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The Creation Of High Resolution Bathymetry Grids for the Lord Howe Island Region

Richard Mleczko, Stephen Sagar, Michele Spinoccia and Brendan Brooke

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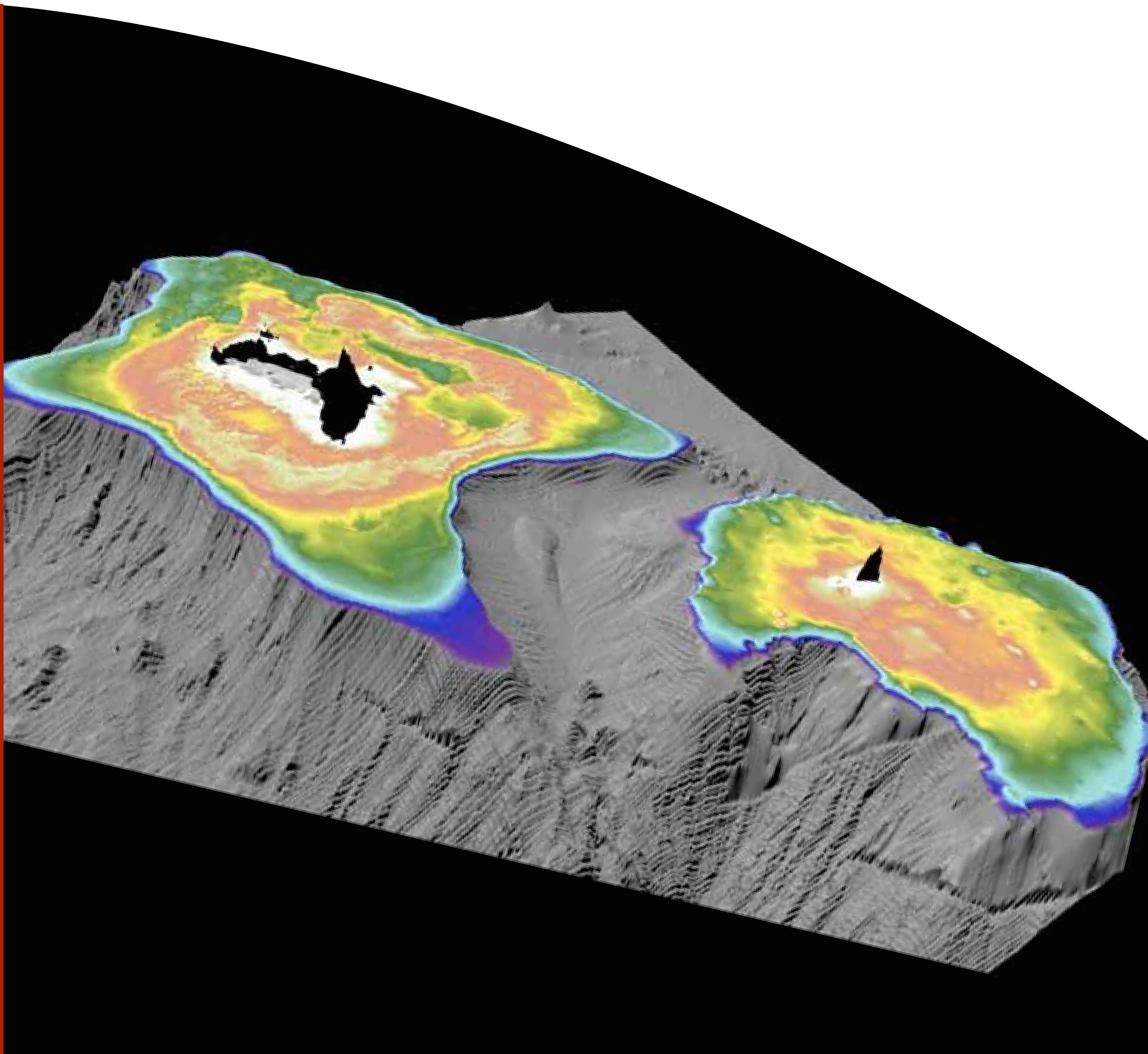

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

The Creation of High Resolution Bathymetry Grids for the Lord Howe Island Region

GEOSCIENCE AUSTRALIA
RECORD 2010/36

by

Richard Mleczko, Stephen Sagar, Michele Spinoccia and Brendan Brooke.

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Executive Summary

Lord Howe Island lies approximately 580 km off the northern coast of New South Wales. It is a volcanic island with a shallow (20 – 120 m) shelf; a fringing coral reef lies on its western shore.

Detailed bathymetric data are needed to better understand the marine environment. These data provide useful insights into physical processes that act on the seabed and reveal the location of different types of habitats, especially relict reef structures. The final bathymetric models will enable the modelling of tsunami as these interact with the shelf, reef and the coast.

This report describes the methodology employed in creating detailed bathymetric grids of the Lord Howe Island region. It covers data collation, quality control and gridding. Descriptions are provided for each dataset employed, the methods used to integrate the different datasets and the attributes of the new bathymetry models.

Four new bathymetry grids are presented, including grids that integrate bathymetry with the island's topography.

1. Introduction

Australia's marine estate is one of the largest and most diverse in the world and for much of it we have very limited knowledge of the physical environment, major marine ecosystem processes and patterns of biological diversity. Obtaining and collating detailed bathymetric data is an essential early step along the path of better understanding the marine environment. Models of seabed morphology derived from these data provide useful insights into the physical processes acting on the seabed and the location of different types of habitats. For Lord Howe Island, these data are required by the Marine Biodiversity Hub, which is part of the Commonwealth Environment Research Facilities (CERF) Program. The data are used to map seabed geomorphology as a means of identifying major seabed processes and habitats, especially relict reef structures, and to measure how well physical seabed properties act as surrogates of patterns of seabed biodiversity. Lord Howe Island is a useful site to study in detail because it provides an example of a mid-ocean volcano and carbonate shelf that likely experiences erosional and depositional processes and exhibits patterns of benthic biodiversity typical of other remote volcanoes and shallow shelves in the Australian marine estate (e.g. Queensland Plateau, Norfolk Is).

Another important application of detailed bathymetric data is the modelling of tsunami as they interact with the shelf, reef and coast. Hydrodynamic equations used in tsunami modelling in the far field are insensitive to small changes in the earthquake rupture model, however, small changes in the bathymetry of the shelf and nearshore can have a dramatic effect on model outputs. Therefore, accurate, detailed bathymetric data are essential. The earthquake and tsunami generated by the Puysegur subduction zone just south west of New Zealand's south island prompted the Bureau of Meteorology to issue a tsunami warning for the east coast of Australia, including Lord Howe Island (BOM, 2009). The collation of all available bathymetric data for the island and generation of a detailed seabed surface model will enable improved modelling of tsunami interaction with the Lord Howe Island environment.

Lord Howe Island (31^0 33' S, 159^0 05' E) lies approximately 580 km off the northern coast of New South Wales in the northern Tasman Sea. It is a volcanic island that rises 860 m above sea level; a shallow (20 – 120 m) shelf surrounds the island and a coral reef fringes the island's western shore. The island and neighbouring islets lie at the southern end of the Lord Howe Seamount chain, at the southern latitudinal limit to coral reef growth (Woodroffe et al., 2006). Lord Howe Island and adjacent Balls Pyramid are part of the same volcano and comprise basalts that erupted around 7 million years ago (McDougall et al., 1981).

This report provides a detailed description of the diverse datasets that were collated to produce the new bathymetric grids. The grids cover the nearshore and shallow shelf that surrounds the island, the Lord Howe submarine volcano, and the broader area of the western margin of the Lord Howe Rise that includes Lord Howe Island and a number of seamounts. Maps of data distribution and three dimensional seabed surface models are provided for each of these areas.

2. Existing Bathymetry Grids

WHAT IS AVAILABLE?

There are many publicly available bathymetry grids (Marks and Smith, 2006) but none dedicated to the Lord Howe region. Subsets of four global or large regional grids in this area (158.13° E to 160.2° E and 30.63°S to 32.6°S) are discussed and compared.

The Australian Bathymetry and Topography grid

In 2005 Geoscience Australia (GA) released its 250 metre (9 sec of arc) grid of the Australian region. The grid in this region was based on limited datasets, and chart data from the Australian Hydrographic Service (AHS) were not included. A full explanation of the datasets and the construction of this grid can be found in Webster (2005). The 2009 GA grid (Whiteway, 2009) is not compared here as the grids from this work went into that grid. An extract of the model that covers the Lord Howe region is shown in Figure 1.

Features of the Geoscience Australia 250 m grid are:

- Four seamounts are identified, in addition to the larger Lord Howe volcano.
- Islands in the Lord Howe Island group are incorrectly located.
- There is some level of detail in the representation of the flanks of the Lord Howe volcano.
- There is an erroneous deep hole on the south of the volcano region.

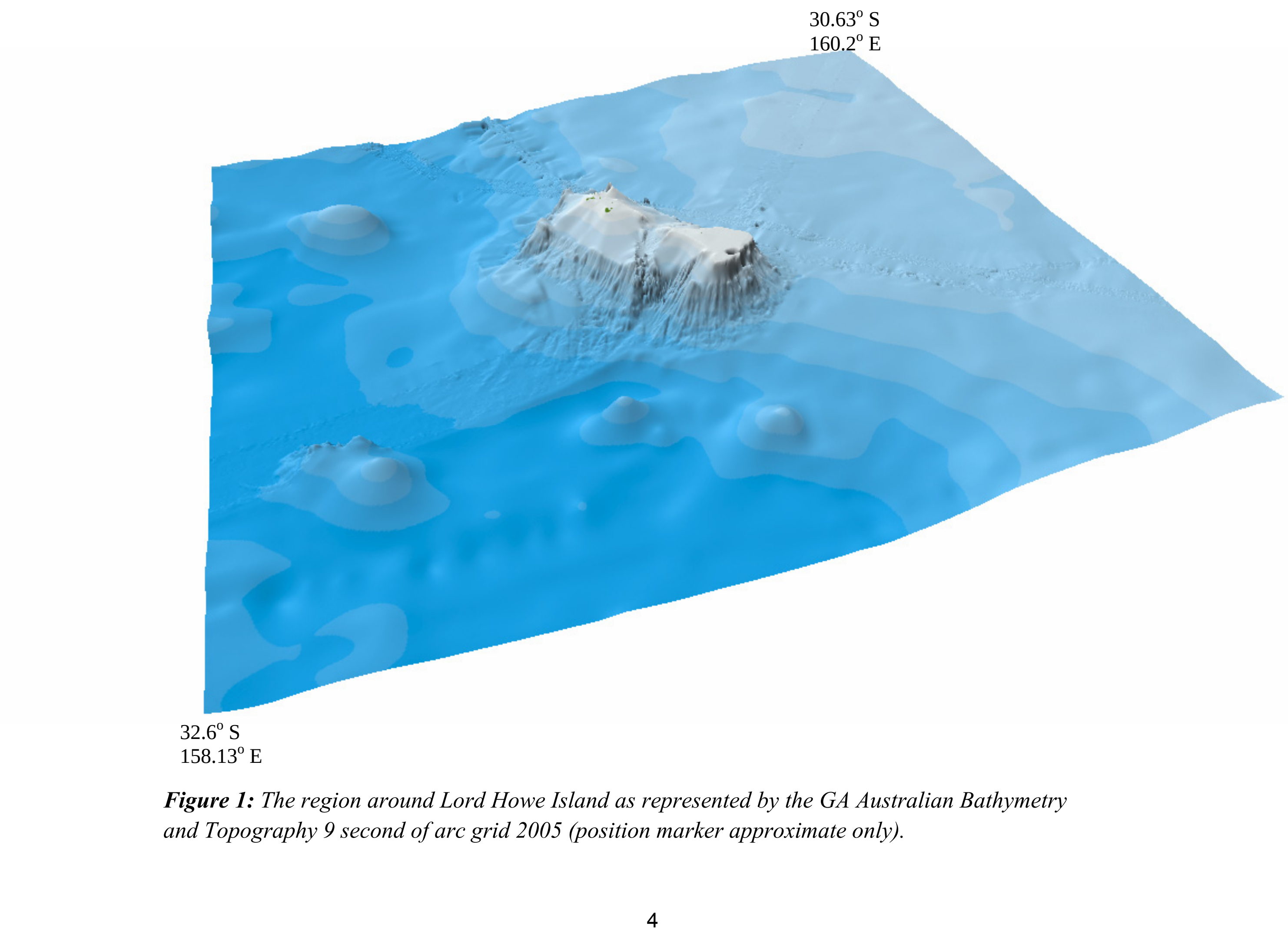


Figure 1: *The region around Lord Howe Island as represented by the GA Australian Bathymetry and Topography 9 second of arc grid 2005 (position marker approximate only).*

Digital Bathymetry Database 2 minute (DBDB2) grid

The DBDB2 grid is a 2 minute of arc global bathymetry and topography data grid. It was developed by the US Naval Research Laboratory (NRL) and is based on the earlier DBDB5. Global topography from satellite altimetry and ship depth soundings were used in deep water as well as data from GA's 2002 Australian Bathymetry and Topography grid. More information on the construction of this global grid can be found at http://www7320.nrlssc.navy.mil/DBDB2_WWW/. An extract of the model that covers the Lord Howe region is shown in Figure 2.

Features of the DBDB2 model for the Lord Howe Island region are:

- Four seamounts are identified, in addition to the larger Lord Howe volcano.
- Islands in the Lord Howe Island group are incorrectly located.
- There is a lack of detail in the representation of the Lord Howe volcano.

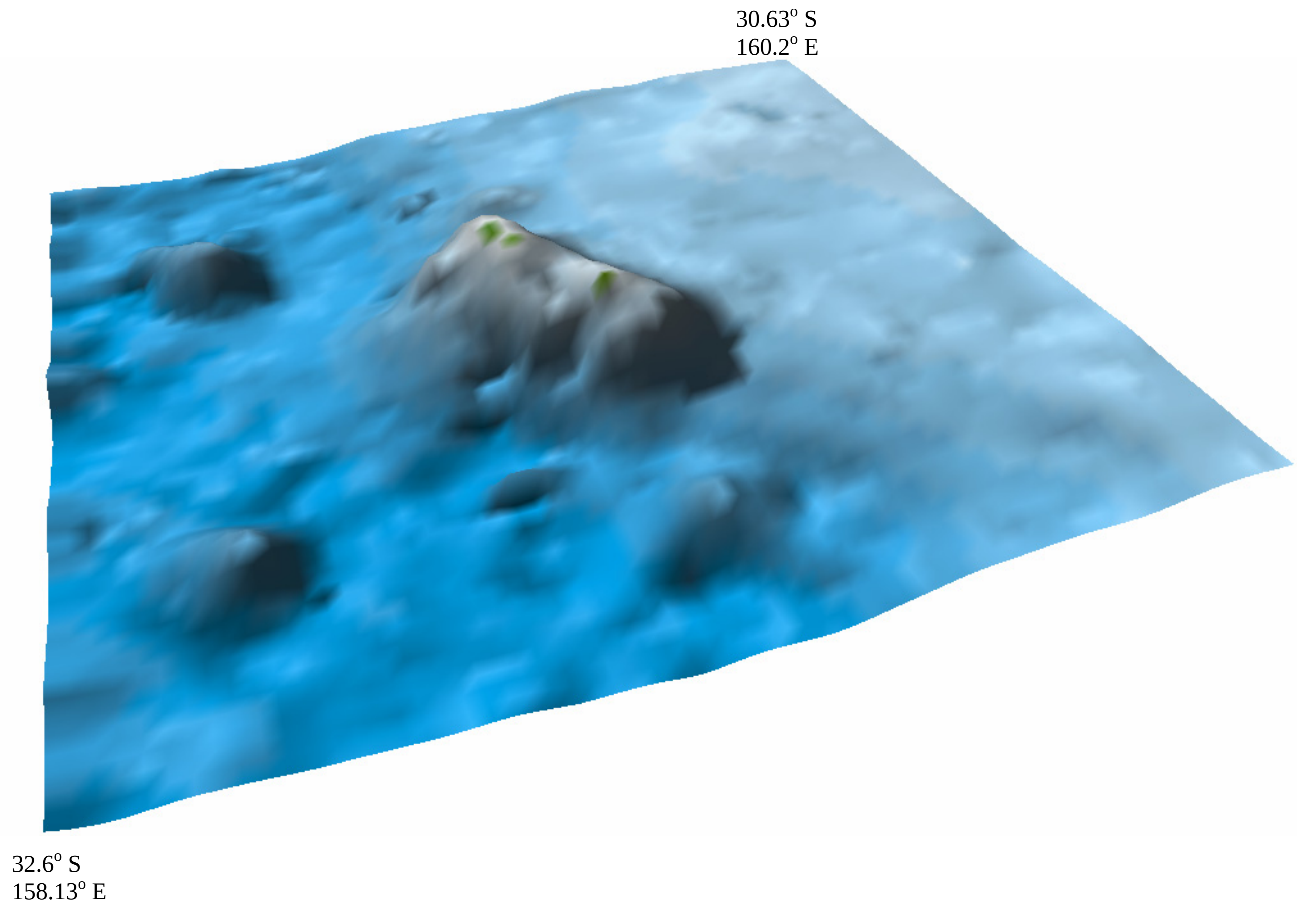


Figure 2: *The region around Lord Howe Island as represented by the DBDB2 2 minute of arc grid (position marker approximate only).*

Earth Topography 1 minute (ETOPO1) grid

The ETOPO1 grid is a 1 minute of arc global bathymetry and topography data grid. Data for this grid are derived from sea-surface altimetry measurements, ocean soundings, Space Shuttle Radar Topography Mission 30 minute elevation data (SRTM30) and the 30 minute Global Topography dataset (GTOPO30). An extract of the model that covers the Lord Howe Island region is shown in Figure 3. A full description (http://www.ngdc.noaa.gov/mgg/global/etopo1sources.html) of the grid can be found at the link.

Features of the ETOPO1 model for the Lord Howe Island region are:

- Three seamounts are identified, in addition to the larger Lord Howe volcano.
- Islands in the Lord Howe Island group are incorrectly located.
- There is a lack of detail in the representation of the Lord Howe volcano.

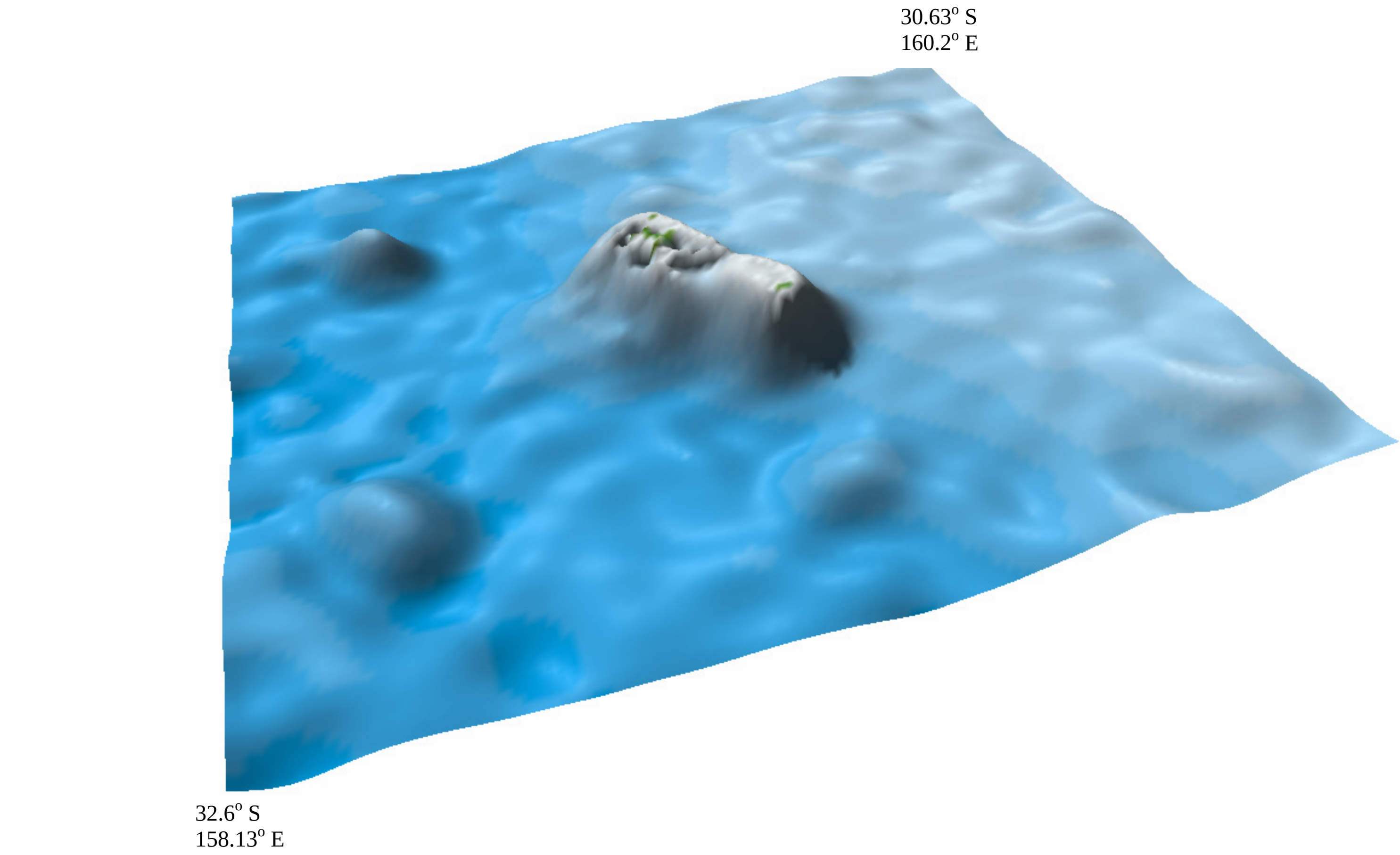


Figure 3: *The region around Lord Howe Island as represented by the ETOPO 1 minute of arc grid (position marker approximate only).*

General Bathymetric Chart of the Oceans (GEBCO) grid

The GEBCO grid is a 1 minute of arc global bathymetry and topography data grid. GEBCO is based on the most recent set of contours contained within the GEBCO Digital Atlas. More information on the construction of this global grid and the GEBCO Digital Atlas can be found at http://www.gebco.net/data_and_products/gridded_bathymetry_data/. An extract of the model that covers the Lord Howe region is shown in Figure 4.

Features of the GEBCO model for the Lord Howe Island region are:

- Three seamounts are identified, in addition to the larger Lord Howe volcano.
- Islands in the Lord Howe Island group are incorrectly located and are too large.
- There is a lack of detail in the representation of the Lord Howe volcano.
- There is a missing seamount in the south compared with the other grids.

