Seismogenesis Hikurangi Integrated Research Experiment (SHIRE): Onshore Seismic Acquisition Field Report

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ABSTRACT

This report documents the acquisition and archiving of a major controlled source and passive seismic imaging project, the Seismogenesis Hikurangi Integrated Research Experiment (SHIRE). The SHIRE project aims to identify and quantify factors controlling the long-term evolution of the Hikurangi margin and the mode of slip along the subduction megathrust. The components of the data volume were acquired in two phases; between October 2017 – April 2018 (SHIRE I) and February–March 2019 (SHIRE II). The project was conducted by GNS Science; the University of Southern California, USA; the University of Texas Institute for Geophysics, USA; Victoria University of Wellington; and the Earthquake Research Institute, University of Tokyo, Japan.

During SHIRE I, 5489 km of 2D seismic reflection data was collected offshore Bay of Plenty and East Coast by the *R/V Marcus G. Langseth*, and wide-angle refraction and reflection data were recorded onshore by 89 short-period seismograph sites along a transect from the Bay of Plenty to Gisborne and distributed array throughout the Tairāwhiti / Raukumara Peninsula. In addition, 25 short-period seismometers were located along the Bay of Plenty coast between October–December 2017. The SHIRE I land instruments also recorded signals from the 15 x 60 km volume of 3D seismic reflection data that was collected offshore Gisborne by the *R/V Marcus G. Langseth* during January 2018, plus four months of local and teleseismic earthquakes. SHIRE II aimed to directly image the crust beneath the Tairāwhiti / Raukumara Peninsula. Five borehole explosive sources were distributed along the central transect. The energy was recorded on 583 temporary seismograph stations comprising 304 vertical component and 269 three-component seismometers. The explosions were detonated during 26–28 February 2019. In addition, 19 SHIRE I 2D array sites were reoccupied for 20 days. The quality of the data recorded was excellent for all the explosion sources.

PLAIN LANGUAGE SUMMARY

The Hikurangi subduction zone, where the Pacific tectonic plate dives beneath the North Island along the East Coast, is a globally unique natural laboratory to understand the processes that control the generation of earthquakes and tsunami. This report documents the acquisition of seismic data to provide three-dimensional CAT-scan-like images of the subduction zone to determine what influences slip behaviour on the subducting interface. The project is called SHIRE (Seismogenesis Hikurangi Integrated Research Experiment) and is one of several national and international Earth Science projects aimed at unlocking the secrets of the Hikurangi subduction zone.

Scientists undertook SHIRE in two phases; between October 2017 – April 2018 and then, a year later, February–March 2019. In the first year, 114 temporary seismographs were located along a profile running between Gisborne and Ōpōtiki. They were also placed at other localities across the Tairāwhiti / Raukumara Peninsula and along the Bay of Plenty coast. The instruments recorded energy from sound sources, generated by a scientific research vessel operating offshore, and recorded natural earthquakes during the four-month period. In the second year, an array of 602 seismograph sites were deployed from coast to coast to record five controlled underground explosions. The explosions occurred during 26–28 February 2019, and the echoes recorded at each site add to data collected in phase one. These data provide the best detail of the Hikurangi subduction zone to date. The combined land and marine SHIRE project involved more than six years of planning. The success of the project is attributed to careful long-term planning with iwi, landowners, Regional Councils and contractors.

KEYWORDS

Seismogenesis Hikurangi Integrated Research Experiment, SHIRE, Active Source, Seismic Array, Hikurangi Margin, Tairāwhiti, Raukumara, Gisborne, subduction interface, SHIRE I Media library ID U00076 , SHIRE II Media library ID U00087, doi 10.21420/PEQZ-BR17

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DEDICATION

This report is dedicated to Kirk McIntosh, who was the lead investigator of the United States science party for the SHIRE project. Kirk had a lifelong passion for forearc tectonics and the geological processes that contribute to seismic hazards along subduction zones. As a graduate student at the University of California at Santa Cruz, Kirk became well known for seismic imaging of the Costa Rica subduction zone. He later took a position at the University of Texas Institute for Geophysics, where he carried out field projects in Nicaragua, Taiwan and many other places. Kirk's observations of subduction zones, including normal faulting in bending plates, the fate of subducting seamounts and the interaction between incoming sediments and forearc prisms, has improved our understanding of tectonic plate boundaries worldwide. With his easy-going demeanour and generous spirit, Kirk helped to form a large international team of scientists from different research disciplines to carry out the SHIRE project. He took the lead on several proposals that ultimately led to funding for the concerted multi-institutional effort. In the year before data acquisition, Kirk took the lead in the design of the offshore seismic survey and helped with scouting for the SHIRE I fieldwork. Kirk's smile and charm was greatly appreciated by farmers and landowners throughout the Tairāwhiti/Raukumara region. Though we miss Kirk, we are honoured to dedicate this report to him in fulfilling his dream of acquiring the SHIRE data and helping to contribute to understanding of earthquake hazard potential to a wide community.

Kirk McIntosh at Site 523, 27 February 2017. Photo courtesy of Stuart Henrys.

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1.0 INTRODUCTION

Knowledge of the processes governing earthquakes at subduction zones is needed to understand and mitigate hazards posed by these major plate boundaries. Recent devastating subduction earthquakes and tsunami highlight our lack of understanding of the nucleation and propagation of seismic slip at subduction plate boundaries (Lay et al. 2012). The Hikurangi subduction margin, New Zealand (Figure 1.1), has not experienced any major (> Mw 7.2) subduction interface earthquakes since historical record-keeping began ~160 years ago (Webb and Anderson 1998). In the period from 1840 to the present day, there have been 10 large (Mw 7.0) damaging earthquakes in the overriding Australian plate, including the devastating 1931 Napier Mw 7.8 event (Webb and Anderson 1998). Paleoseismic interpretations reveal up to 10 subduction earthquakes may have occurred in the past 7000 years, with the strongest evidence for a full Hikurangi margin rupture at 870–815 years BP (Clark et al. 2019). Determining the seismogenic potential of the interface, and possible resulting tsunami, is critical for estimating seismic hazard in the North Island of New Zealand.

The Hikurangi subduction margin is also an ideal locale to investigate subduction plate boundary processes as it exhibits contrasting behaviour along its length (Figure 1.1); in the south, the plate boundary is mostly locked, accumulating stress to be relieved by future earthquakes (stick-slip behaviour), whereas, in the north, it appears to relieve stress by creeping or via slow-slip events (Wallace et al. 2009). This transition in fault behaviour is accompanied by systematic changes in other parameters of the margin (Wallace et al. 2009). Although substantial progress has been made in this area, no single parameter successfully explains the spectrum of slip modes globally, and important questions for science and society remain, including: what governs slip and long-term deformation at subduction zones? To investigate the physical attributes of the Hikurangi margin and the influence of the plate interface slip behaviour and long-term forearc deformation, research institutions in the USA, New Zealand and Japan embarked in 2017 on an ambitious project, integrating paleoseismological studies with geodetic modelling and controlled and natural source seismic imaging onshore and offshore of the Raukumara Peninsula and North Island, New Zealand – the Seismogenesis Hikurangi Integrated Research Experiment (SHIRE) project.

The SHIRE project aims to identify and quantify factors controlling the long-term evolution of the margin and mode of slip along the subduction megathrust. SHIRE will also investigate the long-term geological record that likely reflects processes linking forearc uplift, sediment transfer and underplating, plate boundary strength and seismogenesis. Specifically, the hypotheses being tested by the SHIRE project include:

- High fluid pressure on the megathrust reduces effective normal stress, promoting stable sliding and/or failure in repeating slow-slip events.
- Rough subducting seafloor promotes aseismic creep associated with heterogeneously distributed pore pressure, stress and frictional behaviour along the plate interface.
- Subduction of thickened Hikurangi Plateau crust drives both long-term uplift of the forearc and increased normal stress across the plate interface.
- Both the locations of slow-slip events (SSEs) and forearc uplift are related to underplating of sediment to the lower crust of the overriding plate.
- The distribution of stick-slip versus creep behaviour persists through many seismic cycles.

To address the goals, controlled and passive source datasets were acquired along the Hikurangi margin, focused on the northern Hikurangi margin and Raukumara Peninsula (Table 1.1, Figure 1.1, Figure 1.2 and Figure 1.3). This report documents the acquisition and archiving of onshore SHIRE data that was acquired in two field seasons between October 2017 – April 2018 (SHIRE I) and February–March 2019 (SHIRE II). Marine seismic reflection data (Bangs and Shipboard Party 2018) and ocean bottom seismometer (OBS) refraction data (Barker et al. 2019) that were gathered during concurrent voyages on the *R/V Marcus G. Langseth* and the *R/V Tangaroa* are described in two cruise reports (Table 1.1).

SHIRE data add to and complement previous seismic projects along the East Coast of the North Island; NIGHT (Henrys et al. 2003a, b; Henrys et al. 2006), 05CM (Barker et al. 2009), RAU07 (Bassett et al. 2010; Sutherland et al. 2009), MANGO-1 (Scherwath et al. 2010), PEG09 (Bland et al. 2015) and SAHKE (Henrys et al. 2020; Henrys et al. 2013; Seward et al. 2010, 2011) (see Figure 1.1). The combined new and legacy seismic surveys provide a margin-wide dataset capable of imaging the 3D architecture of the subduction margin. The new constraints on physical properties and deformation, provided by seismic imaging, will be integrated using numerical modelling to test controls on subduction thrust slip behaviour and long-term margin evolution. Many components of the SHIRE I and II projects employed protocols and permitting process, established during the SAHKE I and II projects (Seward et al. 2010, 2011).

Table 1.1 Available datasets collected throughout the two SHIRE field campaigns, 2017–2019.

SHIRE Deployments	Controlled Source Dataset	Purpose	Date	Reference
SHIRE	Marine multichannel seismic, MGL1708	Near-vertical incidence seismic imaging	1 November – 7 December 2017	(Bangs and Ship Board Science Party 2018)
	Marine sources recorded by Ocean Bottom Seismographs, TAN1710	Provides shallow velocity information; receiver gathers provide crustal velocity and wide-angle imaging	23 October – 20 November 2017	(Barker et al. 2019)
	Marine sources recorded by portable land recorders	Receiver gathers provide crustal velocity and wide-angle imaging beneath the coastline	October 2017 – April 2018	This report
	Natural earthquakes recorded by portable land recorders	Provide velocity imaging beneath the land array	October 2017 – April 2018	This report
SHIRE II	Land explosions recorded by portable land recorders	Source gathers provide crustal velocity and wide-angle imaging beneath the land array	February–March 2019	This report
	Natural earthquakes recorded by portable land recorders	Provide velocity imaging beneath the SHIRE II array	February–March 2019	This report

The timing of the SHIRE I components (Table 1.2) also benefited logistically and interacted with several other large ancillary science projects focused in the region (Table 1.3).

Table 1.2 Schedule of SHIRE I, Integrated Ocean Drilling Program D/V JOIDES Resolution expeditions and NZ3D project in the Gisborne region between October 2017 and April 2018.

October 2017	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JOIDES Resolution																															
R/V Marcus Langseth																															
R/V Tangaroa																								SHIRE OBS Deployment							
Land Stations (GSX3)																				ERI deployment											
Land stations (SHIRE I)																SHIRE land station deployment															
Land Stations (NZ3D)																															
Japanese OBS preparation	OBSs arrive at GNS																														
November																															x
JOIDES Resolution																										Exp 372					
R/V Marcus Langseth	SHIRE MCS Seismic Reflection, Oct 26 - Dec 1 at sea																														
R/V Tangaroa	SHIRE OBS Deployment 23-Oct - 22Nov																														
Land stations (SHIRE I)																															
Japanese OBS refurbishment																															
December																															
JOIDES Resolution	Expedition 372 - LWD including Expedition 375 drill sites within the NZ3D area, 26 Nov 2017 - 4 Jan 2018.																														
R/V Marcus Langseth																															
R/V Tangaroa																	NZ3D OBS deployment														
Land Stations (GSX3)												ERI retrieval																			
Land stations (SHIRE I)					SHIRE land servicing																										
Land Stations (NZ3D)															NZ3D land station deployment																
JOIDES Resolution																															
Japanese OBS refurbishment																															
January 2018																															
JOIDES Resolution	Exp 372																														
R/V Marcus Langseth						NZ3D MCS Seismic Reflection, 6 Jan-9 Feb																									
R/V Tangaroa																															
Land stations (SHIRE I)																															
Land Stations (NZ3D)	NZ3D land station deployment (CUBE, GSX, and Broadband instruments)																														
February																													x	x	x
R/V Marcus Langseth																				SISIE Seismic											
R/V Tangaroa																															
Land stations (SHIRE I)															SHIRE land station retrieval																
Land Stations (NZ3D)											NZ3D CUBE/GSX retrieval						NZ3D Broadband deployment until Oct 2018...										-	-	-	-	-
March																															
JOIDES Resolution								Expedition 375, 8 March – 5 May																							
R/V Marcus Langseth	SISE Seismic. 19 Feb. to 20 March																														
R/V Tangaroa																															
Japanese OBS																															
Land Stations (NZ3D)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
April																															x
JOIDES Resolution																									Expedition 375, 8 March – 5 May						
R/V Marcus Langseth																															
R/V Tangaroa	NZ3D OBS pickup																														
Japanese OBS																															
Land Stations (NZ3D)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	NZ3D Broadband deployment until Oct 2018...									

Table 1.3 Ancillary science projects to SHIRE I and II.

