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GREAT BARRIER REEF DEPTH AND ELEVATION MODEL: GBRDEM

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FOREWORD

Over the last 200 years, information about the large-scale bathymetric structure of the Great Barrier Reef (GBR) region has expanded from isolated soundings with lead-weighted ropes, sextant readings and pen sketches of reef outlines to satellite imagery of reef complexes and dense swaths of depth readings collected with airborne lasers. Large amounts of bathymetric data have been collected throughout the GBR region by a variety of organisations for a variety of reasons. This information base has not been well integrated. Much of this depth information has been collected for navigational purposes and is largely presented as navigational charts which are not always optimal for scientific, engineering and management needs.

Adam Lewis and his co-workers have brought together the widest possible body of bathymetric information relevant to the GBR and applied Geographic Information System (GIS) tools to produce a detailed bathymetric model of the GBR region. This effort has produced an extremely valuable resource for the management, study and wise use of the GBR. At the simplest level, it is now possible to estimate the volume and distribution of water within the GBR, information important for estimating the productivity of the reef and understanding the effects of terrestrial runoff on water quality. A bathymetric context provides an intuitive backdrop against which the large-scale distribution of reef habitats, attributes and biodiversity can be viewed and analysed.

Beyond visualisation, an accurate and fine-grained depth model is essential for the development of regional-scale three-dimensional oceanographic models to simulate the complex and ever-changing movement of water through the reefs. These models are making it possible to predict and visualise the transport and dispersal of pollutants, reef organisms with pelagic life stages, and other drifting objects.

The GBR Depth and Elevation Model is more than just a map or tool to present bathymetric and topographic data, it is also a process which will allow new and improved information to be added and the model updated. This should make it both a widely used and long-lived resource.

Dr Miles Furnas
Principal Research Scientist
Australian Institute of Marine Science

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PREFACE

This report describes a Depth and Elevation Model of the Great Barrier Reef (GBRDEM) with the methods used to develop the model, data sources, accuracy of the interpolated depths and some preliminary findings.

GBRDEM is a terrain model covering the Great Barrier Reef, including catchments which flow into the Great Barrier Reef and, where data are available, depths beyond the edge of the continental shelf. It is designed to enable studies on a regional scale.

Primary data were compiled from multiple sources licensed to, or owned by, several partners of the CRC Reef Research Centre, the Australian Institute of Marine Science, School of Tropical Environmental Studies & Geography at James Cook University and the Great Barrier Reef Marine Park Authority. Data include spot elevations on land, the mapped coastline and outlines of islands, depth soundings captured by the Royal Australian Navy Hydrographic Office, LASER Airborne Depth Sounder (LADS) data, seabeam multi-beam echo-sounder data, soundings taken from charts and, in deep water beyond the continental shelf, depths modelled from remotely sensed data (Smith and Sandwell 1997).

In most cases, primary data consist of irregular point depth soundings. To produce GBRDEM these are interpolated to a regular 250 m lattice using ANUDEM software (Hutchinson 1988, 1989). The lattice is then stored in ARCINFO™[1] GRID format from which it is analysed, manipulated and converted to other file formats.

A unique aspect of this depth model is that it is under continual improvement. It is a process, rather than a static model or dataset. New depth and elevation data can be included at any time and there are some places, for instance, the Pompey and Swains sections where data are clearly lacking. New data are incorporated by re-interpolating the lattice over the relevant areas and then merging the updated surface back into the original model.

[1] ARCINFO is a registered trade mark of Environmental Systems Research Institute, Redlands, California.

The accuracy of the depth model has been established by comparison of the interpolated depths with a large number of withheld data points. Initial accuracy assessment research is reported in Lewis (1999).

GBRDEM is available to researchers within CRC Reef, subject to an agreement limiting the use and distribution of the digital data. At this time, it is not available beyond CRC Reef. We hope that a range of researchers and managers will use this resource which has been developed, and will continue to develop, by collaboration between numerous individuals and organisations.

ACKNOWLEDGEMENTS

I am grateful for the guidance and encouragement of Terry Done during this research. The initial dataset and early versions of the depth model were compiled and developed by Rick Smith who also provided valuable technical support. My sincere thanks to Amanda Walmsley who wrestled some of the more complex spatial analysis tasks into submission, Susanne Hutchinson for technical and administrative support, Cathy Waldron who provided editorial assistance, and Lindsey Jones who has latterly incorporated several new datasets into GBRDEM.

This research was funded by the CRC Reef Research Centre, School of Tropical Environmental Studies and Geography at James Cook University and the Australian Institute of Marine Science. A number of organisations and several individuals have contributed to this work. The Great Barrier Reef Marine Park Authority (especially Jeff Shearin, Dan Breen and Donna Audas), the Australian Institute of Marine Science (especially Miles Furnas who precipitated the initial development of a depth model of the GBR), Schools of Earth Sciences (Gavin Dunbar) and Computer Science, Maths and Physics (Luciano Mason and Lance Bode) at James Cook University. My thanks to these and others who have helped in various ways. The necessary collaboration was made possible by the CRC Reef Research Centre. Dr Chris Jenkins has kindly provided depths from sediment sample datasets. Thanks to two anonymous reviewers who provided valued comments.

EXECUTIVE SUMMARY

Bathymetry is fundamental to the marine environment. A knowledge of ocean floor topography is essential for informed and sustainable marine resource management. It is also vital to scientific understanding of the physical and biological marine environments which are strongly linked to depth.

We have produced a bathymetry ? a 'depth model' ? of the Great Barrier Reef as a research and management tool. Working from extensive experience with terrain models on land, we have used the best data and processes we believe to exist. More importantly, we have established a process so that the bathymetry can continue to improve as new data are added.

The model allows us to visualise, either as pictures or as graphs, the structure of the Great Barrier Reef to improve our qualitative and quantitative understanding of the region. In the far north, the 'lagoon' is shallow, with a complex bottom topography and a steep continental slope. In the south, the outer reefs are hundreds of kilometres from shore and the waters are deep, the bottom topography varies from smooth in the lagoon to extremely complex toward the outermost reefs, and the continental slope is gentle. The model shows large areas of submerged reef which are not visible from the air, and therefore, do not appear on other maps. These areas alone may have important implications for resource management.

The depth model depends on data: depth soundings, and parts of the Great Barrier Reef are notoriously poorly mapped. In areas like the Swains, commitment to bathymetric survey work is essential if the picture is to improve. Technology such as the LASER Airborne Depth Sounder (LADS) can map reef areas to depths of approximately 30 metres.

Research and other vessels also have an important role to play. In stark contrast to the situation two hundred years ago, thousands of vessel hours yield little data on depth. Continuous real-time data logging of position and depth, by only a few research vessels, would lead to great improvements with minimal cost.

Our depth model is available to all managers and scientists within the CRC Reef Research Centre. Given a low level of funding for technical support, it will be maintained and improved through the new CRC.

INTRODUCTION

The Great Barrier Reef (GBR) presents one of Australia's most challenging and intriguing natural resource management problems. The reef extends 2000 kilometres over 14 degrees of latitude (Figure 1). Resource use is diverse, economically significant and intensifying (McPhail 1997).

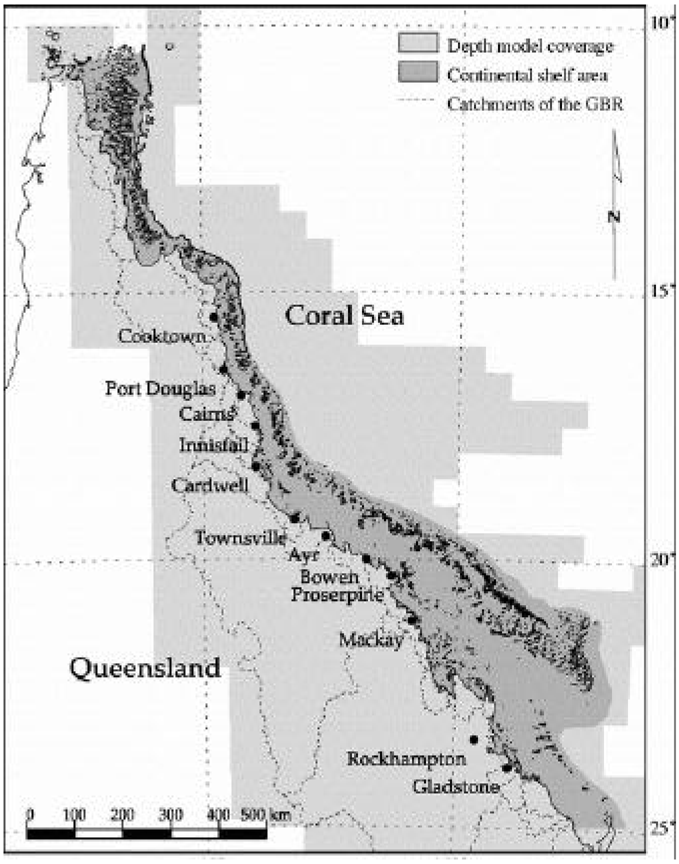

Figure 1. The Great Barrier Reef Region and the extent of elevation model coverage.

Knowledge of habitats and ecosystems within the region, including the extent of sea-grasses, the nature of the lagoon sediments, and the types and distribution of coral and benthic communities, is limited but constantly increasing. Understanding of biological and physical processes is also limited but developing rapidly as a result of continuing research projects. Keeping up to date and integrating new information into their activities is a constant challenge for both managers and researchers. The scale of the GBR resource also poses challenges for policy-makers, scientists and managers. Scientists would like to collect and integrate data over the entire region, and managers face the same problem in pursuing sustainable resource management. Addressing the entire region is part of the aim of this project.

The biological and physical processes in the marine environment are more complex, dynamic and difficult to study than those encountered by terrestrial scientists and resource managers. The paradigms developed on land often need to be re-appraised before being applied to the marine environment. Nonetheless, just as altitude plays a powerful role on land, many biological and physical processes are fundamentally depth-dependent, including the strength and direction of currents and waves, the efficiency of photosynthesis and the re-suspension of sediments by wave action.

Terrain Models

Terrain models are static models of the earth's surface, generated and maintained within a computer. They have been extensively studied and applied over land areas to estimate long-term climate means, determine catchment - scale hydrology and calculate visibility from one site to another. Terrain can be represented in a computer in many different ways. The method which is most convenient and efficient for analysis is a regular lattice of points or grid cells (Moore *et al.* 1991) with an elevation value stored for each lattice point (Figure 2). The spatial resolution of the lattice is defined by the distance between points which is constant in both directions (i.e. along the rows and columns of the lattice). The vertical resolution of the model is determined by the numerical precision with which this elevation is stored. The lattice is usually populated by estimates of elevation; so the accuracy of the model is the difference between each estimate and the true elevation at that lattice point. Over the entire model, this accuracy can be stated as a root mean square error.

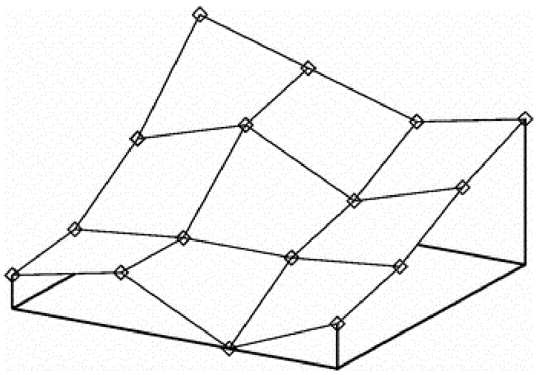

Figure 2. The lattice model of surface representation. Points are regularly spaced in the horizontal plane. Distance above the plane indicates the surface value.

Lattice elevations are estimated from data points, e.g. depth soundings. Since data points rarely coincide with lattice points, spatial interpolation methods were used to estimate lattice point elevations from the data points. On land, the data used for the interpolation are, typically, either isolated points or contour strings drawn from topographic maps. More recently, digital photogrammetry and satellite radar altimetry have also become important. The accuracy of terrain models developed in this way depends on the spatial density of the points or contours from which the model is interpolated. In general, the contour map was an essential ingredient to terrain modelling, giving both quantitative and qualitative information (the latter by defining the form of the landscape).

As a data source, isobaths are not comparable to contours. Over land, a photogrammetrist drawing contours can see the surface of the land. Over water, this is not possible. Therefore, contours are a continuous trace over the photographic image, but isobaths are an interpolation or interpretation between point estimates of depth. As a result, depth models are inherently more difficult to interpolate than elevation models; there are simply fewer data to start with.

Work on the depth model was initiated at the Australian Institute of Marine Science due to an interest in calculating water volumes within certain contour bands which could be used to calculate nutrient budgets. Further development of the depth model has evolved through creation of the Spatial Information and Decision Support Systems Task (1.5.2) under CRC Reef Research Project 1.5, System Modelling. This project has been a collaboration between the School of Tropical Environmental Studies & Geography at James Cook University and the Australian Institute of Marine Science.

The project aimed to develop regional views of the physical and biological diversity of the GBR. It also aimed to increase integration of data and research products among scientists and managers, and develop spatial datasets, such as GBRDEM, for general use within the research and management community. GBRDEM enables scientists, managers and educators to visualise, quantify and analyse the physical surface of the GBR region including the catchments contributing to the lagoon and the deep waters beyond the continental shelf.

STUDY AREA

The GBR extends from at least 10?41'S to 24?30'S (Figure 1). Management focuses between the coast and edge of the continental shelf (the estimated location of the 150 m isobath), an area of approximately 251,000 km^2. The Great Barrier Reef Marine Park and the World Heritage Area (WHA) extend beyond the continental shelf. The WHA is about 344,000 km^2 and includes islands and estuaries. The Marine Park is restricted to the low water mark. GBRDEM exceeds the WHA and extends inland to include all catchments contributing to the GBR and, data permitting, beyond the continental shelf. It comprises a total area of approximately 1,213,000 km^2. Within this area, GBRDEM is interpolated to a regular lattice resolution of 250 m (in ocean areas) and 500 m (over land areas). It is then re-sampled to 500 m or coarser resolution depending upon need. The high resolution is achieved by interpolation of subsets of the data using an overlapping tile structure, defined by 0.5 degree rectangles consistent with those used by Hopley *et al.* (1989). These tiles also form the boundary of the standard 1:100,000 map series.

DATA SOURCES

Data from several sources are used in the depth modelling process. Datasets are imported, processed as necessary, and maintained as ARCINFO™ spatial (Geographic Information Systems or GIS) datasets (coverages). Storage as GIS datasets allows substantial pre-processing of large datasets in a completely automated and therefore, both repeatable and fully documented, manner.

Datums and coordinate systems

GBRDEM uses Zone 55 of the Australian Map Grid (AMG) which is based on the Australian Geographic Datum (AGD66), and the Australian National Spheroid. This is equivalent to the Universal Transverse Mercator (UTM) coordinate system which is the Australian mapping standard used on all 1:100,000 maps. The model can be projected into other coordinate systems including GDA94 (Geocentric Datum of Australian), GRS80 (the 'Global Reference System' spheroid) and longitude-latitude, when required. For continuity, Zone 55 is used even where the data extend into Zone 54 (west of 144? E; around Princess Charlotte Bay) or into Zone 56 (beyond 150? E; to the east of Broad Sound). Although UTM is a standard for terrestrial mapping, it does not preserve areas. We determined that the distortion in area estimates resulting from the choice of projection was negligible. Datasets provided in latitude - longitude are projected into AMG in a data preparation stage.

The model is referenced to Mean Sea Level (MSL). MSL is indistinguishable from the Australian Height Datum (AHD) in accuracy at the regional scale. Marine soundings are referenced to lowest astronomical tide (LAT) and other datums are adjusted according to the Australian National Tide Tables (Australian Navy Office 1998), unless a datum correction is specified in the dataset by the provider. The choice of MSL as a datum is driven by precedent ? the large number of historical soundings referenced to MSL ? and the consistency between MSL and AHD. LAT is a spatially variable datum because it depends on the tidal range. It is hoped that other CRC projects will, in future, provide a spatially contiguous conversion between MSL and LAT based on oceanographic or remotely-sensed tidal models. However, in this project where corrections between LAT and MSL were not available with the dataset, the difference was estimated using a spline-based spatial interpolation between all tidal stations along the GBR, as listed in the Australian National Tide Tables (Australian Navy Office 1998).

Royal Australian Navy Hydrography

The main data for the model were 176,000 depth soundings referenced to MSL from the Royal Australian Navy (RAN) Hydrographic Survey Office. These soundings cover much of the GBR Lagoon, at varying spatial density. The density of soundings usually increases over the deeper waters away from both coasts and reefs (Figure 3).

In this dataset, soundings in the northern and southern ends of the GBR are extremely sparse and in these areas some additional depths have been digitised from hydrological charts 375 and 4621.

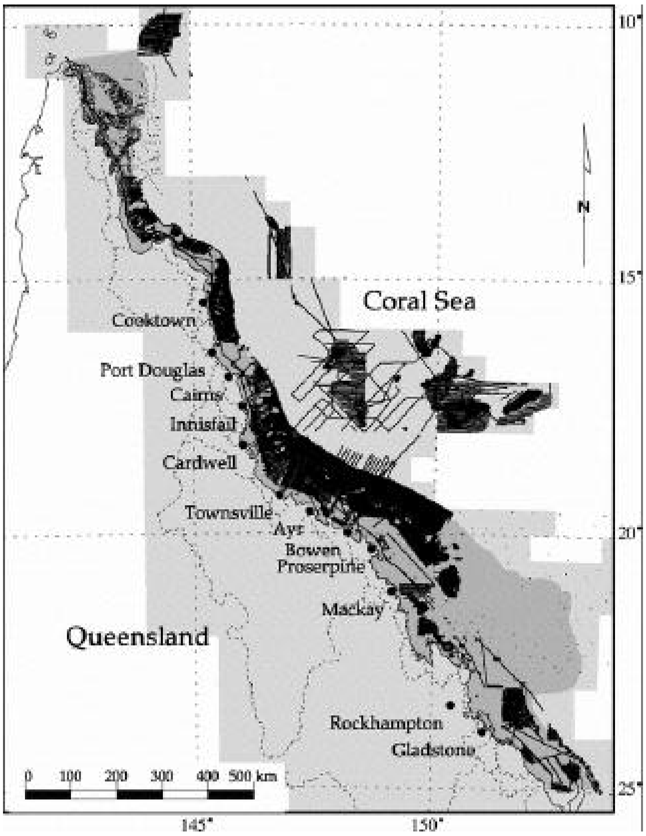

Figure 3. Depth soundings from the Royal Australian Navy Hydrographic Survey.