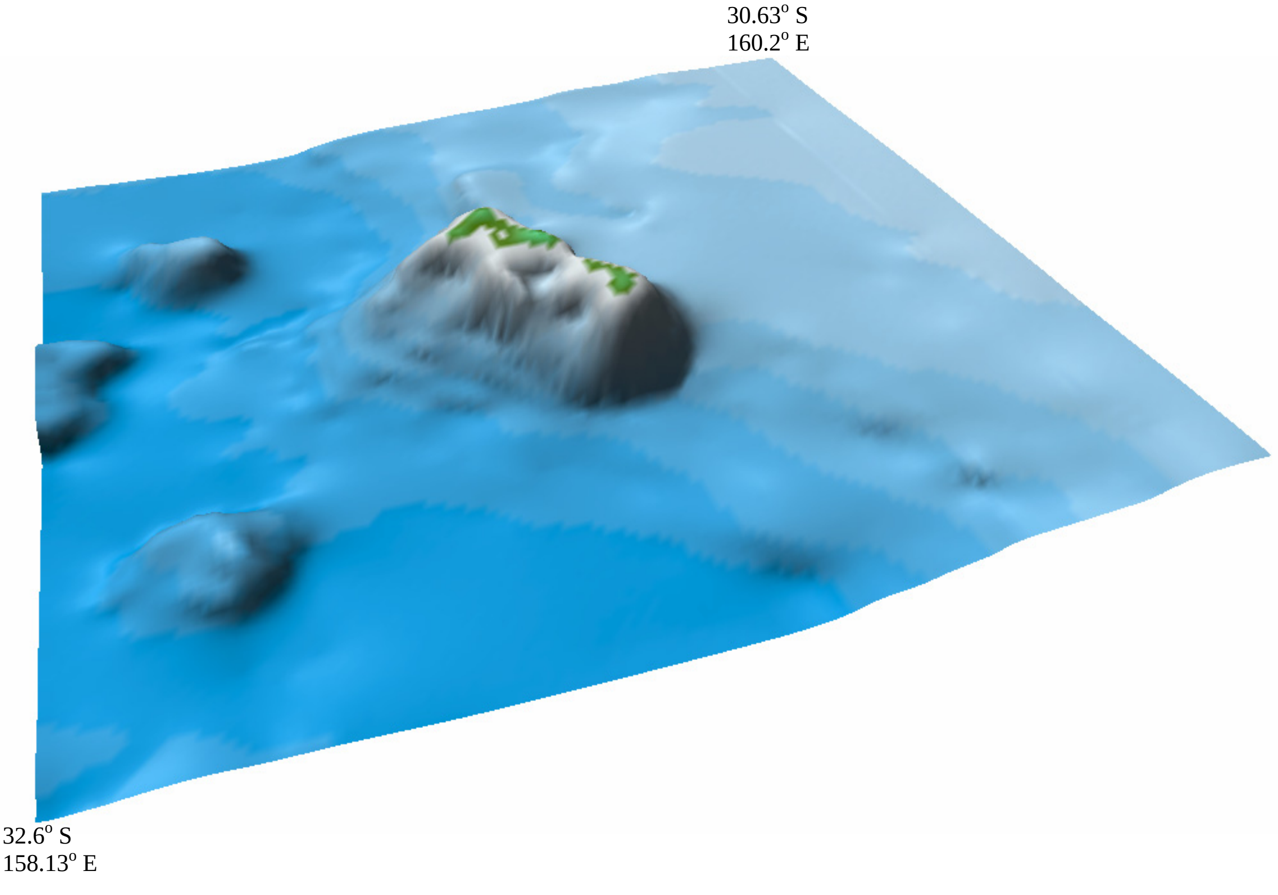


Figure 4: *The region around Lord Howe Island as represented by the GEBCO 1 minute of arc grid (position marker approximate only).*

COMPARISON OF THE FOUR GRIDS

The Lord Howe Island region as represented by the global and Australian bathymetry grids are shown in Figure 5.

Major differences in the representation of the Lord Howe Island region by the four datasets include:

- Only the GA grid has detail on the volcano.
- The number and size of seamounts differs greatly.
- The location and size of the land component differs greatly.

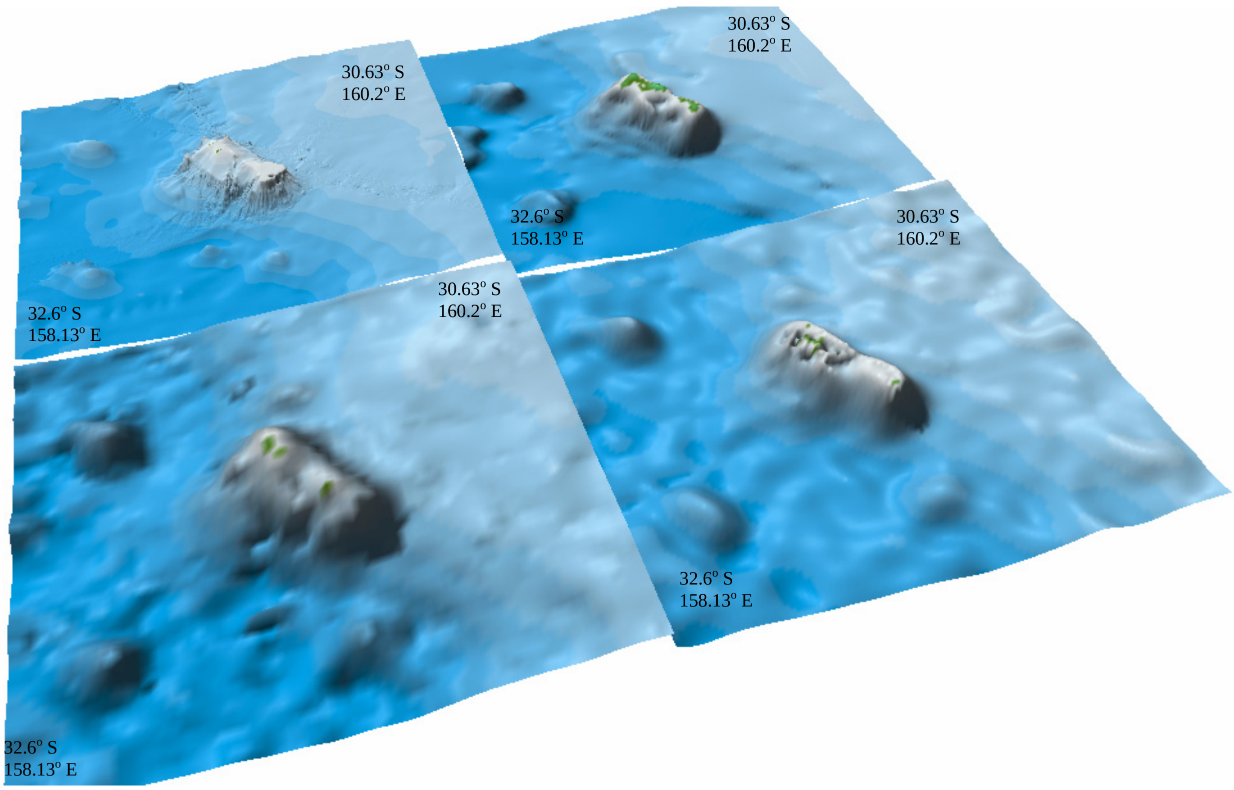


Figure 5: *Comparison of 4 widely used bathymetry grids. Clockwise from the top left: the GA grid, GEBCO, ETOPO1, and DBDB2 (position markers approximate only).*

Dataset Discussion

All four grids were produced using relatively sparse data. The Australian grid seems to be the most accurate, largely due to its higher resolution through the incorporation of more survey data, including multibeam sonar bathymetry data. However, even the Australian grid is heavily interpolated on the upper portion of the Lord Howe volcano due to the low density of data in this shallow area. The ETOPO1 grid appears 150 m too shallow when compared to the other grids and actual survey soundings.

There is also inconsistency in the positioning of the seamounts and islands. The purpose of this study is to improve on the Australian bathymetry grid in this area with the inclusion of new bathymetric data, topographic data and a thorough assessment of the quality of the data employed.

3. Available Data

BATHYMETRIC DATA

A review of existing bathymetric data holdings at Geoscience Australia and a search for other bathymetric datasets that cover the Lord Howe Island region was undertaken. Only surveys that fell within the area bounded by the coordinates 158.15^o to 160.35^o E and 30.65^o to 32.85 ^{o} S were considered (Table 1). Basically four data types were found: singlebeam echosounder, multibeam echosounder (swath), satellite derived bathymetry and laser airborne depth sounder (LADS, also known as LIDAR). The history and characteristics of each dataset are described below.

Table 1: Lord Howe region bathymetry

SURVEY NAME	VESSEL NAME	DATA TYPE	SOURCE INSTITUTION*
"AHS Chart"	unknown	chart	AHS
"AHS LADS"	unknown	LADS	AHS
Sonne 7	R/V Sonne	echo sounder	BGR
Sonne 36A	R/V Sonne	echo sounder	BGR
FR01/97	R/V Franklin	echo sounder	CSIRO
FR12/98	R/V Franklin	echo sounder	CSIRO
TAN0308 - NORFANZ	R/V Tangaroa	multibeam	CSIRO
SS0906	R/V Southern Surveyor	multibeam	CSIRO
SS0608	R/V Southern Surveyor	multibeam	CSIRO
SS2009 T02	R/V Southern Surveyor	multibeam	CSIRO
GA 12	M/V Hamme	echo sounder	GA
GA 14	M/V Lady Christine	echo sounder	GA
GA 15	M/V Lady Christine	echo sounder	GA
GA 77	R/V Rig Seismic	echo sounder	GA
GA 222 – AUSTREA 1	N/O L'Atalante	multibeam	GA
TAN0713	R/V Tangaroa	multibeam	GA
"Satellite data"	Quick Bird satellite	derived bathy.	GA
ETOPO1		grid	NGDC
VI49	M/V Vityaz	echo sounder	NGDC
DME06	M/V Dmitrij Mendeleev	echo sounder	NGDC
19920013	HMY Britannia	echo sounder	NGDC
EW9202	R/V Maurice Ewing	multibeam	NGDC
"CEEDUCER"	Small unknown dinghy	echo sounder	UOW

*AHS=Australian Hydrographic Service, BGR=Bundesanstalt für Geowissenschaften und Rohstoffe, CSIRO=Commonwealth Scientific and Industrial Research Organisation, GA=Geoscience Australia, NGDC= National Geophysical Data Center, UOW= University of Wollongong.

Australian Hydrographic Service data

The Australian Hydrographic Service (AHS) acquires and maintains a large collection of bathymetric data for the purposes of hydrographic surveying. Older data that were collected by using a lead line or single beam echosounder have generally been collated into a series of bathymetric charts; whereas more recent data such as those acquired using multibeam echosounders and airborne lasers are stored in digital data files. The datasets from the AHS are usually supplied in an AHS exchange format (.htf – hydrographic transfer format).

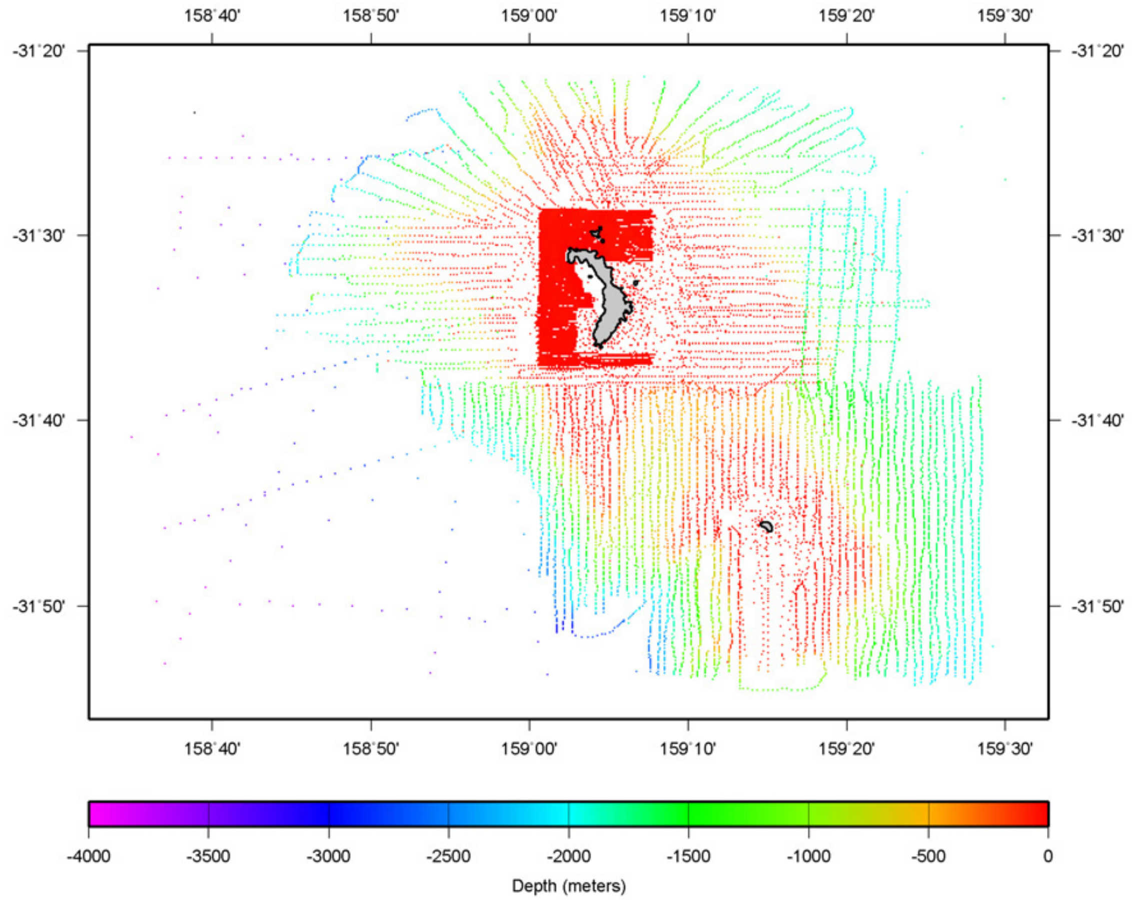


Figure 6: *AHS chart data covering both the Lord Howe Island and Ball's Pyramid region.*

Chart data

In recent years the AHS has undertaken the major task of digitising its large collection of bathymetric charts. Under a memorandum of understanding (MOU) GA now has access to much of these data.

Two independent sets of chart data exist: one collected by the Australian Navy; the other by National Mapping. The digitised values taken from the charts were obtained via the University of Wollongong which maintains a GIS of Lord Howe bathymetry.

The Navy data were collected circa 1959 and the National Mapping data circa 1984. Both datasets have been converted to mean sea level (MSL) and WGS84. Many of the depths when overlaid on chart AUS610 (http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus610&subchart=0) match up, which indicates that the digitising process has been reliably conducted. The stated positional accuracy of the chart is anywhere from 5 m to 500 m. More information on these datasets can be found in Dickson et al. (2002). The data distribution of both the Navy and National Mapping chart data are shown in Figure 6.

Laser Airborne Depth Sounder data

The laser airborne depth soundings (LADS) data were acquired by the Australian Navy in 1997. The data have been converted to MSL and are referenced to the WGS84 datum. The positional accuracy of this dataset is stated as 20 m. More information on this dataset can be found in Dickson et al. (2002). The data distribution is shown in Figure 7.

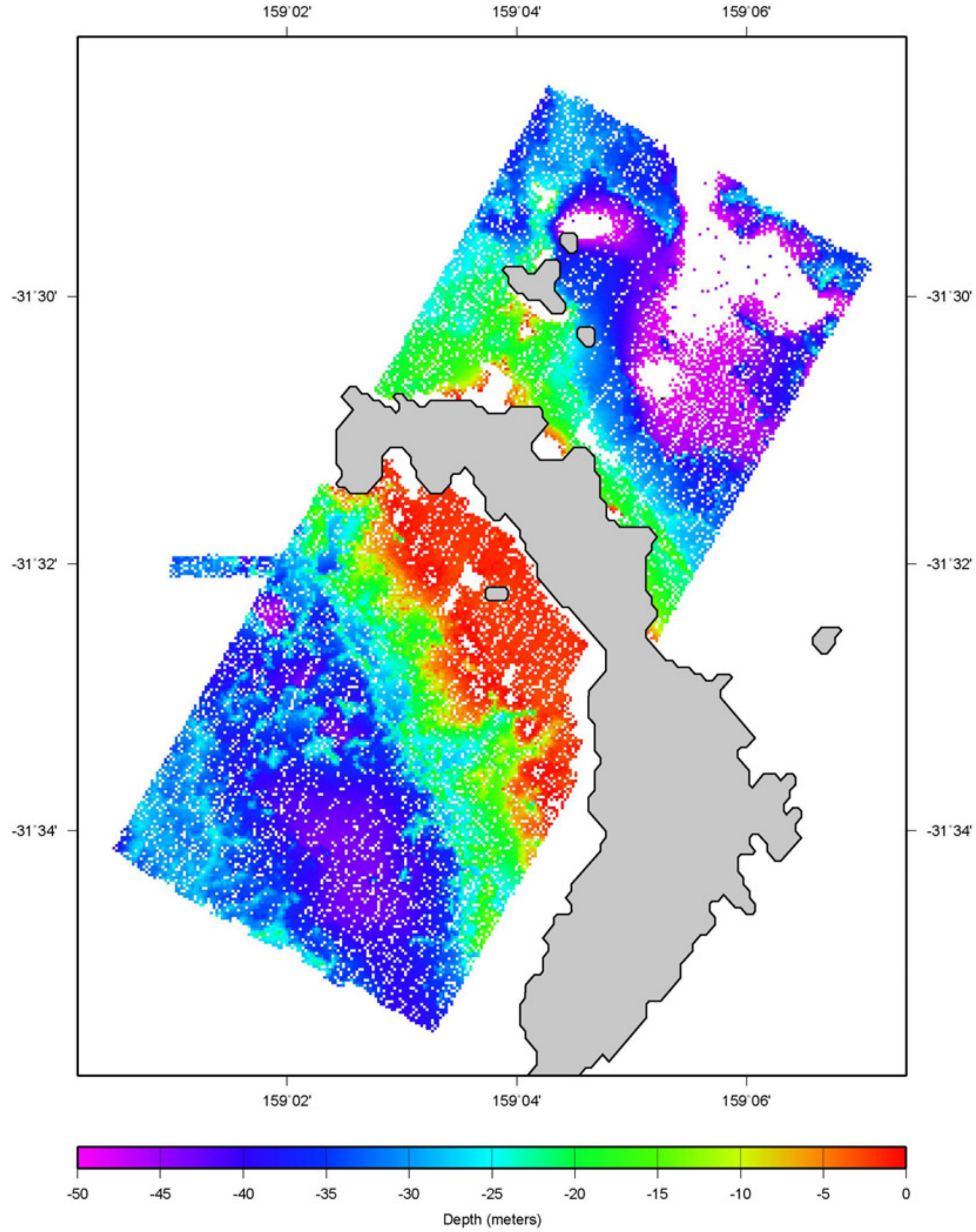


Figure 7: *AHS LADS data showing detail in the reef (used under licence, not to be used for navigation).*

Bundesanstalt für Geowissenschaften und Rohstoffe surveys

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) is the Federal Institute for Geosciences and Natural Resources in Germany. GA holds the data for two R/V *Sonne* surveys undertaken in the Lord Howe region. More information on BGR can be found from the following website: http://www.bgr.bund.de/cln_101/nn_322882/EN/Home/.

Sonne 7 survey data (also known as GA survey 1031)

In 1978 the R/V *Sonne* collected bathymetric data around Lord Howe Island. These data were only acquired in deep water and have not been converted to MSL. The navigation data have been converted from WGS72 to WGS84 and was based on the transit satellite system and the positional accuracy is stated as 500 m. More information on this survey can be found in Wilcox et al. (1981). The data distribution is shown in Figure 8.

Sonne 36A survey data (also known as GA survey 52)

In 1985 the R/V *Sonne* again collected bathymetric data in the Lord Howe Island region. These data were only in deep water and have not been converted to MSL. The navigation was converted from WGS72 to WGS84; it was based on the transit satellite system with additional post-processing. The final positional accuracy is stated as 250 m. More information on this survey can be obtained from Roeser et al. (1985). The data distribution is also shown in Figure 8. From this figure, a criss-cross track near the bottom shows that some multibeam data acquisition was conducted during this survey. A request was made to BGR for access to these data; unfortunately the original field tapes have proved to be unreadable. More information on this survey can be obtained from Roeser et al. (1985).

