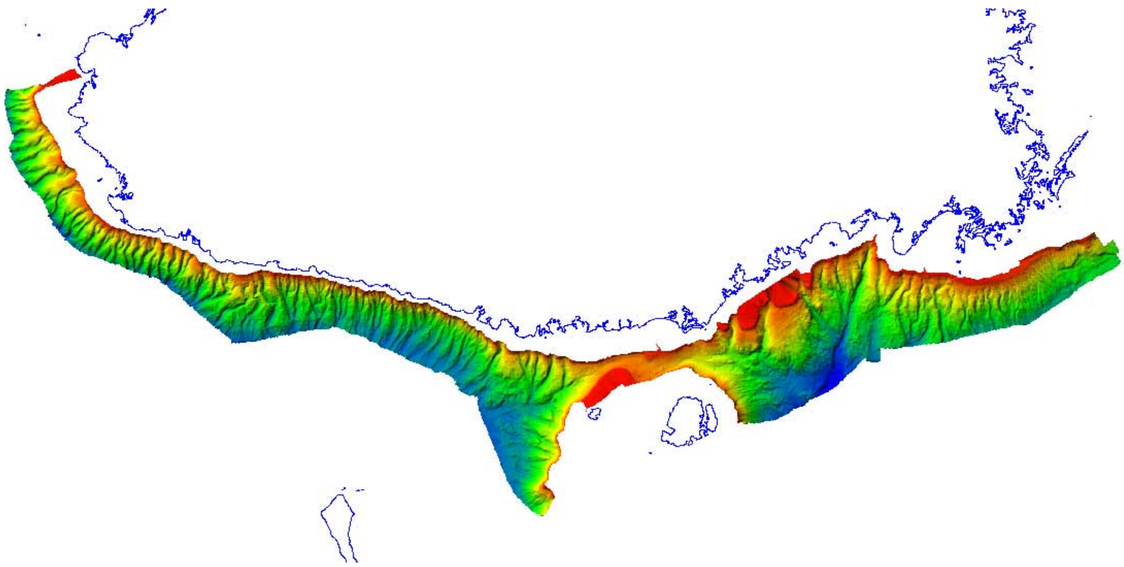
EU EDF 8 - SOPAC Project Report 109
Reducing Vulnerability of Pacific ACP States

FIJI TECHNICAL REPORT
High-Resolution Bathymetric Survey of South Viti Levu
Fieldwork undertaken from 3 May to 1 July 2003

October 2008



Three-dimensional perspective image of south coast Viti Levu, Fiji.

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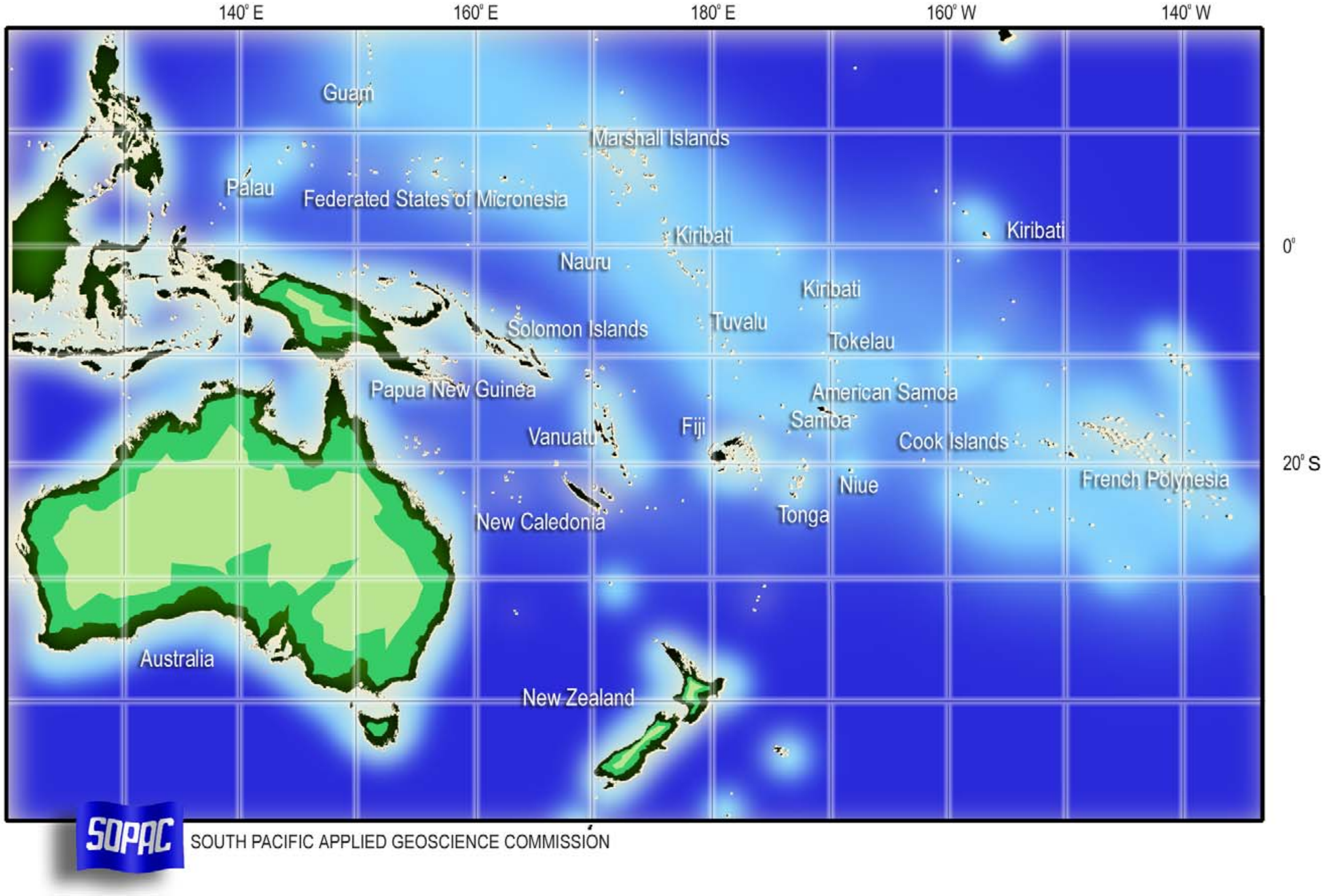


Figure 1. Location map of Pacific Island countries and territories constituting SOPAC.

Acronyms and their meaning

ACP	African, Caribbean, and Pacific
ADCP	Acoustic Doppler current profilers
ARGO	Array for real-time geostrophic oceanography
ASCII	American standard code for information interchange
CD	Chart datum
CTD	Conductivity – temperature – depth
DEM	Digital elevation model
DTM	Digital terrain model
EEZ	Exclusive economic zone
GDEM	Generalised digital environmental model
GEBCO	General bathymetric chart of the oceans
GPS	Global positioning system
HDOP	Horizontal dilution of precision
LAT	Lowest astronomical tide
MBES	Multibeam echosounder
MRU	Motion reference unit
MSL	Mean sea level
NTC	National Tide Centre
PI-GOOS	Pacific Islands global ocean observing system
RTK	Real-time-kinematic GPS (centimetre accuracy)
SMNT	Seamount catalogue
SOPAC	Pacific Islands Applied Geoscience Commission
SPCZ	South Pacific convergence zone
SRTM	Shuttle radar topography model
TAO	Tropical atmosphere ocean array
UTM	Universal transverse Mercator
WGS	World geodetic system

EXECUTIVE SUMMARY

Krüger, J. and Kumar, S. 2008. High-Resolution Bathymetric Survey of south Viti Levu, Fiji. *EU EDF 8 – SOPAC Project Report 109*. Pacific Islands Applied Geoscience Commission: Suva, Fiji, vi + 26 p. + 9 charts.

The Pacific Islands Applied Geoscience Commission (SOPAC) carried out a marine survey for Fiji around the south coast of Viti Levu. The objective was to investigate the seabed and provide information about the water depths around the island using a multibeam echosounder (MBES).

This report describes the high-resolution bathymetric mapping survey carried out for the south coast of Viti Levu, Fiji, from Nasalei (Suva) to Momi (Nadi) over a period of 8 weeks from 3 May to 1 July 2003.

The survey achieved 100% coverage of the seafloor from approximately 20 m depth nearshore area to an average offshore distance of 4 km, reaching water depths of some 2000 m. Coverage was significantly less in other areas.

The resultant data compilation was used to produce nine bathymetry charts for the south coast of Viti Levu at a scale of 1 : 50 000. These new bathymetric maps provide a descriptive picture of the ocean bottom terrain, vividly revealing the size, shape and distribution of underwater features. They can serve as the basic tool for scientific, engineering, marine geophysical and environmental studies, as well as for marine and coastal resource management.

1. INTRODUCTION

1.1 Background

A marine survey was carried out around the southcoast of Viti Levu from Nasalei (Suva) to Momi (Nadi) (Figure 1 and Figure 2). The object was to investigate the seabed and provide information about water depths around the islands using a multibeam echosounder (MBES). The strength of the magnetic field was also continuously logged during the survey using a towed magnetometer. This report presents the results of the MBES survey (data collected by the magnetometer is covered elsewhere).The work was initiated by the SOPAC/EU Reducing Vulnerability of Pacific ACP States Project, under the European Development Fund.

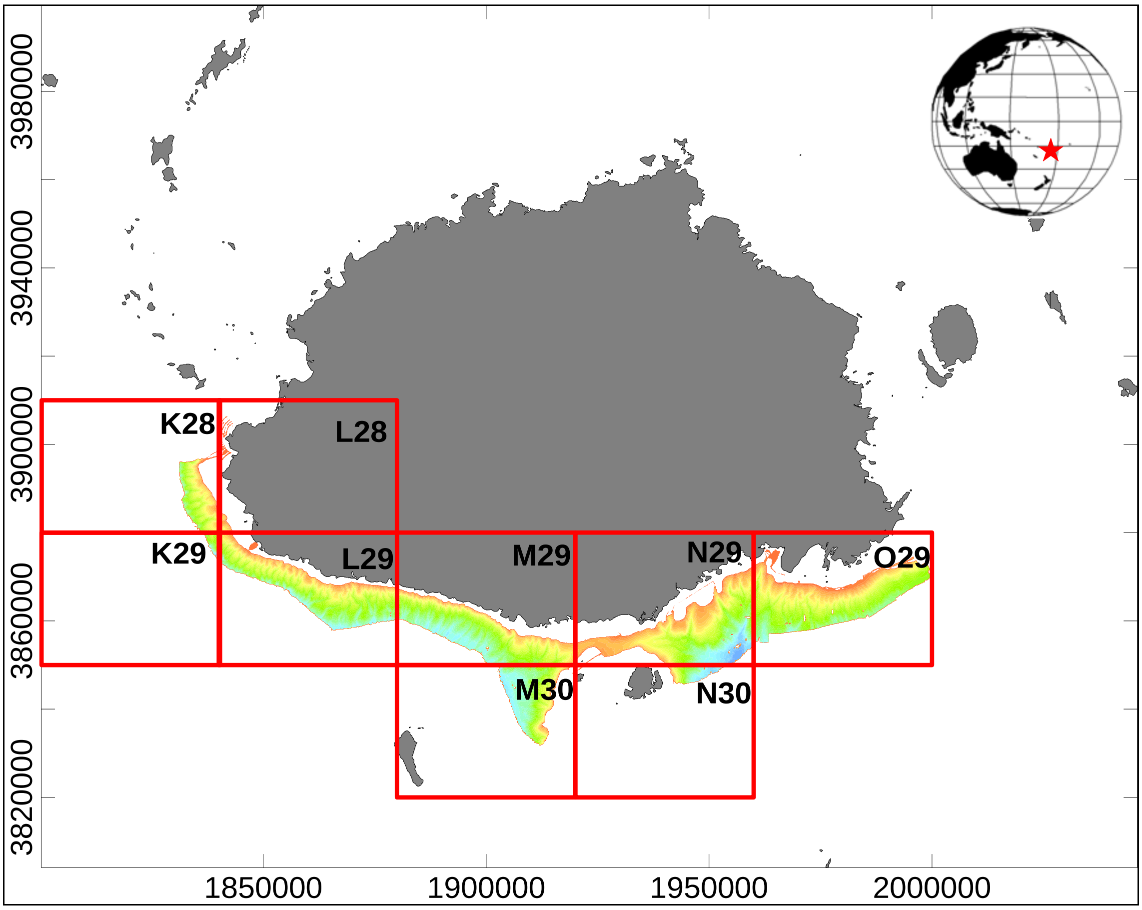


Figure 2. Bathymetric map of the south coast of Viti Levu, Fiji. The map boundaries are shown as red boxes.

1.2 Geographic Situation

Fiji is an archipelago of over 320 islands scattered over approximately 1.3 million km^2 of the South Pacific Ocean. Its total land area is about 18 333 km^2 and the maximum height is 1324 m above sea level. Selected geographic facts about the islands are provided in the Table 1.

Table 1. Summary of geography of Fiji

Location	176°50′ E to 178° W, and16° S to 20° S
Population	831 600 (2003 est.)
Land area	18 333 km^2
Coastline	From Suva to the mouth of Navua river a broad barrier reef is developed, commonly over a kilometre in width, separated from locally well-developed fringing reefs. Immediately west of the mouth of the Navua river, coral growth is inhibited by the influx of fresh water and there is a series of sandy, crescent-shaped bays. The barrier and fringing reefs are again well developed south of Galoa village. Further west the reefs coalesce to form a broad fringing reef but west of Manggumanggua village this narrows rapidly; along the reminder of the coastline a narrow fringing reef is present.
Tides	Semi-diurnal
Climate	Temperatures are 16 - 22°C. May to October is dominated by southeast trade winds and is relatively cool and dry. November to April is the warm and wet season during which tropical depressions, often with winds of hurricane force, are the major influence on weather. Average annual rainfall ranges from 1 500 mm on the smaller islands to over 7 000 mm on the larger islands. The latter value is large because of orographic effects.
Exclusive Economic Zone, EEZ	1.26 million km^2

1.3 Tectonic Setting

Fiji lies in the southwest Pacific Ocean along the convergent boundary between the Indo-Australian and Pacific Plates This boundary is marked by a complex of ridges and basins that extend from New Guinea through Fiji to New Zealand (Gill 1976). The islands of Fiji are the emergent parts of a remnant arc (Gill 1976), which includes Fiji Platform and the Lau-Colville Ridge (Figure 3). The main islands of Vanua Levu and Viti Levu are on the Fiji Platform, and the outer islands of the Lau Group are on the northern part of the Lau-Colville Ridge.