Topo250-K

Terrestrial elevation was estimated from approximately 402,000 spot heights drawn from the Australian Surveying and Land Information Group (AUSLIG) Topo250-K dataset licensed to the Australian Institute of Marine Science (Figure 4). These points are sampled from 1:100,000 topographic maps at a relatively uniform spatial density of about one point per square kilometre. Sample points, taken from the contours on the topographic maps, are selected from ridges, peaks and along streams to ensure that important topographic variation is captured. The point density on land is generally higher than the density of soundings over the ocean (Figure 3).

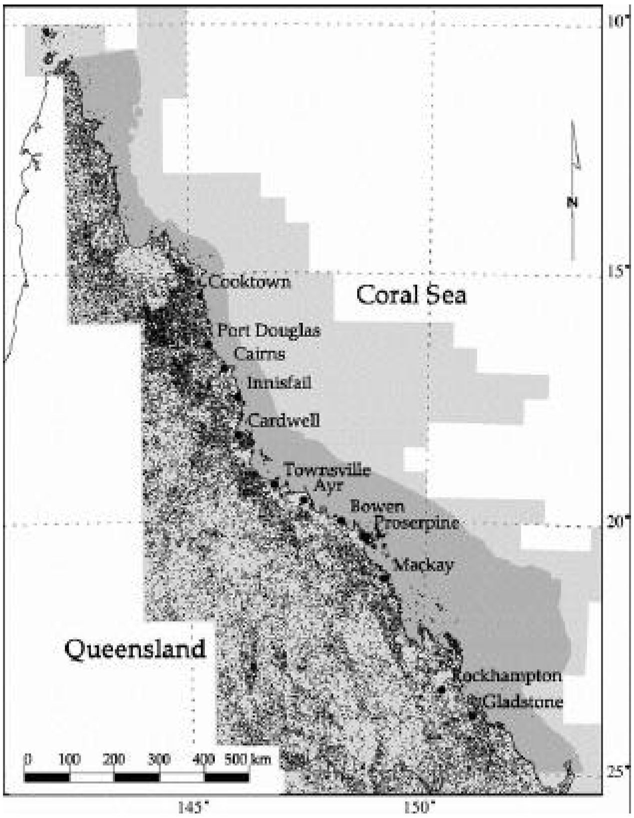

Figure 4. Elevation data from the Australian Land Information Group (AUSLIG). Data points are indicated by dots. Every 10^{th} point is shown.

Reef Outlines

Approximately 2,500 reefs are mapped as polygons in the Great Barrier Reef Marine Park Authority (GBRMPA) ARCINFO™ database (Figure 5). The reef outlines provide some information about the depth of the water at the location of the outline. When compared with the depths measured by detailed AUSLIG surveys, the mapped outlines[2] correspond to a depth of approximately 10.5 m below MSL. Although this information is imprecise, it is valuable when other data are lacking, despite the fact that reefs vary in present day morphology (Hopley 1983).

[2] The Great Barrier Reef Marine Park Authority have two types of mapped outline referred to as Reef and Reef-Dry. This result relates to the boundaries of Reef'

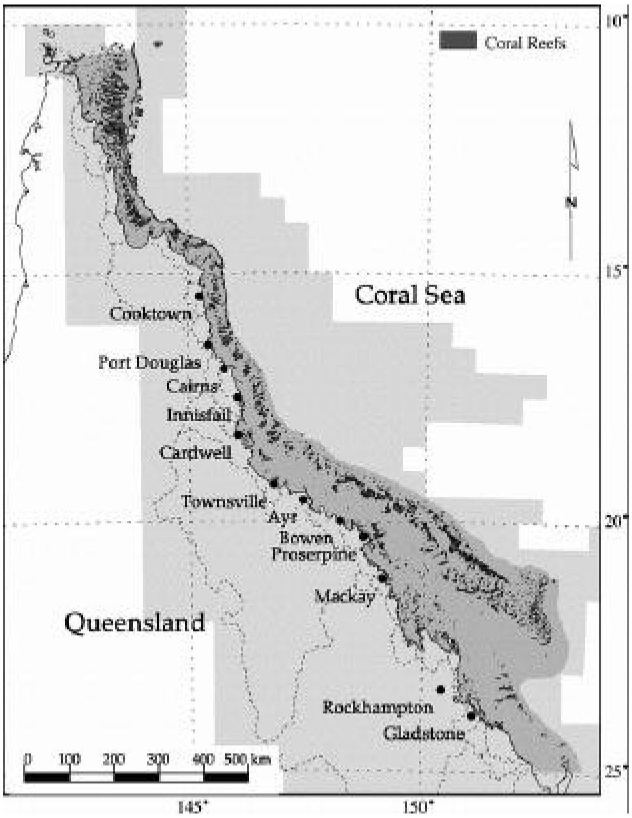

Figure 5. Reef outlines mapped as polygons and maintained by the Great Barrier Reef Marine Park Authority GIS unit.

The reef outline dataset also includes a number of *Halimeda* algal beds, especially in the far north. Although these were regarded as submerged reefs by Hopley (1983) and are commonly illustrated on maps as reefs, they have been excluded from the GBRDEM analysis because they are considered to be uncharacteristic of reef areas. *Halimeda* beds were differentiated from other reefs by checking the spatial database against aerial photographs (where available) and LANDSAT Multi-Spectral Scanner (MSS) images. To support validation, the reef database has also been linked with the digital gazetteer maintained by the GBRMPA and generally attributed to Prof David Hopley. *Halimeda* beds are usually listed as 'submerged reef' in the gazetteer.

Coastline

The mapped coastline provided in ARCINFO vector format by GBRMPA is a vital component in modelling the terrain of the region. The digital coastline runs to the landward side of the foreshore and mangrove areas. It is assumed to represent Mean High Water Springs (MHWS). From the tide stations along the length of the GBR, this corresponds to approximately 0.8 m above MSL. This elevation is assigned to the coastline for interpolation of the depth model. The coastline is used to divide the land from the sea so that these can be interpolated separately.

Seabeam multi-beam echo-sounder

Depth soundings are scarce for deep waters beyond the edge of the continental shelf. However, geological surveys have produced a large number of soundings in limited areas. Seabeam data from the geological survey carried out from HMAS Cook in July 1989 (Johnson *et al.* 1989) were provided in ascii format by the School of Earth Sciences at James Cook University. Seabeam is a 12 kHz multi-beam echo-sounder used to provide bathymetric information to allow correction of data produced by GLORIA, a deep-sea-floor imaging system (Twichell and Nelson 1997, Johnson *et al.* 1989, Hughes-Clarke 1989). As the seabeam data were sampled along the ship-track at resolutions between 80-100 m, the data were processed by filtering closely spaced data points to reduce the number of data points from approximately 70,000 to 10,936. The reduced dataset was converted to an ARCINFO^{TM} 'point coverage' and is illustrated in Figure 6. The width of the path scanned by the Seabeam sounding data was in the order of 1,000 m. Given the generally deep waters of these surveys (> 2000 m), this corresponds to less than 50% of the depth. Under these conditions, and with gross water column velocity profiles updated on a daily basis, the echo-sounder is reported to be accurate to within 5 m or 0.5% (Johnson *et al.* 1989).

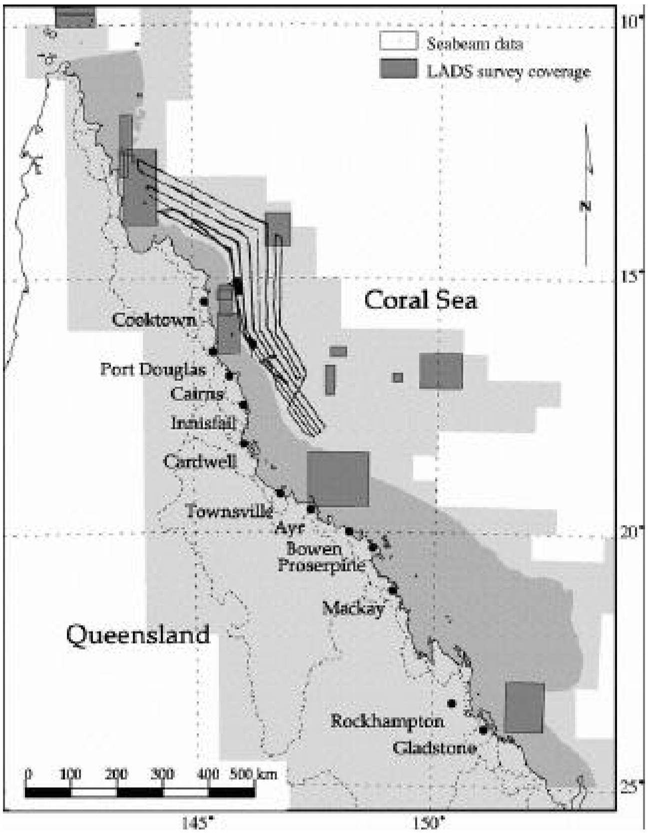

Figure 6. Seabeam multi-beam echo-sounder data and gross coverage of LADS data.

Bathymetric Survey data

AUSLIG completed numerous high-resolution surveys over reef and lagoon areas during the 1980s. Digital data from 49 of these surveys have been accessed by this project. The surveys produced ~405,000 soundings with variable (but usually high) density over specific reefs (Table 1). These allow detailed representation of some reefs and for the majority of Bowling Green Bay. These data were originally withheld from the interpolation to estimate the accuracy of the model (Lewis 1999), however, they are now included.

Table 1. Reefs and areas for which detailed surveys have been undertaken.

REEF NAME	POINTS	AREA (KM^2)	DENSITY (POINTS PER KM^2)
BAIT	2,579	19	136
BELLCAY	4,264	43.9	97
BOULT	1,261	16.1	78
BOWLING GREEN BAY	131,586	1,703.0	77
BROOMFIELD	388	14.8	26
BUSHY	1,483	28.5	52
CAYLEY	820	20.1	41
CHAUVEL	16,968	141.5	120
CHESTERMAN	395	12.8	31
DAVIES	30,328	7.5	4,044
ERSKINE	1,267	48.7	26
FAIRFAX	1,049	14.9	70
FITZROY	1,873	40	47
HASTINGS	21,188	36.9	574
HERON	1,496	80.9	18
HOOKIS	2,304	14.8	156
HOSKYN	788	15.1	52
IRVING	924	48.3	19
IRV POL	1,410	61.4	23
J BREWER	8,704	50.9	171
KELSO	4,275	31.7	135
LADYELLIOT	351	8.6	41
LAMONT	630	13.9	45
LLEWELLYN	1,980	31.5	63
MASTHEAD	883	36.2	24
MUSGRAVE	102,648	14.3	7,178
MYRMIDON	7,005	13.8	508
NORMAN	17,546	27.6	636
NORTH	778	12.7	61
NORTHWEST	1,571	71.4	22
ONE TREE	1,288	33.6	38
PANDORA	1,509	13.8	109
PEART	39	3.4	11
RIB	4,423	15.2	291
SANDPIPE	506	10.0	51
SANDSHOE	662	18.0	37
SAXON	12,563	13.2	952
SYKES	770	22.7	34
TERN	1,146	16.5	69
TRYON	560	12.6	44
UN17-020	124	7.8	16
UN17-021	151	7.2	21
UN19-151	202	5.2	39
UN20-103	482	13.5	36
WARDLE	2,788	47.7	58
WILSON	890	102.7	9
WISTARI	727	37.6	19
WRECK	488	16.6	29
YONGE	6,914	42.8	162
TOTAL:	404,974	3,120.9	130

Area includes all places within 500 m of any data point. The point density is the quotient of the number of points and the area.

LASER Airborne Depth Sounder (LADS)

LADS Corporation, a subsidiary of Vision Systems Ltd, in conjunction with the Royal Australian Navy, have surveyed some of the GBR using airborne LASER altimetry. LADS data are captured by airborne LASER methods which utilise the tendency of short-wave electromagnetic radiation (green light) to penetrate the water column and reflect off the substrate while longer wavelengths (infra-red) reflect from the water surface (LADS Corporation Ltd). This method has several advantages over ship-based hydrographic survey. Most obviously it quickly produces a high density of data points over large areas and is accurate in shallow water. LADS has the potential to greatly enhance the resolution of bathymetric data over the GBR and will play an increasingly important role in depth modelling of the GBR.

The LADS coverage for GBRDEM is limited to small parts of the GBR Lagoon (Figure 6). The system *can* penetrate to 70 m but penetration depends on the clarity of the water column. Data over the GBR are limited to approximately 40 m depth. Nonetheless, 430 reefs covering some 3,800 km^2 are encompassed within the gross spatial limits of the LADS surveys (Figure 6). This suggests that 22% of the reefal area of the GBR is covered. Data points are irregularly spaced, approximately 50 m apart. Horizontal and vertical accuracy are unknown due to a lack of meta-data and scarce documentation. Data are referenced to LAT, and a spatially variable adjustment to MSL is required if large areas are covered. For efficiency, LADS data are included within GBRDEM in a two-step process; the LADS data are interpolated to a 250 m lattice and these gridded points are taken as data within GBRDEM.

DEPTH MODEL DEVELOPMENT AND INTERPOLATION PROCEDURES

The depth model is constructed using two distinct procedures: an interpolation process and a reef modelling process. The latter ensures that reefs are represented even where data are absent. Figure 7 is a simplified representation of the processing steps. These are automated in an ARCINFO™ Macro Language (AML) procedure.

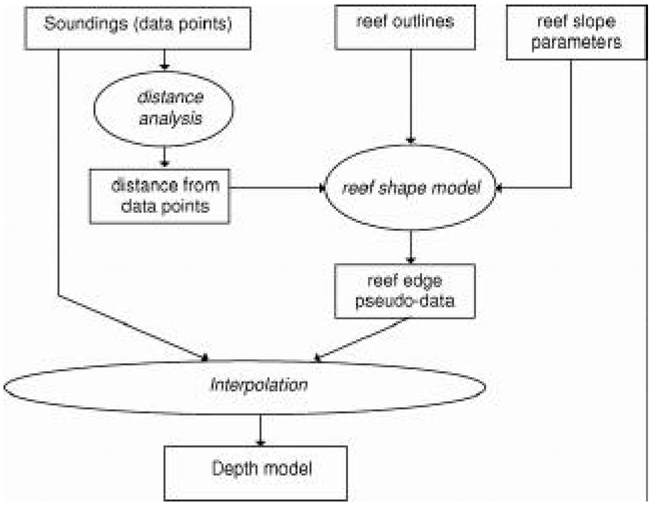

Figure 7. A simplified representation of the data analysis steps used in interpolation of the depth model from depth soundings and reef outline data.

The structure of the land, the lagoon and the ocean floor are interpolated from a large number of points at which depth (or elevation) is known. These points are maintained within several digital datasets maintained as ARCINFO coverages, as described previously. The accuracy of the depth or elevation coordinates (x, y, z) for each point is known only within broad ranges. This situation is typical of GIS datasets which are notoriously poorly documented.

Data points are augmented by a number of linear elevation features. These are the coastline, the mapped boundary of islands, and the mapped outlines of reefs. Given the extent of the study area, the range of depths and the accuracy of the data points, the coastline can be equated with MHWS, which can be related to MSL using tide tables. Reef outlines are assigned a depth of about 10.5 m below MSL, on the basis of comparisons undertaken as part of this project.

Land and ocean areas are interpolated separately. Discontinuity in landform between terrestrial and marine environments makes this necessary. For instance, continental islands in the lagoon drop relatively steeply into the sea, while below sea level, the surface flattens out to a gentle slope in the order of 0.1% overall. A difficulty of interpolation by splines, as used here, is a tendency to over-shoot where data are sparse (Mitasova and Mitas 1993). This would lead to a moat effect around these islands unless there were data around the edge of each island to control the surface. Separate interpolation of the land and sea allows both marine and terrestrial environments to be accurately represented.

Interpolation Procedures

Spatial interpolation is a statistical procedure, however, interpolation of terrain involves a degree of technical judgement. Selection of the optimum parameters for a terrain model does not reduce to a single statistical indicator. Qualitative indicators, such as the ability of the surface to represent the shapes of important features, and an absence of interpolation artefacts, are important and best assessed by visualisation. The current interpolation procedures, continue to evolve with data, software and knowledge. They are based on experience, exploration, and visual appraisal of results. Substantial improvement in the representation of shallow water reef areas may be possible using existing image analysis methods and LANDSAT data (Bierwirth *et al.* 1993). However, image data are not available at this time.

GBRDEM is interpolated using the iterative finite-difference interpolation method of Hutchinson (1988) implemented in the ANUDEM software (Hutchinson 1998). The method is related to mathematical splines because the interpolation tries to fit the smoothest possible surface to the data by minimising some combination of the derivatives of the fitted surface. Mitasova and Hofierka (1993), and Mitasova and Mitas (1993) also developed and applied spline methods for interpolation of terrain, leading to its implementation in the GRASS GIS software in 1992.

ANUDEM is incorporated in the ARCINFO™ TOPOGRID system. This method is widely accepted as an effective approach to the interpolation of elevation models and also appears to be effective for depth models. The method underpins the digital terrain models developed and marketed by AUSLIG (http://www.auslig.gov.au/products/digidat/dem9s). It is also a standard for at least one Australian state agency[3]. It has been applied in both broad and fine-scale terrain analysis (Hutchinson and Dowling 1991, Lewis 1996).