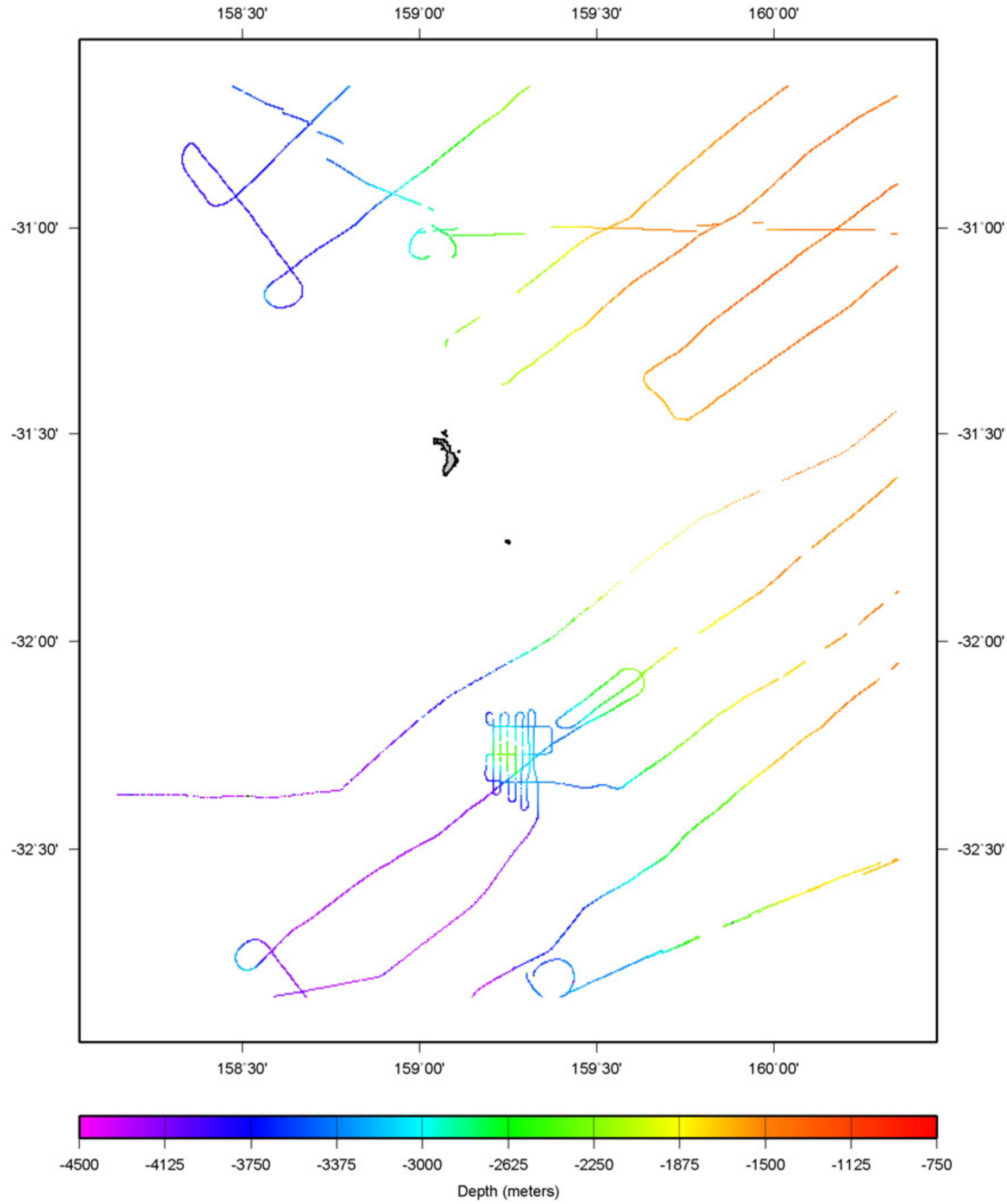


Figure 8: *R/V Sonne data mainly in deep water, note the detailed survey tracks over the seamount in the south.*

Marine National Facility surveys

CSIRO operates the Marine National Facility (http://www.marine.csiro.au/nationalfacility/) and has undertaken five surveys that have acquired bathymetric data around Lord Howe Island using the R/V *Franklin* and the R/V *Southern Surveyor*. The early *Franklin* surveys used a singlebeam echosounder whilst the *Southern Surveyor* surveys employed EM300 multibeam systems.

Franklin Surveys (FR0197 and FR1298)

The R/V *Franklin* surveyed the area in 1997 and 1998. For surveys of this vintage the Global Positioning System (GPS) would have been used for the navigation with a horizontal positional accuracy of 100 m. The data distribution is shown in Figure 9. More details on these surveys can be found at the following links:
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4464.
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5137.

SS0906 (also known as GA 2416)

In 2006 the R/V *Southern Surveyor* collected swath data around Lord Howe Island. The data coverage is shown in Figure 10. Differential GPS (DGPS) was used for the navigation with a horizontal positional accuracy of 2 to 5 m. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=6815.

SS0608 (also known as GA 2461)

In 2008 the R/V *Southern Surveyor* again collected swath data around Lord Howe Island (Figure 11). DGPS was used for the navigation with a horizontal positional accuracy of 2 to 5 m. More details on this survey can be found at the following links:
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=8221.
http://www.marine.csiro.au/nationalfacility/voyagedocs/2008/MNF-SS0608-plan.pdf.

SS2009T02 (also known as GA 2488)

In 2009 the R/V *Southern Surveyor* transited from Noumea to Hobart with the swath equipment turned on. The data coverage is shown in Figure 12. DGPS was used for the navigation system with a horizontal positional accuracy of 2 to 5 m. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=8527.

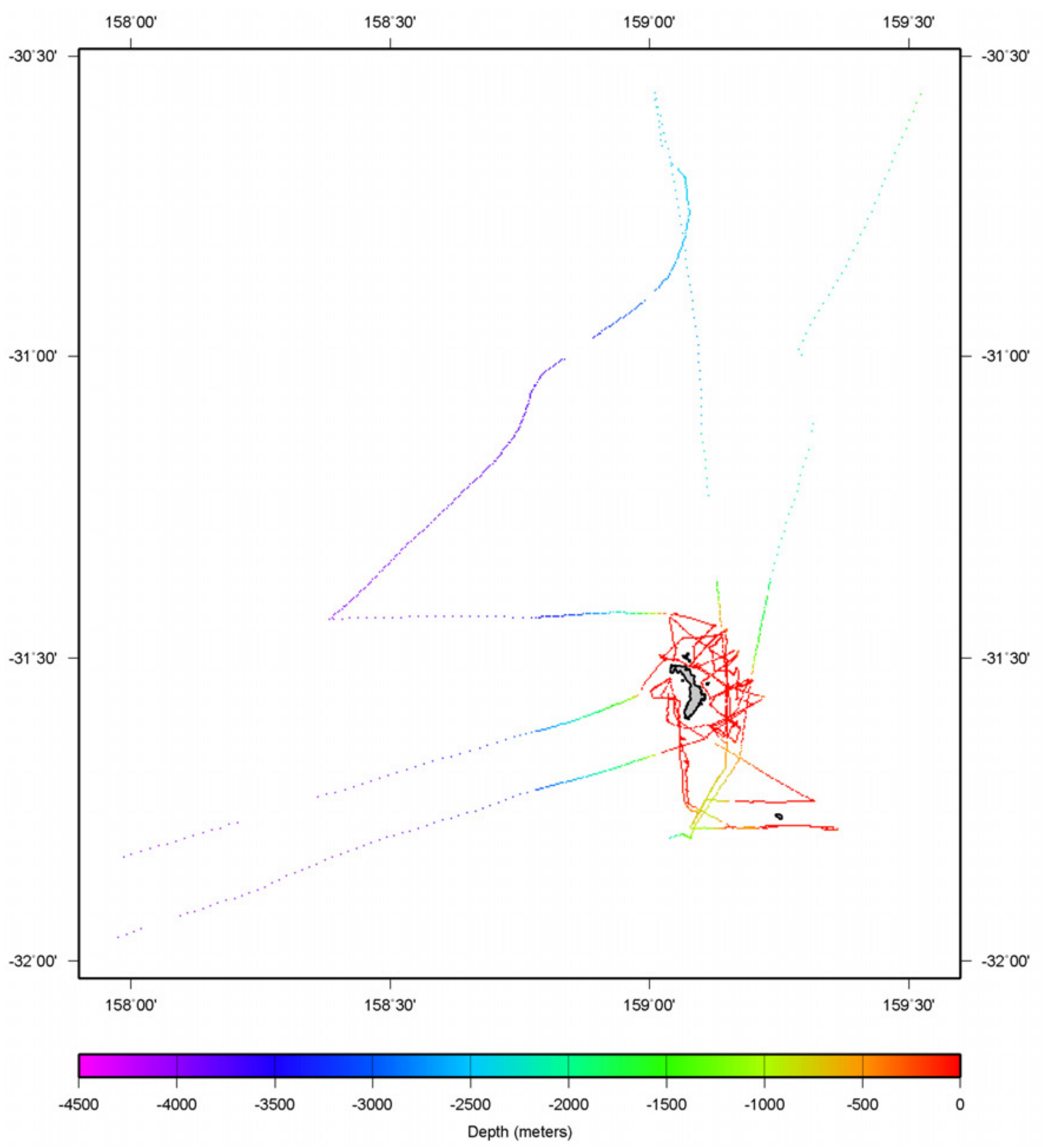


Figure 9: *R/V Franklin data mainly on the plateau.*

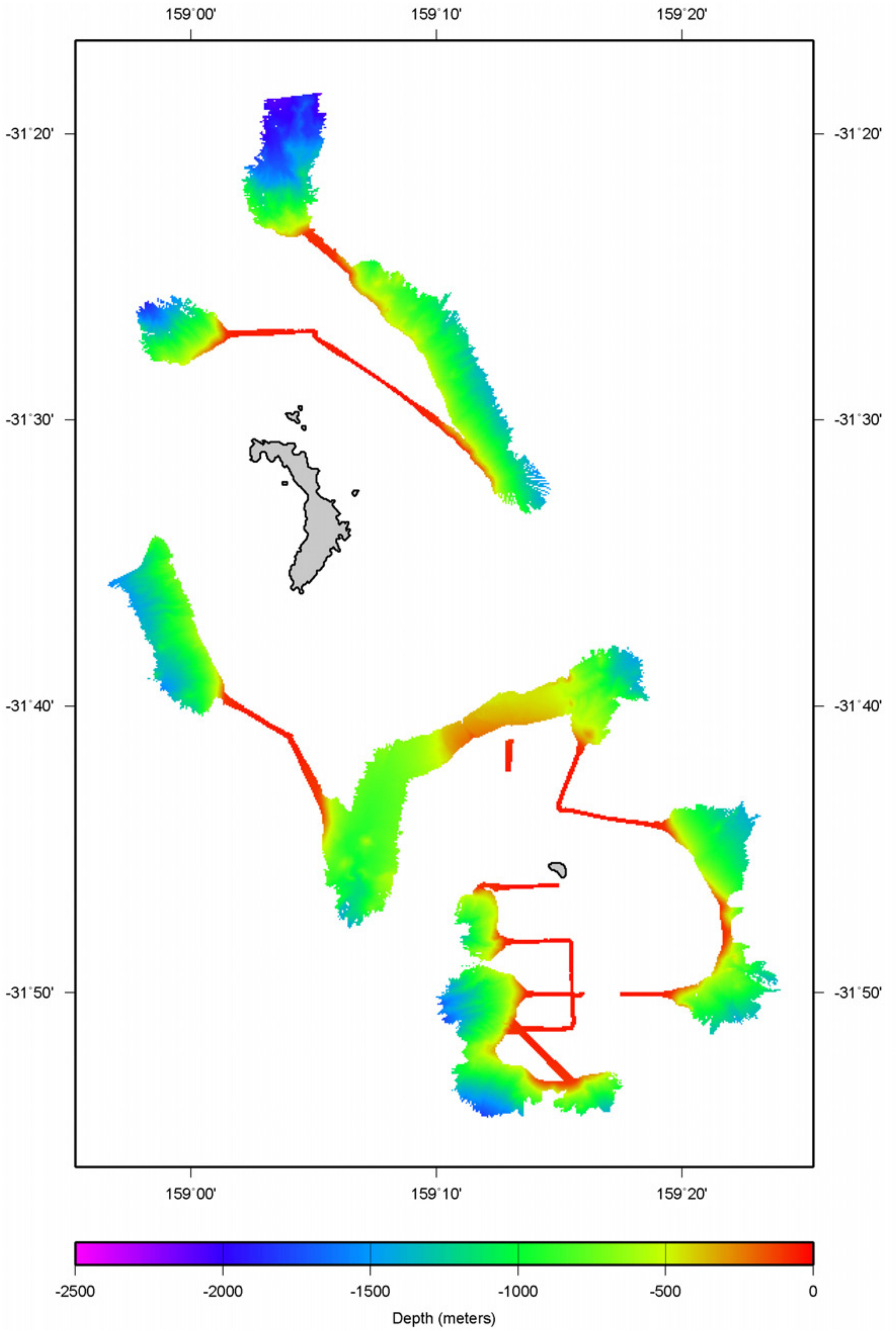


Figure 10: *SS0906 data mainly on the flanks of the volcano.*

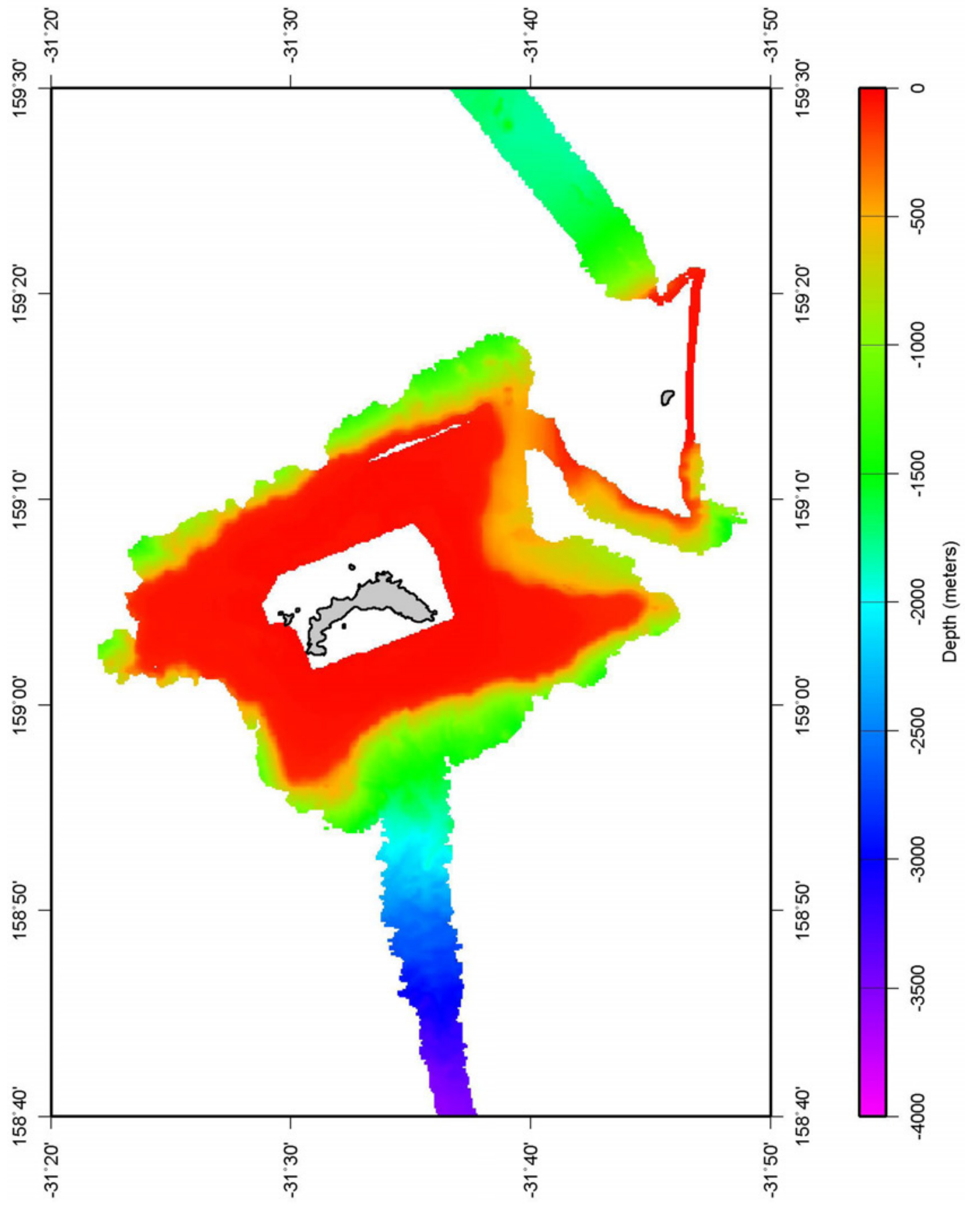


Figure 11: *SS0608 data includes high resolution data on the plateau.*

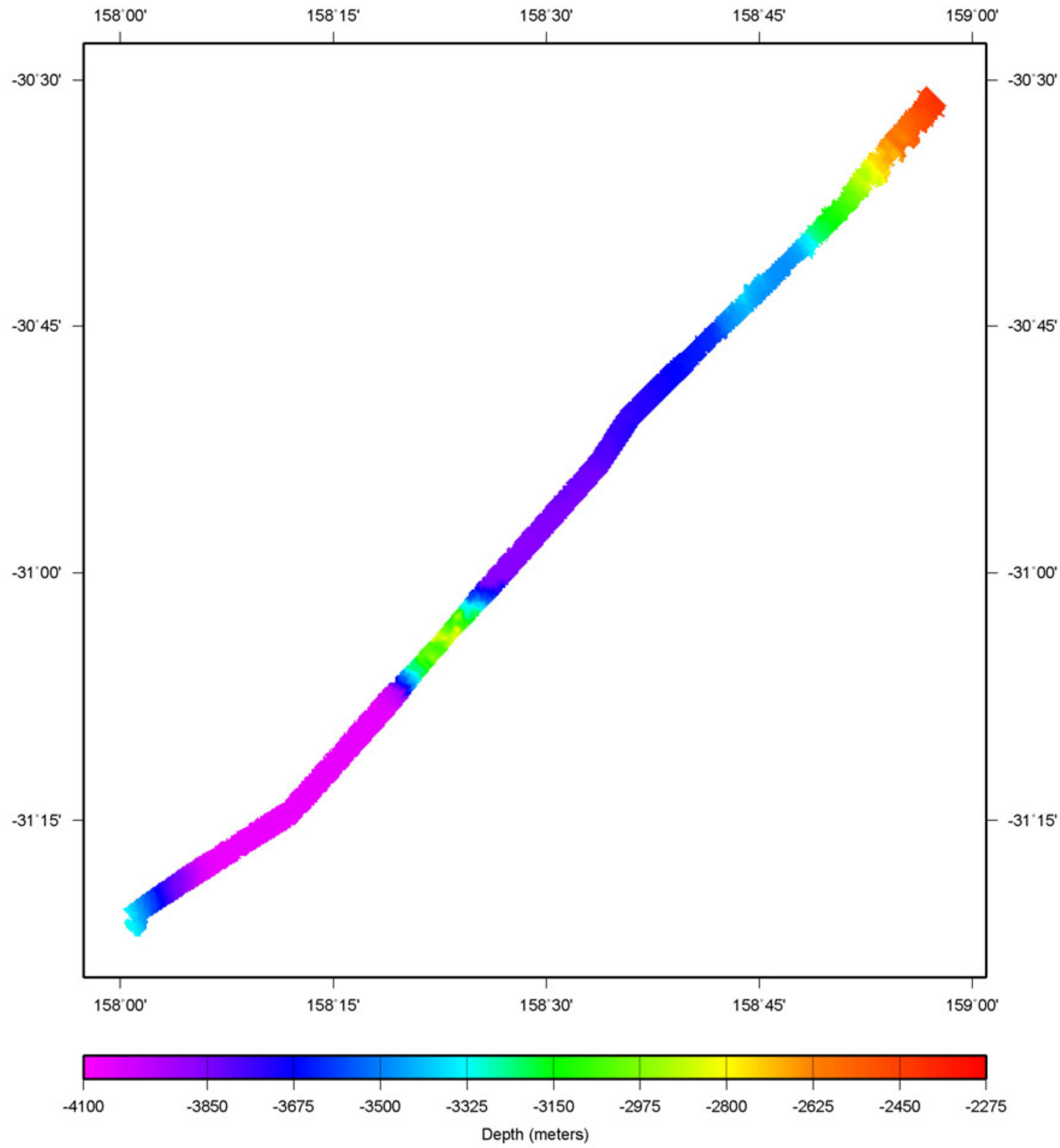


Figure 12: *SS2009 T02 data on a transit from Noumea to Hobart showing only the section in the Lord Howe Island region.*

Geoscience Australia surveys

GA has conducted six surveys around Lord Howe Island that have acquired marine geophysical data. Two surveys have collected swath data. The surveys are:

Lady Christine surveys (GA 12, GA 14, and GA 15)

In 1971 the M/V *Hamme* and the M/V *Lady Christine* (formally known as the M/V *Hamme*) surveyed the east coast of Australia as far east as Lord Howe Island (Figure 13). The transit satellite navigation system was used coupled to sonar Doppler with an accuracy in the vicinity of 500 to 1500 m. More details on this survey can be found in Compagnie (1974, 1975) and Cameron (1974).

GA 77

In 1988 the R/V *Rig Seismic* surveyed around the Lord Howe Island region. The extent of the ship's track is shown in Figure 13. The transit satellite navigation system was used coupled to sonar Doppler with an accuracy in the vicinity of 500 to 1500 m. However with post processing this was improved to about 250 m. More details on this survey can be found in Marks (1989).

GA 222 (AUSTREA 1)

The N/O *L'Atalante* is a French owned vessel operated by IFREMER (Institut Français Recherche pour l'Exploitation de la Mer: http://www.ifremer.fr/anglais/), which is the French Research Institute for Exploitation of the Sea. In 1999 the N/O *L'Atalante*, under contract to GA swath mapped around the plateau of Lord Howe Island and Ball's Pyramid (Figure 14). DGPS navigation was used, with a positional accuracy of 10 to 20 m. More details on this survey can be found in Hill et al. (2001).

TAN0308 (NORFANZ, also known as GA survey 2312)

The National Institute of Water & Atmospheric Research (NIWA; http://www.niwa.co.nz/) is a New Zealand government owned research and consultancy company which owns and operates the R/V *Tangaroa*. In 2003 the R/V *Tangaroa* carried out a survey around Lord Howe Island. In collaboration with the CSIRO and Geoscience Australia, swath data were collected and are shown in Figure 15. GPS navigation was used with a positional accuracy of 2 to 5 m. See the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=6482 for more details on this survey.

TAN0713 (also known as GA survey 2436)

In 2007 the R/V *Tangaroa*, under contract to GA, collected swath data over the northern Lord Howe Rise and in the vicinity of the island (Figure 16). DGPS navigation was used with a positional accuracy of 2 to 5 m. More details on this survey can be found in Heap et al. (2009).

