Voyage Report

TECTA

Tectonic Event of the Cenozoic
in the Tasman Area

3 September – 9 October 2015
R/V L'Atalante

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SGNC Service Géologique de NOUVELLE-CALÉDONIE

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IRD Institut de recherche pour le développement

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1 Introduction

1.1 Nature and objectives of the project

The process of subduction initiation is of interest to a wide range of geoscientists because it has played a profound role in the Cenozoic development of regions such as the Mediterranean and western Pacific, and because it represents a mechanism by which plate driving forces and hence plate motions can change. Although lithosphere in many places is gravitationally unstable, due to its colder temperature and higher density than asthenosphere beneath, the strength of the lithosphere resists subduction initiation. Mc Kenzie suggested “ridges start easily but trenches do not”. However, subduction initiation is demonstrated to have occurred and a range of numerical models have been proposed to explain what happens. Unfortunately, subduction is a destructive process and high-quality evidence of how it started is rarely preserved. Hence it is difficult to answer the question: where, when and how does subduction start, and what are the consequences of subduction initiation? We are able to collect unique observations from the southwest Pacific, where Tonga-Kermadec subduction initiated during Eocene-Oligocene time, and this was a primary goal of the TECTA voyage.

We concluded from our preliminary analysis of existing data that:

1. The Tonga-Kermadec system is the best place on Earth to study subduction initiation because the geology and plate motion history is well-known and geometry relatively simple, the region escaped later deformation due to rapid roll-back of the subducted slab, and the region preserved a near-complete record of events due to its elevation near or below sea level over most of the area for most of the time.
2. New data were required to tie existing surveys together and to wells, so that a synthesis of the relative and absolute timing and magnitude of deformation and vertical motions can be determined.
3. A new class of subduction initiation models is required that can explain the patterns, magnitude, and timing of deformation and vertical motions. In particular, how did Mesozoic tectonic events pre-condition the region for Cenozoic subduction renewal, and what constraints can we place on Eocene initial conditions in the lithosphere?

The TECTA project grew out of 15 years of scientific research performed by governments of New Zealand, Australia and France to underpin sovereign rights under the United Nations Convention on the Law of the Sea (UNCLOS). Our international team developed two scientific voyage proposals, in order to address science questions related to subduction zone initiation. Both proposals target the area of the volcanic arc systems located to the west of the present Tonga-Kermadec system, an archetypal locality for the study of subduction zone processes. These two voyages are: TECTA (this report) and VESPA (Principal scientist: M. Patriat). The VESPA voyage took place in May-June 2015, and aimed to address in particular the volcanic responses that took place during initiation of the Tonga-Kermadec system. The VESPA survey mapped seabed features and collected volcanic rocks along the Cook Fracture Zone, where we expect the first manifestations of the arc formed as the new slab descended into the asthenosphere and rolled back (Figure 1).

The aim of the TECTA survey was to map and quantify effects felt by sedimentary basins on the proximal part of the overriding plate (Figure 1), to determine the timing and style of both horizontal deformation and vertical motion in relation to calculated plate motions and geodynamic models of slab creation. We collected multi-channel seismic data to study those motions as recorded in the sedimentary basins. Our results will provide new insight into lithospheric processes and dynamic topography during subduction initiation, and the timing of Tonga-Kermadec initiation relative to other events in the Pacific will provide constraints on plate driving forces.

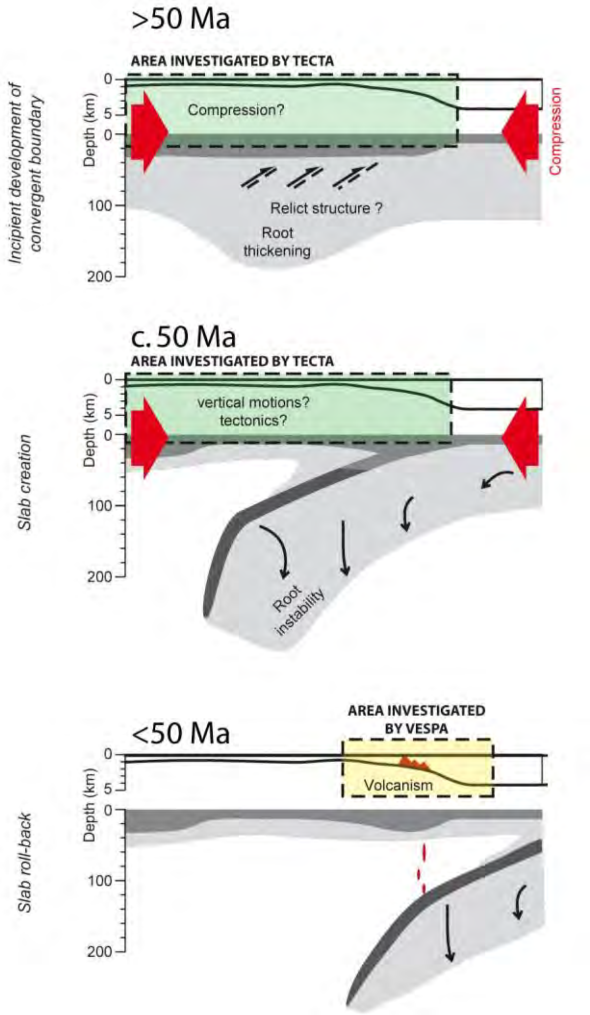

Figure 1 - Subduction initiation model tested by TECTA and VESPA and location of investigated areas (modified from Sutherland et al., 2010).

Each voyage was designed to provide a unique insight into the process of subduction initiation, and the combined outputs of TECTA and VESPA will link seamlessly to provide an integrated mechanical and geochemical dataset with general implications for the early evolution of subduction plate boundaries, and specifically the widespread Pacific changes at around the time of the Emperor-Hawaii seamount bend.

Broader regional outcomes include the understanding of sedimentary basin history and composition, past climate, oceanography, and paleogeography during a greenhouse world, species dispersal, and evolution of local flora and fauna.

1.2 Relevant previous and future research voyages

The TECTA survey is part of a wider scientific program studying subduction initiation that includes other collaborative marine data acquisition:

- The TAN1312 voyage was conducted in December 2013 onboard New Zealand RV Tangaroa. Principal scientists: F. Bache (GNS Science) and R. Sutherland (GNS-Science). SGNC staff participated.
- The TAN1409 voyage was conducted in August 2014 onboard New Zealand RV Tangaroa. Principal scientists: R. Sutherland (GNS-Science) and J. Collot (SGNC).
- The VESPA (Volcanic Evolution of the South Pacific Area) voyage was conducted in May-June 2015 onboard RV L'Atalante. Principal Scientists: M. Patriat (Ifremer, New Caledonia) and N. Mortimer (GNS-Science, NZ).
- The SIPC (Subduction Initiation and Paleogene Climate) full proposal (IODP 832) submitted to the Integrated Ocean Drilling Program (IODP) in 2013 and revised in 2015, and which could be achieved in 2017-2019.

1.3 Funding of the TECTA voyage

This TECTA voyage was for the first time submitted to the French marine national science panel "*Commission Nationale Flotte Hauturière*" in 2010. After several iterations, improving the project based on the comments provided by independent reviewers and members of the Commission, TECTA was ranked as "Priority 1" in 2012. The voyage is therefore 100% funded by French governmental research funds, through Ifremer, as part of its mandate to manage and operate the French oceanographic fleet for the scientific community. The TECTA voyage is part of a collaborative international scientific program between France, New Caledonia, New Zealand, Australia.

Ifremer's research vessels are operated by Genavir, a maritime company that is a subsidiary of Ifremer, and linked to it within a "*Groupement d'Intérêt Economique et Sociale"*. Ifremer owns, and Genavir operates the research vessel R/V L'Atalante (Figure 2) used for this survey.

Figure 2 - Research Vessel L'Atalante

The research vessel R/V L'Atalante is well known in the southwest Pacific, as it has conducted several surveys in areas under New Caledonian, Australian and New Zealand jurisdiction, notably within the framework of extended continental shelf programs undertaken by the different coastal states within the framework of the United Nations Convention on the Law of the Sea (UNCLOS). In the waters of New Caledonia, L'Atalante has realized several of the Zoneco voyages, since the early 1990s, with the financial support of the *Agence de Développement Economique de la Nouvelle-Calédonie* (ADECAL).

2 Southwest Pacific geodynamic models and tectonic framework

The SW Pacific basin and ridge system is the result of the fragmentation of the Gondwana eastern margin mainly through a trench roll-back / backarc extension process (Cluzel et al., 2001; Crawford et al., 2002; Karig, 1971; Schellart et al., 2006; Symonds et al., 1996) resulting in the formation of successive backarc basins, continental fragments and remnant volcanic arcs (see structural provinces on Figure 3). During this fragmentation, a large continent fragment, named Zealandia, was isolated from Gondwana. Seismic refraction data collected on this submerged continent revealed the continental nature of the Lord Howe Rise and Norfolk Ridge, which has a present average crustal thicknesses of 25 km and acoustic wave propagation velocities of 6 km/s (Klingelhoefer et al., 2007).

Table 1 - Geological evolution of the Southwest Pacific described in terms of four main tectonic phases.

Age	Tectonic event	Evidence
Phase 1 : Permian to Cretaceous	Gondwana subduction	"Basement" geology of New Zealand, New Caledonia and Queensland (Collot et al., 2009; Mortimer, 2003; Mortimer et al., 2002; Mortimer et al., 2008; Mortimer et al., 1999; Sutherland, 1999)
Phase 2 : 100-50 Ma	Widespread extension phase	End of Gondwana subduction. Magnetic anomalies in the Tasman Sea. Widespread Cretaceous [100-80 Ma] normal faulting and subsidence onshore eastern Australia, New Zealand and New Caledonia and alkaline volcanics. (Cluzel et al., 2010; Cluzel et al., 2001; Cook et al., 1999; Gaina et al., 1998; Griffiths et al., 1972; Hayes Dennis et al., 1973; King et al., 1996; Laird, 1993; Nathan et al., 1986; Nicholson et al., 2000).
Phase 3 : 50-24 Ma	Compression, obduction, initiation of subduction	Allochthon emplacement in New Caledonia and New Zealand, and the onset of arc and backarc processes east of Norfolk Ridge (Aitchison et al., 1995; Aubouin, 1981; Auzende et al., 2000; Clarke et al., 1997; Cluzel et al., 2001; Collot et al., 1987; Dubois et al., 1973; Dubois et al., 1974; Kroenke, 1984; Meffre, 1995)
Phase 4: 24-0 Ma	Tonga-Kermadec subduction and backarc spreading	Arc rocks in Tonga-Kermadec, Lau Colville and Three Kings ridges. Magnetic anomalies in South Fiji, Norfolk, and Lau basins, confirmed by IODP leg 135 (Bonnardot et al., 2007; Ewart et al., 1977; Graham et al., 2008; Hawkins, 1995; Hawkins et al., 1984; McDougall et al., 1994; Parson et al., 1992; Smith et al., 2006; Taylor et al., 1996; Taylor et al., 2004)

Phase 1 is identified from basement geology in New Zealand, Queensland, New Caledonia and Mary Byrd Land, Antarctica, where the Gondwana subduction fore-arc and arc is identified (Mortimer et al., 2008). The easternmost limit of the forearc of this Mesozoic paleo-subduction zone lies in New Caledonia and along the Norfolk Ridge (Figure 3). Phase 1 is essentially related to the peri-Pacific subduction zone along Gondwana.

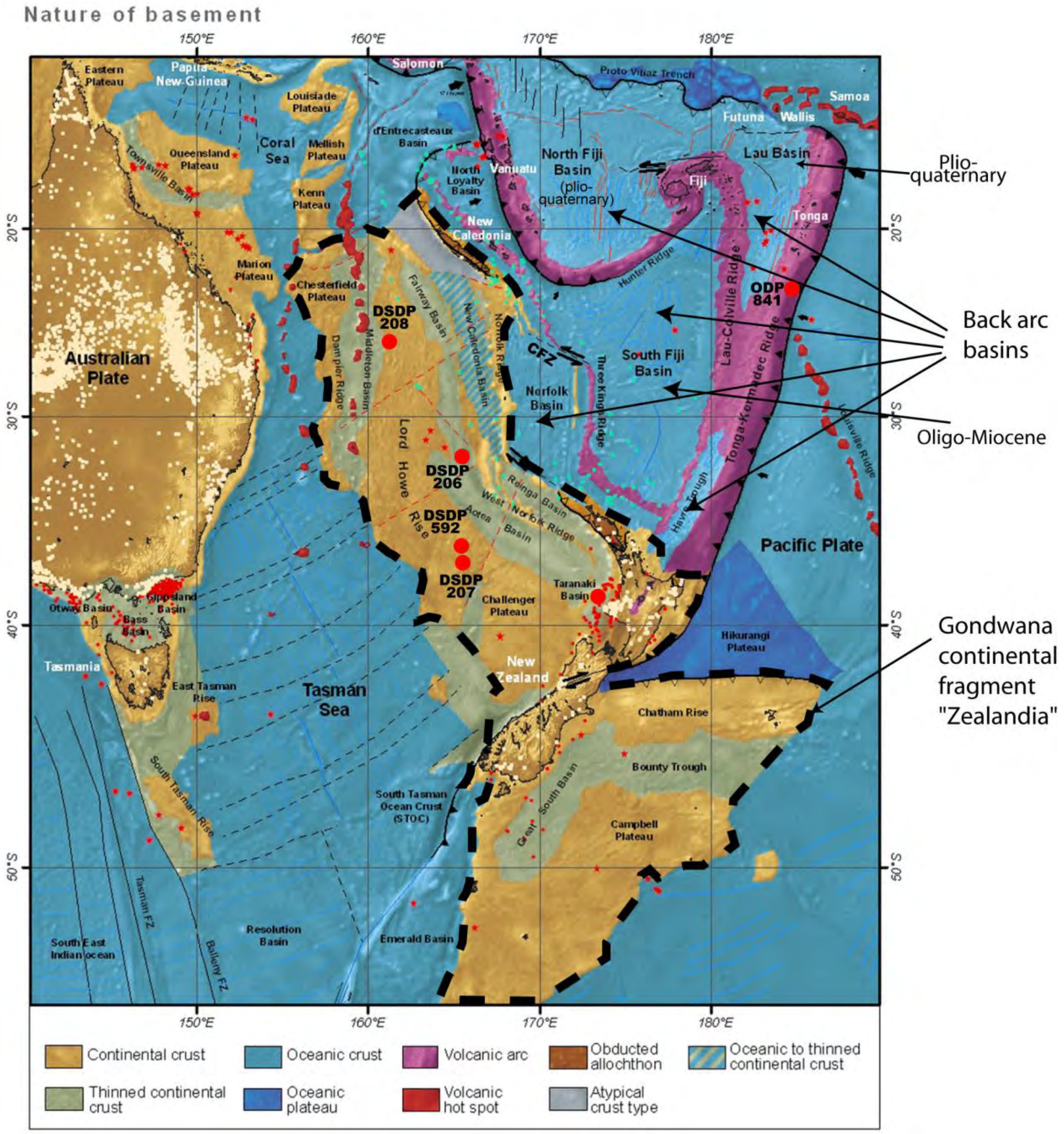

Figure 3 - Structural provinces of the Southwest Pacific (Collot et al., 2012). Red stars are DSDP/ODP wells, red circles are petroleum exploration wells and large red circles are wells usefull to this study. CFZ=Cook Fracture Zone

The extension phases (2 and 4) are constrained by magnetic anomalies, seafloor texture analyses and/or dredge/drill samples (Auzende, 1988; Cande et al., 2004; Gaina et al., 1998; Griffiths, 1971; Griffiths et al., 1972; Hayes Dennis et al., 1973; Mortimer, 1998; Mortimer et al., 2007; Sdrolias et al., 2003). The origin of phase 2 is related to the cessation of the Gondwana subduction during mid-Cretaceous and the break up of Gondwana materialized in the southwest Pacific by the rifting which preceded the seafloor spreading of the Tasman Sea and the South East Indian Ocean. This is supported by the youngest Gondwana arc rocks found in New Zealand (Mortimer, 2003; Mortimer et al., 2008; Mortimer et al., 1999), the end of convergence between the Gondwana and Pacific plates according to (Müller et al., 2000) and the arrival of the Hikurangi Plateau in the subduction zone (Collot et al., 2009; Davy et al., 2008).

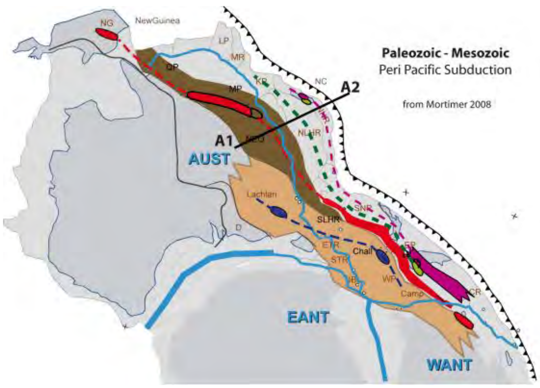

Figure 4 - Permian - mid Cretaceous subduction zone along the Gondwana Margin modified after [Mortimer et al., 2008] - In red, the Median batholith (Gondwana continental arc) - In green, the Brookstreet-Teremba terrane (forearc sediments) - In pink, the Otago Schist - Boghen terrane (forearc exhumed prism)

The origin of the compression phase (3) is subject to much debate because there is a lack of marine ground truth data and there have been only sparsely separated studies of the submarine structures associated with this event. Geological observations used to constrain the models during phase 3 are limited to allochthonous outcrops in New Caledonia and northern New Zealand. These onshore structures indicate an emplacement event that is thought to mark the local resumption of convergence in the Southwest Pacific during Eocene time (Aitchison et al., 1995; Cluzel et al., 2006; Gurnis et al., 2004; Müller et al., 2000). These observations led to plate reconstruction models that involve two subduction zones: (i) the west-dipping Tonga Kermadec subduction zone that migrates towards the east since late Cretaceous; and (ii) a short-lived NE-dipping subduction zone that migrates towards the west during Eocene. According to these models, the origin of the compression phase is related to the arrival of the Norfolk Ridge in this short-lived subduction zone. However, no volcanic arc rocks nor arc-products of any kind related to this short lived Eocene subduction have ever been found (one objective of the VESPA proposal).

It is widely accepted that the Tonga-Kermadec subduction zone led to the opening of the South Fiji (Oligocene) and Lau (Plio-Quaternary) basins in back arc positions, as the trench retreated by slab roll-back (Figure 3, Figure 5), see (Schellart et al., 2006) for synthesis. The age of Tonga-Kermadec subduction initiation is constrained through a study of the Tonga forearc (Bloomer et al., 1995) and the oldest rocks dated in ODP 841 drill hole cluster around 45 Ma, with the oldest being 46 Ma (McDougall et al., 1994). A similar age range has been found from 'Eua, an island on the Tonga platform (Duncan et al., 1985). The uniquely-precise determinations of regional plate kinematics at this age reveals that the Australia-Pacific plate boundary was located along the Norfolk Ridge and that this plate boundary underwent 150 km of convergence (Gurnis et al., 2004). These data led Sterna and Bloomer (1992), Hall (2003) and Gurnis et al. (2004) to suggest that the present-day Tonga Kermadec subduction zone initiated along the Norfolk Ridge during Eocene time (cf. Figure 5b). This is consistent with the fact that the Lord Howe Rise and Norfolk Ridge lie at the former Gondwana subduction front which ceased during mid-Cretaceous according to (Collot et al., 2009; Davy et al., 2008; Mortimer et al., 2008; Müller et al., 2000).

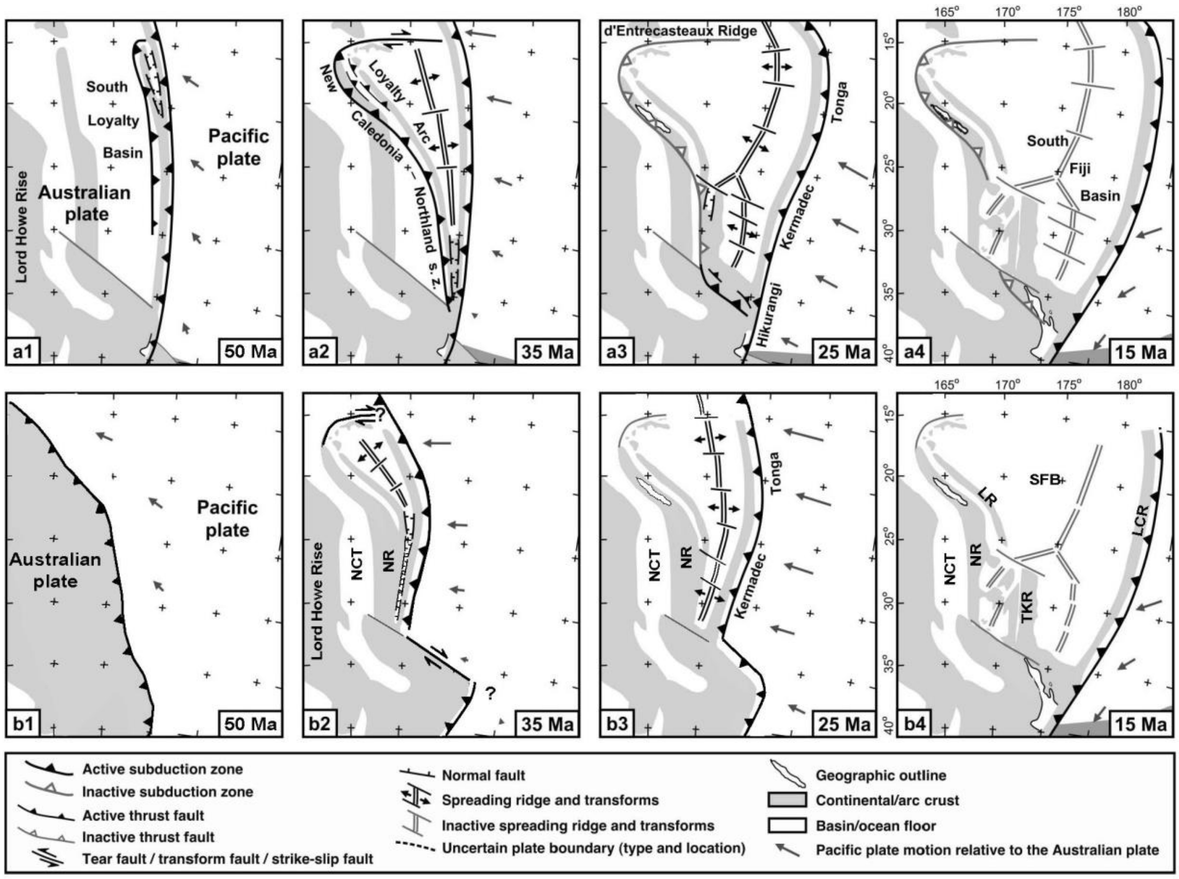

Figure 5 - Two different schematic reconstructions of the Tonga–Kermadec subduction zone from 50 Ma to the present. (a) Reconstruction with two subduction zones, namely a west-dipping Tonga–Kermadec subduction zone and a northeast-dipping subduction zone. (b) Reconstruction with one west-dipping Tonga–Kermadec subduction zone initiated along the Norfolk Ridge. Figure modified from [Schellart and Spakman, 2012].

Finding traces of an Eocene arc and understanding its origin is an objective of the VESPA voyage which will dredge the Norfolk and Loyalty ridges in particular locations where the ridges have been cut and exposed by the Cook Fracture Zone.

In summary, there exists strong geological and geodynamical evidence that the present-day Tonga-Kermadec subduction initiated during Eocene time near the eastern edge of Norfolk Ridge and was followed by rapid roll-back and back arc basin formation. The TECTA voyage aims at contributing to the understanding of the processes which led to the initiation of this subduction zone by investigating the upper plate of where subduction initiated (i.e. Norfolk Ridge, New Caledonia Trough and Lord Howe Rise).

3 TECTA Voyage Overview

3.1 Introduction

After a day of mobilization in Nouméa on 2nd September 2015, R/V L'Atalante left port at 21 hours on 2nd September 2015 UTC for a 36 day voyage with on its board 19 scientists, 11 technical staff and 24 crew members (see Appendix 2 for details).
Magnetometer, multibeam EM122, sub-bottom profiler (echo-sounder) and other acoustic instruments (ACDP, fishing echo-sounder) were deployed and turned on once out of the lagoon through the Passe de Dumbéa at 22:30 UTC. Deployment of the seismic streamer and source took 5 hours and profile TEC001 started at 08:20 UTC on the 3rd of September. TECTA investigated the New Caledonia Trough, Norfolk Ridge, Fairway Basin, Lord Howe Rise and West Norfolk Ridge between 22°S and 33°S, and 163°E and 169°E (see navigation on Figure 6). Because of a medical emergency on 15th September at 23h30 UTC, L'Atalante returned towards Nouméa and the 16th September at 21h50 UTC the injured member of the crew was evacuated by helicopter. Seismic acquisition restarted on 17th September at 20h54 UTC.
On 7th October at 20:00 UTC, the last acquisition profile, TEC032, was terminated and after a 37 hour transit the vessel returned to Noumea at 09:00 UTC on 9th October.
We were unable to collect the originally planned profiles south of DSDP206. This change was due to delays in the acquisition related to: technical issues (e.g. many air-gun source failures), marine mammal shutdowns, and poor actual and forecasted weather conditions (particularly when we reached the southern region).