Project	Description	Lead PIs	Institutions	Reference
NZ3D-FWI	Onshore component. Imaging the Hikurangi subduction zone along the north Hikurangi margin	Bell R, Fagereng Å, McNeill L	Imperial College London, UK; University of Southampton; Cardiff University; GNS Science	(Bell et al. 2019)
NZ3D	Offshore component. Imaging the Hikurangi subduction zone along the north Hikurangi margin	Bangs N, Silver E, Moore G, Tobin H	University of Texas Institute for Geophysics, University of California Santa Cruz	(MGL1801 Participants 2018)
IODP 372	Creeping gas hydrate slides and Hikurangi LWD	Pecher I, Barnes P	Integrated Ocean Drilling Program	(Pecher et al. 2018)
IODP 375	Hikurangi subduction margin coring and observatories	Saffer D, Wallace L	Integrated Ocean Drilling Program	(Saffer et al. 2018)
BRANZ	Locate earthquakes and determine focal mechanism solutions in the northern TVZ and Whakatane basin	Ebinger C	Tulane University, Victoria University of Wellington, University of Auckland	(Ebinger 2017)
SISIE	South Island Subduction Initiative Experiment	Gurnis M, Gulick S, Stock J, Van Avendonk H, Sutherland R	California Institute of Technology, University of Texas Institute for Geophysics, Victoria University of Wellington	(Stratford et al. 2019)
SAFRONZ	Slow Slip and Fluid Flow Response Offshore New Zealand	Torres M, Harris R, Solomon E	Oregon State University, University of Washington	-
HT-RESIST	Hikurangi Trench Regional Electromagnetic Survey to Image the Subduction Thrust	Chesley C, Naif S, Key K	Lamont-Doherty Earth Observatory, Columbia University	-
-	Study of the impact of seamount subduction on the outer wedge of the Hikurangi margin from combined lab analyses of rock properties and marine seismic data	Van Avendonk H	University of Texas Institute for Geophysics	-

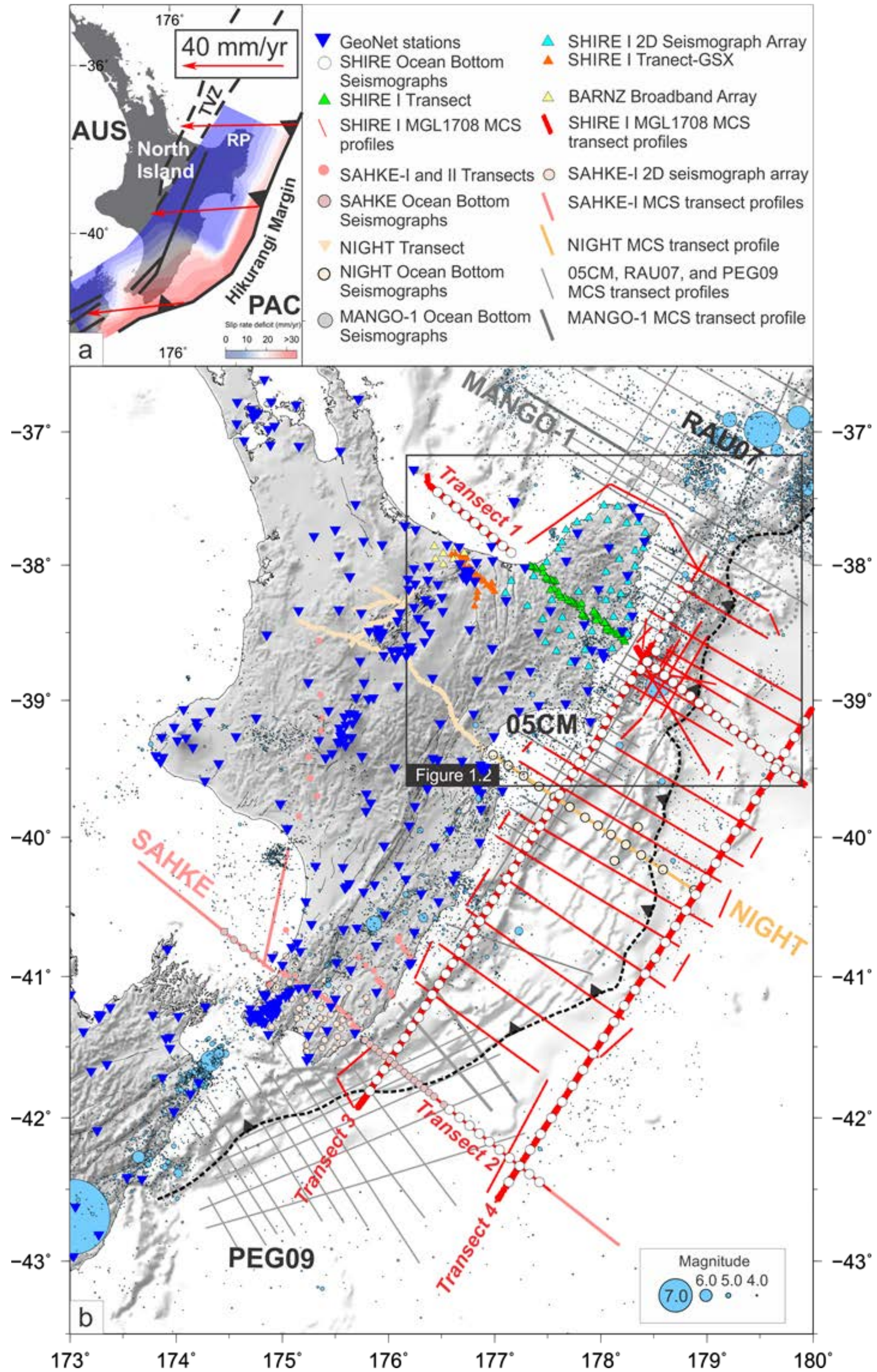

Figure 1.1 Location map. (a) Slip-rate deficit distribution at the plate interface (Wallace et al. 2012a). Red regions are where the plate interface is interseismically locked. PAC = Pacific Plate; AUS = Australian Plate; TVZ = Taupō Volcanic Zone; RP = Raukumara Peninsula. Red vectors show the long-term estimate of convergence between the east coast margin relative to the Pacific Plate in mm/yr. (b) Seismic reflection data coverage of the NIGHT, 05CM, RAU07, MANGO-1, PEG09, SAHKE and SHIRE I surveys across the Hikurangi margin. Earthquake epicentres (Mw >3) from 2000 to 2020 in the depth range 12–36 km (GeoNet catalogue: https://quakesearch.geonet.org.nz/) are shown as light-blue dots; these incorporate plate interface and overlying upper plate events. The size of dots shows the magnitude of the event. Onshore active faults are shown as black lines (http://data.gns.cri.nz/af/).

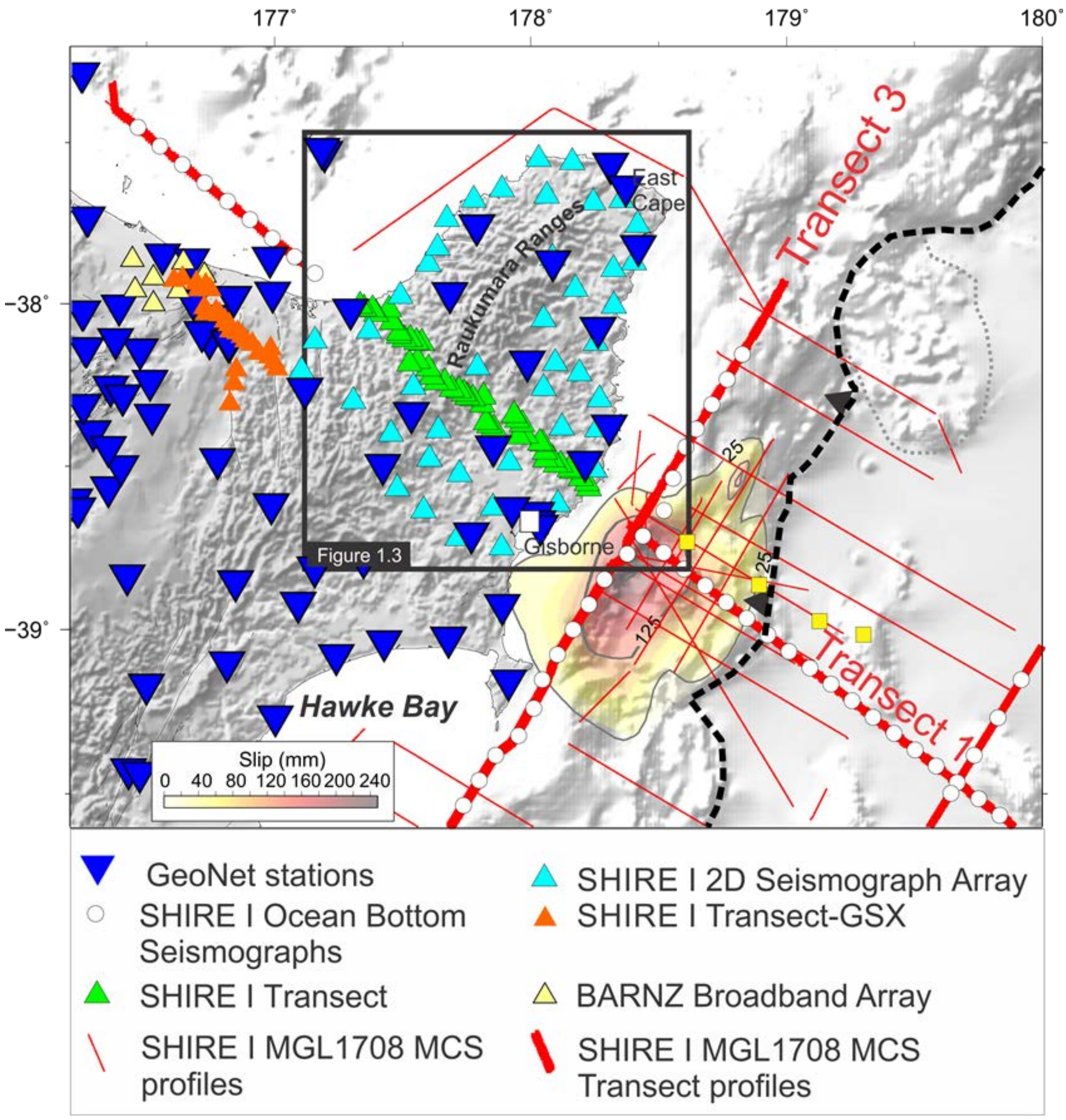

Figure 1.2 Detail of Raukumara Peninsula and SHIRE I onshore seismograph stations (green and light-blue filled triangles are Incorporated Research Institutions for Seismology [IRIS] PASSCAL short-period REFTEK RT130 datalogger and seismometers) and *R/V Marcus G. Langseth* ship tracks (red lines, Bangs and Ship Board Science Party 2018). White-filled circles are ocean bottom seismograph locations (Barker et al. 2019). Orange-filled triangles are GSX3 temporary recorders and seismometers deployed by the Earthquake Research Institute, University of Tokyo. Light-yellow-filled triangles are broadband seismographs deployed by Tulane University. Blue-filled triangles are permanent GeoNet seismograph stations. Yellow boxes are International Ocean Discovery Program Expeditions 372 and 375 drill sites (Pecher et al. 2018; Saffer et al. 2018). Cumulative slip on the interface in the September–October 2014 Gisborne slow-slip event from Wallace et al. (2016) is represented in yellow to brown colours (contours labelled in millimetres).

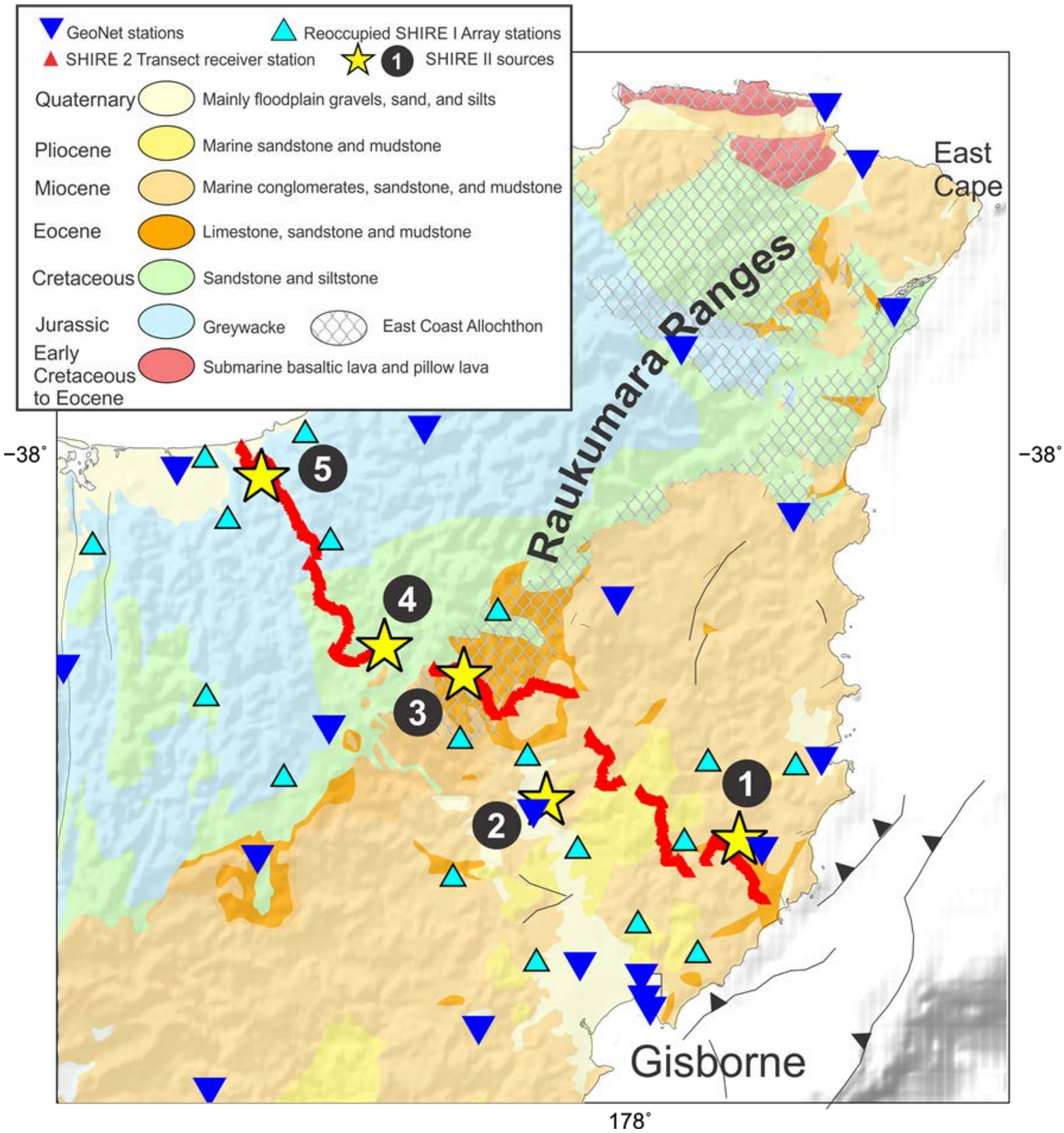

Figure 1.3 Geology of onshore Raukumara Peninsula (Mazengarb and Speden 2000). The annotated circles and yellow stars indicate controlled source locations, and red triangles, merging to form line segments at this scale, show the SHIRE II sites. Over 630 temporary seismograph stations were deployed between February–March 2019 to record five controlled borehole explosions. Light-blue-filled triangles are re-occupied SHIRE I seismograph stations deployed during the same time interval. Onshore active faults are shown as black lines (http://data.gns.cri.nz/af/).