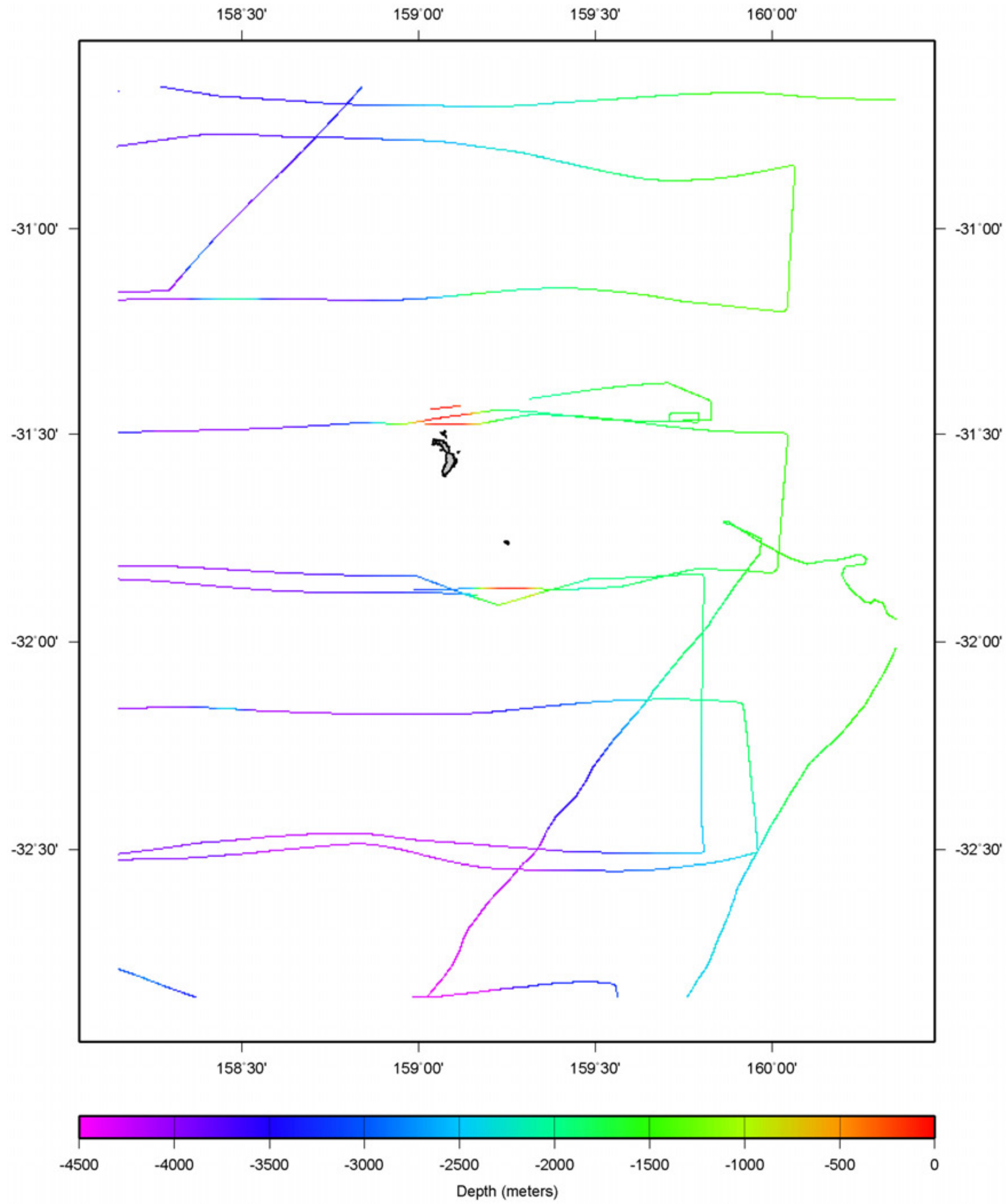


Figure 13: *GA singlebeam survey data mainly in deeper water.*

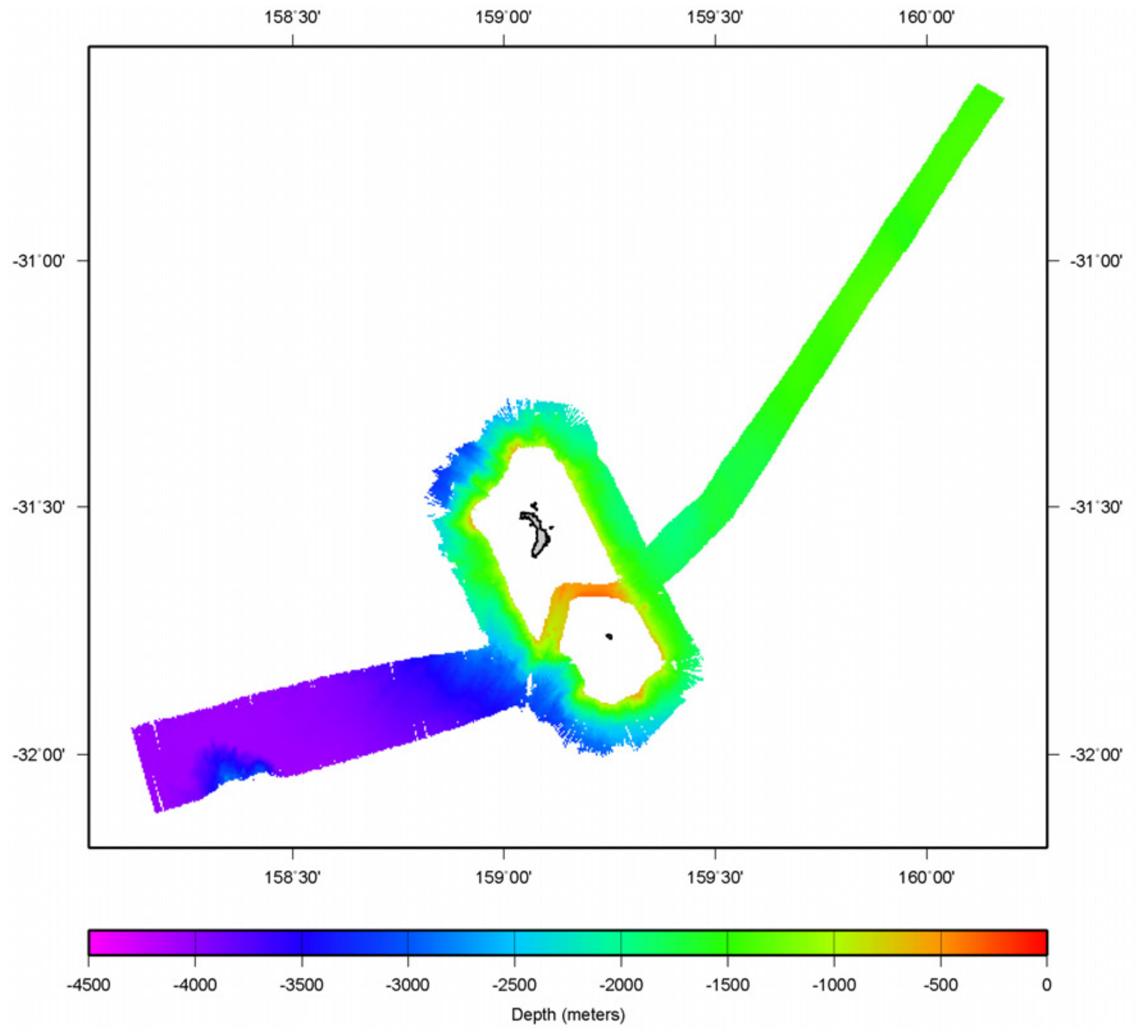


Figure 14: *AUSTREA 1 data mainly on the flanks of the volcano.*

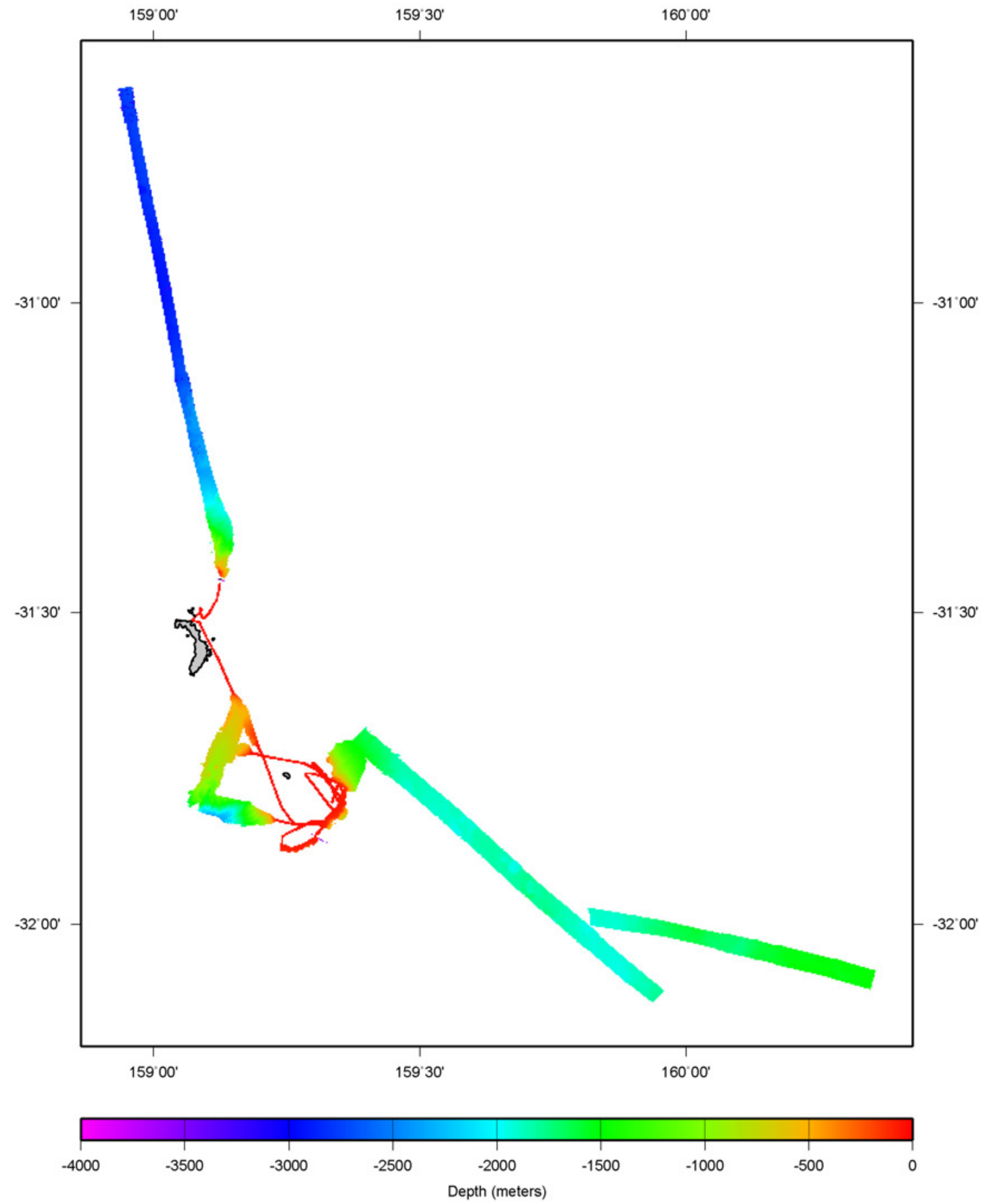


Figure 15: *NORFANZ data mainly around Ball's Pyramid.*

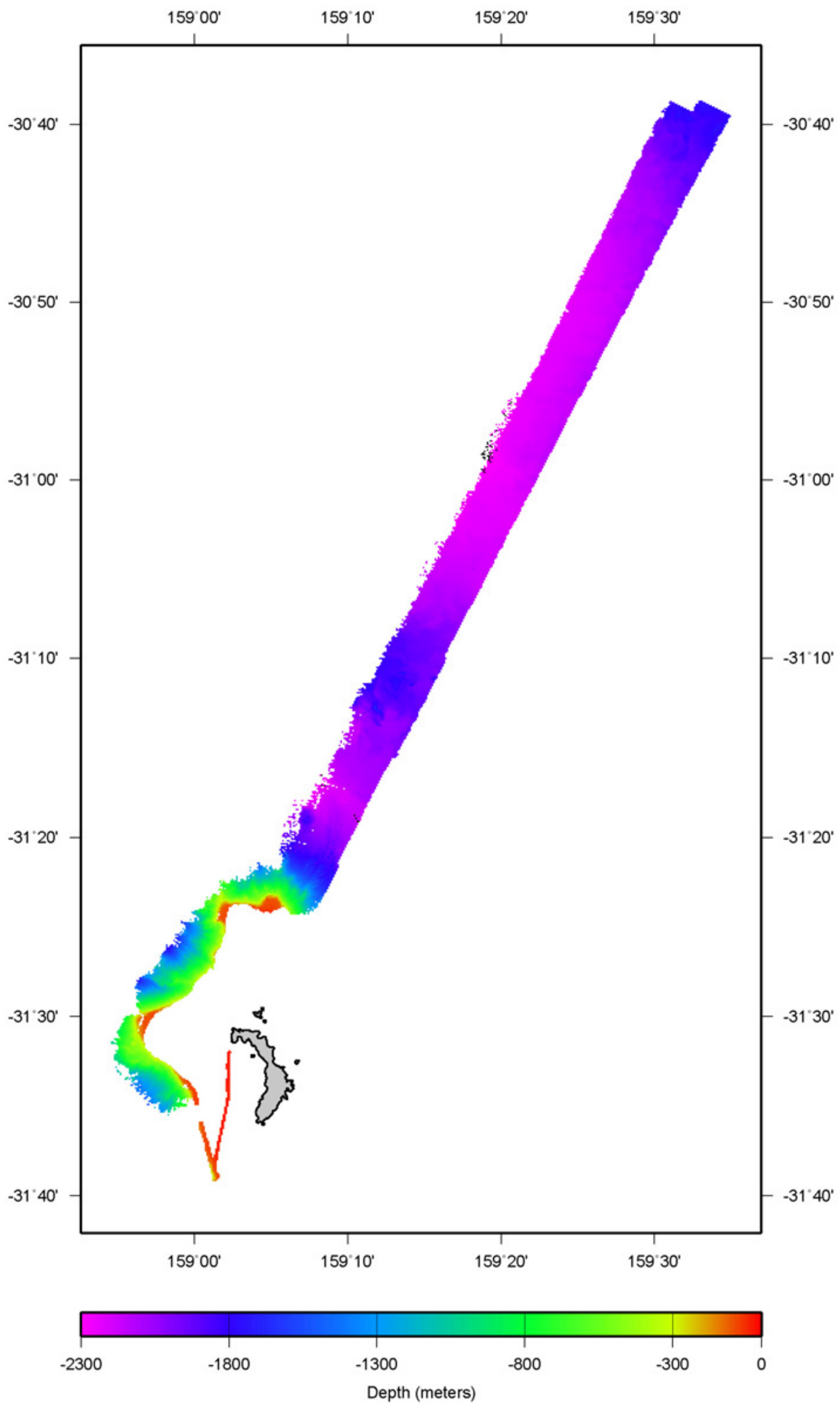


Figure 16: *TAN0713 data mainly in deeper water.*

National Geophysical Data Center

The National Geophysical Data Center (NGDC; http://www.ngdc.noaa.gov) is a part of the US Department of Commerce, National Oceanographic & Atmospheric Administration (NOAA). It is the primary data centre for US derived marine geophysical data, but also houses data from other nations. Suitable data from four surveys were found at this site and their distributions are shown in Figure 17. These surveys are:

19920013

In 1988 the HMY *Britannia* sailed past Lord Howe Island. The transit satellite navigation system was used with accuracy in the vicinity of 500 to 1500 m. More details on this survey can be found at: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=19920013&t=102697&s=6&d=7 which is the link to the NGDC.

DME06

In 1971 the Russian vessel the *Dmitrij Mendeleev* surveyed near Lord Howe Island. The navigation system used Loran-C, radar and sextant, which has a low accuracy in to order of 3,500 to 10,000 m. More details on this survey can be found at the following link to the NGDC website at: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=DME06&t=102697&s=6&d=7.

EW9202

In 1992 the R/V *Maurice Ewing* was transiting past the east coast of Lord Howe Island with the swath mapping equipment turned on. The transit satellite navigation system was used with an accuracy of 500 to 1500 m. More details on this survey can be found at the following link to the NGDC:http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=EW9202&t=102697&s=6&d=7.

VI49

In 1971 the Russian vessel the *Vityaz* surveyed near Lord Howe Island. No navigation system is stated for this survey; given the vintage it is assumed that the transit satellite system was used with an accuracy of 500 to 1500 m. More details on this survey can be found at the following link to the NGDC: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=VI49&t=102697&s=6&d=7.

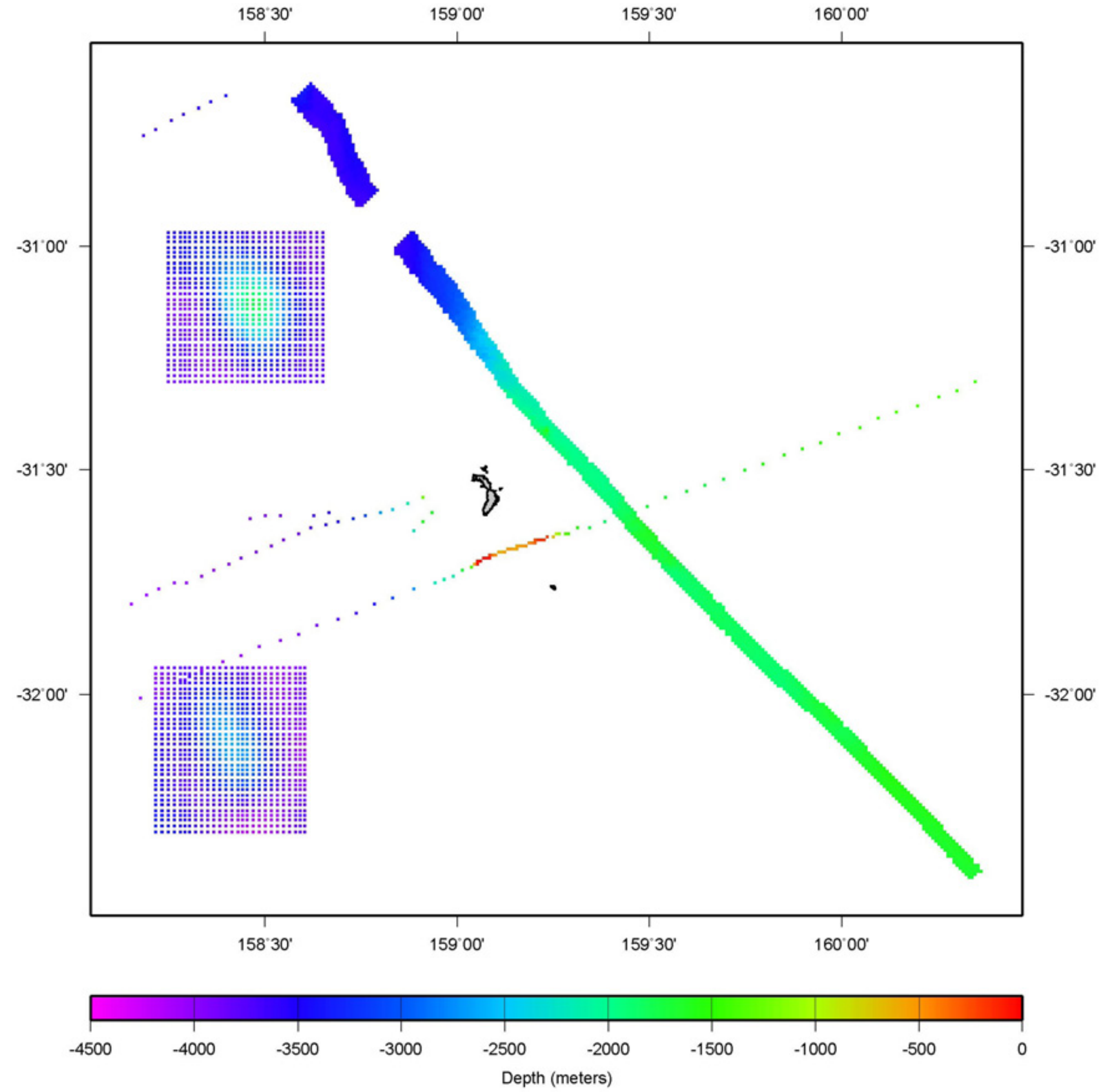


Figure 17: *NGDC data showing swath, singlebeam and ETOPO1.*

University of Wollongong data

GA obtained this data from the University of Wollongong which maintains a GIS of Lord Howe bathymetric data, (Dickson, 2002). In 1999 and in 2001, the university mounted a CEEDUCER echo sounder on a small dinghy and collected bathymetric data around Lord Howe Island. The navigation used was GPS with an accuracy of 100 m. The extents of the data are shown in Figure 18.

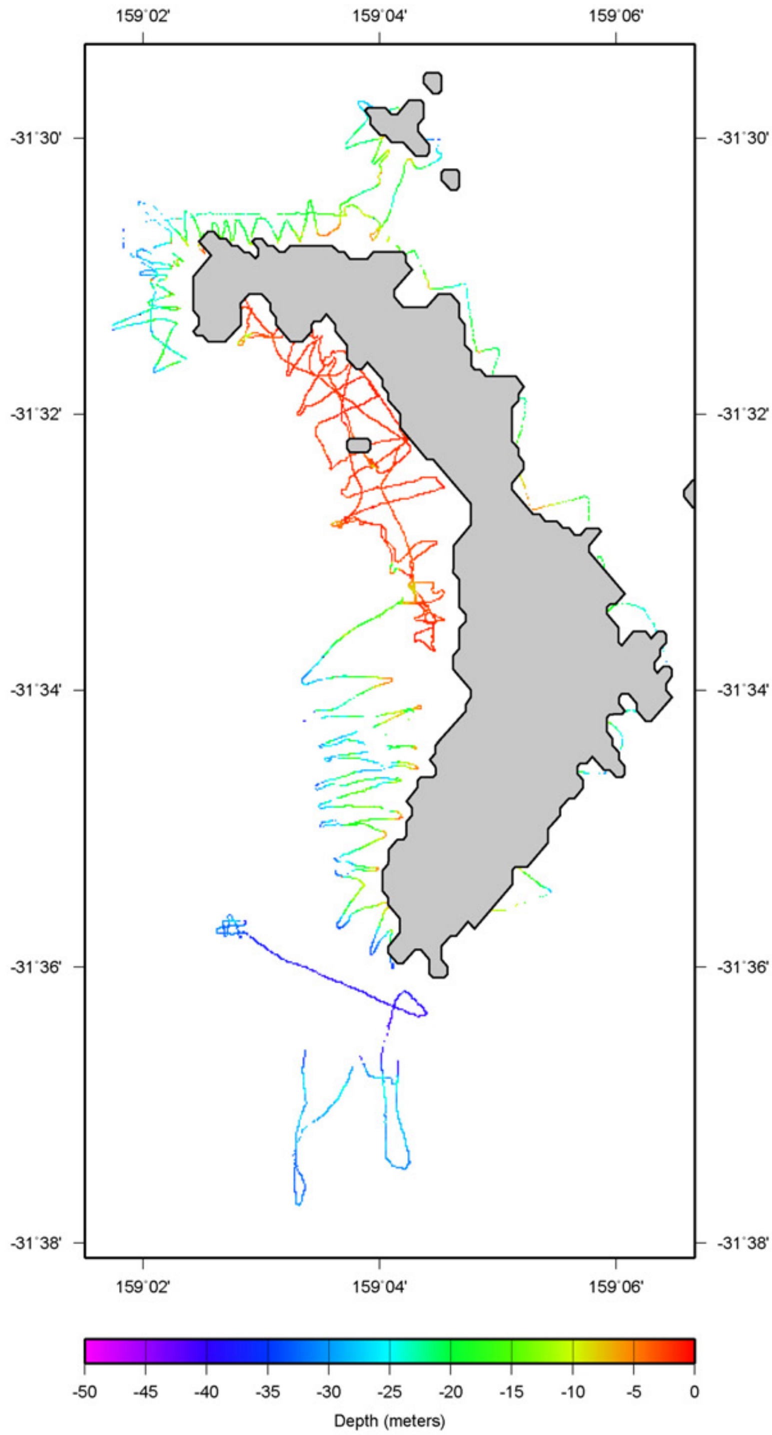


Figure 18: *The CEEDUCER data mostly in very shallow areas around the island.*

SATELLITE DERIVED BATHYMETRY DATA

Two sources of satellite derived bathymetric data were available.