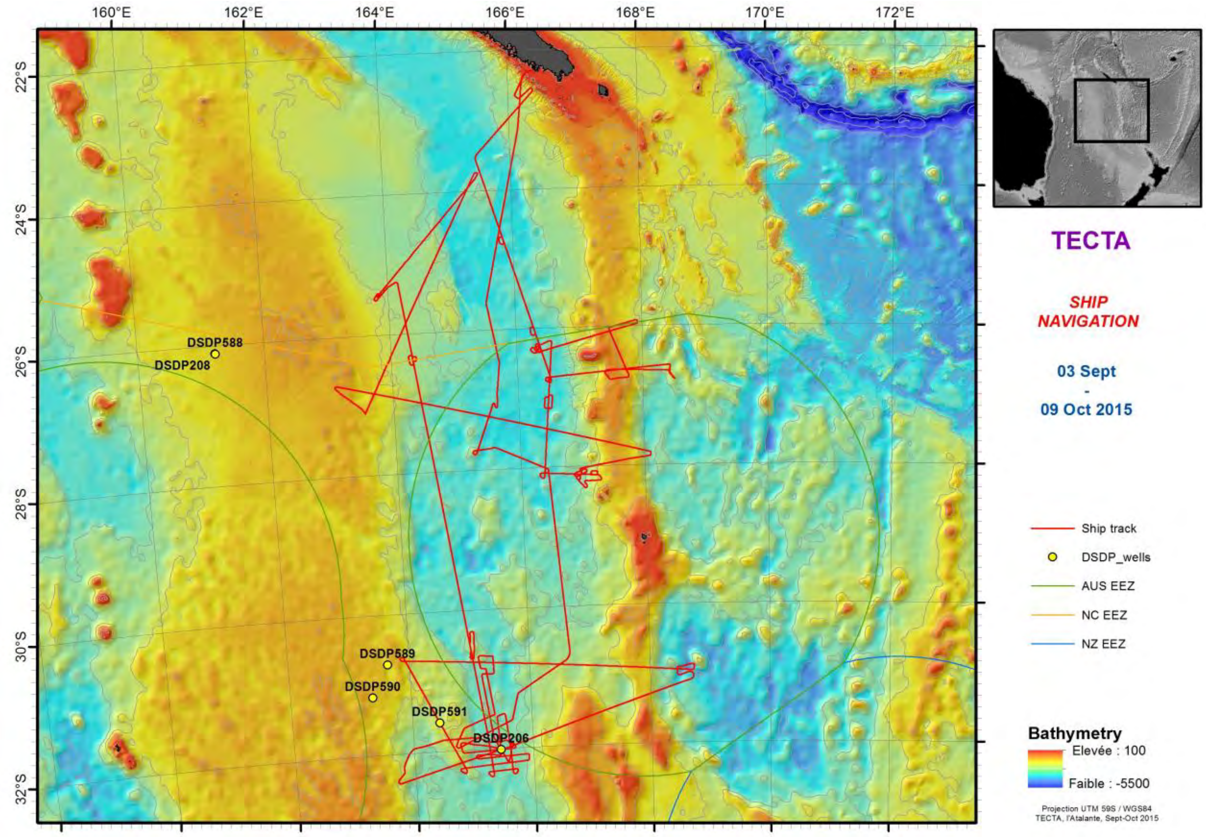

Figure 6 - Map of the navigation of TECTA

3.2 Multi-beam echo sounder EM122

Multi-beam echo sounder EM122 was set to record bathymetry, backscatter and full water column signal and recorded data during the entire length of the voyage. Data were processed onboard using Caraibes software. A total of 71,000 km^2 of swath bathymetry was acquired.

3.3 Sub-bottom Profiler (CHIRP)

The sub-bottom profiler (SBP) recorded data during the entire length of the voyage. Because of interference between the SBP and the multibeam echosounder, the SBP was synchronized to the multibeam ping rate, which increased the inter-ping time interval. To test the effect of the SBP on the multibeam data and to see the difference in quality of the SBP data at different inter-ping times, we tried de-synchronizing the SBP. This mode was tested along profile TEC001. It was then set as synchronized during the entire rest of the voyage except between profile TEC006 ping 5984 and the start of profile TEC008, when passing on proposed IODP 832 NCTN sites. Data were processed onboard using the Subop software. A total of 8400 km of profiles were recorded.

3.4 Multi-channel seismic Data (MCS)

The TECTA voyage was designed to image the sedimentary records of the Tonga Kermadec subduction initiation in the northern sector of Zealandia. For this, key profiles were positioned and the choice of the seismic equipment was such as to allow imaging the entire sedimentary column, reaching in some places more than 5 km in thickness. MCS data acquisition was the primary goal of the voyage.

Seismic data acquisition was discontinuous because of shutdowns related to marine mammal observations in the exclusion zones (see mitigation protocol section for more details), maintenance of seismic equipment, bad weather conditions, and transits (includes evacuation of an injured member of the crew). Appendix 1 provides the details of the duration of the operations; Table 2 summarizes these durations and Figure 7 illustrates them. 68% of the total time of the voyage was dedicated to seismic data acquisition, 6% of the time was occupied by marine mammal detection related shutdowns, 10% by maintenance of seismic equipment. Transits represent 8% of the time whereas weather downtime amounted to 7%. It is important to note that during all these phases, the other instruments – with the exception of the magnetometer - were recording.

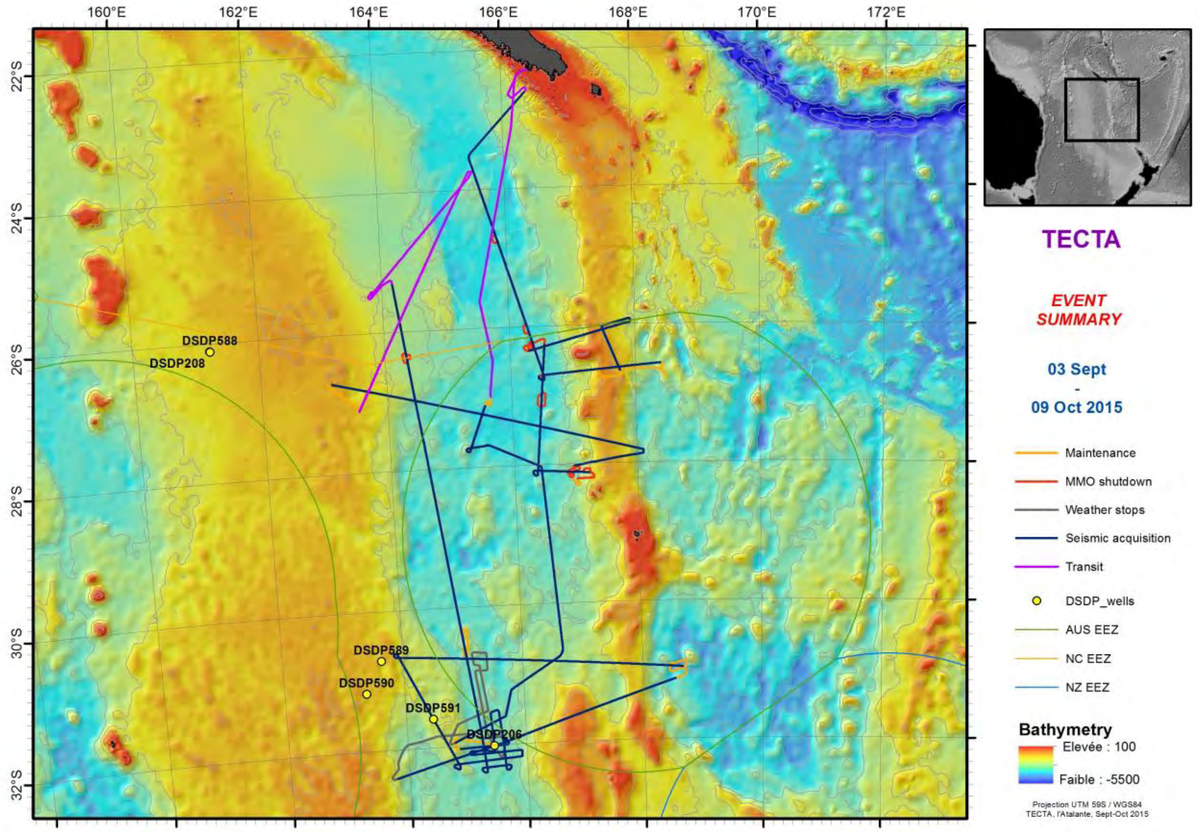

Figure 7 - Map of operations during TECTA voyage

Duration	Seismic acquisition	Marine mammal related shutdowns	Maintenance	Transits	Weather standby	TOTAL
TOTAL (hours)	588:27:19	54:29:01	82:51:08	71:36:00	64:16:00	861:39:27
TOTAL (days)	24,52	2,27	3,45	2,98	2,68	35,90
Percentage	68,29	6,32	9,62	8,31	7,46	100,00

Table 2 - Summary of operations. Duration of shutdowns, maintenance, weather standby and transits, including pre-watch and ramp-ups times.

Post-stack time-migrated sections were produced onboard using Ifremer's SolidQC, CGG Geocluster, Seismic Unix and Globe Claritas. A total of 5200 km of MCS profiles were collected. All final SEGY EBCDIC headers are documented. Figure 8 and Figure 9 show the location of seismic profiles.

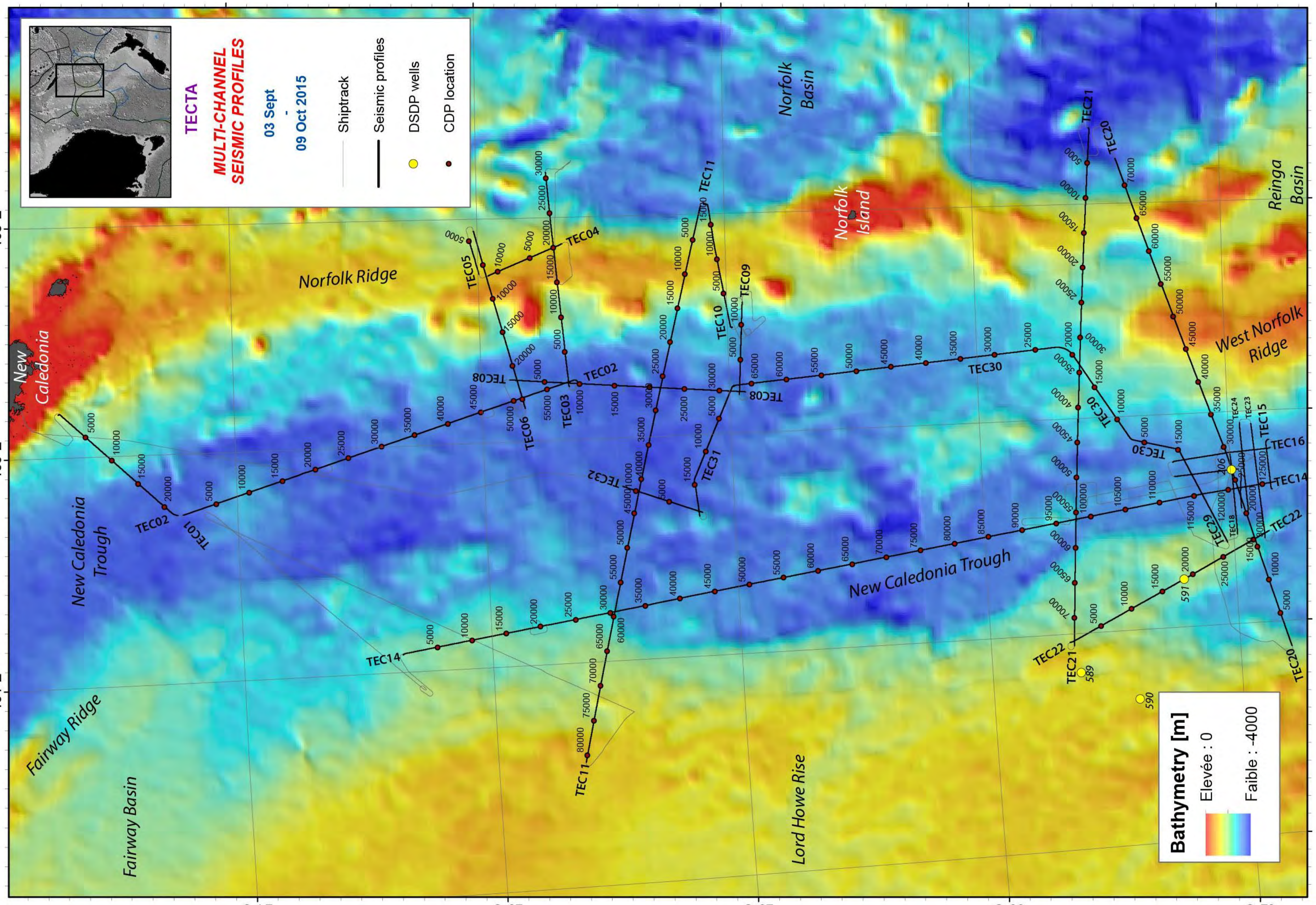

Figure 8 - MCS seismic acquisition location map. See Figure 9 for location map around DSDP 206

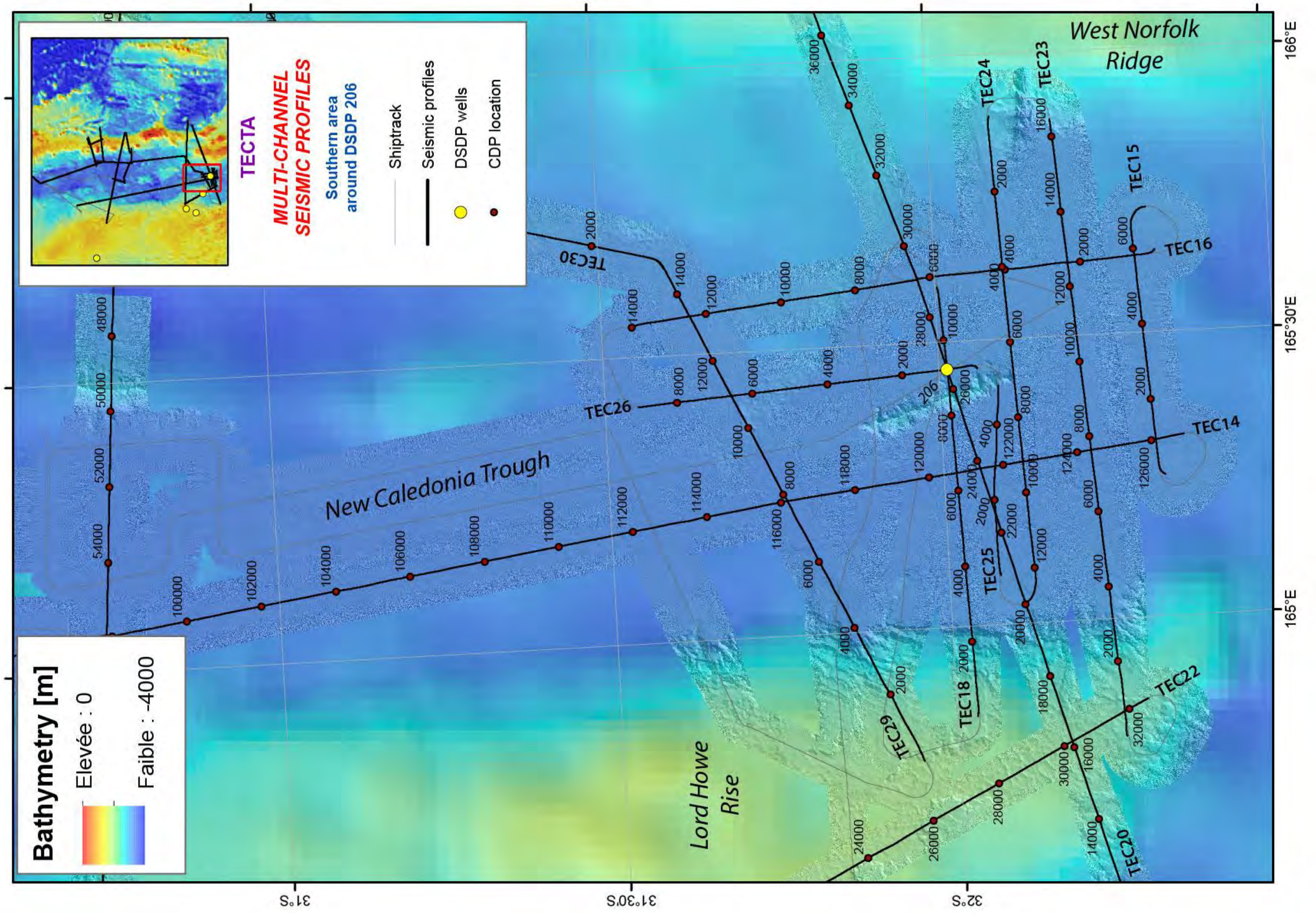

Figure 9 - MCS seismic acquisition location map around DSDP 206

3.5 Magnetic data

The magnetometer was towed 50 m behind the seismic streamer tail buoy, so magnetic data were recorded only when the streamer was deployed. Furthermore, connection problems with the magnetometer prevented acquiring data along profiles TEC01, TEC02 and TEC03.

3.6 Environmental Data

In order to understand the potential impact of seismic sources on marine mammals, an impact study was conducted prior to the voyage. In order to limit potential impacts, strict protocols were followed during the seismic acquisition. These are detailed in paragraph 4.6 and were implemented by 5 independent observers from ULR Valor: 3 Marine Mammal Observers (MMO) and 2 Passive Acoustic Monitoring (PAM) operators. Instruments recording environmental data were also turned on during the voyage. Wild life and basic environmental data are hence briefly presented in this report. 78 detections of marine mammals were reported during the voyage. 61 of them were PAM detections and 17 were MMO sightings. 16 observations led to mitigation actions, from which 4 were MMO sightings and 12 PAM detections.

4 Data Acquisition and processing

4.1 Navigation and GIS

Navigation of the ship was tracked in real-time using navigation files provided by the Genavir operator. File conversion was performed following specific procedures for each of the acquisition instruments. Navigation maps were created to precisely monitor the ship track as well as all recorded data (i.e. multibeam echosounder, SBP, MCS, etc.).

Figure 10 is an example of a detailed navigation map around the Norfolk Ridge area, in which date and hour marks are plotted. The map shows the different loops at profile ends or within profiles, some of which are related to marine mammal shutdowns.

All maps produced during and after the TECTA voyage used a WGS84 reference ellipsoid and a UTM projection (zone 59S).

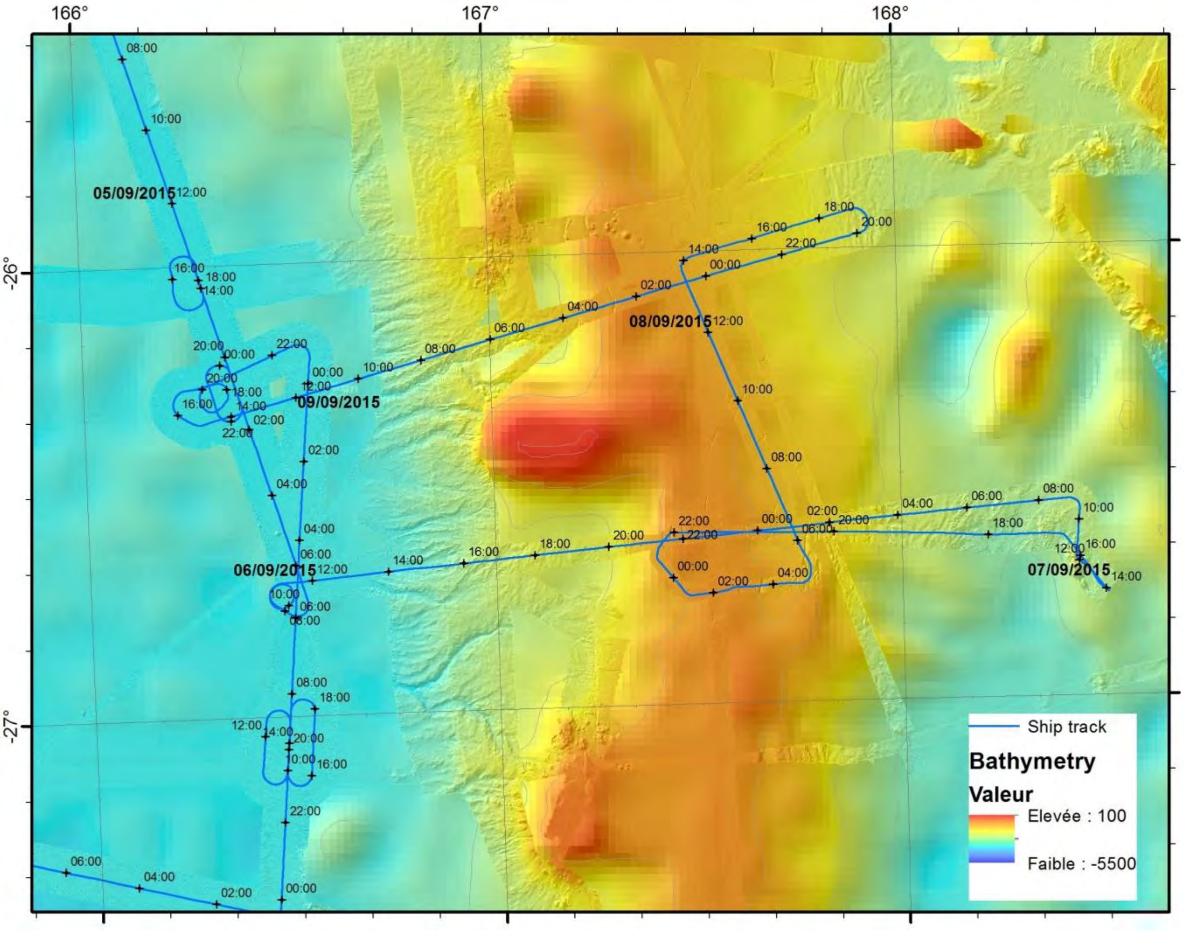

Figure 10 - Example of detailed navigation map of the TECTA voyage, Norfolk Ridge area

4.1.1 GIS STRUCTURE

GIS work was undertaken exclusively with the ArcGIS 10.2 software, with its “spatial analyst and “3D analyst” extensions. All GIS related materials were stored during the voyage within the “science” drive of the onboard network, divided into the following folders (see Figure 11):

- The preparation of operations, ie. working GIS project which notably contains the provisional navigation route of the voyage: PREVI_TECTA
- All relevant, geolocalised data for the survey area: DONNEES_SIG_SW_PAC
- The GIS database of the TECTA voyage, which contains all newly acquired geographical data and which forms the basis for the post-voyage finalized GIS: SIG_TECTA
- Finalized maps for the voyage report: REPORT_MAPS
- Useful documentation and tools such as ArcGIS supplementary toolboxes: Outils
- A folder for personal projects: Users.

All newly acquired data from the TECTA voyage were converted to GIS format and are organized as follows:

- Donnees_Source contains all raw data directly coming from processing tools (e.g. .nvi or .txt files for navigations, .flt files for multibeam data.
- SIG comprises all finalized geographical layers of the voyage such as complete navigation files (.shp), bathymetrical/backscatter grids (rasters), MCS and CHIRP seismic profiles with CDP/SP numbers (.shp) and Sippican shots positions (.shp).

Figure 11 - Organization of the onboard GIS working area and final GIS project for the TECTA voyage.

4.2 *Simrad EM122 Multi-beam Echo Sounder*

4.2.1 Introduction

The multi-beam echo sounder Simrad EM122 (see Appendix 3.2) was in continuous operation during the voyage. EM122 data were acquired at speeds between 4.5 and 5 knots along the seismic profiles and at speeds of up to 11.5 / 12 knots during transits. Given the water depths in most of the study area, the echo sounder was operated mainly in "deep" mode. In addition to bathymetric data, the EM122 multi-beam echo sounder collected backscatter imagery, and acoustics within the water column.

The "very deep" mode was not used during the voyage. In addition, the FM mode was disabled most of the time because a better quality for the outermost beams was preferred rather than a wider swath. Differential GPS was the positioning system used for multi-beam acquisition.

XBT probes (Sippican) were deployed regularly throughout the voyage (see Appendix 1.3 for a table with the position of all XBT launches). They enable determination of the sound velocity profile of the water column and are used during the processing of the multi-beam data. Figure 12 shows the location of the deployed XBT probes and the area covered by multibeam data.

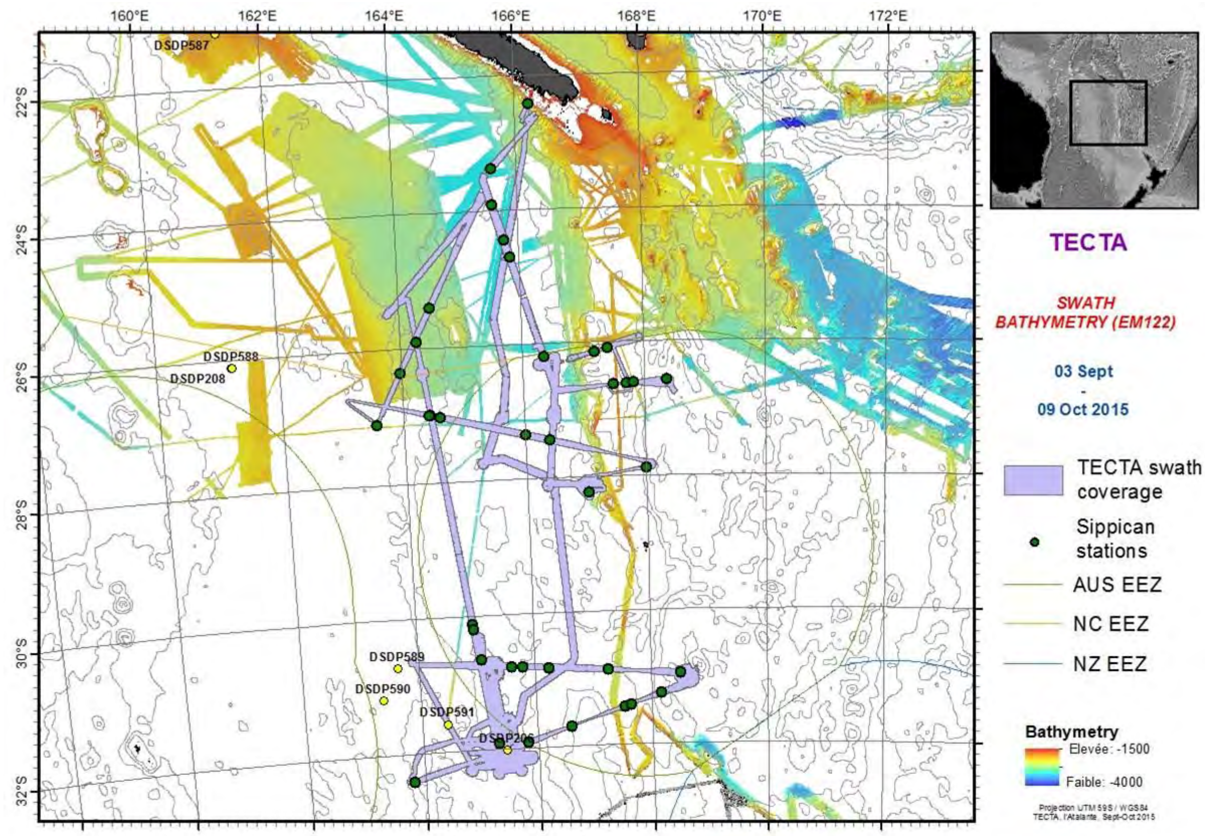

Figure 12 – Map showing the location of deployment of XBT probes, TECTA swath coverage and existing swath data.

