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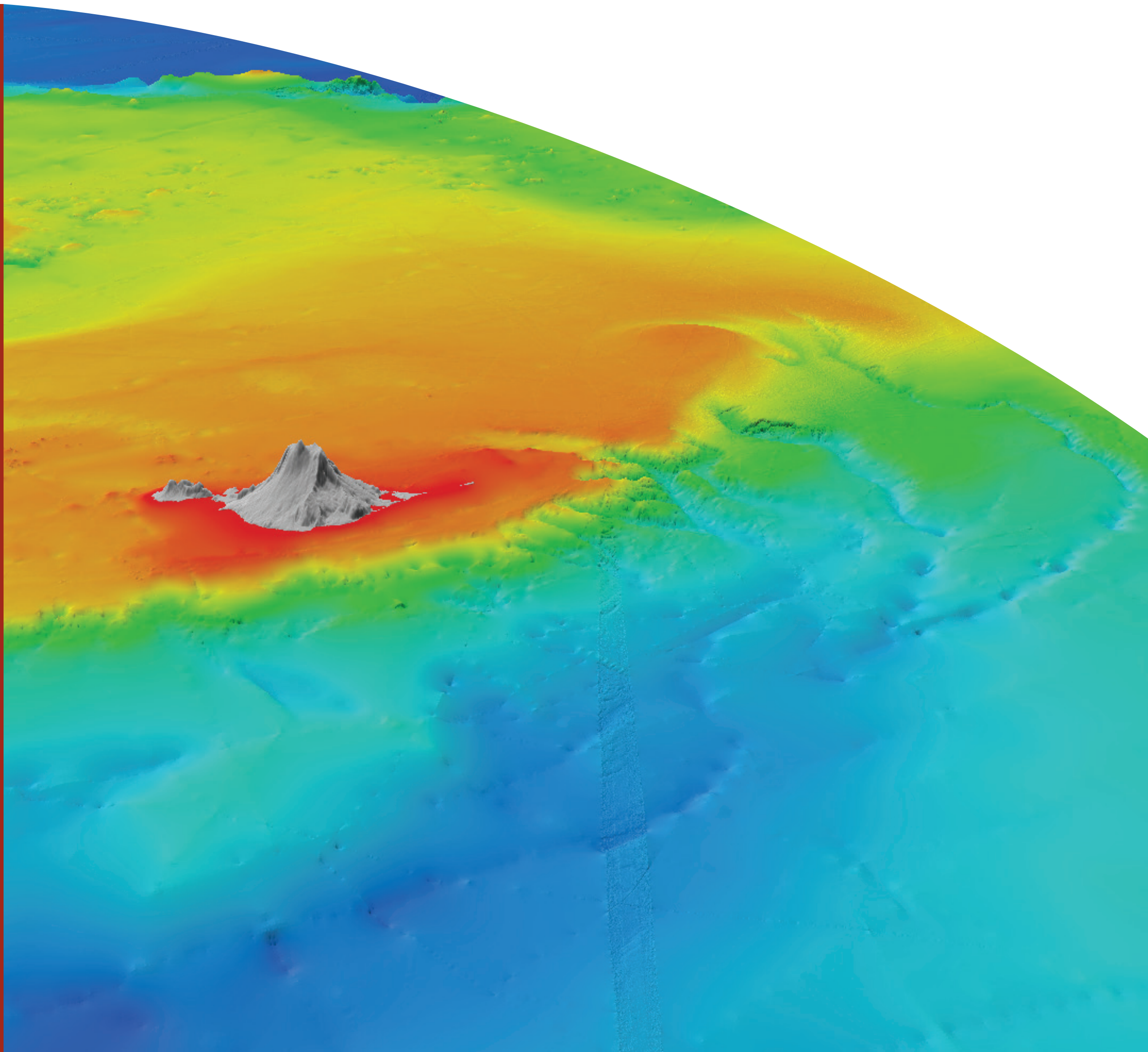

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by

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Contents

Abstract

The existing regional bathymetric grid of the Kerguelen Plateau, south-west Indian Ocean, was updated using new singlebeam echosounder data from commercial fishing and research voyages, and some new multibeam swath bathymetry data. Source bathymetry data varies from International Hydrographic Organisation (IHO) S44 Order 1a to 2. The source data were subjected to area-based editing to remove data spikes, then combined with the previous Sexton (2005) grid to produce a new grid with a resolution of 0.001-arcdegree. Satellite-derived datasets were used to provide island topography and to fill in areas of no data. The new grid improves the resolution of morphological features observed in earlier grids, including submarine volcanic hills on the top of the Kerguelen Plateau and a complex of submarine channels draining the southern flank of the bank on which Heard Island sits.

IMPORTANT INFORMATION

Geoscience Australia (GA) Notice: This bathymetry grid is not suitable for use as an aid to navigation, or to replace any products produced by the Australian Hydrographic Service. Geoscience Australia produces the bathymetry grid of the Kerguelen Plateau specifically to provide regional- and local- scale context for scientific and industry projects, and for public education.

Service Hydrographique et Océanographique de la Marine (SHOM) Notice: No official hydrographic office has verified the information contained in this document and may not be held liable for the reliability of its reproduction or any subsequent amendment. The possession of this document does not constitute an exemption from the obligation to use the appropriate naval documents provided for by national and international regulations.

Introduction

Heard Island and McDonald Islands are situated on the Kerguelen Plateau within the south-west Indian Ocean and lie within Australia's marine jurisdiction (Figure 1). Heard Island and McDonald Islands (HIMI) are surrounded by an Exclusive Economic Zone extending 200 nautical miles from their coasts and much of the Kerguelen Plateau south of Heard Island has been recognised as Australian Extended Continental Shelf by the UN Commission for the Legal Continental Shelf. The area is currently targeted by fishers licensed under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR).

Geoscience Australia (GA) and Australian Antarctic Division (AAD) scientists have a need to revise the Kerguelen Plateau digital elevation model (DEM), or bathymetry grid, in order to better define the seabed geomorphology and depth contours, to assist in marine environmental management of this sensitive area. This would particularly help with the management of the Marine Reserves and Conservation Zones declared by Australia around HIMI

(http://www.heardisland.aq/__data/assets/pdf_file/0017/638/marine_reserves.pdf).

Ongoing improvements in bathymetric mapping will help improve the understanding of the marine environment in these areas. The remoteness of the region means that the amount of data available is small but growing as research and fishing vessels visit the area. Therefore periodic updates of existing bathymetry grid compilations using new data will continue to improve the DEM for other activities. This new grid includes the new data available in 2010.