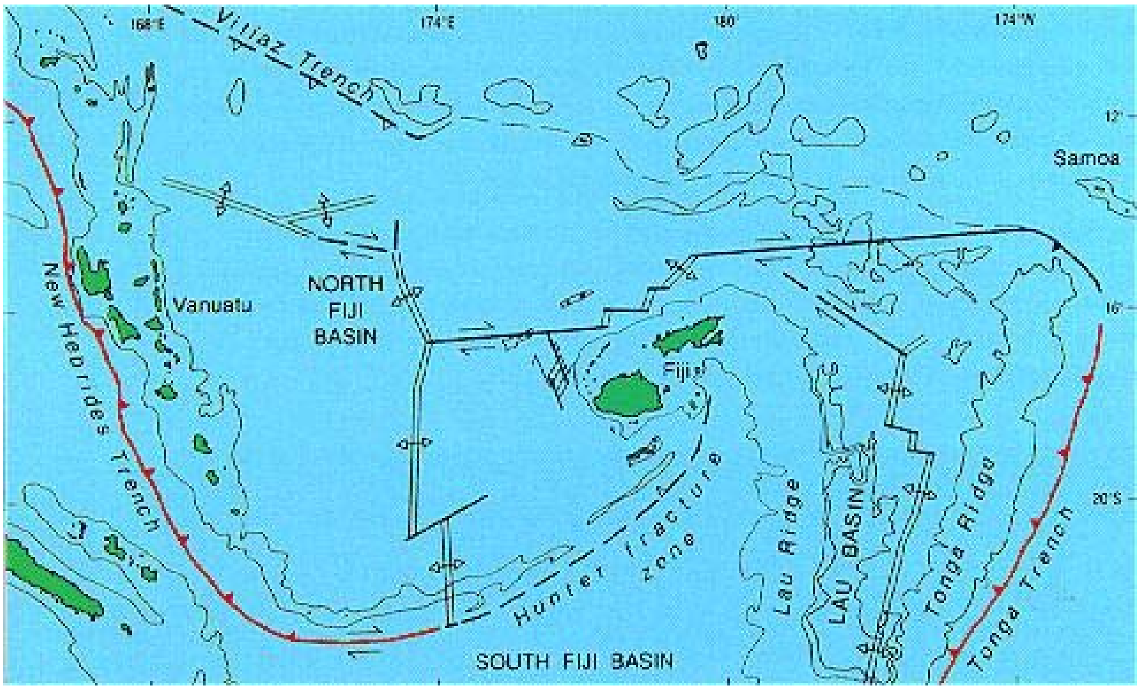


Figure 3. Tectonic setting of Fiji platform in the southwest Pacific showing areas of active subduction, major seafloor fracture zones and active seafloor spreading centres. Source: www.mrd.gov.fj

1.4 Previous Bathymetry Compilations

Bathymetric maps are topographic maps of the sea floor, giving a descriptive picture of the ocean bottom terrain. With an exclusive economic zone (EEZ) of approximately 1.26 square million kilometres, the available bathymetric data is limited and the exact nature of the seafloor is poorly known. Most available bathymetric data originates from sparse single-beam soundings from oceanographic cruises, and, more recently, from MBES systems as well as satellite-derived predicted depth.

Table 2. Public Multibeam datasets for southern Viti Levu, Fiji

Ship	Survey ID/Instrument	Year
RV *Thomas Washington*	RNDB14WT/SeaBeam	1989
RV *Thomas Washington*	RNDB13WT/SeaBeam	1989
RV *Maurice Ewing*	EW9511/Atlas Hydrosweep DS	1995
RV *Sonne*	SO99/ Atlas Hydrosweep DS	1995
RV *Maurice Ewing*	EW9512/Atlas Hydrosweep DS	1995
RV *Melville*	BMRG08MV/SeaBeam 2000	1996
RV *Melville*	BMRG07MV/ SeaBeam 2000	1996
RV *Roger Revelle*	KIWI10RR/ SeaBeam 2100	1998
RV *Melville*	EW0003/ Atlas Hydrosweep DS	2000
RV *Maurice Ewing*	EW0002/ Atlas Hydrosweep DS	2000

A search for public Multibeam data on NOAA'S national geophysical data centre (http://www.ngdc.noaa.gov) and the seamount Catalogue, SMNT (earthref.org) in February 2008 produced the following scientific cruises for the area of interest as shown in Table 2 and Figure 4.

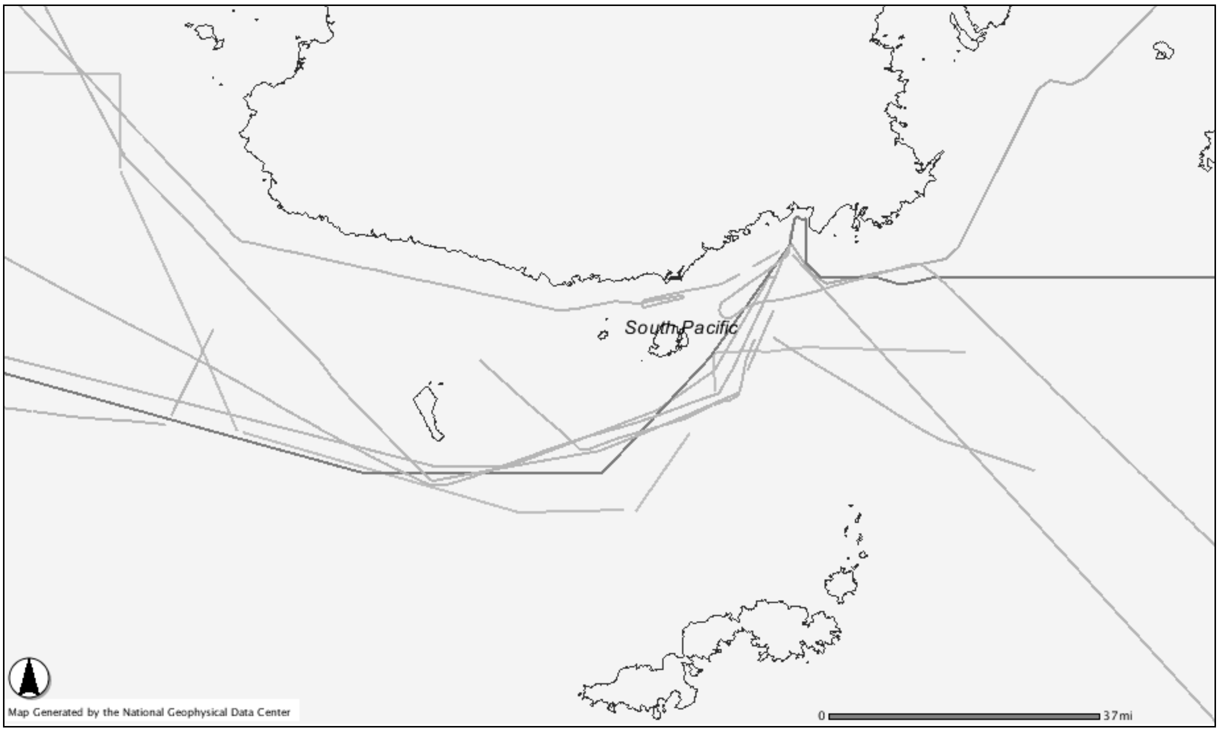


Figure 4. Ship tracks in the area of southern Viti Levu for oceanic cruises with multibeam data in the public domain as listed in Table 2..
(source: http://www.ngdc.noaa.gov)

2. RESULTS AND DISCUSSION

2.1 Bathymetry and Derivatives

The multibeam echosounder (MBES) bathymetry acquired during this survey is shown on 9 charts (K28, K29, L28, L29, M29, M30, N29, N30, and O29) at a scale of 1 : 50 000 and contoured at intervals of 50 m. The grid files, as well as charts, meta data, and report are available through the SOPAC Geonetwork site. The report and full-size charts (841x1189 mm) are also available from the SOPAC virtual library.

The surveyed area extends from the coast to approximately 20 km offshore. Water depths within the surveyed area ranged from 100 to 2000 m offshore. Minimum water depths were measured near the coast on the outer slope of the fringing reef with depths becoming greater in a general seaward direction: irregular slope angles ranging from 0º to 83º with a mean slope angle of 31º.

Bathymetric data provide information on the depth and morphology of the seafloor, as well as the shape and size of submarine features. Three bathymetry derivatives namely, slope angle maps, shaded relief maps, and three-dimensional rendered surfaces (Table 3) were used in addition to the high-resolution bathymetry to aid visual interpretation of the seabed morphology. The SOPAC/EU Multibeam echosounder data was used to create these bathymetric derivatives for each of the areas. These results are shown in Figure 5, Figure 6, and Figure 7.

Table 3. Bathymetric derivatives

Slope angle	Slope is a measure of steepness between locations on the seabed, and is reported in degrees from zero (horizontal). Slope values are computed as a mean value for one grid cell from the slope gradient between it and the eight neighbouring grid cells.
Shaded relief	Shaded relief maps use shades of grey to indicate the local orientation of the seafloor relative to a user-defined light source direction. The light source can be thought of as the sun shining on a topographic surface, much like artificial hillshading that illuminates bathymetric roughness. Portions of the surface that face away from the light source reflect less light toward the viewer, and thus appear darker.
Three-dimensional surface	For three-dimensional surfaces the height of the surface corresponds to the depth of the seafloor.

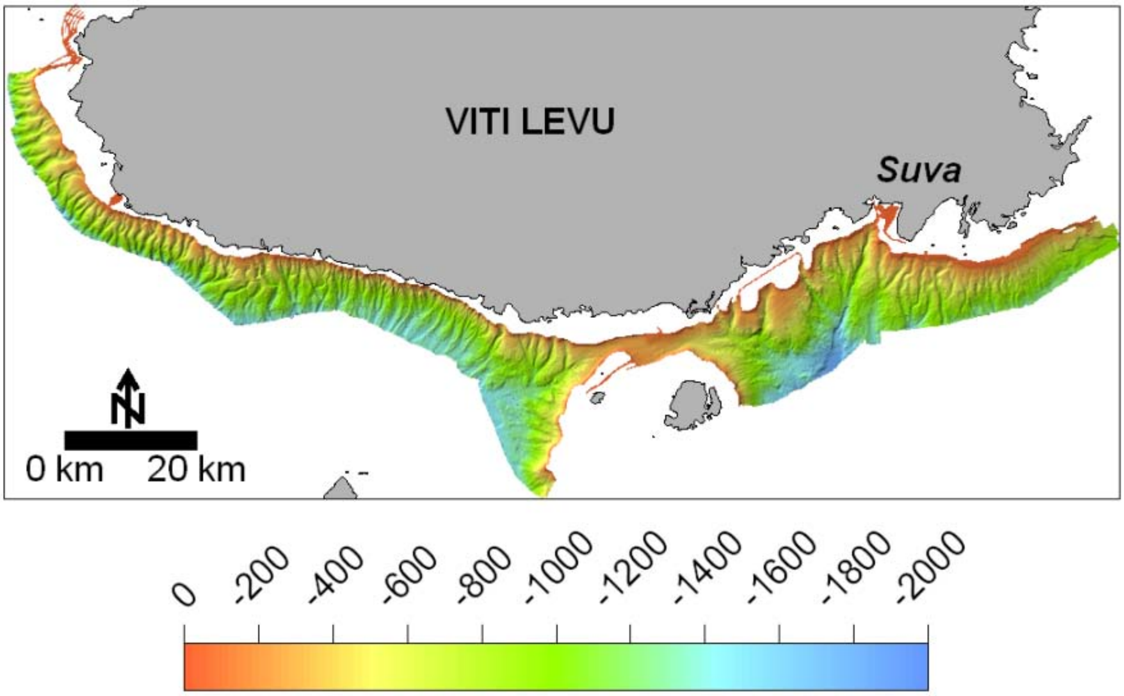


Figure 5. Three-dimensional surface map showing the SOPAC/EU MBES bathymetry for southern Viti Levu.

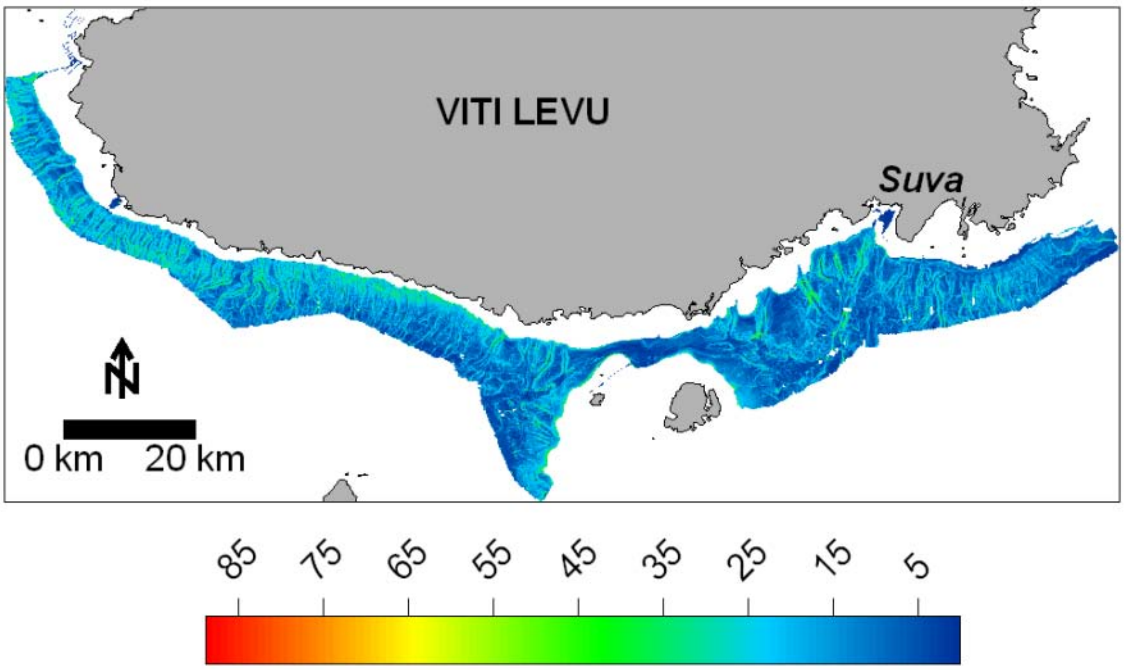


Figure 6. Slope angle map for the southern Viti Levu seabed derived from 75 m gridded SOPAC/EU MBES bathymetry.

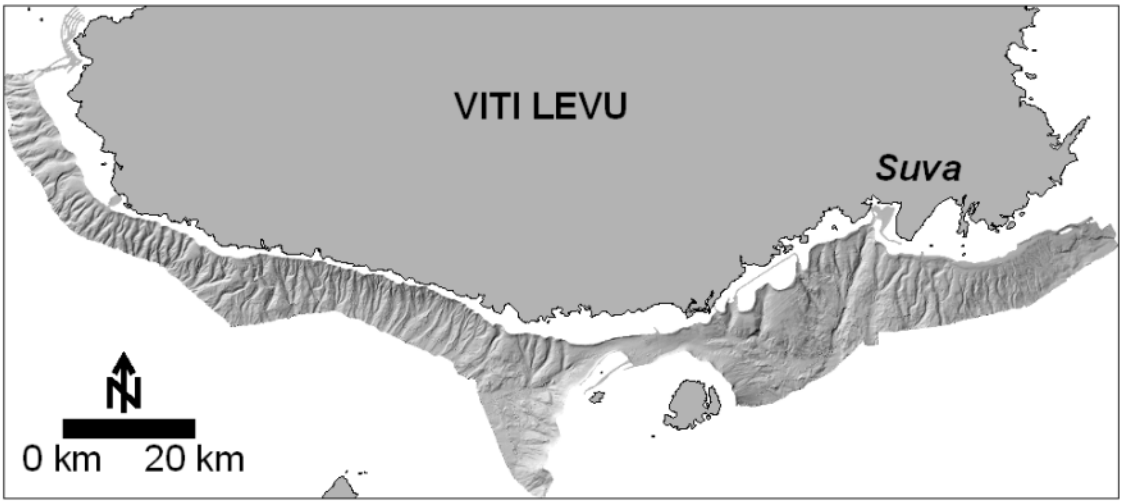


Figure 7. Shaded relief map showing the SOPAC/EU MBES bathymetry for southern Viti Levu.

2.2 Morphological Features

Table 4 presents a brief summary of the seabed morphology of the surveyed area.

Table 4. Summary of offshore seabed morphology, south coast Viti Levu, Fiji.