4.2.2 Multi-beam Bathymetry

The acquired bathymetric data are of good quality. The generally good sea state contributed to this quality. However, as the survey covered an area with significant north-south extent and subject to ocean currents, seawater temperature sometimes changed quite rapidly. Particular attention was paid to use the correct sound velocity profile. Also, during acquisition of bathymetric data in areas characterized by a very flat seafloor, significant noise was detected on the outer beams. This issue is discussed later in this chapter.

The Seafloor Information System (SIS) developed by Kongsberg allows the visualization of a variety of parameters related to the acquisition of the EM122 multi-beam echo sounder. Figure 13 gives an example of the real-time tracking. The left panel shows the different parameters related to the acquisition. Also shown is a vertical cross-section of one entire cycle, including the water column and an image of the backscatter. The depth, as determined by the central beam of the system is displayed on the left hand side, on top of the transverse bathymetric profile determined by this particular cycle. On the right panel, a 3D view of the bathymetry is presented, showing the data collected during the last approximately 20 minutes. In this particular image, taken on the eastern flank of the Norfolk Ridge, one can observe sediment waves that are parallel to the isobaths and also parallel to the ship track. Red colors represent shallower bathymetry, and blue colors the deeper parts.

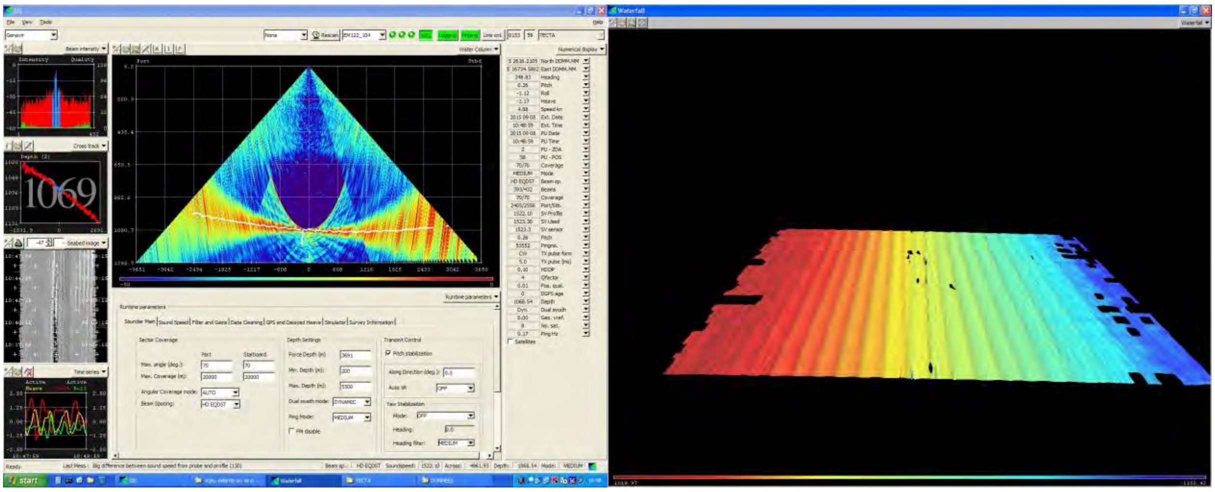

Figure 13 – Screen shot of the SIS acquisition visualization system, showing real time images of the multi-beam echo sounder data acquired by the EM122 system. Sediment waves are visible in this image.

The EM122 data processing was carried out with the Caraïbes 4.3 software of Ifremer.
Regional Digital Terrain Models (DTM) were created with a mesh of 50 m. A 25 m mesh was used for particular targets.

4.2.2.1 Multi-beam Quality Control

As mentioned above, significant noise was detected on the outer beams, in areas that were flat, and at water depths around 2800 m or deeper. Crossings between different profiles were used to quantify the problem (Figure 14).

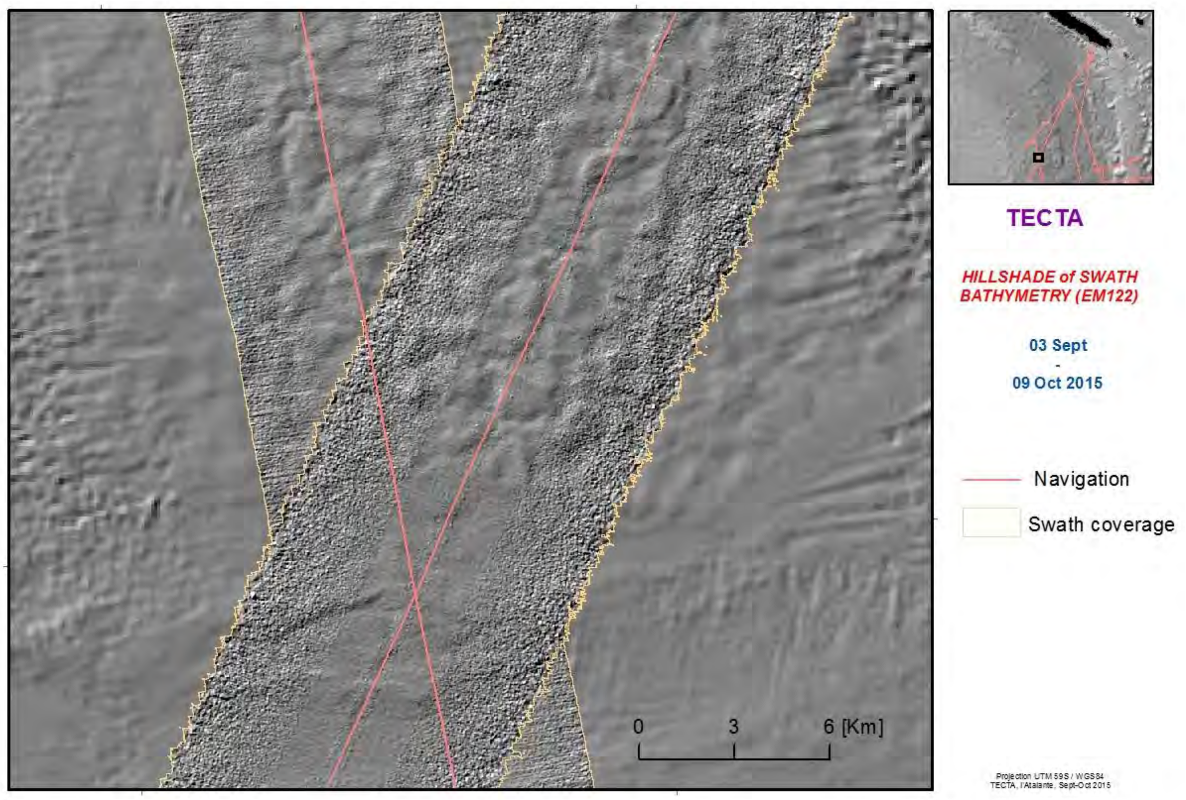

Figure 14 – Crossing of bathymetric profiles revealing noisy outer beams. Background is EM12 data from Zoneco05 voyage (1999).

Furthermore, the data is also being tested at the crossing of different profiles to ensure that no bias is present in the data.

4.2.2.2 Bathymetric Data Processing

The multi-beam data are recorded in a native file format with the filename extension .all. These .all files are converted to bathymetry files (.MBG) and navigation (.nvi) in the format of Caraïbes, the Ifremer software package for processing and presentation of marine geophysical data. The sound velocity profiles are also imported (.vel). The longer profiles are usually cut in sections of shorter duration. Since the use of the multi-channel seismic system limits turning rates of the vessel at 3° per minute, we decided to also process the bathymetric data collected during the turns.

Bathymetry data were systematically processed as follows:

· Import in the Caraïbes software,
· Cutting files,

· Automatic filtering. This method is based on the comparison of each sounding with its neighbors (filtri module),
· Manual Invalidation aberrant soundings (Odicce module),
· Grid data to construct DTMs with a mesh of 50 and 25 m.

4.2.2.3 Illustrations

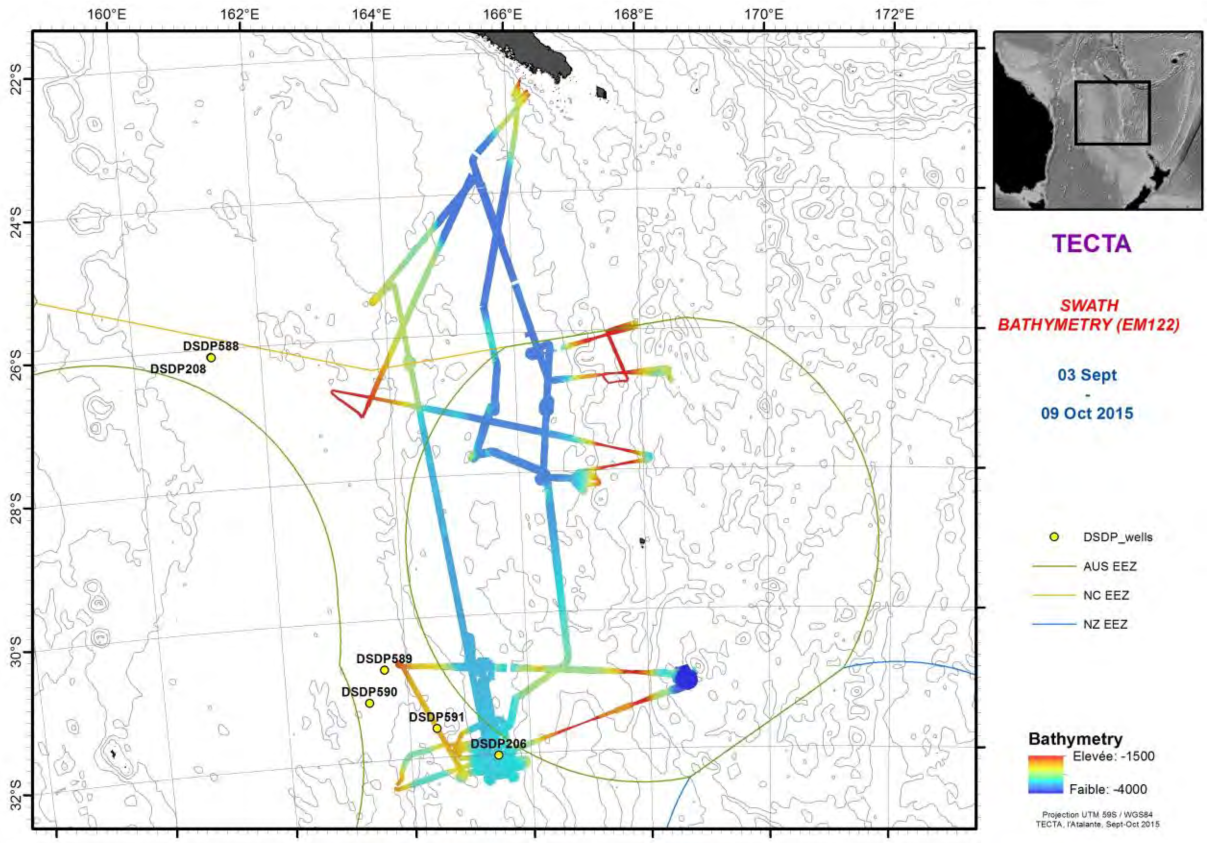

Figure 15 - General view of bathymetry acquired during the TECTA voyage

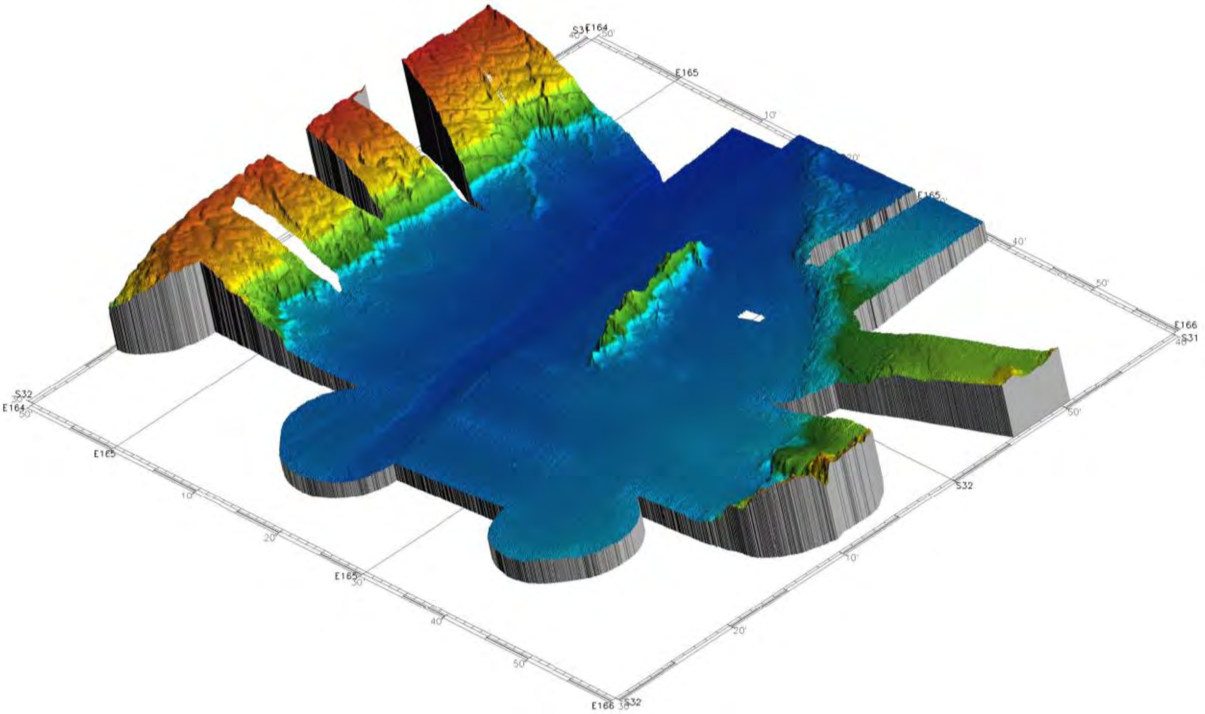

Figure 16 – 3D view of bathymetric data in the New Caledonia Trough around DSDP 206, which was drilled on the ridge that is located in the center of the basin

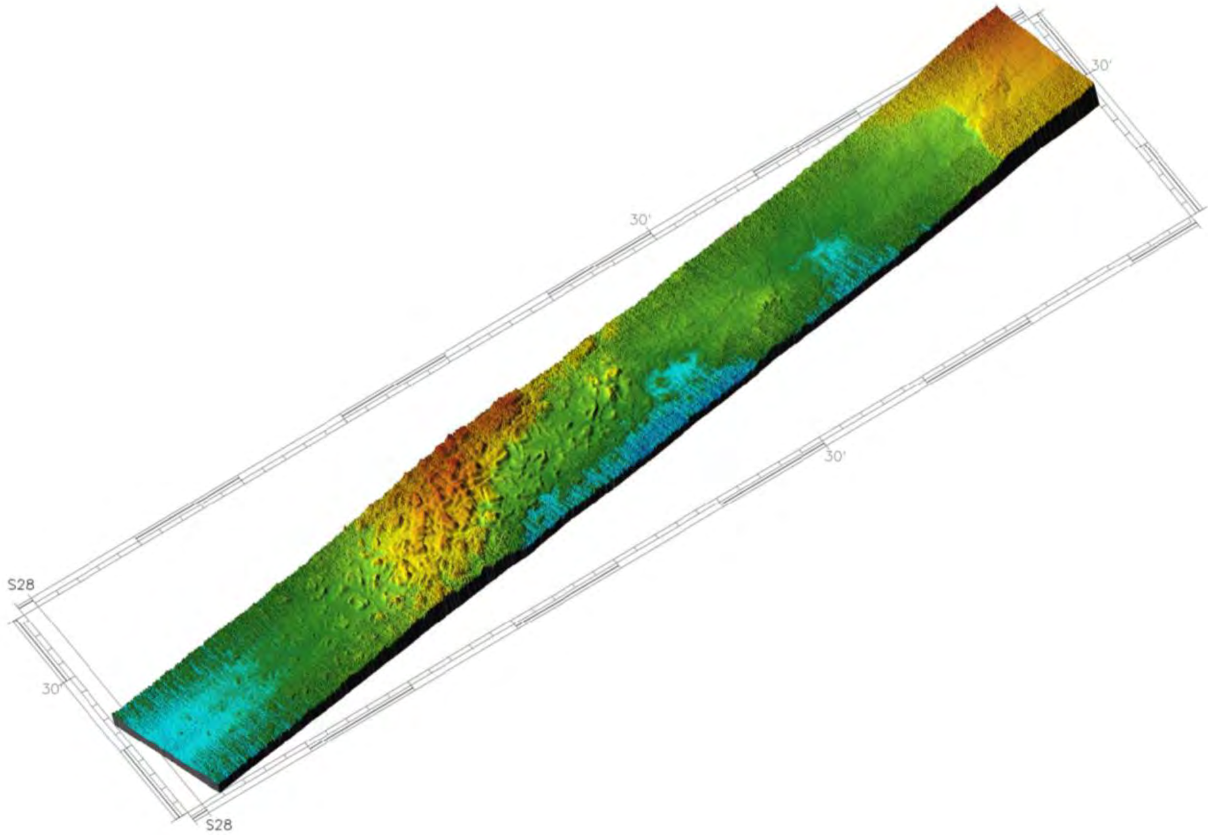

Figure 17 – 3D bathymetric view along profile TEC014. Polygonal faults on the flanks of the Lord Howe Rise.

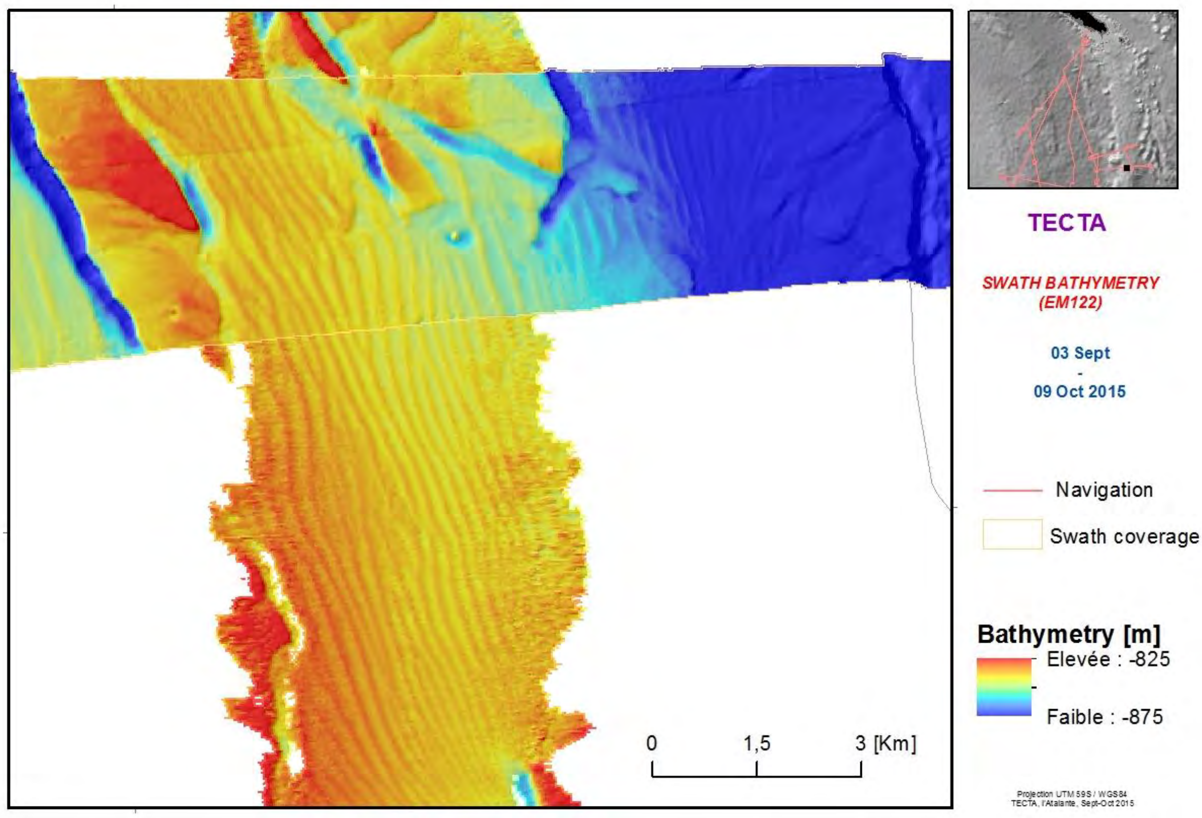

Figure 18 – Sediment waves on the crest of the Norfolk Ridge with a wavelength of about 200 m and heights up to 10 m. Data from both the TECTA and VESPA voyages.

4.2.3 Acoustic Backscatter Imagery

The multi-beam data are recorded in a native file format with the filename extension .all. These .all files are converted to imagery files and navigation (.nvi) in the format of Caraïbes, the Ifremer software package for processing and presentation of marine geophysical data. The longer profiles are usually split into of sections of shorter duration. The data were processed along rectilinear profiles. The turns were not processed. Finally, the image files were combined in a mosaic (.mos).

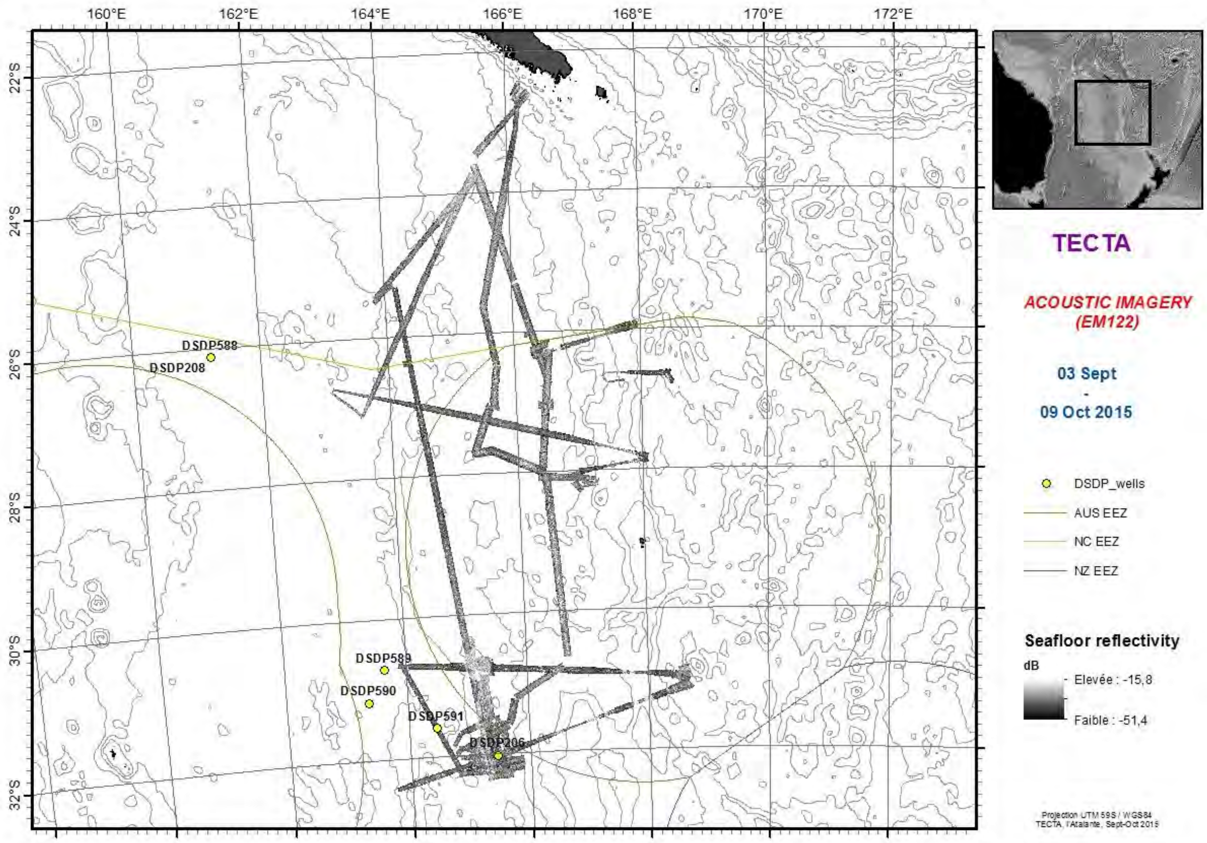

Figure 19 Acoustic imagery data acquired during the TECTA voyage

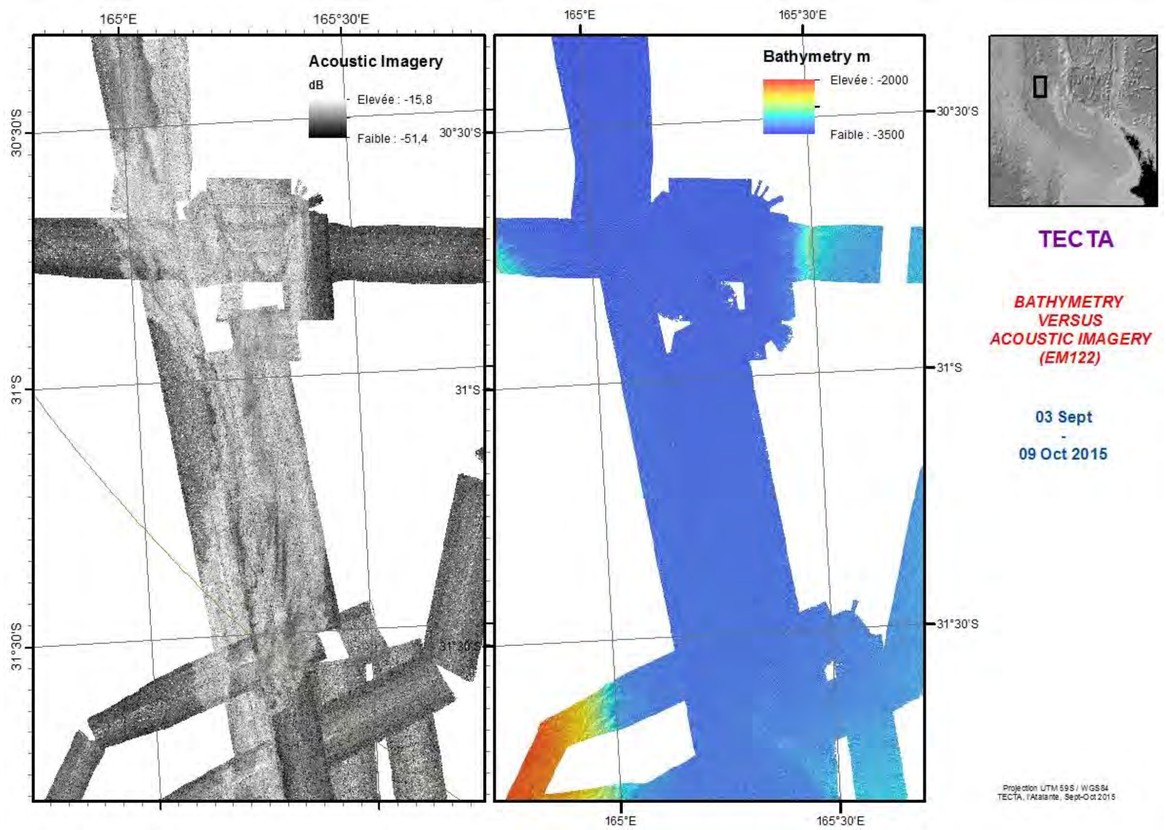

Figure 20 – Example of acoustic imagery data, central New Caledonia Trough. Deepwater sedimentary features are distinguishable on acoustic imagery where bathymetry data reveals a flat sea bottom.