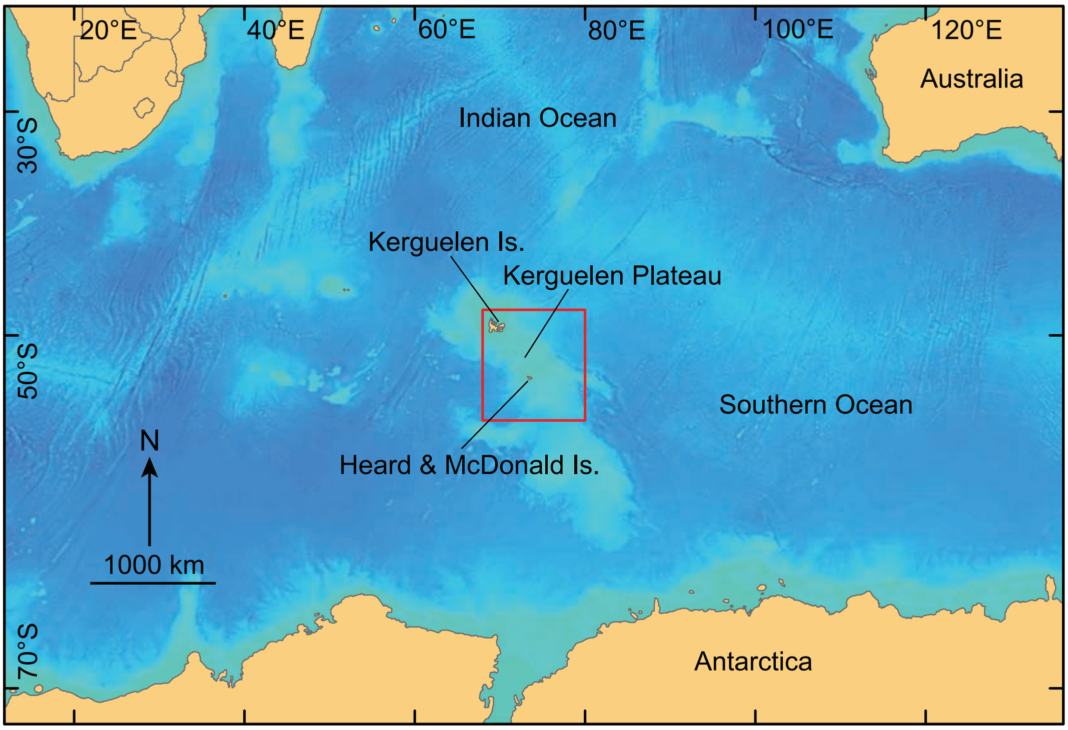

Figure 1: *Mercator projection map of the Kerguelen Plateau within the south-west Indian Ocean. The red box outlines the grid area. Scale is correct at latitude 52°South*

Sexton (2005) compiled Geoscience Australia's first digital elevation model (DEM) of the Kerguelen Plateau based upon the available source bathymetry datasets at the time (Figure 2). This grid covered the geographic area: latitude 48° to 56° South, longitude 68° to 80° East. The grid used a horizontal datum of WGS84 and a vertical datum of Mean Sea Level (MSL), with a grid pixel resolution of 0.005-arcdegree (ca. 500m).

Other bathymetry grids which covered the Kerguelen Plateau region are the global-scale GEBCO (IOC et al., 2003), ETOPO1 (Amante and Eakins, 2008), and SRTM30_Plus (Becker et al., 2009) datasets, with grid pixel resolutions of ca. 1 nautical mile, 1 nautical mile, and 1 km respectively. However, these global-scale datasets lack the source data coverage and have coarser grid pixel resolutions compared to the regional-scale Sexton (2005) grid. The Sexton (2005) grid provided improvements in the definition of the major banks and detected previously unknown features, such as channelling south of Heard Island.

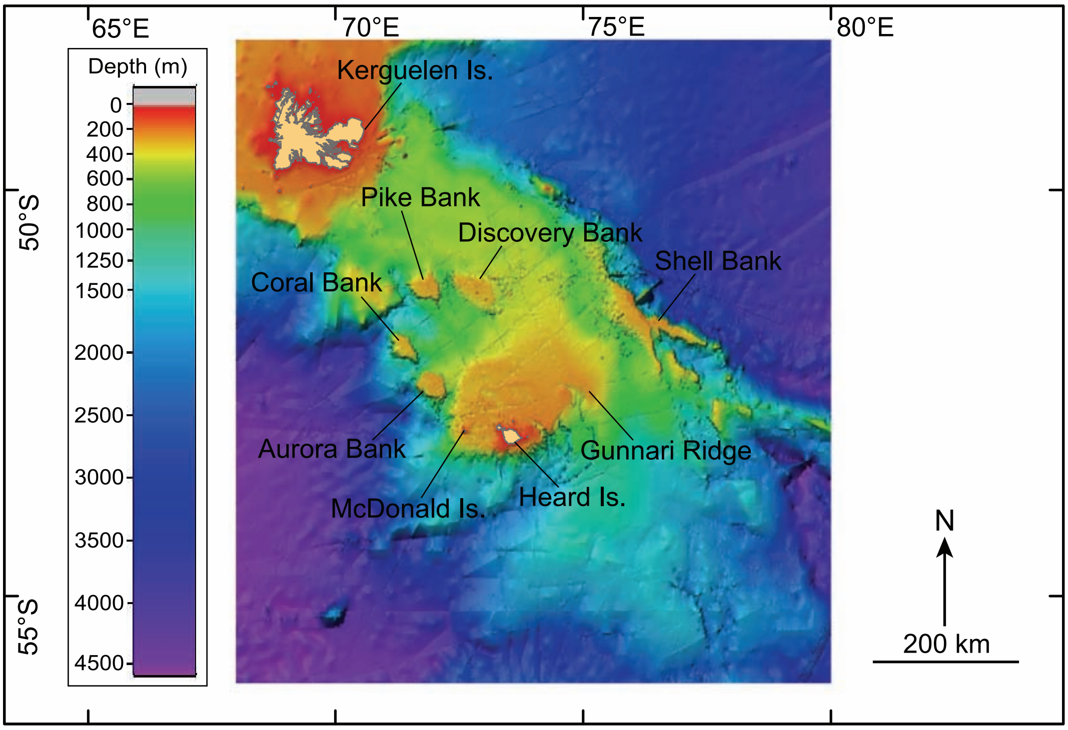

Figure 2: *Mercator projection map of the Sexton (2005) grid and the major geomorphic features on the Kerguelen Plateau. Scale is correct at latitude 52°South*

Then in 2010, significant additional bathymetric datasets became available, including research vessel multibeam swath data and extensive commercial fishing vessel shiptrack data. Therefore this project aimed to revise the current Sexton (2005) grid for the Kerguelen Plateau region at a more detailed grid pixel resolution of 0.001-arcdegree (ca. 100 m). The new grid utilised the latest data sourced from ship-based multibeam and singlebeam echosounder surveys, as well as satellite land elevation data.

This report describes the development of a new high-resolution bathymetry grid for the Kerguelen Plateau region, called kerg_dem, short for Kerguelen digital elevation model. The kerg_dem grid spans an area latitude 48° to 56° South, longitude 68° to 80° East, with a grid pixel resolution of 0.001-arcdegree (ca. 100 m). The total area of the kerg_dem grid is about 736,000 km^2. Further detail is presented about the methods used to derive additional grids and layers, as well as the Total Vertical Uncertainty (TVU) grid associated with the new kerg_dem grid.

Input Datasets

SINGLEBEAM DATA

New singlebeam echosounder data were provided from fishing vessel shiptrack data, acquired on behalf of the Australian Antarctic Division (AAD) and supplied to the authors on the proviso that the datasets are commercial-in-confidence and not publicly-available, nor identified as such in the Figure 3 coverage map. These data are simply listed in Appendix 1 as ‘Fisheries’. No account was taken of the tidal range, so all data were assumed to have a vertical datum approximating Mean Sea Level (MSL). All horizontal positions were referenced to the WGS84 datum.

The Australian Hydrographic Service (AHS) has conducted singlebeam echosounder surveys through the area from 1998-1999 while Royal Australian Navy hydrographic survey personnel were embarked onboard the RV *Aurora Australis*. Data were acquired using the AHS survey motor boat and are of generally high quality. The AHS data have previously been incorporated into the Sexton (2005) grid, however, the addition of the AHS source data into the higher-resolution kerg_dem grid provides greater geomorphic detail.

The AAD have acquired singlebeam data using the RV *Aurora Australis* during numerous surveys from 1990-2008. A major Heard Island survey during 2003-2004, called HIPPIES, provided extensive singlebeam data coverage. The data supplied to the authors were generally of good quality but still required extensive editing of noise. These data have previously been incorporated into the Sexton (2005) grid but provides additional useful detail at the resolution of the kerg_dem grid.

