datasets. The imagery acquired using sidescan gives resolution to decimetre accuracy and is a relatively simple and inexpensive survey method.

The morphological interpretation has been integrated with interpretations of the sub-surface to result in an overall understanding of the palaeo-valley complex and its evolution. The use of this approach has been developed by the multidisciplinary team and has previously been noted as the most effective method for performing this type of investigation (Duncan et al., 2000).

Archaeological assessments in the marine environment rely on both the topographic mapping provided by multibeam, and the sub-bottom profiles provided by the seismic data to establish a framework in which to assess the palaeo-environment. The geophysical methods enable the archaeologist to locate sites in the context of the depositional system and understand the dynamics of the environment. This will lead to far more reliable predictions of potential find sites, and allow marine archaeologists to work on a “landscape scale” rather than localised areas of seafloor explored by scuba divers.

The recommendations chapter outlines the lessons learned from this study and how future studies can be optimised to gain maximum benefit from using multibeam on archaeological site investigations. New technological developments in positioning, sonar, and computing are likely to further increase the accuracy and reduce the expense of multibeam surveys over the next few years. It is anticipated
therefore that multibeam will become a standard technique employed by geo-archaeologists working on future projects in the marine environment.
3.7 REFERENCES