4.2.4 Water Column Data

During the entire length of the voyage, the multi-beam EM122 system was set to record full water column data. These were recorded in .wcd files but were not processed nor interpreted during the voyage.

4.3 Multi-channel Seismics

4.3.1 Acquisition parameters

4.3.1.1 Seismic streamer

Seismic acquisition was carried out using a Sercel SSRD 4.5 km long solid streamer with 720 channels (6.25 m inter-channel distance) towed at nominal 7 m depth (Figure 21). The near offset was 110 m. Data were collected with a 2 ms sampling rate and a 15 second record-length. A full description of the streamer can be found in Appendix 3.3.3.

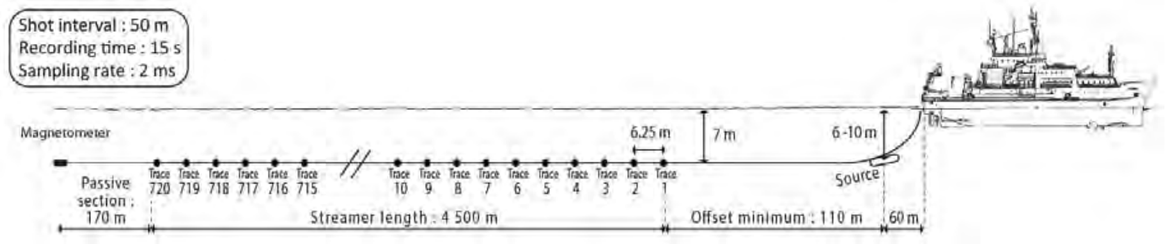

Figure 21 – Simplified illustration of the seismic acquisition system

4.3.1.2 Seismic sources

The nominal source used during TECTA was a 2690 cu array of 18 air guns (12 active and 6 spare) towed between 6 and 10 m depths, at 60 m behind the ship and synchronized on the first peak. Figure 22 shows the configuration of the array. Source characteristics (modelled source signature and spectrum) are detailed in Appendix 1.1.3.

The intershot distance was set at 50 m. Depending on the exact speed of of the ship relative to seafloor (around 5 Kt), inter-shot time was around 19.4 s. Three Hamworthy compressors supplied 140 bar compressed air (1200 cu/hour).

More details on the seismic source can be found in Appendix 1.1.2.

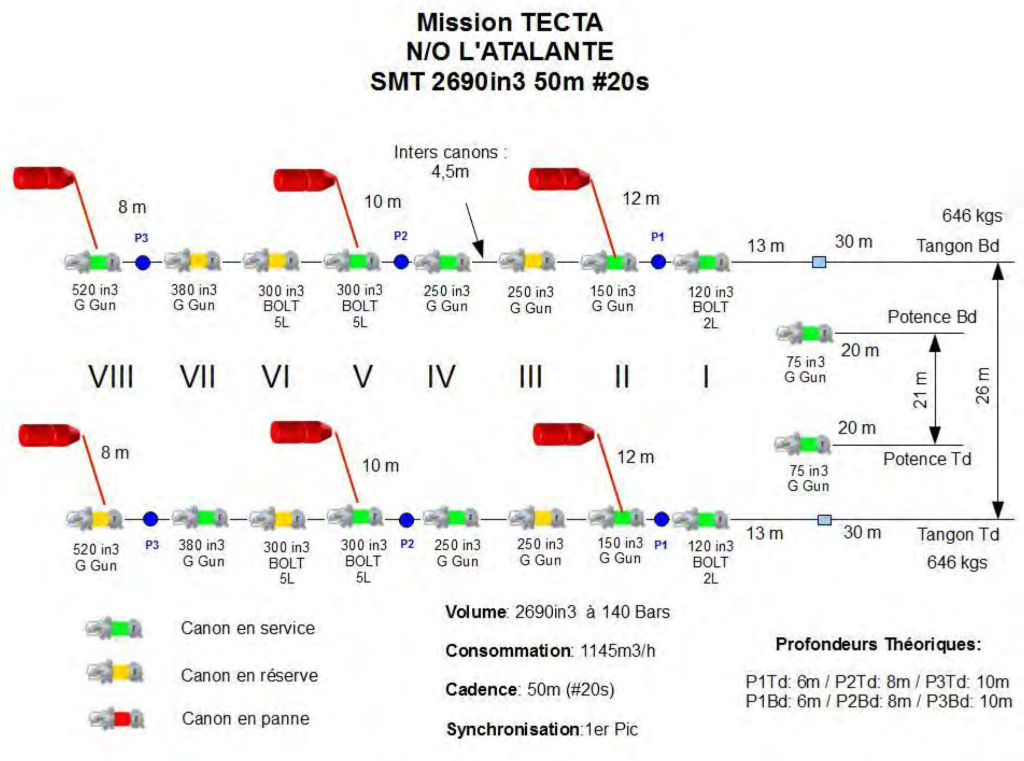

Figure 22 – TECTA nominal source array

In response to technical failure of air guns (broken or cracked piston heads and torn flexible hoses), spare air guns were immediately activated. Pictures of broken and cracked piston heads are shown in Appendix 1.1.2. Due to these technical problems, the volume of the source varied between the nominal value of 2690 cu and a minimum of 1790 cu. Table 2 in Appendix 1.1.2 details the evolution of the source volume throughout the voyage. The modelled source signatures for each secondary source can be found in Appendix 1.1.3.

A ramp-up procedure was applied during the voyage to avoid impact on marine mammals. For more details on mitigation procedures, see paragraph 4.6.2 and Table 5 which details the ramp-up.

4.3.2 Processing

Multichannel seismic data collected during the TECTA voyage were processed from raw shot data into preliminary migrated stacks while at sea. The onboard seismic data processing produced stacked and migrated data suitable for integration with the Tasman Frontier regional seismic database (Sutherland et al., 2012) and importation into interpretation software. Onboard processing of data into stacked sections allowed an extra level of data quality control during acquisition. Furthermore, onboard processing and interpretation of newly acquired data enabled us to revise the remaining seismic acquisition plan accordingly, and provided confidence that the survey goals would be met with the data acquired.

The onboard processing sequence was done in three steps, carried out with different software packages:

1. Pre-processing: Solid-QC was used for initial quality control, calculating the geometry, and CDP binning, and writing out shot gathers in SEGY format with geometry and additional survey parameters stored in the headers. A basic, migrated, and stacked seismic section was produced at this step for QC purposes.
2. Processing: More detailed processing was performed using CGG Geocluster ®. The software was used for high resolution velocity analysis of the CDP sorted data, using semblance. The output from this step was a stacked seismic section with improved resolution derived from accurate velocity and mute picking, filtering, deconvolution, and multiple suppression.
3. Post-stack processing: This includes post-stack migration of the stacked seismic data (Claritas or Seismic Unix) and conversion of trace location headers from geographical latitude and longitude to UTM coordinates (python obsPy and proj packages).

All trace header information and SEG formats are documented in Appendix 3.3.6.

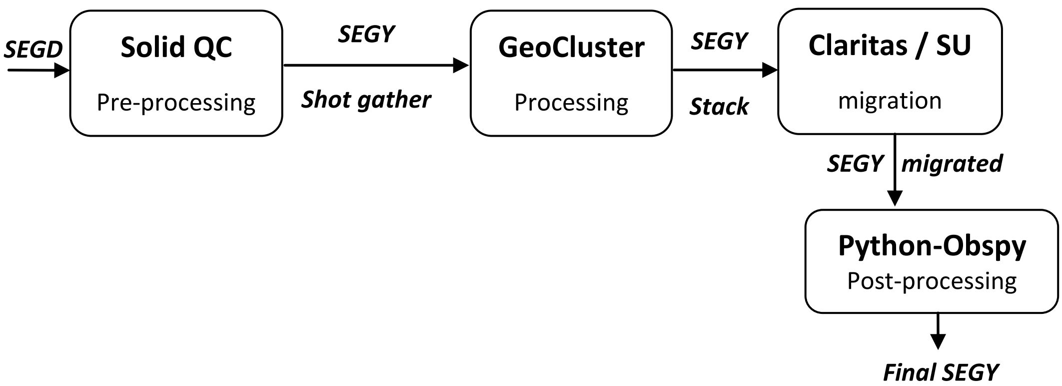

Figure 23 - Summary of seismic processing sequence

4.3.2.1 Solid-QC pre-processing

Solid-QC was developed by IFREMER to read, format and process SEGD data recorded using the Genavir seismic acquisition system into SEGY format shot gathers, and initial stacked sections. Navigation information from the ships GPS positioning system is written into the headers of the SEGD data files during acquisition.

The main processing steps carried out using Solid-QC are described below and shown in the flow diagrams in Figure 24, and in figures in Appendix 3.3.5. The input files are survey geometry files (created by Solid-QC) and SEGD data with ship navigation information in the headers (see Appendix 3.3.6 for details). The output files are post-stack migrated sections with constant velocity and a shot gather SEGY file with, shot, receiver and CDP bin positions written into the headers.

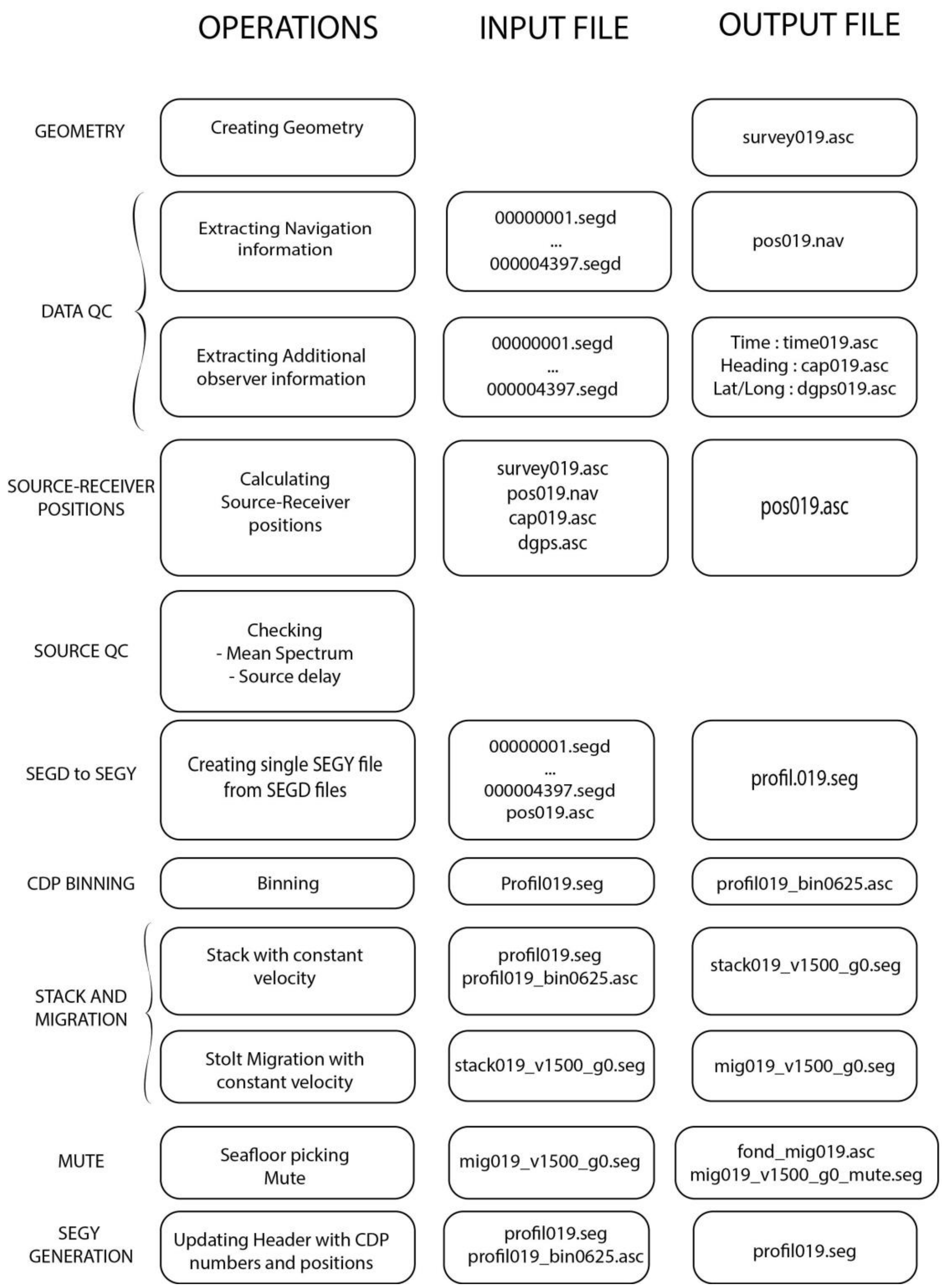

Figure 24 - Processing steps in Solid QC-, input and output files generated.

Geometry

Shot and receiver geometry are entered using the user interface in Solid-QC. Basic survey geometry, including geophone spacing, shot offset to the streamer and the number of recording channels, is exported to a survey file named *surveyXXX.asc*.

Data QC

A position file named *posXXX.nav* is created by extracting navigation informationfrom the shot gather SEGD data files: Date, Time, Latitude and Longitude of the shot points. The number of shots, position and time of the first and last shots are displayed. The software also checks that all the SEGD files are of the correct length (e.g., not truncated). Additional observer information is extracted from the SEGD to create three further parameter files:

- A time file (*timeXXX.asc*) which has shot positions and times and is used to check the shot spacing (see Appendix 3.3.5),
- A bird heading file which is used to calculate the streamer position for each shot (*capXXX.asc*) and,
- A GPS file which contains the recorded ship positions, and can be smoothed to remove small fluctuations in positioning (*dgps.asc*). At this stage the GPS data can be plotted to check for errors or missing shots.

Source – receiver positions

The survey and observer information in the four files *(posXXX.nav, timeXXX.asc, capXXX.asc, dgps.asc)* are combined to calculate all source and receiver positions for the seismic array. These are written out in a survey geometry file named *posXXX.asc* for all shots and receiver positions. The geometry of the seismic profile is shown graphically in Appendix 3.3.5.

Source QC

The source signature can be assessed at this step to check for any shot delays. The software has a visual display window to show the mean spectrum of the source and a graphical display of the shot source. This step enables individual airgun delays to be observed for mis-timing (Figure 33 in Appendix 3.3.5) and allows identification of the overall source delay for a given shot (synchronized), and an indication of the source frequency spectrum.

SEGD to SEGY

A single SEGY file of shot gathers containing geometry (*profilXXX.seg*) is then created by reading the SEGD files and writing position information into trace headers (see Appendix 3.3.6 for trace header information) from the posXXX.asc position file. SEGY were created in 4-byte IEEE Float format and big endian byte order.

CDP binning

Position information is read from the SEGY file generated in the preceding step (*profilXXX.seg*) to calculate CDP bin positions for the seismic array. Solid-QC generates a binning file (*profilXXX_bin0625.asc*) containing bin positions at 6.25m spacing in line, bin numbers, and the maximum and mean fold of the bins. Bin width is 512 m. Bin number is documented into the headers (bytes 21-24) see summary in Appendix 3.3.6.

Stack and migration

An initial stacked section is produced (*stackXXX_v1500_g0.seg*) using the CDP bin file (profilXXX_bin0625.asc) and the shot gather SEGY file (profilXXX.seg), both computed with a constant velocity of 1500 m/s. The section is then migrated (migXXX_v1500_g0.seg) using the Stolt migration with a constant velocity of 1500 m/s.

Mute
The seafloor horizon is digitized from the migrated profile (fond_migXXX.asc) to be used in subsequent processing and noise analysis (see Appendix 3.3.5). Two files are produced: *fond_migXXX.asc* and *migXXX_v1500_g0_mute.seg*.

Noise analysis
Noisy data can be removed in Solid-QC. Each trace is analyzed for raw noise and signal/noise ratio (see Figure 27, Appendix 3.3.5) with results displayed as a plot of trace position (a grid of shot vs. receiver) and depths in seconds TWT for each shot. Noisy geophones or shots show up on the trace position plot as vertical or horizontal trends facilitating the identification of noisy receivers or shots. Consistently noisy traces (e.g., faulty receiver or bird-related noise on adjacent receivers) can be readily identified and removed during the processing sequence.

SEGY generation
The final step in Solid-QC is to write the CDP positions from the geometry file (profilXXX_bin0625.asc) into the SEGY shot gather file (profilXXX.seg). This output file from the pre-processing sequence with QC-solid is a SEGY shot gather file with trace headers populated with all geometry (source and receiver locations; source-receiver offsets) and CDP binning information (CDP bin numbers, bin locations, number of traces in the CDP gathers). At this stage, the data files contain no filters, mutes or trace amplitude balancing. This SEGY shot gather file is in the data format for import to CGG Geocluster® software for further analysis and seismic processing. The exported SEGY file is in IEEE floating point format. Note that non-standard extended SEGY headers are used to store CDP location information (bytes 181-188). Significant header format is documented in Table 16 in Appendix 3.3.6.

4.3.2.2 CGG Geocluster® processing

This software was used to convert shot gather data to stacked CDP domain data and apply signal enhancing processes. The software was used for thorough velocity analysis of the CDP sorted data, using semblance. The output from Geocluster was a stacked seismic section (unmigrated) with high density velocity picks, seafloor mute, filtering, deconvolution, and multiple suppression. Figure 25 synthetizes the processing sequence.

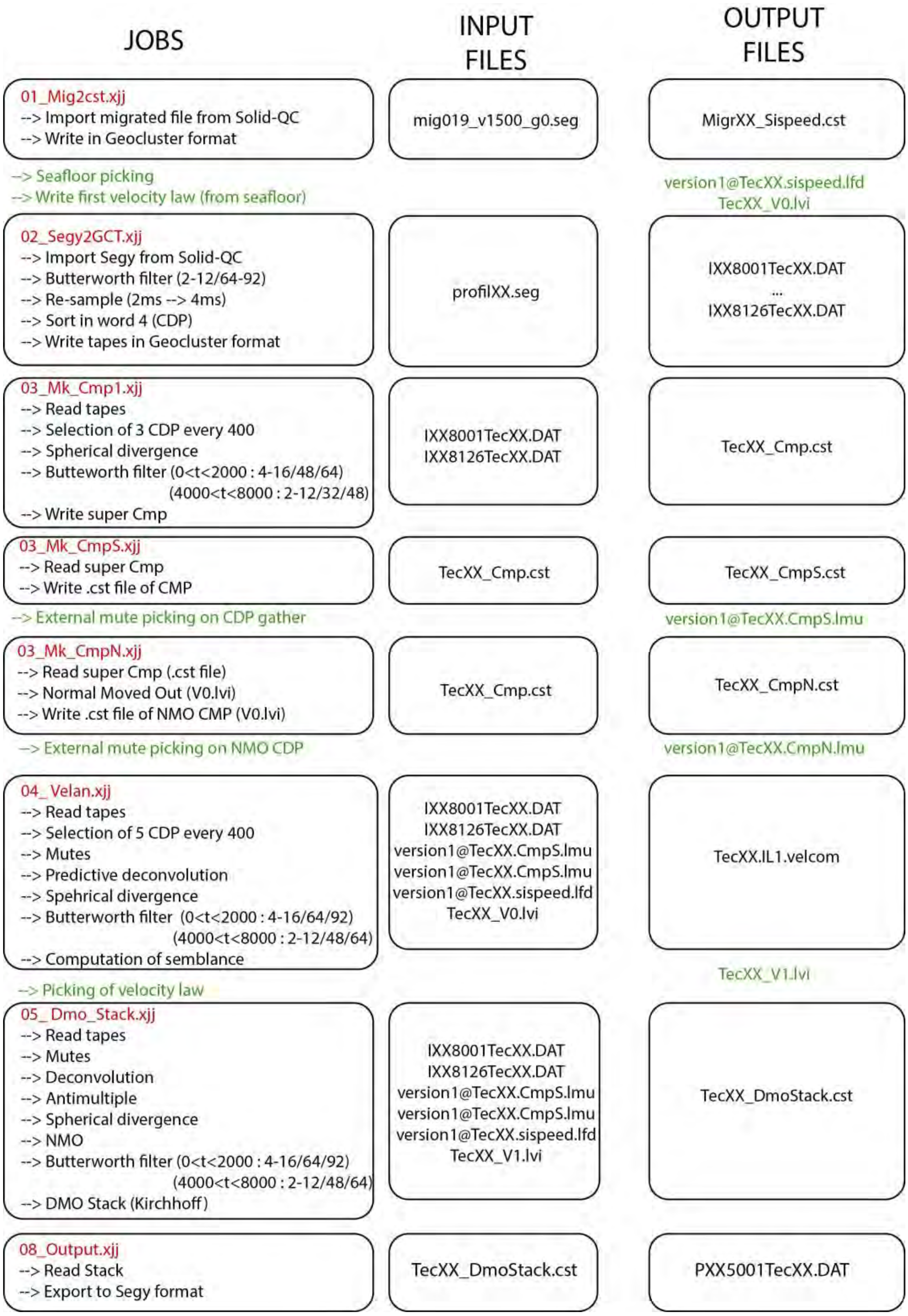

Figure 25 - Geocluster processing sequence. The numbers in the left column indicate different processing steps applied to the data using the Geocluster software. The central column indicates the input files at each step and the right column the output files.

4.3.2.2.1 Import migrated seismic data

The migrated seismic line created with Solid-QC is read in and converted from SEGY to Geocluster format. We create headers, named word 72 and 73 in Geocluster format and populate these headers with the geographical coordinates written in headers word 42 and 44 in the Segy file. Similarly, the header for the line number, word 19, is also populated. The

Sispeed processor is then used to reformat the migrated seismic line into Geocluster format, and a file named MigrXX_Sispeed.cst is created, with additional positions in the headers.

(1)=1537.0, (2)=1537.0, (163)=1544.0, (535)=1615.0, (905)=1678.0, (1354)=1756.0, (1873)=1850.0, (2180)=1905.0, (2563)=1976.0, (3058)=2077.0,	(1)=T1594V1500,T4094V2200,VF7000, (1000)=T1728V1500,T4228V2200,VF7000, (2000)=T1906V1500,T4406V2200,VF7000, (3000)=T2100V1500,T4600V2200,VF7000,
Seafloor horizon file, from CDP 1 to 3058, picked from the seismic line migrated with Sispeed. This horizon file is named version1@TecXX.sispeed.lfd	Corresponding first velocity model from CDP 1 to 3000, named TecXX_V0.lvi. The velocity is 1500 m/s at the seafloor, 2200 m/s 2 s below seafloor and 7000 m/s at the end of the trace.

Table 3 - Seafloor horizon and initial velocity model file. The seafloor horizon digitized from the migrated seismic line in the Teamview application is represented by CDP/TWT time pairs in the left column. The right column shows the CDP/velocity pairs of an initial velocity model based on the digitized seafloor TWT.

Seafloor horizon picking: The migrated line is displayed in the Teamview application to enable picking of the seafloor horizon, which is written out as CDP number/TWT pairs in the file MigXX_Sispeed.lfd. We use this seafloor horizon file to create the first velocity model as shown in the table 2.1. The right column shows an initial velocity model (TecXX_V0.lvi) constructed with a water velocity (V1500) above the digitized TWT of the seafloor and two further velocity constraints with depth, an estimated base of sediment at 2 seconds below seafloor (V2200) and a basement velocity (V7000) at the bottom of the section.

4.3.2.2.2 Import SEGY shot gathers

Import SEGY shot gathers and convert to Geocluster format, CDP sorted files. The shot gather SEGY files (profilXXX.seg), containing survey geometry in the headers, are output from Solid-QC and read into Geocluster. The data are frequency filtered with a Butterworth bandbass filter (2-12-64-92 Hz) and resampled at 4ms (from 2 ms) to reduce file sizes. The data are then CDP sorted using the binning geometry stored in the shot gather header files and written out to Geocluster format. Geocluster outputs the sorted CDP file as a series of "stripes", or segment files with a set number of CDP's per file. The stripe files have a naming convention, e.g. IXX8001TecXX.DAT -> IXX8126TecXX.DAT.

4.3.2.2.3 Seafloor Mute

Sort CDP's into super-CDP Bins to pick seafloor mutes. The seafloor mutes are picked on uncorrected and NMO corrected CDP data. To do this, the Geocluster format stripe files are downsampled by reading three CDP's in 400 (i.e. CDP's 1-3 are used, 4-400 are rejected) from the files and resorting these into super CDP's. The super gathers are sorted by CDP trace. The combination of using mutes picked on NMO corrected and uncorrected data is used to remove NMO stretch (corrected mute), water column noise, direct arrivals (water wave) and refractions (see Figure 26). The data are corrected for spherical divergence and a Butterworth bandpass filter is applied (2-12-64-92 Hz) before the data are written out to a CDP sorted file (TecXX_Cmp.cst). This file is then re-written as TecXX_CmpS.cst to be used as the uncorrected file for muting and a mute horizon is digitized at the onset and written as CDP/TWT pairs (version1@TecXX_CmpS.lmu).
To pick a mute on NMO corrected data, the (TecXX_Cmp.cst) CDP super gather file is read again, and NMO corrected using the velocity model constructed from the original seafloor

horizon and the two layer, sediment and basement velocity structure (see section 1., table 2.1, TecXX_V0.lvi). An NMO corrected file is written out (TecXX_CmpN.cst). A mute file from the NMO corrected data CDP data is exported to version1@TecXX_CmpN.lmu.