~ 0 m	Modern fringing reef and rock platform
~100–200 m	Seaward sloping seabed, slope angles 25–30º
~200–1500 m	Numerous small canyons originating at the base of 200 m contour and flatten out at around 1500 m water depths
~ 600 m	A small submarine terrace at the southeast corner of chart O29, 2–4 km wide and ~5 km long. No canyons are observed at the base of this terrace.

The nearshore bathymetry shows numerous ridges about 2000 m apart originating at the base of 200 m contours and gradually descending to 1500 m water depths and then levelling off to the surrounding abyssal plain at a depth of approximately 2000 m.

These submarine ridges descend around 30 degrees on either side.

A detailed morphological interpretation of the south eastern slope of Viti Levu (Rahiman and Pettinga 2006) is illustrated in Figure 8 and Figure 9.

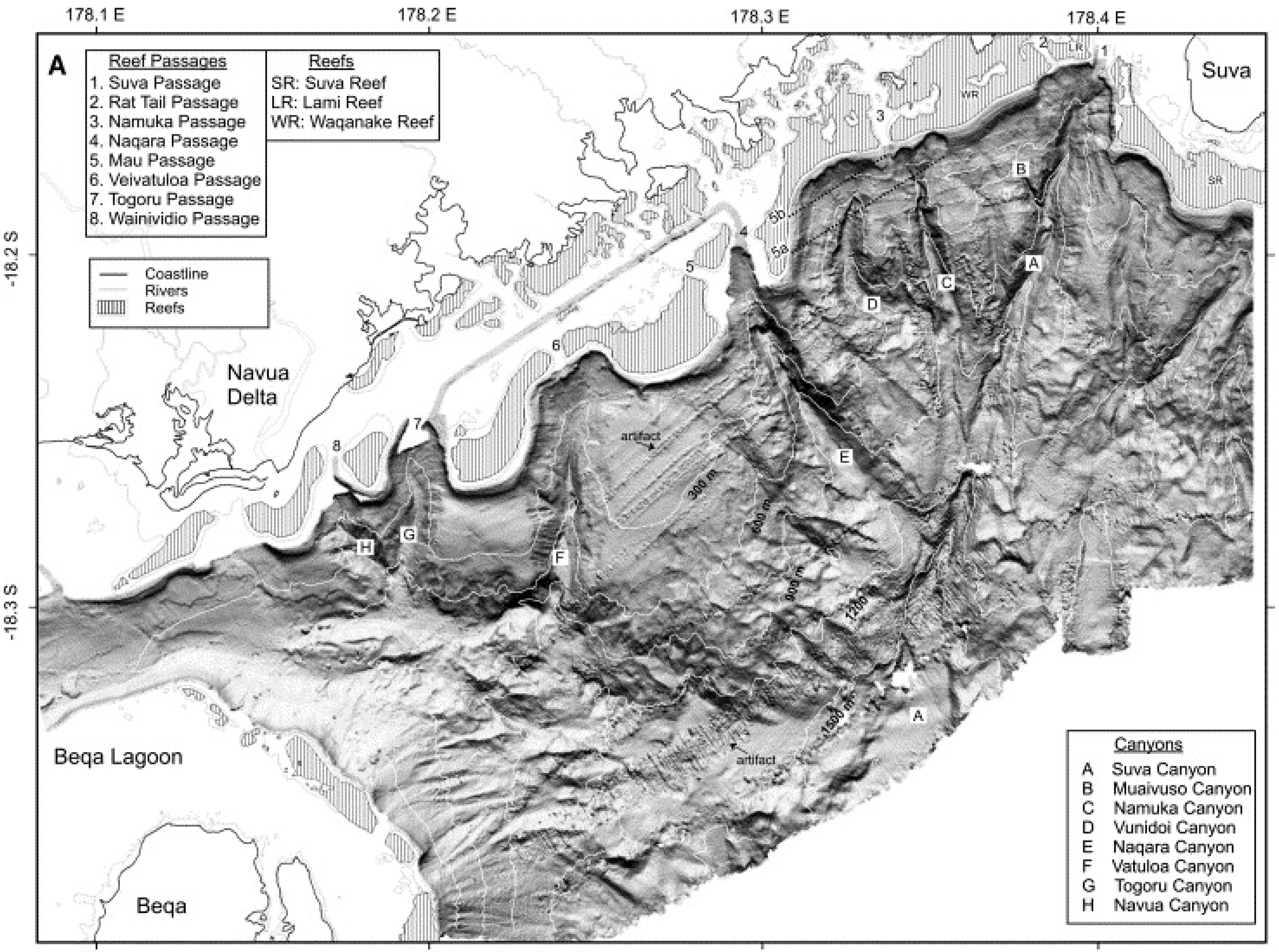


Figure 8. Shaded relief image of the southeastern slope of Viti Levu showing the various reef passages and canyons. Sun illumination is from the north (source: Rahiman and Pettinga 2006).

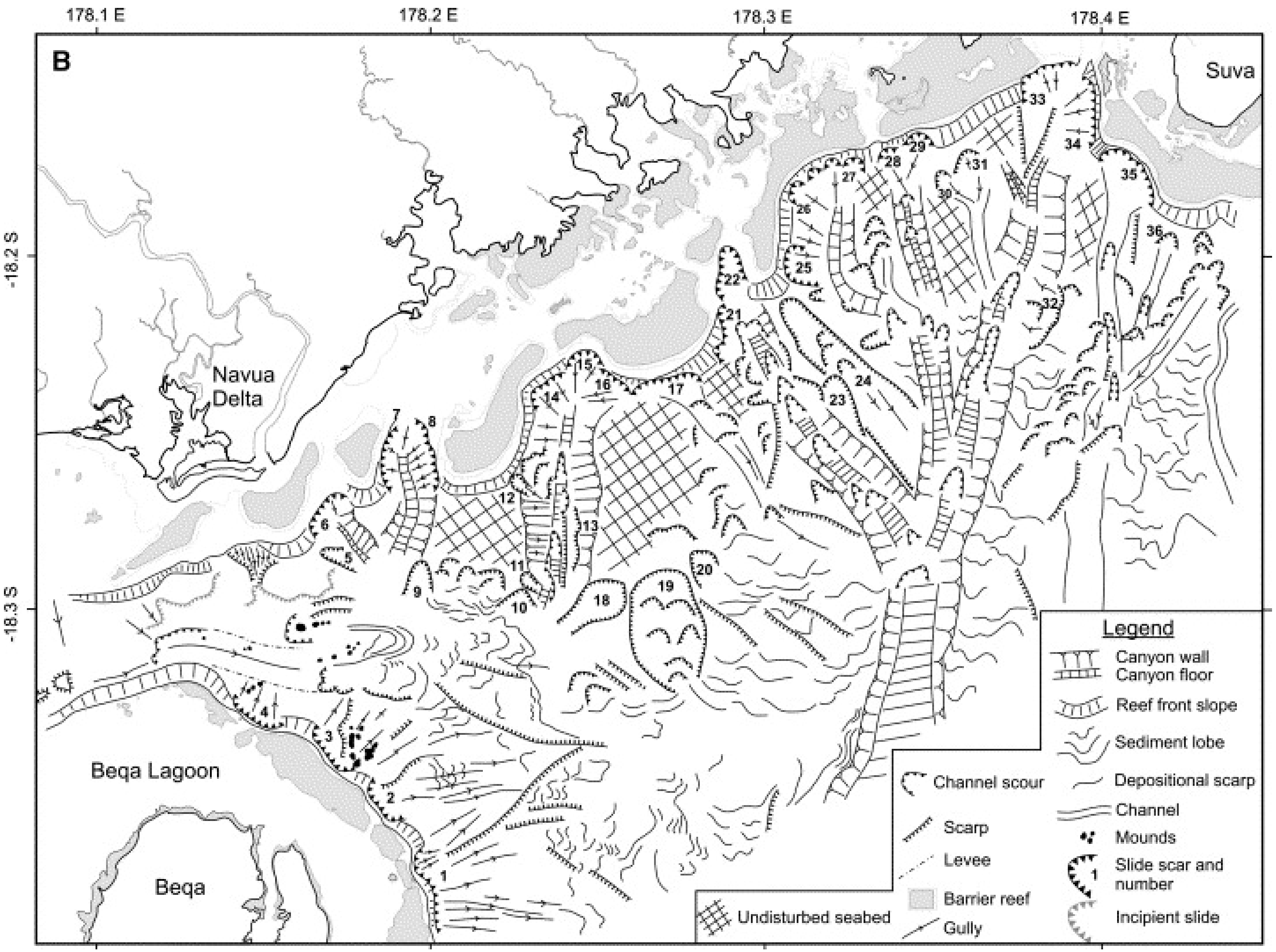


Figure 9. Morpho-sedimentary and morpho-structural map of the southeastern slope of Viti Levu (source: Rahiman and Pettinga 2006).

3. DATA ACQUISITION AND PROCESSING

3.1 Survey Particulars

Survey vessel	RV *Turangalevu*
Fieldwork date	3 May to 1 July 2003
Equipment used	Reson 8160, deep water MBES,

3.2 Field Personnel

SOPAC:	Robert Smith (Geophysicist), Quan Chung (Technical Officer), Simon Young (Electronic Engineer), Benjamin Gouldby (Physical Oceanographer).
Vessel:	Steven Hay (Captain), Jon Tikokandavu (Engineer), Edward Smith (Mate).
Observer:	Luna Wong (Mineral Resources Department, Fiji).

3.3 Geodetic Reference System

The survey results were mapped in terms of the following geodetic reference system as shown in Table 5.

Table 5. Geodetic datum – Fiji Mag Grid, Fiji Geodetic Datum, 1986

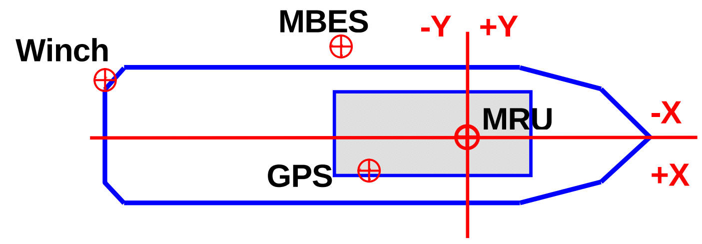
Ellipsoid	Airy 1830	
	Semi-major axis (a)	6377563.39600000
	Semi-major axis (b)	6356256.90923729
	Inverse flattening (1/f)	298.324964600000
	Eccentricity sq. (e^2)	0.081673373874
Projection	Transverse Mercator/Gauss-kruger	
	Projection type	Transverse Mercator
	Origin latitude	17° 00' 00.000" South
	Origin longitude	178° 45' 00.000" East
	Origin false easting	2000000.0000
	Origin false northing	4000000.0000
	Scale factor	0.99985
	Grid unit	metres

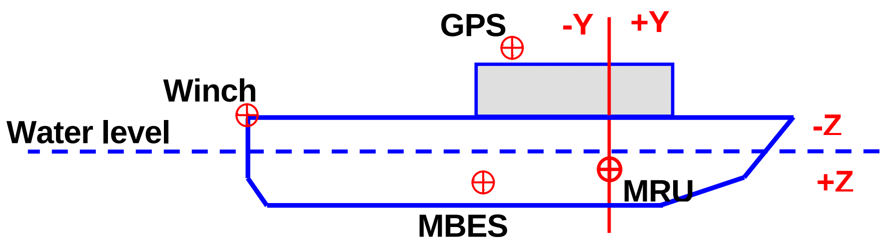
3.4 Vessel Description and Static Offsets

Details regarding the survey vessel are shown in Figure 10 and Figure 11.

Sensor	X (m)	Y (m)	Z (m)
Reference point at water level	0.00	0.00	0.00
Motion Reference Unit (MRU)	0.00	0.00	–0.28
Positioning Antenna (GPS)	1.54	–2.31	4.39
Multibeam Echo Sounder (MBES)	–2.90	–4.98	–1.65

Vessel	
Name	RV *Turagalevu*
Length overall	18 m
Breadth (mid)	6 m
Draft (mid)	1.5 m
Displacement	26 t
Port of registry	Suva
Radion Call Sign	3DN6531
Classification	Westcoaster, Freemantle, Australia





Not to scale

Figure 10. Diagrams and measurements of the chartered survey vessel Turagalevu.

Figure 11. The chartered survey vessel RV Turagalevu*.*

3.5 Positioning Control

The vessel's reference point (X=0, Y=0, Z=0) was the motion reference unit (MRU) position at the waterline. The positioning system was DGPS using a Trimble DSM 12/212 receiver using three base stations: Tamavua, Nabau and Donawale.

A good satellite constellation status was observed throughout the survey with horizontal dilution of precision (HDOP) ≤ 0.9.The patch test was conducted in Suva, Fiji, using RTK GPS.

3.6 Survey Computer

The survey computer was a Windows PC running Navisoft 2.2.1 This computer was used for continuous on-line data logging and computation of positioning and digital bathymetry. The package also provided a line control display for the helm. The on-line operator continuously monitored a range of quality control parameters.

An off-line Navisoft 2.2.2 package was used in the office for replaying and post-processing of track data and bathymetry. An A0 plotter was available for the production of charts.

3.7 Multibeam Echosounder

A Reson SeaBat 8160 multibeam echosounder (MBES) was temporarily installed on MV *Turangalevu*, and was used to provide swath bathymetry data. A MBES provides high-resolution information about the depth of water from the surface to the seafloor in a water body. The main instrumental and operating parameters are listed below.

3.7.1 Instrumentation

Multibeam echosounder	Reson SeaBat 8160
Transducer mount	Port side pole-mounted
Motion reference unit	TSS DMS 2-05 Dynamic Motion Sensor
Gyro	SG Brown Meridian Surveyor Gyro Compass
Sound velocity probe at transducer	Installed

3.7.2 Operating Parameters 8160

Transducer frequency	50 kHz
General water depth	10–2000 m
Average ship's speed	7 knots (3.6 m/s)
Transmit power	Variable 1–16
Pulse length	Variable 0.5–10.0 ms
Horizontal coverage	Approximately two times water depth
No of beams / beam spacing	126 / 1.2°
Ping rate	Variable

3.7.3 Dynamic Offset Calibration, Suva, Fiji, 3 May 2003

Roll correction	–1.39
Pitch correction	–0.16
Yaw correction	3.77
GPS Latency correction	–350
Gyro correction	Not determined

3.7.4 Dynamic Offset Calibration, Suva, Fiji, 18 June 2003

Roll correction	–2.17
Pitch correction	–1.56
Yaw correction	1.90
GPS Latency correction	–150
Gyro correction	Not determined

3.8 Multibeam Echosounder Data Processing

Upon return to the SOPAC office in Suva, Navisoft 2.2.2 and Terramodel/Terravisualiser software were used for the post-processing of the MBES survey data. The Navisoft Sweep 'Calculate' module was used to correct the raw survey data for tides and sound velocity profile. This module also enables the removal of significant spikes within the data. The Navisoft Sweep 'Data Edit' Module was used to further 'clean' and prepare the data.

Table 6. Map production sequence

Input	XYZ output data from Navisoft reduced to 1 mm at charting scale (e.g. 50 m grid size for a chart at 1 : 50 000).
Surface Model	XYZ output data were gridded using the Kriging method in Surfer 8.05. Data gaps were interpolated using three times the grid spacing.
Output	DXF contours, PDF chart, backdrop images, and DTM model in the project coordinate system.

The data output from Navisoft Sweep was imported into Terravisualiser where a final data cleaning process was carried out, before transferred to Terramodel. The production of contour maps was done using Surfer 8.05 software. The processing and gridding sequences are listed in Table 6. Various levels of smoothing were applied to the contours and DTM, which gave a realistic impression of the seabed without removing any real features from the data set.