Quickbird

In shallow water areas less than about 20 metres deep it is possible to use multi-spectral satellite data for the determination of water depth. Images from the Quickbird satellite were obtained and processed to extract bathymetry in areas close to shore. A complete explanation of the processes involved in obtaining bathymetry from multi-spectral satellite data is given in Appendix 2. The data distribution is shown in Figure 19.

ETOPO1

In deep water areas, satellite observations of sea height can be processed to determine the gravitational field over the ocean surface and estimate an underlying bathymetry (Smith and Sandwell, 1997). The latest release of this bathymetric dataset is known as ETOPO1 which was mentioned earlier as one of the publicly available grids covering the Lord Howe Island area.

Unfortunately in the Lord Howe Island area ETOPO1 was found to be about 150 metres too shallow in many places and too deep in others when compared to soundings data. It was decided to only use subsets of this dataset in the vicinity of two seamounts. This data was obtained from the NGDC and is shown with other NGDC data as the two squares of data in Figure 17.

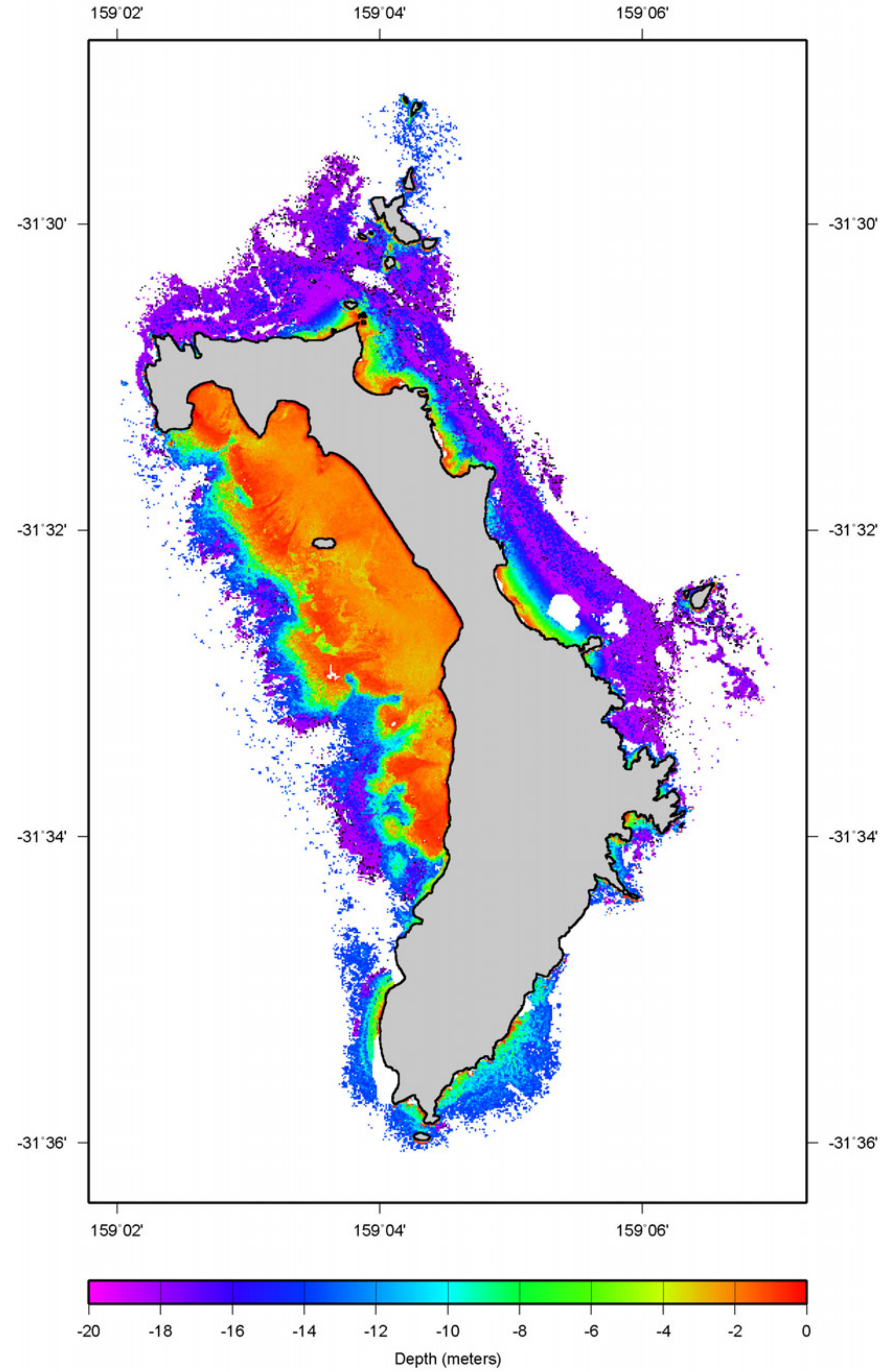


Figure 19: *Satellite derived bathymetry gives fine-scale coverage in the very shallow regions.*

TOPOGRAPHIC DATA

The four publicly available bathymetric grids of the Lord Howe Island area depict the exposed land surface and coastlines poorly. To rectify this deficiency and to provide some constraints to the bathymetric gridding process, a number of high quality topographic and coastline datasets were evaluated (Table 2).

Table 2: Lord Howe Island topography.

NAME	RESOLUTION	SOURCE INSTITUTION
coast	2 metre intervals	Geoscience Australia
spot heights	5 to 1500 metre intervals	NSW LPMA*
contour lines	3 to 100 metre intervals	NSW LPMA*
SRTM*	90 metre intervals	US Geological Survey

*LPMA=Land and Property Information Management Authority, SRTM=Shuttle Radar Topography Mission.

NSW Land and Property Information Management Authority data

Topographic data were obtained from the NSW Land and Property Information Management Authority (LPMA) in the form of a GIS containing coast, height and contour line data. These data were converted to WGS84 and exported to an xyz format file containing points. The spatial accuracy of these data are about 2 m. GA has a *deed of agreement* with the LPMA which gives it access to the data. From this dataset, the coast for Ball's Pyramid and the height data distribution are shown in Figure 20. The contour data are shown in Figure 21.

GA Coastline data

The coastline data was obtained by masking out the land in a satellite image based on the infrared signature of the pixel. A shapefile of the land was then created and exported as points at 2 metre resolution. The spatial accuracy of these data is about 2 m. The satellite derived coastline of Lord Howe Island (but not Ball's Pyramid) was superior to that supplied by the LPMA and was used instead. The data are shown in Figure 20.

Space Shuttle Radar Topography Mission (SRTM) data

Topographic data were obtained from the USGS web site and are shown in Figure 22. The dataset has a resolution of 90 metres with values rounded to the nearest integer. The positional accuracies are stated as 20 metres in both horizontal and vertical directions. However, in lieu of any other data it can be a useful dataset. Some data in the vicinity of the very steep mountain peaks are missing. More information on the SRTM dataset can be found from the following link: http://srtm.usgs.gov/index.php.

OTHER DATA

Charts and Images

Though naval charts, satellite images and aerial photography are not part of the dataset to be gridded they serve as a valuable tool for assessing the data. The position of coastlines, islands and general depths and heights can be cross-checked against these images in visualisation software mentioned in the following chapters. In this work chart number AUS610 obtained from the AHS (http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus610&subchart=0; under the MOU) was used and is shown in Figure 23. Aerial photography, which was obtained from the NSW LPMA and which had superior geo-referencing than the chart, was also used and is shown in Figure 24.

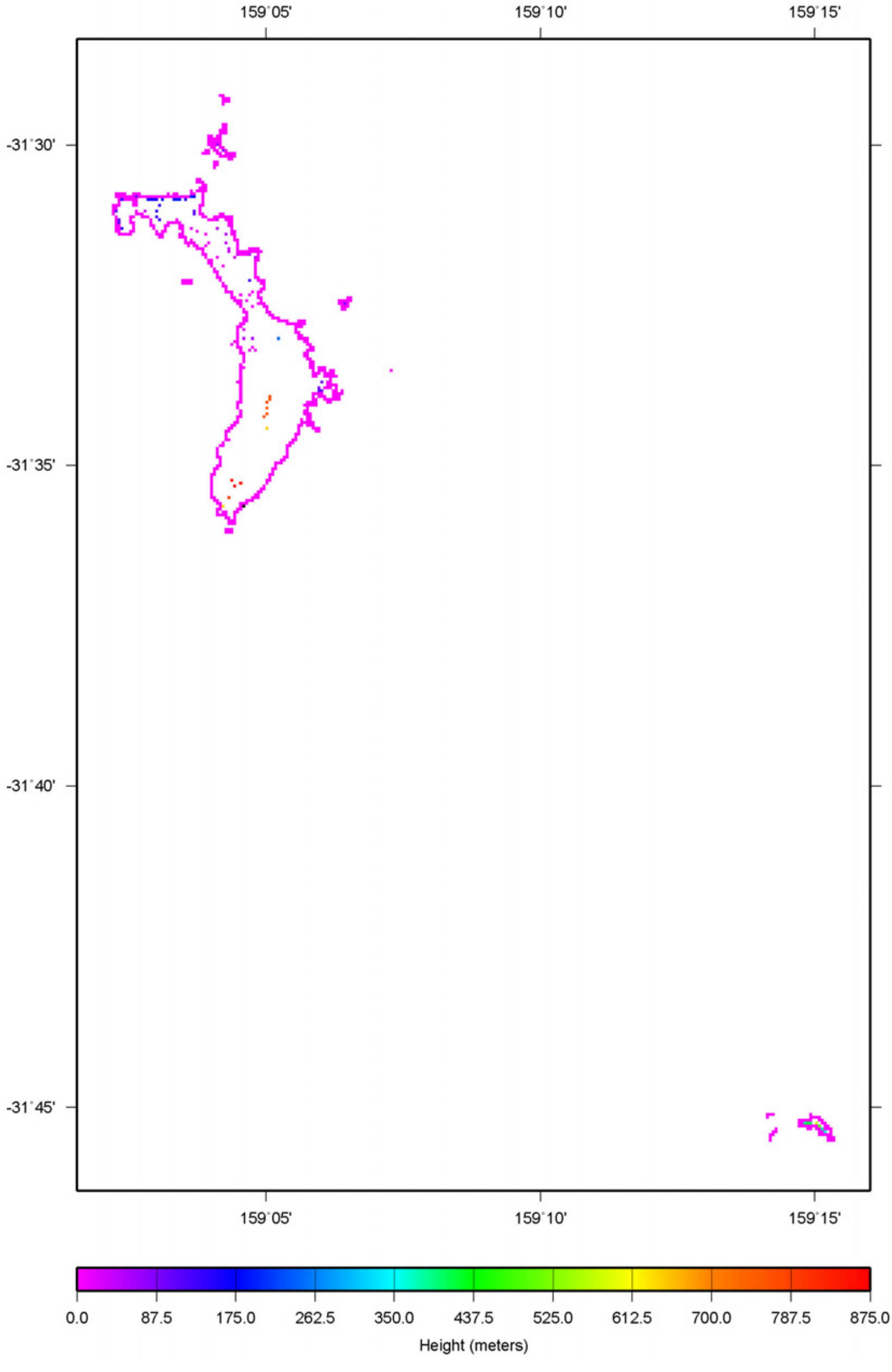


Figure 20: *Coastline and topographic data for Lord Howe Island and Ball's Pyramid.*

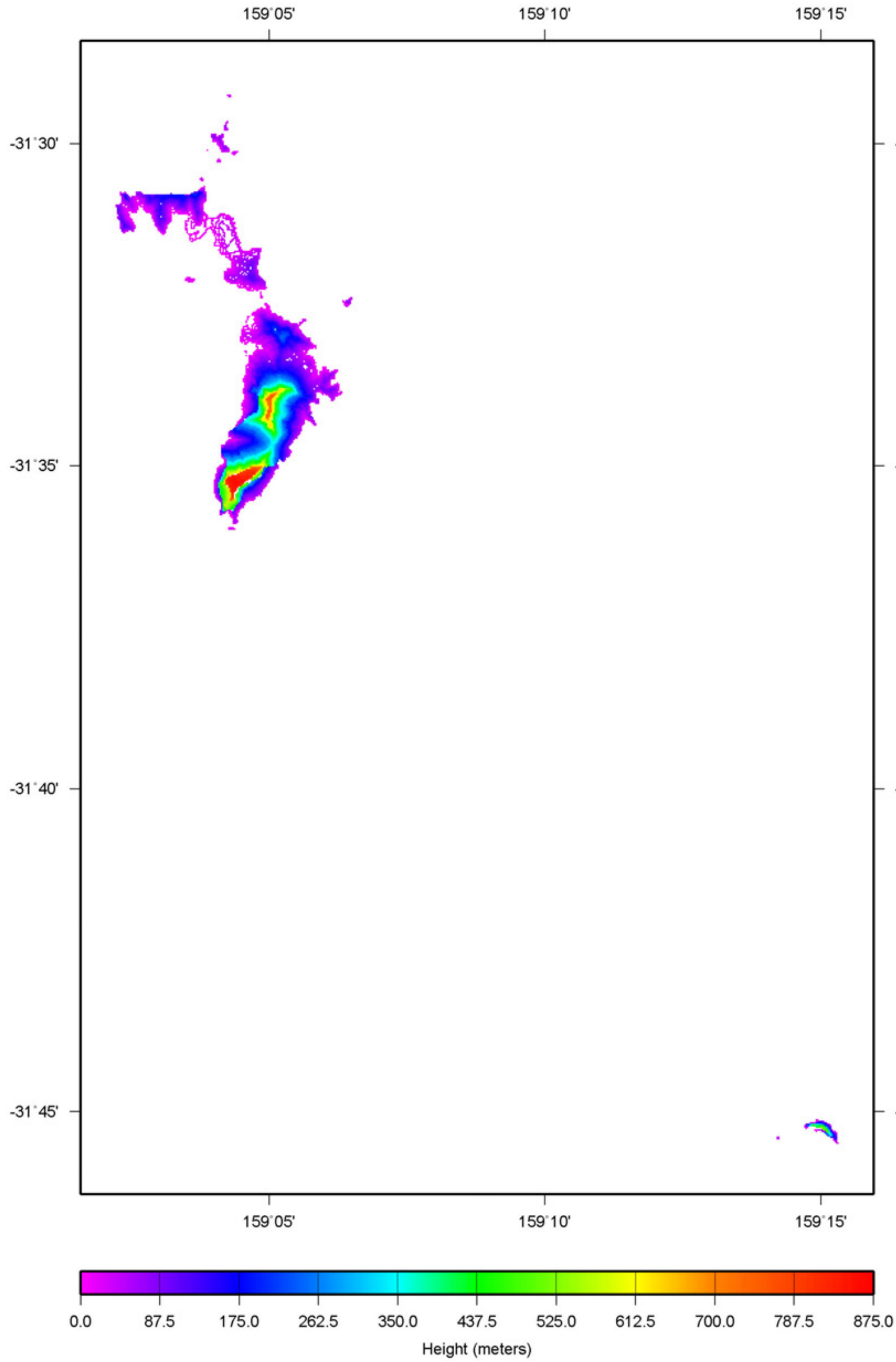


Figure 21: *Contour data for Lord Howe Island and Ball's Pyramid.*

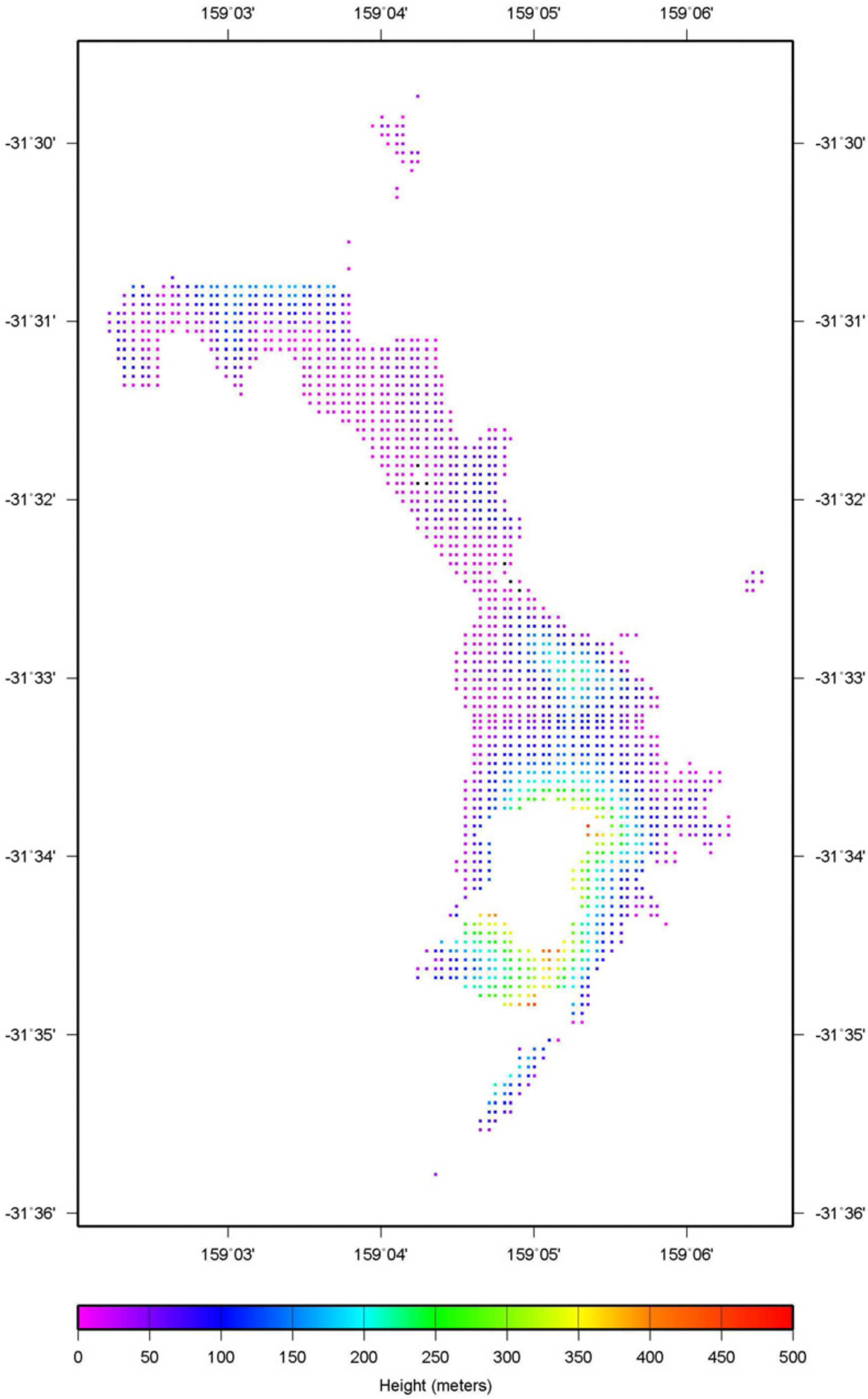


Figure 22: *Incomplete SRTM data coverage for Lord Howe Island.*

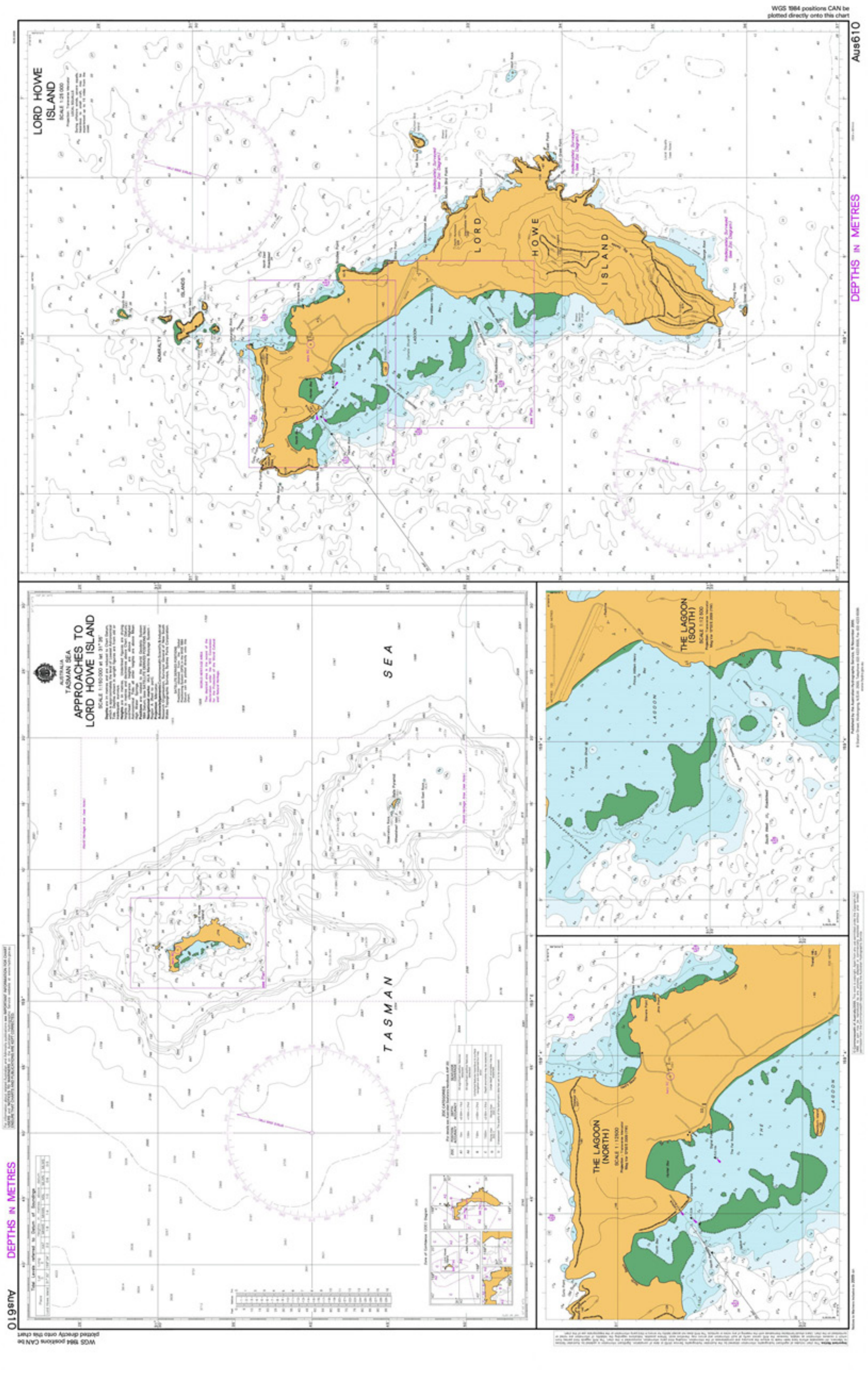


Figure 23: *Chart AUS610 (used under licence AHS, not to be used for navigation).*

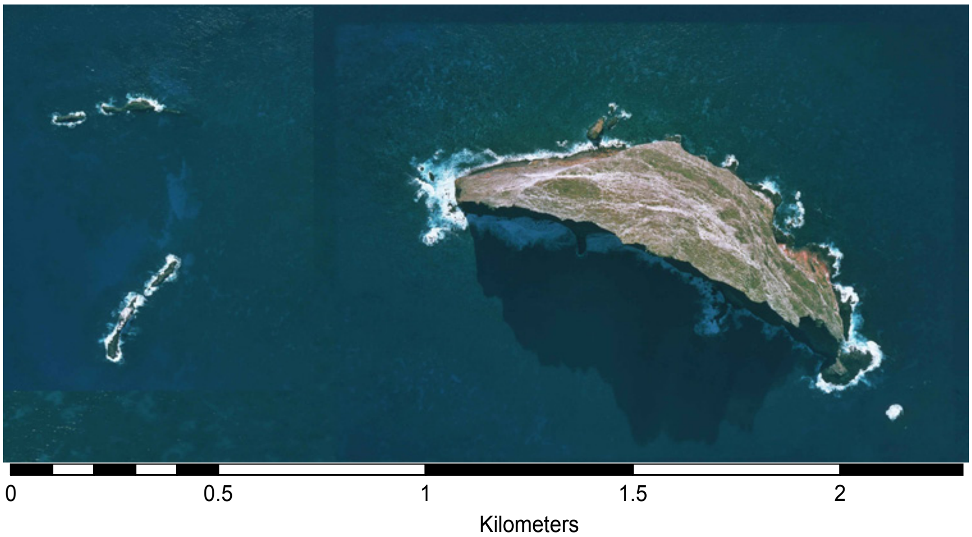


Figure 24: *Aerial photography depicting Lord Howe Island and Ball's Pyramid. (used with permission LPMA).*

4. Data Processing

The various datasets had all undergone some level of data processing prior to their importation into the gridding algorithm. Whilst much of this work was conducted outside of this project, the data processing is a key component in making a valid gridded surface. As a first step, all datasets were converted to the WGS84 datum and, if possible, the depths were referenced to mean sea level. The following gives a brief description of the processing steps employed.