1.1 Northern Hikurangi Margin and Raukumara Peninsula Tectonic Setting

The Hikurangi subduction margin marks the boundary between the Australian and Pacific plates, at which the plates converge obliquely at rates ranging from 27 mm/yr in the south to 57 mm/yr in the north (DeMets et al. 1994), due in part to the extension (~ 50 mm/yr) occurring in the Taupo Volcanic Zone (TVZ) further to the west (Figure 1.1). Along the North Island, plate motion is partitioned with the margin normal component occurring largely on the subduction thrust (Nicol and Beavan 2003) and the margin parallel component accommodated by strike-slip faulting in the upper plate and clockwise rotation of the North Island forearc (Beanland and Haines 1998; Wallace et al. 2004).

The northern end of the Hikurangi margin is marked by the northward transition from the high topography of the Raukumara Ranges into the deep (<10 km sediment thickness) Raukumara Basin (Sutherland et al. 2009). Overthickened oceanic crust of the Hikurangi Plateau (10± km thick, Mochizuki et al. 2019) is being subducted offshore to the east and the buoyancy of the plateau, together with underplated sediments, is thought to drive the low rates of regional long-term uplift (~1 mm/yr) documented along the whole margin (Litchfield et al. 2007). The geometry of the shallow plate interface east of the Raukumara Peninsula has been imaged by seismic reflection surveys (Barker et al. 2009; Bell et al. 2010). Offshore Gisborne, high-amplitude reflectivity zones, at depths of 5–15 km, are interpreted as ~3.0-km-thick fluid-rich subducting sediments entrained ahead of subducting seamounts (Bell et al. 2010). Beneath the coast, the plate interface lies at relatively shallow depths of 12–15 km and extends to >100 km depth beneath the offshore TVZ (Barker et al. 2009; Williams et al. 2013). Moho depth beneath the northern Raukumara Peninsula is ~25 km (Bassett et al. 2010) but is estimated to reach 30–40 km depth further south (Reyners et al. 1999).

Earthquake hypocentres cluster within the upper part of the subducting plate and in the crust between the east coast of Raukumara Peninsula and the subduction front (Reyners and McGinty 1999; Yarce et al. 2019). Earthquake focal mechanisms indicate down-dip tensional strain within the subducting plate and NNW–SSE extensional strain within the shallow part of the upper plate (Reyners and McGinty 1999), consistent with geological and geodetic observations (Dimitrova et al. 2016).

A diverse array of aseismic creep and slow-slip event (SSE) behaviour has been documented along the Hikurangi subduction interface (Wallace et al. 2012b; Wallace 2020; Wallace and Beavan 2010). In the northern part of the margin, offshore Gisborne, small, frequent and short duration SSEs occur at <10–15 km depth at the down-dip end of the shallow interseismic coupling zone (Wallace and Beavan 2010; Wallace et al. 2016). The region of maximum SSE slip occurs where a zone of high seismicity connects high Vp/Vs in the overriding plate and upper oceanic crust (Eberhart-Phillips and Bannister 2015) and where repeating earthquake clusters and tremor have been observed (e.g. Jacobs et al. 2016; Shaddox and Schwartz 2019; Warren-Smith et al. 2019; Yarce et al. 2019). Variations in Vp/Vs also appear to coincide with areas of high conductivity / low resistivity on the plate interface (Heise et al. 2017) and where multichannel seismic data have also imaged high-amplitude reflectivity zones (Bell et al. 2010). These observations imply that there is high pore pressure ratio on the plate interface consistent with the presence of fluid overpressures in exploration bore holes (Darby and Funnell 2001), heat flow observations (Antriasian et al. 2018) and numerical model calculations (Ellis et al. 2015).

Geologically, the Raukumara Peninsula can be divided into three broad structural units (Figure 1.3): (1) a western unit of Early Cretaceous greywacke in the Raukumara Range, (2) a belt of Late Cretaceous and Early Tertiary rocks that were emplaced allochthonous from the northeast over and against unit 1 during the earliest Miocene and (3) an eastern unit consisting of Neogene turbidites and mudstones that overlie the allochthon and extend offshore (Mazengarb and Speden 2000). These Neogene rocks have been faulted and folded. Onshore, folds are intruded by mud diapirs and fluid seeps are common (e.g. Pettinga 2003; Ridd 1970). Offshore cold seeps occurrence is influenced by structural permeability, and drainage pathways may be enhanced by seamount subduction (Watson et al. 2020). Along the northern Hikurangi margin, contractional faults splay from the subduction interface and form a zone of offshore reverse faults, exhibiting complex fault segmentation, within the accretionary wedge (Litchfield et al. 2020; Mountjoy and Barnes 2011).

2.0 SHIRE I

2.1 SHIRE I Introduction

The SHIRE I *R/V Marcus G. Langseth* voyage (MGL1708 Bangs and Ship Board Science Party 2018) collected 48 multichannel seismic reflection lines, including four wide-angle transects where airgun sources were recorded by OBS instruments deployed from the *R/V Tangaroa* (Barker et al. 2019). Transect 1 (Line MC03 and OBS02, Line MC10 and OBS09) was the primary focus for onshore recording of offshore airgun sources. The aim of Transect 1 (Figures 1.1 and 1.2) was to image the crust and subducting Pacific Plate beneath the northern Hikurangi margin. The principle of recording double-sided offshore marine airgun sources on static onshore seismograph stations is to create 'receiver gathers' for each site (Okaya et al. 2002) to construct a dense set of refraction and wide-angle reflection data that can be inverted for crustal structure and velocity. In this section, we describe the onshore deployment of the linear transect (Transect) and distributed array (2D Array) of 89 Incorporated Research Institutions for Seismology (IRIS) PASSCAL short-period seismometers and REFTEK RT130 dataloggers between October 2017 – February 2018 (Figure 1.2 and Figure 2.1). The SHIRE I onshore deployment was able to capture the airgun sources of the MGL1708 voyage and the sources of the NZ3D MGL1802 voyage (Bell et al. 2019), offshore Gisborne, as well as earthquake events. In addition, 25 short-period GSX3 digital data recorder and seismometers (Transect-GSX) from ERI, University of Tokyo, were located along the Bay of Plenty coast between October–December 2017. Scouting for all instrument locations, community engagement and planning for the SHIRE I land-and-sea combined operation took more than 12 months to complete.

2.2 Deployment Overview and Timing

Seismometer locations were chosen to give three-dimensional (3D) coverage of the Tairāwhiti / Raukumara Peninsula, away from main roads, on private land and, for the most part, accessible by four-wheel-drive vehicle.

Forty-six of the IRIS-PASSCAL short-period seismometers and RT130 instruments were deployed along the Transect segment aligned with offshore lines MC03 (Bay of Plenty) and MC10 (Gisborne) (Figure 2.1). Another 43 were distributed as part of the 2D Array. The lack of road infrastructure in the Raukumara Ranges prevented a regular areal deployment grid and limited coverage mainly to the coastal region of the Peninsula (Figure 2.1). In addition to designing site spacing for earthquake detection and location, some of the 2D Array stations were deployed parallel to the Transect to provide 3D onshore-offshore coverage. A separate transect of 25 short-period GSX3 instruments (Transect-GSX) was deployed along the Bay of Plenty coast to record an additional onshore-offshore transect across the TVZ. In addition, Tulane University, in a separate project, deployed five broadband seismometers (BARNZ) as part of a year-long study to better understand the crustal rifting process in the northern TVZ and Bay of Plenty (Figure 1.2).

We scheduled the SHIRE I onshore deployment so that the network would be fully operational before the offshore acquisition began on the *R/V Marcus G. Langseth* (scheduled to leave port 24 October 2017). The *Langseth* was delayed due to Ministry of Primary Industry requirements to undergo anti-fouling before entering New Zealand territorial waters. The *Langseth* gained final clearance to berth on 29 October 2017 and left port again on 1 November 2017. As deployment efforts were already well underway, we continued with our original schedule and the onshore network was fully operational by 27 October 2017.

Although the deployment was ahead of the *Langseth* acquisition, the timing was fortunate as the Transect and 2D Array captured a swarm of earthquakes occurring near White Island between 29 October – 1 November 2017 (see Section 2.4.1.2, Figures 2.2 and 2.3). The *Langseth* SHIRE MGL1708 voyage took place between 1 November – 7 December 2017 (Bangs and Ship Board Science Party 2018). Figure A2.2 shows the timeline of station deployments, servicing and site removal from October 2017 – February 2018.

2.3 SHIRE Onshore Array

The Transect comprised 46 seismic sites at approximately 2 km spacing aligned with offshore Line MC03 and OBS02 (Bay of Plenty) and Line MC10 and OBS09 (Gisborne) (Figure 2.1). The 2D Array consisted of the remaining 43 instrument set-ups and were distributed throughout the Tairāwhiti / Raukumara Peninsula (Figure 2.1).

Unlike the offshore portion of the experiment, the onshore SHIRE I deployment required very little permitting. Councils were made aware of onshore plans during consultations related to the offshore OBS deployments, but formal Council approval for the sites on private land was not necessary, apart from a review of locations by Heritage New Zealand Pouhere Taonga (HNZPT). To protect New Zealand's heritage, any intention to dig must be filed with HNZPT to ensure that the planned location does not correspond to a known archaeological site. While temporary seismometer installations do not require extensive digging and are largely within pre-disturbed areas (forestry and farmland), they still required review by HNZPT. A shapefile containing the locations of archaeological sites is publicly available; however, newer sites and non-disclosed sites also exist. Therefore, all locations must be submitted for review and approval by HNZPT to ensure that sites do not require an archaeological authority or the presence of an archaeologist on site during work. All intended sites were submitted to HNZPT and given clearance to operate under an Accidental Discovery Protocol (ADP), which outlines procedure in the event that anything of archaeological significance is encountered during the work. This process was also undertaken for SHIRE II seismic and drill sites and is covered further in Section 3.3.2. A version of the ADP used for the SHIRE sites is given in Appendix 3.3.

Although the initial delays of the *Langseth* had relatively little impact on the land deployment, it did mean that the beginning of the onshore SHIRE sites servicing commenced on 5 December 2017, the same day as the final Bay of Plenty seismic lines were collected. The intention had been to wait until the end of the *Langseth* SHIRE cruise, but the instrument service was started for a number of reasons, including delayed cruise start, field crew availability and the impending NZ3D deployment (Bell et al. 2019). Most onshore SHIRE sites were serviced between 5–8 December 2017 (Figure A2.2).

The SHIRE and NZ3D teams collaborated during demobilisation following the end of the NZ3D active recording period. Some of the NZ3D equipment required immediate pick-up and shipping to the UK and were recovered prior to the final SHIRE recovery of sites in February. The 50 Guralp CMG-6TD broadband seismometers, deployed as part of the NZ3D Gisborne Array, remained to record until October 2018 (Bell et al. 2019). Full details of SHIRE instrument deployment, service and demobilisation times are given in Figure A2.2.

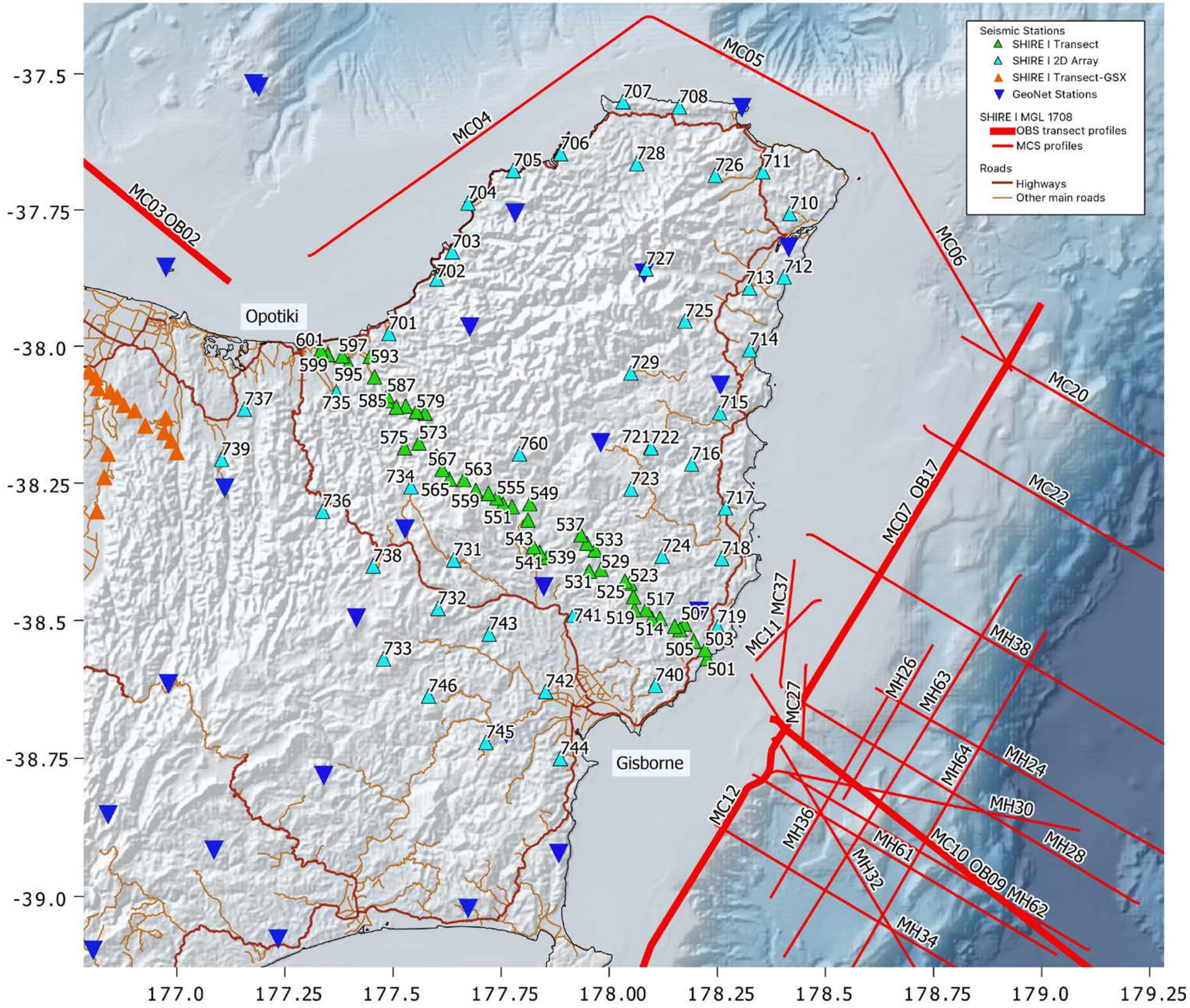

Figure 2.1 Onshore SHIRE I seismic sites. Roads in the Tairāwhiti / Raukumara Peninsula dictate spatial distribution of seismometer stations.