3.9 Multibeam Backscatter

The MBES records echo strength data (reflected energy) that can be presented as seabed backscatter maps, similar to sidescan sonar mosaic, or backscatter image, shows information on the composition of the seafloor. The backscatter signal recorded at offshore was of very poor quality and therefore not processed or interpreted.

3.10 Tidal Information

Observed soundings have been reduced to Lowest Astronomical Tide (LAT) tidal datum using observed tidal elevations for Suva and Lautoka. The datum is defined as approximate LAT, 1.1538 m below mean sea level (MSL 1993), and 3.0893 m below the fixed height of benchmark BM4343, using observed water levels from the Lautoka Tide gauge provided by the Australian Bureau of Meteorology (http:/www.bom.gov.au/oceanography/) through the South Pacific Sea level and Climate Monitoring Project (http:/www.bom.gov.au/pacificsealevel/index.shtm). The results are plotted in Figure 12.

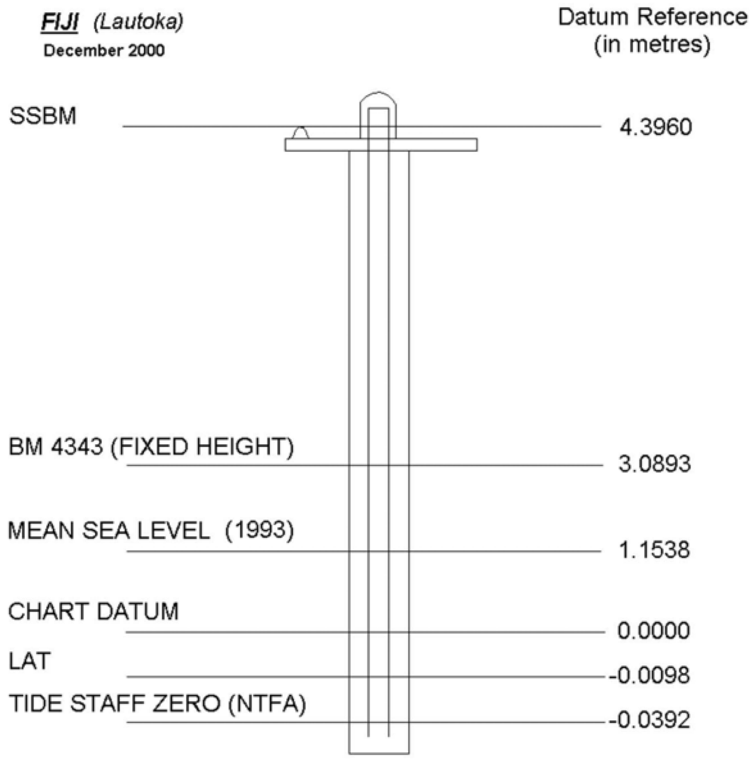


Figure 12. SEAFRAME tide gauge datum definition and other geodetic levels at Lautoka, Fiji (from NTFA 2005)

3.11 Sound Velocity Profiling

The accuracy of the depth soundings depends in part on the variation of the speed of sound with water depth. Sound velocity profiles are therefore required in order to find the correct depth and location of water depth soundings. The speed of sound in seawater varies with temperature, salinity and depth, and was determined by measuring the conductivity, temperature and depth (CTD) through the water column. The main instrumental, operational, processing parameters are listed below.

3.11.1 CTD Instrumentation

Make	SeaBird Electronics
Model	SeaCat 19+ (self-powered, self-contained)
Serial number	4172
Depth rating	3000 m

3.11.2 Operating Parameters

Sample rate	1 scan every 0.5 s
Maximum depth	Limited to 400 m due to wire rope length
Data recorded	Profiles of conductivity, temperature, and pressure

3.11.3 Data Processing

Positioning — The profile position was taken at the GPS antenna near the start of the downcast. No allowance was made for instrument or vessel drift over the duration of the profile, which may be significant (>500 m).

Data conversion — Convert raw data (.hex) to a .cnv file. The following values are output from the recorded data:

- Pressure, dbar
- Depth, m (derived using salt water at local latitude)
- Temperature, ºC (ITS-90)
- Salinity, psu (derived)
- Density, kg m^{-3} (derived)
- Sound velocity, m/s (derived using Chen and Miller 1977)

Bin average — Average data into 1 m depth bins. No filtering was applied.

Output — Processed data is saved in ASCII text format with the file name date_location_bin.cnv.

4. CTD Profile data

The CTD profile details are listed in Table 7, and locations are shown in Figure 13. The summaries of the CTD profile data in graphical form are shown in Appendix 3.

Table 7. CTD profile details

Profile location	Date	Time	Easting	Northing	Depth (m)
Patch test	02/05/03	11:45	1957449	3864466	410
DaVita	03/05/03	09:43	1961320	3869970	430
Reba Roads	05/05/03	12:45	1978826	3864363	445
Natalia	06/05/03	13:01	1997348	3873119	450
Shallow water	06/05/03	14:46	1984079	3868460	100
Natalia	07/05/03	13:41	1991775	3870353	435
Navua	11/05/03	10:46	1935005	3855544	345
Cast	12/05/03	14:25	1941882	3861137	180
Deepwater	16/05/03	10:33	1962294	3864041	540
DaVita	20/05/03	12:28	1957721	3857684	550
Navua area	22/05/03	07:26	1940036	3858891	275
Sigatoka	28/05/03	11:25	1868945	3868156	215
Serua	30/05/03	08:00	1901463	3854664	550
West Bega	18/06/03	16:59	1904639	3847690	540
Momi	30/06/03	17:50	1832924	3888830	550

The on-board CTD probe could only be operated to maximum depth of 400 m due to restrictions on the wire rope length.

As depths well in excess of 600 m have been surveyed, assumptions regarding the nature of the sound velocity profile at depths greater than those measured have to be made for post-processing purposes. These assumptions fall into two categories:

- Use of historical data
- Recommended extrapolation procedure

The historical data was obtained from the SOPAC CTD database. A deep water CTD cast, reaching a depth of approximately 1500m, was made off Naqara (southeast coast of Viti Levu, Fiji) in May of 1994. It was assumed that the sound velocity profiles measured during this current survey behaved in a similar fashion to the May 1994 Naqara profile at depths greater than those we measured. The Naqara profile was therefore appended to each of the recently measured profiles. Where discontinuities arose between the measured data and the Naqara 1994 data, a smoothing algorithm was applied over the transition stage between the two data sets.

For depths greater than 1500m, a recommended procedure was used to extrapolate the sound velocity profile. The assumption underlying the procedure is that the salinity and temperature remain constant at their last measured values, the pressure is then assumed to vary hydrostatically, giving the required variables for a sound velocity calculation.

A FORTRAN programme was written to automate the sound velocity calculation, appending historical data, including the smoothing algorithm, and extrapolating to greater depths.

NB: The historical data and the extrapolation procedure were applied to all CTD data measured during the survey; however the depth of water in which some of the data was collected is significantly less than that provided when the profile extension procedures have been applied. For processing purposes, only the depths of water that are valid will have been used. For all the CTD casts that were performed during this survey, only two data sets were currently available and the plots for these are shown in Appendix 3 – CTD Profiles.

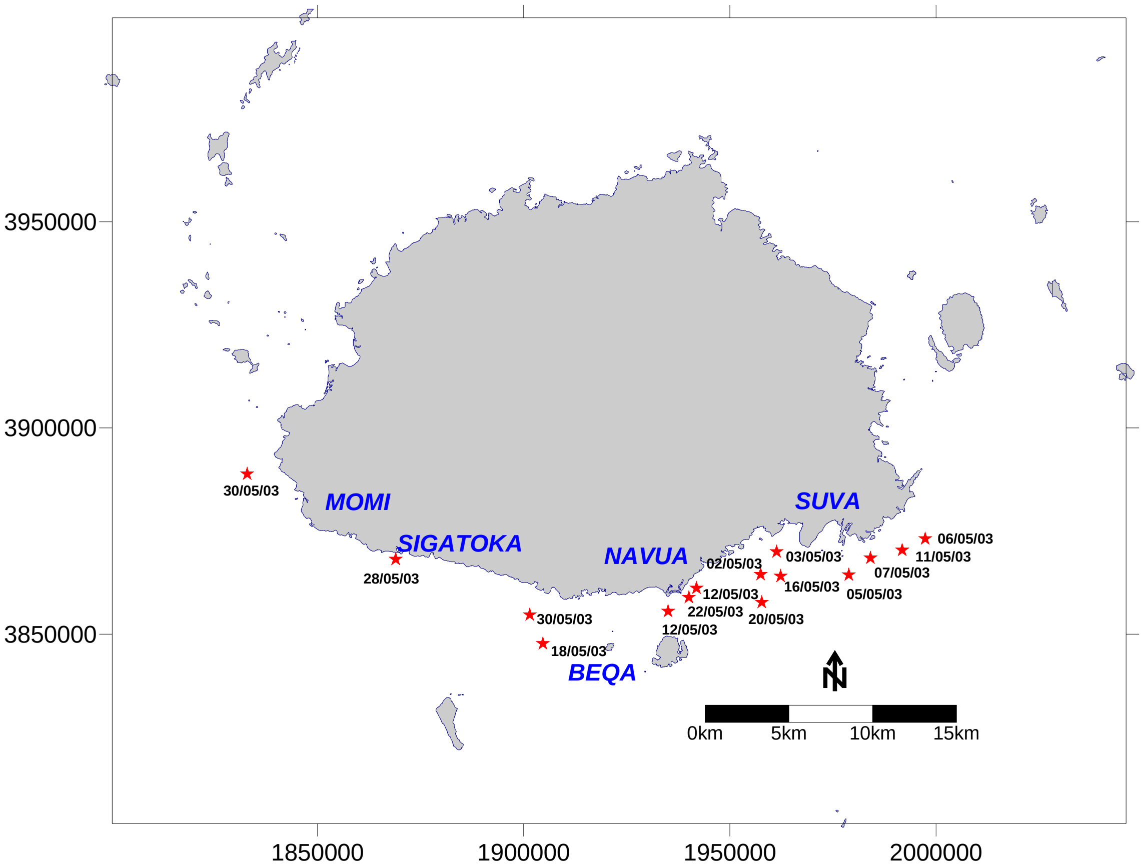


Figure 13. Map showing the location of CTD profiles for south coast of Viti Levu, Fiji.

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Tropical Atmosphere Ocean Project. TAO. http://tao.noaa.gov/

APPENDICES

Appendix 1 – Statement of Accuracy and Suitability for Charting

Bathymetric maps are topographic maps of the sea floor. The bathymetric map serves as a basic tool for performing scientific, engineering, marine geophysical and environmental studies. The information presented in this report and enclosed charts are intended to assist persons and authorities engaged in recreation, tourism, marine resource related industries, hydrographic mapping, coastal development, trade and commerce, sovereignty and security, and environmental management. It is therefore important that users be informed of the uncertainties associated with the data and with products constructed from it. The following is an outline of the survey equipment used and the operating principles, including limitations and estimates regarding the data accuracy.

A1.1 Horizontal positioning

The methods used to acquire survey data will affect the final product accuracy. The global positioning system, GPS, uses radio signals from satellites that orbit the earth to calculate the position of the GPS receiver. Standalone GPS has an estimated accuracy as good as approximately 10 m, depending on satellite configuration and atmospheric conditions. In addition to this, equipment and measurements errors also need to be considered.

A general rule of thumb is that surveys should be conducted with a positioning accuracy of 1 mm at the scale of the chart. Therefore, at a scale of 1 : 10 000, the survey would be required to be accurate to 10 m.

The present S-44 4th Edition Standard of the International Hydrographic Office (IHO) includes a depth-dependent factor that takes into account the added uncertainty of the positions of soundings from multibeam echosounder (MBES) systems as depth increases. The relevant survey orders are listed in Table A1.1, with Multibeam surveys conducted by SOPAC generally falling into orders 2 and 3.

Table A1.1. Recommended accuracy of survey orders

Survey order	Application	Recommended accuracy
Order 1	Harbours and navigation channels	5 m + 5% of depth
Order 2	Depths < 200 m	20 m + 5% of depth
Order 3	Depths > 200 m	150 m + 5% of depth

For the purpose of this survey, it was assumed that the use of GPS provided adequate precision in terms of horizontal position. Therefore, it is not recommended to interpret nearshore data at scales larger than 1 : 10 000, or a grid size smaller than 10 m. For areas with water depths greater than 200 m, a charting scale of least 1 : 50 000 is recommended.

A1.2 Depth measurements

Bathymetric maps provide information about the depth of water from the water surface to the seabed. Through the use of detailed depth contours and full use of bathymetric data, the size, shape and distribution of underwater features are clearly revealed. The depth is measured using a ship-mounted multibeam echo sounder. The MBES transducer produces an acoustic pulse designed as a fan that is wide in the across-track and narrow in the along-track direction (Figure A1.1). The swath of seabed covered by this transmit beam is typically twice the water depth. The pulse of sound emitted from the MBES travels through the water column and is reflected back as an echo and received as numerous narrow beams by the receiving elements of the MBES. The measurements are time-based, and by using the speed of sound in seawater each time is converted first to a range and then, knowing the beam angle, to a depth. The distance to the seabed is then combined with the movement of the vessel to stabilise it into a real-world framework. The framework is then positioned to provide XYZ soundings for each beam's interaction with the seabed. A series of these swaths are then combined to produce a three-dimensional representation of the seafloor topography.

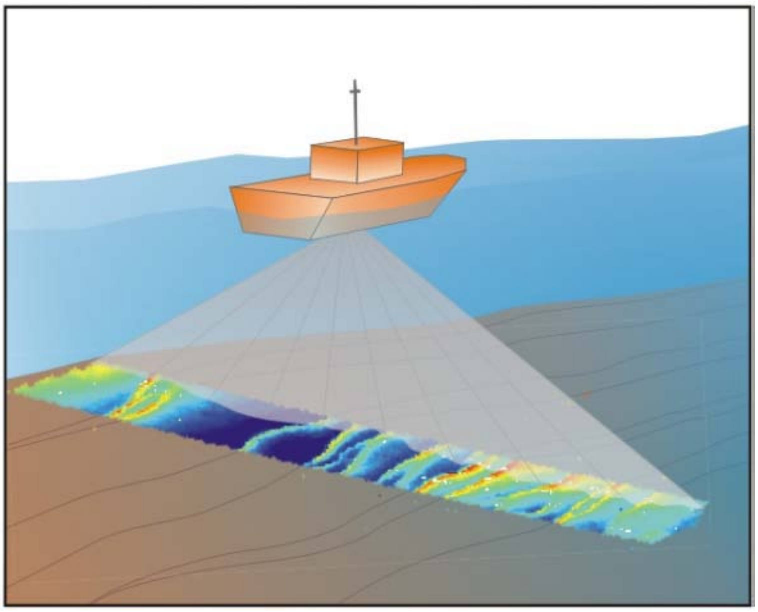


Figure A1.1. Conceptual illustration of bathymetric data acquisition with a multibeam echosounder, MBES (source: http://www.rcom.marum.de, accessed 10/01/2007)

The accuracy of the MBES system is critically dependent on the corrections applied for vessel motion (heave, pitch, roll, yaw, and heading). However, the absolute accuracy of single-beam and multibeam bathymetry depends on several factors that are not easy to determine. For single-beam data, probably the principal errors that may be introduced are due to topographic features falling between survey lines. Multibeam systems give far better coverage.