SWATH PROCESSING

Multibeam data are usually partially processed at sea during data acquisition. This phase of processing usually concentrates on the removal of erroneous beams. At GA, all of the available multibeam data have been imported into the CARIS processing application (http://www.caris.com/) and undergone further cleaning of bad beams as well as detailed corrections for tides and speed of sound variations. As the number of beams in the multibeam datasets was so large, the data were internally gridded within CARIS and exported at 100, 40 and 8 metre ASCII xyz grids. These xyz data formed the basis of further work using the multibeam data. A more detailed description of the swath data processing is contained in Appendix 1.

SINGLEBEAM ECHOSOUNDER PROCESSING

All echo sounder data had already been processed to some degree by the source institutions. These data have also been examined a number of times within GA by other projects and any serious problems had been removed. Invariably, the bathymetric soundings are referenced to the sea surface at the time of observation and not mean sea level. This was not an issue as most of the singlebeam soundings were in deep water.

CHART DATA

These data were entirely processed by the AHS. No further processing was undertaken at GA. The vertical datum was the Lowest Astronomical Tide (LAT) and a small (1 metre) correction was applied to correct them to mean sea level.

LADS DATA

These data were entirely processed by the AHS. No further processing was undertaken at GA. The vertical datum was the Lowest Astronomical Tide (LAT) and a small (1 metre) correction was applied to correct to mean sea level.

SATELLITE DATA PROCESSING

The shallow water satellite-derived bathymetry was obtained by processing multi-spectral data from the Quickbird satellite. Briefly, the processing steps involved the masking of land and inter-tidal areas, a deglinting and an atmospheric correction procedure followed by the extraction of a bathymetry value utilising the SAMBUCA algorithm (Wettle & Brando, 2006), and validated against existing LADS bathymetry in the area. The final depths were then tide and datum adjusted.
For further details on the data and methodology refer to Appendix 2.

Similarly the bathymetry obtained from the satellite altimeter data was a result of extensive data processing at NOAA and the Scripps Institution of Oceanography. This process is complex and involves the averaging of many years of observations of sea height from satellite based RADAR. These averaged heights give a good measure of the height of the geoid relative to the theoretical ellipsoid. The variations in geoidal height can be converted into gravitational field values, which can then be modelled as variations in bathymetry if a crustal model is assumed. No further processing was possible at GA, which is unfortunate given the significant deviations this dataset had from actual soundings.

5. Analysis and QC of Bathymetric Data

The fully processed datasets were checked against each other for consistency as an additional check of data quality. Two tools were used extensively in an iterative fashion to achieve this: Fledermaus and ArcMap.

FLEDERMAUS

Fledermaus is a bathymetry display and processing tool which allows data points to be viewed in 3D (http://www.ivs3d.com/). In this work it was used to compare datasets from different surveys and assess their reliability. Included in the Fledermaus set of tools is a program called DMAGIC. It was used to create shaded 3D terrain models which where then inspected for data and gridding problems.

ARCMAP

ArcMap (http://www.esri.com) was used to visualise the spatial distribution of the survey data, look at different surveys in relation to each other, delete suspect or incorrect data points and delete inferior surveys in the regions where they overlapped with more reliable swath and LADS surveys. This was done in conjunction with Fledermaus. The final data were then exported in ASCII xyz format ready to be gridded.

PROCEDURE

All final processed datasets were loaded into ArcMap, except for the swath data where only a geo-TIFF was loaded to show the spatial extent of the multibeam coverage (the actual multibeam dataset was too large for ArcMap). In deciding which data points to keep for the gridding process, the following tasks were performed:

- All data points that fell on areas covered by swath and/or LADs datasets were immediately discarded.
- Data points adjacent to swath data were checked to see if they were consistent with the multibeam data.
- All surveys that intersected with each other were checked for cross-over errors.

The data were then checked with Fledermaus in 3D for similar inconsistencies. Here it was found that many of the digitised chart soundings were not consistent with surrounding echosounder data. Much of this inconsistency could be attributed to inferior navigation in the older chart data, but the inconsistency possibly stems from the physics of the original echosounders employed. These echosounders probably had a significant beamwidth (> 30°) which would lead to shallower depths being detected in areas of steep bottom slope. Such a situation is observed in the digitised chart data just to the east of Lord Howe Island (Figure 6). The east-west transects are in an area of steep slope and where they overlap multibeam data (which have a very small beamwidth of less than 2°) they are consistently shallower. On the other hand, the north-south transects in the digitised chart data are in deeper water with a much smaller slope and are in agreement with multibeam data where the two datasets overlap. Consequently, it was decided to ignore all of the data from the east-west transects and keep all of the north-south transect data (except where they intersected multibeam data). Unfortunately, Dickson and Woodroffe (2002) came to exactly the opposite conclusion when they observed that the north-south data did not fit a gridded surface; produced by a Kriging technique that was heavily influenced by the more numerous east-west data.

Clearly the physics of the acquisition must be well understood and accounted for when making a bathymetric grid. Furthermore hydrographic charts are principally for safety of navigation, reporting shallower than actual water depths is not a problem in such work and correcting for diffraction effects from pronounced submarine topographic features is not routinely undertaken. For bathymetric mapping however, all echosounder observations should be corrected for these diffraction effects if the beamwidth of the instrumentation and the slope of the surface are significant.

As mentioned earlier ETOPO1 data were about 150 m too shallow when compared with survey data. In the area of the Lord Howe Island and two areas over probable seamounts, the ETOPO1 data in this region exhibited some features not supported by survey data. For more information regarding the problems with the ETOPO dataset consult Marks and Smith (2005). Only data from around the two seamounts were extracted from ETOPO1 and used. These data underwent an additional block shift to bring them into better agreement with the other sparse data in these areas.

The CEEDUCER data were acquired during a period when differential GPS corrections were not available. Consequently the navigational accuracy of these data are no better than 100 metres. Fortunately the survey followed the coastline and entered small bays and circled small islets. It was possible to apply a horizontal shift to the navigation data to better fit the coastline. This brought these data into better agreement with LADS. Nevertheless, where the CEEDUCER data overlapped areas containing the satellite derived shallow water data, the CEEDUCER data were discarded.

The SRTM, LPMA and coast datasets were also checked against georeferenced TIFF images of the island. It was decided to use the contour data from LPMA in preference to the other datasets, although a small portion of SRTM data were used where contour data were lacking.

The process was iterative in nature with both ArcMap and Fledermaus being used to make decisions. When finished, the final quality-controlled data points showed good general agreement with each other and were considered suitable to be gridded (Figure 25).

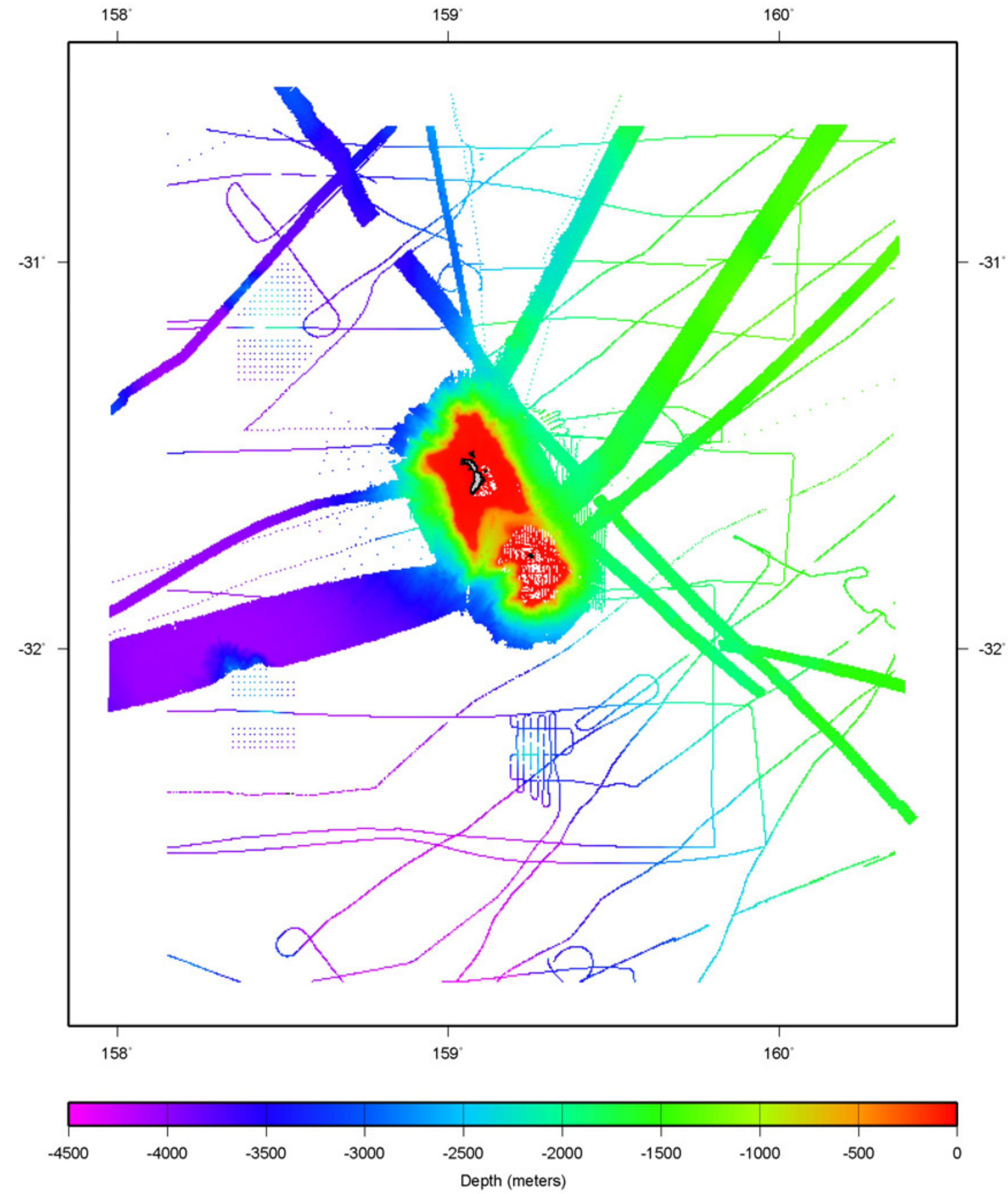


Figure 25: *The final dataset showing all data used to create the final grid including: satellite, LADS, multibeam, chart and singlebeam echosounder.*

6. Gridding

PRELIMINARY CONSIDERATIONS

It is possible to produce a gridded surface with any cell size subject to the limitations of the software available and the computer used. The data however can only safely support (without creating gridding artefacts) a cell size that fits the sampling interval of the dataset. In an area such as the Lord Howe Rise, the data sources and their sampling densities vary widely (Table 3). As a result some areas will be able to be gridded with a small cell size (areas of high density data), whilst other areas can only justify a much coarser cell size (in areas of sparse data). To create a visually appealing grid (without null values) it is often necessary to produce a grid at a finer cell size (therefore interpolating in areas of no data) even though the data density may not support it

Table 3: Data density

SURVEY NAME	DATA TYPE	DURING ACQUISITION	AS USED IN THIS WORK
REEFAL AREA			
"Satellite data"	derived bathy.	2.4 m	2.4 m
"CEEDUCER"	echosounder	5 m	5 m
"AHS LADS"	LADS	10 m	35 m
"AHS Chart inner"	chart	unknown	50 m
PLATEAU AREA			
SS0608	multibeam	1.5 – 30 m	8/40/100 m
TAN0308 - NORFANZ	multibeam	0.7 – 25 m	40/100 m
"AHS Chart inner"	chart	unknown	50 m
UPPER SLOPE AREA			
TAN0713	multibeam	0.8 – 40 m	40/100 m
GA 222 – AUSTREA 1	multibeam	15 – 130 m	40/100 m
SS0906	multibeam	0.8 – 50 m	40/100 m
DEEP WATER			
TAN0308 - NORFANZ	multibeam	0.7 – 25 m	40/100 m
SS2009 T02	multibeam	16 – 500 m	100 m
GA 77	echosounder	20 m	120 m
FR12/98	echosounder	unknown	140/500/1500 m
Sonne 7	echosounder	unknown	170 m
GA 12	echosounder	Unknown	210 m
GA 14	echosounder	Unknown	280 m
GA 15	echosounder	Unknown	290 m
Sonne 36A	echosounder	unknown	380 m
FR01/97	echosounder	unknown	1500 m
"AHS Chart outer"	chart	unknown	1500 m
ETOPO1	grid	N/A	1850 m
VI49	echosounder	Unknown	3800 m
DME06	echosounder	Unknown	3800 m
19920013	echosounder	Unknown	5000 m

For the single beam datasets the table shows along track data density as the distance between points. As the lines of the ship's tracks are often kilometres apart, this measure of data density may not be all that meaningful but it is all that is available. Multibeam data density contains an along-line and cross-line component and varies with water depth. Sometimes these two measures can be quite different. Once again, the values are more qualitative than quantitative. It was found necessary to split the chart data into "inner" and "outer" sets as there was a considerably higher data density in the areas closer to the island.

A decision was made to produce four grids. A fine-scaled grid with an 8 m cell size was seen as possible in the reefal areas around the island. A 40 m cell size grid would be suitable over the plateau area surrounding Lord Howe Island and Balls Pyramid, whilst a 100 m cell size grid would be appropriate for the top and upper slopes of the volcano complex. A 250 m cell size grid was made of the entire region to compare with previous grids.

GRIDDING PROCESS

Various gridding packages were available to this study but it was decided to use the Intrepid (Des Fitzgerald and Associates: http://www.intrepid-geophysics.com/ig/index.php) application as it is widely used at GA and can handle large separate datasets. The gridding method employed was nearest neighbour with minimum curvature smoothing (Billings and Fitzgerald 1998, Briggs 1974).

As mentioned earlier, CARIS had been used to grid the multibeam data prior to making an export. This gridding operation is viewed as a "data thinning" exercise rather than being part of the gridding process; exporting the multibeam data to a more useable data volume. Data were exported at three resolutions (8, 40 and 100 m cell size) from CARIS and the appropriate version used to produce the final bathymetric grids.

All of the data were imported into the Intrepid Point Databases, a gridding job was set up with the required parameters and a batch job executed. The final product was an ERMapper compatible grid file that can be displayed using ERMapper or converted into any other grid format. A cosmetic clip was applied to the edges of the grids to remove possible edge effects.

On the examination of the resultant grids it was found that there were some deeper holes or rises that were not supported by the data in the final dataset. This was more evident in the 40 and 8 m grids in the Ball's Pyramid region where data were sparse and the interpolations often produced artefacts. Regions most affected were very close to land where the lack of bathymetric data and the steep topographic gradients from sea to land produced gridding artefacts. The problem was reduced by introducing "control points". These points were inserted into areas where the interpolation had created unrealistic values. The data points were interpolated by using an average of neighbouring points. The data were then re-gridded and the artefacts disappeared.

All final grids were validated against the original data points. This was done by importing the final grids into DMAGIC and creating 3D DEM surfaces. These were viewed in Fledermaus with the original data points overlaid. All data points fell on this surface, which was to be expected as an option in Intrepid was chosen to honour the original data points. This final check was also necessary in case cells contained unrealistic interpolated data.

Tables 4 to 8 and their accompanying discussion detail the parameters used in the production of the various grids. The large values used for the maximum iterations and extrapolation limit were chosen to ensure that the maximum residual was met and that large gaps in the data were completely interpolated over leaving no null values. These gridding parameters had no significant increase in computation time.

Lord Howe Regional 250 metre grid

The Lord Howe regional 250 metre (or 9 second of arc) grid is shown in Figure 26. It uses all the data that is shown in Figure 25. The computational parameters used in Intrepid are shown in Table 4. The grid on this scale is a good representation of the bathymetry in the region. All the original data were honoured and only one gridding artefact was detected. This is located at the bottom left hand corner of the grid. The ship's track seems to be a bit noisy and this has resulted in an oscillation. As no other data is available in that region it is something that will remain until better data becomes available. However, it is still a significant improvement of any grid so far at this resolution.

Table 4: Intrepid gridding parameters for the ~250 m grid.