ANUDEM, like spline methods, requires a choice of parameters. Spline interpolations fit a smooth, continuous surface to a set of data points. Intuitively, a 'smooth' surface is either flat,

[3] The Victorian Department of Natural Resources uses ANUDEM to interpolate terrain models from 1:25,000 scale contour maps for use in forest management planning.

or changes consistently, properties that can be defined in terms of the first and second derivatives of the surface, respectively. Therefore, mathematical splining fits the 'smoothest' possible surface to the data by minimising the sum of the squared derivatives over the entire fitted surface. However, one must choose which derivatives. 'Thin-plate' or 'minimum curvature' splines minimise the second order derivative. 'Splining with tension' emphasises the first derivative and gives a flatter surface. 'Regularised' splining emphasises the third and potentially higher order derivatives with more realistic curvature characteristics (Mitasova and Mitas, 1993). Hutchinson (1988) refers to minimisation of the first derivatives as fitting a 'minimum potential' surface but notes that this option is only a well-defined problem in the discretised form (Hutchinson 1989).

The choice of how much weight to apply to each derivative, ie. how tense or stiff the interpolation should be is usually set by the user. Hutchinson (1988) recommends that zero weight be applied to the first derivatives if the sample data are primarily contours. Conversely, when the sample data are primarily points, Hutchinson (1988) recommends that the first derivatives be given a weight of 0.5 times the weight given to the second derivatives. Independent experience by the first author agrees with these suggestions. Future version of ANUDEM may allow an automatic, spatially adaptive interpolation criterion (Hutchinson 1997).

The present version of ANUDEM fits the surface f which minimises the function $J(f)$:

$$J(f) = \lambda J_1(f) + J_2(f)$$

where

$$J_1(f) = \iint \left(f_x^2 + f_y^2\right) dxdy$$

$$J_2(f) = \iint \left(f_{xx}^2 + 2f_{xy}^2 + f_{yy}^2\right) dxdy$$

The range of integration is the area of the fitted surface (Hutchinson 1988). f_x is the partial derivative of f with respect to x (and likewise for f_y, f_{xx}, f_{xy}, f_{yy}) and λ is the relative weight applied to the first derivatives (minimisation of overall slope), referred to as a 'roughness penalty trade-off'. λ is varied between 0 and 0.5, while the weight applied to the second derivatives (minimisation of curvature) is always 1. In TOPOGRID, λ is hidden in the choice of 'spot data' (λ = 0.5) versus 'contour data' (λ = 0) options, the latter producing the stiffer surface. For interpolation of depth data in the GBR Region, the spot option is superior.

Splining may use smoothing parameters related to uncertainty in the data. This, rather than the choice of derivatives, is the main emphasis when smoothing splines of various forms are used as statistical tools to interpolate smooth surfaces from noisy data (Wahba 1990, Hutchinson 1995).

ANUDEM also allows the data points to be regarded as noisy, where the fitted surface is not an exact interpolation, but passes sufficiently close to the data points that a user-specified root-mean-square (RMS) error is met. The interpolation will fit the smoothest surface which can achieve the specified RMS error. Therefore, the larger the RMS, the smoother the surface. Experience has demonstrated that if the RMS is too small, it can contribute to an unrealistic model. A bias can occur toward contour values (applicable, in this case, only over land areas) and localised peaks and pits at individual data points, where the surface departs from minimum potential (flat) to 'collect' a data point. This indicates an imbalance between the minimum potential aim and the data fidelity aim. In part, these problems arise because the software allocates data points to the centre of grid cells, introducing a 'discretisation error' (Hutchinson 1988 Hutchinson 1997). Recent revisions of ANUDEM reduce the weight given to gridded data points in the interpolation by converting the local slope into an estimate of elevation variance for each gridded data point (Hutchinson 1997). This addresses the discretisation error problem by recognising that steeper local slopes introduce more error when allocating the data point to the centre of the grid cell. A prior estimate of local slope is required; this is possible because the terrain model is developed iteratively (Hutchinson 1997).

In the present implementation of GBRDEM discretisation error is not addressed. The RMS tolerance is set to 0.5 metres, reflecting both the presumed accuracy of the data and the concerns expressed above. In future, we expect to adopt the recent versions of ANUDEM and reduce the specified RMS tolerance and possibly ?.

ANUDEM has several other advantages for interpolating terrain models from a large, irregularly spaced dataset. These are computational efficiency, robustness to variations in the density of data points, and the explicit representation of surface morphology in the form of ridge-lines, drainage lines and sink removal (Hutchinson 1988, 1989). The first two of these are relevant to modelling of bathymetry.

ANUDEM combines the benefits of a global approach to interpolation with the computational advantages of methods which segment the dataset (Hutchinson 1988). In global approaches such as Kriging and splining, computation time is proportional to n^3, where n is the number of data points. For practical purposes, this is intractable for large datasets. Segmentation of the dataset, for example Mitasova and Mitas (1993) reduces the computing effort. However, there are difficulties with how (where) to segment the data and with data-sparse areas (Hutchinson 1988). ANUDEM does not segment the dataset but fits a surface at successively finer grid resolutions until the user-specified grid resolution is met (the grid cell size is halved at each pass). The computational cost is proportional to the number of interpolated grid cells. However, the method remains insensitive to data-sparse areas (Hutchinson 1988).

We do not use those aspects of ANUDEM designed to reflect land surface morphology and hydrology. Hutchinson (1988, 1989) demonstrates that superior interpolation from contours is possible by explicit representation of ridge-lines and drainage lines. This is not applicable here because most of our data are points. ANUDEM can also automatically enforce surface drainage by defining stream networks and clearing sinks (local minima) (Hutchinson 1988, 1989). The hydrological and morphological reasoning which underlies this is not applicable to the GBR lagoon or reef structures.

Reef modelling

Coral reefs are distinct structures within the GBR Lagoon. Compared with the sea floor they are abrupt with steep sides and flat tops, reflecting the nature of coral reef growth. In the context of the GBR Region, reefs are also fine-scaled, though a typical reef might cover tens and, in a few cases, hundreds of square kilometres. Our data yield a mean reef area of 6.8 km^2, compared with 6.9 km^2 estimated by Hopley *et al.* (1989). Reef shapes will not be captured in a typical interpolated surface except where the density of data points is very high; in the order of one data point per square kilometre.

Additional pseudo-data points are added to the interpolation to effectively represent reefs in data-sparse areas. These pseudo-data are based on a structural model of reef form and applied only where all genuine data points are more than 1 km apart and in the vicinity of reef edges.

The structural model of reefs has several inputs: the mapped limits of each reef (digital polygon data) which have a mean depth of ~10.5 m; the magnitude of the reef slope, determined by examining data for several reefs where accurate survey data are available, is assumed to be constant for each reef; the depth of the ocean floor, estimated by interpolation of depth soundings excluding those that are near (~3 km) reefs; and the assumption that the reef flat lies at 1.0 m below MSL. Despite obvious limitations, these parameters provide a generalised model of reefs that is appropriate for use at broad scales and where data are lacking.

The structural reef model is constructed using grid-cell spatial analysis methods with a lattice resolution of 100 m. Assuming a constant slope for the reef edge, the distance from the closest part of the mapped reef outline translates directly into a measure of depth; depth increasing outward from the reef and decreasing toward the centre. The model is truncated where the depth exceeds upper or lower bounds. A circular reef outline would be modelled as a truncated cone using this system.

Reef edge slope was estimated by examining profiles developed from several reefs for which high density, detailed surveys were available. Slope varies substantially between reefs as a function of latitude and location on the continental shelf, possibly as a function of exposure. Variation within reefs is pronounced where the reef has a clear exposed edge, leading to a steep outer face and a gradually sloping back. However, many reefs show little variation of slope with orientation, with slopes usually much lower than observed in the outer reefs (Table 2).

Yonge Reef is a typical ribbon reef and has a slope on the outer edge of about 40% when measured over a 2 km baseline. Side-slopes are also high (~30%) but the slope off the back of the reef is only ~1.8%. Myrmidon is another outer reef and also has steep slopes but with less directional difference; 20.4% (SE 0.5%) over three transects. However mid-shelf, inner-shelf, and southern reefs are much less dramatic. For these, only once from 42 profiles was slope in more than 10% (11.6% on John Brewer reef), while variations with orientation were minor. It should be noted that slopes observed *in situ*, over short distances, will usually be steeper than those measured over longer baselines using a depth model. This is a result of spatial scale (Lewis 1996).

Excluding outer reefs a mean slope of 4.8% (N=42, SE=0.07) was calculated for 42 transects covering various directions over fourteen reefs. Pandora reef, an unusual inner shelf reef, has a uniform slope of 5.5% extending about 270 m from the edge of the reef flat.

Table 2. Estimates of reef edge slopes.

		SLOPE (%)		
REEF TYPE/ LOCATION	**REEFS EXAMINED**	**FRONT**	**SIDES**	**BACK**
northern, ribbon	Yonge	43.0	28.5	1.8
central, outer	Myrmidon	21.0	14.6	2.6
central, mid-shelf	John Brewer, Rib	9.3	2.0	-
central, inner	Pandora	5.5	5.5	5.5
southern, outer	Boult, Llewellyn, North, Broomfield, Onetree	4.3	6.1	-
southern, mid	Lamont, Erskine, Masthead, Irving, Heron, Northwest Island	3.0	3.3	4.8

Given the opportunistic and incomplete nature of the samples used to derive these results (most of the reefs are in the Capricorn Bunker) slopes of 30%, 20% and 5% are used in the reef modelling procedure for ribbon/outer, mid-shelf and inner/southern reefs, respectively. Pseudo-data points are taken from the sloping section of the reef model by randomly selecting every third grid cell in the reef model and converting it to an x, y, z coordinate. Points within 1 km of a real data point are removed and the remainder are used in the interpolation.

The inclusion of a reef model in GBRDEM allows reef structures to be represented despite extremely sparse data. The use of pseudo-data, rather than imposing a 'hard' reef model onto the depth model, ensures that existing genuine data points are given priority and that surface continuity is maintained. The success of the approach is illustrated by Figure 8 which shows Yonge Reef modelled from three distinct sources. Sounding data alone will not allow the reef shape to be represented (Figure 8). However, modelling the structure of the reefs ensures that the broad-scale features of the reef are represented even with a paucity of real data. Using the reef model, the general structure of Yonge reef is present but lacks detail. Smoothing due to the 250 m lattice resolution is also evident; the channels between Yonge reef and Carter Reef (to the north / right) and No Name Reef (to the south / left) are approximately 750 metres wide from reef-crest to reef-crest. Therefore only three lattice cells in the regional scale-depth model represent this feature and some detail is lost.

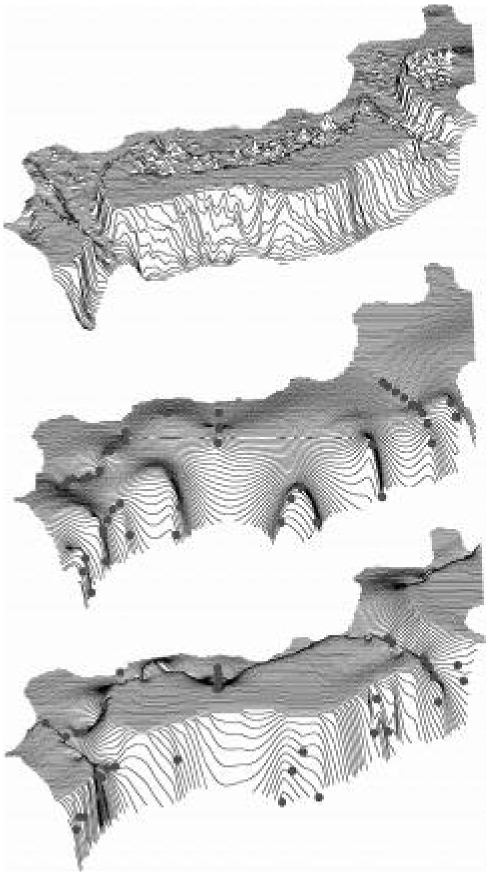

Figure 8. Yonge reef interpolated using a range of datasets and methods. **Top:** A precise model developed from 6914 data points (the distance between data points is ~80 metres) from a detailed reef survey undertaken by the Australian Survey and Land Information Group. **Middle:** the same reef interpolated from basic depth soundings only (~ 158 points indicated by dots). **Bottom:** the interpolation after including pseudo-data from the structural modelling process.

CROSS-SHELF TRANSECTS

Cross-shelf transects were generated to allow statistical and graphical summaries of terrain characteristics by latitude. The aim of such transects is to isolate cross-shelf from long-shore variation (often thought of as latitudinal in the GBR). It is therefore appropriate that the transects be perpendicular to both the coastline and the edge of the continental shelf. We generated a set of curvilinear transects extending from the coast to the limit of the GBR (determined as the 150 m isobath, as defined by the depth model) approximately perpendicular to the 'direction' of the lagoon itself (Figure 9). The midpoint of each transect is located on a specific latitude at ~0.25 degree intervals. This latitude is used as a label for the transect.

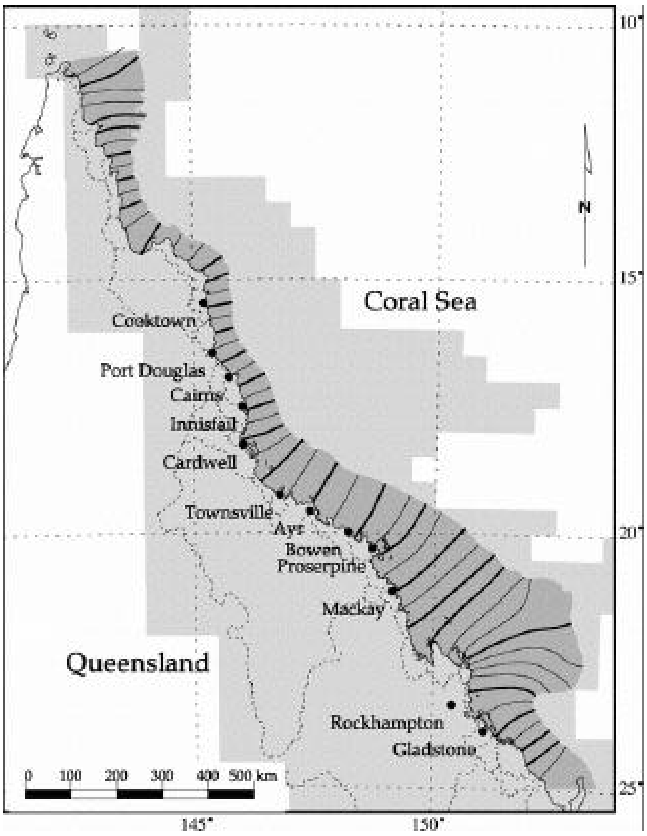

Figure 9. Curvilinear transects across the GBR Lagoon. Thicker lines correspond to transects for which a profile has been generated (see Figure 24).

Transects were used to generate a series of cross-shelf profiles and, through a series of spatial operations, to generate estimates for latitudinal variations in the physical properties: *area of reef*, *volume of water* and *number of reefs.* Transects were also used to segment the Lagoon into areas by allocating places to the nearest transect. Profile data were generated by overlay of transects with the depth model to gain an estimate of depth at a series of locations along each transect.

SPATIAL ANALYSIS METHODS FOR ESTIMATION OF PHYSICAL PROPERTIES

Spatial analyses were undertaken in ARCINFO™ GRID to determine qualitative and quantitative characteristics of the terrain model at the regional scale.

A number of summaries of area features (reefs, cays, etc) were generated from the available GIS data for reference purposes. The overall boundary used approximated the Great Barrier Reef Marine Park; from the land to beyond the edge of the continental shelf, and from

10?41’S to 24?30’S degrees south. For a summary of reef types within the GBR ’lagoon’, the overall boundary was restricted to the area between the high water mark and the estimated location of the 150 m isobath. Spatial datasets, including a table identifying the reef type, were made available by GBRMPA in ARCINFO™ format. Spatial analysis was by overlay operations in ARCINFO™.

Areas and types of reef by latitude

The area of each reef type was estimated from the polygon coverage of reefs provided by GBRMPA. Where counts of reefs were required, the data were first ‘dissolved’ to aggregate all relevant parts of each reef into a single polygon, as some of the ‘reefs’ are arbitrarily sub-divided. Islands and cays *within* reefs were likewise excluded. Where the *type* of reef was required, the tabular data were linked to the reef polygons using the polygon attributes ‘reef-id’ and ‘sub-id’ as a composite key. Where summary by transect was required, each reef polygon feature was allocated to the transect to which the majority of the polygon, by area, was closest. Reef types were aggregated following the system proposed by Hopley *et al.* (1989), based on Hopley (1982). This categorises reefs according to their level of development and by the nature of the platform on which the reef has developed. Development varies from juvenile (submerged reefs and reef patches) through mature (crescentic and lagoonal reefs) to senile (planar reefs). Ribbon reefs are distinct because they are considered to have evolved from narrow, elongate pre-Holocene foundations. Incipient and fringing reefs are distinguished by development on continental islands or the coastline.

Statistics based on the number of reefs depend on the ability of mapping methods to ‘see’ reefs. This may omit submerged reefs in deeper waters, and include features such as *Halimeda* beds in shallow water. Estimation of reef areas also requires that the ‘boundary’ of the reef be defined which may lead to error. The datasets used here attempt to show the limits of the reef shoal. In both cases, estimates will be more accurate for large well-developed reefs than for smaller, more submerged features.

Volumes of water by depth ranges

The volume of water over the continental shelf within set depth ranges was estimated in three ways: (i) the volumes of water within *horizontally defined* strata (0-10 m, 10-20 m, 20-40 m, 40-80 m, 80-160 m); (ii) the volumes in *vertically defined* regions where the boundaries between regions are defined by total bottom depth, using the same classes as above; and (iii) volumes *moving outward from the shore*, i.e. as for (ii) but with an added continuity constraint so that regions are built by migrating outward from the coastline (Figure 10). This may be of interest in interpreting the volumes of Lagoon available to dilute terrigenous inputs, including fresh water from flood events. While (i) and (ii) are readily estimated from a depth model, (iii) requires an iterative cell-by-cell process in which a cell is added to a stratum only if one or more adjacent cells meet specified criteria. Using a 500 m resolution, (i) and (ii) were estimated from the terrain model, after removing areas of land and areas outside the GBR Lagoon. (iii) was estimated after re-sampling the depth-model to 1500 m spatial resolution. This loss of spatial resolution was necessary to process the terrain model within a reasonable time. Islands were excluded from all volume calculations.