The S-44 4th Edition Standard of the IHO lists values "a" and "b", (Table A1.2) that should be introduced into the following equation to calculate the error limits for depth accuracy:

$\pm\sqrt{a^2 + (b \times d)^2}$, where d = depth.

Table A1.2. Values for calculating error limits for depth accuracy

Survey order	Application	Constants
Order 1	Harbours and navigation channels	a = 0.5 m, b = 0.013
Order 2	Depths < 200 m	a = 1.0 m, b = 0.023
Order 3	Depths > 200 m	a = 1.0 m, b = 0.023

For example, the IHO recommends that a near-shore coastal survey (Order 2) in water depths of 20 m should have a maximum error of ±1.1 m.

A MBES has, as any other measuring instrument, an inherent limit in its achievable accuracy. The total measurement accuracy, i.e. the uncertainty in the depth and location of the soundings, also depends upon the errors of the auxiliary instruments such as the motion reference unit, the gyro compass, and the measurements of the speed of sound through the water column. The sea state at the time of the survey also contributes significantly to the quality of the data. The possible accuracy of the measured depths may be estimated by considering the following main error sources.

A1.3 Error budget analysis for depths

Measurement	The nadir-beam bottom detection range resolution of the multibeam system has a maximum limit of 0.1 m (Reson 2002). However, multibeam systems are particularly susceptible to errors in the far range (outer beams), and detection is estimated at ±0.3 m plus 0.5 % of the depth. Errors also include the detection of the sea floor due to local variations of depth within the beam footprint, especially in the outer beams, and a varying density of the bottom material. This may be significant if a relatively low frequency transducer is used on soft marine muds in shallow water.
Transducer draft	The transducer depth may be accurate to ± 0.1 m. However, the draft of the vessel due to the variability in vessel loading, e.g. fuel and fresh water storage, was not determined. It is estimated that this introduced a water depth independent error of up to ± 0.2 m. Dynamic draft errors, e.g. vessel squat, may also be significant.
Sound velocity	The sound velocity profiles measured by the conductivity-temperature-depth sensor (CTD) probe did not reach full survey depths in waters exceeding 400 m water depths. An inaccurate sound path from the transducer to the bottom and back will affect not only the observed depth of water, but also the apparent position of the observed sounding. This error is presumed to exceed 0.5% of the water depth beyond the direct CTD measurements. In order to minimise this error, ARGO and GDEM data may be used to supplement the CTD data.
Heave	This error is directly dependent on the sea state and the sensitivity of the motion sensor and installation parameters. The MRU installation did not account for the offset distance between MRU, the centre of gravity, and the MBES transducer mount. The software was able to perform lever arm calculations and heave compensation during post-processing, and the vertical error is assumed to be significant only in heavy seas.
Tide/water level	Uncertainties due to tides may be significant, especially where predicted tides some distance from the survey area are used. Perhaps ± 0.3 m for uncertainty in tidal datum need to be considered.

From the listing above, it is estimated that the measured depths in 20 m have an accuracy of ± 1.5 m. However, the complete bathymetric model, or digital terrain model (DTM), is based on some form of interpolation between the sampled depths from several survey lines. Consequently, the total uncertainty associated with a bathymetric model will include uncertainties due to horizontal positioning, and uncertainties introduced by the interpolation process, and will therefore be larger than the depth sounding uncertainty.

A1.4 Multibeam echosounder data density

The density of data used to construct a bathymetric grid is an important factor in its resolution – the denser the data, the higher the resolution that can be achieved. Sounding density is critical in terms of seabed feature detection and delineation. The two main factors that control the potential bathymetric target resolution capability of a multibeam echosounder are the distance between individual soundings (both in the cross-track and along-track dimensions), and the footprint size. The footprint is the area on the bottom covered by the sound pulse. Footprint size is a function of range, beam angle, and receiver and transmitter beam widths. A high sounding density and small footprint will result in higher-resolution data. Conversely, the target detection capability is going to decay as a result of a growing projected beam footprint and decreasing data density.

The along-track spacing is controlled by the ping rate, which in turn is limited by the two-way travel time from the source to the furthermost point imaged. The maximum across-track spacing depends again primarily on the range, but also on the equiangular beam spacing. The size of the beams received by the MBES system is between one and one-and-a-half degrees. This means that a system mounted on a ship will have a larger projected footprint as the water depth increases. The footprint will also be larger at the outer beams than at the centre of the swath, as the range and incident angles increase with distance from the nadir beam. It is possible to have local variations of depth within the beam footprint, causing vertical error and affecting amplitude detection.

Table A1.3 shows a summary of the projected beam footprint size under varying water depths for the two MBES systems currently in use by SOPAC. It should be noted that the higher frequency system (SeaBat 8101) is not appropriate for applications in waters deeper than 200 m. Due to the constant beam width, the sounded area varies according to the depth and slope, which results in a variable data density in the survey area.

Table A1.3. Projected footprint size under varying water depths

Water depth (m)	SeaBat 8160 (deep water) 50 kHz, 126 beams at 1.2 °		SeaBat 8101 (shallow water) 240 kHz, 101 beams at 1.5 °	
	Inner footprint, nadir (m)	Outer footprint (m)	Inner footprint, nadir (m)	Outer footprint (m)
20	0.4	5.8	0.5	3.5
50	1.0	14.4	1.3	17.6
100	2.1	28.8	2.6	35.3
200	4.2	57.6	5.2	70.6
500	10.5	143.9	N/A	N/A
1000	20.9	287.9	N/A	N/A
1500	31.4	431.8	N/A	N/A

Table A1.3 assumes a horizontal seabed, and shows the variation in across-track footprint size with water depth and beam angle. The sounding density and swath width will also vary when surveying steep slopes, or highly incised margins, as the footprint size varies strongly with topography. Therefore, deeper sections have larger projected footprints and fewer data point. This has the effect that a bathymetric feature whose lateral dimensions are less than the beam footprint size will not be resolved.

It should also be noted that the along-track resolution usually exceeds the across-track resolution due to ping rates, especially in deep water. Since ping rates are limited by the two-way travel time, rates for water depths of 20 m and 1 500 m are 12.9 and 0.2 pings per second, respectively. Using maximum ping rates, or when surveying in deep water, the same area may be measured with the outer beams for several pings, which may give inconsistent sounding data due to the poor repeatability on uneven seabed.

In order to take into account depth-dependent point density, it is generally accepted to grid bathymetric data at a resolution that is on the order of the average beam footprint size, typically 10% of the water depth.

Appendix 2 – Data Coverage for Southeast Viti Levu

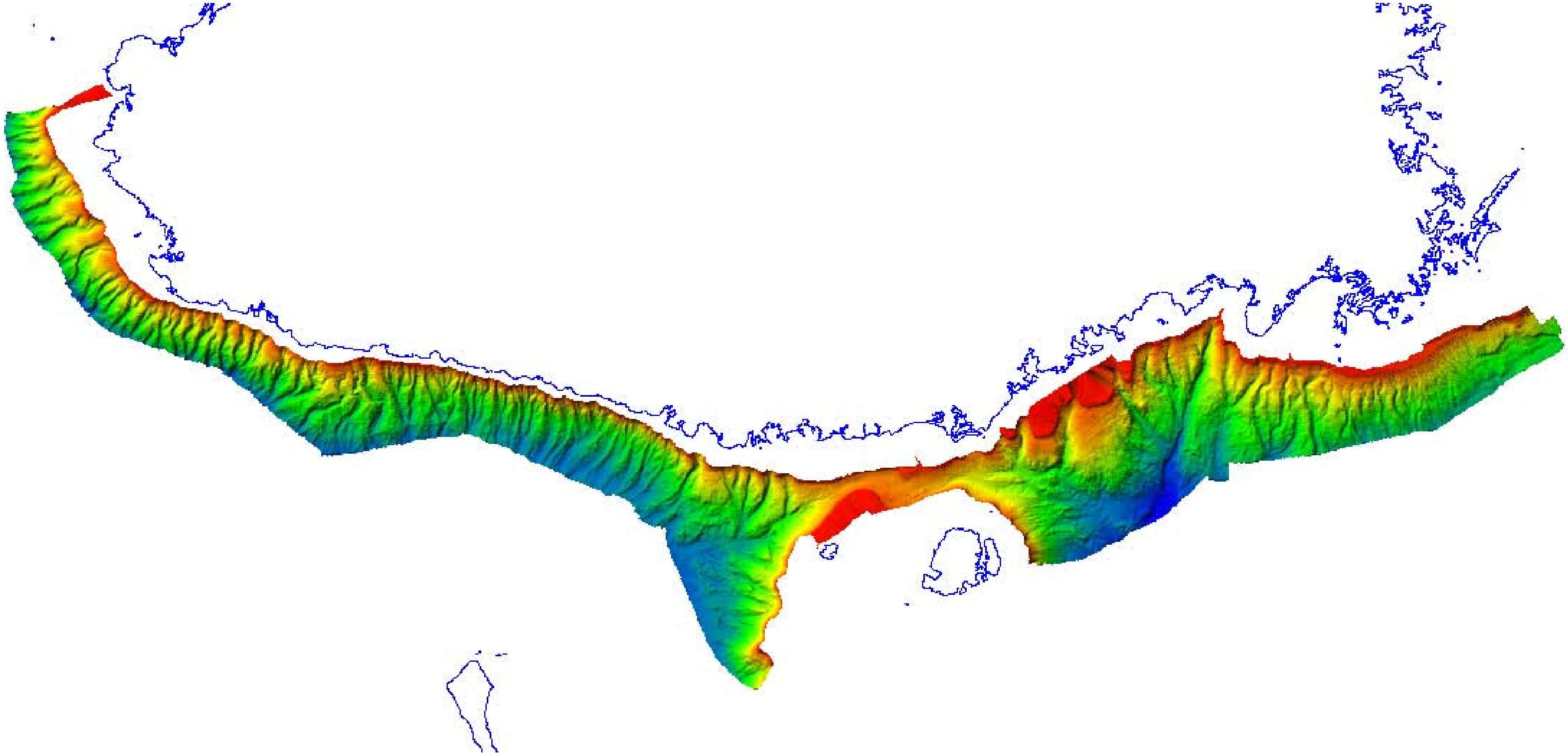
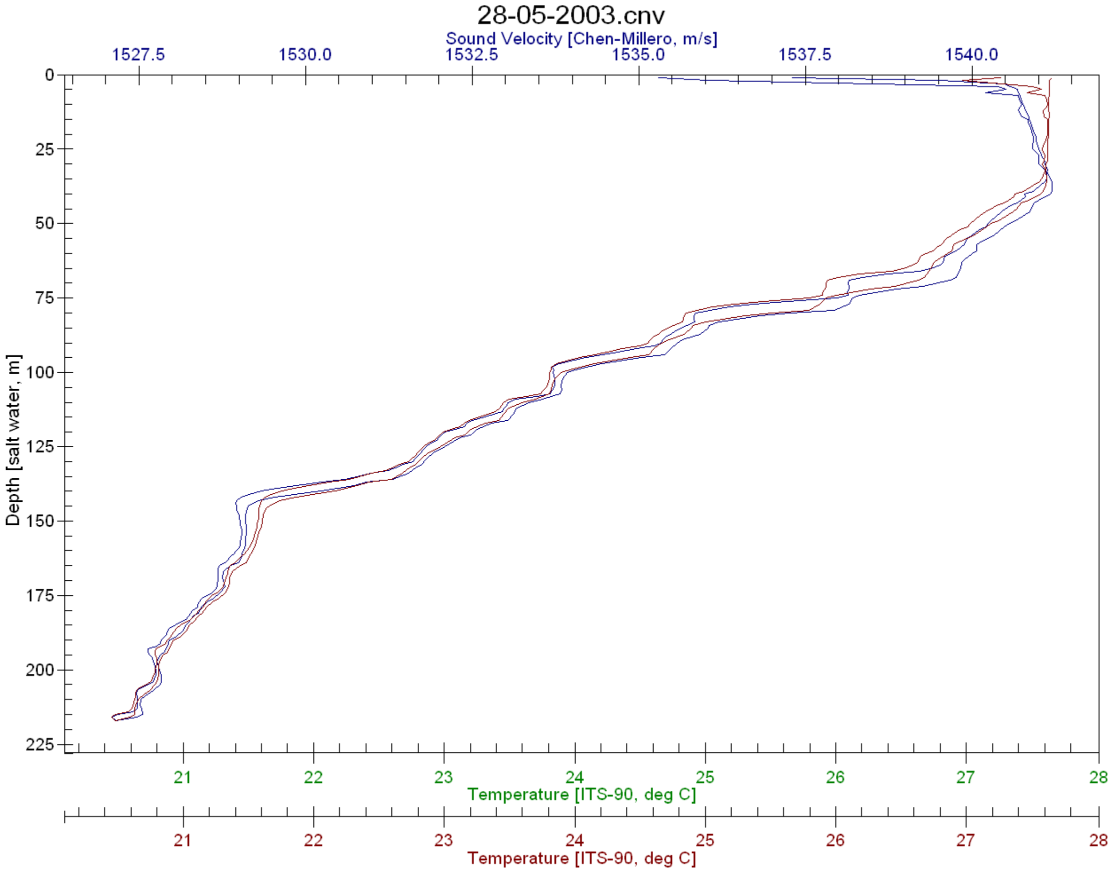
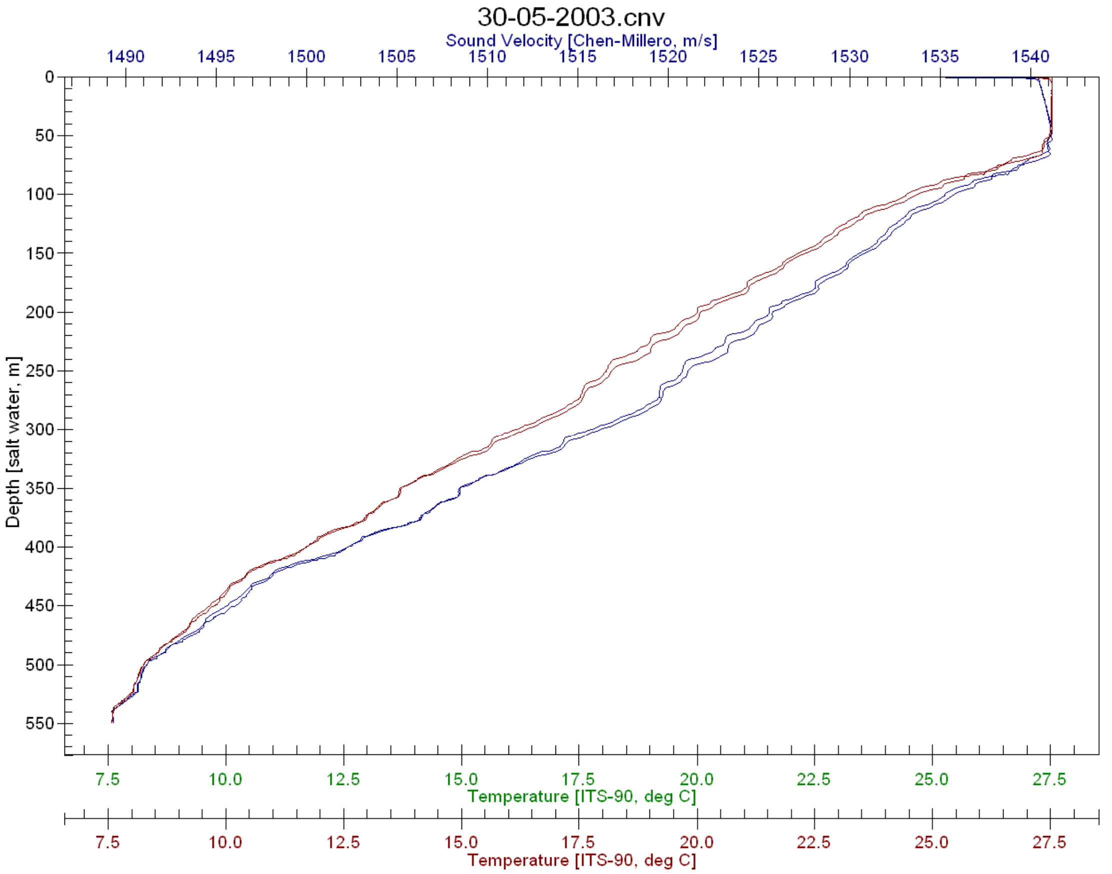


Figure A2.1. Map showing the SOPAC/EU MBES 3D coverage for south coast of Viti Levu, Fiji.