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2.4 Instrumentation

Onshore temporary stations were short-period L-22 and L-28 seismometers. The only broadband instruments deployed during this period were the existing GeoNet national network seismometers (https://www.geonet.org.nz/) and the NZ3D Guralp CMG-6TD seismometers that made up the Gisborne Array (Bell et al. 2019). Offshore, there was a combination of OBSs and hydrophone recording streamers. Most sites recorded both controlled source energy and passive seismicity. This section will briefly outline the various characteristics of each instrument and the different energy sources recorded.

2.4.1 Energy Sources

2.4.1.1 Active Source – Airgun Array

From 1 November through to 7 December 2017, the seismic vessel *R/V Marcus G. Langseth* conducted a margin-wide survey of the Hikurangi Margin, collecting 1443 km of OBS transect along four lines, and 4046 km of marine multichannel seismic (MCS) lines. Approximately 39 OBS instruments were deployed offshore adjacent to the onshore array along Line MC03 and OBS02 (Bay of Plenty) and Line MC10 and OBS09 (Gisborne) (Figure 2.2). An additional 75 OBS locations were occupied further south and east along the margin. The large spatial scope of the offshore SHIRE survey will help to characterise along-strike variation of the margin. The OBS instruments were deployed and collected by the *R/V Tangaroa* TAN1710 voyage (Barker et al. 2019). Two additional *R/V Tangaroa* voyages were also involved in OBS deployment (TAN1712) and recovery (TAN1803) associated with the subsequent NZ3D experiment (Kellett et al. 2019).

The acoustic source for all lines was a 6600 in three 36-element airgun array with four gun-strings, each with nine Bolt airguns. Airgun source spacing along the five OBS Transect lines (OBS02, OBS07, OB09, OB16, OB18) varied from 37.5 to 150 m. Most MCS lines were acquired with 50 m source spacing. For full details, see Barker et al. (2019) and the MGL1708 Cruise report (Bangs and Ship Board Science Party 2018).

2.4.1.2 Passive Source – Local and Global Earthquakes

Over the ~130 days that the SHIRE I onshore array was deployed, GeoNet located 1730 earthquakes (Figure 2.2, https://www.geonet.org.nz/data/types/eq_catalogue). During the same time, the United States Geological Survey (USGS) located 47 earthquakes Mw >6.0, with five greater than M 7.0 globally (https://earthquake.usgs.gov/earthquakes/search/).

The most notable regional seismicity during the SHIRE I deployment was a large swarm of earthquakes in the Bay of Plenty, east of Whakaari / White Island (Figure 2.2). The swarm region contains nearly 30% of all located earthquakes (500/1730). The concentration of activity is even more prominent at larger magnitudes, hosting almost half of the earthquakes with magnitude >3 (30/62). The most active period in the swarm occurred between 29 October 2017 and 1 November 2017, with 217 events occurring in those four days. An initial relocation with GeoNet and SHIRE data, using the probabilistic non-linear global-search inversion approach of Lomax et al. (2009), showed that the swarm occurred at depths between 20–30 km and roughly outline a plane dipping to the northwest (Figure 2.3).

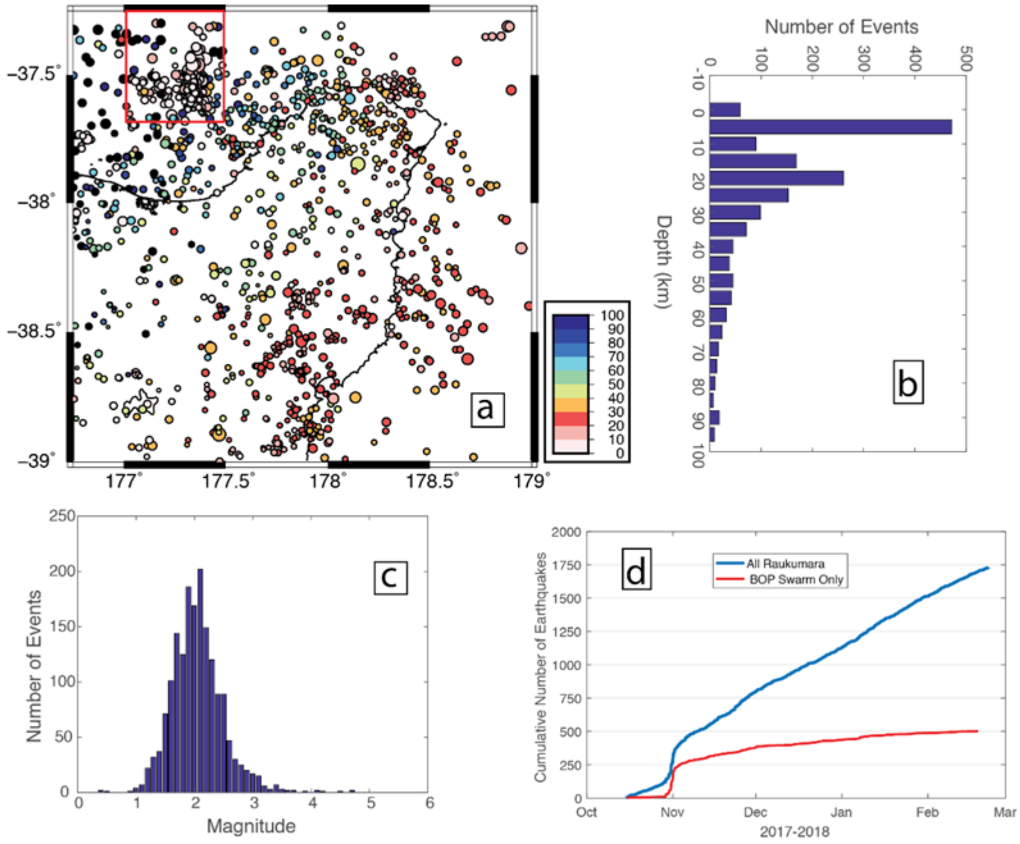

Figure 2.2 GeoNet earthquakes recorded during the SHIRE I passive deployment, 15 October 2017 through to 22 February 2018. a) Locations of 1730 earthquakes. Red box shows region used to delineate Bay of Plenty swarm in (d). b) Depth histogram, c) magnitude histogram and d) cumulative number of earthquakes with time for whole region shown in (a) (blue) and region in red box around the Bay of Plenty swarm (red).

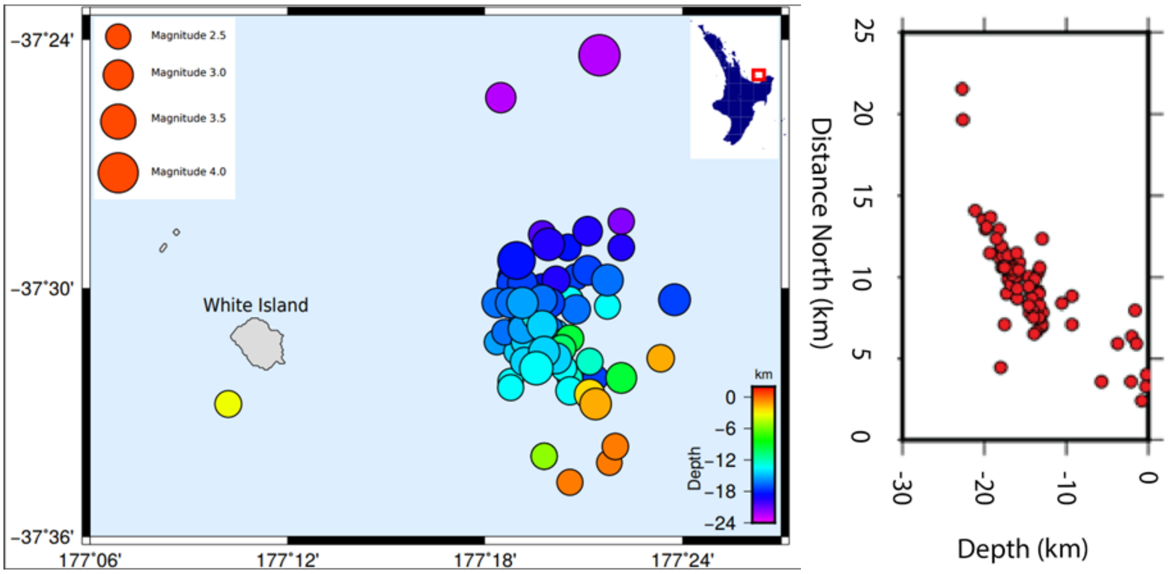

Figure 2.3 Map showing the NonLinLoc relocations of the 29 October 2017 – 1 November 2017 earthquake swarm (left). Magnitudes are the original GeoNet locations, as NonLinLoc does not calculate revised magnitudes. Colours show earthquake depths. (Right) North-South depth cross-section.

2.4.2 Onshore Instruments

Nearly all sites deployed during this project used a 2 Hz, three-component (3C) L-22 sensor. Four of the 4.5 Hz, 3C L-28 sensors were also used (Appendix 6). The L-28 sensors were deployed at sites close to Gisborne so that they could be collected quickly at the end of the experiment, ready to be re-deployed for the South Island Subduction Initiative Experiment (SISIE; Stratford et al. 2019). Regardless of sensor type, all stations were deployed with REKTEK RT130 data recorders and a GPS unit and powered by 1 x 75 amp-hour deep-cycle battery paired with a 20-watt solar panel.

A single L-22 sensor was used as a roving station to preview data quality at the western and eastern ends of the onshore Transect at stations 601 and 514, which was eventually deployed more permanently at Site 760 near the Tarndale slip (Figure 2.1). The deployment at the Tarndale slip site (760) did not utilise a solar panel and was deployed with 2 x 75 amp-hour batteries that were completely buried. It was a suitable site to be deployed differently as it was remote, and a prominent solar panel may have compromised the site security. Further details of equipment set up at each site can be found in Appendix 6 (site-specific location and equipment details) and Appendix 7 (general description and problems).

The sampling rate for seismic sensors was set to 100 Hz and the GPS mode set to 'Duty Cycle' so that they would get a lock and phase shift once an hour. The Duty Cycle operation maximises battery life by leaving the GPS off most of the time.

All instruments were provided by IRIS PASSCAL (www.passcal.nmt.edu). The response characteristics of different sensors can be found at https://www.passcal.nmt.edu/content/instrumentation/sensors/sensor-comparison-chart. For the sensors used in this experiment, a summary table of characteristics can be found in Table 2.1.

2.4.2.1 Sercel L-22

The L-22 sensors (Figure 2.4) are short-period sensors with a natural frequency of 2 Hz, ideal for local earthquake and aftershock studies and some active source projects. Each sensor has two arrows, which should be aligned with North and East, and a levelling bubble. Levelling can be difficult because the sensors do not have adjustable legs or spikes of any kind that fix them in one place. We primed each site with loose sand at the bottom of 30–40 cm holes and carefully levelled each sensor prior to back-filling. Initial back-filling was done by hand to ensure that the instrument stayed level and became stable in place.

Figure 2.4 The L-22 sensor (left; photo courtesy of PASSCAL instrument centre). L-22 sensor deployed in hole during SHIRE I deployment (right; photo courtesy of Jenny Black).

2.4.2.2 Sercel L-28-3D

The L-28 sensors (Figure 2.5) are 4.5 Hz sensors, ideal for active source, local earthquake and aftershock studies. They are robust enough to stand on, and the three spike legs allow for easy installation and good coupling. Like the L-22s, they have two arrows that should be aligned with North and East and a levelling bubble. The spikes make them slightly easier to level than the L-22 sensors and means they typically do not require sand as a levelling aid. The more flexible cabling also allows for a smaller overall hole footprint. These sensors were used in the Transect and 2D Array.

Figure 2.5 The L-28 sensor (left; photo courtesy of PASSCAL Instrument Centre). L-28 sensor installed in a soil site (right; photo courtesy of Pasan Herath).

Table 2.1 Sensor response comparisons.

Sensor	Corner Frequency	Sensitivity (v/m/s)	Poles	Zeros
Mark Product L-22	2.0 Hz	88	-8.89, 8.89 -8.89, -8.89	0,0 0,0
Mark Product L-28	4.5 Hz	30.4	-19.8, 20.2 -19.8, -20.2	0,0 0,0

2.4.2.3 Site Set-Up

In addition to the data loggers and sensors, PASSCAL also supplied quick deploy boxes (also known as quick-deploy stations or QDS; Figure 2.6) that served to house both the data logger and battery, as well as a mounting system for the solar panel. This made both site set-up and transportation practicable, as everything needed for a site, aside from the battery, sensor and fence material, could be housed inside the QDS box for transport. An individual QDS box could be removed from the vehicle at each site. The boxes also kept solar panels safe during transport. Many sites were in wind-prone areas, but the weight of the battery and other equipment, along with the relatively low profile, was sufficient to stabilise the QDS boxes. Some solar-panel straps needed tightening at the December 2017 service, but, overall, the QDS boxes were very robust. Although the straps were covered by tape or hoses to protect them against chewing from birds or stock, a few sites had collapsed solar panels from stock rubbing on the unit where the fence was either not wide enough or damaged by stock (Appendix 7). The solar panel placement on the QDS box means they are relatively low to the ground, so small tarpaulins were staked out in front of each box to prevent plant growth from blocking the solar panel (Figure 2.6a). Another advantage of the QDS box is that the GPS unit can be deployed inside the box (Figure 2.6b). The in-box deployment further reduces set-up time and safeguards the GPS cable and antennae from stock and other disturbance.

Almost all of the instrument sites were in areas of active farming, including cattle, sheep and pigs. Fences made from metal fence posts and tensioned wire were erected around the instruments to protect the sites (see Appendix 7 for fencing description, suggestions and photos). Site installation took a team of two people approximately two hours. Most SHIRE I Transect and 2D Array sites were within 100 m of 4WD vehicle access.