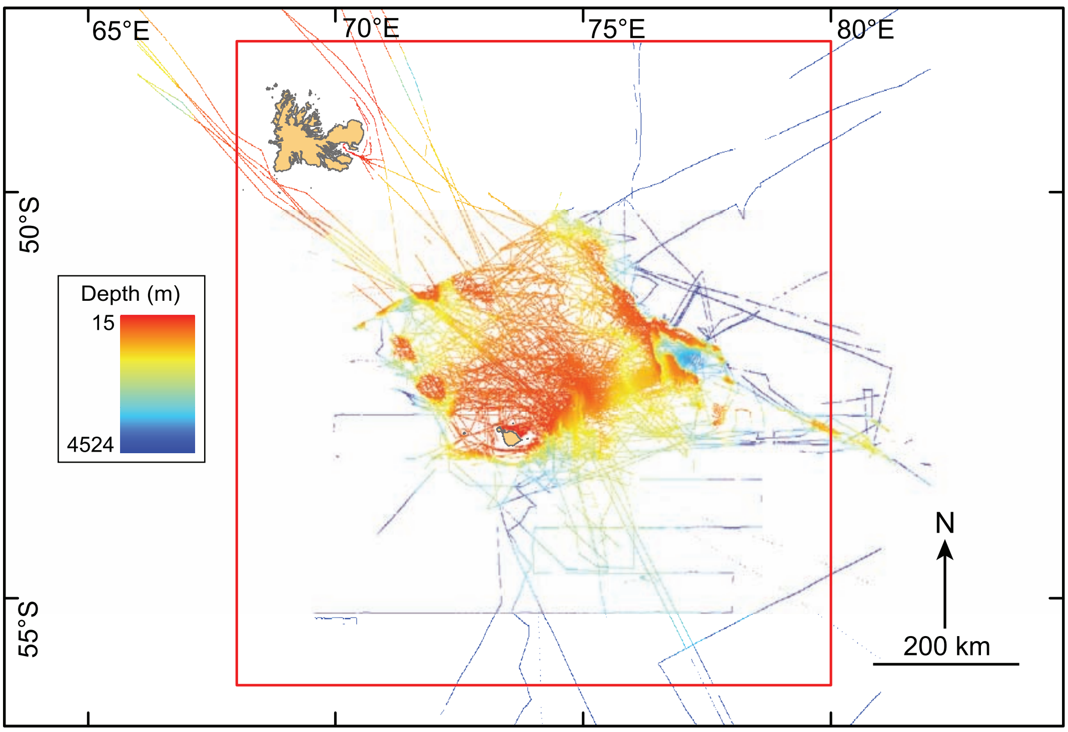

Figure 3: *Mercator projection map of the combined singlebeam data used in the kerg_dem grid*

MULTIBEAM SWATH DATA

In 2007, the German RV *Polar Stern* conducted a vessel transit from Punta Arenas, Chile, to Cape Town, South Africa, passing through the area via Heard Island and visiting Kerguelen Island (Figure 4). As far as we are aware, the RV *Polar Stern* dataset provides the only new multibeam coverage within the grid area within Australia's Exclusive Economic Zone (EEZ). The data are of high quality but still required extensive manual editing to remove noise.

The Japanese RV *Mirai* has previously transited through the project area and provides a minor area of multibeam data coverage in the south-east area of the grid. The data have previously been incorporated within the Sexton (2005) grid, however, the inclusion of the RV *Mirai* multibeam data provides more detail for the higher-resolution kerg_dem grid. The data are of high quality but also required manual editing of noise.

The Service Hydrographique et Océanographique de la Marine (SHOM) has conducted numerous multibeam surveys mostly within the deeper waters of the French EEZ around Kerguelen Island. Minor singlebeam surveys have also been conducted within the narrow bays and near-coastal areas of Kerguelen Island. The data were supplied as one file and could not be differentiated into separate multibeam and singlebeam surveys, hence the data were simply listed as one multibeam survey within Appendix 1. The SHOM data are of high quality, requiring only minimal editing of noise.

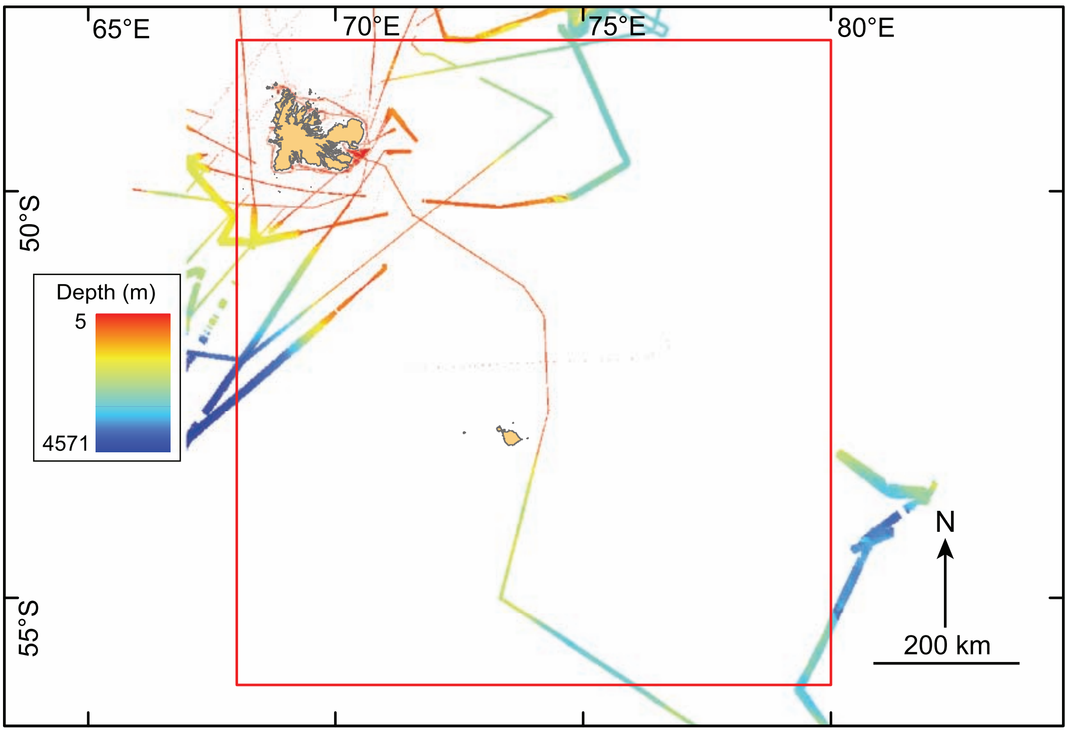

Figure 4: *Mercator projection map of the combined multibeam data used in the kerg_dem grid*

SATELLITE TOPOGRAPHY DATA

A 10 m-resolution TerraSAR DEM grid of Heard Island was acquired on behalf of the AAD and supplied to the authors for use as land elevation grid data (Figure 5). The grid data are referenced to the WGS84 horizontal datum and Australian Height Datum (AHD) vertical datum. AHD approximates MSL, therefore the Heard Island grid required no vertical adjustment in relation to the bathymetry data. All 0 m grid pixel values were changed to NoData, providing a clean grid with only positive land elevation pixel values. The grid data were resampled in ESRI Arc Toolbox using a bilinear sampling process to the same grid pixel resolution of 0.001-arcdegree as the final kerg_dem.

For the remaining islands in the vicinity of Heard island (e.g. McDonald Island and Shag Rock) and the numerous islands and islets comprising Kerguelen Island, the 3-arcsecond Shuttle Radar Topographic Mission (SRTM) (Farr et al., 2007) data were downloaded from the CGIAR Consortium for Spatial Information website (Jarvis et al., 2008). These data have been modified from the raw 3-arcsecond SRTM data to fill data voids thereby providing more complete land elevation coverage (Reuter et al., 2007). The SRTM grid data were resampled to a similar 0.001-arcdegree resolution as kerg_dem.