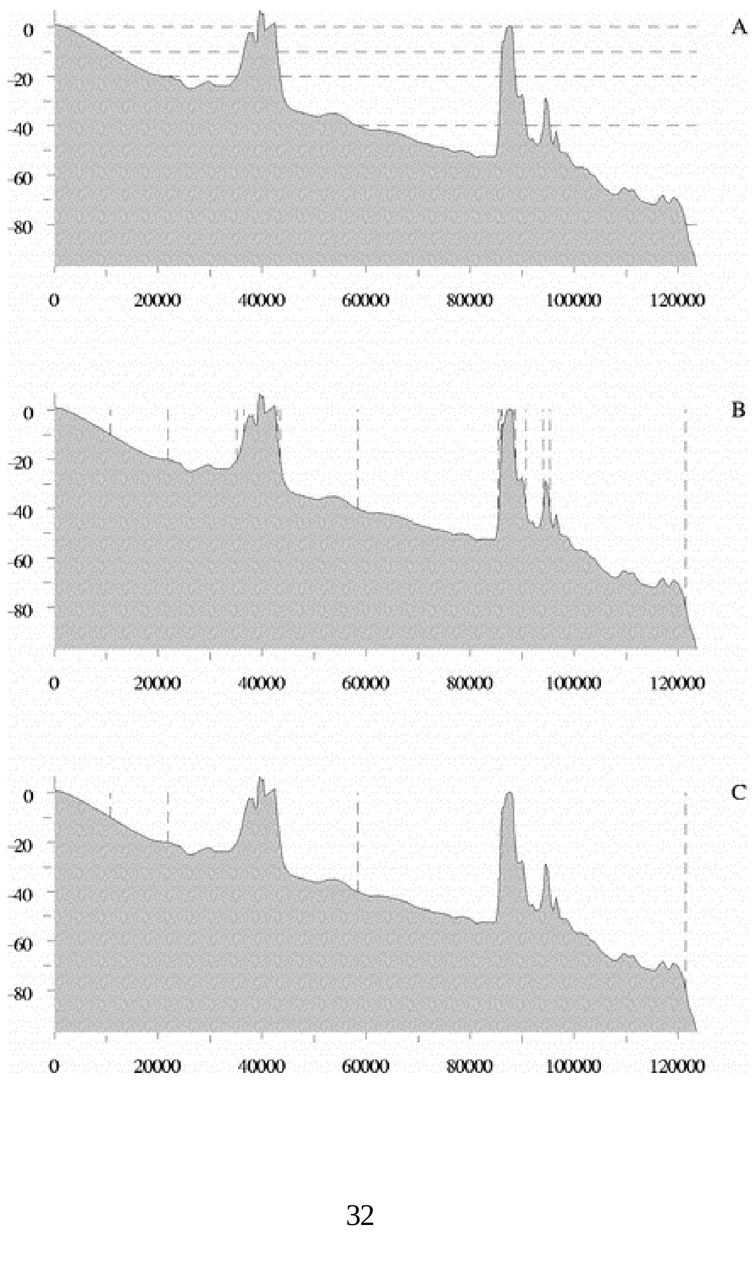

Figure 10. Explanation of volume calculations of the Great Barrier Reef Lagoon. A: the lagoon is segmented into horizontal layers corresponding to selected depth ranges. B: segmentation into regions corresponding to depth ranges. C: segmentation into regions based on depth ranges with the added condition that regions are contiguous.

‘Closure’ of the outer reef

The Great Barrier Reef presents an almost continuous physical barrier between the ocean and the lagoon north of Cooktown (~ 16?S). South of Cooktown, this characteristic is increasingly less pronounced and outer reefs are more scattered. To measure this ‘closure’, we determined the path from the northernmost outer reef to the southernmost outer reef, which maximised the distance over reef rather than sea; a ‘line of most reef’. Cost-path functions in ARCINFO^{TM} GRID were used to determine this path with some user-intervention. The path was converted to vector format and intersected with reef polygons to determine those parts of the path that lay over reef. For any interval along this path, the proportion of the distance over reef offers a dimensionless measure of closure (Figure 11). Closure was estimated for each transect by sub-dividing the path into sections according to the nearest transect.

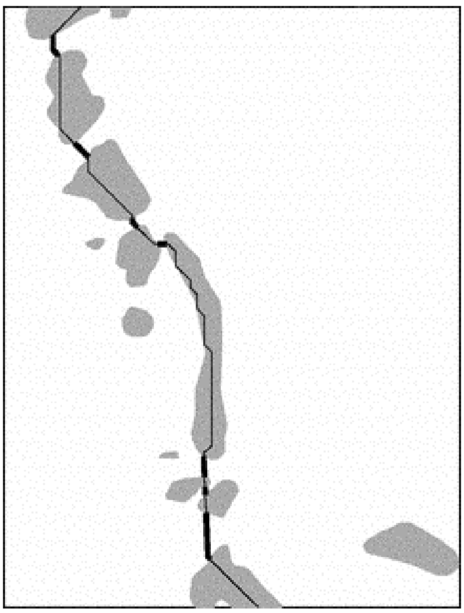

Figure 11. Explanation of the measure of Lagoon ‘closure’. A path is constructed along the GBR Lagoon which minimises the distance travelled between, rather than over, reefs. The proportion of the path which lies over reef (shaded) is a measure of closure. For the section shown, percent closure = 100 * 22.0 km / 26.6 km = 83%.

Continental slope

The continental slope ? the slope off the edge of the continental shelf ? varies strongly with latitude. We measured this by estimating the depth to the sea-bed at a fixed distance (10 km) beyond the continental shelf. As the latter is defined as the 150 m isobath, the continental slope (*CS*) is estimated as:

$$CS ? (D ? 150) / 10000 * 100\%$$

Where *D* is the depth measured 10,000 m beyond the 150 m isobath.

Estimates of steepness in terrain are scale-dependent with the horizontal baseline (in this case 10,000 m) defining the spatial scale (Moore *et al.* 1993, Lewis 1996). If a shorter baseline is used, steeper slopes will usually be observed.

Index of exposure

Exposure was defined as the integral of fetch distances taken at all angles between east and south. Fetch distance was defined as the distance, in a specified direction to the nearest reef or area of land. This index which can be regarded as preliminary was implemented in the ARCINFO™ GRID environment at a 500 m lattice resolution using a macro which allows adjustment of the defining parameters. The angles of integration, the choice of distance rather than (for instance) a non-linear transform of distance, and the use of reef / land areas rather than (for instance) a depth threshold, can be varied within this routine. The index was evaluated for all cells in the Lagoon and aggregated to transects as required.

RESULTS

Visualisation

Visualisation is a powerful method of presenting information for terrain modelling, especially for studies of marine geomorphology (e.g. Twichell and Nelson 1997). GBRDEM can be visualised either as a map or by generation of simulated three-dimensional views. Maps of GBRDEM are provided in Figures 12 to 23. These should be examined in conjunction with the section on accuracy. Figures 24 and 25 provide simulated three-dimensional views of smaller parts of the region. They are intended to illustrate the potential for visualisation of the depth model as a means of study of the submarine terrain of the GBR Lagoon.

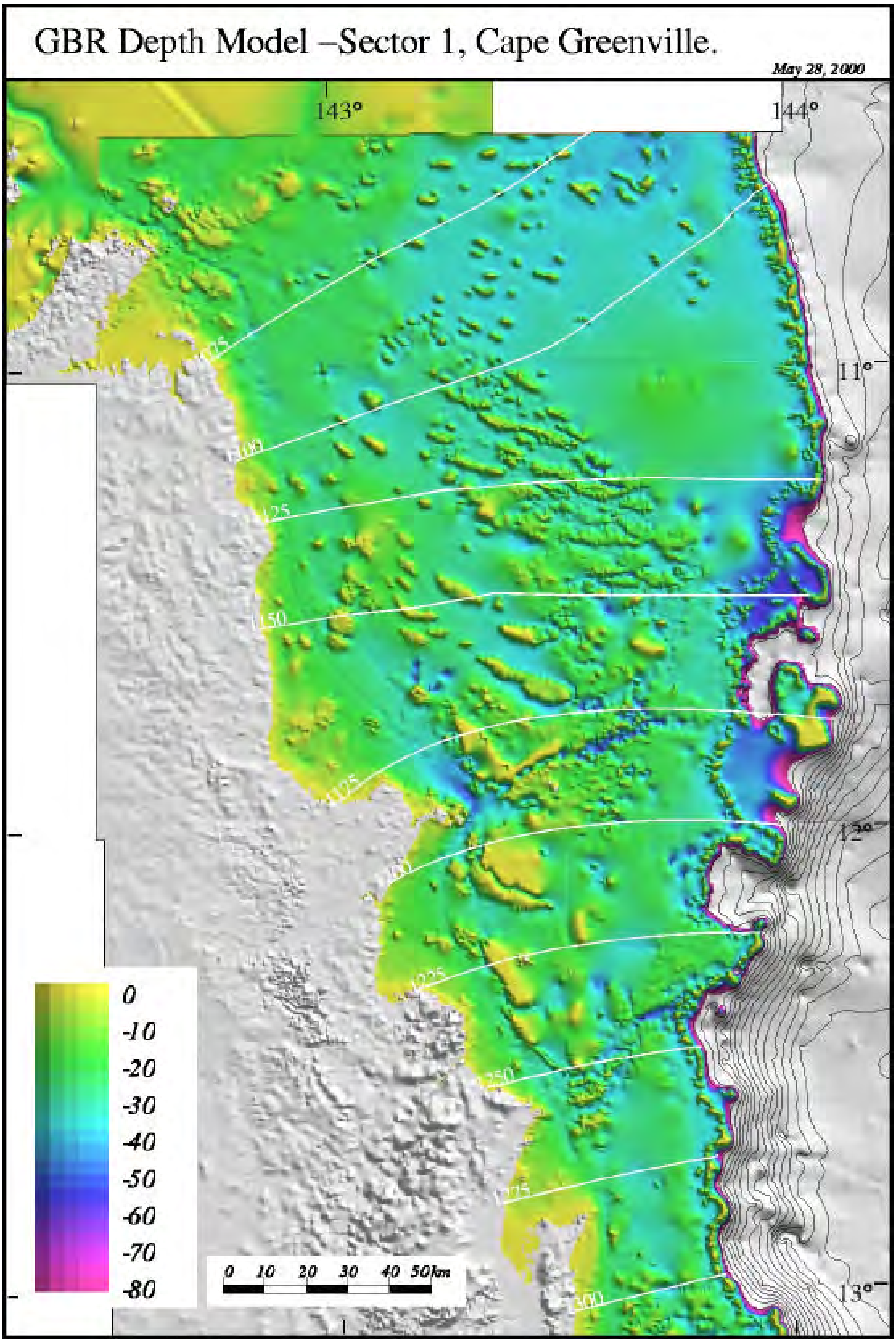

Figure 12. Depth model of the Great Barrier Reef: Cape Greenville.

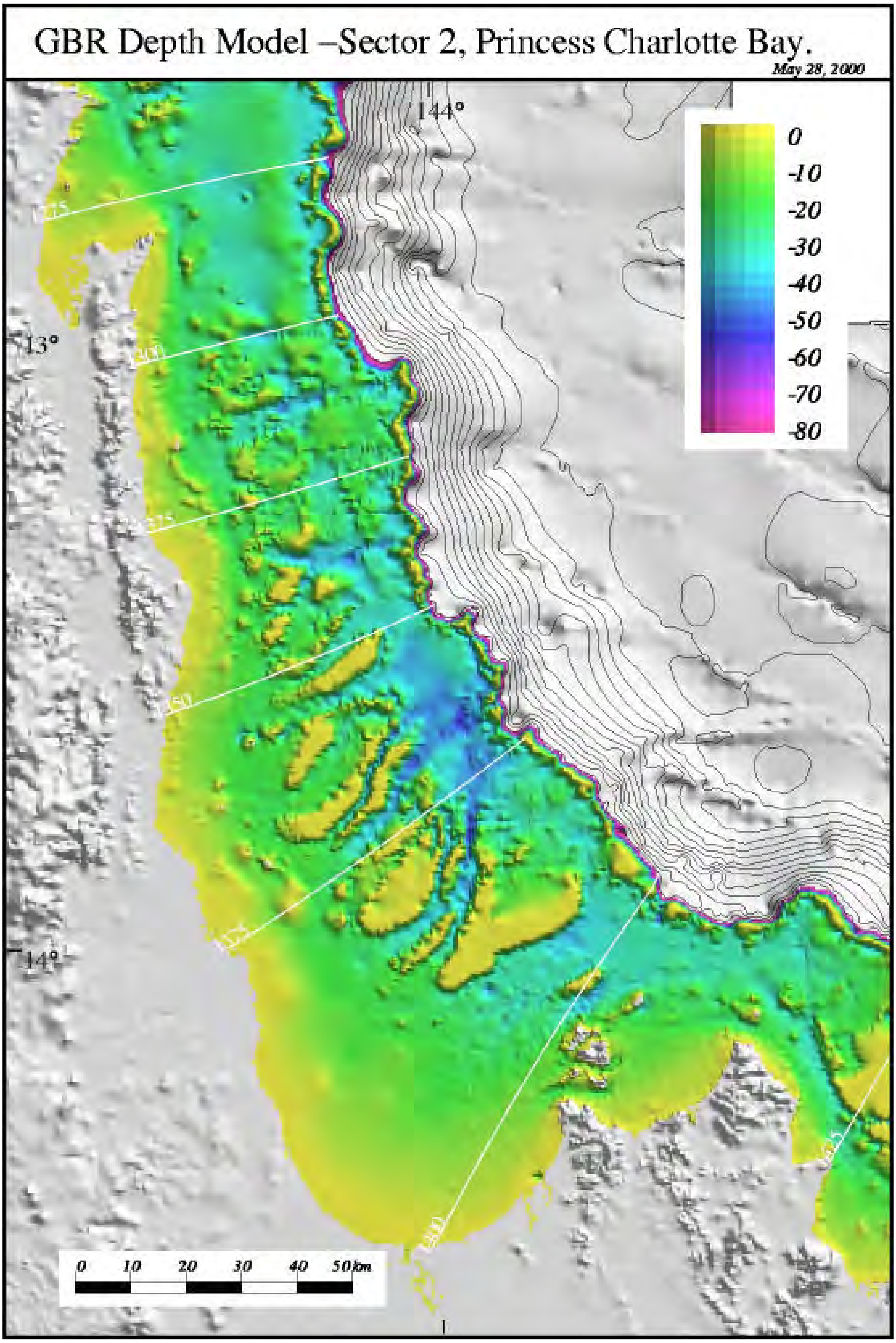

Figure 13. Depth model of the Great Barrier Reef: Princess Charlotte Bay.

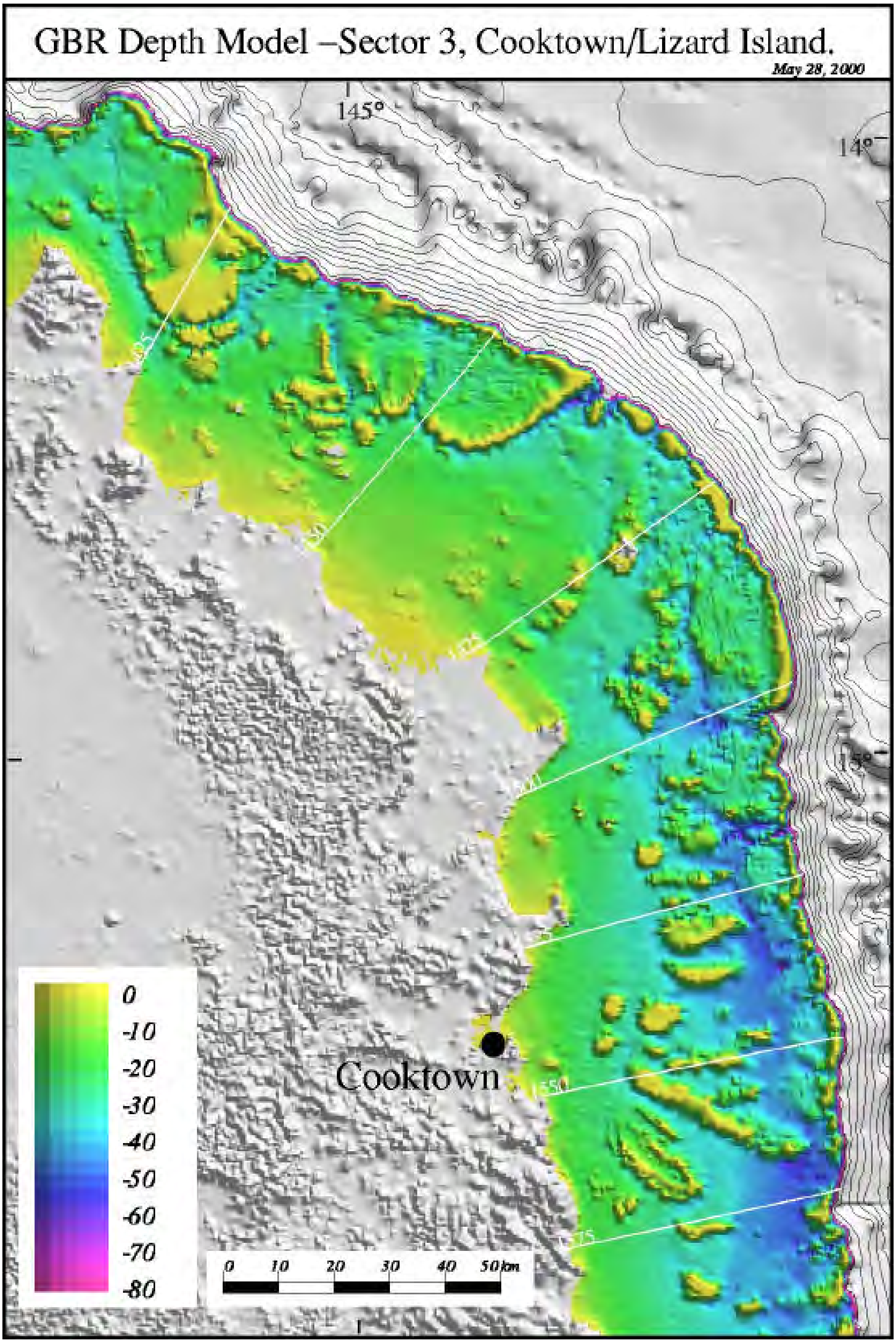

Figure 14. Depth model of the Great Barrier Reef: Cooktown/Lizard Island.