Appendix 3 – CTD Profiles

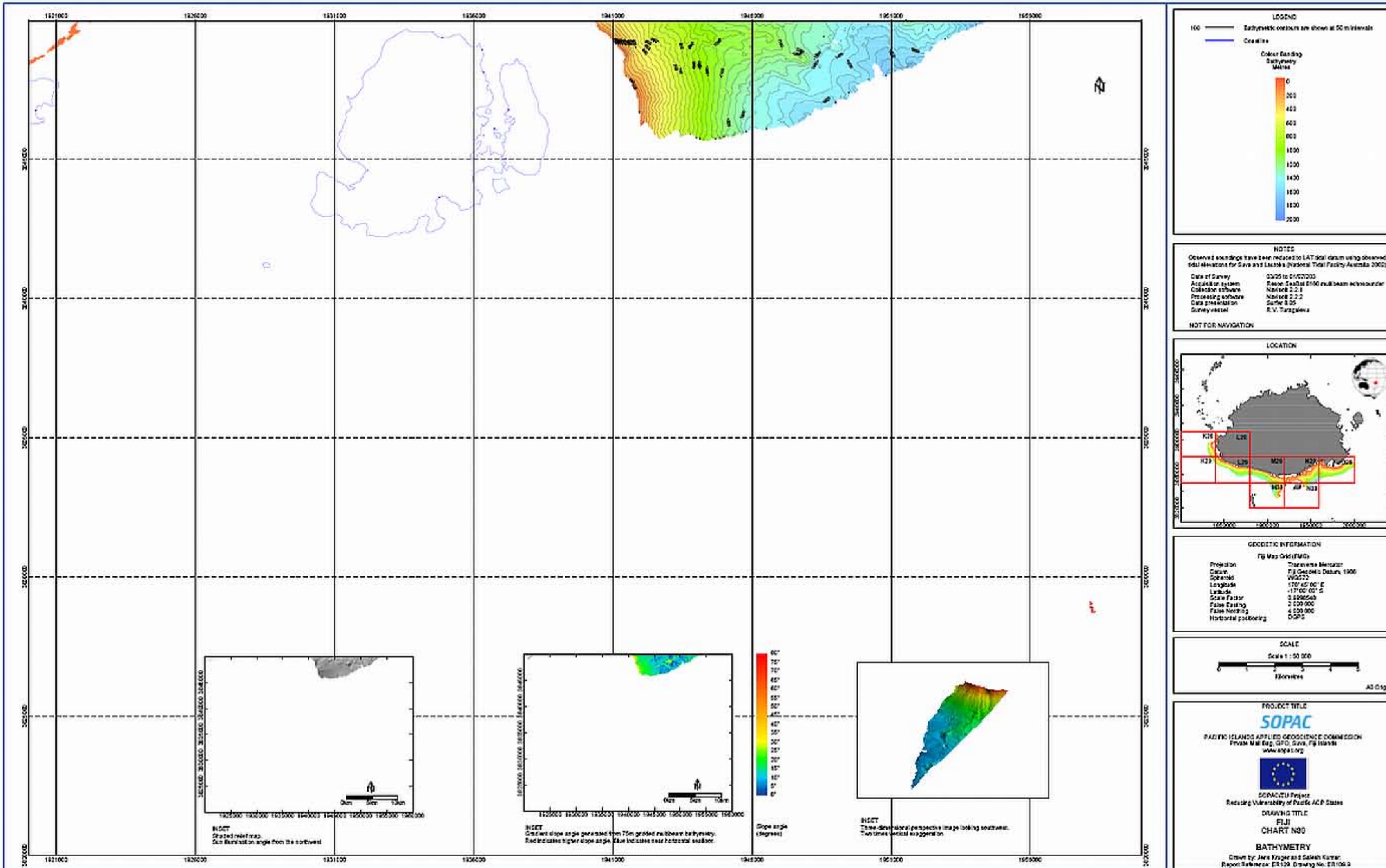


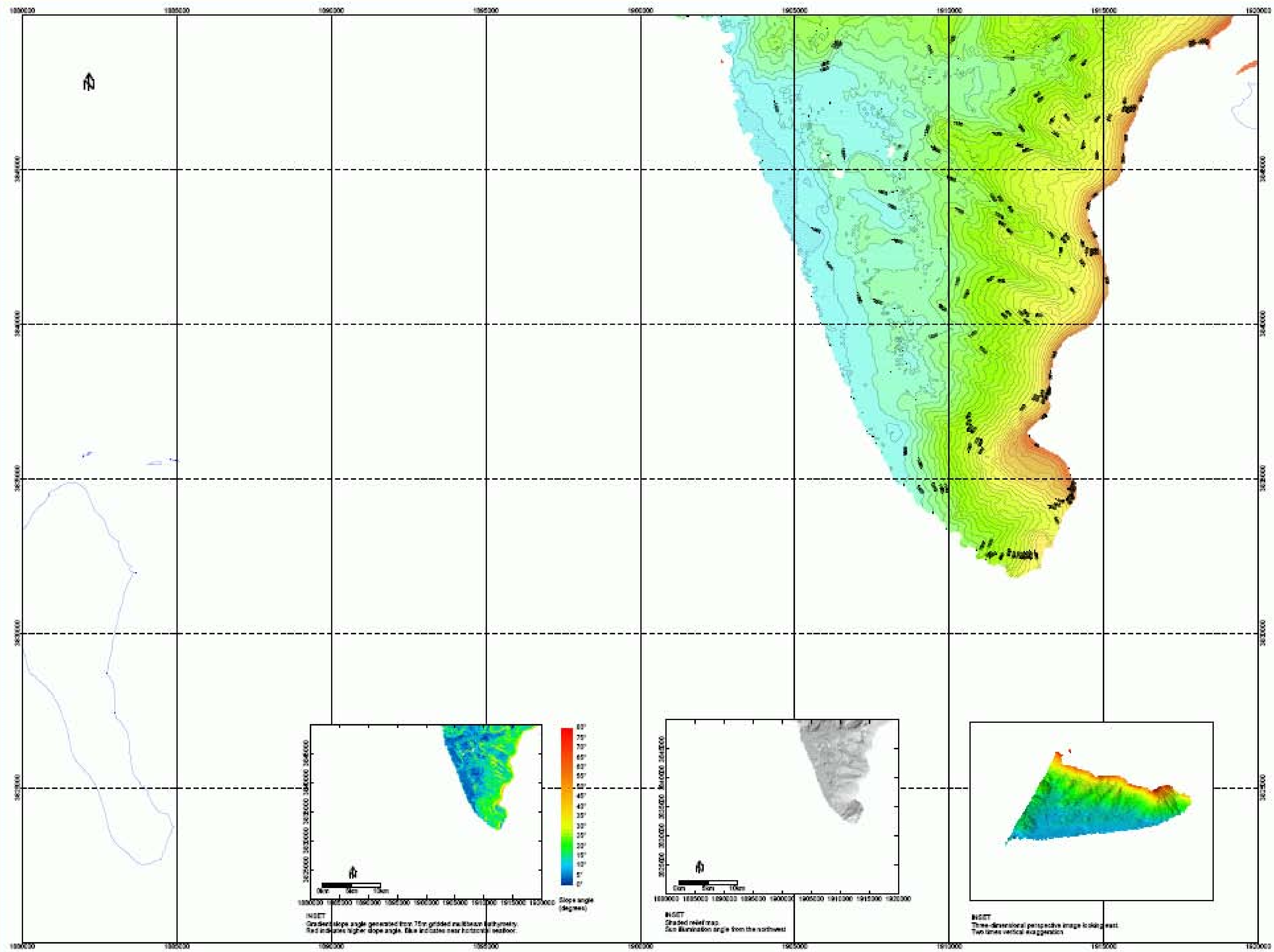


Appendix 4 – High-resolution A0 charts, Fiji bathymetry

Charts are available from SOPAC, and can be downloaded from its website (www.sopac.org). Full size is 841 x 1189 mm. (Low-resolution A4 representations follow.)

Chart No	Title	Scale	Drawing No.
1	Suva, Fiji. Chart K28 Bathymetry	1 : 50 000	ER109.1
2	Suva, Fiji. Chart L28 Bathymetry	1 : 50 000	ER109.2
3	Suva, Fiji. Chart K29 Bathymetry	1 : 50 000	ER109.3
4	Suva, Fiji. Chart L29 Bathymetry	1 : 50 000	ER109.4
5	Suva, Fiji. Chart M29 Bathymetry	1 : 50 000	ER109.5
6	Suva, Fiji. Chart N29 Bathymetry	1 : 50 000	ER109.6
7	Suva, Fiji. Chart O29 Bathymetry	1 : 50 000	ER109.7
8	Suva, Fiji. Chart M30 Bathymetry	1 : 50 000	ER109.8
9	Suva, Fiji. Chart N30 Bathymetry	1 : 50 000	ER109.9


LEGEND
Bathymetric contours are shown at 50 m intervals
Coastline
Colour Banding
Bathymetry
Metres
NOTES
Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia 2002)
Date of Survey
Acquisition system
Reson SeaBat 8160 multibeam echosounder
Collection software
Processing software
Data presentation
Survey vessel
R.V. Turagaleva
NOT FOR NAVIGATION
LOCATION
GEODETIC INFORMATION
Fiji Map Grid (FMG)
Projection
Transverse Mercator
Datum
Fiji Geodetic Datum, 1986
Spheroid
WGS72
Longitude
Latitude
Scale Factor
False Easting
False Northing
Horizontal positioning
DGPS
SCALE
Scale 1 : 50 000
Kilometres
A3 Original
PROJECT TITLE
SOPAC
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org
SOPAC/EU Project
Reducing Vulnerability of Pacific ACP States
DRAWING TITLE
FIJI
CHART N30
BATHYMETRY
Drawn by: Jens Kruger and Salesh Kumar.
INSET
Shaded relief map.
Sun illumination angle from the northwest
INSET
Gradient slope angle generated from 75m gridded multibeam bathymetry.
Red indicates higher slope angle. Blue indicates near horizontal seafloor.
Slope angle (degrees)
INSET
Three-dimensional perspective image looking southwest.
Two times vertical exaggeration.



LEGEND

100 —— Bathymetric contours are shown at 50 m intervals

—— Coastline

Colour Banding
Bathymetry
Metres

0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

NOTES

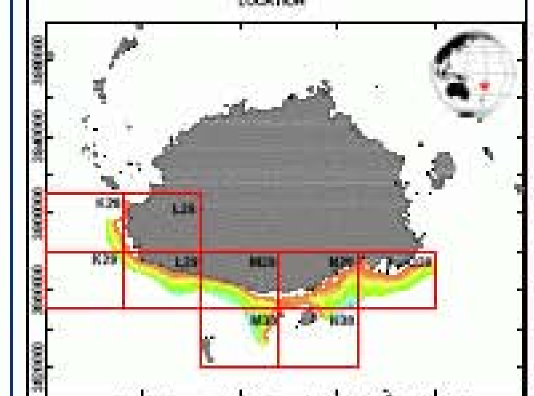
Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia 2002).

Date of Survey	03/06 to 01/07/2003
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.2
Data presentation	Surfer 8.05
Survey vessel	R.V. Turagaleva

Backdrop Landsat image taken on 13/10/1999

NOT FOR NAVIGATION

LOCATION



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
Datum	Fiji Geodetic Datum, 1986
Spheroid	WGS72
Longitude	178° 45' 00" E
Latitude	-17° 00' 00" S
Scale Factor	0.9998540
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

0 1 2 3 4 5

Kilometres

A0 Original

PROJECT TITLE

SOPAC

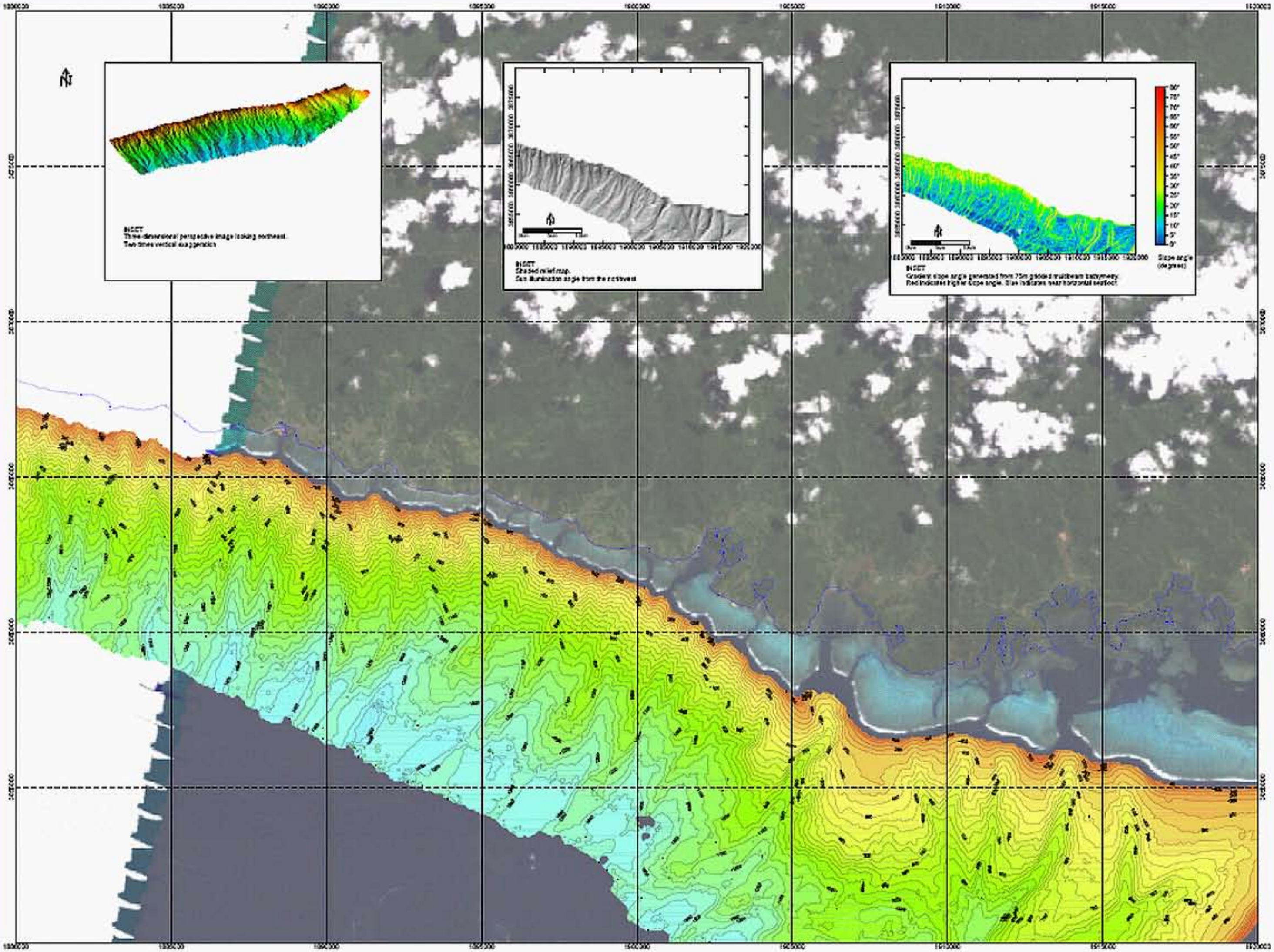
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project:
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

FIJI
BATHYMETRY
CHART M30

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER108. Drawing No. ER108.8



LEGEND

100 — Bathymetric contours are shown at 50 m intervals.