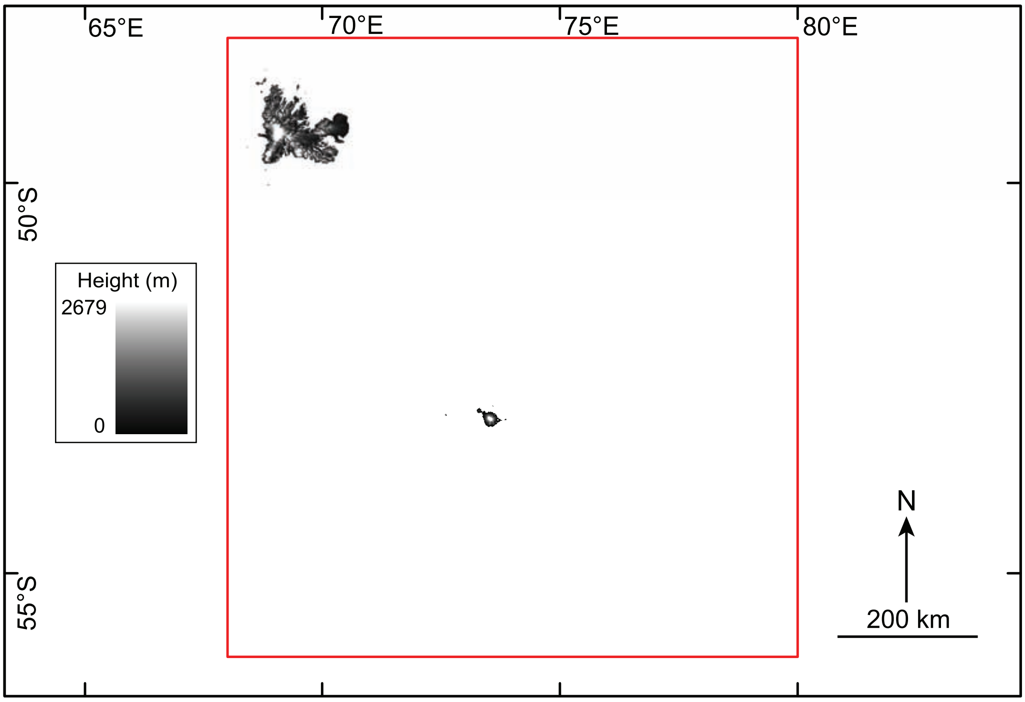

Figure 5: *Mercator projection map of the combined TerraSAR and SRTM grid data used in kerg_dem*

In addition, several ‘repair’ files of xyz data were created to smooth obvious errors in the Sexton (2005) grid due to unedited source data being used in this earlier grid. As the Sexton (2005) grid was used as a base surface during the gridding process for the new kerg_dem grid, it was important to remove these errors from the Sexton (2005) grid otherwise the errors would be carried through to the new kerg_dem grid, if there were no other co-located data to correct the errors. A combination of software tools, including Fledermaus 3DEditor, ArcGIS Spatial Analyst, and the ArcGIS Topogrid application were used to create the 'repair' files.

SOURCE DATA STATISTICS

As of 02 November 2010, the total number of individual surveys provided as source data to develop the kerg_dem grid were 17 (Table 1 and Figure 6). The singlebeam surveys provide the greater number of data sources (14) followed by the multibeam surveys (3), however, the SHOM data combined an unknown number of surveys so there are actually more multibeam surveys than recorded here. The multibeam data provides a relatively higher proportion of the xyz data at approximately 55% of the total file size (in bytes). The combined singlebeam data have a lower proportion of the xyz data at 45% of the total file size (in bytes). When taken together, the total source data files approximates >21 million individual xyz records for the development of the new kerg_dem grid.

Table 1: Descriptive statistics showing the contribution for the various ASCII xyz data sources used to develop the kerg_dem grid, as of 02 November 2010

	MULTIBEAM	SINGLEBEAM	TOTAL
No. Folders (surveys)	3	14	17
File size (bytes)	392,109,054	327,017,072	719,126,126
Percentage (bytes)	54.53	45.47	100.00
xyz records (approx.)	11,506,489	9,596,357	21,102,845

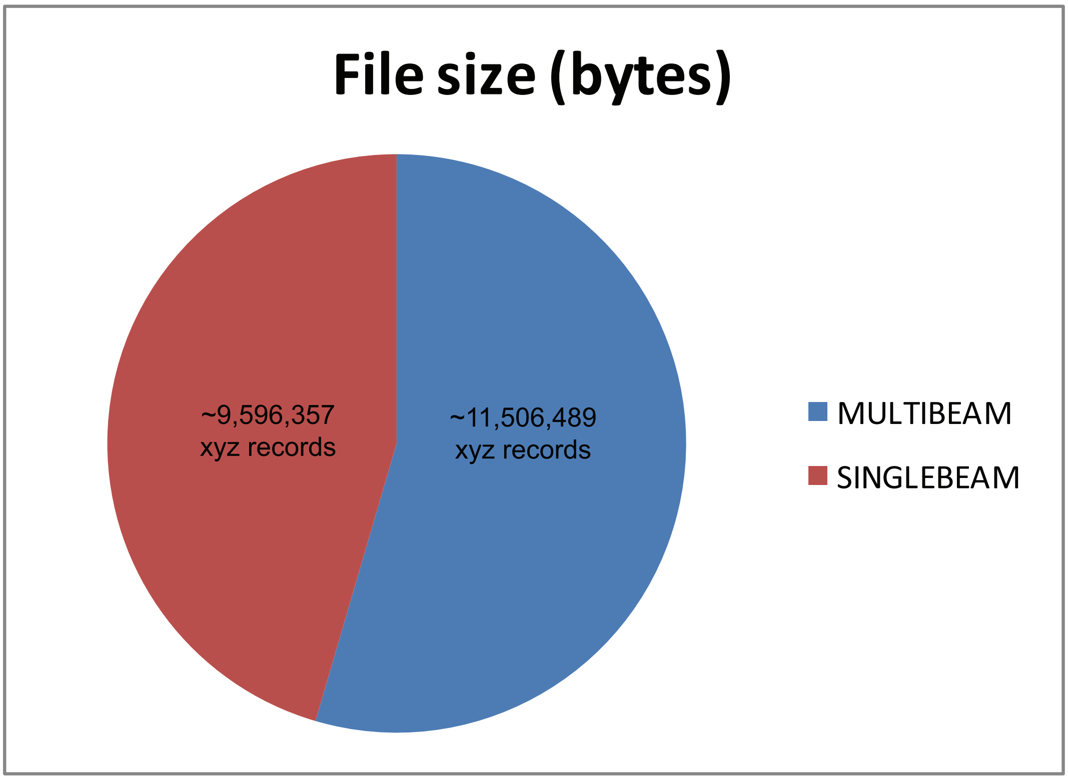

Figure 6: *Pie chart showing the contribution (as a proportion of bytes) for the various bathymetry source data types used to develop the new kerg_dem grid*

The Process

PRE-PROCESSING

All bathymetry source data required extensive area-based editing to remove noise and errors in the data (Figure 7). Individual survey xyz files were imported to PFM files using IVS3D™ Fledermaus DMagic software, which generated a gridded 3D surface based upon the combined point cloud. The PFM files could then be edited and cleaned of noise with the Fledermaus 3DEditor tool. 3DEditor makes it possible to edit the underlying data while dynamically updating the 3D surface model representation. Following extensive cleaning of the point cloud for noise and errors, the accepted soundings were exported from the PFM files as the final xyz source files used in the next grid development phase.