During the December 2017 service, several sites had lost GPS lock. Two spare GPS units that were part of the original shipment of equipment were used to replace one of the problematic stations near Gisborne and to put a back time stamp and GPS lock on before removing the disks at several sites. At other sites with GPS problems, disks were removed before this was possible or due to distance from a field base. PASSCAL was aware of this GPS issue from previous deployments and was able to send a set of 20 replacement GPS units. There was a desire to have accurate timing for the remaining two months of deployment for passive recording, and especially for sites on the eastern side of the array to be able to accurately record the active source NZ3D survey offshore Gisborne. Eastern sites were prioritised, and six sites with GPS issues were re-visited and GPS units swapped by 1 January 2018, with a further two by 5 January 2018 during the NZ3D deployment. However, it was not possible to visit all sites with potential problems, as some required escort into forestry land (553–557) and some were too far for a service trip to be practical (575). There were also stations that appeared functional at servicing but were found to be faulty when they were recovered. GPS provides the timing synchronisation, so stations with GPS issues should be checked thoroughly before using data in downstream analysis. Appendix 7 has details of GPS problems and fixes where applicable, along with other station issues.

Figure 2.6 Quick deploy station boxes (QDS) in the field. a) Open box showing battery, data logger with connecting cables and small green tarpaulin to limit vegetation growth from blocking the low solar panel. b) Open QDS box shown as configured to leave the site and close the box. c) General site set-up with sensor in foreground, showing solar panel on top of QDS box and cabling buried underground to sensor.

2.4.3 GSX3

A set of 25 GSX3 seismic recorders from the Earthquake Research Institute (ERI), University of Tokyo, were used in the experiment (Figure 2.7). These 3C recorders are attached to a 4.5 Hz Geo Space, GS-11D 3C geophone. These instruments are light-weight, with the geophones weighing 1.8 kg and the GSX3 0.9 kg. The instrument is powered by two battery packs, which each weigh 2.75 kg. These batteries allowed operation for 40 days.

The GSX3 instruments were deployed shortly before the seismic acquisition started to ensure that the batteries would not need charging during the controlled source experiment. The sample rate used during the experiment was 200 samples per second.

The installation of these instruments involved digging a ~30-cm-deep hole for the geophone. The recorder and batteries were kept at the ground surface. A large plastic box was put over the top and fixed to the ground with stakes to protect it from cattle. The GSX3 data were processed into SEGD format from native GSX3 format by ERI and the data sent to GNS Science.

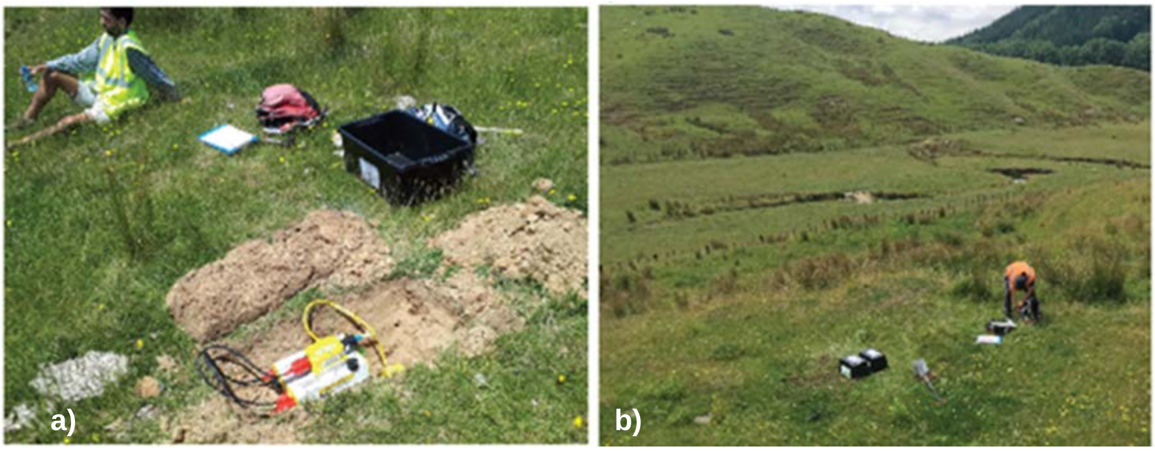

Figure 2.7 Deployment of the GSX3 involved a) digging a ~30-cm-deep hole and stabbing the geophone into the ground. The geophone is then buried (on the right-hand side of the hole), with the two batteries and yellow GSX3 recorder buried to the left of the geophone. b) The area is then covered by two plastic boxes in order to protect it from livestock.

2.4.4 Offshore Instruments

A brief overview of offshore instrumentation is provided below, and further details can be found in TAN1710 and MGL1708 reports (Bangs and Ship Board Science Party 2018; Barker et al. 2019).

2.4.4.1 Ocean Bottom Seismometers

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) deployed 100 short-period OBS instruments on TAN1710 in 114 different locations along lines 1–4, as shown in Figure 1.1 (Barker et al. 2019). The OBS instruments are comprised of four sensors, a 3C geophone and a hydrophone.

2.4.4.2 Hydrophone Streamer

The *R/V Marcus G. Langseth* towed a 12.5-km-long streamer with a Sentinel Solid Acquisition Section (SSAS) with 1008 3-Hz hydrophones at 12.5 m spacing. Fifty-three lines of MCS data were recorded during the SHIRE voyage (Figure 1.1). In general, 18 s of data was recorded for each shot, with 20–35 s intervals between shots. Given the number of lines, parameters do vary and a complete list of acquisition parameters for each line can be found in the MGL SHIRE Cruise report (Bangs and Ship Board Science Party 2018).

2.5 Data

Some data was returned from all sites. In the field, data were downloaded and backed up to minimise any chance of data loss. Several sites had disk problems at the service, and a further four stations were found to have disk trouble on retrieval (Table A7.1). PASSCAL was able to retrieve data from the disks that could not be downloaded in the field but, in cases of disk failure, no data was written to the disks on site. Overall data recovery was good, but sites that experienced GPS trouble will require further analysis of timing drift before use. Onshore data will be available through IRIS and archived at GNS Science in raw REFTEK 130 format.

- Short-period PASSCAL data at a sample rate of 100 sps continuously recorded from October 2017 – February 2018. Archived in PH5 format with IRIS/PASSCAL.
- Short-period GSX3 data at a sample rate of 200 sps from October–December 2017. Archived and stored in SEGD format. Each data file contains 60 s of data for all 25 stations.

The required PASSCAL format for archiving active source data is PH5, which is PASSCAL's implementation of a Hierarchical Data Format version 5 (HDF5) data model. HDF5 can evolve and operate on a variety of platforms and can be used through a number of programming interfaces. It is self-describing, which allows direct access to parts of a file (metadata) without the need to parse the entire file (Folk and Pourmal 2010). The PH5 experiment dataset contains multiple HDF5 files that are referenced from the master.ph5 file. The PH5 package contains Python command line utilities and APIs for building and interacting with PH5 datasets and is designed to be installed and run through an Anaconda environment (https://github.com/PIC-IRIS/PH5). The PH5 system is cumbersome to learn and use, as it requires specific file structures and formats. However, documentation and guides are available directly from PASSCAL, and cutting subsets of the data and outputting a variety of formats becomes easy and scriptable. Initial receiver gathers, from the SHIRE I phase, show a good transmission of energy and are discussed in Section 5.

2.5.1 Comment on Orientations

During deployment, teams were instructed to orient seismometers to True North, and a small training session and check was done in conjunction with the huddle test at the Gisborne field centre. Orientations were checked as stations were collected at the end of the experiment, and most stations were found to be well oriented to True North, with nearly half reporting exact orientations and over 95% of stations reporting orientations within 10 degrees of True North, an error range consistent with post-experiment orientation methods (Figure 2.8). A few sites show orientations consistent with using the magnetic declination from the magnetic orientation (orientations around 22 degrees).

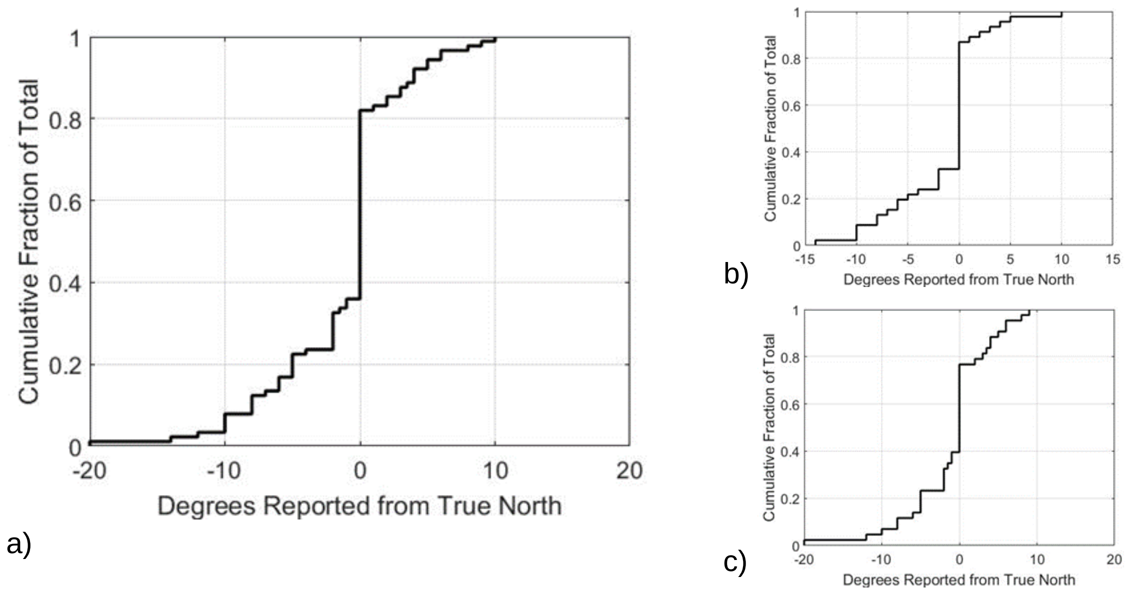

Figure 2.8 Cumulative distribution of measured orientations of instruments on retrieval from the field. a) All 89 onshore stations. b) 46 Transect sites. c) 43 2D Array sites.

The simultaneous operation of the transect and 2D arrays allowed good recording of earthquakes through the entire four-month deployment. Figure 2.9 below shows an hour of data across the SHIRE I network on 31 October 2017. Larger earthquakes from the Bay of Plenty swarm (Section 2.4.1.2) are seen across the whole array and smaller signals can be seen more regionally. The network will be able to detect much smaller events than the GeoNet permanent array (Petersen et al. 2011). No orientation correction has been applied to the data shown in Figure 2.9 below.

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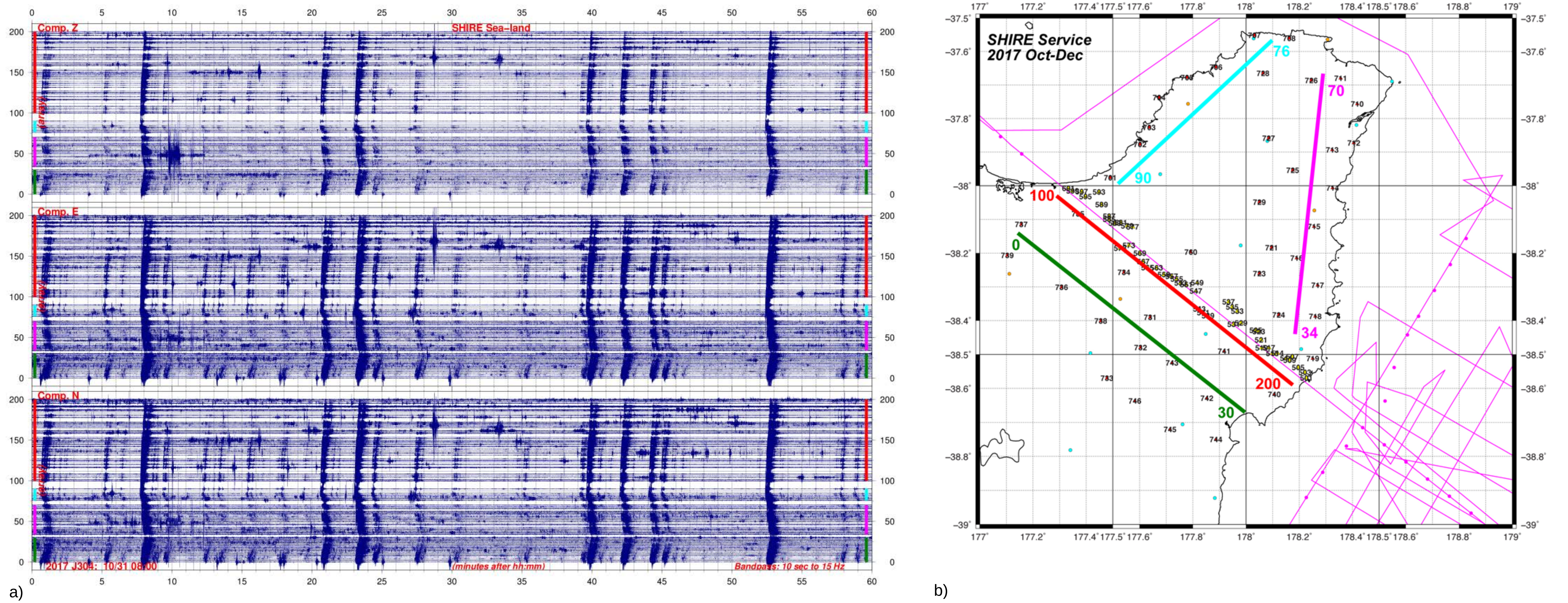

Figure 2.9 Example of earthquakes travelling across the 89-station array on 31 October 2019. a) Hour-long station records. Seismograms are filtered 0.1–15 Hz and trace-normalised. Stations are grouped into four subsets, marked by the coloured bands on the lateral edges of each waveform panel and map (b). The main transect (red) is shown at true distance (kilometres along transect) and 2D stations are simply evenly spaced. Earthquakes here are likely part of the Bay of Plenty swarm discussed in Section 2.4.1.2 and Figure 2.3. Note the delayed P arrival times and increasing P-S separation along the Transect (red) from the west (100) to east (200). b) Map showing colours used in (a) and offshore transects.

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3.0 SHIRE II

3.1 SHIRE II Introduction

SHIRE II is the onshore component of the SHIRE Transect 1, a ~350-km-long geophysical transect across the northern Hikurangi margin intended to address the dynamics of convergent plate boundary processes (see Section 2). SHIRE I acquired onshore-offshore wide-angle refraction data, OBS wide-angle data (Barker et al. 2019) and marine seismic reflection data (Bangs and Ship Board Science Party 2018) along this transect (Line MC03 and OBS02, Line MC10 and OBS09). The aim of SHIRE II was to directly image the crust beneath the uplifted Hikurangi accretionary prism exposed onshore along the Raukumara axial ranges. In this section, we present the details of SHIRE II, which extended from the east coast north of Gisborne to the Bay of Plenty coast, east of Ōpōtiki (Figure 3.2). In this phase of SHIRE, 583 temporary seismograph sites were occupied (314 vertical component and 269 3C) and five borehole explosions were detonated during 26–28 February 2019 (see Figure 3.1). In addition, 19 SHIRE I 2D Array sites were re-occupied for 20 days. Permitting, planning decisions, contract negotiations and engagement took 12 months to complete.