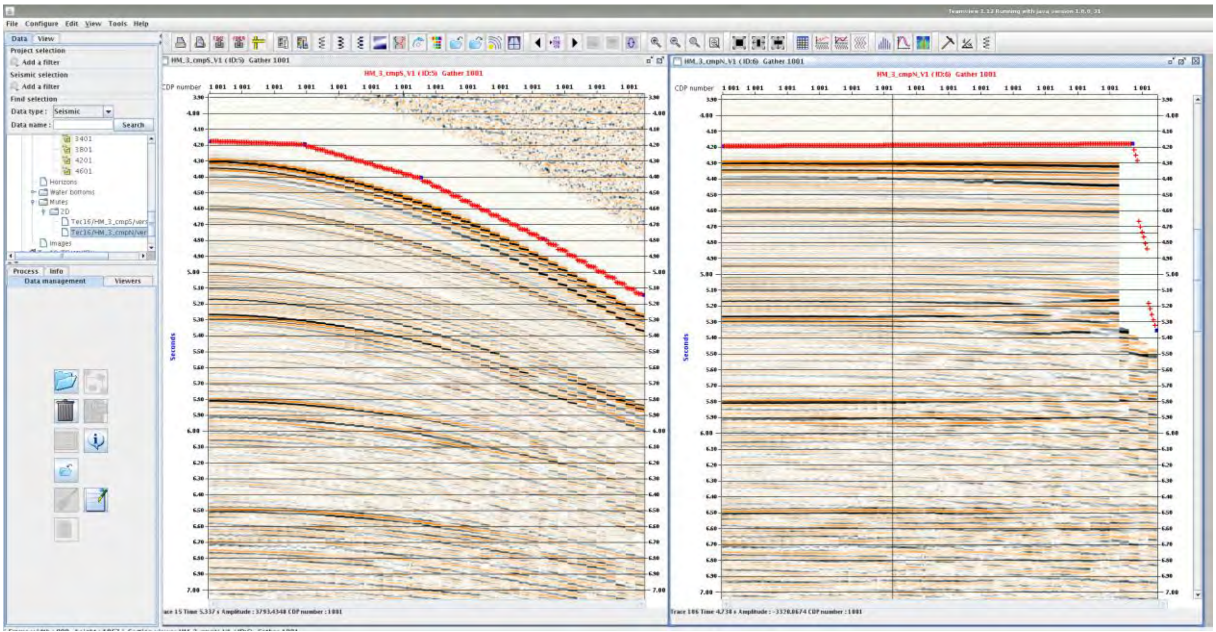

Figure 26 – Example of seafloor mute from uncorrected and NMO corrected data

4.3.2.2.4 Velocity Analysis.

The Geocluster format CDP sorted "stripe" data (e.g. 1XX8001XXTec.DAT -> 1XX8126XXTex.DAT) is read in and down-sampled for velocity analysis. Five CDP's in every 400 are selected (CDP's 1-5 used, CDP's 6-400 rejected) and are used to calculate the semblance panels. The seafloor mutes from the previous step are applied (version1@TecXX_CmpS.lmu, version1@TecXX_CmpN.lmu), the data are deconvolved, corrected for spherical divergence, and band pass filtered (Butterworth, 4-16-64-92 Hz for 0<t<2000 ms beneath seafloor and 2-12-48-64 Hz for 4000<t<8000ms beneath seafloor. An output file, TecXX.iL1.velcom is created to be read into the velocity picking module.

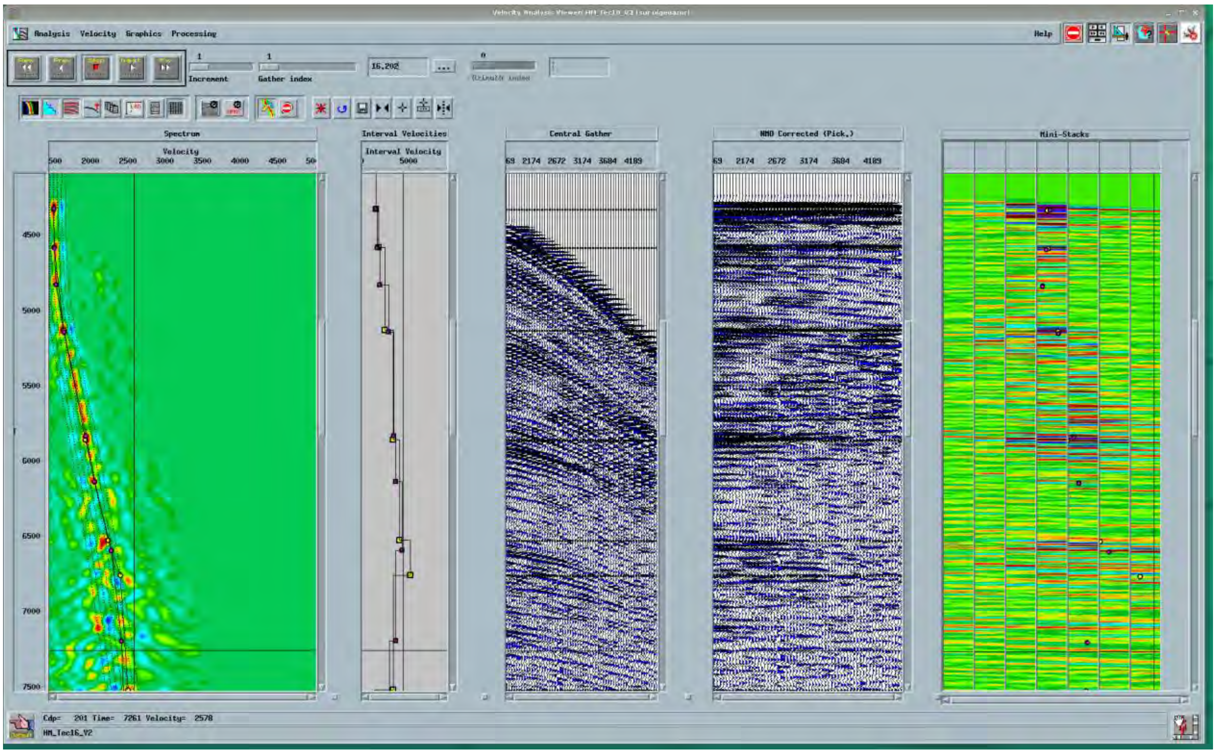

Figure 27 – Example of velocity picking panel with semblance in Geocluster

Velocity analysis is carried out on semblance plots. The central CDP from the 5 located within the “stripe”(no, 3.) is plotted alongside the semblance energy window as a constant velocity gather, to check for coherency in arrivals. An interval velocity panel is also used to guide the velocity picks from the semblance window.

Velocities picked from the semblance window are written to an updated velocity file (TecXX_V1.lvi).

4.3.2.2.5 Final stacking routine

The Geocluster format CDP sorted “stripe” data (e.g. 1XX8001XXTec.DAT -> 1XX8126XXTex.DAT) are read in, in full. The seafloor mutes from the previous step are applied (version1@TecXX_CmpS.lmu, version1@TecXX_CmpN.lmu). The data are processed with the following modules.

Deconvolution

A predictive deconvolution filter with an operator length of 190 ms, and design gate window of 0-4000 ms is applied on non NMO-corrected data. The deconvolution filter start time is based on seafloor TWT from the digitized seafloor horizon (version1@TecXX_CmpS.lmu) and on velocity law 1, from semblance (TecXX_V1.lvi). The filter does not otherwise vary laterally or with depth, except for the start time relative to the sea floor. The length of the active part of the operator is 220 ms (option LAR, must be less than calculation window length/5).

Demultiple
A multiple suppression process is applied using the velocity file created from velocity picking in semblance with a percentage of tolerance of 7. The file is CDP sorted but not corrected for NMO. The demultiple routine uses a hyperbolic move out model to estimate multiples, and subtracts the estimated multiples from the data for frequencies contained between 2 and 64 Hz. It analyses the velocity functions to define the length of the processing time windows (minimum length of this windows is 204 ms) and is operating between 0 and 15000 ms. It considers the maximum number of traces in a gather equal to 111, the length of seismic wavelet used to calculate the curve increment in the tolerance analysis is 60 ms and the maximum permitted number of moveout curves per event is equal to 31. This routine is successful at removing long period multiples such as the seafloor multiple, and coherent energy that has a known moveout.

Spherical divergence correction
The spherical divergence correction calculates compensations for the effects of geometrical spreading computed using P. Newman's formulae and takes the offset into account. It applies on no NMO-corrected data and uses velocity law 1, from semblance (TecXX_V1.lvi). Output traces are normalized thanks to a coefficient equal to 9 000 000.

NMO correction
The data are NMO corrected using the velocity file written out from the semblance velocity picking routine (TecXX_V1.lvi) with the seafloor mutes applied to remove stretch.

DMO correction
The data are band pass filtered (Butterworth, 4-16-64-92 Hz for $0<t<2000$ms beneath seafloor and 2-12-48-64 Hz for $4000<t<8000$ms beneath seafloor) before being corrected for dip moveout using an integral (Kirchhoff) method. Traces of a same bin are then stacked using the TecXX_V1.lvi velocity file and considering the maximum zero offset time dip of the DMO operator set to 2ms/m. The distance between bins is 6.25 m and the threshold offset value beyond which traces are not taken into account is 4850 m.

Stack
A new GEOCLUSTER format stacked section is written out (TecXX_DmoStack.cst).

Export to SEGY
Data are exported to SEGY format using a specific file nomenclature, e.g. PXX5001TecXX.DAT
The output SEGY file with 4-byte IBM floating point sample format is written with trace header information as documented in Appendix 3.3.6.

4.3.2.3 Time migration

The post-stack time migration were performed with Seismic Unix and Globe Claritas rather than with the Geocluster software, in order to merge the profiles that have been processed as subsections (generally due to acquisition interruptions) and in order to build proper SEG-Y text headers. The subsection merging points have been manually defined from the vicinity as well as the quality of the stacked sub-sections.

4.3.2.3.1 Claritas migration

Migration of a number of seismic lines (Profiles 8,14,14B,15,16,18,20,24,25,27,29,30,31,32) was done using Globe Claritas to test for an improved outcome. The Geocluster format stacked SEGY data (e.g. PXX5001TecXX.DAT) can be read into Claritas with readsegy. The stacking velocity file from Geocluster (TecXX_V1.1vi) requires conversion to a Claritas format velocity file before it can be read (see Appendix 3.3.5.3 for conversion script). Migration in Claritas was done using the FDMIG module. FDMIG is a finite difference time migration routine that produces good results for dips of up to ~60 degrees. The routine works in the X-T domain using a velocity field which can vary in time and space. The Claritas Isovels module is used to smooth the stacking velocity file in the X direction before converting it to interval velocities used in the migration routine.

The data are migrated using FDMIG with 20 ms time slice, 0.707 dip filter factor (cosine of maximum migrated dip) using the interval velocity file (e.g. TecXX.V1.Vint.nmo) calculated from the Geocluster stacking velocity file. The input stacked data are tapered at the end of the trace (Cosine taper, 100 samples in length) and padded with 500 dummy traces either side of the data traces. A seafloor mute is applied before the file is written out to TECXXX_FDMIG.sgy.

4.3.2.3.2 Seismic Unix migration

A Stolt (frequency / wave-number) time migration was performed with a constant 1550 m/s velocity and a 0.7 stretch factor that accounts for increasing velocities in sedimentary basins. Finally, voyage details, the minimum and maximum shot numbers and common mid-points as well as the Geocluster sub-section names (e.g. PXX5001TecXX.DAT) were included in the SEG-Y text headers. A composite seismic and interval velocity plot was also created to assist in identifying future post-voyage processing needs.

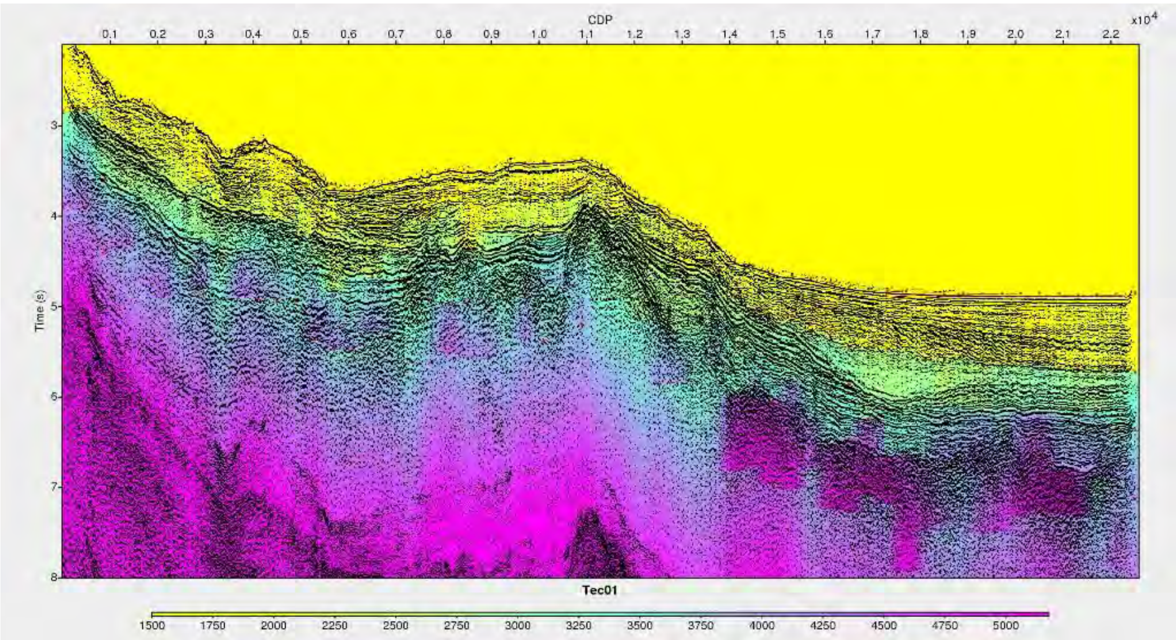

Figure 28 – Time migrated section of profile TEC001 with stacking velocities superimposed.

4.3.2.4 Post-processing – Python Obspy

Python scripts utilizing obspy.segy and pyproj were used for post-processing.

Coordinate conversion
Trace (CDP/bins) locations were converted from latitude/longitude geographical coordinates in DDDMMSSss format to decimal degrees and subsequently to UTM Zone 59S projected coordinates. The WGS84 ellipsoid was used.

Longitudes and latitudes for trace locations in decimal degrees had a scalar of 10,000,000 applied, and were written into trace headers 81:84 and 85:88, respectively.

UTM 59 S eastings and northings for trace location, with a scalar multiplier of 100, were written into trace headers bytes 73:76 and 77:80, respectively.

SEGY header updates
Python was also used to tidy up some reel and trace header info (e.g. fold, coordinate scale), and to insert a full text (3200-byte) header into the SEGY files. The textual header contains basic file parameters (number of CDP, spacing, record length, etc) and information about the survey, acquisition system, contact details for archived data, essential trace header information (e.g., trace location, byte positions and coordinate system), and other archived files relating to the processing scheme e.g. shot gathers, CDP gathers, velocity libraries, etc).

An example of the 3200-byte textual header for profile TEC001 is shown below.

```
C01 AREA           : TASMAN FRONTIER, NEW CALEDONIA TROUGH
C02 DESCRIPTION    : 2D SEISMIC COVERAGE
C03 ========================================================================
C04 LINE : TEC01      N_TRACES: 22568   TRACE SPACING : 6.25 m
C05 CDP : 1 - 22568   CDP SPACING : 6.25 m
C06 SAMPLE RATE : 4    ORIGINAL RECORD LENGTH : 15000
C07 ========================================================================
C08 ===   TECTA VOYAGE, RV L'ATALANTE, 2015/09/03 TO 2015/10/09 ===
C09 CHIEF SCIENTISTS: JULIEN COLLOT,SGNC, DIMENC, NEW CALEDONIA;
C10 RUPERT SUTHERLAND, GNS SCIENCE, NEW ZEALAND; AND
C11 WALTER ROEST, IFREMER, FRANCE
C12 THESE DATA AND LICENCE TERMS CAN BE OBTAINED FROM:
C13 SISMER, Centre IFREMER de Brest, BP 70 29280 PLOUZANE, FRANCE
C14 HTTP://WWW.IFREMER.FR/SISMER  Email: sismer@ifremer.fr
C15 Tel: +33 2 98 22 49 16  Fax: +33 2 98 22 46 44
C16 THESE DATA ARE SUPPLIED UNDER LICENCE AND MAY NOT BE PUBLIC.
C17 ATTRIBUTION MUST BE GIVEN TO THE TECTA VOYAGE REPORT AND/OR PUBLICATIONS.
C18 ========================================================================
C19 TRACE HEADER BYTE LOCATIONS
C20 CDP            : BYTES 21-24
C21 CDP EASTING    : BYTES 73-76  SCALAR MULTIPLIER : 100
C22 CDP NORTHING   : BYTES 77-80  SCALAR MULTIPLIER : 100
C23 CDP LONGITUDE  : BYTES 81-84  SCALAR MULTIPLIER : 10000000
C24 CDP LATITUDE   : BYTES 85-88  SCALAR MULTIPLIER : 10000000
C25 PROJECTION     : UTM ZONE 59 SOUTH
C26 ELLIPSOID      : WGS84
C27 DATUM          : WGS84
C28 ========================================================================
C29 SOURCE: 12 AIRGUN ARRAY, 2690 cu in, 6-10 m depth
C30 CHANNELS: 720 SPACING: 6.25 m NEAR OFFSET: 118 m FAR OFFSET: 4611.75 m
C31 See voyage report published by SGNC,DIMENC for processing/archive details
C32 SHOTS WITH GEOMETRY    : Profil001A-Z.seg
C33 GEOCLUSTER CDP GATHERS : I018xxx.cst  (xxx are sequential numbers)
C34 VELOCITY LIBRARY       : Tec01_V1.lvi
C35 GEOCLUSTER STACK       : Tec01_Dmostk_V1.cst
C36 SEGY STACK             : P015001.DAT
C37 MIGRATION              : Kirchoff (Seismic Unix)
C38 Some lines have multiple shot files (suffix A-Z) if acquired in segments
C39 SEG Y REV1
C40 END TEXTUAL HEADER
```

Figure 29 – Example of final 3200-byte textual EBCDIC header

The output SEGY file with 4-byte IBM floating point sample format is written with trace header information as documented in the table in Appendix 3.3.6.

Final SEGY files are named TECXX_SUMIG6.sgy or TECXX_FDMIG6.sgy. Alternate Seismic Unix or Claritas (Finite Difference) migrations respectively have suffixes SUMIG or FDMIG.

Trace stacking
In order to reduce the size of the files, a 25 m bin spacing version of each profile was also created by stacking traces n, n+1, n-1 and 25% of trace n+2 and n-2. The original bin/cdp number is retained (CDP numbers increment by 4), so that comparison to original processing is possible.

These super-bin files are named TECXX_SUMIG25.sgy or TECXX_FDMIG25.sgy. Alternate Seismic Unix or Claritas (Finite Difference) migrations respectively have suffixes SUMIG or FDMIG.

4.3.3 Notes

Profile TEC07
Line abandoned for air gun maintenance. This line was originally a transit line.

Profile TEC10
Many pilot whales at start of line. Original line was TEC09 to go across Norfolk Ridge. New line TEC10 planned to take a different route but more pilot whales encountered.
Second attempt along Line 10a eventually was OK. Line 10 was deleted (very short and not overlapping) and 10a renamed to TEC10.

Profiles TEC12, TEC13
Due to an injured crew member, the ship had to transit back towards Nouméa. These two lines were abandoned to make up for the time lost during this medical evacuation.

Profile TEC17
Line was abandoned due to a problem with the streamer. The Line was reshot from other direction and records were merged into line TEC18 at the Solid-QC stage, then CDPs renumbered in GeoCluster.

Profile TEC19
Line was abandoned due to bad weather, streamer at surface, big swell. The line was not processed.

Profile TEC28
Line TEC028 was abandoned because of bad weather. No MCS data acquired, just bathymetry, CHIRP, etc.

4.3.4 Results

Seismic profiles acquired during the voyage are illustrated in Appendix 4.1. Figure 6 shows the location map.

4.4 *Sub-bottom Profiler - Chirp*

4.4.1 Introduction

The R/V L'Atalante has a CHIRP (nominal emission frequency 3.5 kHz) sub-bottom profiler (SBP) able to image the first few hundred meters of sediments below the sea floor. Appendix 3.4 provides the technical description of the CHIRP system. SBP data were acquired using the software SUBOP of Ifremer. This software also allows real-time inspection of the data acquired. Figure 30 shows an example of a screenshot of the SUBOP. Different parameters related to the data acquisition can be seen, and adjusted as required.

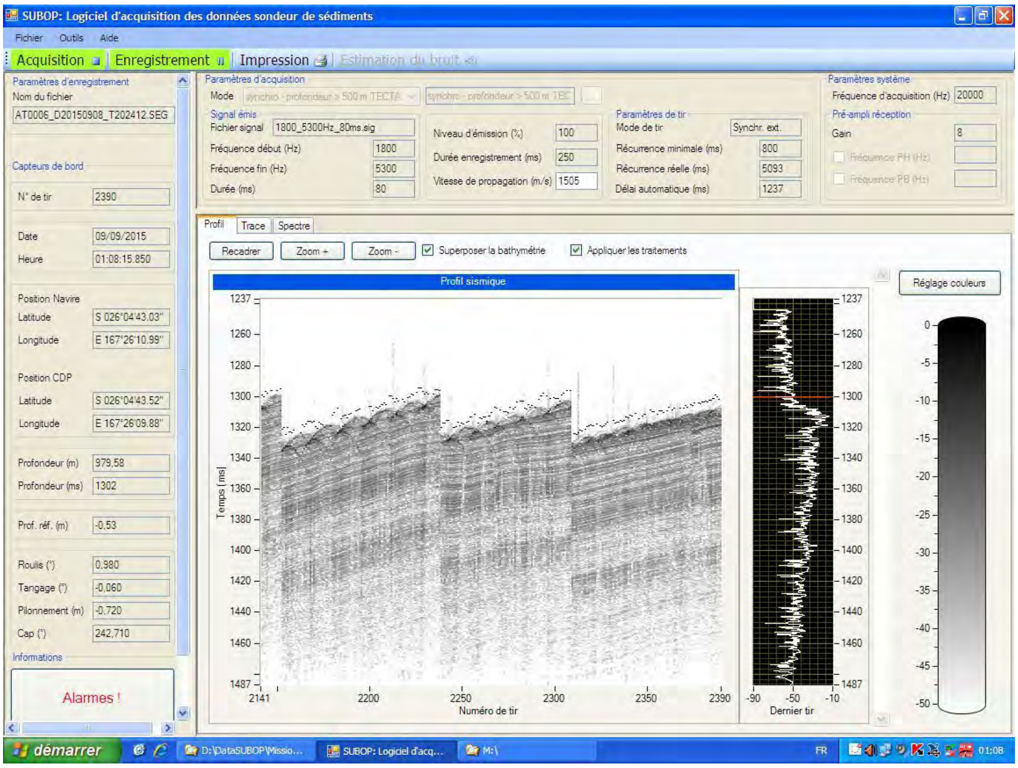

Figure 30 – Screen shot of the SUBOP acquisition system visualization, showing real time images of the sub-bottom profiler data acquisition

Transmitted signals are linear frequency modulation with a duration of 10 to 100 ms. The received signal consists of a time series of echoes reflected on sedimentary interfaces. In the case of the TECTA voyage, the signal transmission time was 80 ms with frequencies ranging from 1800 Hz to 5300 Hz and the recording time was 250 ms. The emission rate varies with the depth of sea floor. The deeper the seafloor, the more the emissions are separated in time, and the more transmission power is needed. Since acquisition was taking place mostly in deep waters, the transmitting power of the sub-bottom profiler was set to 100%.

The CHIRP system of L'Atalante is capable of simple or nested shooting modes. In the nested shooting mode, one ping is fired about every second. It turns out, however, that the sub-bottom profiler operated in this mode causes significant noise in the water column and also affects the quality of the bathymetric data collected by the EM122 multi-beam echo sounder; in particular the outer beams were very noisy.

Desynchronising was tested along profile TEC001. The SPB was subsequently operated synchronized with the multi-beam echo sounder during the entire voyage, except between profile TEC006 ping 5984 and the start of profile TEC008, when passing over proposed IODP 832 NCTN sites.

Data were processed onboard using the Subop software. A total of 8400 km of profiles was recorded (see Figure 31).

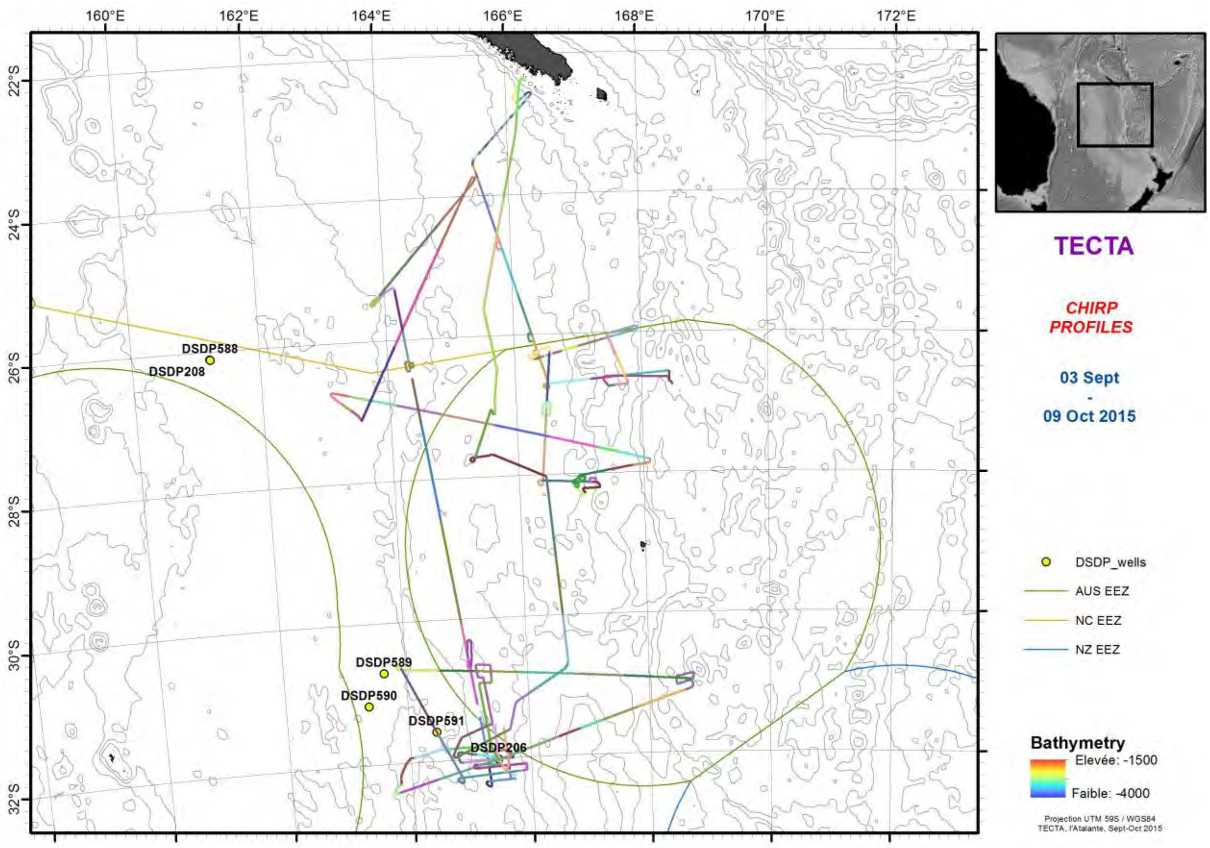

Figure 31 – Navigation of sub-bottom profiles. Each color corresponds to a separate profile.