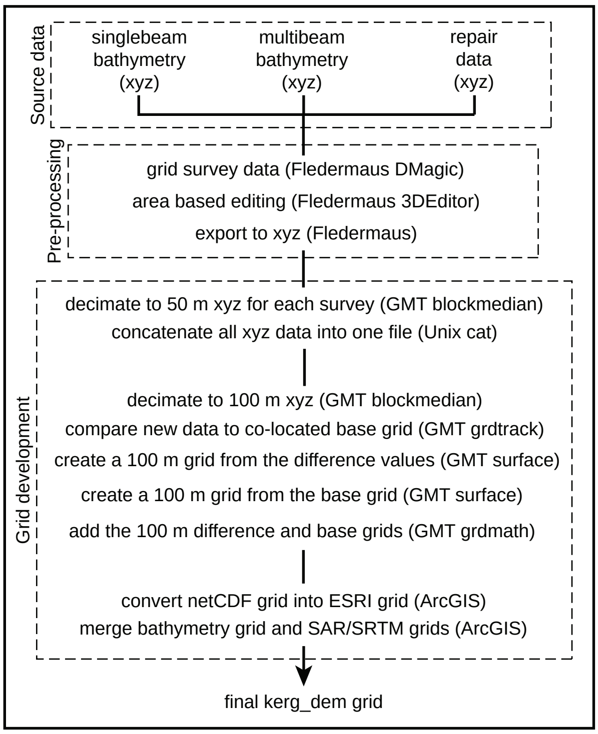

Figure 7: *Processing scheme used to develop the kerg_dem grid*

GRID DEVELOPMENT

The next phase of grid development was conducted with Generic Mapping Tools (GMT) software (Wessel and Smith, 1991) following the methodology used in Becker et al. (2009). GMT is a Unix-based gridding and plotting software package that can deal with large datasets. The cleaned xyz data for each survey were decimated using GMT blockmedian into xyz data representing single node points at 0.0005-arcdegree (ca. 50 m) resolution. The decimated data files were then concatenated into one large xyz file. Next, GMT blockmedian was conducted on the single large file to decimate the data to 0.001-arcdegree (ca. 100 m) resolution in order to produce one valid depth point for each pixel location used in the new grid.

The 0.001-arcdegree blockmedian depth values were then compared with the co-located depths from an underlying base grid, in this case the Sexton (2005) grid. This base grid has a pixel size of 0.005-arcdegree (ca. 500 m). The purpose of using a lower-resolution depth grid was firstly to use the base grid as a comparison to flag any new source data that may be greatly in error, and thus be rejected, and secondly to provide additional depth data for areas that lack spatial coverage by the new source data. GMT grdtrack was used to find the comparative depth differences between the co-located new data and the underlying base data.

A temporary grid surface was made with GMT surface, using those difference values between the co-located new data and the base data. GMT surface was also used to resample the lower-resolution base grid at a higher-resolution of 0.001-arcdegree. The temporary difference grid and the resampled base grid were then added together with GMT grdmath. The output of this process was a network Common Data Form (netCDF) file that was converted into an ESRI raster grid using ArcGIS. Lastly, the 0.001-arcdegree SRTM and TerraSAR land elevation grids were merged with the new ESRI grid to produce the final grid, called kerg_dem (Figures 8 and 9).

DERIVED GRIDS AND LAYERS

A useful derived grid from continuous data such as a DEM, is a slope model which shows the angular variation in seafloor gradient relative to a horizontal or flat value of 0°. For this project, the final 0.001-arcdegree grid was reprojected in ArcGIS to a new Mercator projection grid (Central Meridian 74°E, Standard Parallel 52°S) with a pixel size of 100 m. The slope model was generated utilising the ArcInfo Slope application by fitting a window with a 3 x 3 cell neighbourhood around each processing or centre cell of the 100 m grid. Thus slope was averaged over a distance of 300 m for each cell of the projected grid in order to derive a slope grid (Figure 10).

Another useful derived layer is a contour map, used as a traditional means of visualising steep versus relatively flatter areas. Utilising the ArcGIS Spatial Analyst tool, an additional contour map was derived from the final 0.001-arcdegree grid at a contour interval of 100 m. For the purposes of this report, the derived contour lines were placed over the kerg_dem grid, which was coloured using histogram equalise to increase the visual contrast of the background (Figure 11).

ACCURACY

The source bathymetric data vertical and horizontal accuracies were classified according to the International Hydrographic Organization Standards for Hydrographic Surveys Special Publication 44 (IHO, 2008). Source bathymetry data can be classified into four categories of uncertainty: Special Order, Order 1a, Order 1b and Order 2 (see Table 2).

Table 2: Minimum standards for hydrographic surveys, adapted from IHO (2008)[ab]

ORDER	SPECIAL	1A	1B	2
Maximum allowable THU 95% Confidence level	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Maximum allowable TVU 95% Confidence level	a = 0.25 metre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.013	a = 1.0 metre b = 0.023

[a]THU = Total Horizontal Uncertainty. TVU = Total Vertical Uncertainty.
[b]Recognising that there are both constant and depth dependent uncertainties that affect the uncertainty of the depths, the formula below is used to compute, at the 95% confidence level, the maximum allowable TVU:

$$\pm\sqrt{(a^2 + (b \times d)^2)}$$

Where:

a represents that portion of the uncertainty that does not vary with depth.
b coefficient which represents the portion of the uncertainty varying with depth.
d is the depth.
b x d represents that portion of the uncertainty that varies with depth.

For this project, we considered the multibeam source data, and the AHS and AAD singlebeam data to conform to Orders 1a and 1b. The lower-quality Fisheries singlebeam data conforms to Order 2 (see Appendix 1). The kerg_dem grid generally conforms to an Order 2 Total Horizontal Accuracy (THU) and Total Vertical Accuracy (TVU), based upon the worse case source data accuracy of Order 2. Both THU and TVU increase according to depth, so the maximum allowable THU is: 30 m up to 100 m depth; 70 m up to 500 m depth; 120 m up to 1000 m depth; 220 m up to 2000 m depth, and so on. Realistically, however, the accuracy of GPS used for positioning during modern surveys is far better than the maximum allowable THU for Order 2 surveys, and so the THU figures quoted here are very conservative. The maximum allowable TVU for Order 2 surveys is: 2.5 m up to 100 m depth; 11.5 m up to 500 m depth; 23 m up to 1000 m depth; and 46 m up to 2000 m depth, and so on.

A useful derived grid is the Total Vertical Uncertainty (TVU) showing the maximum allowable uncertainty, at the 95% confidence level, with a grid pixel resolution of 0.001-arcdegree. Users can therefore identify the calculated TVU in metres for co-located bathymetry values on the new kerg_dem grid, taking into account the IHO S44 Order codes of the underlying source data. To develop the TVU grid, the GMT gmtmath application was used to recalculate all edited xyz bathymetry records using the TVU formulae in Table 2, depending on whether the surveys were considered Order 1a, 1b or 2. The recalculated TVU source data were then input to the grid development process, as per Figure 7, except that the base grid used the Sexton (2005) grid and recalculated as a TVU Order 2 grid. In the final TVU grid, all land areas were converted to NoData pixel values (Figure 12).

Final Products

The new kerg_dem grid and associated derived map products are shown in Figures 8 to 12. Figure 13 shows a comparison between the new grid and the Sexton (2005) grid. The additional data and increased editing improve the detail of many of the geomorphic features first identified by Sexton (2005). For example, submarine channelling on the southern and south-eastern flanks of the Heard Island platform and Gunnari Ridge are now much clearer. Many of the small, rounded features on the top of the Kerguelen Plateau, first seen on the Sexton (2005) grid, can now be clearly identified and are probably small volcanic cones.