PARAMETER	VALUE
Latitude range	-32.85° to -30.65°
Longitude range	158.15° to 160.35°
Cell size	0.00225 degrees (~9 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	2,000 cells

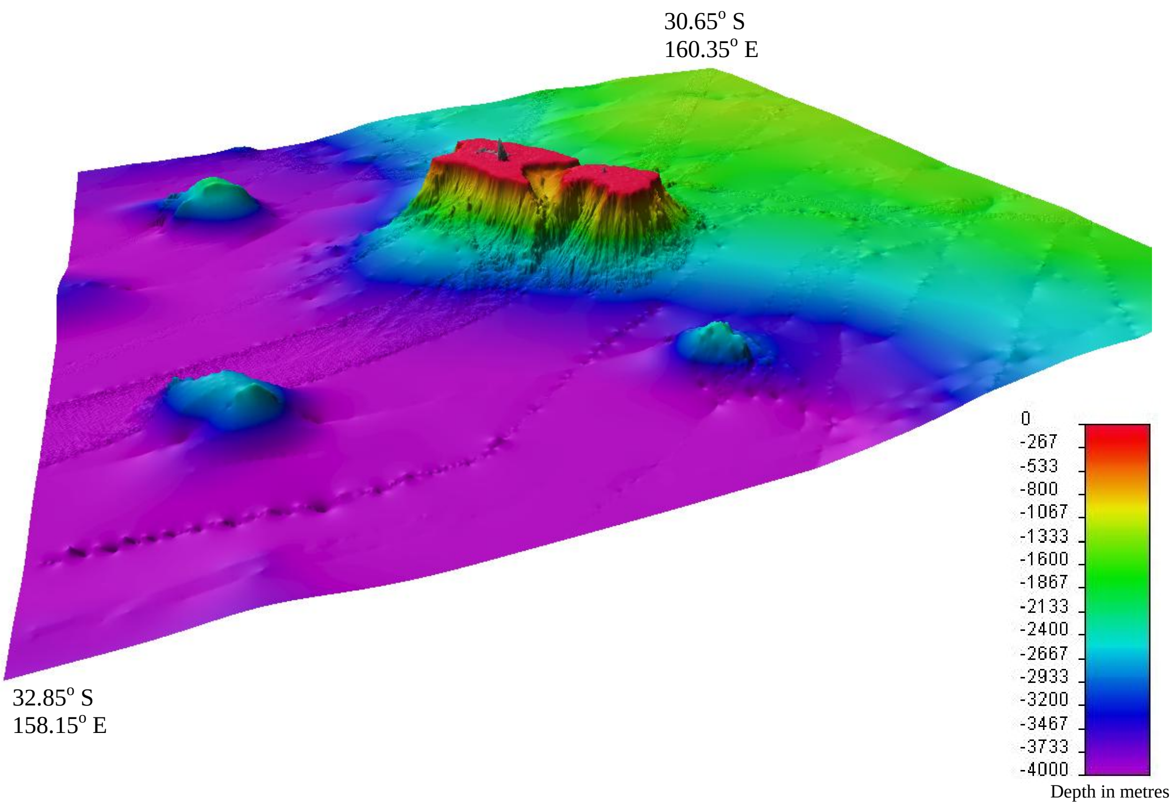
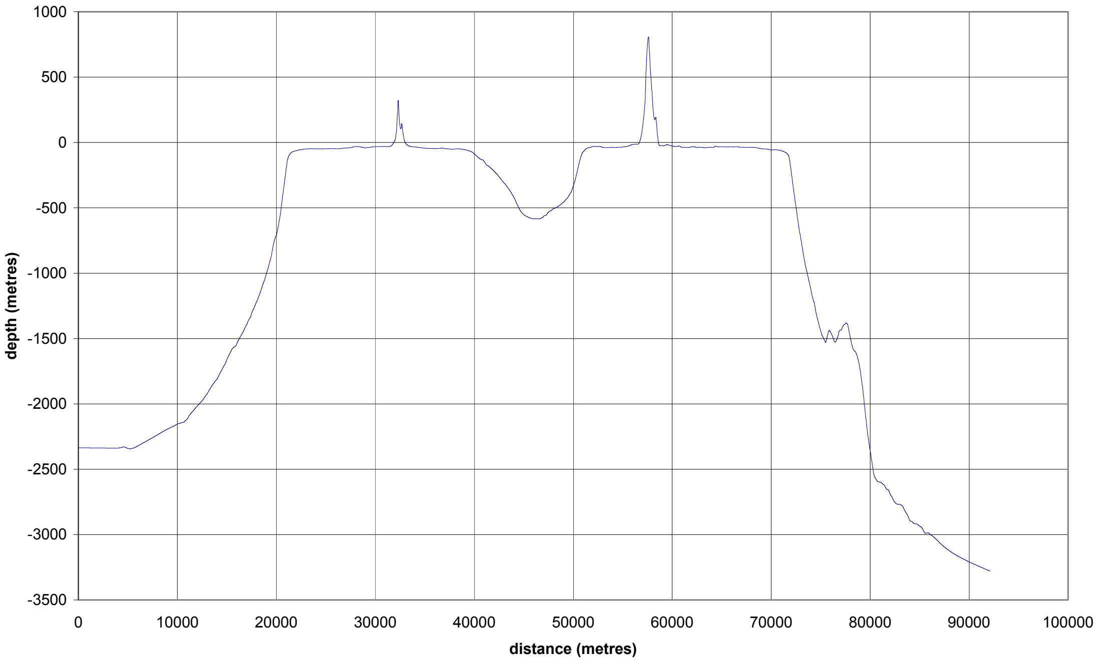
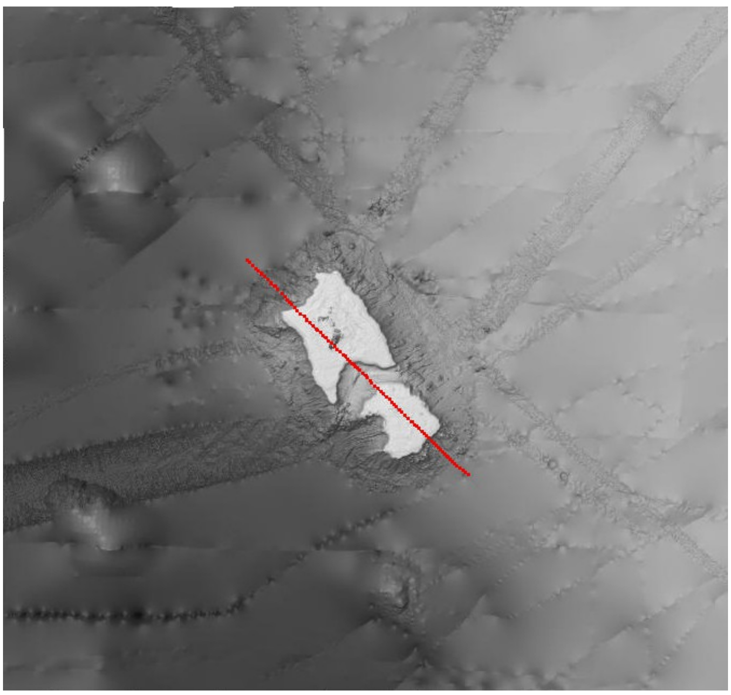


Figure 26: *The Lord Howe regional 250 m grid 2010 from this work (vertical exaggeration X 6, position marker approximate only).*

A profile (south to north) passing through Ball's Pyramid and Mount Gower was extracted from this grid using the Fledermaus profile tool as shown in Figure 27. It clearly reveals the wave-cut platform of the volcano complex and how little land remains of a once much larger island.



30.65° S
160.35° E



32.85° S
158.15° E

Figure 27: *A profile from south to north across the plateaus of Ball's Pyramid and Lord Howe Island (top) and the 9 km profile path (bottom).*

Lord Howe Island and Ball's Pyramid Plateau 100 metre grid

The higher resolution grid is shown in Figure 28. This grid focuses on the flanks of the volcano which show considerable detail. At this resolution not much detail is seen on the plateau. This grid may not match up perfectly at the edges with the 250 m grid as it used a subset of the data shown in Figure 25, using mainly the swath data from the base of the plateau inward as well as the LADS, satellite derived bathymetry, chart and topographic data in the shallow water. The computational parameters used in Intrepid are shown in the table.

Table 5: Intrepid gridding parameters for the ~100 m grid.

PARAMETER	VALUE
Latitude range	-32.2° to -31.12°
Longitude range	158.62° to 159.7°
Cell size	0.0009 degrees (~3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	1,000 cells

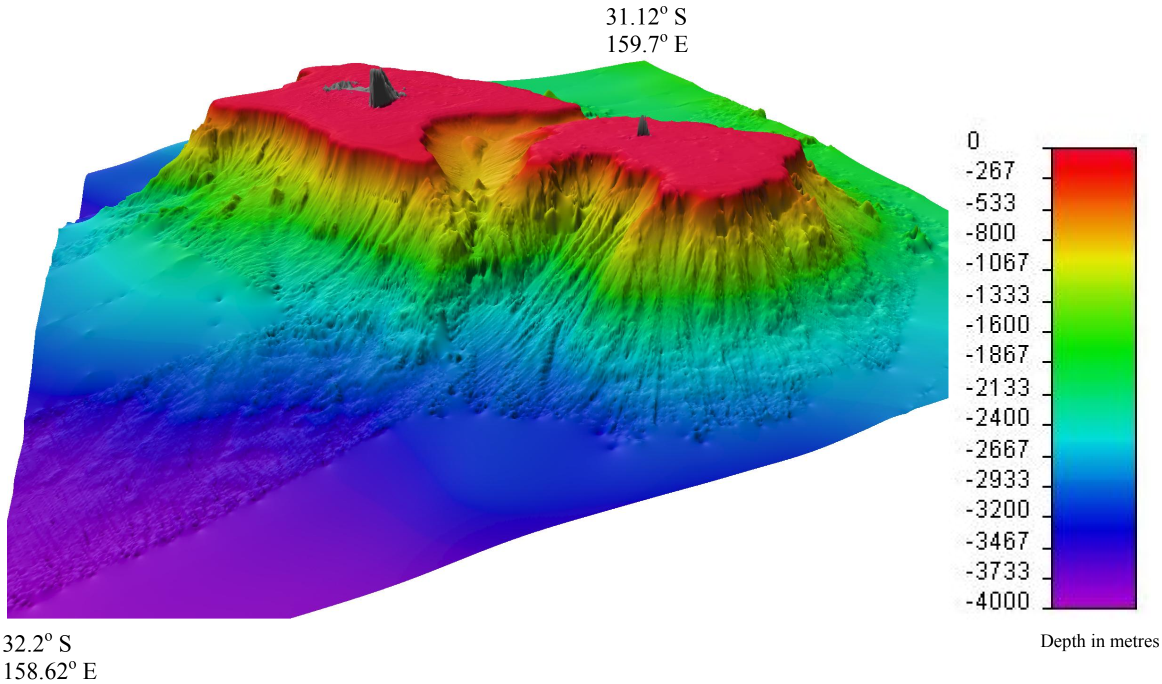


Figure 28: *The Lord Howe volcano base 100 m grid showing the fine detail in the flanks (vertical exaggeration X 4, position marker approximate only).*

Lord Howe Island, Ball's Pyramid and reef 40 metre grid

The even higher resolution grid showing detail in the reef is shown in Figure 29. It uses a subset of the data shown in Figure 25 as described for the 100 m grid. The computational parameters used in Intrepid are shown in Table 6. This grid is only valid in the coloured region and the grey area of the grid should be ignored. Numerous ripples can be seen in the grey area which is an artefact of the CARIS gridding scheme, due to gridding a lower resolution 13 kHz dataset. Also, because a subset of the original data was used for gridding due to computational limitations, the grid in the grey area does not match up perfectly with the 250 and 100 metre grids. On the plateau (coloured region) no gridding artefacts were observed, due to the higher resolution 32 kHz dataset and the grid in this region can be considered reliable when compared to the original data.

Table 6: Intrepid gridding parameters for the ~40 m grid.

PARAMETER	VALUE
Latitude range	-32.01° to -31.24°
Longitude range	158.8° to 159.506°
Cell size	0.00036 degrees (~1.3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	2,000 cells

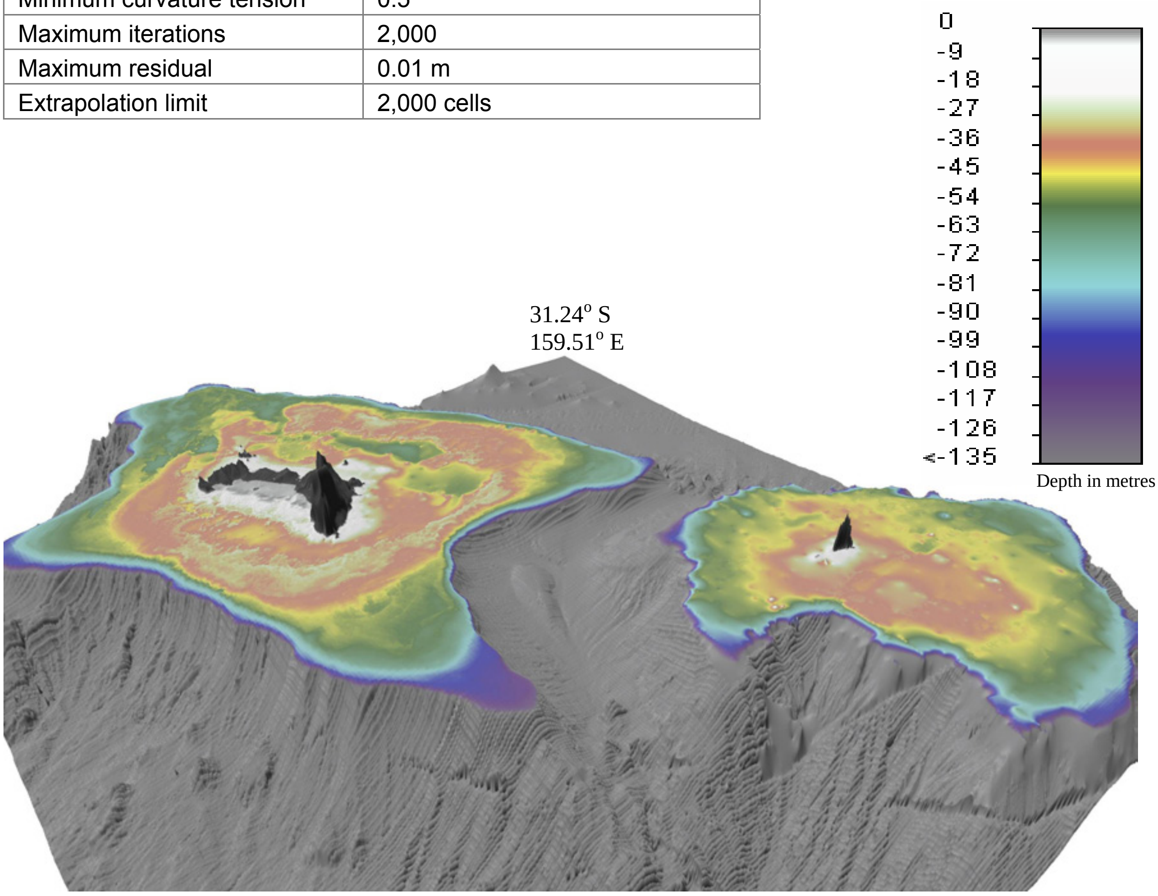


***Figure 29:** The Lord Howe Island plateau 40 m grid showing detail in the reef structure (vertical exaggeration X 4, position marker approximate only).*

Lord Howe Island reef 8 metre grid

In the reefal areas surrounding Lord Howe Island, a higher resolution grid (8 m cell size) was considered appropriate. This grid was achieved by taking the following steps:

- An 8 m cell-sized grid (from CARIS) of the multibeam data areas was obtained (Figure 30). This grid has a large gap in the area of Lord Howe Island and only sparse information in the Balls Pyramid area.
- In the area of the gap, mentioned above, the shallow water satellite data, LADS, topography, chart data and a small amount of multibeam data were gridded (using Intrepid) to a grid with an 8 m cell-size.
- These two 8 m grids and the 40 m grid produced previously were merged using the Intrepid program *Gridmerge*. This program not only merges the grids but incorporates a feathering process which smoothes the boundaries between the original grids and is able to interpolate areas where the cell-size was originally 40 m down to an 8 m cell size.

The end result (Figure 31) was highly satisfactory as the input grids were quite consistent with each other. This is no doubt due to the considerable effort expended in ensuring that the original soundings were reliable. The parameters used in making the 8 m grid and the merge are given in Tables 7 and 8 respectively. This grid is only valid in the coloured region and the grey area of the grid should be ignored for the same reasons that were noted for the 40 metre grid.

Table 7: Intrepid gridding parameters for the ~8 m grid (non CARIS data)

PARAMETER	VALUE
Latitude range	-31.6165° to -31.4730°
Longitude range	159.0240° to 159.1510°
Cell size	0.000072 degrees (~0.3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	500 cells

Table 8: Intrepid Grid Merge parameters for the ~8 m grid.

PARAMETER	VALUE
Overlap limit	500
Filter length	5,000 m
Smoothing iterations	3
Soothing residual	0

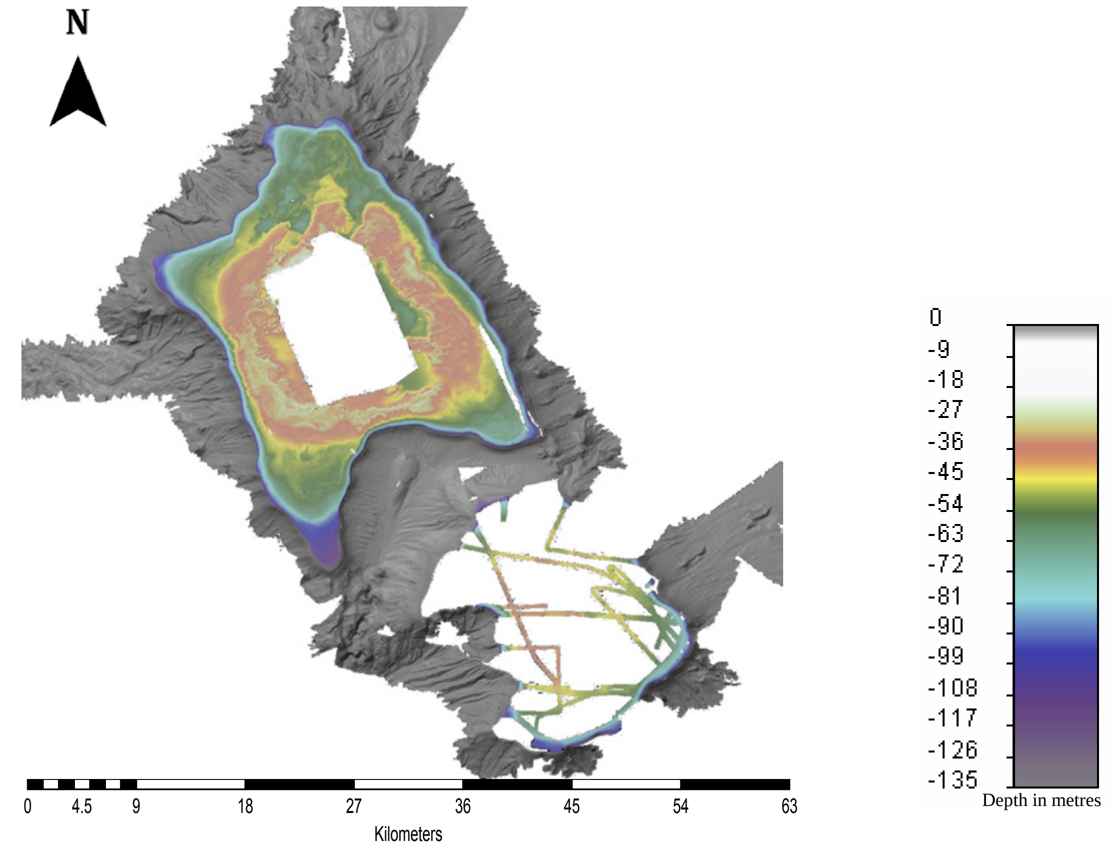


Figure 30: *The 8 m dataset export from Caris.*

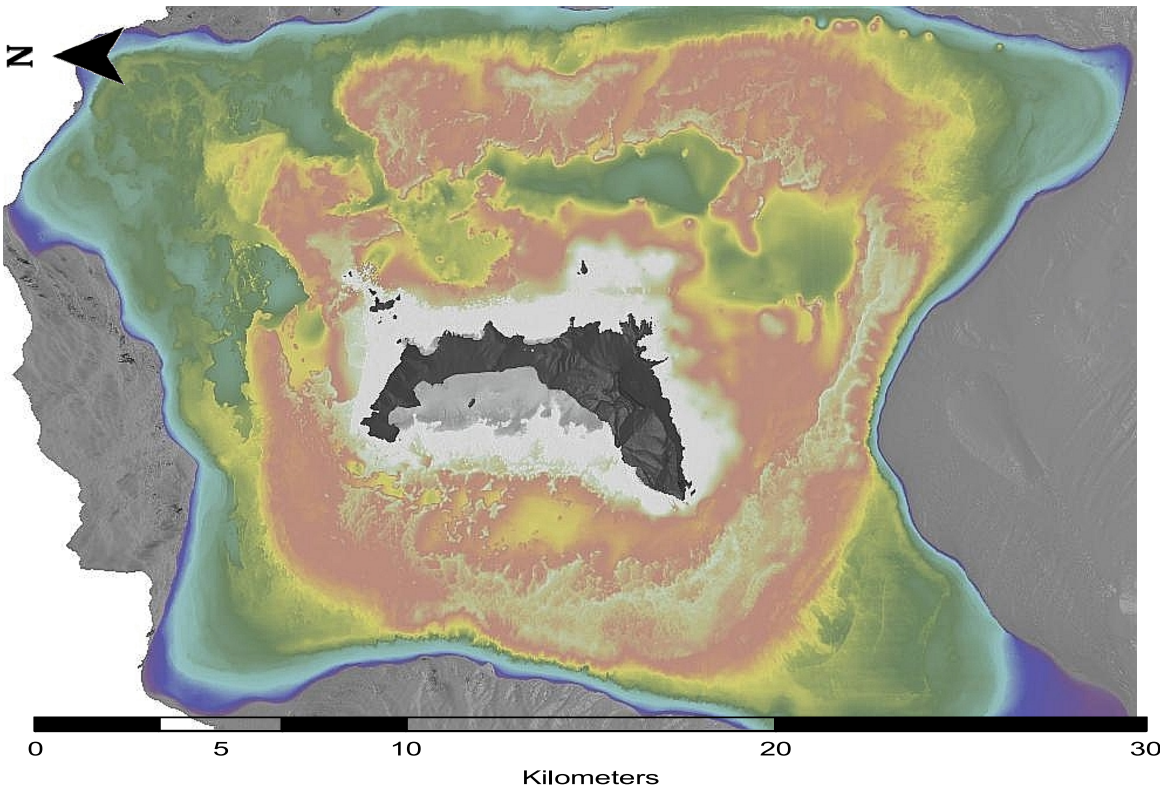


Figure 31: *The Lord Howe final merged 8 m grid focusing on the reef.*

7. Final Grids

The Final Grids are known as:

1. Lord_Howe_8m_grid_2010 (.ers, .sd, .xyz …)
2. Lord_Howe_40m_grid_2010 (.ers, .sd, .xyz …)
3. Lord_Howe_100m_grid_2010 (.ers, .sd, .xyz …)
4. Lord_Howe_250m_grid_2010 (.ers, .sd, .xyz …)

and exist in ERMapper, ArcGrid, Fledermaus and ASCII xyz grid formats. A copy of the gridded files reside on the project unix disks /nas/pmd/bathy/grids along with other grids that have been produced by the Geophysical Analysis and Data Access (GADA) group. Appendix 3 provides the ANZLIC compliant metadata.

These sets of grids of the Lord Howe Island region are clearly an improvement on previously available grids. In comparison to those grids, the new grids:

- Show a high level of detail in the reefal areas around Lord Howe Island and the volcanic plateau.
- Show a good level of detail down the flanks of the volcano.
- Show the various islands in their correct spatial locations and in their correct form.

These grids are made up of many different datasets employing many technologies and sounding methods as well as coming from different eras in time. In terms of the reliability in both the navigation and the sounding the following ranking should be considered:

- Multibeam swath
- Laser airborne depth sounder
- Singlebeam echosounder
- Naval charts
- Satellite derived bathymetry

However it should be noted that some old chart soundings may be accurate but the navigation not that certain. This may also apply to other older echosounder surveys. Modern multibeam and singlebeam echosounder data may be considered to be the most accurate both in terms of navigation and soundings. Many bathymetry surveys now claim navigation with an uncertainty to within 3 m while the sounding is to within 1 m. So in conclusion it may be assumed that the highest confidence in these grids can be placed in the regions of the grid where data has come from the newer multibeam, LADS and singlebeam surveys. In regions where data was sparse and heavily interpolated the final gridded bathymetry is *only* an indication of possible values there based on the nearest measured bathymetry.

The new Australian Bathymetry and Topography Grid (Whiteway, 2009) incorporated an earlier version of the 250 m grid created here for the Lord Howe region. This prototype used all the data available at the time which included singlebeam, multibeam and SRTM data. The resulting grid for the Lord Howe region is better than the previous version (Webster and Petkovic, 2005), but it uses the unreliable ETOPO1 to fill in unsurveyed areas.

It is envisaged that the new grids would be suitable for:

- Tsunami modelling
- Storm surge modelling
- Ocean and tide modelling
- Environmental impact studies
- Marine conservation
- Fisheries management
- Law of the sea territorial zoning

Possible future work may include detailed bathymetric mapping around Ball's Pyramid (a proposal has been submitted), and surveying closer to the south eastern end of Lord Howe Island.