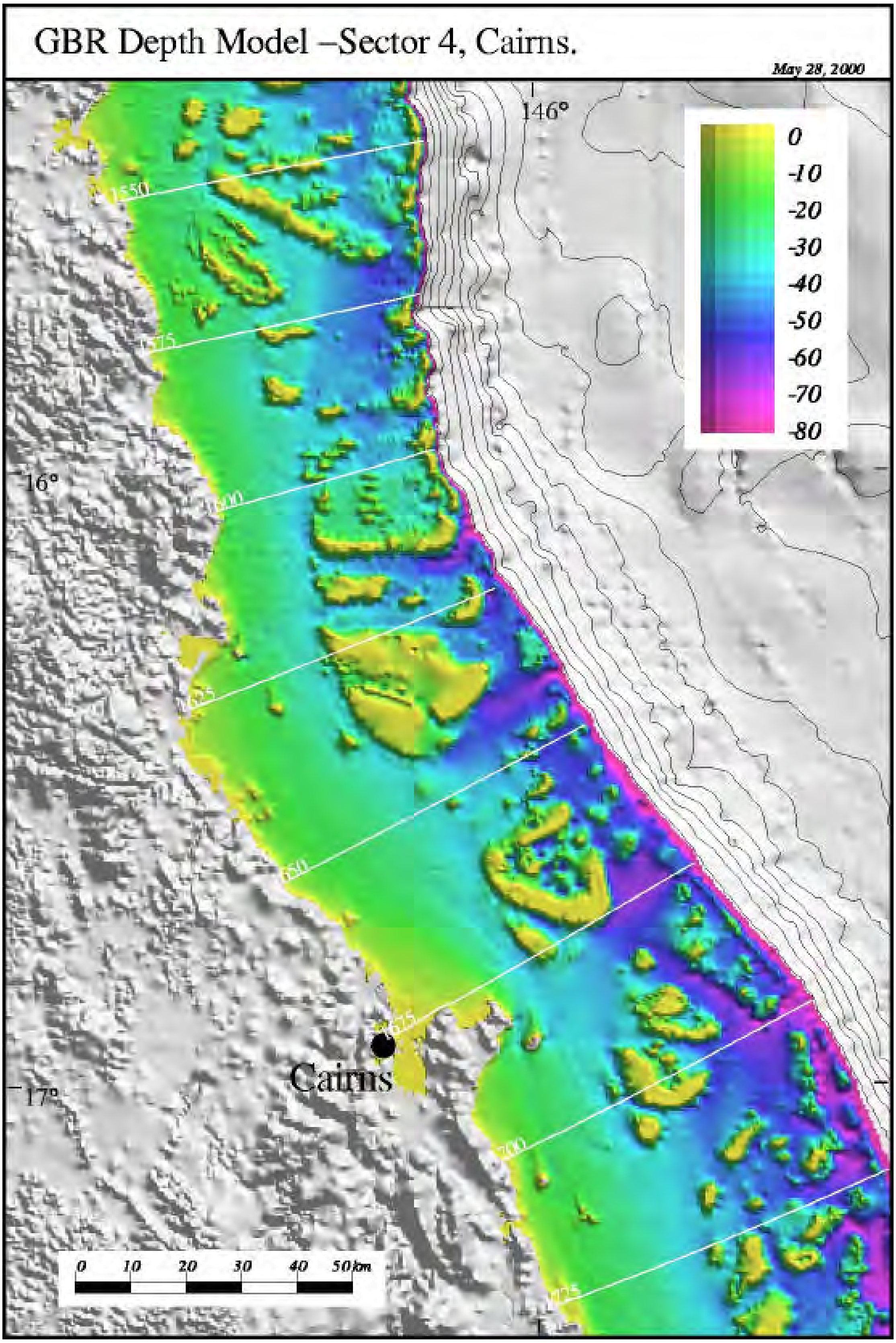

Figure 15. Depth model of the Great Barrier Reef: Cairns.

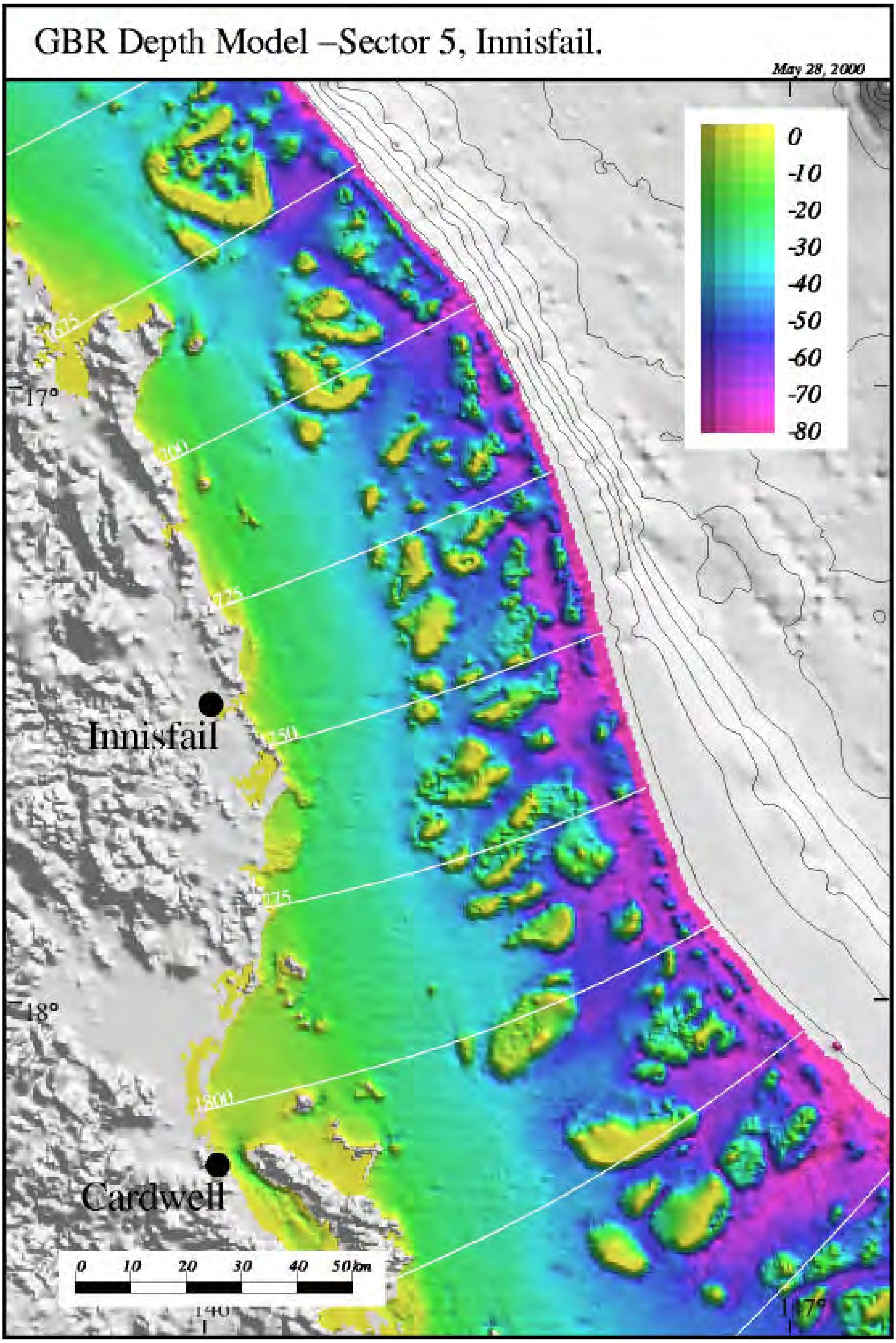

Figure 16. Depth model of the Great Barrier Reef: Innisfail.

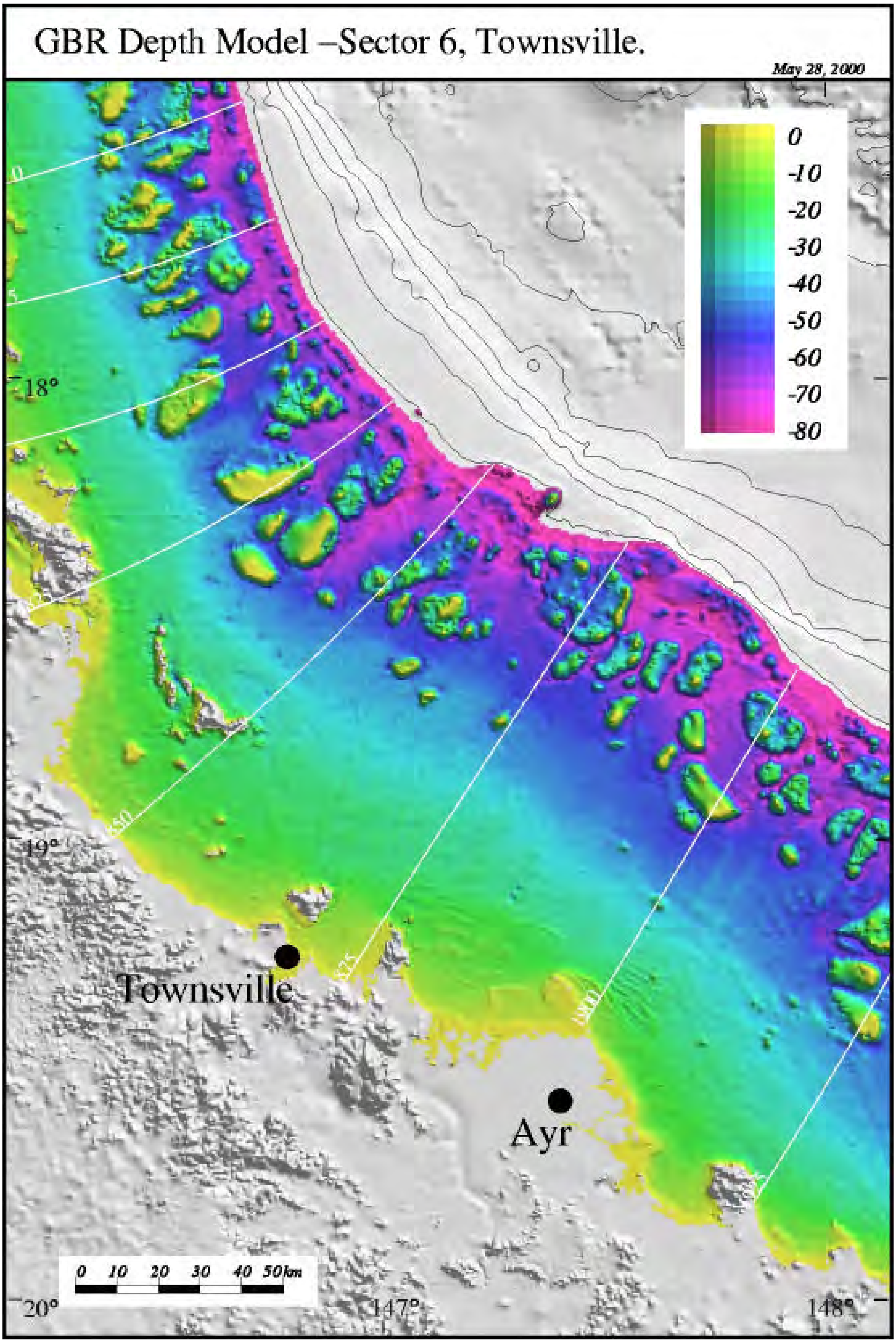

Figure 17. Depth model of the Great Barrier Reef: Townsville.

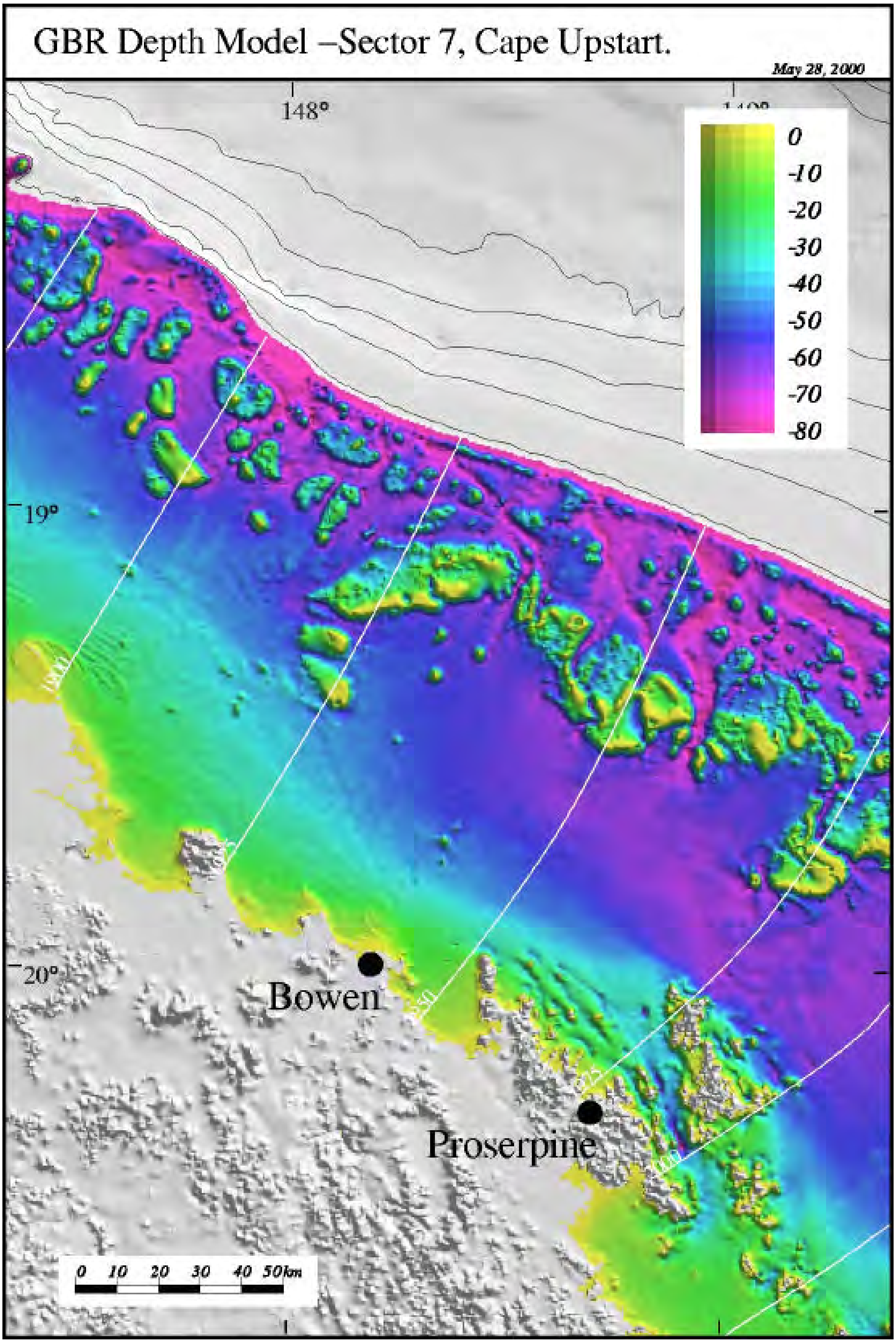

Figure 18. Depth model of the Great Barrier Reef: Cape Upstart.

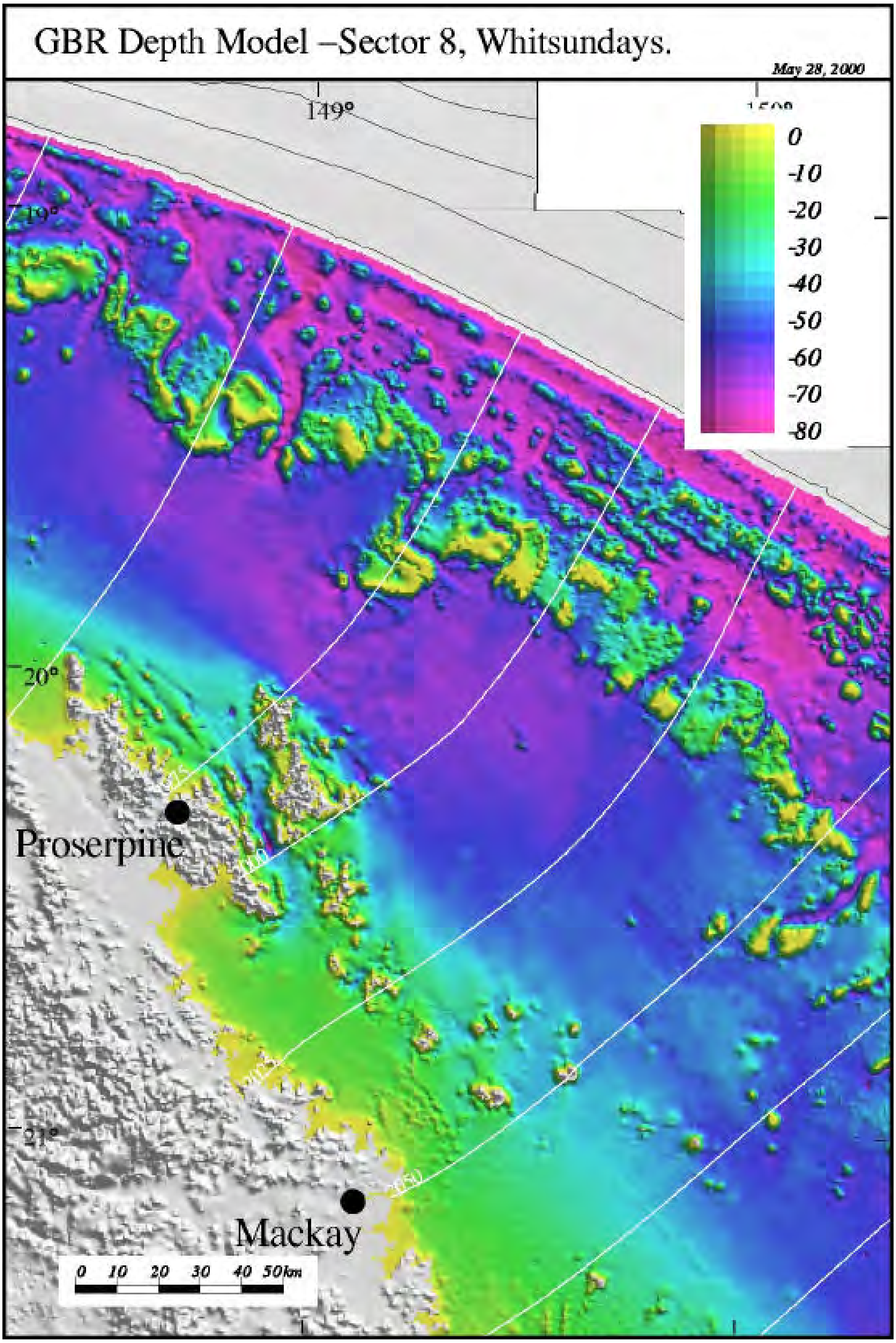

Figure 19. Depth model of the Great Barrier Reef: Whitsundays.