The additional data and area-based editing have substantially reduced some of the anomalous shiptracks seen in the Sexton (2005) grid (Figure 13a vs 13b), however, some anomalous shiptracks do persist, most obviously viewed in Figure 10, possibly reflecting variations in the assumed sound velocity used in the original depth calculations. This seems more likely than the use of different vertical datums as the anomalous shiptracks are seen in deep water where vertical datum shifts are small compared to the water depth.

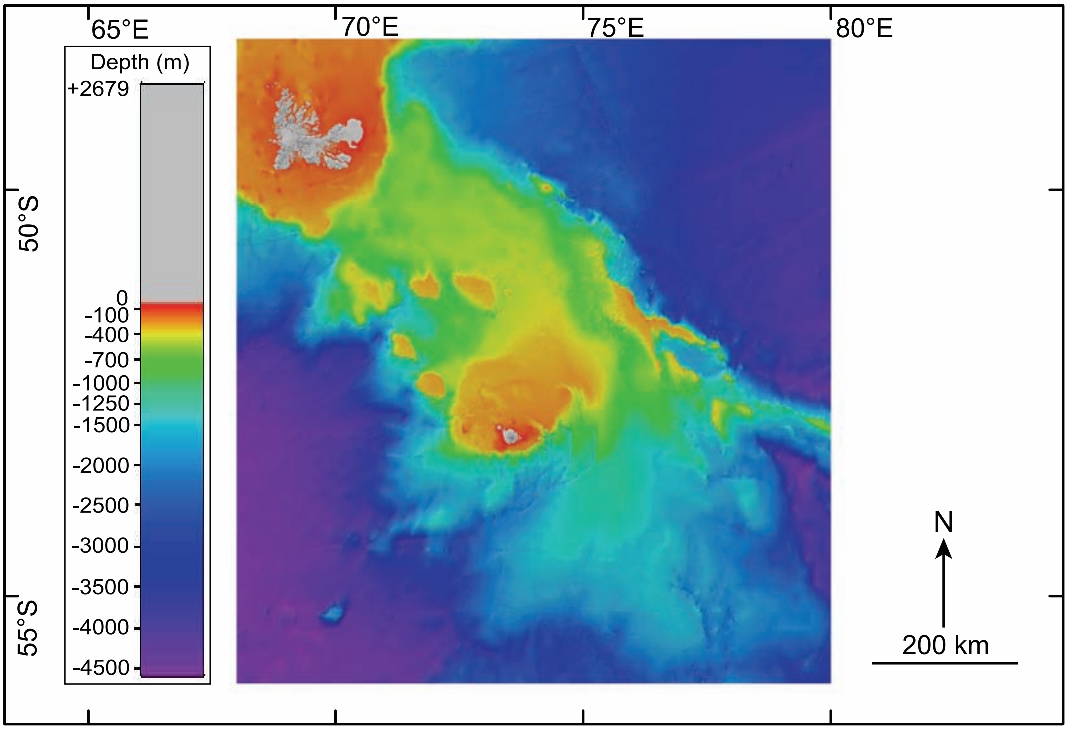

Figure 8: *Mercator projection map of the new kerg_dem grid. All hill-shaded images are shown with vertical exaggeration x6, sun azimuth 315°, and sun angle 51°*

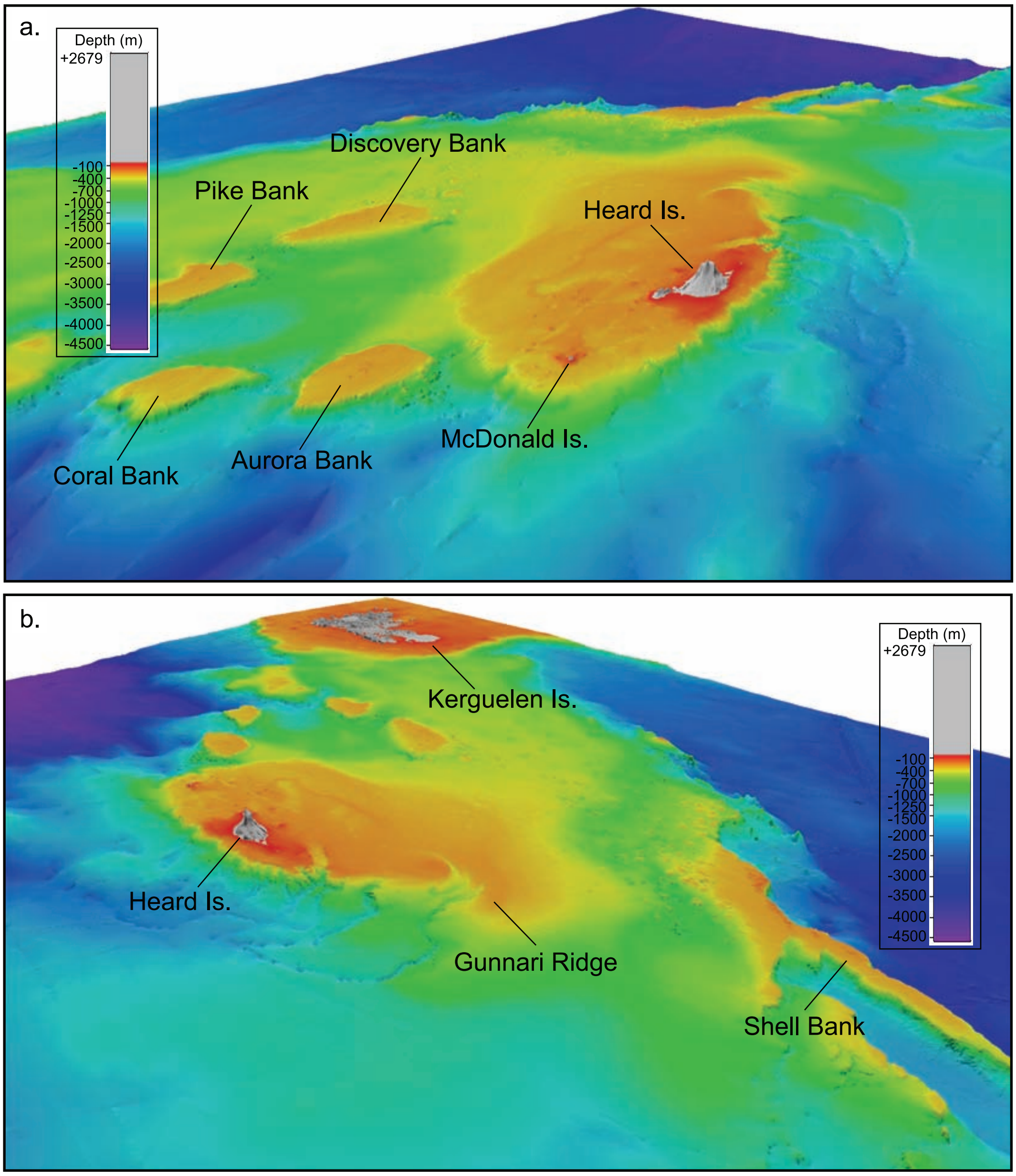

Figure 9: *3D oblique views of the kerg_dem grid showing: a. north-easterly view of the southern Kerguelen Plateau, and b. north-westerly view of the plateau and adjacent abyssal plain. Small volcanic cones dot the surface of the plateau*