Only the 250 m grid is available for public release as part of the Australian Bathymetry and Topography Grid 2009 or as a dedicated Lord Howe Island grid from this work.

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Appendix 1

MULTIBEAM SYSTEMS

The swath data were acquired by four research vessels (Table 9): IFREMER's *L'Atalante*, CSIRO's *Southern Surveyor*, Lamont-Doherty's *Maurice Ewing* and NIWA's *Tangaroa*.

These vessels have bathymetry multibeam acquisition systems designed for different depth ranges. The *Southern Surveyor* and *Tangaroa* operate in the mid-depths (1000-2500 m), whilst the *L'Atalante* and *Ewing* systems are more suitable for deep water operations (> 3000 m). Most of the multibeam swath data collected in the shallow depths were acquired by the *Southern Surveyor* on voyage GA-2461 (SS06/2008).

The table below summarises the different acquisition systems, operating frequencies, number of beams and depth range for each vessel.

Table 9: Multibeam systems

ECHO SOUNDER	EM12D	EM300	ATLAS HYROSWEEP DS
Builder	Kongsberg Simrad	Kongsberg Simrad	Atlas Hydrographic
Vessel	L'Atalante	Southern Surveyor/ Tangaroa	Maurice Ewing
Antenna	Flat (V shape)	Flat horizontal	?
Depth range (m)	50 – 12000	20 – 4000	3000 – 11000
Depth category	Very deep	Moderate	Very Deep
Frequencies (kHz)	13	32	15.5
No. of beams/ping	162	135	59
Angular aperture	150º	150º	90°
Width of beams emitting X receiving	1.8°x3.5°	1°x1°	2°x2°

Figure 32 shows the relationship between swath width and water depth for the EM300 and EM12D systems illustrates the mapping potential of 13 kHz systems in deeper water. The 32 kHz EM300 system reaches its optimal mapping capacity in about 2500 m water depth, which limits it to the upper portions of the Lord Howe Island volcano.

The EM300 however has narrower beamwidths, higher sonar frequency and a close beam spacing than the other systems which makes it more useful for higher resolution investigations in shallower areas (< 1000 m).

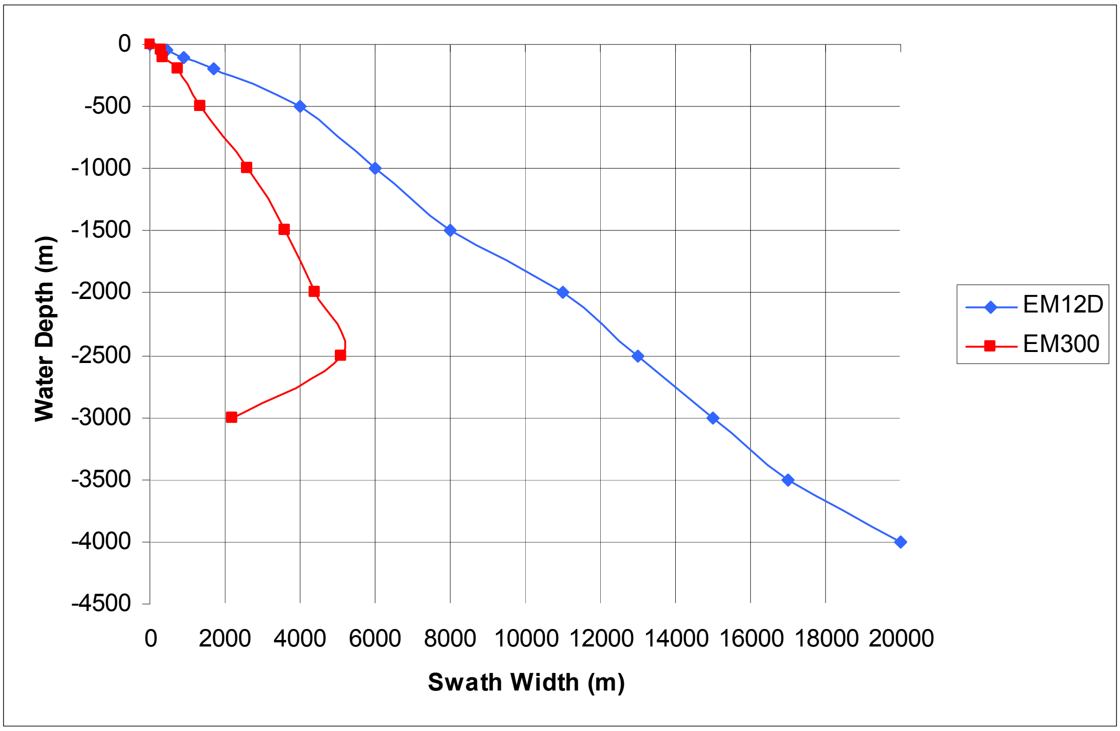

Figure 32: *Coverage versus depth for two multibeam systems.*

MULTIBEAM PROCESSING

Prior to the Intrepid gridding operation all of the multbeam data had been extensively edited and corrected using the CARIS HIPS & SIPS processing software. Figure 33 below shows the CARIS workflow.

Essentially a file describing the configuration of the various sensors (GPS antenna, motion sensor unit and transducer heads) and any biases (roll, pitch, yaw and time latency) is created so that the soundings can be located in their correct spatial positions. Measurements of the speed of sound in water and an estimate of tidal heights (determined using WXTide32 software) are made and also entered into the CARIS application.

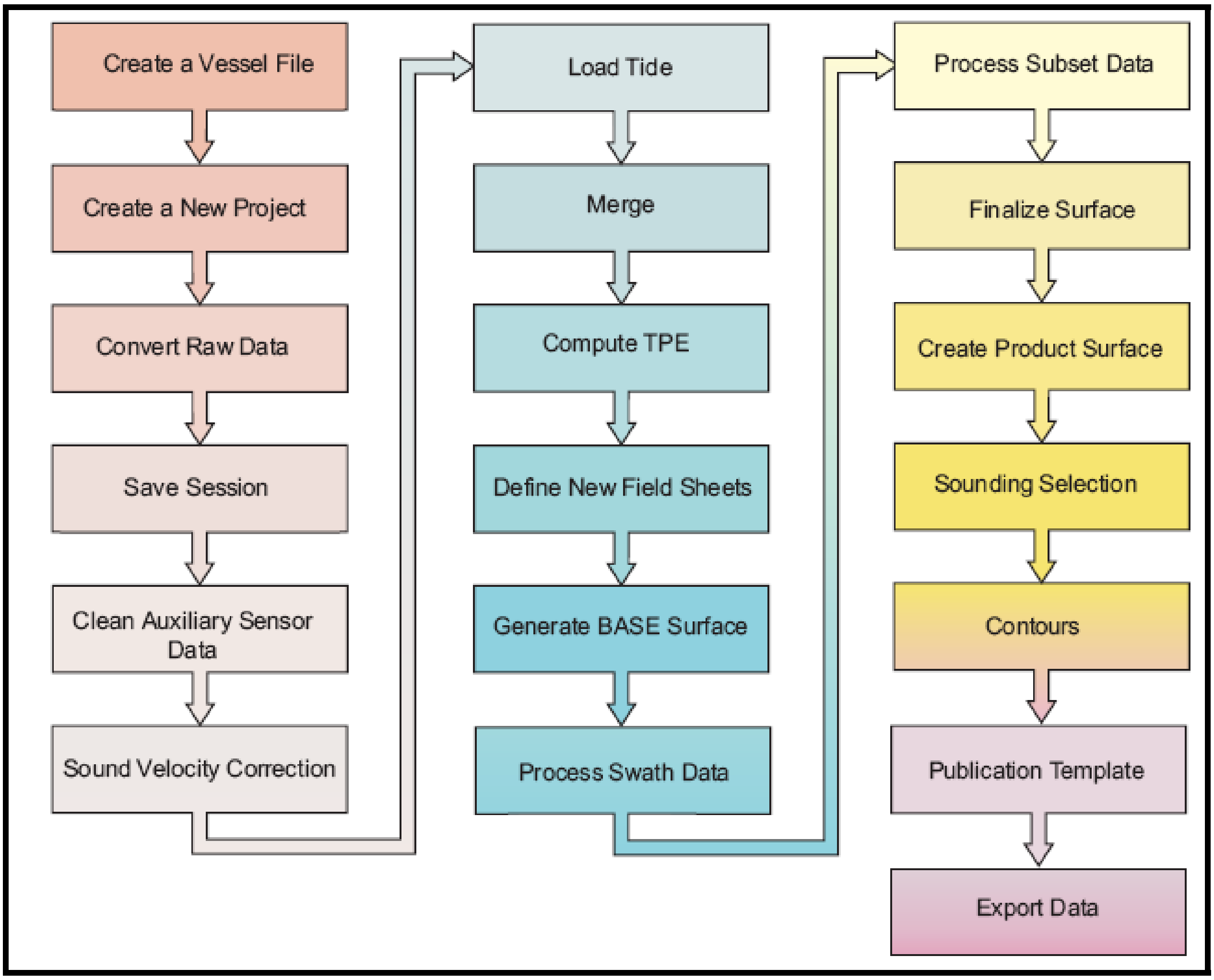

Figure 33: *CARIS HIPS Data Processing Flow (non CUBE).*

The raw multibeam data for each survey are then imported and the appropriate vessel information assigned to the data. Next, the various sensor data (navigation, attitude and soundings) are cleaned and edited using a range of tools within the application.

The soundings are then corrected using the appropriate sound velocity and tidal models applying at the time and location of the acquisition.

Finally a BASE surface (ie a grid) is made at whatever resolution is desired. For this work an 8 m, 40 m and 100 m cell-sized grids were produced for areas that represented the reefal areas, the plateau area of the volcano and the entire area of interest respectively. These were than exported as an ASCII grid for incorporation with the other datasets.

Appendix 2

SATELLITE DATA PROCESSING

Method

A multi-spectral scene from the Quickbird sensor (480 – 805 nm), acquired on the 9th February 2009, was used for this study. To convert the raw satellite data to reflectance data a MODTRAN based atmospheric correction procedure was completed using the c-WOMBAT-c interface (Brando and Dekker, 2003).

De-glinting; the removable of water-surface specular reflection was completed, using a commonly used glint-correction technique for optical imagery, which assumes a linear relationship across glinted and non-glinted pixels between each of the visible bands and the near-infrared (NIR) in optically deep water (Hochberg et al. 2003, Hedley et al. 2005). Land and exposed inter-tidal areas were masked from the imagery using a NIR threshold approach.

Depths were then derived through the application a physics-based bathymetry mapping technique: SAMBUCA (Semi-Analytical Model for Bathymetry, Un-mixing, and Concentration Assessment) which was developed in the ENVI/IDL environment as an objective and repeatable algorithm for extracting aquatic environmental information on a pixel-by-pixel basis from remote sensing data (Wettle and Brando, 2006). It is based on the Lee et al. (1998, 1999) for retrieving environmental variables from remote sensing data using an analytical model and optimization routine.

The basis of this approach is the expression of the subsurface remote sensing reflectance as a set of variables and a parameterization of this model to define it as a function of a set of environmental parameters. An optimization routine is used to minimize the difference/error between the measured subsurface remote sensing reflectance and the model by altering the variables and retrieving the environmental parameters, including water depth, that correspond to the lowest error. This process uses a library of benthic substrate spectral signatures to determine, on a pixel-by-pixel basis, the ratio composition of any two substrates for example 70% sand 30% coral. The library used in this project consisted of 3 common benthic substrates (sand, massive coral, seagrass) provided by the University of Queensland.

Quality Control

The optimisation process in SAMBUCA varies the environmental parameters associated with the water properties, depth and bottom substrate until the modelled spectra for each pixel is as close to the observed data as possible. Pixels where the error between the modelled and observed reflectance spectra is large indicate areas where the derived depth and other environmental variables may be considered more unreliable, and these were masked from the model as a quality control measure.

Validation

The derived depths were validated against a selection of 8750 LADS data points across the lagoon to a depth of 15 m. The resulting scatter-plot is shown in Figure 34 with a regression coefficient value of 0.879. Issues arising from this validation, including a general overestimation of depth beyond 4 m and a section of underestimated depths at approximately 2 and 3.7 m, are scheduled to be addressed by upcoming field work at the island. Acquisition of site-specific substrate spectra and water quality measurements are expected to improve the modelling results and accuracy in subsequent versions of the bathymetry model.

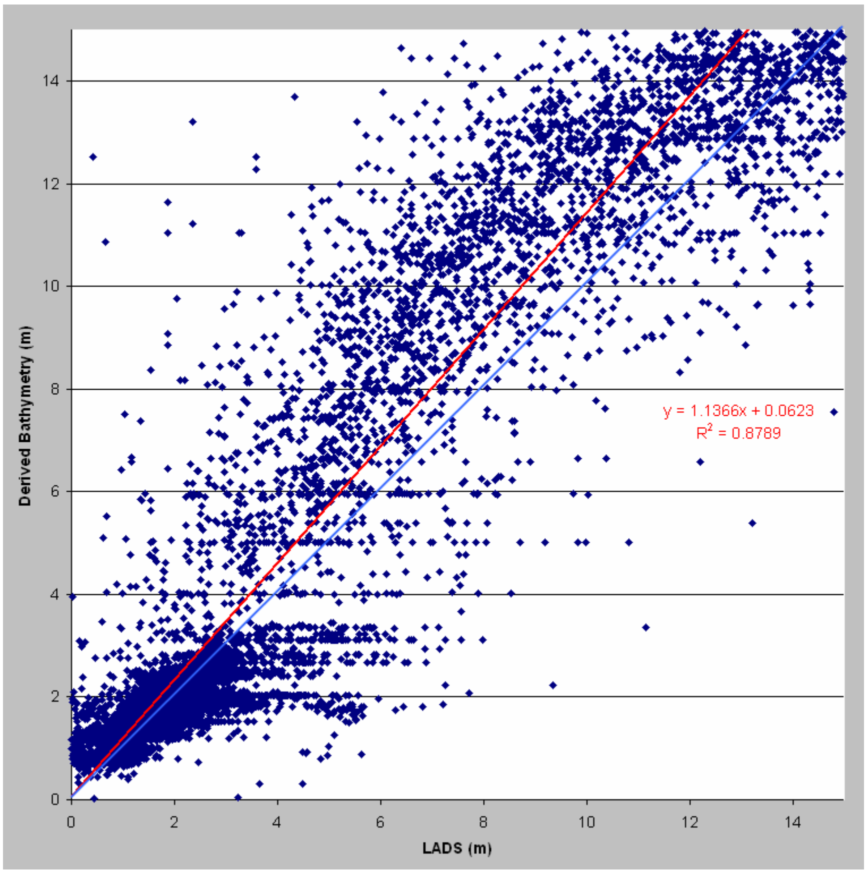

Figure 34: *Regression of Quickbird derived depths versus LADS data (regression line: red, 1:1 line: blue).*

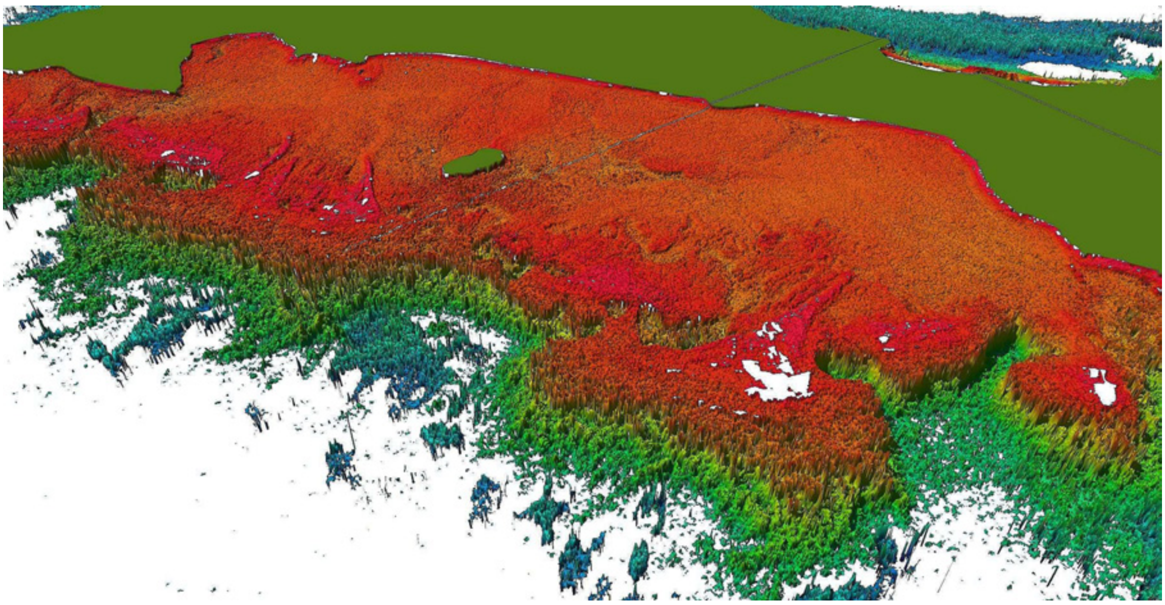

Figure 35: *A close- up of the bay of the Lord Howe Island bathymetry revealing many features which are visible at the resolution of satellite data (each pixel is 2.4 m, land is in olive green).*

Appendix 3

ANZLIC METADATA RECORD

Metadata Element	Entry
ANZLIC Identifier	ANZCW0703013935
Title	High Resolution Bathymetry Grids of the Lord Howe Island Region
Custodian	Geoscience Australia
Jurisdiction	NSW
Abstract	Detailed seabed bathymetric data are needed to better understand our marine environment because models of seabed morphology derived from these data provide useful insights into physical processes that act on the seabed and the location of different types of seabed habitats. Lord Howe Island lies approximately 580 km off the northern coast of New South Wales. It is a volcanic island with a fringing coral reef on its western shore, and a shallow (20 – 120 m) shelf surrounds the island. Bathymetry data are required in this area to help identify major seabed processes and habitats, especially relict reef structures, and to measure how well physical seabed properties act as surrogates of patterns of biodiversity on this mid-ocean carbonate shelf. The data are also required to enable modelling of tsunami as they interact with the shelf around the island and the coast. Four new bathymetry grids have been created, including grids that integrate bathymetry with the island's topography.
Search Word(s)	GEOSCIENCES Geomorphology GEOSCIENCES Geophysics MARINE OCEANOGRAPHY Physical MARINE Reefs MARINE Coasts
Geographic Extent Polygon	158.15^{o} -30.65^{o}, 160.35^{o} -30.65^{o}, 160.35^{o} -32.85^{o}, 158.15^{o} -32.85^{o}
North Bounding Latitude	-30.65^{o}
South Bounding Latitude	-32.85^{o}
East Bounding Longitude	160.35^{o}
West Bounding Longitude	158.15^{o}
Beginning Date	2009-07-01
Ending Date	2010-06-31
Progress	Complete
Maintenance and Update Frequency	As Required
Stored Data Format	DIGITAL ER Mapper raster dataset, WGS84 Spheroid, WGS84 Datum
Available Format Type	DIGITAL - ER Mapper raster dataset, WGS84 Spheroid, WGS84 Datum DIGITAL - ARC/INFO 4 byte integer DIGITAL – Fledermaus SD file – ASCII X, Y, Z Grid File.

Access Constraint	Only the 250 m grid is available for public release.
Lineage	The grids are derived from data in Geoscience Australia's databases and recent sources which will eventually be entered into those databases. Satellite derived bathymetry was used in shallow waters. Seven swath datasets acquired between 1992 and 2009 were used. Five of the surveys supply extensive regional coverage, whilst the others are basically multibeam transits of the area. One LADS survey from the AHS was used. A high quality coastline, as well as topography data of Lord Howe and its islands were obtained from the Land and Property Information Management Authority. Eleven singlebeam surveys from the GA MARDAT database. These data range in vintage from 1971 to 1998 and were edited to remove suspect datapoints, but were left uncorrected with regards speed of sound issues. Chart data from the AHS were used in both deep and shallow water but most of it was superseded by swath data. ETOPO1 data was used in the area of two seamounts where data were sparse. One singlebeam survey fro the University of Wollongong that was previously unknown to GA was used.
Positional Accuracy	The grid incorporates data from surveys acquired since 1959. Modern surveys which use GPS have a positional accuracy of 5 - 30 m depending on several factors, while earlier surveys which used dead reckoning and Transit satellite fixes had positions accurate to 50 - 2000 m depending upon the water depth and strength of currents. These surveys overlap in an irregular distribution and the more extensive, higher quality swath datasets were used to mask data of lower quality and extent. Effectively there are two regions in the grid. One covered by multibeam data of high positional and bathymetric accuracy and the other heavily reliant on chart data and singlebeam surveys which are of lower positional and bathymetric accuracy. The grid cell sizes are 0.00225˚ (nominal 250 m), 0.0009˚ (nominal 100 m), 0.00036˚ (nominal 40 m) and 0.000072˚ (nominal 8 m).
Attribute Accuracy	The attribute accuracy varies depending upon the predominant data source in an area. Where modern, high quality swath bathymetric data that form an areal coverage exists, overlapping swaths and speed of sound corrections show that the data are quite accurate. Some transit swath data also have speed of sound corrections applied and are assumed to be highly accurate. Other transit swath surveys have utilized a nominal speed of sound of 1500 m/s and are not as accurate (problems were encountered trying to apply correction). Most other data assume a nominal speed of sound of 1500 m/s, although some have had corrections applied. For a significant portion of the region, predicted bathymetry from satellite data are the only source of data. No attempts have been made to compare bathymetry from high quality datasets to that which would be obtained from lesser datasets, although all the data exist to perform such a task.
Logical Consistency	Each of the input datasets were examined in detail and edited where necessary. Areas of poor navigation and obviously bad bathymetry were discarded. A hierarchical system was employed whereby the best and most extensive datasets replaced data of lesser datasets. All the various datasets were then brought together by the gridding algorithm (Intrepid – Desmond Fitzgerald Associates) and an ERMapper format grid produced.

Completeness	All of the known, available data (to 2010) were used in the production of the grids. The GA databases which underpin this grid will be updated as new surveys are completed and older surveys have corrections applied to them. A data density map was produced as a means of assessing the completeness of coverage and it could possibly be used as a variably opaque overlay of the bathymetric grid to highlight good quality areas and darken lesser quality areas.
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Electronic Mail Address	sales@ga.gov.au
Metadata Date	2010-06-10
Additional Metadata	Mleczko, R., Sagar, S., Spinoccia, M., and Brooke, B. 2010. The Creation of High Resolution Bathymetry Grids for the Lord Howe Island Region. Geoscience Australia Record 2010/36.