4.4.2 QC_Subop processing (Quality Control)

The data acquired by the CHIRP sub-bottom profiler and those produced by subsequent processing are organized in several file types:

- Raw files, archived directly by the SISMER data center of Ifremer
- Intermediate files: homogeneous standard SEGY, pre-processed in order to assess the quality of the data. These files are not corrected for the offset of the recording window
- The concatenated files: one or more files according to file size and when the shot point numbers are consecutive, making concatenation possible

During the voyage, the quality of the data is assessed with utilities in the QC_Subop software (Ifremer/GM), using the following steps:

- Data quality control (navigation, recording delay, noise, signal, …)
- Correction time of acquisition,
- Correction for the attitude of the vessel
- Correction of the spherical divergence of the acoustic signal,
- Concatenation of individual files recorded during single profiles,
- Visualization.

A detailed description of the processing sequence is given in Appendix 3.4.2.

4.4.3 Data Quality

The quality of data depends on several parameters, which are geological and technical in nature.

Amongst the geological parameters that affect the quality of the sub-bottom profiler data we can list:

- the nature of the substrate: soft sediments versus hard bottom, for example
- the presence of faults or other geological structures
- the water depth
- more or less significant variations in the depth along the profile, and or the presence of relatively steep slopes

Technical parameters that influence the data quality include:

- the signal strength, which was set to 100% during TECTA
- the gain (signal amplification)
- the ping interval: during the TECTA voyage, we mainly operated the sub-bottom profiler in synchronization mode with the multi-beam echo sounder. This meant an average shot interval of 5 to 10 seconds. Using nested pinging (one emission about every second) caused significant interference with the bathymetric data acquisition leading to data loss, as well as significant noise in the CHIRP data (see 4.4.5 below)

4.4.4 Illustrations

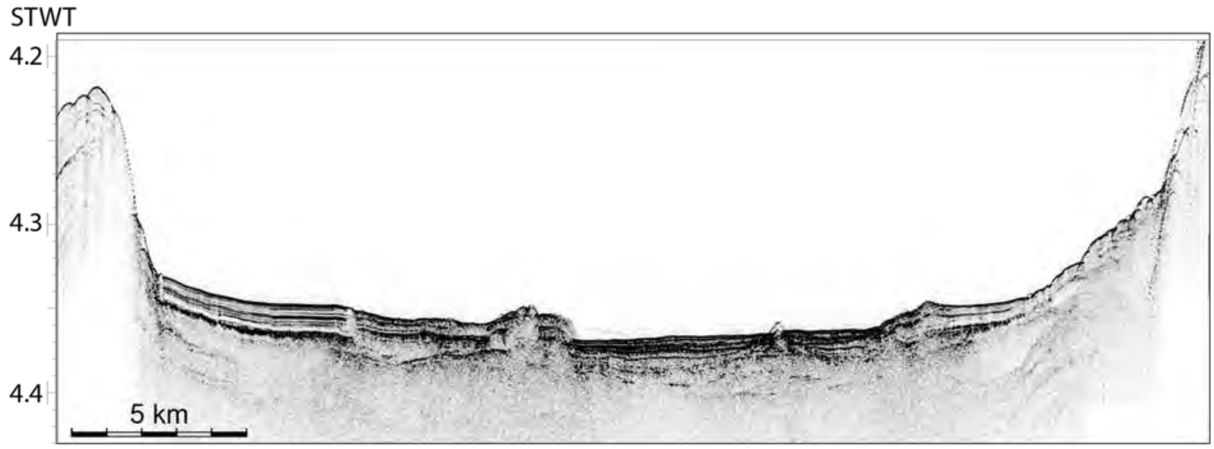

Figure 32 - Section view of sub-bottom profiler data in the New Caledonia Trough, near DSDP 206, showing a channel with associated levees in the center of the basin (This channel is visible in bathymetry; i.e. Figure 16)

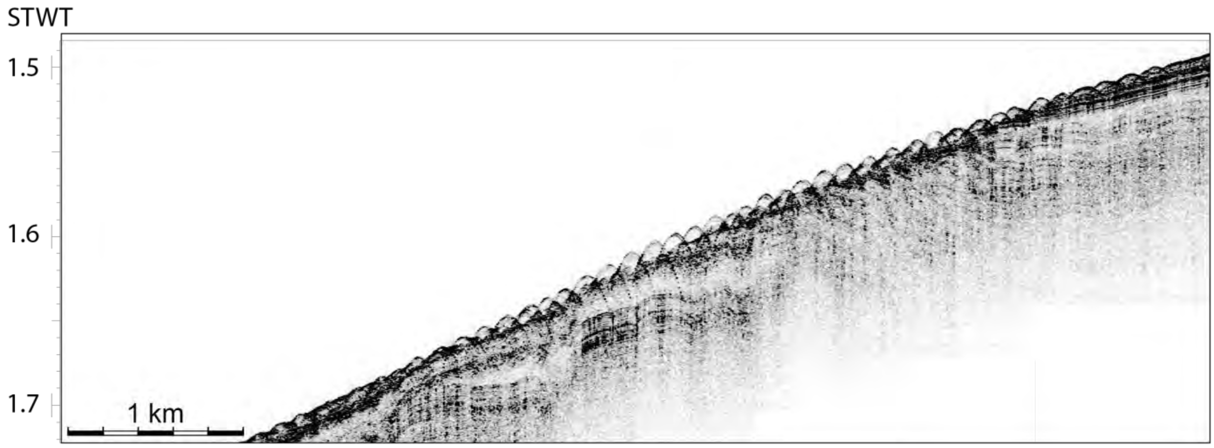

Figure 33 - Section view of sub-bottom profiler data showing sediment waves on the crest of the Norfolk Ridge. Note that these sediment waves are also visible in bathymetry; i.e. Figure 18

4.4.5 Issues identified

4.4.5.1 Issues related to data acquisition

During the TECTA voyage, two issues related to CHIRP data acquisition were identified:

- The use of nested shots causes noise and interference
- The delay set for the start of the recording window is not always reliable

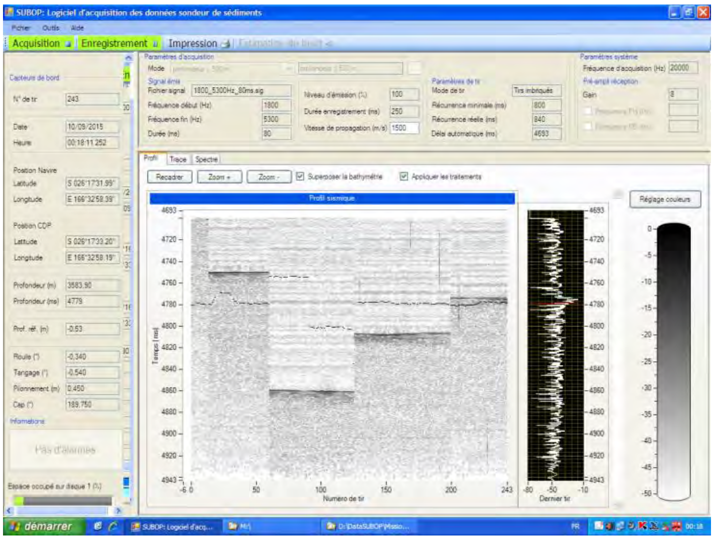

Figure 34 - Example of acquisition window of SUBOP during nested shooting mode. Significant noise can be observed in the water column. The signal to noise ratio determined for this profile by QC-Subop is –2 dB.

The use of nested shots (in French: *tirs imbriqués*) significantly improves the horizontal resolution of the sub-bottom profiler, particularly when the vessel travels at speeds of 10 knots or more. The interval between subsequent emissions is around 1 second in this mode, as compared to an average of 8 seconds when operating in synchronized mode with the multi-beam echo sounder, i.e. when the shot interval depends on the return of echoes of the outer beams of the multi-beam echo sounder. However, during the TECTA voyage, at water depths around 2000 to 3000 m, we found that the sub-bottom profiler pings, when using nested shots, strongly interfered with the EM122 multi-beam echo sounder. The result was significant noise on the outer beams of the EM122, and often the loss of the automatic bottom detection, hence deteriorating the data and reducing the swath width of the multi-beam echo sounder significantly. In addition, nested shots also seem to produce significant noise in the CHIRP data themselves, often reducing signal to noise ratios to below 5 dB. Figure 34 shows an example of such noise, visible in the water column.

A second acquisition issue identified during TECTA relates to the delay applied to the recording window. SUBOP acquires data during a time window of 250 ms, which is positioned as a function of the depth of the seafloor. The depth information is derived from the single beam or multi-beam echo sounder, and acquired in ms TWT. Depth conversion is done with a constant sound velocity, which can cause significant errors in the positioning of the recording window. In particular, two general cases were identified during the TECTA voyage:

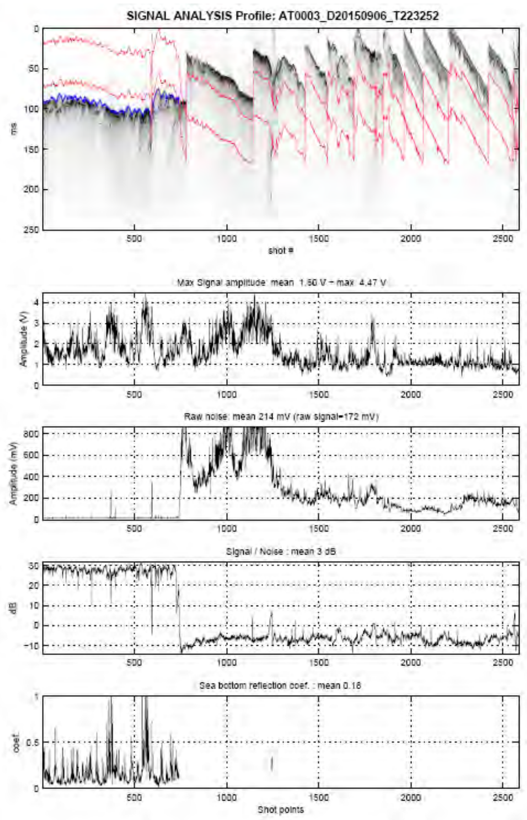

Figure 35 - Example of error in seafloor detection : the start of the profile uses a correct value for the water depth. Starting from shot point 750, the acquisition window is too deep, leading to occasional data loss of the seafloor reflector, and erroneous calculation of the signal to noise ratio.

- Seafloor position used by SUBOP deeper than its real position: this results in a recording window that starts too deep, and sometimes does not even include the seafloor reflector itself. The result of such an error is not only the loss of data, but also a difficulty in determining the correct signal to noise ratios, using QC-Subop. Figure 35 shows an example of this problem. Whereas the beginning of the profile has calculated signal to noise ratios of about 30 dB, the latter part of the profile has calculated signal to noise ratios of around –5 dB due to erroneous seafloor detection.
- Seafloor position used by SUBOP too shallow as compared to the real depth: this leads to recording of noise in the water column rather than signal related to sediment layers. In some cases, only 50 ms of useful data was collected within the 250 ms long record. Figure 36 shows an example of such a problem, with only 90 ms of useful data being recorded.

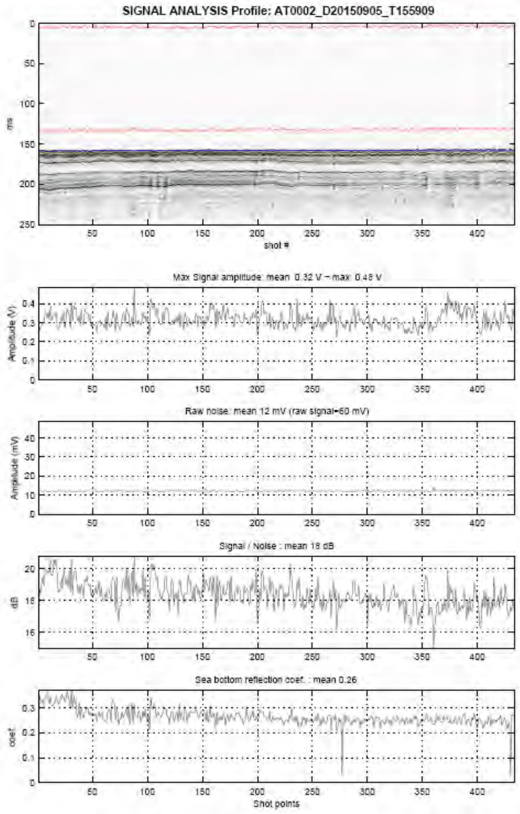

Figure 36- Example of Subop acquisition window starting too early. The result is that only about 90 ms of useful data are acquired, which is significantly less than the maximum penetration in this particular area.

4.4.5.2 Issues related to data processing

The QC-SUBOP data processing is virtually automatic, but requires many interventions by the operator:

- Copy the archived raw data files to the RAW directory on the SCIENCE drive
- Start processing for each individual file
- Occasional correction of the bathymetry and the delay of the recording window (This has to be done twice, once on observed, and then again on smoother data, while this repetition would appear to be redundant)
- Rename subdirectories for each file or group of files that the operator wants to concatenate during subsequent steps (this is done blindly, as the operator does not know in advance whether or not concatenation will be possible depending on the size of the final output file: often concatenation is rejected and the operator has to start over again)
- Concatenation of all files in each of the subdirectories created (sometimes obliging the recreate subdirectories if the output files were too large for concatenation)
- Manually enter the necessary quality related information (which is accessible only in image format and not in text format in the PDF files produced by QC-Subop) in a summary table destined for Sismer

For a survey like TECTA, which was mainly using the sub-bottom profiler in mode synchronized with the multibeam echosounder (on average about one ping every 8 seconds), this represents 200 files to process and over 50 hours of operator time. Most steps could be entirely automated without intervention by a person. If nested pings had been used throughout, this would have represented 10 times more files and an estimated 12 hours of processing time a day.

Detailed examination of the sub-bottom profiler data through the QC-Subop processing sequence allows quick identification of acquisition problems. These may be due to:

- Improper calibration of the acquisition window (erroneous bottom detection, either too shallow or too deep, see above)
- The use of nested fire. This caused unacceptable interference with the bottom detection on the muti-beam sonar and an initially unexplained noise in the water column on the sediment sounder.

It appears that concatenation greatly increases the size of the files (in particular in areas with significant relief). It would appear that all traces in the SEGY file are resampled to represent the entire range between the shallowest and deepest acquisition windows. It would be interesting to examine the possibility to integrate SEGY files, while taking into account the acquisition offset time per ping, rather than filling an entire matrix with zeros.

We make the following suggestions to improve the processing sequence in Subop:

1) Reflect on a more efficient output file format after concatenation.
2) Ensure that all the necessary information to fill out the Excel file with quality control parameters, which will be send to Sismer, is available in a text file and can be integrated in a (semi-)automatic fashion rather then entered manually, which is time consuming and leads to possible errors.
3) Rather than a trial and error method to cut profiles in sections, develop a semi-automatic system to cut profiles when concatenating (selection of files in each subdirectory and shooting ranges).

4.5 Magnetic Data

4.5.1 Introduction

The main purpose of magnetic data acquisition was to identify linear magnetic anomalies associated with the oceanic crust as well as strong magnetic anomalies related to volcanic or basement rocks. In the case of oceanic crust, basaltic rocks record the Earth's magnetic field at the time that they were formed at the mid-ocean ridge. Positive and negative magnetic anomalies over oceanic crust allow, by correlation with the geomagnetic time scale, to date the ocean floor where one can identify these anomalies. On the other hand, volcanic edifices are usually characterized by strong magnetic anomalies.

The magnetic field was measured with a SeaSpy magnetometer (see Appendix 3.5). During the acquisition of multi-channel seismic data, the SeaSpy magnetometer was towed behind the tail buoy of the streamer, i.e. at a distance of more than 4.8 km behind the vessel.

Magnetic data processing was performed with the Caraïbes software (see Appendix 3.5.2 for details). After reformatting files and cleaning to remove a few outliers, the final step is to subtract the magnetic given the value of the Earth's magnetic field at the point considered (this field varies in space and time). At the time of the TECTA cruise, the Caraïbes software was using the IGRF2010 as the geomagnetic reference field for this correction. We then obtain the magnetic anomaly which corresponds to that component of the measured Earth's magnetic field that reflects the magnetization of the geological units present in the area.

Further details on the magnetometer and the processing are provided in Appendix 3.5.2. Since the study area is far away from the nearest land station, no diurnal corrections were applied.

4.5.2 Results

During the TECTA voyage, magnetic data were only collected when the seismic streamer was in use. As described above, the magnetometer was towed behind the tail buoy of the seismic streamer, at a distance of 4850 m from the reference point of the vessel.

During the beginning of the voyage, no magnetic data were acquired, due to a problem related to a connector between the magnetometer cable and the streamer. This problem was solved at the first opportunity that presented itself, when the streamer had to be taken on board as a result of a problem related to the birds.

The magnetic data are generally of good quality, only a few spikes were manually removed during the processing phase. Also, after inspection of the data, which represents short wavelength noise levels of up to 1 nT, it is clear that no magnetic storms took place during the voyage.

After updating the processing with the IGRF2015 reference fields, it will also be possible to assess the data quality by looking at the difference in measured values at track line cross-over points. Such analysis has not as yet been performed for the TECTA voyage.

After processing, the data were exported in ASCII latitude, longitude format, and displayed using the GMT software in Figure 37 and Figure 38.

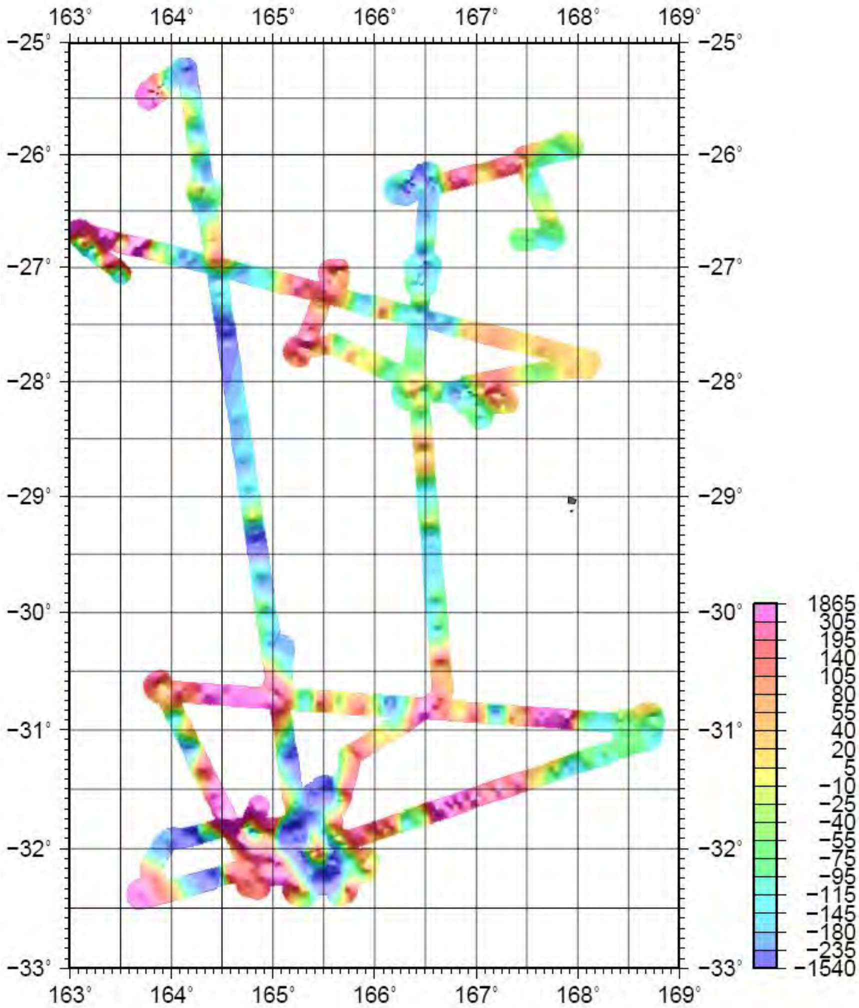

Figure 37 - Shaded relief map of the magnetic anomalies (color scale indicates values in nT)

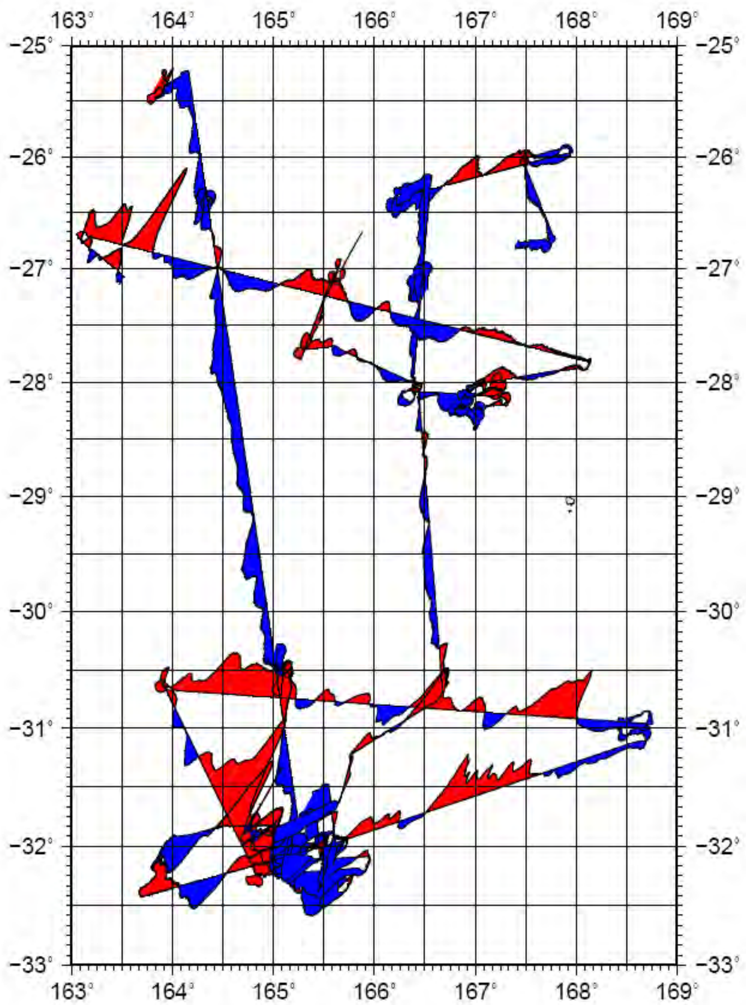

Figure 38 – Wiggle plot of the magnetic anomalies; positive anomalies are shown in red, negative in blue

4.6 Environmental Data

4.6.1 Weather, Currents

During the entire TECTA voyage, environmental parameters are recorded. The RV L'Atalante is equipped with a BATOS system, for this purpose. The BATOS system is an automatic measuring station of meteorological and, where appropriate, oceanographic parameters. It allows automatic acquisition: wind, air pressure, humidity, air and water temperature, electrical-conductivity of sea water. Some of these parameters recorded during the TECTA voyage are illustrated in the following figures