Colour Banding
Bathymetry
Metres

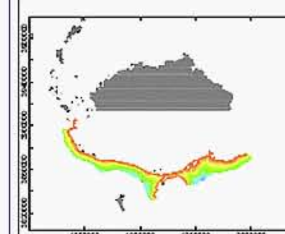
0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

NOTES

Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia 2000).

Date of Survey	03/05 to 01/07/2000
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.3
Data presentation	Surfer 8.05
Survey vessel	R.V. Tangaloa

Backdrop Landsat image taken on 13/10/1999



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
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Spheroid	WGS72
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Latitude	-17°00' 00" S
Scale Factor	0.9996548
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

Kilometres

NOT FOR NAVIGATION

A3 Original

PROJECT TITLE

SOPAC

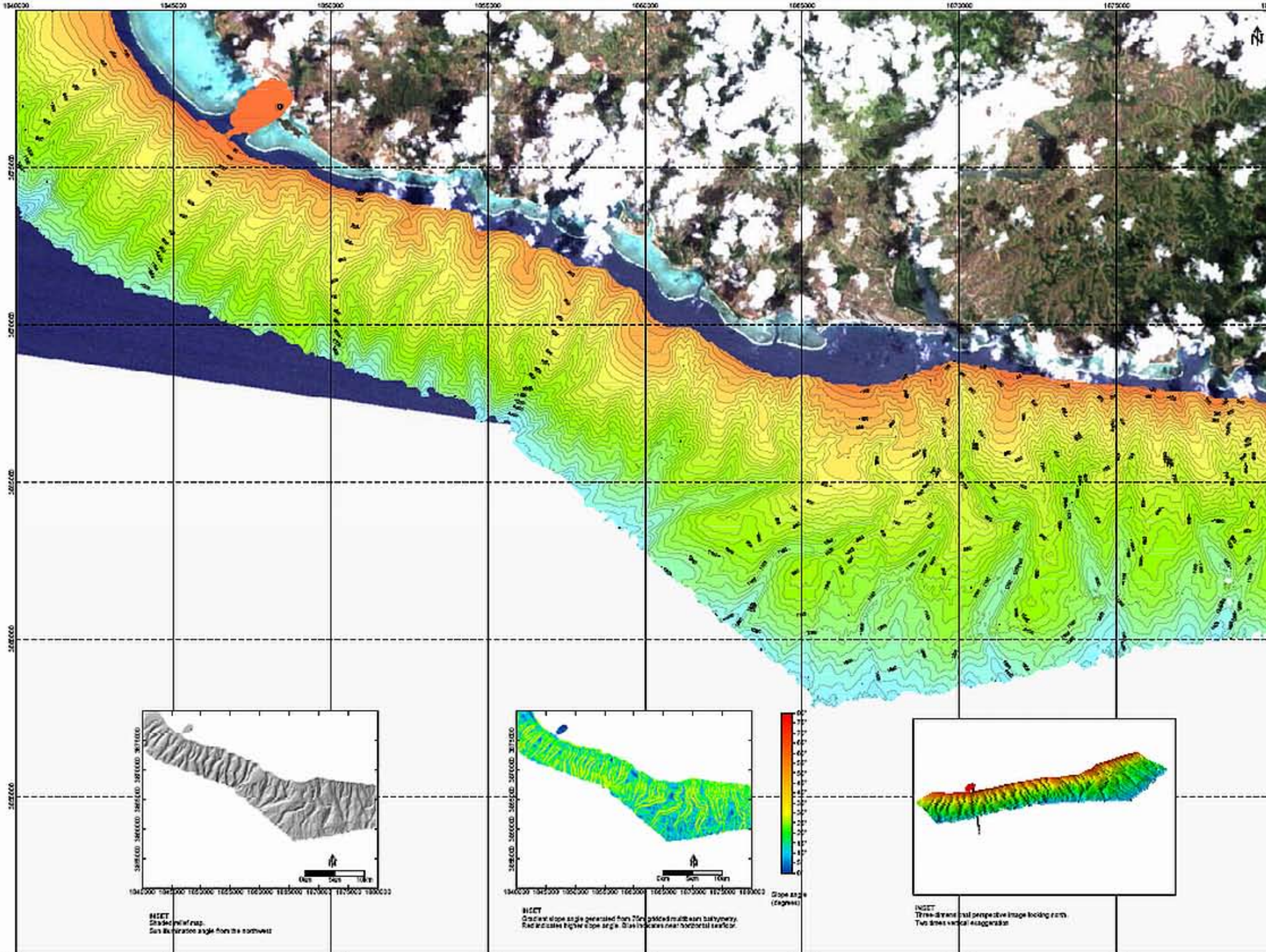
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project:
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

FIJI
BATHYMETRY
CHART M29

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: CR109. Drawing No. CR109.5



INSET
Shaded relief map.
Sun illumination angle from the northwest.

INSET
Gradient slope angle generated from 25m gridded multibeam bathymetry.
Red indicates higher slope angle. Blue indicates near horizontal seafloor.

Slope angle (degrees)

INSET
Three-dimensional perspective image looking north.
Two times vertical exaggeration.

LEGEND

100 — Bathymetric contours shown at 50 m intervals

Colour Banding
Bathymetry
Metres

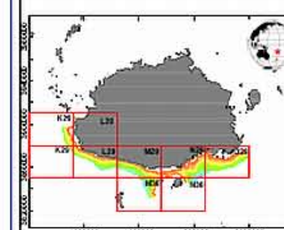
0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

NOTES

Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia 2002).

Date of Survey	03/06 to 01/07/2003
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.2
Data presentation	Surfer 8.05
Survey vessel	R.V. Turagalevu

Backdrop Landsat image taken on 13/10/1999



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
Datum	Fiji Geodetic Datum, 1986
Spheroid	WGS72
Longitude	178° 45' 00" E
Latitude	-17° 00' 00" S
Scale Factor	0.9996540
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

0 1 2 3 4 5
Kilometres

NOT FOR NAVIGATION

A0 Original

PROJECT TITLE

SOPAC

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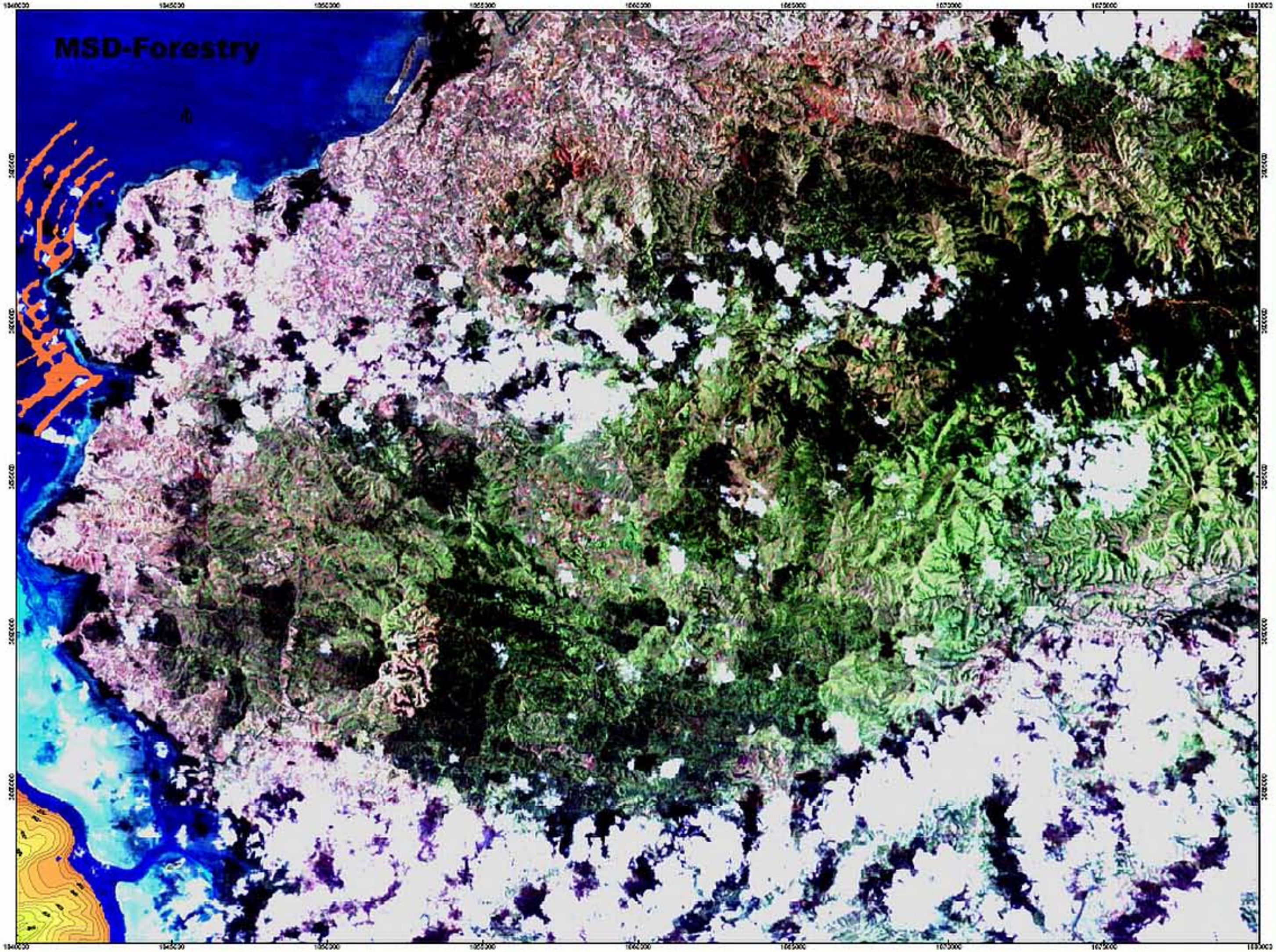
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project:
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE
FIJI
BATHYMETRY
CHART L20

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER129. Drawing No.: ER129.4



LEGEND

100 —— Bathymetric contours are shown at 50 m intervals

Colour Banding
Bathymetry
Metres

0
200
400
600
800
1000
1200
1400
1600
1800
2000

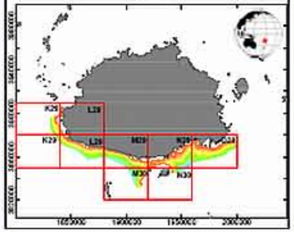
NOTES

Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia 2002)

Date of Survey	03/05 to 01/07/2003
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.2
Data presentation	Surfer 8.05
Survey vessel	R.V. Tasagalevu

Backdrop landsat image taken on 13/10/1999

LOCATION



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
Datum	Fiji Geodetic Datum, 1986
Spheroid	WGS72
Longitude	178° 45' 00" E
Latitude	-17° 00' 00" S
Scale Factor	0.9996540
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

0 1 2 3 4 5
Kilometres

NOT FOR NAVIGATION

A0 Original

PROJECT TITLE

SOPAC

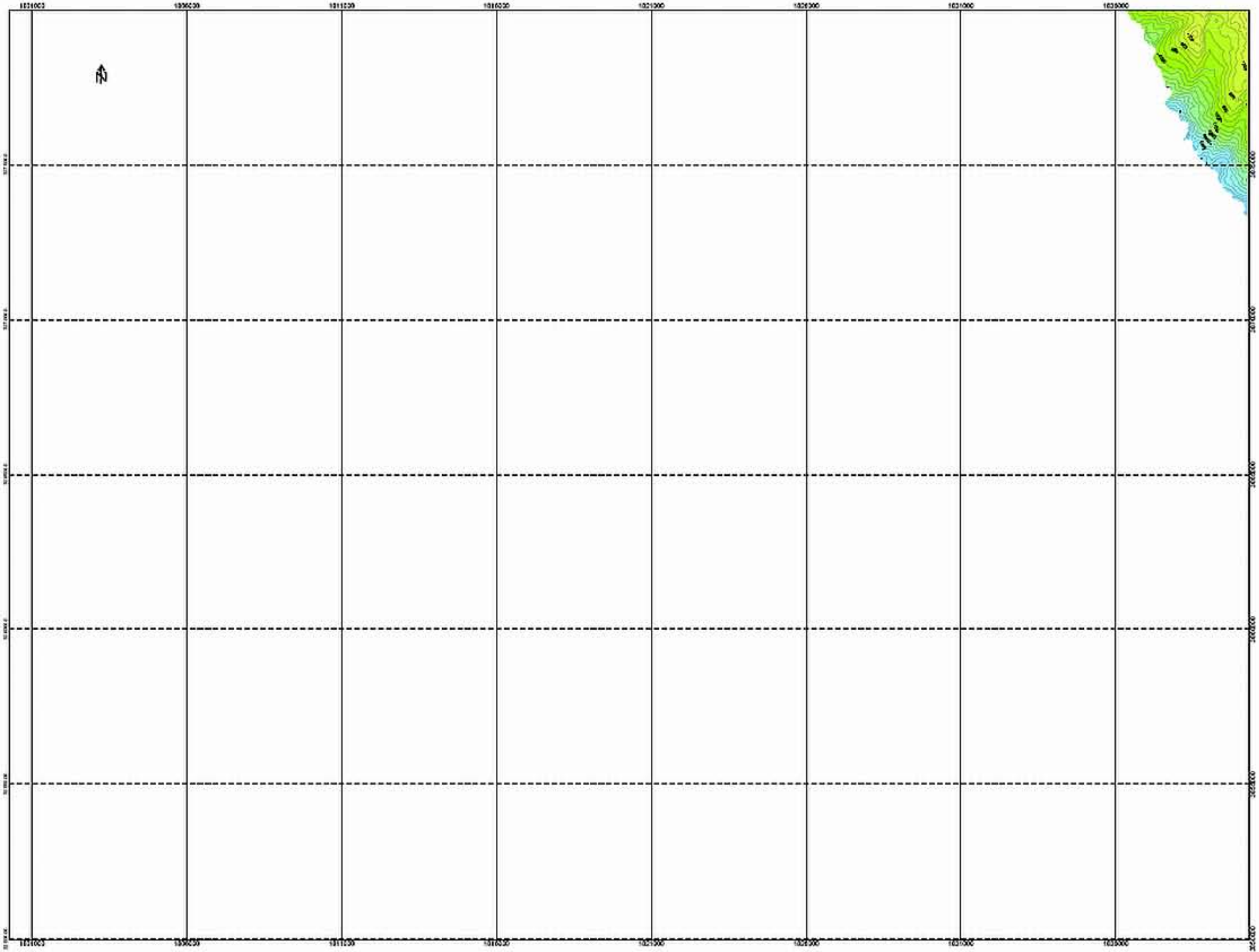
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project:
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

FIJI
BATHYMETRY
CHART L28

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER129. Drawing No. ER109.2



LEGEND

100 —— Bathymetric contours are shown at 50 m intervals

Colour Banding
Bathymetry
Metres

0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

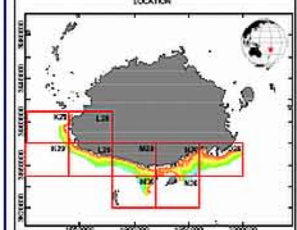
NOTES

Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal facility Australia 2002).