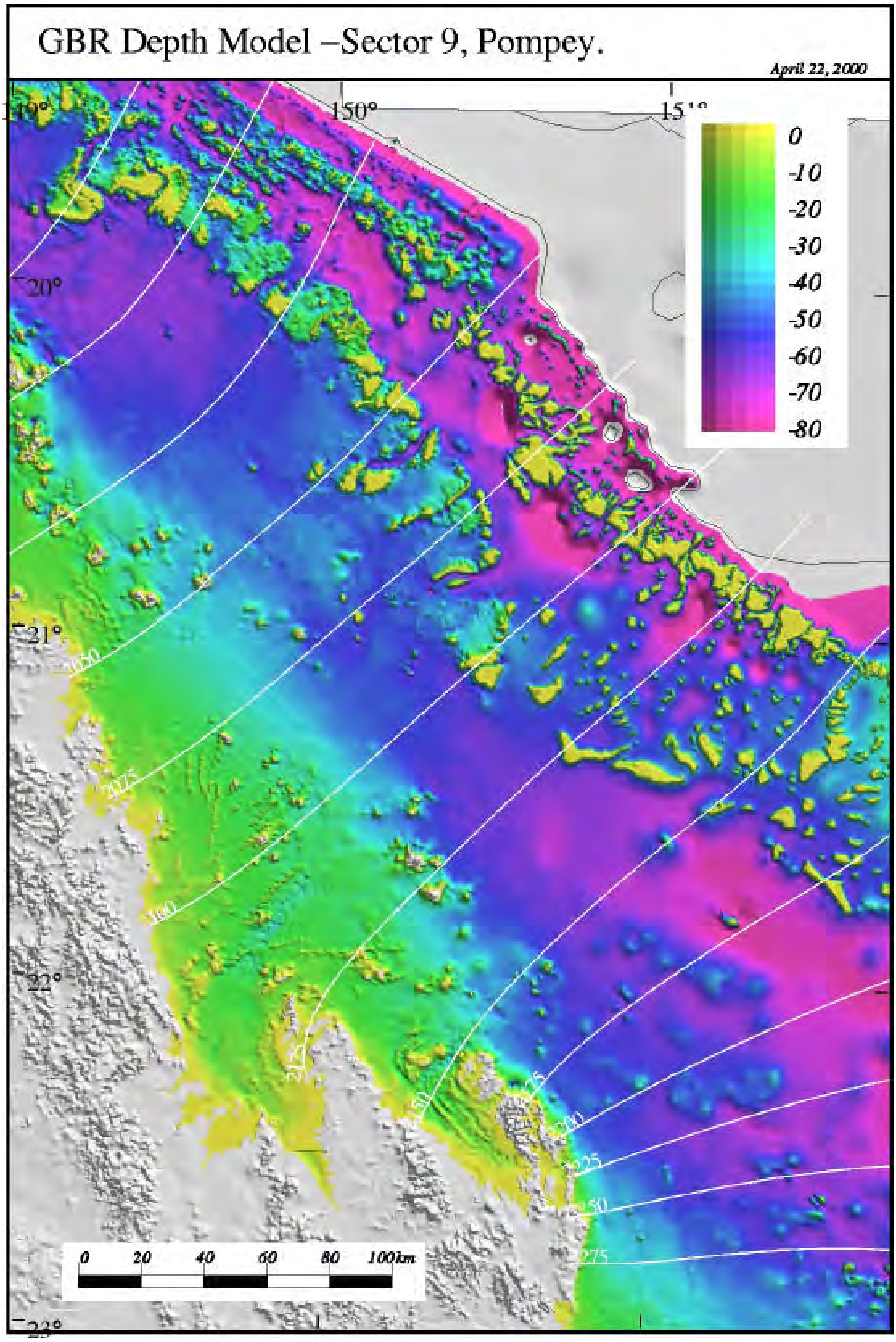

Figure 20. Depth model of the Great Barrier Reef: Pompey.

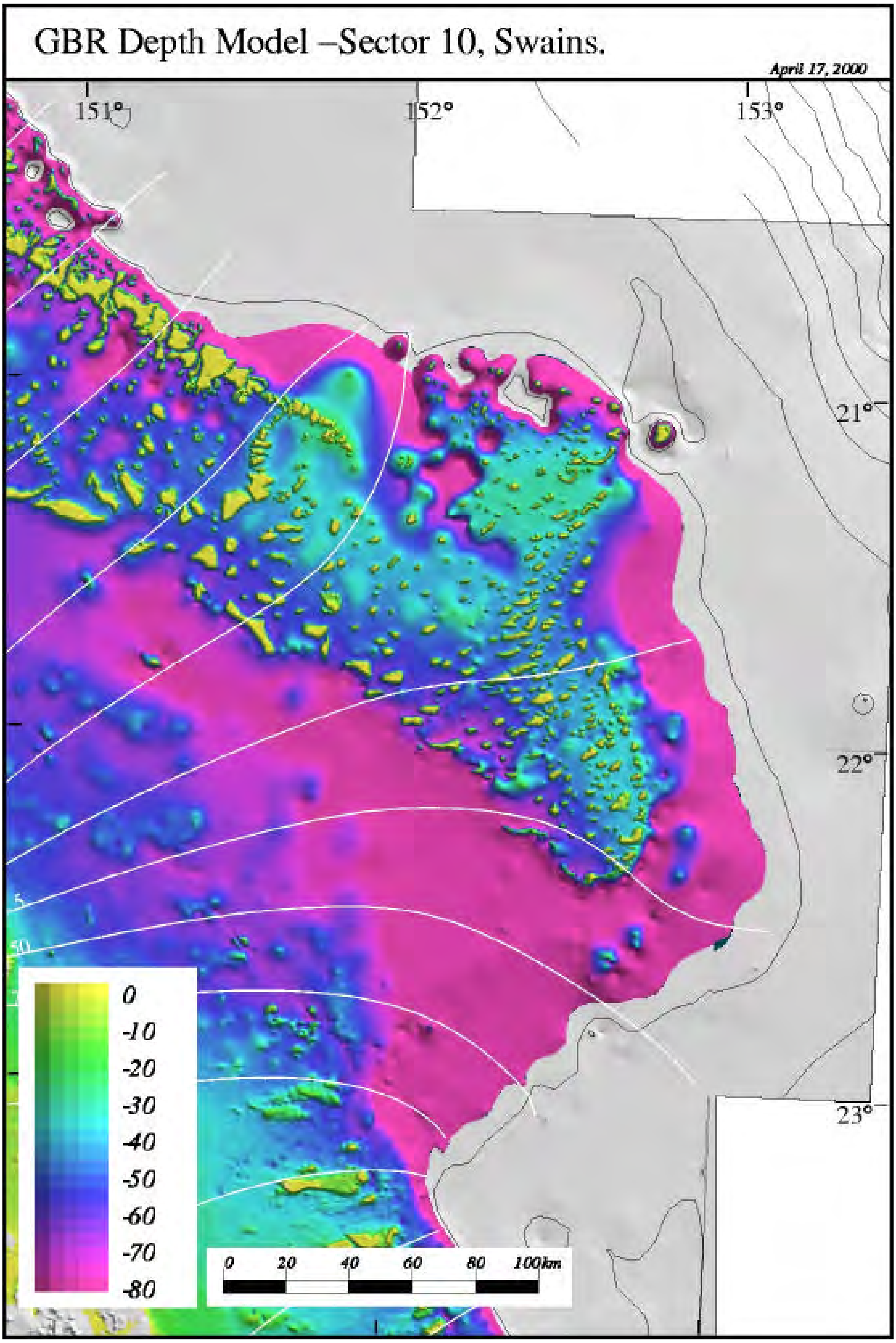

Figure 21. Depth model of the Great Barrier Reef: Swains.

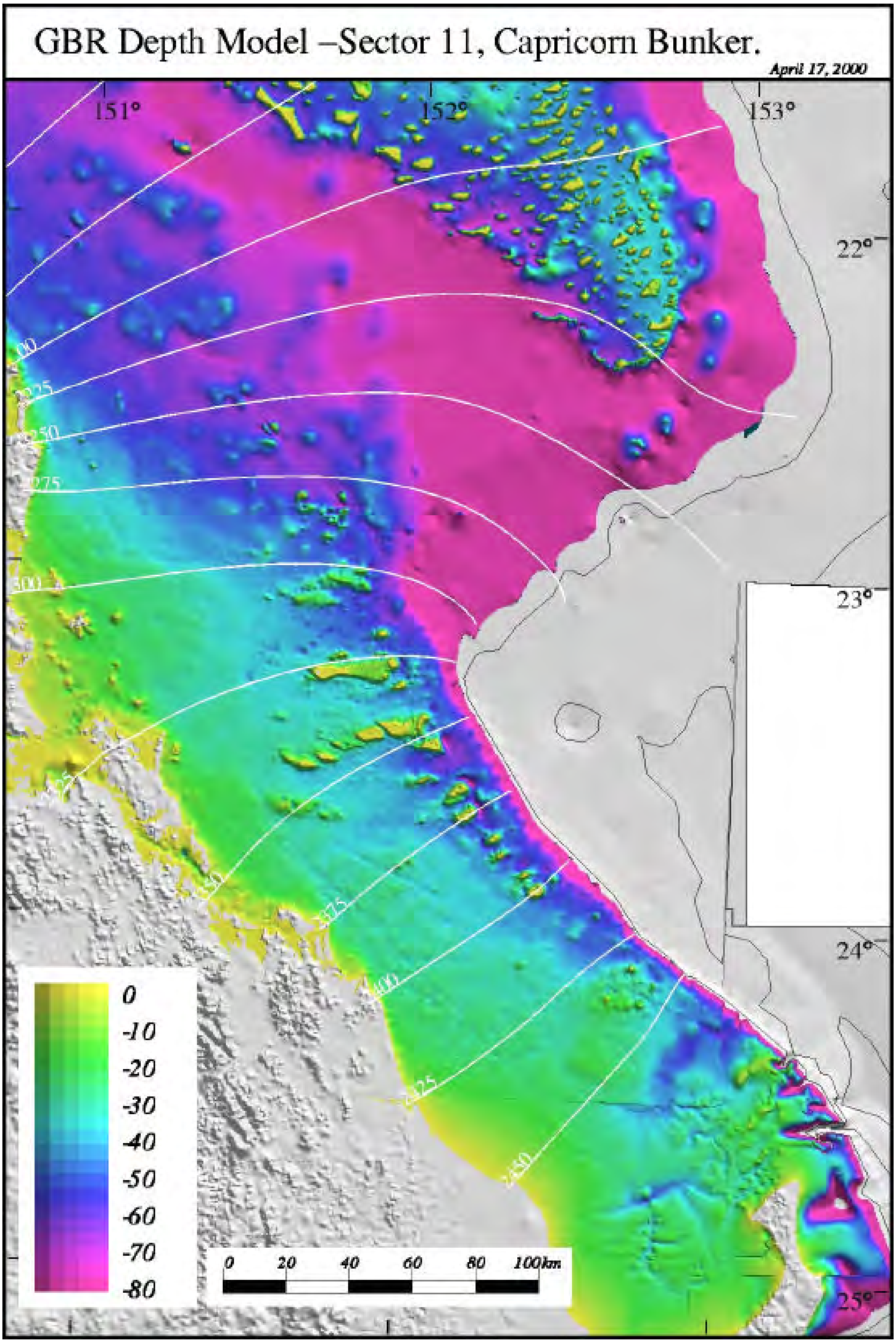

Figure 22. Depth model of the Great Barrier Reef: Capricorn Bunker.

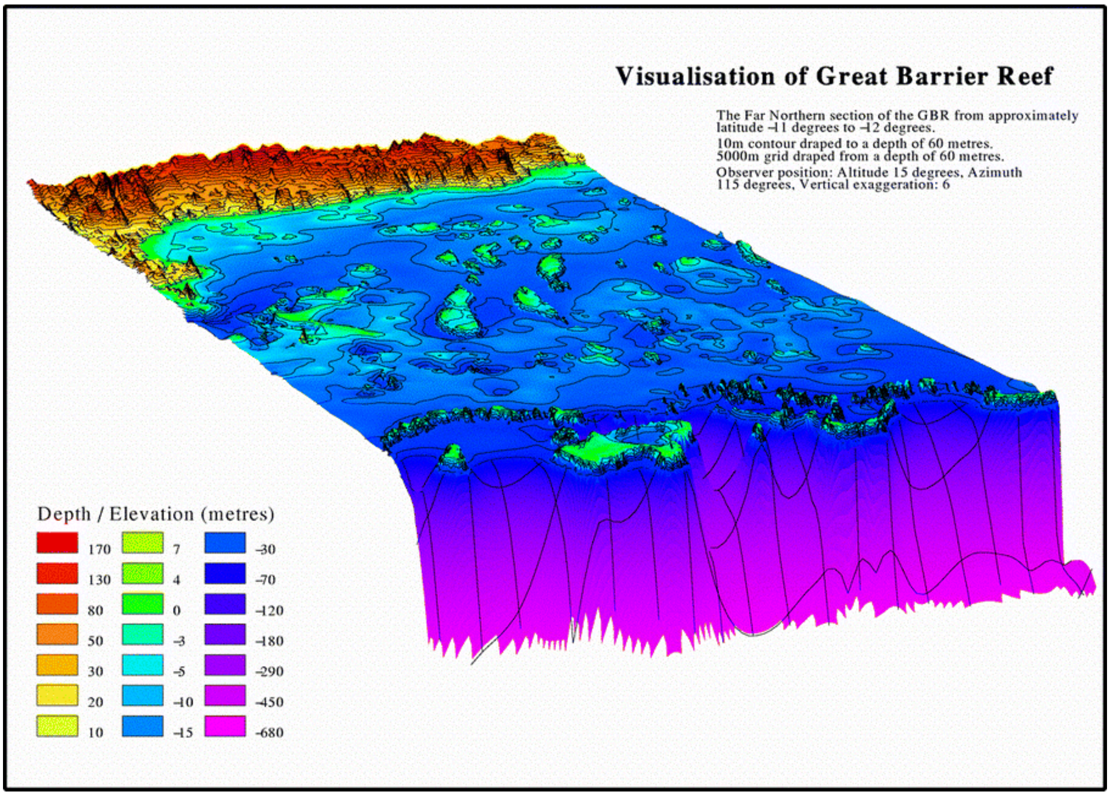

Figure 23. Simulated 3-D view of the sea floor in the Princess Charlotte Bay area.

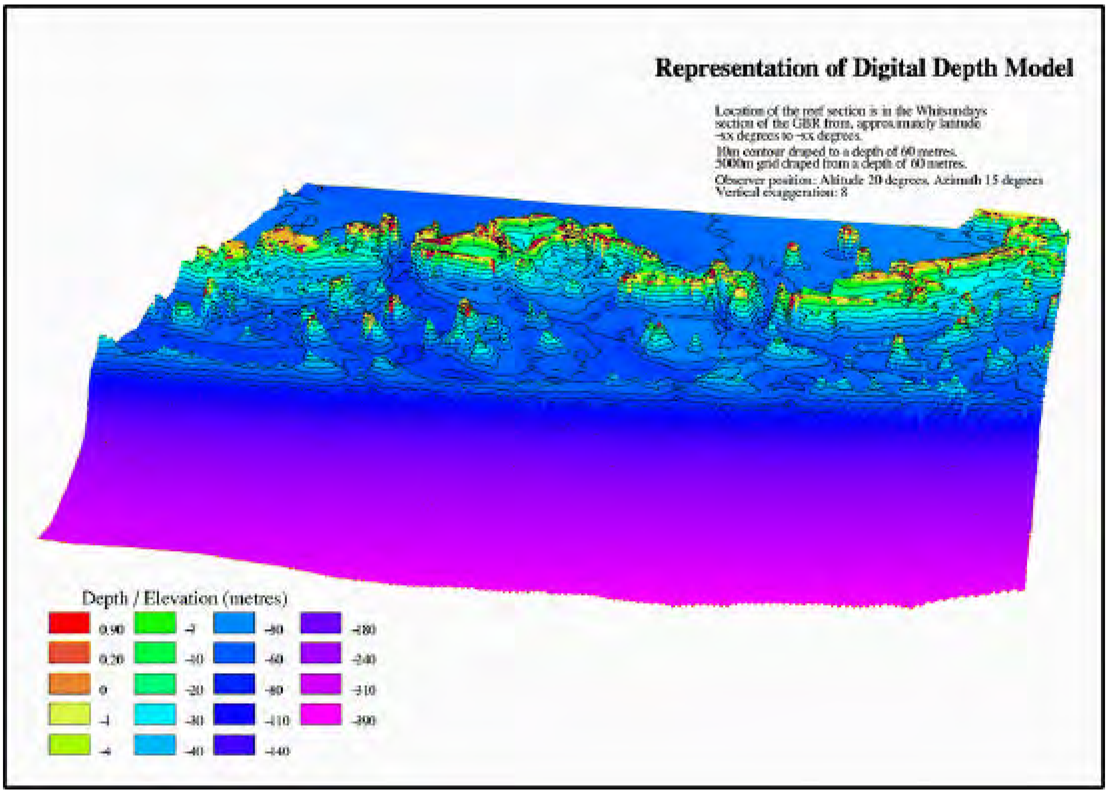

Figure 24. Simulated 3-D view of the sea floor for part of the outer reef in the Whitsunday area. The model shows two unusually deep channels between reefs, and the prevalence of submerged structures, presumably either incipient or drowned reefs, which do not appear on reef maps.