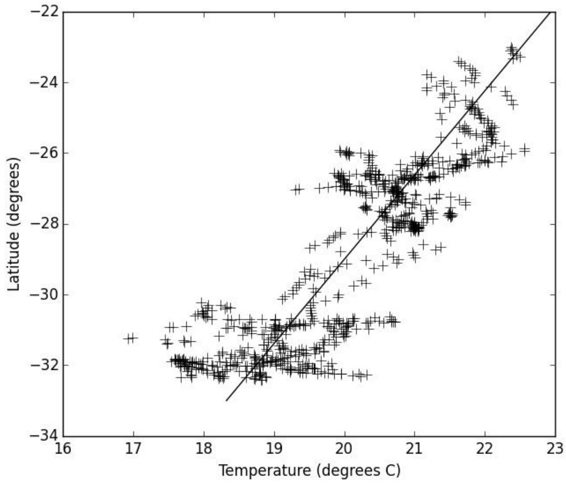

Figure 39 – Water temperature and Latitude

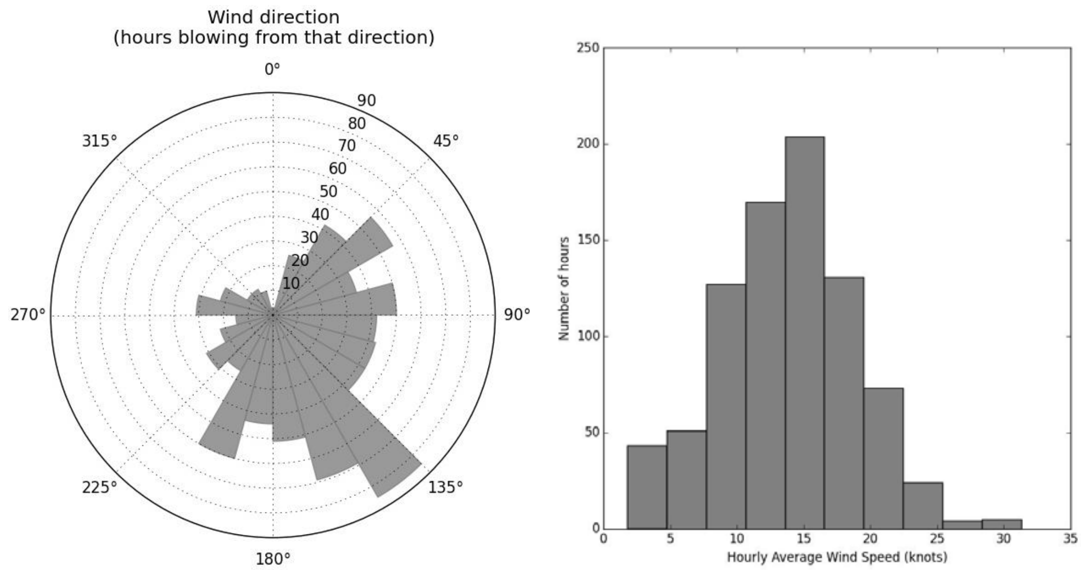

Figure 40 – Wind direction and speed

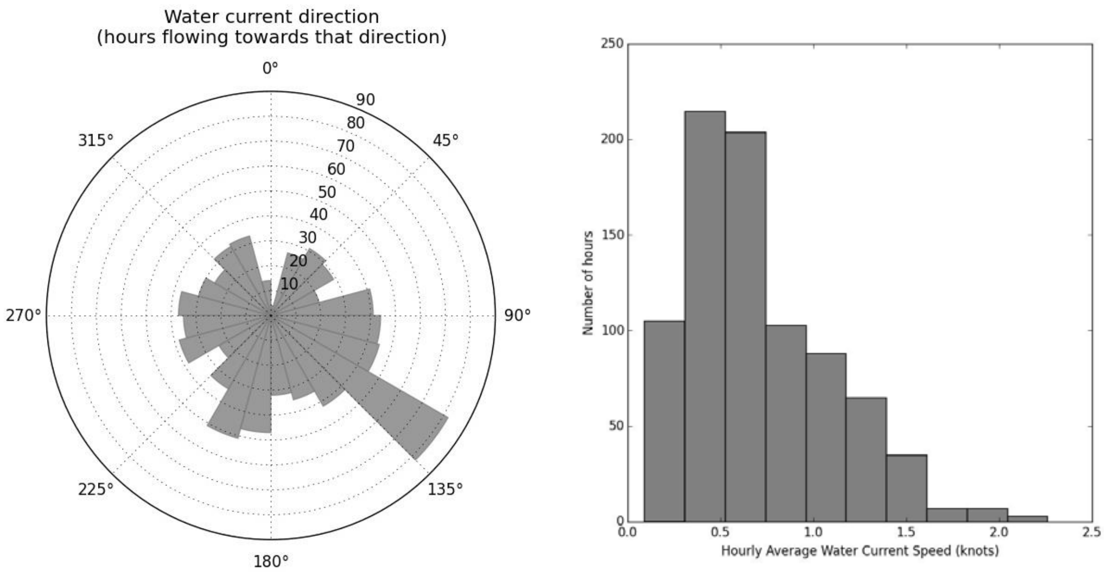

Figure 41 – Water current direction and speed

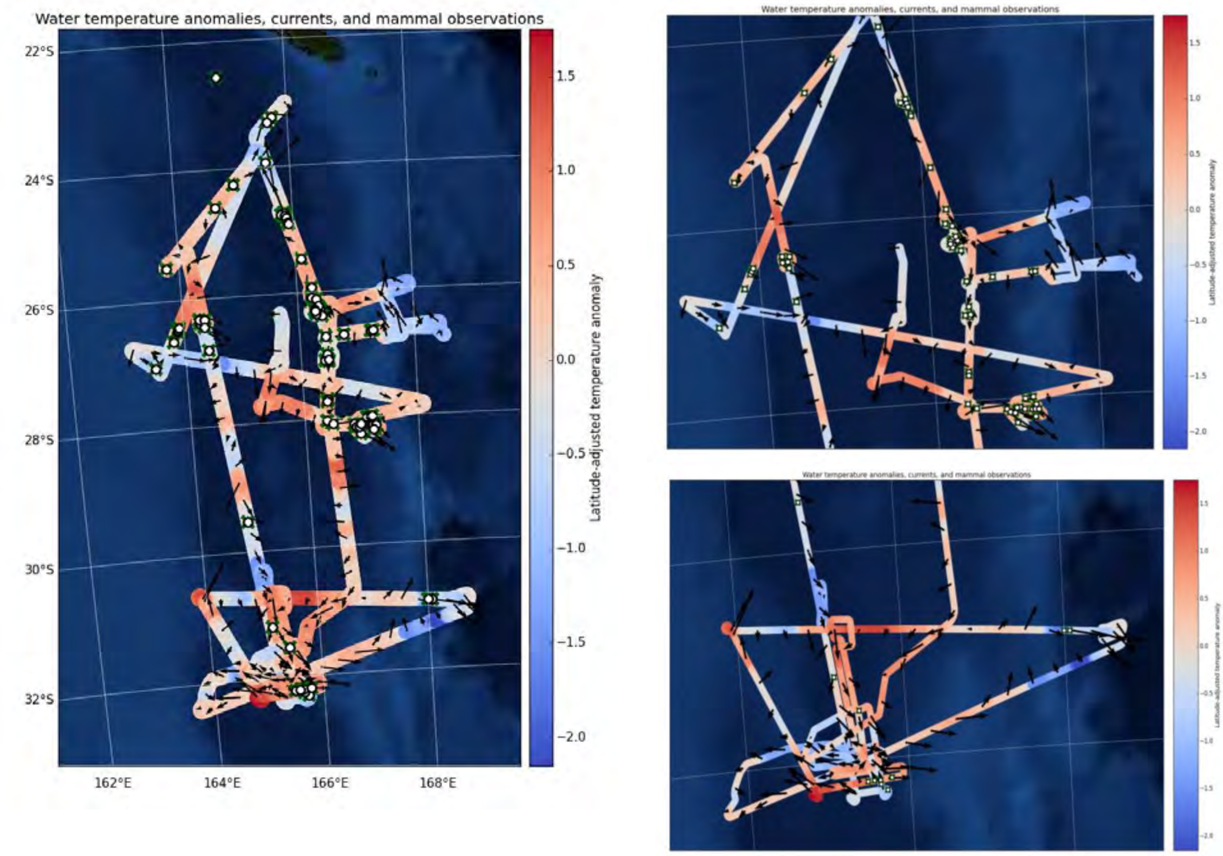

Figure 42- Map of water temperature anomalies, currents and marine mammal observations

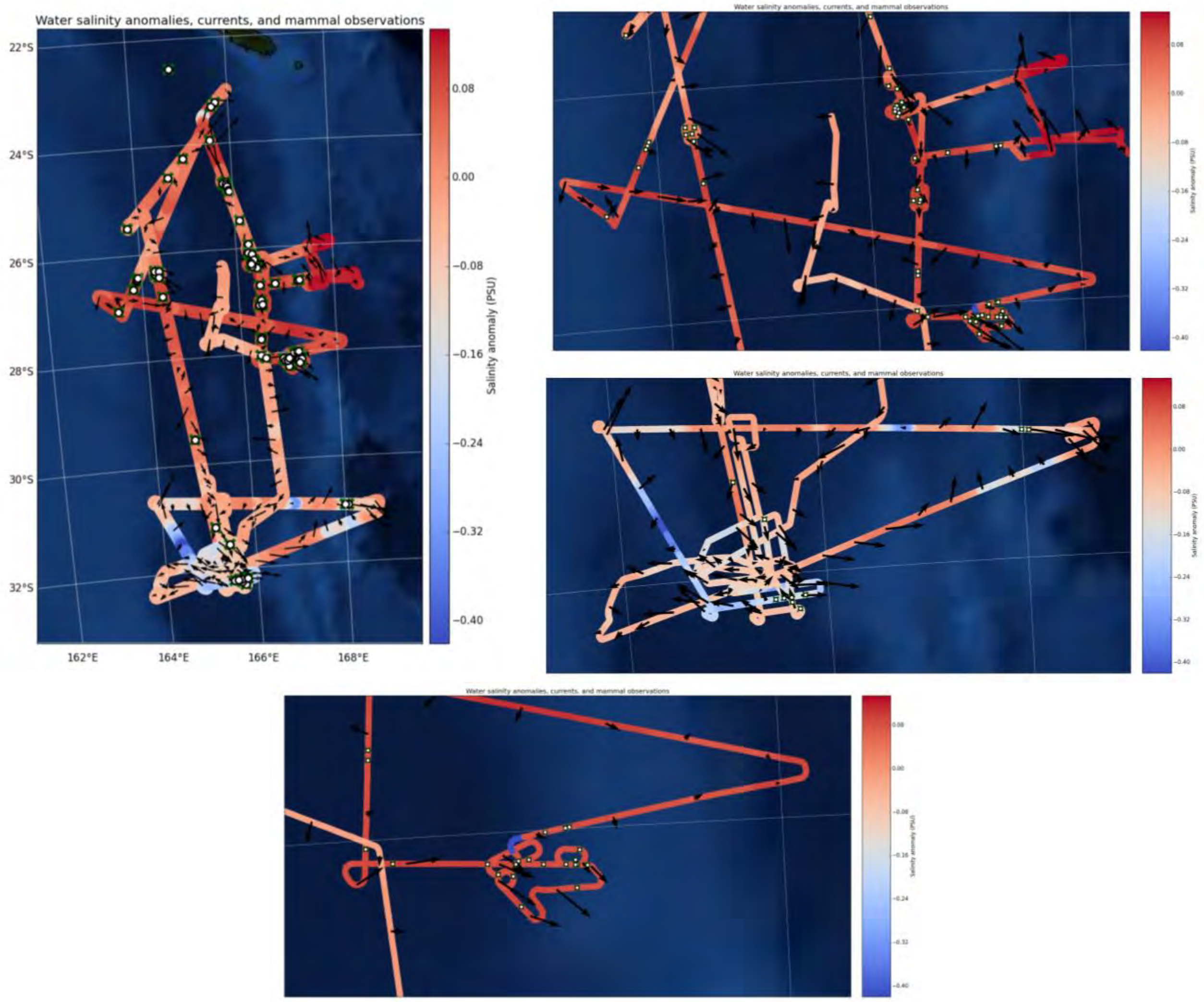

Figure 43- Map of water salinity anomalies, currents and marine mammal observations

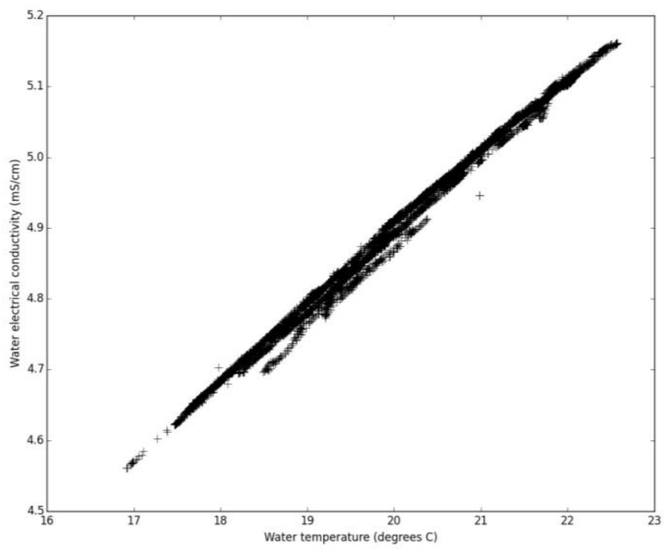

Figure 44 – Water temperature vs. water electrical conductivity

4.6.2 Environmental impact mitigation

The acquisition of seismic reflection data is subject to stringent environmental control, notably with respect to the impact of acoustic noise on marine mammals. An impact study was conducted prior to the voyage (Ducatel et al., 2014). This study reviewed the known marine fauna in the study area, and modeled the acoustic signature of the source in order to establish thresholds risks, exclusion zones and mitigation procedures.

Five independent observers from ULR Valor of the University of La Rochelle organized their work in shifts in order to make observations 24 hour a day. A summary of the protocols and of the of marine wildlife observed are presented in this report. Full details can be found in the dedicated report prepared by the observers (Peltier et al., 2015).

4.6.2.1 Marine mammal observers and PAM operators

During the entire length of the voyage, protocols for the mitigation of the impact on marine mammals of the sound emitted by the seismic source were implemented. Three independent Marine Mammal Observers (MMOs) and two dedicated Passive Acoustic Monitoring (PAM) operators were contracted for this task. The MMOs visually observed all mega-fauna during daylight hours. The PAM operators complemented the visual observations during the day, and monitored presence of marine mammals during night time and during periods of low visibility.

Both MMOs and PAM operators had direct authority to stop the seismic source.

4.6.2.2 Mitigation protocols

Because no regulation exists for New Caledonia waters regarding seismic acquisition, the Ifremer Guidelines were implemented when the vessel was in New Caledonia waters (see Appendix 6.2 for full protocol).

For Australian waters, International waters and Extended Continental Shelf of New Zealand waters, the Australian guidelines (EPBC Act Policy Statement 2.1) were used, as they were more strict, due to two additional conditions (see Appendix 6.1 for full protocol).

Ifremer and Australian guidelines follow very similar mitigation schemes with slight differences in procedures. Table 4 synthesizes these differences.

	IFREMER Guidelines	AUSTRALIAN Guidelines
Species	All marine mammals	Whales including all baleen whales, sperm whales, beaked whales, pilot whales, killer whales, false killer whales
Pre-search	Required (30 minutes)	Required (30 minutes)
Reduced Power	none	2 km radius from source (Low power zone)
Shut Down Zone	500 m	500 m
Soft Start/Ramp Up	Required (30 minutes)	Required (30 minutes)
Delay soft start	Delayed until cetacean detected outside of 500m or not detected for 30 minutes	Delayed until cetacean detected outside of 2km or not detected for 30 minutes
Extra rules	none	If during a 24h period, three or more shut-downs or reduced power were initiated due to whale detections, it is not possible to start up again at night or during time of low visibility.
Pre-search at night/low vis	Not allowed	Allowed
Line turns	Not defined	Reduce to lowest gun
After detection	Soft start procedure can commence if animal detected outside of 500m zone or not detected for 20 minutes	Soft start procedure can commence if animal detected outside of 2km zone or not detected for 30 minutes

Table 4 – Comparison between Ifremer and Australian mitigation protocols applied during TECTA

Ifremer mitigation zone

According to the Ifremer guidelines, the mitigation zone was established on the basis of a quantitative predictive analysis of the sound levels generated by the TECTA seismic source (Ducatel et al., 2014). These calculations showed that marine mammals could be physically impacted within a radius of 250 m around the source. A precautionary factor of 2 was taken and the exclusion zone was set to 500 m around the source.

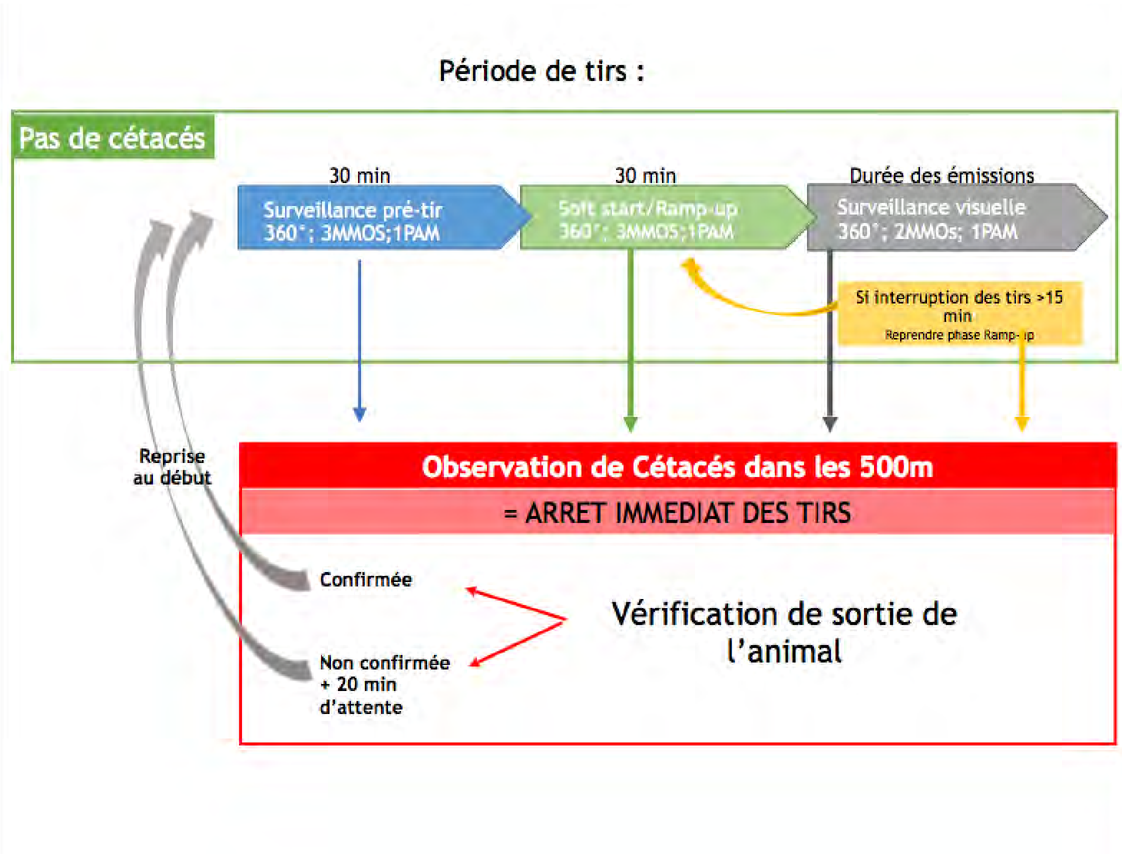

Figure 45 – Scheme of Ifremer mitigation procedure

Ifremer Mitigation procedures

Before initiating firing, a pre-observation (Pre-watch) must be carried out by 3 MMOs and a PAM for at least 30 minutes to detect potential animals within the mitigation zone. Pre-watch cannot be done during night time or low visibility conditions.

If no animals are detected, Ramp-up (low power increasing) can begin during 30 minutes. The source is started progressively. Each airgunis first fired individually, during one minute. After this sequence, airguns are then started one by one, every minute, starting with the smallest volumes to the largest volumes, and progressively increasing the total emission power. Table 5 synthetizes this ramp-up procedure. The goal of the ramp-up is to allow marine mammals which were not detected during the pre-watch or newly arrived in the zone, to leave the exclusion zone. During the ramp-up, 3 MMO and 1 PAM continue visual and acoustic observations.

At the end of the ramp-up, the full power operation of the source array can start. The visual survey is executed continuously by 2 MMOs as long as observation conditions (weather and visibility) allow it. The visual observations are complemented by the PAM operator, who is also operational at night.

If an animal is observed during the pre-watch, a new 30 min pre-watch must be performed once the animal is confirmed to have left the exclusion zone. If the animal is not observed again and it is not possible to confirm it has left the exclusion zone, a 20 min delay must be respected before lead off the 30 min pre-watch.

If an animal is observed during the ramp-up, shots are stopped immediately. A new 30 min pre-watch must be performed once the animal is confirmed to have left the exclusion zone. If the animal is not observed again and it is not possible to confirm it has left the exclusion zone, a 20 min delay must be respected before leading off the 30 min pre-watch.

T=00 min Air Gun 9Bd (140 bars)
T=01 min Air Gun 9Td (140 bars)
T=02 min Air Gun 1Bd (140 bars)
T=03 min Air Gun 1Td (140 bars)
T=04 min Air Gun 2Bd (140 bars)
T=05 min Air Gun 2Td (140 bars)
T=06 min Air Gun 3Bd (140 bars)
T=07 min Air Gun 3Td (140 bars)
T=08 min Air Gun 4Bd (140 bars)
T=09 min Air Gun 4Td (140 bars)
T=10 min Air Gun 5Bd (140 bars)
T=11 min Air Gun 5Td (140 bars)
T=12 min Air Gun 6Bd (140 bars)
T=13 min Air Gun 6Td (140 bars)
T=14 min Air Gun 7Bd (140 bars)
T=15 min Air Gun 7Td (140 bars)
T=16 min Air Gun 8Bd (140 bars)
T=17 min Air Gun 8Td (140 bars)
T=18 min Air Guns 1Bd (140 bars)
T=19 min Air Guns 1Bd + 1Td (140 bars)
T=20 min Air Guns 1Bd + 1Td + 2Bd (140 bars)
T=21 min Air Guns 1Bd + 1Td + 2Bd + 2Td (140 bars)
T=22 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd (140 bars)
T=23 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td (140 bars)
T=24 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd (140 bars)
T=25 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd + 5Td (140 bars)
T=26 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd + 5Td + 7Td (140 bars)
T=27 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd + 5Td + 7Td + 8Bd (140 bars)
T=28 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd + 5Td + 7Td + 8Bd + 9Bd (140 bars)
T=29 min Air Guns 1Bd + 1Td + 2Bd + 2Td + 4Bd + 4Td + 5Bd + 5Td + 7Td + 8Bd + 9Bd + 9Td (140 bars)

Table 5 – Ramp Up procedure for the TECTA Multi-channel seismic source. Shot interval 50 m

If during full power time an animal is detected in the exclusion zone (shutdown zone), seismic air guns have to be stopped immediately. Any discussions have to take place after shutdown. A new 30 min pre-watch must be performed once the animal is confirmed to have left the exclusion zone. If the animal is not observed again and it is not possible to confirm it has left the exclusion zone, a 20 min delay must be respected before lead off the 30 min pre-watch.

If airguns are stopped for a period exceeding 15 minutes, for example related to a technical failure of compressors, the ramp-up procedure must be applied. If the airguns are stopped for a period less than 15 minutes, full power can be re-started without pre-watch and ramp-up.

Australian mitigation zone

In the Australian guidelines, the mitigation zone is differentiated in two exclusion zones:

- a 500 m zone called "exclusion zone" in which if an animal is detected the source should be stopped immediately (shutdown).
- a zone in between 500 m and 2 km called "low power zone" in which if an animal is detected the source should be reduced to the lowest power setting (power down), which was in our case a single 75 cu airgun. However, since the depth imaging penetration objectives of TECTA were not met with a single 75 cu airgun and given the fact that the continuity of seismic reflectors was an important objective of the voyage, we decided to not operate in low power, but rather stop shooting altogether. This procedure was applied during the entire voyage except once along the Norfolk Ridge along profile TEC10, where acquisition continued with a single 75 cu airgun.

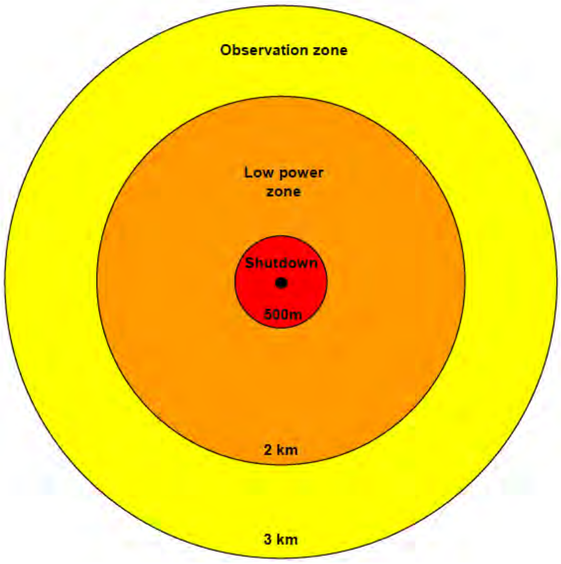

Figure 46 – Australian mitigation zones

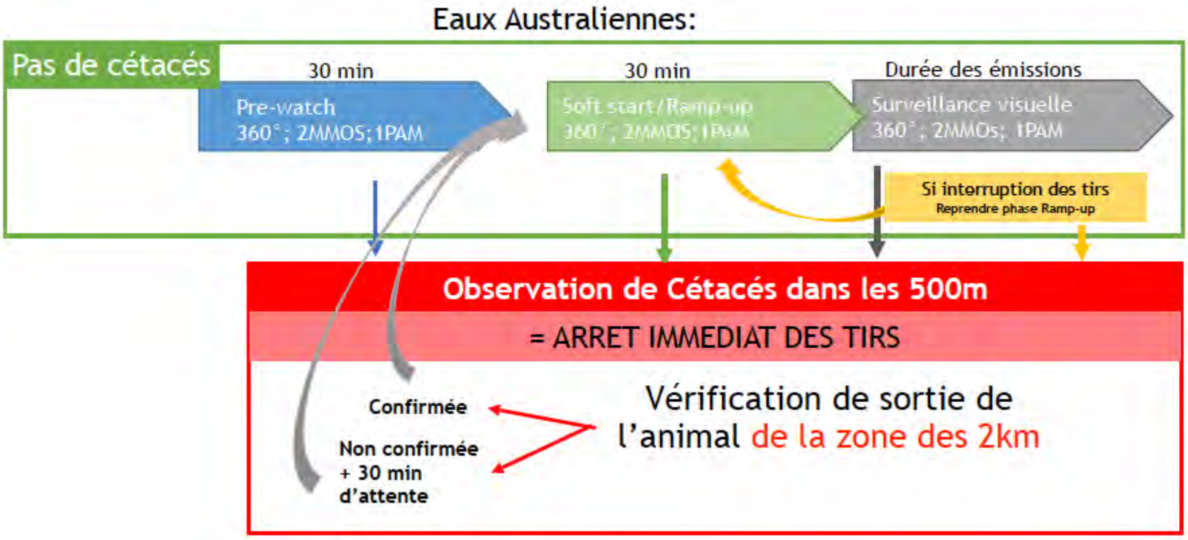

Figure 47 – Scheme of Australian mitigation procedure

Australian Mitigation procedures

Before initiating airgun firing, a pre-observation (Pre-watch) must be carried out by 2 MMOs and a PAM for at least 30 minutes to detect potential animals within the mitigation zone. Pre-watch can be done during night time or with low visibility conditions with the use of PAM.

If no animals are detected, Ramp-up (successive power increase) can begin during 30 minutes. The source is started progressively. Each airguns is first fired individually during one minute, starting with the smallest airgun. Subsequently, all airguns are started, in sequence, every minute, starting with the smallest volumes to the largest volumes, gradually increasing the total power of the source. Table 5 synthetizes this ramp-up procedure. The goal of the ramp-up is to allow marine mammals which were not detected during the pre-watch or newly arrived in the zone, to flee the exclusion zone. During the ramp-up, 2 MMO and a PAM continue visual and acoustic observations.