Date of Survey	03/05 to 01/07/2003
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.2
Data presentation	Surfer 8.05
Survey vessel	M.V. Turagalevu

Backdrop Landsat image taken on 13/10/1999

LOCATION



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
Datum	Fiji Geodetic Datum, 1986
Spheroid	WGS72
Longitude	178°45' 00" E
Latitude	-17°00' 00" S
Scale Factor	0.9996548
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

0 1 2 3 4 5
Kilometres

NOT FOR NAVIGATION

A0 Original

PROJECT TITLE

SOPAC

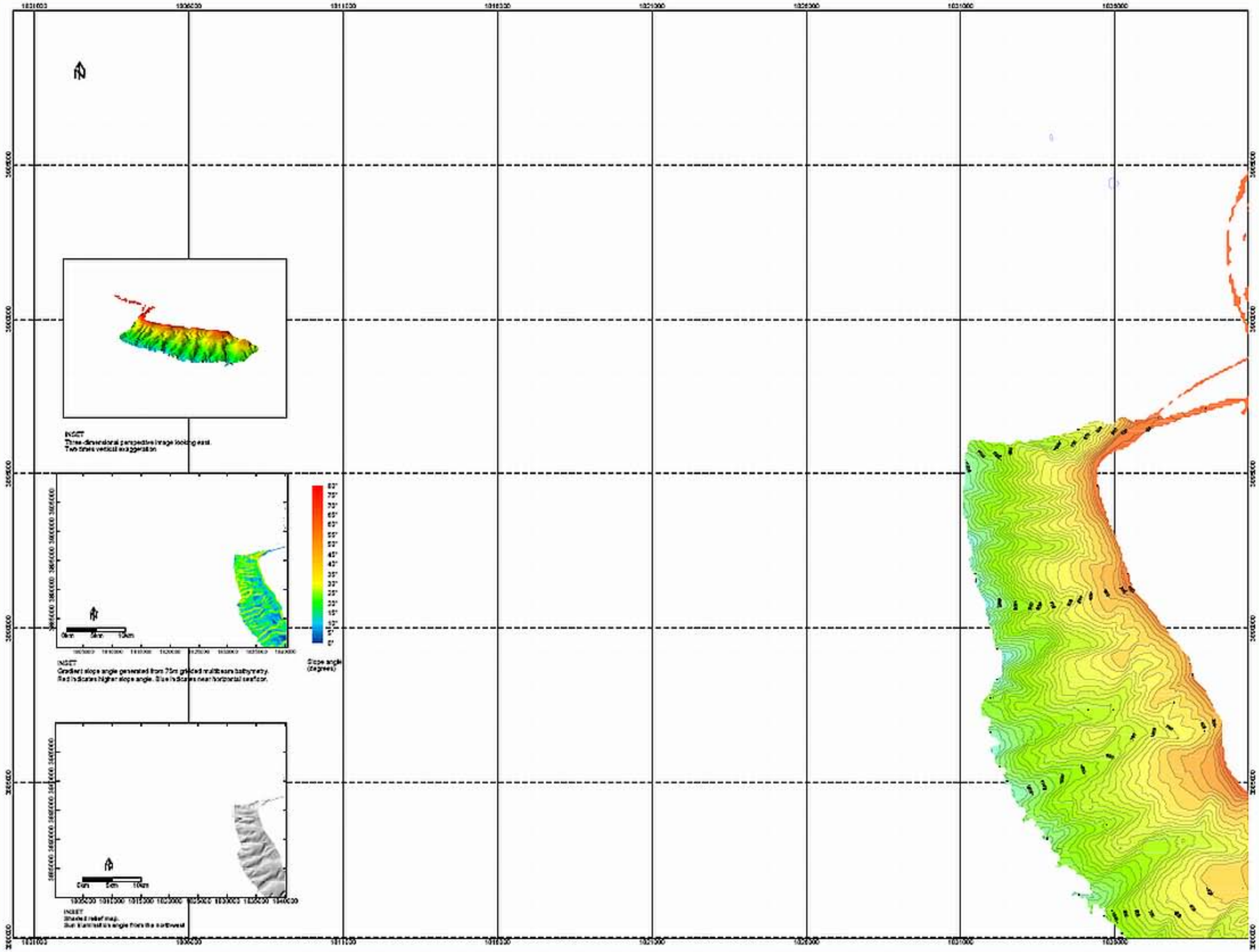
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

FIJI
BATHYMETRY
CHART K20

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER109, Drawing No.:ER109.3



LEGEND

100 —— Bathymetric contours are shown at 50 m intervals

Colour Banding
Bathymetry
Metres

0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

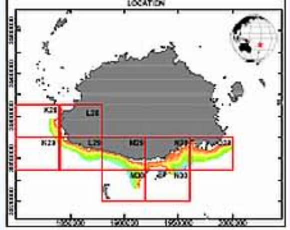
NOTES

Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility/Australia 2002).

Date of Survey	03/05 to 01/07/2003
Acquisition system	Reson SeaBat 8160 multibeam echosounder
Collection software	Navisoft 2.2.1
Processing software	Navisoft 2.2.2
Data presentation	Surfer 8.05
Survey vessel	R.V. Turagalevu

NOT FOR NAVIGATION

LOCATION



GEODETIC INFORMATION

Fiji Map Grid (FMG)

Projection	Transverse Mercator
Datum	Fiji Geodetic Datum, 1986
Spheroid	WGS72
Longitude	178° 45' 00" E
Latitude	-17° 00' 00" S
Scale Factor	0.9996540
False Easting	2 000 000
False Northing	4 000 000
Horizontal positioning	DGPS

SCALE

Scale 1 : 50 000

0 1 2 3 4 5
Kilometres

A0 Original

PROJECT TITLE

SOPAC

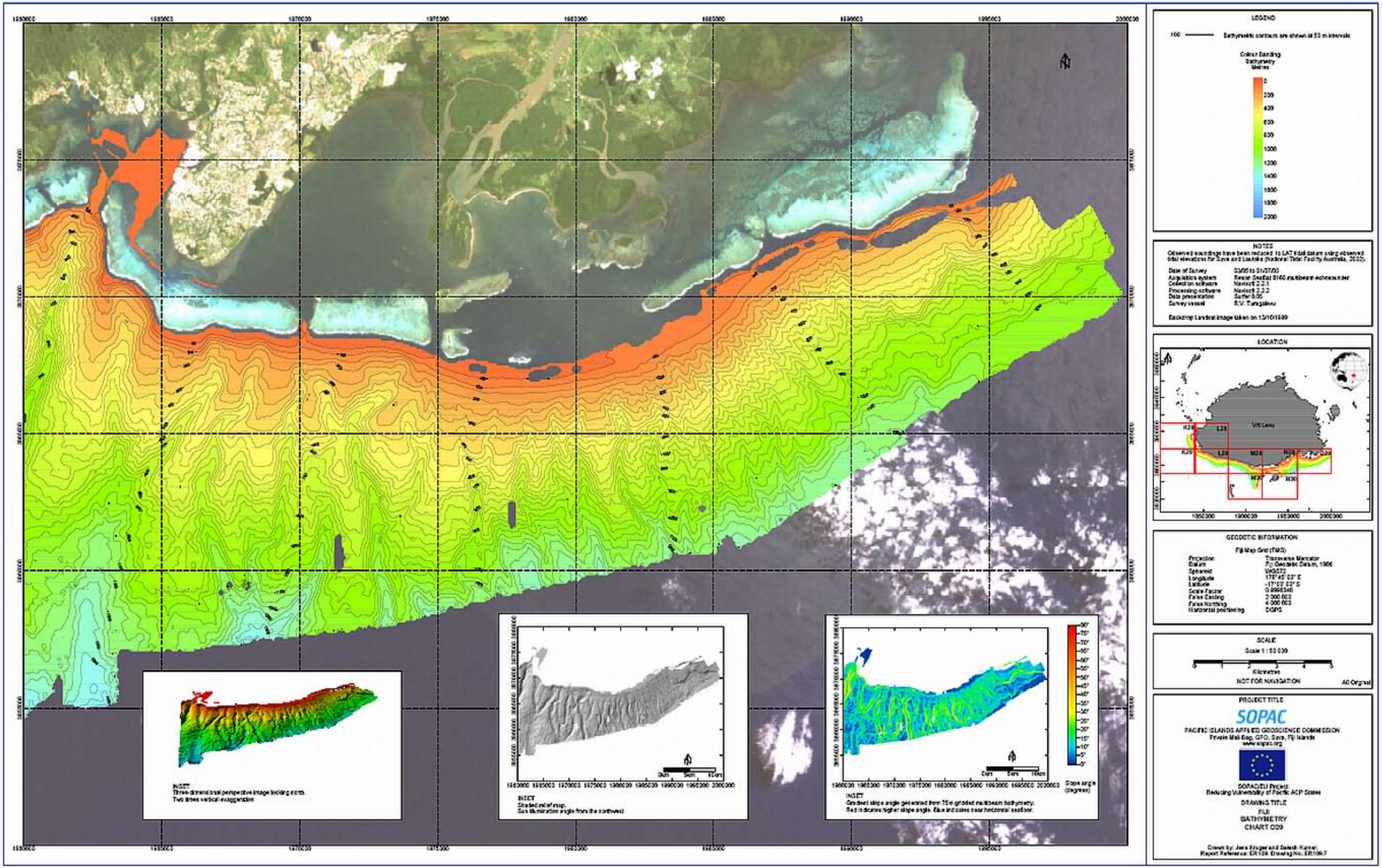
PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

FIJI
BATHYMETRY
CHART K28

Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER169, Drawing No. ER169.1



LEGEND
100
Bathymetric contours are shown at 50 m intervals
Colour Banding
Bathymetry
Metres
0
200
400
600
800
1000
1200
1400
1600
1800
2000
NOTES
Observed soundings have been reduced to LAT tidal datum using observed tidal elevations for Suva and Lautoka (National Tidal Facility Australia, 2002).
Date of Survey
Acquisition system
Collection software
Processing software
Data presentation
Survey vessel
Reson SeaBat 8160 multibeam echosounder
R.V. Turagaiwalu
Backdrop Landsat image taken on 13/10/1999
LOCATION
Viti Levu
GEODETIC INFORMATION
Fiji Map Grid (FMG)
Projection
Datum
Spheroid
Longitude
Latitude
Scale Factor
False Easting
False Northing
Horizontal positioning
Transverse Mercator
Fiji Geodetic Datum, 1986
WGS72
DGPS
SCALE
Scale 1 : 50 000
0
1
2
3
4
5
Kilometres
NOT FOR NAVIGATION
A0 Original
PROJECT TITLE
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SOPAC/EU Project:
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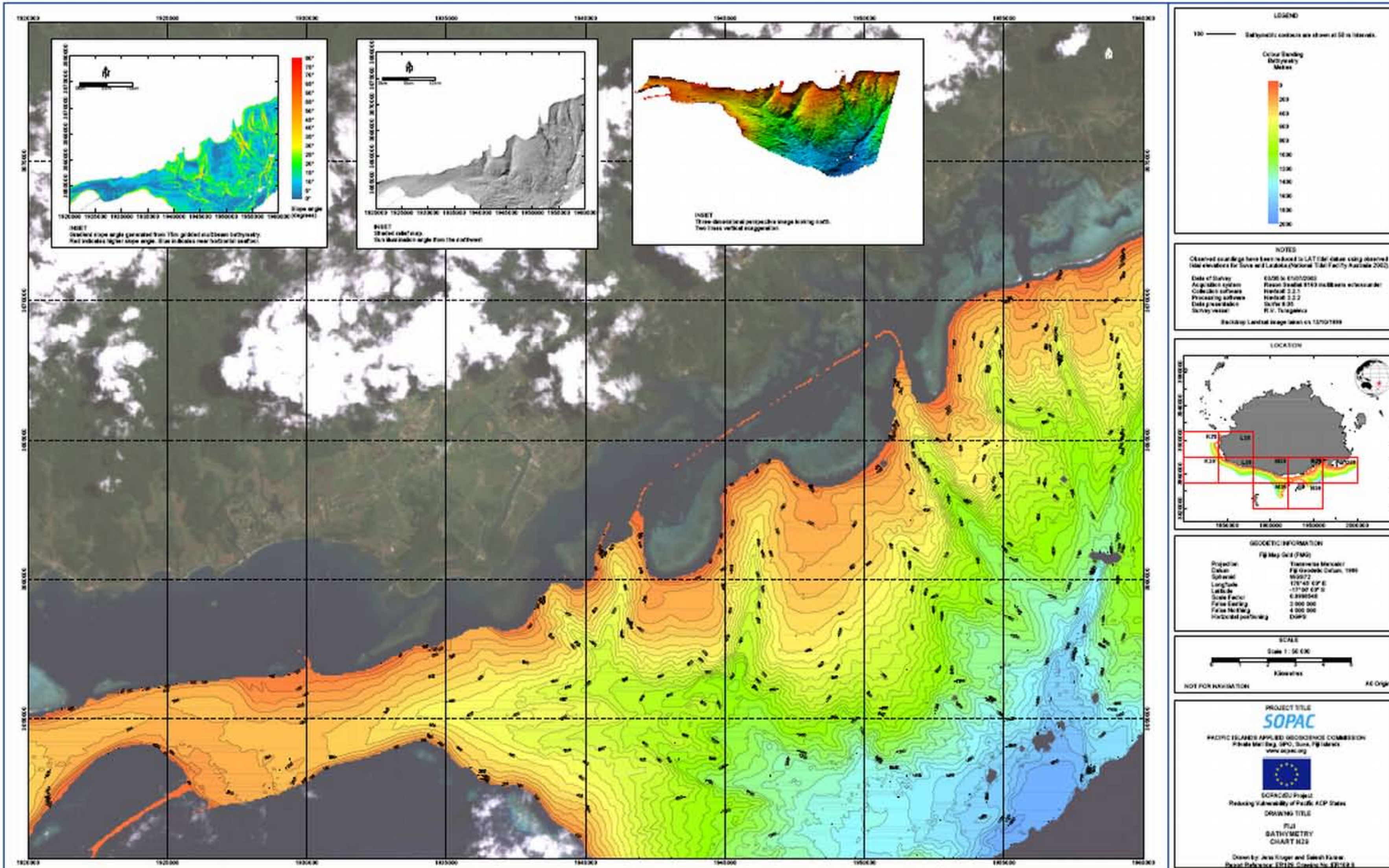
DRAWING TITLE
FIJI
BATHYMETRY
CHART O29
Drawn by: Jens Kruger and Salesh Kumar.
Report Reference: ER139. Drawing No.: ER139.7
INSET
Three-dimensional perspective image looking north.
Two times vertical exaggeration
INSET
Shaded relief map.
Sun illumination angle from the northwest.
INSET
Gradient slope angle generated from 75m gridded multibeam bathymetry.
Red indicates higher slope angle. Blue indicates near horizontal seafloor.
Slope angle
(degrees)


LEGEND
Colour Banding
Bathymetry
Metres
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LOCATION
GEODETIC INFORMATION
Fiji Map Grid (FMG)
Projection
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Horizontal positioning
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DGPS
SCALE
Kilometres
NOT FOR NAVIGATION
A4 Original
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