AREAS AND VOLUMES

Table 3. Estimated water volume to the 150 m isobath by *horizontally defined* depth strata

DEPTH RANGES (m)	VOLUME (km^3)
0-10	2,090
10-20	1,915
20-30	2,930
40-80	2,215
80-150	400
TOTAL	**9,550**

Table 4. Estimated water volume to the 150 m isobath by *vertically defined* depth strata.

DEPTH RANGES (m)	AREA (km^2)	VOLUME (km^3)	MEAN DEPTH (m)
0-10	38,200	80	-2.1
10-20	20,300	320	-15.5
20-30	68,300	2,060	-30.1
40-80	94,800	5,320	-56.1
80-150	17,100	1,770	-103.5
TOTAL	**238,700**	**9,550**	**39.6**

Table 5. Estimated water volume to the 150 m isobath by *spatially constrained, vertically defined* depth strata (refer to methods).

DEPTH RANGES (m)	AREA (km^2)	VOLUME (km^3)	MEAN DEPTH (m)
0-10	25,600	55	-2.1
10-20	15,700	225	-14.2
20-30	65,000	1,760	-27.0
40-80	114,900	5,720	-49.7
80-150	17,500	1,790	-102.5
TOTAL	**238,700**	**9,550**	**39.6**

Table 6. Estimated areas of physical features occurring in each Section of the Great Barrier Reef and adjoining land and island areas.

LAND TYPE	ESTIMATED AREA (km^2)				
	Far Northern Section	Cairns Section	Central Section	Mackay Section	TOTAL
Reef	8,464	2,533	3,925	4,499	19,420
Cay	9	1	1	38	48
Rock	0	0	0	1	1
Island	76	15	746	384	1,221
Mangrove	3	2	97	639	741
Foreshore	177	9	194	797	1,176
Land	0	0	0	63	64
Sea	76,527	32,941	71,899	139,460	320,826
TOTAL	**85,256**	**35,501**	**76,862**	**145,881**	**343,497**

These estimates are based on spatial data provided by the GIS Unit of the Great Barrier Reef Marine Park Authority. The mapping precision is judged to be about 1:100,000.

Table 7. Estimated areas of management zonation within each Section of the Great Barrier Reef Marine Park and adjoining land and island areas.

ZONATION	ESTIMATED AREA (km^2)				
	Far Northern Section	Cairns Section	Central Section	Mackay Section	TOTAL
Preservation	236	106	49	82	473
Marine National Park A	129		667	96	892
Marine National Park B	11,146		1,760	1,979	14,884
Marine National Park Buffer	130				130
National Park		629			629
Conservation Park		153			153
Habitat Protection		8,338			8,338
Buffer		358			358
Scientific Research	31		3	27	61
General Use A	63,053		58,110	121,320	242,482
General Use B	10,387		15,180	19,470	45,037
General Use		25,880			25,880
Island	81	16	840	356	1,294
Na	63	22	252	2,551	2,888
TOTAL	**85,256**	**35,501**	**76,862**	**145,881**	**343,497**

These estimates are based on spatial data provided by the GIS Unit of the Great Barrier Reef Marine Park Authority. The mapping precision is judged to be about 1:100,000. na = places within the region but not within the Marine Park, such as islands.

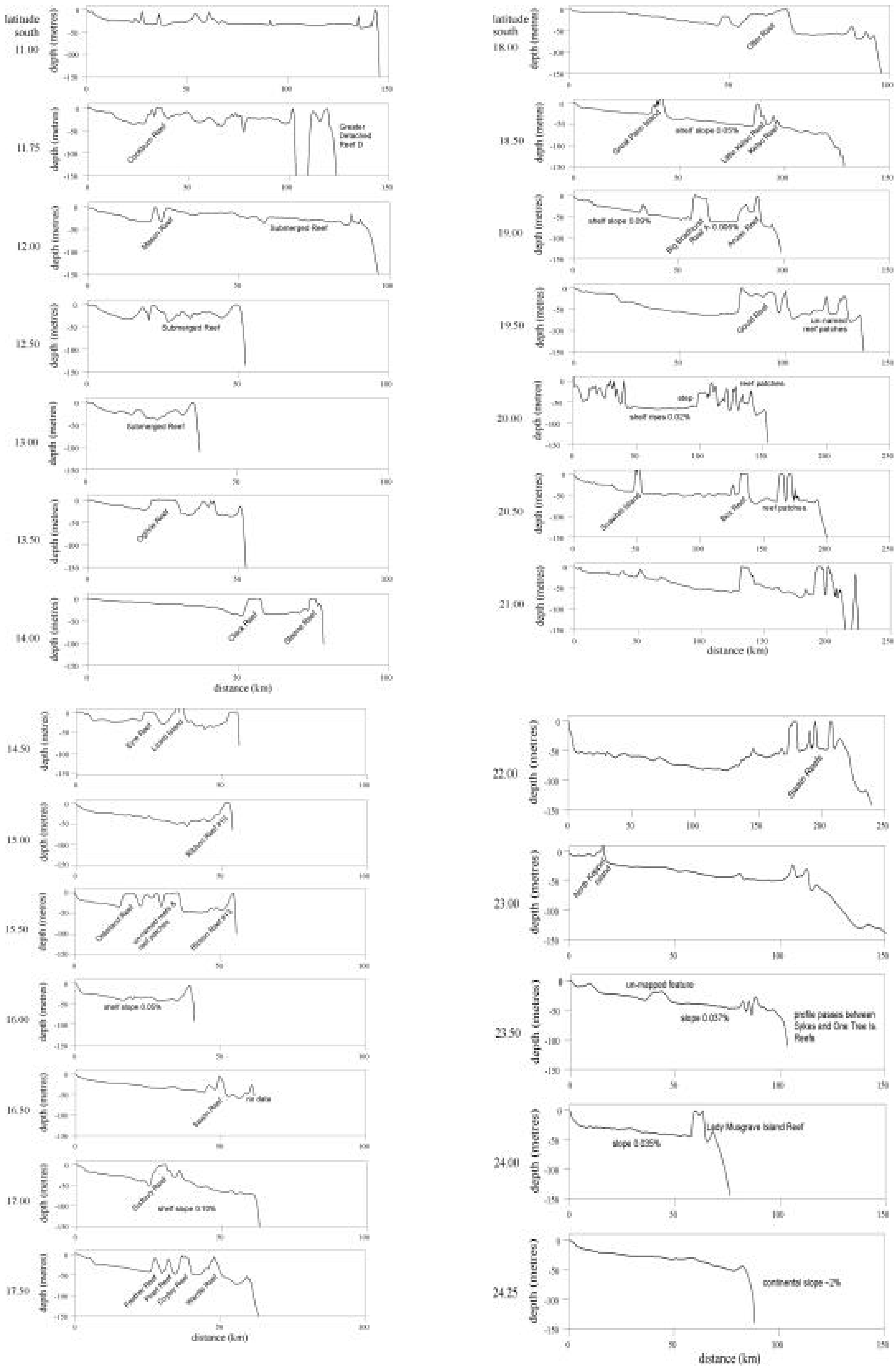

Figure 25. Cross-shelf profiles arranged from north to south. Profiles have been selected to avoid transects where data quality is poor while maintaining approximately equal intervals along the GBR. See text for interpretation.

Figure 25 illustrates cross-shelf profiles arranged from north to south. The location of the profiles can be seen from Figure 9. The curvilinear transects have a clear advantage over straight transects; the section is always more or less directly across the shelf despite the complex geography of the coast. The latitude used to label the transect refers to the central point of the transect.

Transect profiles show many interesting features. These are:

The **11.00**? profile is characterised by small scattered reefs in a shallow, broad lagoon.

The **11.75**? profile shows more complex topography between Cockburn Reef (35 km), and the ribbon reefs (~105 km), as well as a detached reef (Great Detached Reef D).

The **12.00**? profile passes over Mason Reef (~25 km) and some submerged reefs or *Halimeda* beds (40-75 km).

The **12.50**? profile corresponds to a narrowing of the shelf. It passes over features classified as ‘submerged reef’ between ~30 and 45 km.

At **13.00**? profile, the shelf is reduced to ~35 km in width. The transect passes over submerged reef (~25 km) before passing through a gap in the ribbon reefs at the edge of the shelf.

The **13.50**? profile passes over Ogilvie Reef (a planar reef), at ~25-30 km, and touches on an un-named lagoonal reef at ~40 km.

The **14.00**? profile originates in Princess Charlotte Bay. Data are lacking for 35 km from shore and the lagoon is interpolated as a smooth slope. The transect passes over Clack Reef, just south of Stanley Island (~60 km) and finally over Steene Reef, a lagoonal outer reef.

The **14.75**? profile crosses Lizard Island (35 km). The lagoon is noticeably deeper beyond Lizard Island, and is bounded by the ribbon reefs (~55 km).

The **15.00**? profile, north of Cooktown, avoids several mid-shelf reefs to show a consistent deepening of the Lagoon inside the ribbon reefs. It passes over ribbon Reef #10.

The **15.50**? profile, just south of Cooktown, encounters the north end of Osterland Reef and numerous un-named reef patches, before traversing the deeper water between the mid-shelf and the ribbon reefs, passing over Ribbon Reef #3.

The **16.00**? profile avoids mid-shelf reefs and passes between Agincourt Reefs #3 and 4. At this transect, the lagoon shows a consistent slope (of 0.05%) not apparent further north.

The **16.50**? profile passes over Saxon Reef (~50 km). Data are lacking in this area (north of Cairns) however LADS data are available to fill this gap. The gradual shelf slope may be a result of sparse data, but is consistent with transects to the north and south. At this latitude the ribbon reefs have ended.

The **17.00**? profile shows a consistent overall shelf slope (0.10%), interrupted by Sudbury reef, with no outer reefs.

The **17.50**? profile encounters Feather, Peart, Cayley and Wardle Reefs and shows complex bottom topography between these and the edge of the shelf (~50-60 km).

The **18.00**? profile passes just north of Hinchinbrook Island and Goolde Island (both near to the coast where data are lacking), encounters Otter Reef (~55-66 km) and finally shows complex topography at the edge of the shelf which may correspond to 'drowned' reefs.

The **18.50**? profile passes over part of Great Palm Island, Little Kelso Reef, and encounters the southern edge of Kelso Reef. The shelf slope is quite consistent at 0.05%.

The **19.00**? profile crosses big Broadhurst Reef and Anzac Reef. The inner shelf (out to Big Broadhurst Reef) slopes relatively steeply at 0.09% but is flat (0.005%) over the interval between these reefs.

The **19.50**? profile crosses Gould Reef and various un-named reef patches. The first 60 km of the transect lacks data.

The **20.00**? profile shows the channel between the coast and Hamilton Island, and suggests that the ocean floor between the island and the reefs (~100 km) is flat. Complex bottom topography between 100 and 150 km commences with an abrupt change in depth (from 60 m to 30 m), corresponding to a plateau between two lagoonal reefs - Ross Reef and Black Reef East.

The **20.50**? profile crosses Scawfell Island (~50 km) Bax Reef (~130 km) and reef patches. Data are poor on the outer edge of the Lagoon.

The **21.00**? and **22.00**? profiles lack data and should be regarded as reef structures superimposed on a generalised model of the continental shelf.

The **23.00**? profile passes over North Keppel Island. Data are poor to 50 km from the coast. The shelf from 50-100 km is flat. The transect ends on a slight flattening just before the edge of the shelf, which drops with a continental slope of only 0.5%.

The **23.50**? profile passes over an un-mapped feature (40 km) and shows a smooth shelf with slope of 0.037% interrupted where it passes between Sykes Reef and One Tree Island Reef.

The **24.00**? profile also shows a smooth shelf with slope of 0.035%, before encountering Lady Musgrave Island. The continental slope here is 2%.

Trends in physical characteristics

Cross-shelf transects allow trends along the length of the GBR to be examined graphically (Figures 26-32). In each figure, data points are marked with a diamond. These are over-plotted with a trend line produced by a 5 point weighted running average of the data points.

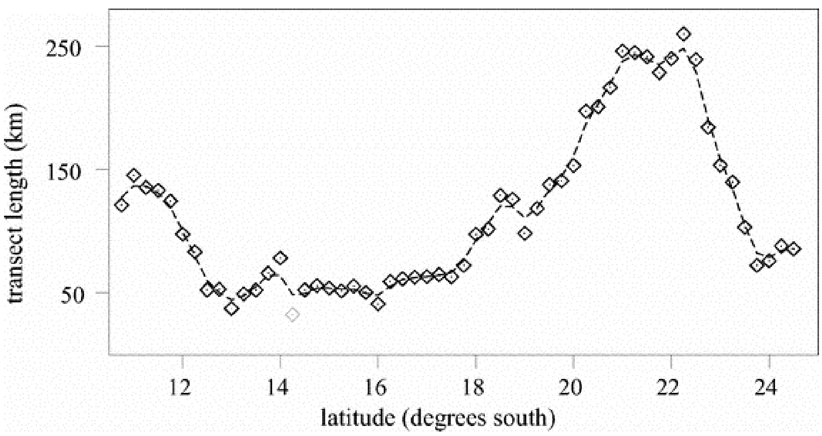

Figure 26. Trends in shelf width with latitude as measured by transect lengths. The shelf is consistently narrow from 13-18°S. It widens steadily between Cardwell and Mackay to a maximum of ~250 km in the Pompey/Swain area and finally contracts to the Capricorn Bunker where the mean cross-shelf distance is ~83 km.

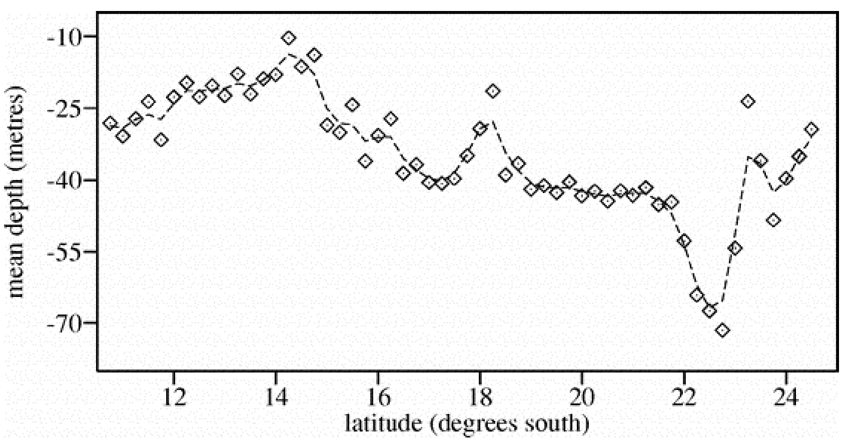

Figure 27. Trends in shelf depth with latitude. Shallowest water is at about 14.5?S in the section to the east of Princess Charlotte Bay. The lagoon is also narrowest at this point. A distinct increase in mean depth coincides with the change in orientation of the lagoon from north-east to east at ~15?S. Depth continues to increase until ~17?S where it reaches ~40 m. From 17?S to 21?S depth increases more gradually. Peaks at 18?S and 18.25?S are outliers due to Hinchinbrook Island. Data between 22?S and 23?S corresponding to the Swain area, are unreliable. This part of the graph should be ignored pending further validation. Depths are shallower in the Capricorn Bunker.

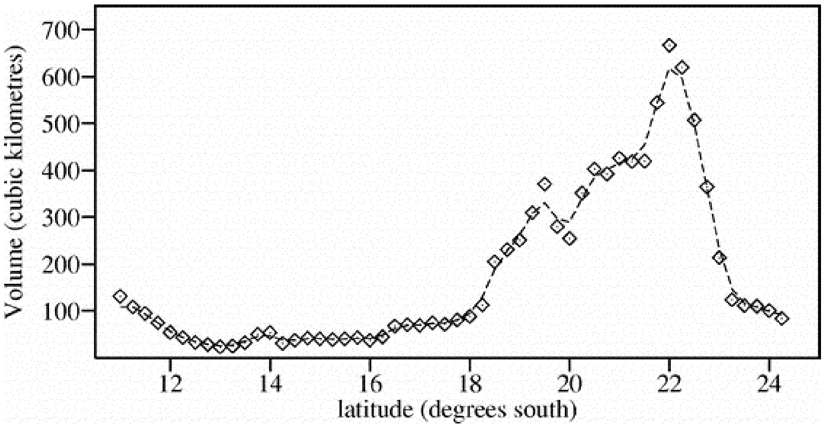

Figure 28. Trends in water volume over the continental shelf with latitude. Trends in water volume are an amplification of width and depth because width and depth tend to increase together. The greatest volume of the shelf water in the GBR is between 18?S and 23?S.