At the end of the ramp-up the full power operation can start. The visual survey is executed continuously by 2 MMOs as long as observations conditions (weather and visibility) allow it. The visual survey is complemented by the PAM operator, who is also operational at night.

If an animal is observed during the pre-watch, a new 30 min pre-watch must be performed once the animal is confirmed to have left the 2 km radius zone. If the animal is not observed again and it is not possible to confirm it has left the 2 km radius zone, a 30 min delay must be respected before lead off the 30 min pre-watch.

If an animal is observed during the ramp-up, shots are stopped immediately. A new 30 min pre-watch must be performed once the animal is confirmed to have left the 2 km radius zone. If the animal is not observed again and it is not possible to confirm it has left the 2 km radius zone, a 30 min delay must be respected before starting the 30 min pre-watch.

If during full power acquisition an animal is detected in the exclusion zone (shut-down zone), seismic air guns have to be stopped immediately. If an animal is observed in the low power zone, the source should be reduced to the lowest power setting (power down), a single 75 cu airgun. Any discussions will have to take place after the stop. A new 30 min pre-watch must be performed once the animal is confirmed to have left the 2 km radius zone. If the animal is not observed again and it is not possible to confirm it has left the 2 km radius zone, a 30 min delay must be respected before lead off the 30 min pre-watch.

If airguns are stopped, for example related to a technical failure of compressors, the ramp-up procedure must be applied.

Additional Conditions of the Australian guidelines:

- If power downs are required for humpback whale 3 times or more per day during consecutives 3 days, the full power can't be executed at night or during low visibility. Recovery in these conditions can't be done after 24h period with good visibility without power down for this species.
- If power downs are required 3 times within 24h for baleen whales visual observations, full power are still allowed at night, but in interruption case (mechanic or as for cetaceans), initiated ramp-up could be initiated only during day.

The Australian guidelines were written entirely for visual observation. There is no indication in the guidelines themselves and the referral did not clarify PAM specific aspects either. PAM was therefore not required but in order to prevent as much as possible the effect of the source on marine mammals, the PAM was used during the entire length of the voyage as a precaution.

In Australian waters, this procedure should be applied to "whales" includes baleen whales and larger toothed whales, such as sperm whales, killer whales, false killer whales, pilot whales and beaked whales. Other (smaller) dolphins and porpoises do not fall under the same regulation, as they have peak sensitivities in higher frequency ranges and are likely to be less disturbed by the lower frequency sounds emitted by the air guns, and less vulnerable to acoustic trauma.

4.6.2.3 Passive Acoustic Monitoring System used

The PAM system used during the TECTA voyage is a 4 channel Seiche hydrophone including a depth sensor. The hardware includes a computer, a buffer box (deck cable interface, signal conditioning and output distribution), two sound cards as well as a depth converter.
The open source software used is Pamguard, currently funded by Pam operators in oil and gas industry. The settings of the software were tailored for the purposes of this survey.
The Pamguard software includes general modules such as utilities (database and binary storage) as well as customized modules to detect cetaceans (spectrograms and click detectors).

Hydrophone Array:

As the system incorporates two sound cards (Fireface 800 and National Instrument card) with four channels the hydrophone array was set up accordingly. The Fireface 800 was used for hardware channels 0, 2 and 3. The distance between the channels was measured to the nearest centimeter. Channel 0 and 2 were used for the low frequency click detector (for sperm whale detection) as a greater distance between hydrophones aids detection for low frequencies. Channel 3 corresponds to the low frequency hydrophone used to construct low frequency spectrograms to detect baleen whales.

During the first week of TECTA voyage, several pod of cetaceans were detected acoustically. A majority of delphinids, but pilot whale, blackfish and humpback whale were also detected.

Figure 48 is a screenshot showing the observation of several train clicks (red oval). Each one is tracked to try and localize the pod. Here, four individuals can be detected. The graph in the bottom middle of the window shows a high level of energy around 25 kHz (green oval), demonstrating the presence of odontocetes clicks.

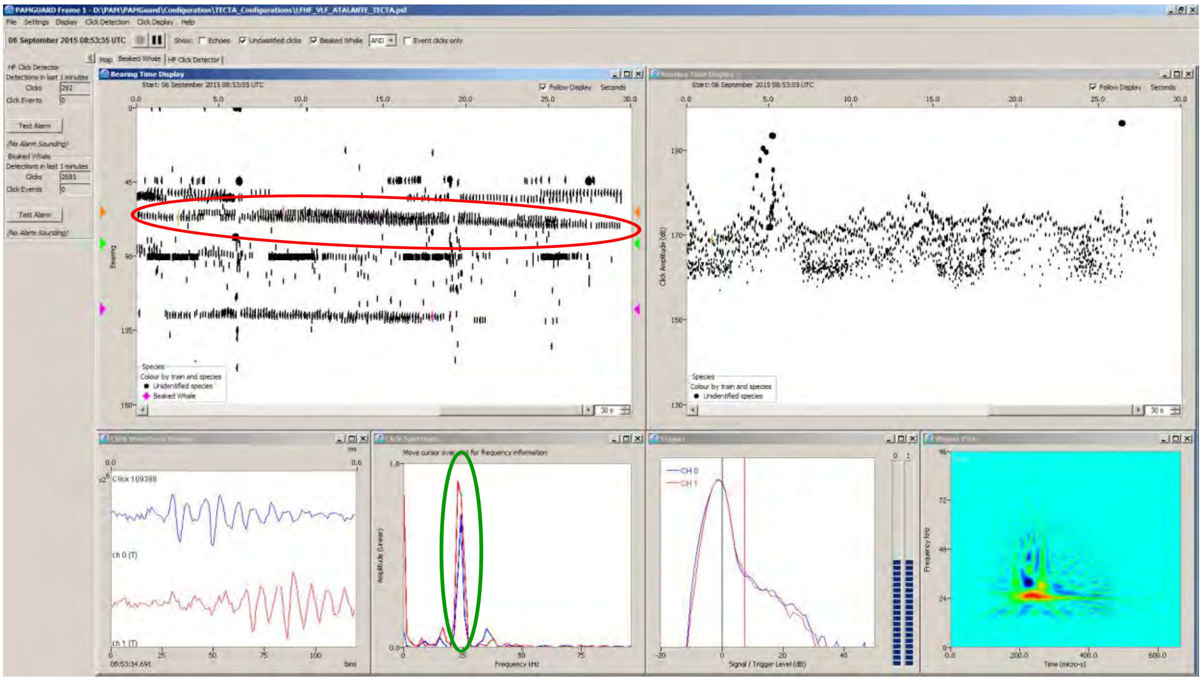

Figure 48 - Screenshot of the Pamguard operation panel

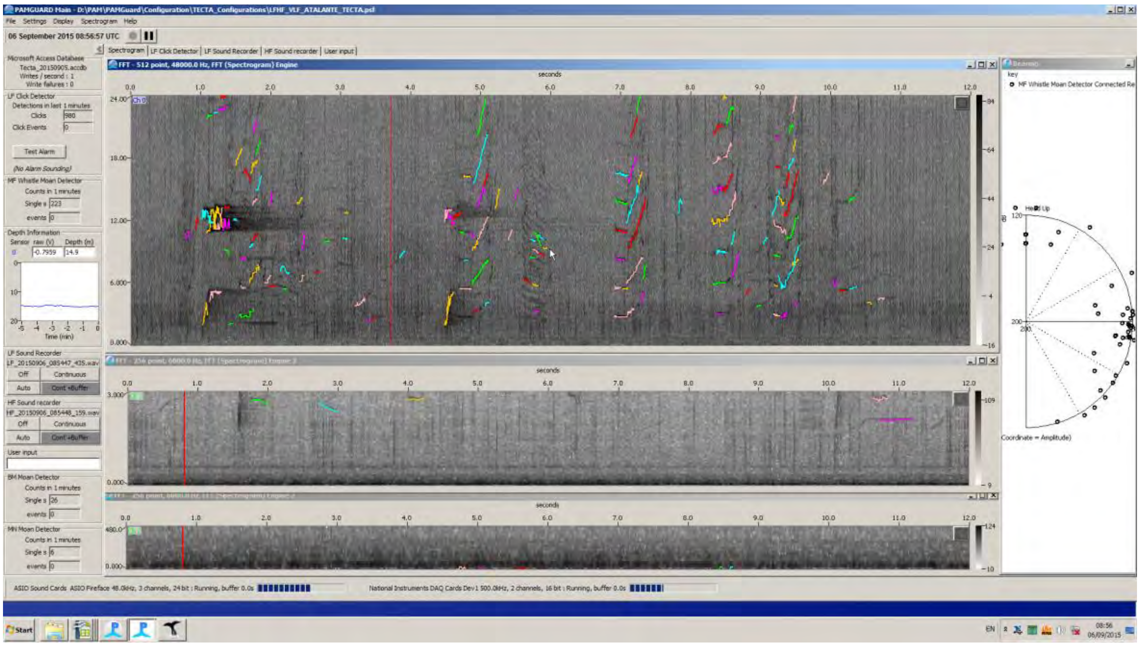

Figure 49 - Visualization of marine mammal whistles using Pamguard

The screenshot in Figure 49 shows whistles that are observed in the frequency range between 3 and 24 kHz. These whistle profiles are characteristic for pilot whale or Fraser's dolphins. On the right-hand side, the software provides an indication of the approximate location of the sources of these whistles.

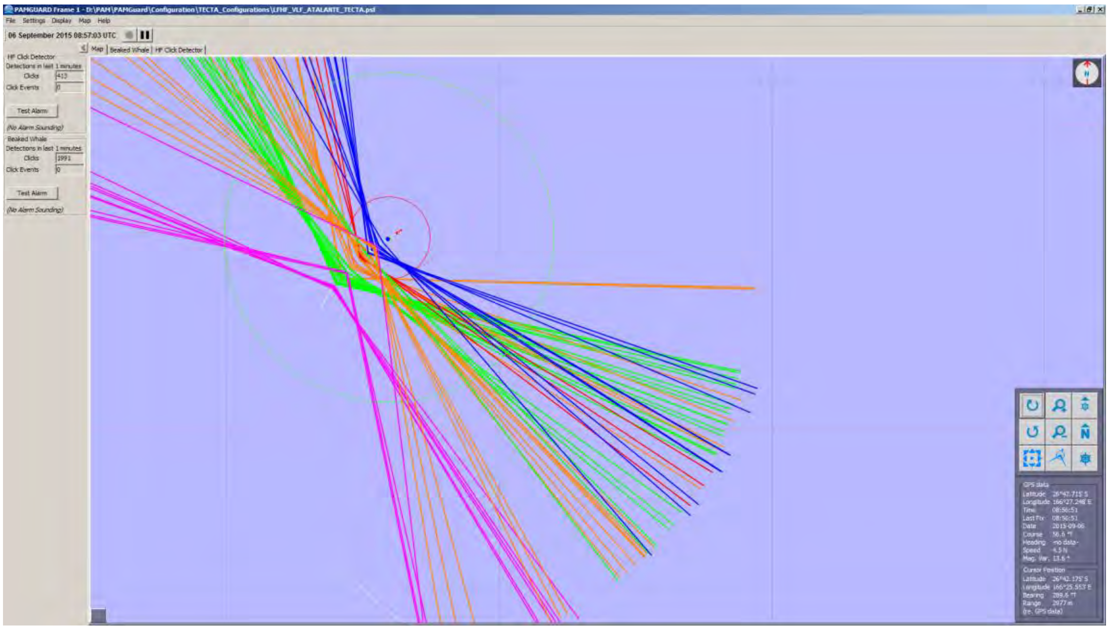

Figure 50 - Map showing the azimuth of click train detections. Subsequent azimuth determinations of the same individual allow estimating its position by triangulation

Finally, Figure 50 shows a map that visualizes the direction from which detected click trains are coming. When several lines of the same color, associated with the same individual, are crossing, this gives an estimation of the location of the animal. Here, blue lines are crossing within the mitigation zone (red circle) and the orange, red, green and blue lines are crossed inside the low power zone (green circle). Using such evidence, the PAM operator orders the air guns to be stopped immediately.

4.6.3 Mitigation actions

During the voyage, 17 observations, out of 78, led to mitigation actions, from which 5 were MMO sightings and 12 PAM detections.

Out of these 17 mitigation actions :

- 12 led to seismic shutdowns : 3 MMO sightings which required direct shutdowns, 6 PAM detections which required direct shutdowns and 3 PAM detections which required reduce power followed by shutdowns,
- 3 led to ramp-up delays : 1 MMO sighting and 2 PAM detections,
- 2 led to reduced power : 1 MMO sighting and 1 PAM detection.

Figure 51 illustrates the mitigation actions taken during the voyage.

Animals related to shutdowns :
All 3 MMO sightings which led to shutdowns were related to pilot whales sightings in the exclusion zone. All were in Australian waters.
From the 6 PAM detections which led to direct shutdowns, 2 were delphinids in the New Caledonia waters and 4 delphinids or/and blackfish (3 in Australian waters and 1 in New Caledonia extended continental shelf).
All 3 PAM detections which led to reduce power followed by shutdowns were Delphinids or/and blackfish in Australian waters.

Animals related to delayed ramp-ups
The MMO sighting which led to ramp up delay was a humpback whale sighting in the low power zone (at about a 1 km distance) in Australian waters.
The 2 PAM detections which led to ramp up delays were related to Blackfish and/or delphinids and were in Australian waters.

Animals related to reduced power
The PAM detection which led to reduce power was related to Blackfish and/or delphinids and the MMO sighting which led to reduce power was related to a pilot whale.

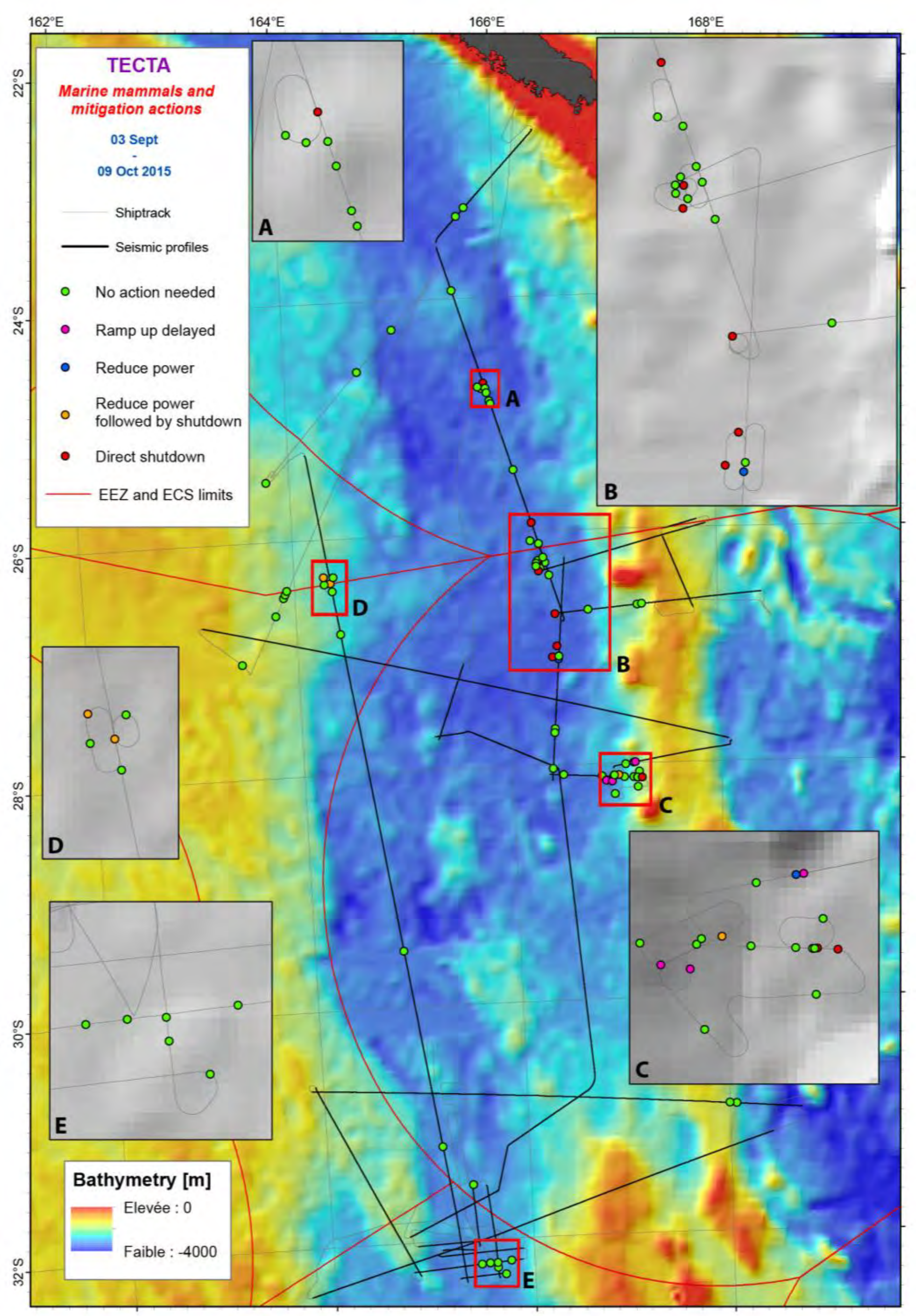

Figure 51 – Location map of marine mammal mitigation actions taken during TECTA

4.6.4 Marine wild-life observations

Research voyages often occur in areas where little is known about marine megafauna. During the TECTA voyage, MMOs and PAM operator had, therefore, in addition to their mitigation role, a data acquisition role. Even out of the seismic acquisition phases (e.g. during transits or maintenance phase) observations of marine wild-life were made. These observations were done according to the protocol of PELAGIS Observatory, also usually used on fishing surveys of Ifremer (protocol MEGASCOPE). All marine megafauna are identified (marine mammals, seabirds, turtles, large pelagic species etc) and the presence of ships, wastes and other human activities.

During TECTA, 78 detections of marine mammals were reported. 61 of them were PAM detections and 17 MMO sightings (see Figure 53).

Figure 52 - Samples of cetaceans observations during TECTA, left to right: group of Fraser dolphins, pod of pilot whales and a humpback whale.

Of particular note was the high incidence of Pilot Whales in the region. To our knowledge, this had not been not previously documented.

Other notable observations were: two turtles, one of which was olive coloured (Lepidochelis olivacea) and a second large individual that could not be identified with confidence but most probably a green turtle or loggerhead turtle, and many flying fish. Regarding seabirds, many Procellariidae and Sulidaes were observed (masked Gannets and albatross howler, black-browed, “timide” and Buller). A large shark was also observed.

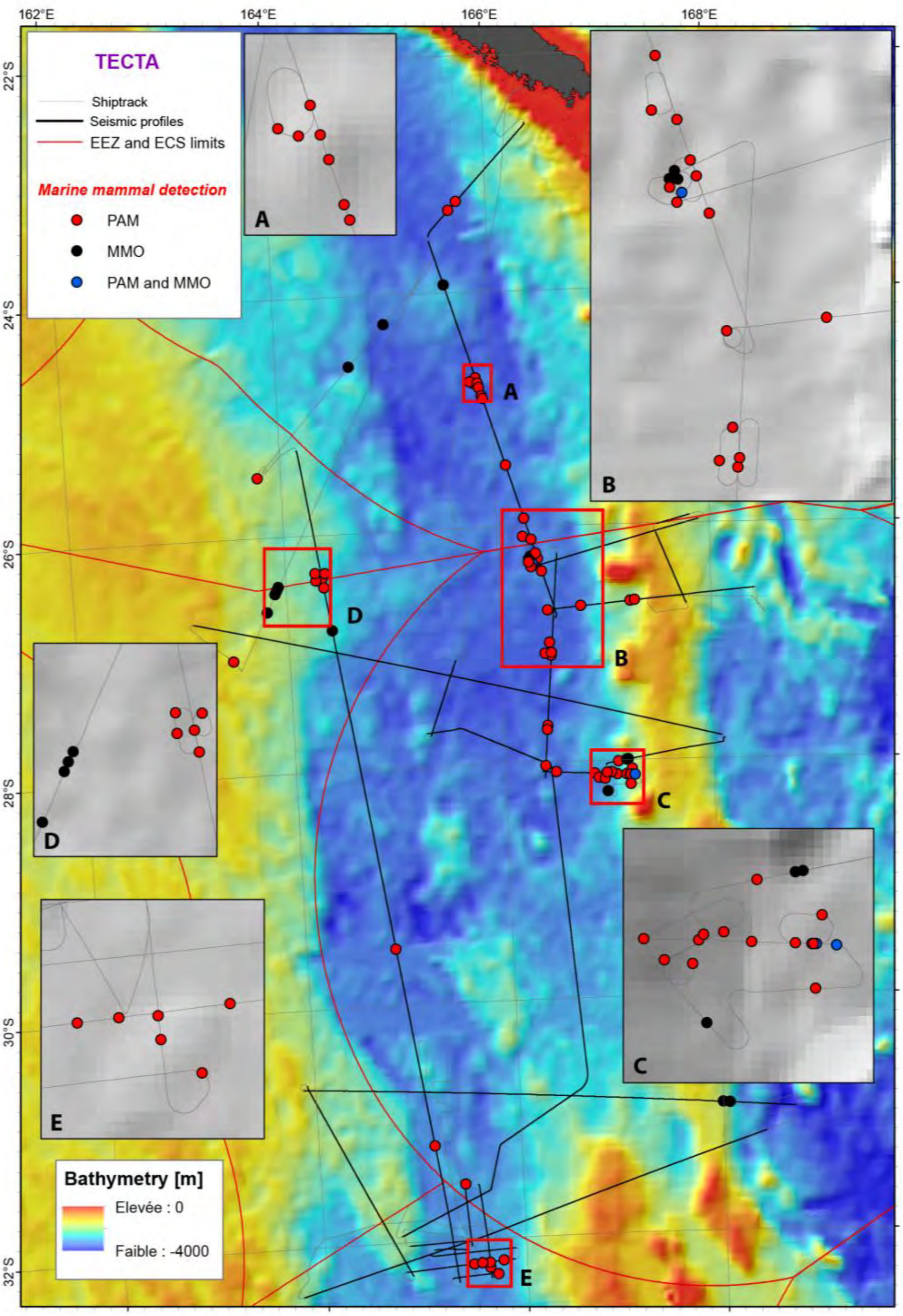

Figure 53 – Location map of marine mammal detections from acoustics (PAM), visual sightings (MMO) or both.

These detections allowed us to identify several species of marine mammals, see Figure 54.

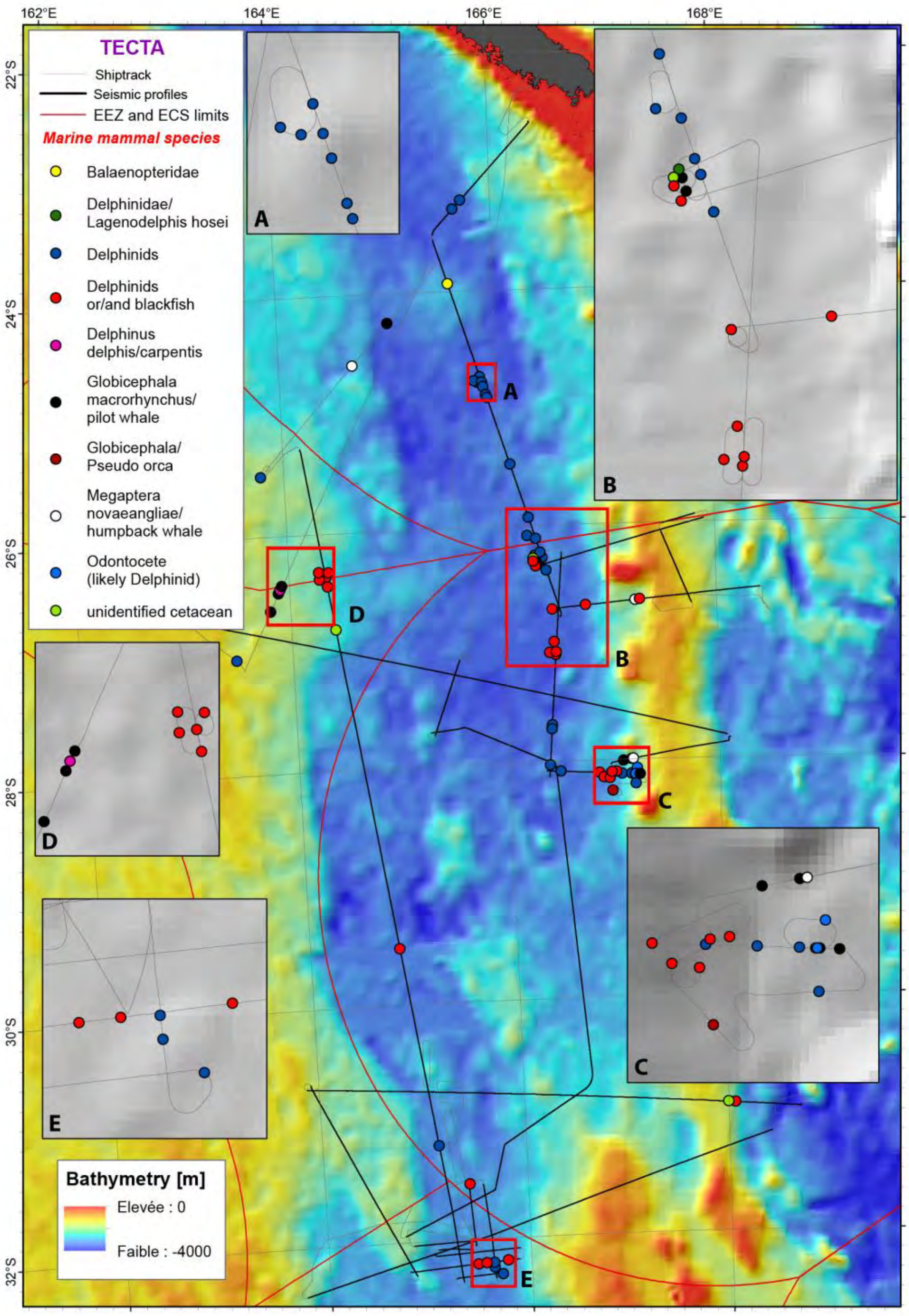

Figure 54 – Location map of marine mammal species identified during TECTA

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