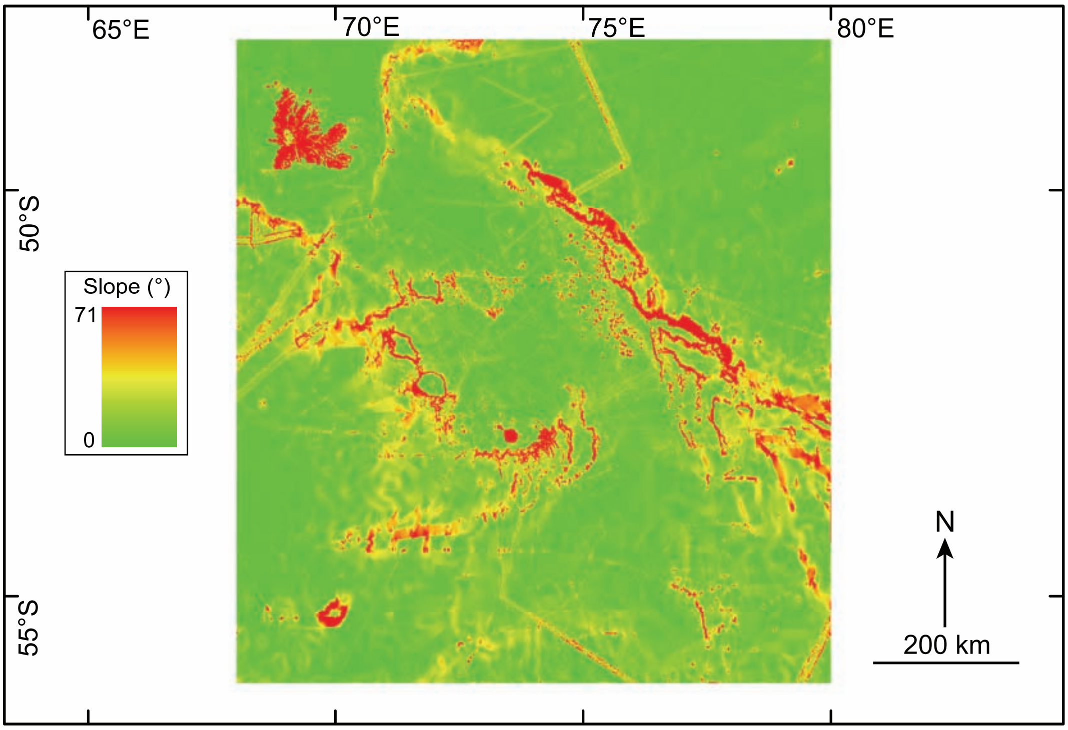

Figure 10: *Mercator projection map of the slope gradient (°) derived from the kerg_dem grid. The striping is due to recent deep-water multibeam tracks merging with adjacent areas that are poorly surveyed, or anomalous shiptrack data using incorrect sound velocity calculations*

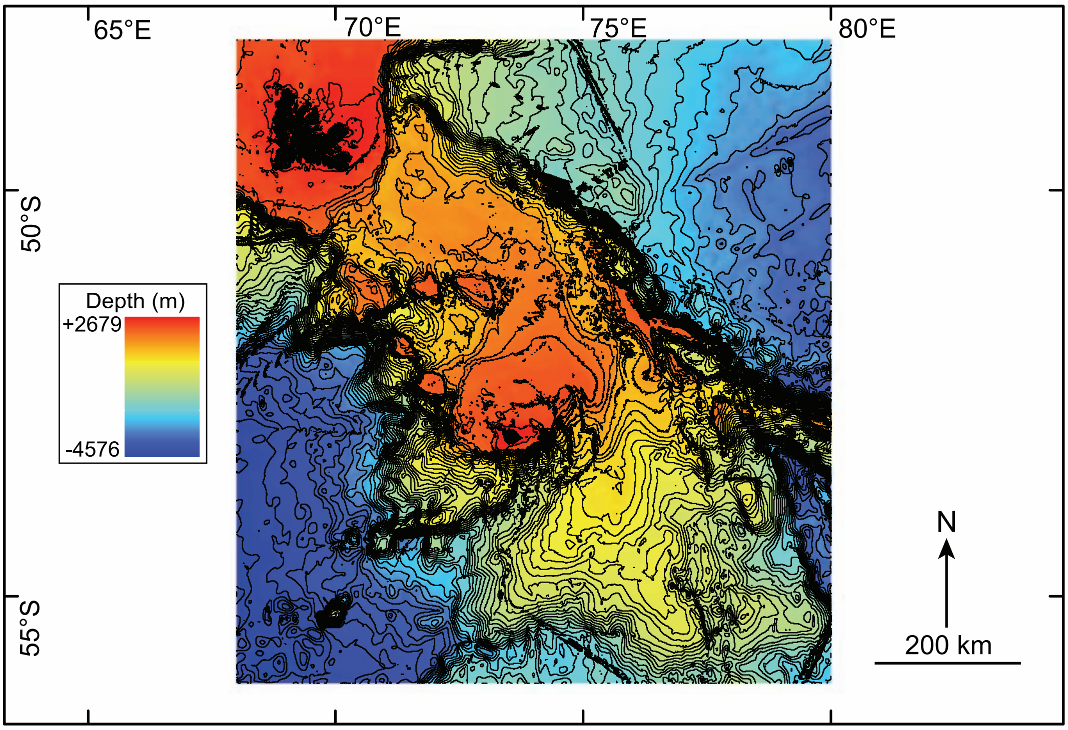

Figure 11: *Mercator projection map of contour lines generated at 100 m intervals and overlaid on the kerg_dem grid, coloured using a histogram equalisation*

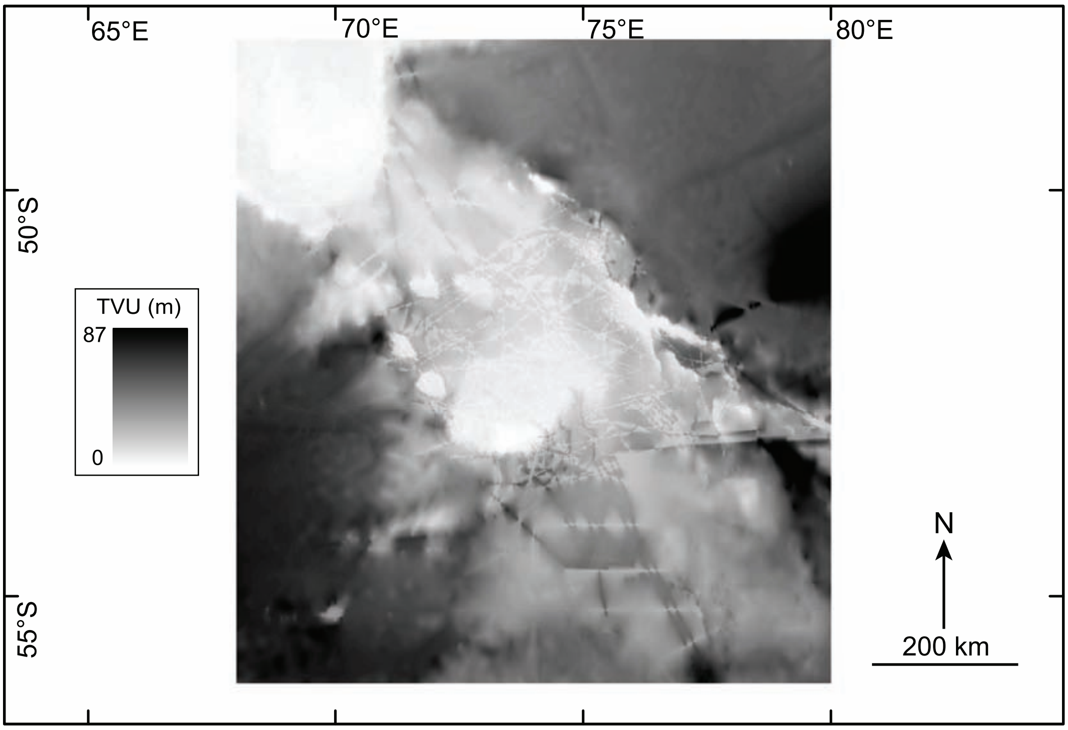

Figure 12: *Mercator projection map of the Total Vertical Uncertainty (TVU) in metres for the kerg_dem grid. The TVU grid provides the maximum allowable uncertainty at the 95% confidence level at the same 0.001-arcdegree grid pixel resolution as the kerg_dem grid. Much of the seabed around Heard Island has a TVU of less than 5 m*