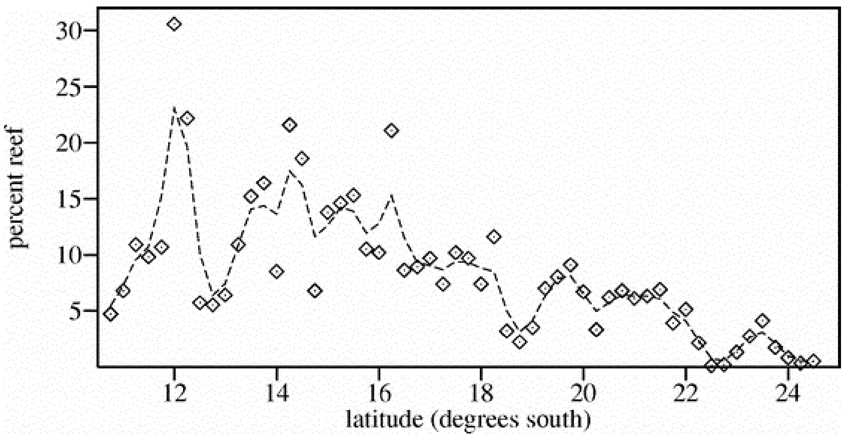

Figure 29. Trends in the percentage area of reef with latitude. The proportion of the continental shelf occupied by reef declines consistently, though noisily (because some transects pass between reefs) with increasing latitude.

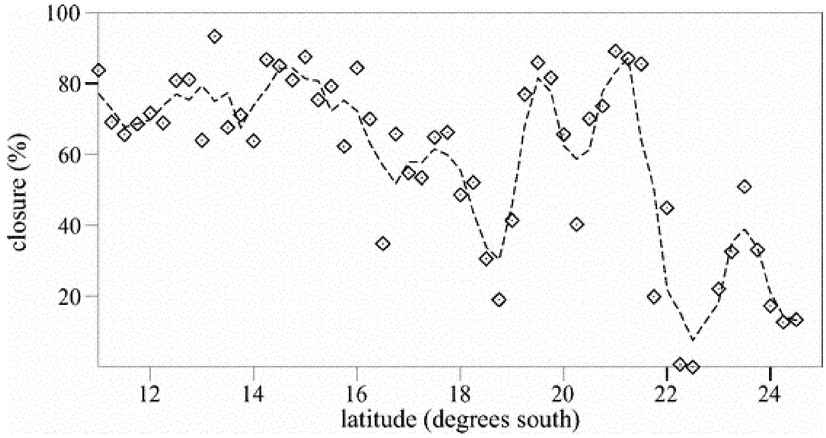

Figure 30. Trends in the degree of 'closure' (see text) of the GBR Lagoon with latitude. The percentage closure varies over the region from more than 80% to less than 10%. Closure peaks in the far north where the Ribbon Reefs impound a distinct lagoon, and also in the Pompey and Swain areas. There is a consistent trend to less closure between 15?S and 19?, but minimum levels are reached in the Capricorn Bunker.

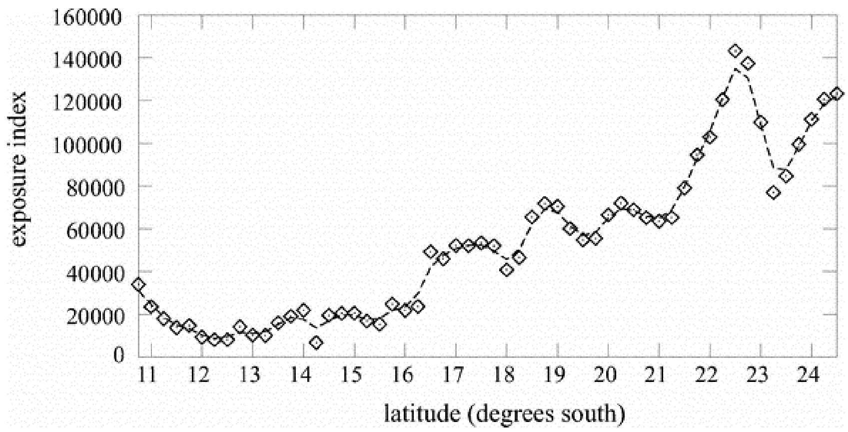

Figure 31. Trends in south-easterly exposure (integrated fetch distances) with latitude. Exposure of the Lagoon increases consistently with latitude. This is a function of the orientation of the coast and the prevalence of reefs and other structures that reduce fetch distances. On the regional scale, the exposure measure is dominated by the lower proportion of reef area with increasing latitude.

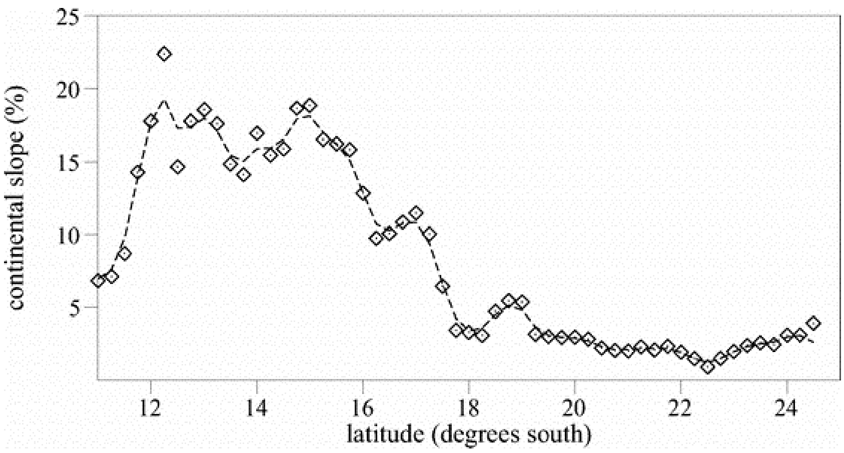

Figure 32. Trends in continental slope with latitude.

Trends in reef types

Latitudinal variations in the area of reef types were first presented by Hopley *et al.* (1989) who grouped reefs according to the latitude of the centroid of the reef (as compared with my use of cross-shelf transects) and presented data numerically but not graphically. The precise relationship between the spatial data used in that study, and the GIS data used here, is not known; however our results (Figure 33) appear to be consistent with those of Hopley *et al.* (1989). We have also grouped reefs according to the classification suggested by Hopley *et al.* (1989) which reflects the genesis and degree of development of the reefs. Submerged reefs and reef patches are regarded as juvenile, crescentic and lagoonal reefs are considered mature forms, while planar reefs are the ultimate, senescent form. Ribbon reefs and fringing reefs are distinguished on the basis of the antecedent platform from which they arise (Hopley 1983).

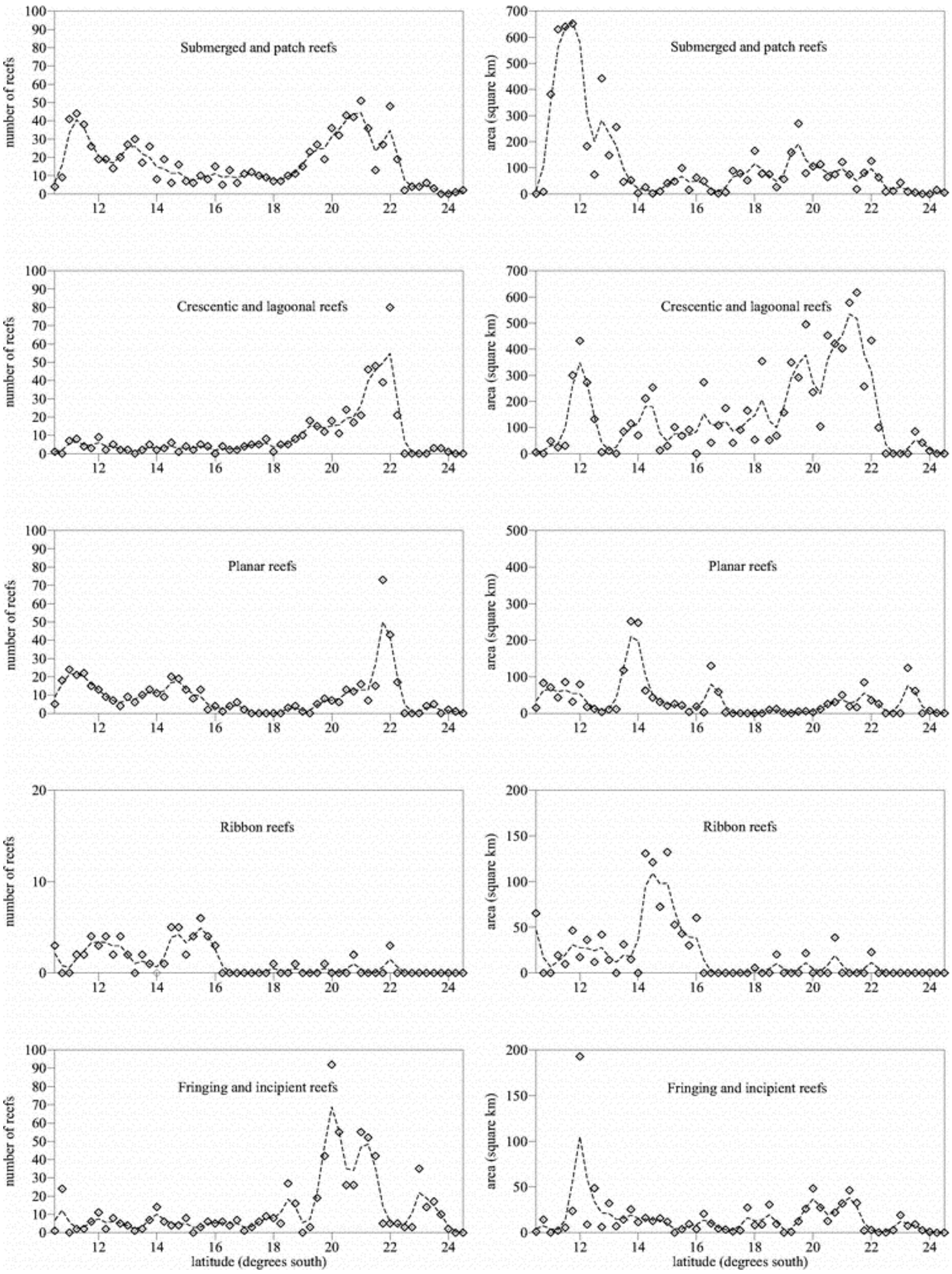

Figure 33. Estimated reef frequency and area by reef type and latitude.

DEPTH MODEL ACCURACY

Uncertainty

Error in GBRDEM arises from three sources: positional error, attribute error and interpolation error. Depth soundings, the primary data on which the model is built, may incorrectly predict location (positional errors) or depth (attribute value errors). On a sloping surface positional errors will lead to attribute errors; the 'right value' in the 'wrong place' can equally be interpreted as the 'wrong value' in the 'right place'. Therefore, these two sources of uncertainty can be unified (e.g. Lewis and Hutchinson 1996). The third source of error is the interpolation itself which must bridge depth soundings. The more distance between soundings (the lower the spatial density of soundings), the less certain the interpolation. Data are generally sparse in places that are not readily accessed by ship-based survey methods including near-shore areas and reef flats and edges. Near to reefs, small changes in position can lead to rapid changes in depth and positional error becomes important.

Reliability model

Lewis (1999) demonstrated that, away from reefs, the accuracy of GBRDEM (the expected discrepancy between the real depth and the depth according the model) could be predicted simply by the distance from the nearest depth sounding. This conclusion was reached after comparison of the depth model values with tens of thousands of more accurate depth soundings in the vicinity of Bowling Green Bay. These additional soundings were intentionally withheld from the interpolation to allow accuracy assessment. The predictions of this error model are illustrated in Figure 34.

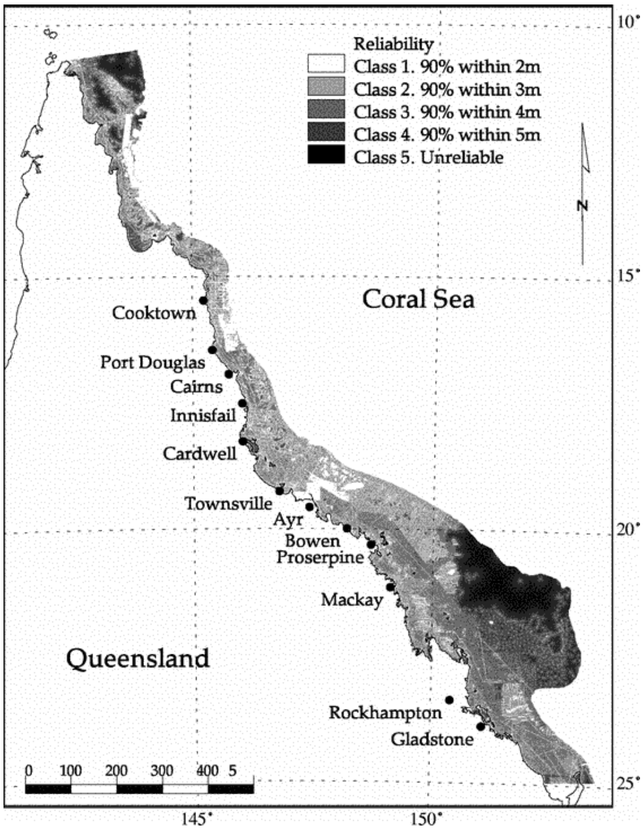

Figure 34. Depth model reliability as predicted by a model relating the density of data points to the expected errors in the depth model.

Figure 34 reflects that reliability is high where data points are dense. Class 1 and 2 reliability indicate that the representation of the terrain will be reliable, informative and quantitatively quite accurate. Where reliability is Class 3 or 4, the terrain will generally be satisfactory but poorly defined in detail. This includes the area between Cairns and Port Douglas, and the coastal areas near Proserpine. Class 5 indicates that the depth model is quite speculative. These areas, which include the Swain reefs, correspond to a virtual absence of data.

While the expected discrepancy between the modelled depth and an isolated sounding is valuable, it gives little idea of how inaccuracy impacts on predicted *form*. Overall, fewer data points lead to a more generalised ? smoother ? representation of the under-sea terrain. The importance of the vertical error is also dependent on the overall depth. A small error in depth is more important in shallow water. In these cases, the *relative error* (the ratio of the expected error to the expected true value) is a better indicator of data quality. Beyond the edge of the continental shelf, the absolute error increases but the relative error decreases due to the rapid increase in depth.

Quality assessment

'Quality' depends largely on the intended use (Lewis and Hutchinson 1996). Therefore, quality assessment is not a trivial task. 'Fitness for use' is a term used to describe the suitability of a given dataset for a specified application (Chrisman 1997). In this case, GBRDEM is the spatial 'dataset' and (as is usually the case) there are many potential uses. Deciding on fitness for a specific use is the responsibility of the user of the dataset. It would be prudent to consult with the producer. Potential users of the model are urged to discuss its fitness for use with the authors.

GBRDEM is intended for use at broad scales and not for quantitative studies of individual reefs. At the individual reef scale, GBRDEM will at best lack detail due to the generalisation imposed by the 250 m lattice interval. For some reefs, high resolution (spatially dense) data are available and these can be applied to study of individual reefs. Examples include Bell Cay, Yonge and Myrmidon reefs (see Table 1) and those reefs with LADS survey coverage. The first author can provide a list of relevant reefs on request. Depth models can readily be interpolated to fine resolution grids over specific reefs for this purpose. Inclusion of these data in GBRDEM is imminent which will increase accuracy in specific areas, especially in the vicinity of reefs.

APPLICATIONS AND ACCESS

Accessibility and Limitations

The first author should be contacted for access to GBRDEM. There are no barriers to use the model within the CRC Reef Research Centre. Users are required to complete a data supply agreement which outlines intended uses, and conditions and limitations on use to protect the authors' intellectual property.

FURTHER DEVELOPMENTS

New Data

The major factor in accurately representing terrain, whether land or sea, is lack of data. The closer the data points, the more precisely the terrain is defined, and the less statistical 'guess-work' is needed to fill the gaps between the data points. Over the GBR depth data are relatively sparse, so that even the macro-structures of most reefs are not well depicted. In places, data are virtually absent. This project aims to continue to include new data in GBRDEM.

Refinements of the interpolation

Fine-tuning of the interpolation procedures may lead to improvements. We expect to upgrade from ANUDEM-4 (as implemented in ARCINFO™ revision 7.0.4) to ANUDEM 4.6. This may enable greater control over the interpolation parameters but will also enable investigation of the suitability of the locally adaptive smoothing parameter implemented in more recent versions of ANUDEM (Hutchinson 1997).

Geocentric Datum for Australia

Conversion to the Geocentric Datum for Australia (GDA94) will be necessary in future. This datum is based on a spheroid which uses the gravitational centre of the earth (GRS80) rather than on a spheroid which suits Australia specifically (the Australian National Spheroid). In this system, geographic coordinates (longitude and latitude) will be described as being in GDA94, and grid (map) coordinates will be in Map Grid of Australia 1994 (MGA94), rather than the previous AMG (Australian Map Grid) standard (ICSM 1998). Conversion to the new datum will lead to changes in all coordinate systems ? even longitude and latitude will change. For the GBR, all coordinates will move about 200 m to the north-east.

CONCLUSIONS AND RECOMMENDATIONS

GBRDEM is a significant resource for study and management of the GBR. It is a foundation for a range of future research, management and visualisation applications. However, GBRDEM is not perfect nor considered complete. GBRDEM is a process for making depth models as much as a depth model *per se*. We hope that scientists and managers will make wide use of GBRDEM (the model) and in doing so help to keep GBRDEM (the process) alive and evolving.

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GLOSSARY

AHD	Australian Height Datum
AGD	Australian Geographic Datum
AMG	Australian Map Grid
AML	ARCINO Macro Language
CRC	Cooperative Research Centre
CRC Reef	Cooperative Research Centre for the Great Barrier Reef World Heritage Area
GBR	Great Barrier Reef
GBRDEM	Depth and Elevation Model of the Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
JCU	James Cook University
GRS	Global Reference System
GIS	Geographic Information System
LADS	Laser Airborne Depth Sounder
LAT	Lowest Astronomical Tide
MHWS	Mean High Water Spring
MSL	Mean Sea Level
MSS	Multi-Spectral Scanner
RAN	Royal Australian Navy
RMS	Root Mean Square
TESAG	School of Tropical Environment Studies and Geography at James Cook University
UTM	Universal Transverse Mercator
AUSLIG	Australian Surveying and Land Information Group