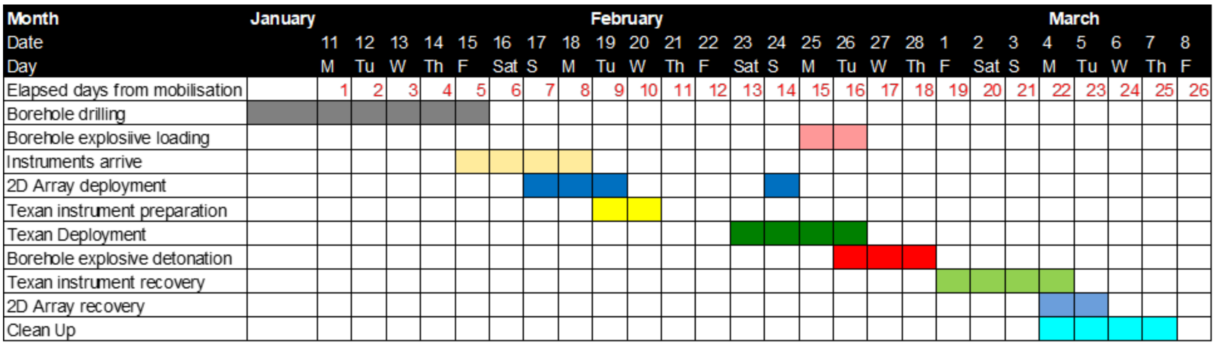


Figure 3.1 Gantt chart of the SHIRE II instrument deployment, recovery and borehole explosive detonation during January, February and March 2019.

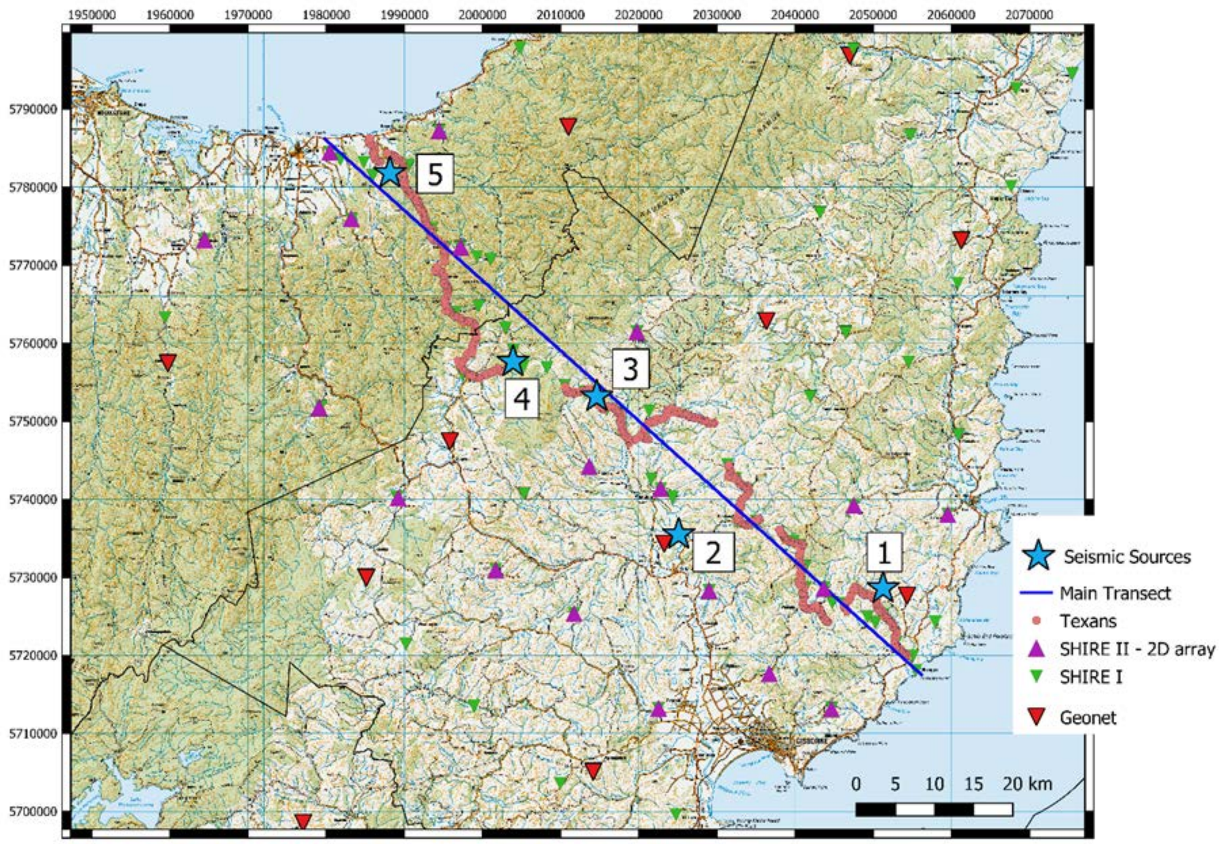


Figure 3.2 Overview map of SHIRE II deployment, showing seismic source locations, Texan instrument locations, re-occupied SHIRE I 2D seismograph array, sites and GeoNet permanent seismometer station. The blue line represents the onshore portion of Transect 1. Thin black lines outline the council boundaries and intersected the transect just west of controlled source Site 4.

3.2 Controlled Source Locations

Controlled source borehole locations for SHIRE II were chosen using several criteria; namely, relatively equally spaced (~25 km) along the transect, in open spaces and accessible by a drill rig and explosive loading vehicle under variable weather conditions. Roads throughout the Tairāwhiti / Raukumara region are sparse, and drill rig access proved to be the limiting factor to finding suitable locations (Figure 1.3, Figures 2.1 and 3.2). Additionally, care was also taken to select locations away from built structures and unstable landforms (Bruce 2018).

All sites were located on private land, with two sites positioned in one forestry block. The Raukumara Peninsula is administered by two Councils, Gisborne District Council (GDC) and Bay of Plenty Regional Council (BOPRC). Site 1 was located in BOPRC, and the remaining four sites within the GDC boundary (Figure 3.2).

A number of scouting trips were completed with council staff and the chosen drilling contractor (Honnor Drilling) to finalise specific site locations, to mitigate any problems with drill rig access and to ensure that the controlled source activity would meet council compliance requirements. Final locations of drill holes are given in Table 3.1.

3.3 Borehole Drilling Specifications

A tender process for borehole drilling was managed by the GNS Science procurement team. The following specifications were stipulated in the Request for Proposal (RFP):

1. All boreholes to be 200 mm (8 inches) in diameter.
2. All boreholes to reach a vertical depth of 50 m.
3. All boreholes to be fully cased with steel casing and provided with suitable security; for example, capped with a lockable cap.
4. Casing must be well coupled to surrounding ground (anchored when necessary) to avoid blowing out of casing.
5. The casing must protrude above the surrounding ground and appropriate steps taken at the casing exit point to prevent entry of surface water.
6. All boreholes to be completed prior to 31 December 2018.

The final specification was added to ensure that the chosen company had the capacity to complete the work in time for the experiment – scheduled for the last week of February 2019. Familiarity with and proximity to the region were also considered in the evaluation of bids, as prior drilling in the area and relationship to local council regulations were considered important. Four companies responded to the RFP and Honnor Drilling was chosen as the preferred tenderer.

3.3.1 Drilling Method

Drilling method was mainly Odex hammer drilling, although some wash drilling was used at Site 5 to deal with the softer material encountered. For information on materials encountered during drilling, see the drill logs and schematic rock-type diagram in Appendix 4.

3.4 Permitting and Consent

3.4.1 Resource Consent for Drilling and Explosive Discharge

The drilling of the boreholes and detonation of the explosions were the activities that required Resource Consent under the Resource Management Act 1991. Four of the five target sites were within the GDC territorial authority, and the westernmost controlled source location, Site 5, was in the BOPRC boundary (see Figures 3.2 and 3.8). Consent application for drilling and explosion discharge were submitted to both Councils. Each Council consent process required consultation with regionally relevant iwi and hapū groups. With only one site, and one iwi, Whakatōhea, the consultation for and application to the BOPRC was completed and submitted prior to the application to GDC. GNS Science contracted WSP (Opus) to help write the formal consent applications. Some documentation of the timeline of the consenting process, along with considerations for future consent applications, are given in Appendix 3.

Each application included a request for consent to drill and discharge. BOPRC chose not to grant a consent for discharge as they considered that no discharge would result from the explosions, since chemicals would be completely consumed during the blasting process. The GDC consent decision also recognised that physical material/chemicals would not be discharged but granted consent for the "discharge of seismic waves". This indirect recognition of discharge caused confusion during the remediation phase of the GDC resource consent, as the council discharge rules trigger a different set of site requirements. A review recognised the remediation of the borehole required under related discharging rules was not necessary.

In the future, we would recommend that applications for drilling be submitted without a consent to discharge.

GDC was also concerned about land movement and other risks posed by the explosions, so a geotechnical assessment was completed for all sites (Bruce 2018). The assessment also included Site 5, within the BOPRC jurisdiction. Another concern around Site 4 was its proximity to the Weka recovery area in the Motu region. Small mesh fencing with a gravel layer around the base was constructed around the Site 4 borehole to address these concerns (see photo in Table 3.1, Site 4). To aid in the assessment, we also used empirical relationships from similar controlled-source projects using borehole explosions (Fuis et al. 2001; Kohler and Fuis 1992) and observations of vertical ground velocity at varying distances from the source point and for different soil and rock types (Figure 3.3). The equations are based on measurements made during the LARSE controlled source refraction project in Southern California and demonstrate the anticipated levels at which humans and structures are likely to be impacted. We used the rock types identified by Fuis et al. (2001) and inferred that the sedimentary rock type was closest to the conditions we would likely expect for SHIRE II Sites 1–4, given the material properties at the surface and the existing mapped geology. Site 5 had the potential to encounter harder volcanic and greywacke rocks, which were exposed in nearby roadcuts (Figure 1.3). Vibration standards from council regulations were converted to Vertical Ground Velocity and plotted for comparison (dashed lines in Figure 3.3). Council vibration standards imply a greater distance threshold. For example, minor damage is expected for the sedimentary material beyond 40 m from the source, using data from Fuis et al. (2001), but the lowest vibration standard for sedimentary rocks is at >150 m. Sites had fences, cattle yards and power poles closer than 200 m, but even these distances are modelled to be unaffected by SHIRE II controlled sources and observed to be the case in previous studies (Seward et al. 2011). We adopted conservative thresholds and all of our controlled sources were greater than 500 m from dwellings. Site 1 had the nearest building, an unoccupied farm shed ~275 m away. The radius for potential damage from the Fuis equations was estimated to be 15 m away from the borehole (Figure 3.3, Fuis et al. 2001).

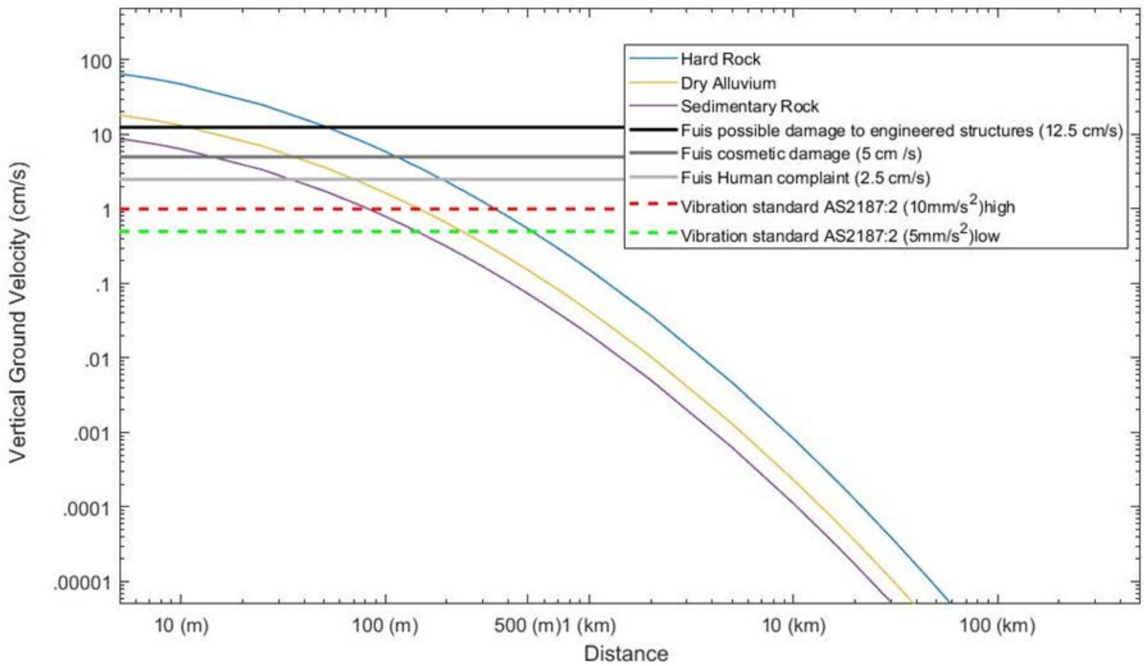


Figure 3.3 Predicted vertical ground velocity versus distance for a 500 kg explosion. The curves are derived from controlled source calibration data (Fuis et al. 2001; Kohler and Fuis 1992).

3.4.2 Other Permits

3.4.2.1 Heritage New Zealand Pouhere Taonga

As for SHIRE I, locations of all planned seismograph and borehole sites were submitted to Heritage New Zealand Pouhere Taonga (HNZPT) for approval. Both borehole sites and instrument locations were approved to be undertaken using Accidental Discovery Protocols (Appendix 3.3). HNZPT use GIS-based location systems, so we were able to submit shapefiles of locations rather than creating map images. We pre-screened all sites during selection using the available layer of archaeological sites; however, HNZPT does not release all site information. This approval process not only met our obligations, but also served as a good indication to iwi and hapū groups that we were following regulations, considered cultural matters seriously and intended to carry out our project respectfully. We offered to add any iwi and hapū contacts directly to the Accidental Discovery Protocol that we used and offered that nominated representatives be present at drilling. Several groups requested the addition of contacts to Accidental Discovery Protocols, but none chose to attend the active drilling operation. No instrument or borehole site uncovered archaeological material or historic artefacts.