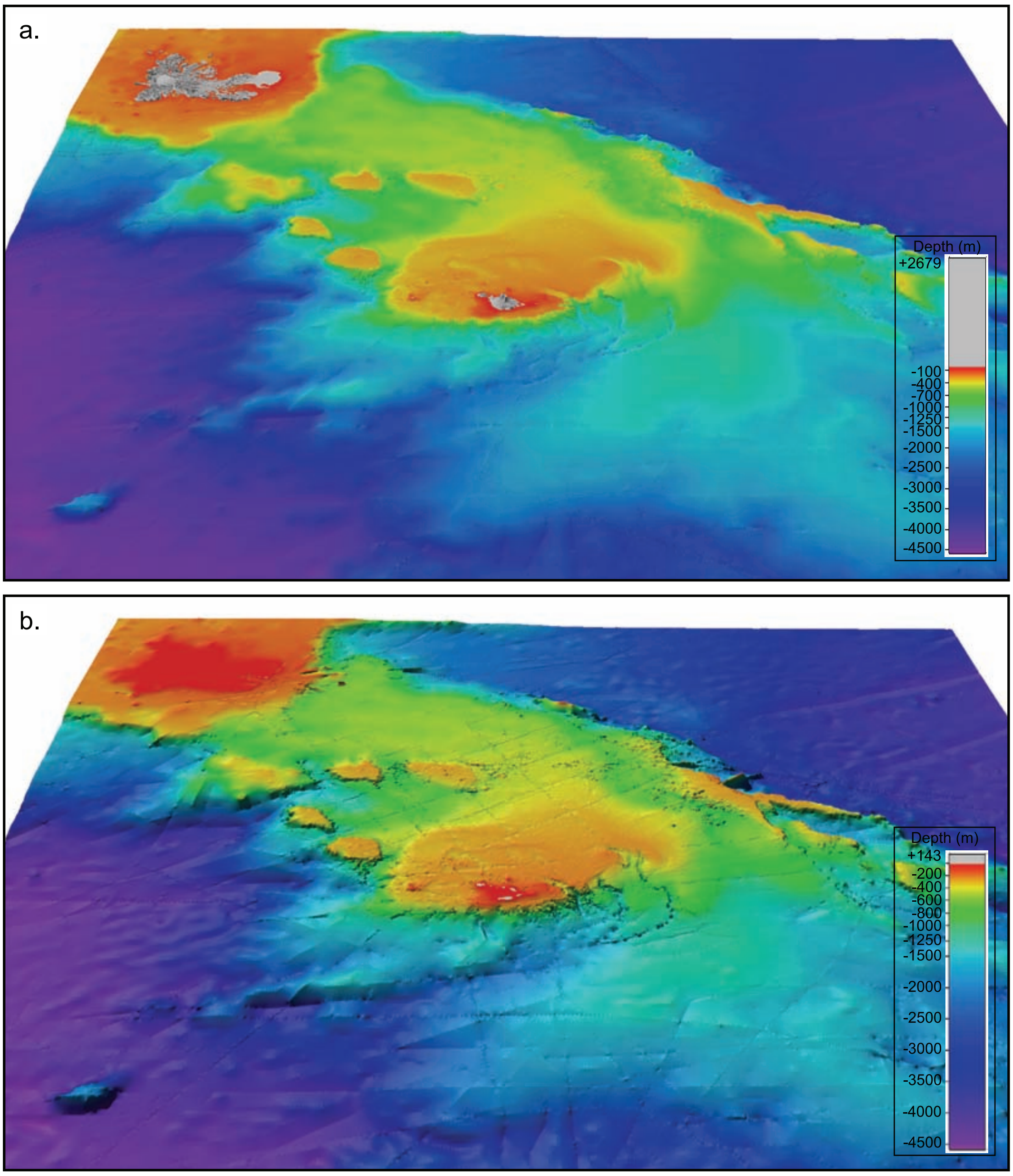

Figure 13: *3D oblique views comparing: a. kerg_dem grid, and b. Sexton (2005) grid. The new grid 'smooths' out anomalous data due to the much improved data coverage and 'sharpens' detail in key physiographic areas, such as the submarine channels draining the Heard Island platform*

Conclusion

A new bathymetry grid, called kerg_dem, was created for the Kerguelen Plateau area with a geographic coverage ranging from latitude 48° to 56° South, longitude 68° to 80° East. The new DEM has a grid pixel size of 0.001-arcdegree (ca. 100m) with a horizontal datum of WGS84 and a vertical datum of MSL. The new grid utilised the latest multibeam and singlebeam bathymetry source datasets provided by Australian and French Government agencies, and commercial fishing companies. The large increase in source bathymetry data, and the higher-resolution grid when compared with the Sexton (2005) grid, therefore added much geomorphic detail. The kerg_dem grid provides new insights into the detailed geomorphic shape and spatial relationships between adjacent seabed features, particularly around the Heard Island platform. The new features revealed by the grid demonstrate the value of regional bathymetry compilations in understanding the seafloor environment.

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Appendix 1: Bathymetry Survey Metadata

SURV_CODE	SURVEY_NAME	DATA_TYPE	VESSEL	START_DATE	END_DATE	START_PORT	END_PORT	DATA_OWNER	SYSTEM	IHO S44 ORDER[A]
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
Fisheries	c-in-c	singlebeam	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	c-in-c	Order 2
HI190	HeardIsland	singlebeam	unknown	30/10/1998	8/03/1999	Hobart	Hobart	AHS	Atlas DESO 25 (33-210 kHz)	Order 1a
AAD	1990-2008	singlebeam	RV *Aurora Australis*	20/05/1990	18/12/2008	Hobart	Hobart	AAD	Simrad EK60 (12 kHz)	Order 1b
AAD	2003-2004	singlebeam	RV *Aurora Australis*	10/12/2003	13/02/2004	Perth	Hobart	AAD	Simrad EK60 (12 kHz)	Order 1b
MR03-K04L6	Fremantle	multibeam	RV *Mirai*	27/01/2004	19/02/2004	Fremantle	Fremantle	JAMSTEC	Seabeam 2112 (12 kHz)	Order 1b
ANT-XXIII9	CapeTown	multibeam	RV *Polar Stern*	2/02/2007	11/04/2007	Punta Arenas	Cape Town	AWI	Atlas Hydrosweep DS2 (14 kHz)	Order 1b
SHOM	Kerguelen	multibeam	unknown	unknown	unknown	unknown	unknown	SHOM	unknown	Order 1a

[a] See the main report for an explanation of the IHO S44 Order codes.

c-in-c = commercial-in-confidence; AHS = Australian Hydrographic Service; AAD = Australian Antarctic Division; JAMSTEC = Japan Agency for Marine Earth Science and Technology; AWI = Alfred Wegener Institute for Polar and Marine Research; SHOM = Service Hydrographique et Océanographique de la Marine.

Appendix 2: SRTM DEM Metadata

PROCESSED SRTM DATA VERSION 4.1

The data distributed here are in ARC GRID, ARC ASCII and Geotiff format, in decimal degrees and datum WGS84. They are derived from the USGS/NASA SRTM data. CIAT have processed this data to provide seamless continuous topography surfaces. Areas with regions of no data in the original SRTM data have been filled using interpolation methods described by Reuter et al. (2007).

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ACKNOWLEDGMENT AND CITATION

We kindly ask any users to cite this data in any published material produced using this data, and if possible link web pages to the CIAT-CSI SRTM website (http://srtm.csi.cgiar.org). Citations should be made as follows:

Jarvis, A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database: http://srtm.csi.cgiar.org.