3.4.2.2 Traffic Management

Health and Safety legislation requires that people working near roads, as part of their job description, to follow New Zealand Transport Agency (NZTA) regulations, including submitting approved Traffic Management Plans (TMPs). These regulations also govern the safety equipment both for signage and Personal Protective Equipment (PPE). Since much of Transect 1 required deployment in or near road reserve, we also needed approved TMPs. The TMPs are aimed at keeping road workers safe, and the plans achieve this by keeping a centralised roading authority aware of all activity on roads in their district. The centralised authority can then inform those using the roads of other hazards they may encounter and help ensure safe and efficient management for all users. Each roading district has different requirements. Tairāwhiti Roads controlled the roads in the Gisborne District Council area, and the Ōpōtiki District Council was responsible for roads in their district. For the SHIRE II project, we were able to use generic TMPs that define broad regions of work and are well suited to mobile roadside deployments. The TMPs outline the NZTA signage employed, the roads used and the hours of work. Due to NZTA equipment regulations, this required the SHIRE II project to be restricted to daylight hours. TMPs require a Site Traffic Management Supervisor (STMS) to be within 60 minutes of sites. However, SHIRE II applied for, and was granted, an exemption due to the large travel distances from the central Gisborne location (>180 minutes). With approval, the generic TMP was able to operate with a single STMS (Stuart Henrys) and have approved Level 1 Traffic Controllers (GNS Science personnel) in each vehicle/site team.

Once lodged, the main requirement of the TMPs was to confirm whether we were undertaking operations each day. For Tairāwhiti roads, the SHIRE II deployment procedures were updated via email and spreadsheet roster. For Ōpōtiki District Council, a phone call was required each morning. The work schedule was possible due to our work taking place on low-volume roads only. Tairāwhiti roads also required that we lodge our locations with the 'beforeUdig' website (https://www.beforeudig.co.nz/nz/home/). Although this was mandatory, the information given by providers, for example, information from Chorus, was not digital and did not contain geographical coordinate data. The feedback information was scanned to look for major issues impacting site planning but was not useful for detailed site locations. No cables or buried structures were encountered while installing sites. Further details are given in Appendix 3.4.

3.5 Drilling SHIRE II Boreholes

Drilling of the boreholes was originally planned for late December 2018; however, delays in the consenting process and scheduled drilling company operations meant that the drilling was delayed until mid-January 2019. Consenting was finalised in the Bay of Plenty Regional Council first and drilling started with Site 5 (Ōpōtiki) on 14 January 2019. Boreholes were drilled by a truck-mounted drill rig (Figure 3.4), which used an Odex drilling system. Initial geological assessments were made during site visits with the Quality Manager from Honnor Drilling to ensure that the drill rig would be able to operate at all the selected sites. It was anticipated that Sites 4 and 5 would encounter solid rock, with possible volcanic material at Site 5. Drilling took more than two weeks at the first site, Site 5, and encountered a number of problems. The hole collapsed about a week into the drilling, and the drill team returned in the morning to find the rig tilting backwards into the site. The landowners at Site 5 assisted with getting the drill rig back on solid ground and helped create a gravel drill pad to shore up the soft ground created by extensive rain. The first hole was bored out to 10 inches and was wash drilled until harder rock was encountered at a depth of 14 m. Odex drilling continued from 14 m, and then an 8-inch casing was cemented inside of the 10-inch hole. The delay in completing Site 5 resulted in postponement to scheduling the loading of the explosives and, in turn, delays in deployment of instruments. The remaining four sites went ahead as planned without problems and were drilled according to the initial schedule and completed by 15 February 2019.

Figure 3.4 Photos of drill rig and equipment setting up at Site 5. a) Drillers positioning the truck to raise the rig. b) Ancillary drilling equipment, including water tank and generator. c) Drill rig raised and truck with casing.

3.6 Borehole Explosives Specifications

Orica was contracted to supply and deliver the Centra™ Gold explosives emulsion and undertake the blasting operation under Health and Safety at Work (Hazardous Substances) Regulations 2017. Richard Sullivan of Sedna D&B was contracted to undertake timing of the controlled sources and was present at all borehole emulsion loading to ensure his timing mechanisms were set-up correctly. Richard also gave helpful advice ahead of time to ensure that the correct stemming material was acquired and safely placed. A full report on recorded firing times and advice for future boreholes is given in Appendix 5.

Each borehole was loaded with explosives to the following specifications:

1. A small amount of gravel was put at the bottom of each borehole before loading the explosives emulsion to ensure that the entire explosives column sat within and not below the casing. This helped to minimise any chance of a casing blowout.
2. Boreholes were filled with at least 500 kg of Centra™ Gold explosive emulsion.
3. All boreholes were primed with three seismic boosters, each 500 g (Pentholite), together with detonators. The Sedna D&B report includes recommendations for future specifications, especially in regard to the shape of primers to ease loading of the product into 50 m+ boreholes (Appendix 5).
4. Explosives were sealed within the blast hole by coarse aggregate. Gas bags were also used in some cases to ensure that the detonation wires would still be accessible in the event of a collapse or degassing of the explosive's column. The top of the borehole was capped and locked to prevent any direct access to the detonation wires. The detonator wire was protected to avoid damage.

Emulsion was delivered to each site by a special purpose vehicle (Mobile Manufacturing Unit, MMU). Boreholes were loaded with emulsion, primed and back-filled with gravel between 25 and 26 February 2019. Angular gravel comprised grade 3 chip from Tracks Whakatane for Site 5 and 20 mm lime chip for the other four sites from Gisborne-based Jukes carrier (see Figure 3.5). Detonation of the explosives was completed by Orica between 26 and 28 February 2019 (Figure 3.6). Table 3.1 summarises borehole times; further details can be found in the Sedna D&B firing times report (Appendix 5).

The final depths of the boreholes and amount of Centra™ Gold explosives varied for each site; these can be found in Table 1 of the Sedna D&B report found in Appendix 5 (Table A5.1).

Figure 3.5 Gravels for stemming the explosives in the borehole. 20 mm lime chip used in Sites 1–4.

Figure 3.6 Explosion Site 3, Mangatu Forest, detonated 27 February 2019. Venting column of gas and stemming took place approximately 52 seconds after the initial detonation. In the subsequent 10 seconds, the column grew to a height of ~50 m before venting stopped. The image was taken with a Go-Pro camera mounted a few metres from the bore hole.

3.6.1 Site Remediation

Site remediation was agreed with landowners as part of the land access agreements and resource consents. Some remediation of 12 boreholes were undertaken as part of the 2011 SAHKE controlled-source project in the Wairarapa. Experience from 2011 was adopted for SHIRE and, where possible, casing cut below the ground surface so that there was less opportunity for water to be channelled to the base of the borehole to create any cavity. Farm Services was contracted to undertake this work (see Figure 3.7).

Figure 3.7 Borehole remediation. a) Casing dug out at Site 4. b) Grinder being used to cut casing at Site 3. c) Site 4 after remediation.

Table 3.1 Controlled source borehole site locations and description.

Site Name	Site Photograph	Site Description
Site 1: Panikau Road		Location: -38.47623, 178.17152 Depth (m): 50.4 Date Loaded: 25-02-2019 Date Detonated: 27-02-2019
Site 2: Rangatira		Location: -38.42757 S, 177.86861 E Depth (m): 50.7 Date Loaded: 26-02-2019 Date Detonated: 28-02-2019
Site 3: Mangatu		Location: -38.27358 S, 177.73906 E Depth (m): 51.2 Date Loaded: 25-02-2019 Date Detonated: 27-02-2019
Site 4: Waitangarua		Location: -38.23843 S, 177.61438 E Depth (m): 50.2 Date Loaded: 26-02-2019 Date Detonated: 28-02-2019
Site 5: Motu		Location: -38.02840 S, 177.42130 E Depth (m): 50.1 Date Loaded: 26-02-2019 Date Detonated: 26-02-2019

3.7 Seismometer Deployment

3.7.1 Location Determination

Seismometer locations were chosen to maximise contiguous segments along the Transect. This resulted in 10 main segments separated by access points (see list in Table 3.2 and map in Figure 3.8).

Table 3.2 Main road and track segments of seismometer locations (Figure 3.8).

Segment	Road and Track
1	Waiomoko and Wharekiri roads
2	Monck, Utting and Waimata Valley roads
3	Ahititi Station track
4	Gilbertson track, Bruce Road, Kanakania
5	Waitangi Road
6	Armstrong Road
7	Mangatu East (from Te Hua station through Wairere and Mangatahu to Okaihau)
8	Mangatu West (access along Motu Falls Road and Waitangarua Station)
9	Motu Road
10	Hikurangi Road

As preliminary locations were required for permitting seismometer sites, these were established in a GIS (QGIS) prior to final site selection and deployment. The locations also helped estimate more precisely how many instruments were needed on each segment. Site positions were determined along the transect by orthogonally projected points at 150 m spacing onto proximal accessible roads. These projections were important during SHIRE II, as limited road access meant that the transect comprised multiple segments and some gaps were unavoidable. To determine station locations, we performed an intersection analysis in QGIS using the transect perpendicular projections and the existing road layers. The intersection analysis assigned coordinates to individual planned seismometer sites. Pre-programmed coordinates allowed use of handheld GPS and navigational phone apps, like OSM, for deployment (see Appendix 8) and reduced the number of decisions that needed to be made in the field (Figure 3.8).

The 10 main Transect segments required a maximum of 570 geophone sites comprising 1140 ‘Texan’ seismic recorders (REFTEK RT125), as every second station (300 m spacing) was chosen as a 3C Texan site connected to 3C-L-28 short-period sensors. The PASSCAL shipment included 1260 Texans so that additional segments could be planned to help follow phases between the 10 primary segments (Figures 3.8 and 3.9). Both the segment numbers and individual instrument numbering follow the SHIRE I convention and increase east to west.

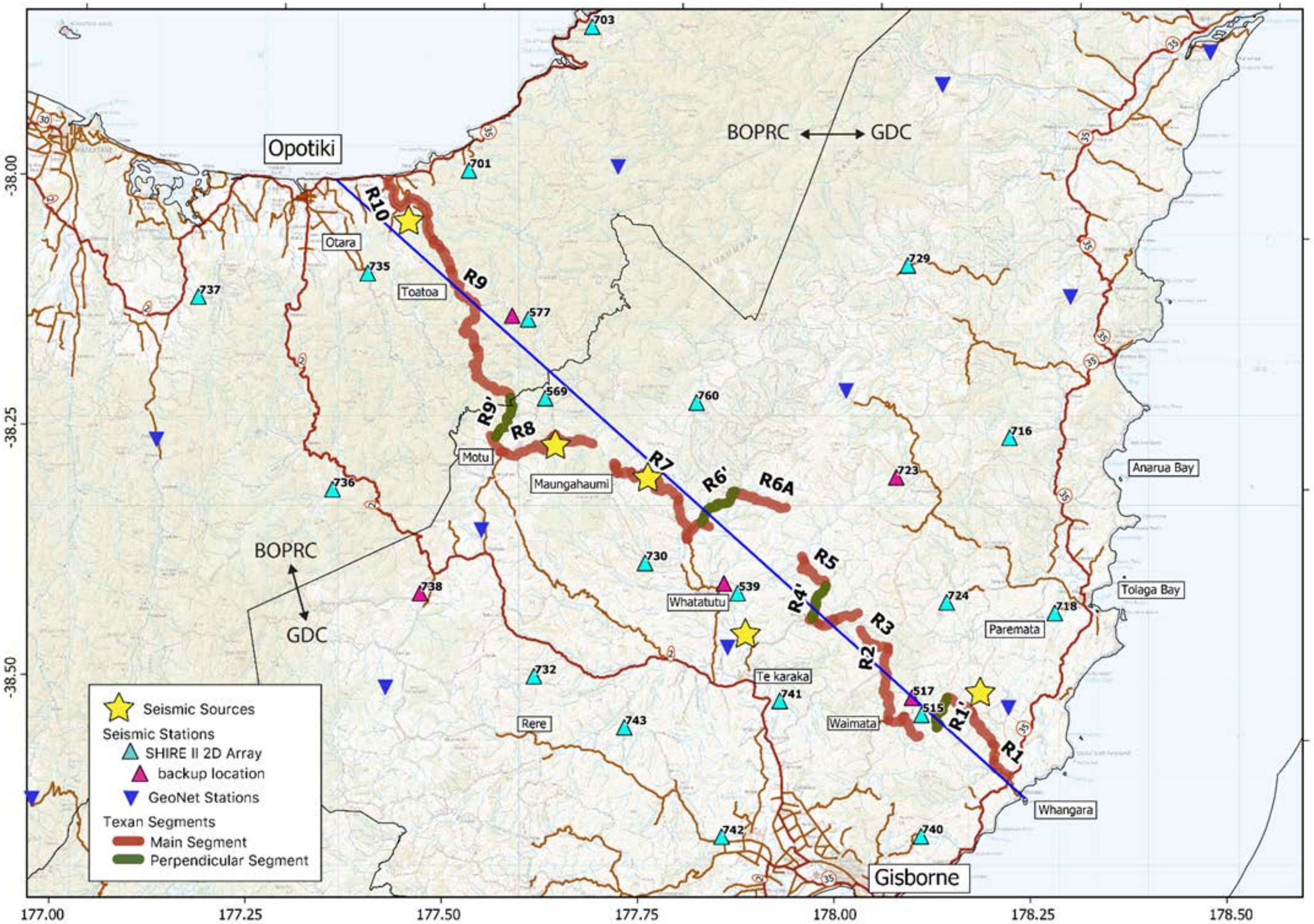


Figure 3.8 Pre-deployment segment overview map. The 10 main Transect segments are marked in bold red. Four perpendicular connecting segments are marked in bold green, followed by a ' mark to note the segment they are accessed with. The thin blue line shows the onshore projection of SHIRE Transect 1. The thin black line running roughly NE–SW marks the boundary between the Gisborne District Council (GDC) and the Bay of Plenty Regional Council (BOPRC) jurisdictions.

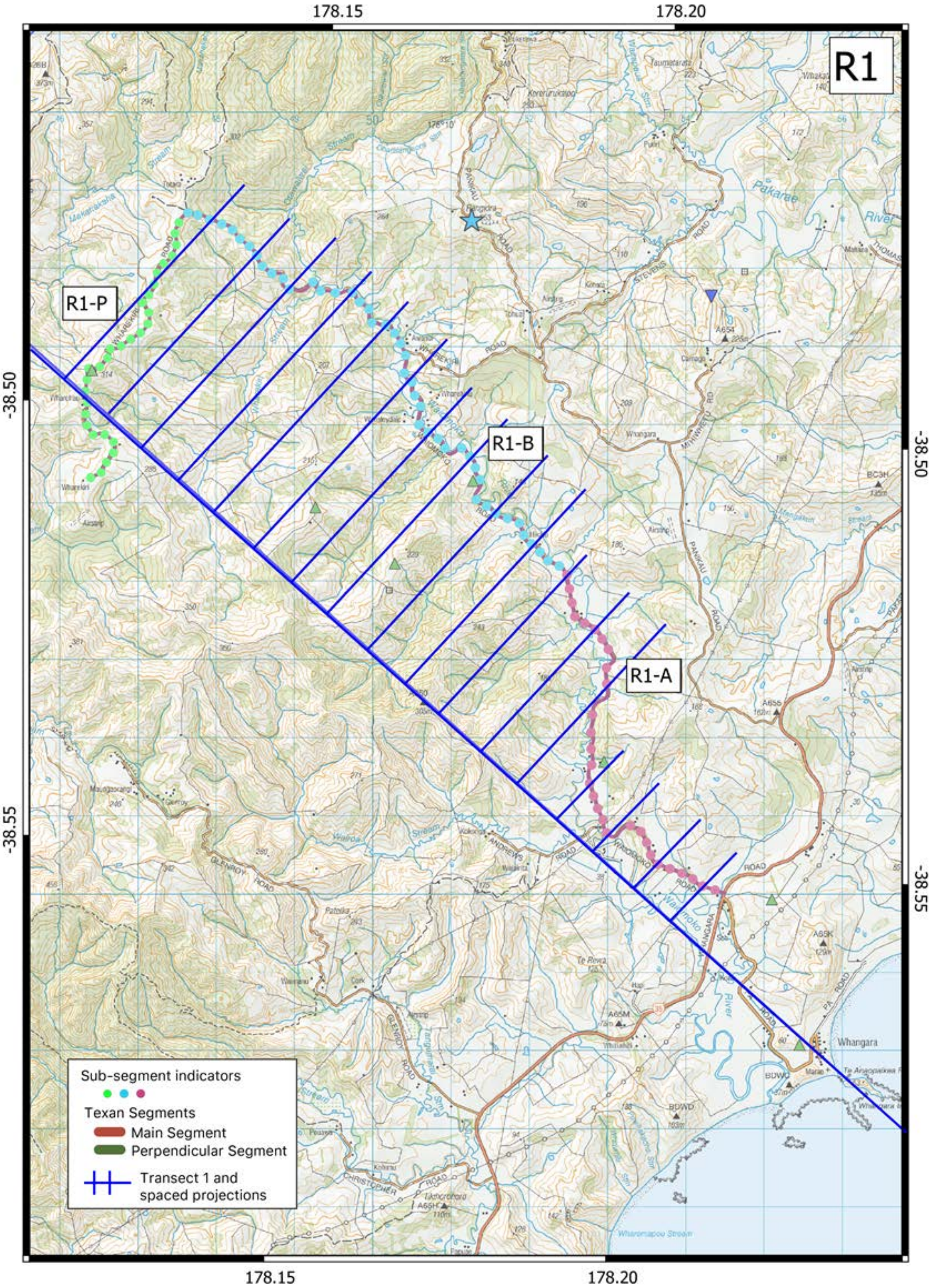


Figure 3.9 Example segment overview map for Segment 1 and 1p. The colours represent stations covered by different detail maps. The thin blue line is SHIRE Transect 1; main transect (NW–SE) and several projected lines are shown to give a feel for their use to calculate road intersection points.

3.7.2 Instruments

In addition to the main Texan RT125 instrumentation, 19 short-period REFTEK RT130 seismometers were also deployed off-transect to better locate earthquakes during the Texan recording times. These were re-deployed at SHIRE I locations, and several were deployed in new locations to fill gaps in the network (Figure 3.8). The 2D Array sites were instrumented with L-28 seismometers and REFTEK RT130 data recorders. These sites were similar to SHIRE I set-up (Section 2.4), but solar panels were not used, as the overall lifetime of the sites was only a matter of weeks and within the expected battery life of the two 75 amp-hour batteries deployed at most sites. The 2D Array did not use the QDS boxes or solar panels, and sites without stock, or with only sheep, were deployed as low-profile sites without fencing. The site set-ups were similar to the GSX operation during SHIRE I (Section 2.4.3, Figure 3.10). The lack of fencing sped up deployment at these sites, but often required digging substantial holes to accommodate battery height.

Since the 2D Array GPS timing and data recovery were not power dependent, and the battery life was much longer than the Texans, these sites were deployed prior to and recovered after the Texan instruments. Station 579 was an exception and was deployed and collected with the Texan deployment due to its proximity to the transect and remoteness compared to other 2D sites (Appendix 2).

Figure 3.10 a) Example of 2D Array low-profile set-up without fencing. b) 3C Texan site showing separate burial of L-28 and the Texans (inside white bag for extra water and dirt protection). Photos courtesy of Jenny Black.

3.7.3 Instrument Programming

Explosives contractor Orica ruled out detonating boreholes in darkness, as they were concerned that they would be unable to fulfil their safety obligations and ensure that the site was clear of livestock and people. The recording windows for the Texans were set to achieve maximum quiet time (recording before sunrise and after sunset) and enough of a dawn and dusk time window to provide a safe working duration for the explosives team.

We determined that a set of eight 4-hour windows was optimum to maximise both the overall recording time and the battery power lasting through instrument retrieval and download (Table 3.3). The calculation used information on the PASSCAL website https://www.passcal.nmt.edu/content/powercalc. The Texan instruments were programmed to record at a sample rate of 250 Hz (4 ms sample rate) and were continuous for each 4-hour window.

Table 3.3 Programmed recording times for the instruments deployed.

Date (2019)	Instrument	Start Time		End Time	
		Local Time	UTC	Local Time	UTC
February 26	-	-	-	-	-
	Evening	18:00	2019:057:05:00:00	22:00	2019:057:09:00:00
February 27	Morning	04:00	2019:057:15:00:00	08:00	2019:057:19:00:00
	Evening	18:00	2019:058:05:00:00	22:00	2019:058:09:00:00
February 28	Morning	04:00	2019:058:15:00:00	08:00	2019:058:19:00:00
	Evening	18:00	2019:059:05:00:00	22:00	2019:059:09:00:00
March 1	Morning	04:00	2019:059:15:00:00	08:00	2019:059:19:00:00
	Evening	18:00	2019:060:05:00:00	22:00	2019:060:09:00:00
March 2	Morning	04:00	2019:060:15:00:00	08:00	2019:060:19:00:00
	-	-	-	-	-

3.7.4 Deployment

Along the 10 main segments of the Transect, sensor spacing was 150 m, and, in general, every other sensor was 3C to establish a 300 m spacing of 3C sensors.

Given the ~5-day battery life of the Texan instruments once programmed, three field teams were split between Gisborne, Motu (north of Matawai) and Ōpōtiki. A fourth team helped organise gear at the field centre and acted as a shuttle crew for other teams to drop off new sets of programmed instruments and any other necessary field supplies each day. The need to have a certified Traffic Controller with each vehicle and the number of available road signs necessary to comply with our TMPs limited the number of vehicle teams we could deploy at one time. For most of the deployment, each vehicle team consisted of four people working in teams of two. At times, teams worked as either just two or three people operating in a single team. As the 3C sensors took longer to deploy, an efficient method, involving two teams per vehicle, was for the vehicle to drive to the 3C site and, from there, one of the sub-teams would walk to and deploy the next 1C site ahead. Once the 3C team had finished, they would drive and collect the 1C sub-team and all team members would drive to the next 3C site. This could be repeated along the length of each segment. This rotating 3C – 1C deployment strategy allowed us to maximise the number of people deploying with a limited number of vehicles. Dry ground and gravel increased digging and site installation times along some segments, but most installation times were between 10–25 minutes, with a daily total of 20–35 sites per sub-team.

Due to the need to be pre-programmed, the Texan data recorders do not store station location information (neither station number or coordinates). The lack of internal location information makes deployment sheets and field notes essential for using the retrieved data. Deployment sheet written information included: array line, station number, instrument serial numbers for 1C or 3C sites, geographical coordinates, installation time/date and team members. The installation time/date and team notes are useful for trying to track down errors in other entries. Completed field sheets also served to make sure all stations were deployed and confirm station retrieval. Hand-recorded coordinates were cross-checked with digital files. Field sheets also allowed for deployment team remarks that organisers could quickly read back at the field centre.

Individual Texan instruments record just one component. For 3C stations, three Texan instruments were attached to a 3C sensor using a 3-to-1 adapter cable that is colour coded for the vertical, north and east sensor components (see Seward et al. 2011 for photograph of cable set-up). The inability to upload station location information into the Texan instruments poses an additional risk of misidentified components at the 3C sites. Therefore, the Texan serial numbers attached to each of the adapter cable's components had to be carefully recorded in the field sheets. To further minimise the risk of swapping component information, sets of three instruments were colour-dotted to match the adapter cable colours in the field centre prior to being sent out for deployment. This sped up both physical deployment and recording of the metadata.

Knowledge of the number and exact location of the Texan sites in each segment helped determine how to prioritise installation efforts and modify lines as the field effort progressed. The decision was made to modify the perpendicular segments to entirely single component stations to speed up deployment and to leave out segment 8a, accessed by light utility vehicle (LUV), to maximise team days elsewhere.

Approximate coordinates were pre-determined for each Texan site and could be loaded into handheld GPS and navigational phone apps. The main phone app used for this purpose during the deployment was a free Android app, OSM+. The OSM+ app had the ability to use downloaded topographic maps even when no phone signal was present. See Appendix 8 for installation and field use instructions for OSM+. The app was also able to 'mark' coordinates if locations were changed during deployment. These phone files were often easier to download than the GPS marks and were a QC check of the recorded field metadata. Both WGS84 latitude/longitude and NZTM were recorded for all sites (Appendix 6). In general, latitude/longitude coordinates are slightly easier to quality control as they have fewer digits that can be transposed when reading or writing onto deployment sheets.

We deployed a total of 583 stations, 269 3C sites and 264 1C sites on the main transect and a further 50 1C sites along supplementary perpendicular segments in four days (Figure 3.1 and Appendix 6.2).

3.7.5 Detonation of Borehole Explosions

Boreholes were loaded with explosive emulsion and detonators one day prior to and on the day of the first detonation. This meant that the total number of days in the field were minimised for the Auckland-based Orica team. This timing resulted in a loading order of sites 3, 2, 1, 4, 5 and a detonation order of 5, 3, 1, 2, 4. Weather was mild for all scheduled shooting days and did not factor in the timing of detonation windows. Following the first two explosions (Sites 5 and 3), Orica experimented with piling leftover stemming material on top of the borehole to further dampen the noise of the explosion. This was largely successful. The first three detonations (Sites 5, 3, 1) went off successfully without misfires. A misfire was recorded at the fourth site, Site 2. Site 2 firing was successful on the second attempt but did not vent steam as the first three detonations had done. The team waited nearly an hour to get close to the site before approaching to ensure safety in case of a delayed venting (venting was delayed several minutes at Sites 3 and 1). We suggest that the lack of venting was related to water level in the hole. This was confirmed by the lack of venting at Site 4, which also had a lower water table (Appendix 4, Figure A4.1). The Sedna D&B report in Appendix 5 addresses this in more detail.

The explosion timing was determined with two different ShotTrack products; both used GPS timing for millisecond accuracy. The primary timing monitor was a Velocity of Detonation (VOD) ShotTrack VOD 305 unit. The back-up monitor was a ShotTrack Vib (vibration recording) unit that relied on a wire break to record timing. At each explosion site, a geophone was installed within 10 m of each borehole as a timing fail safe and for corroboration of the primary timing methods. The primary VOD 305 successfully recorded timing on the first firing (Site 5) but failed to gain a GPS lock on the subsequent two holes (3 and 1). After contact with the manufacturer, a new procedure ahead of firing was established to ensure that the GPS was on and locked prior to detonation, and the VOD 305 successfully recorded the last two sites (2 and 4). The backup ShotTrack Vib unit recorded a break at Sites 3 and 1 but did not trigger properly at the other three sites. The ShotTrack Vib timing was used to do an initial receiver gather after sites were collected, and the recorded detonation timing of Site 3 was found to be delayed by one minute. A table with the times recorded by each system is given below in Table 3.4, and further details of the recording systems, the loading of explosives and suggestions for future projects can be found in Appendix 5.

Table 3.4 Times recovered by Sedna D&B. All times are in February 2018. Texan waveform time is given for Site 3, as the Sedna D&B timing did not match. The Sedna times for all other sites can be used as the detonation time.

Blast Order	Site	Date Fired UTC	Time at Detonation UTC (hh:mm:ss.000)	Date Fired NZDT	Time at Detonation NZDT (hh:mm:ss.000)	Monitor Unit	Monitor GPS Latitude	Monitor GPS Longitude
1	SP5	26-Feb	07:22:51.430	26-Feb	20:22:51.000	305	38° 01.70387' S	177° 25.27799' E
2	SP3	26-Feb	18:14:17.516	27-Feb	07:13:19.331	ViB	38° 16.41506' S	177° 44.34368' E
3	SP1	27-Feb	06:17:49.736	27-Feb	19:17:50.000	ViB	38° 28.57371' S	178° 10.29094' E
4	SP2	27-Feb	18:12:26.692	27-Feb	07:12:27.000	305	38° 25.65443' S	177° 52.11668' E
5	SP4	28-Feb	06:25:31.073	28-Feb	19:25:31.000	305	38° 14.30559' S	177° 36.86278' E

3.8 Data

3.8.1 Data Quality and Archiving

Both the SHIRE I and SHIRE II data has been processed to be archived and stored by IRIS Data Management Center (DMC; network code 6B [2017–2019]). These data are under embargo until 2021-04-07. The quality of the data recorded was good for all explosions. The energy from each blast was recorded clearly at each seismometer from coast to coast. Figure 3.11 shows a preliminary gather from Site 3, Mangatu Forest (Figure 3.2). The data quality is excellent. Every wiggle is a separate instrument location, and they are displayed west (Ōpōtiki to the left) to east (Gisborne to the right) and arranged by offset. The vertical axis is time (sec) from explosion instant. Clear direct arrivals are visible on all traces and distinctive reflections from the probable top of the subducting Pacific Plate. It took the initial wave 9 seconds to reach Ōpōtiki and about 11 seconds to arrive at the equivalent offset on the east coast, near Gisborne, confirming that rocks wave speeds are slower in the east compared to the west.

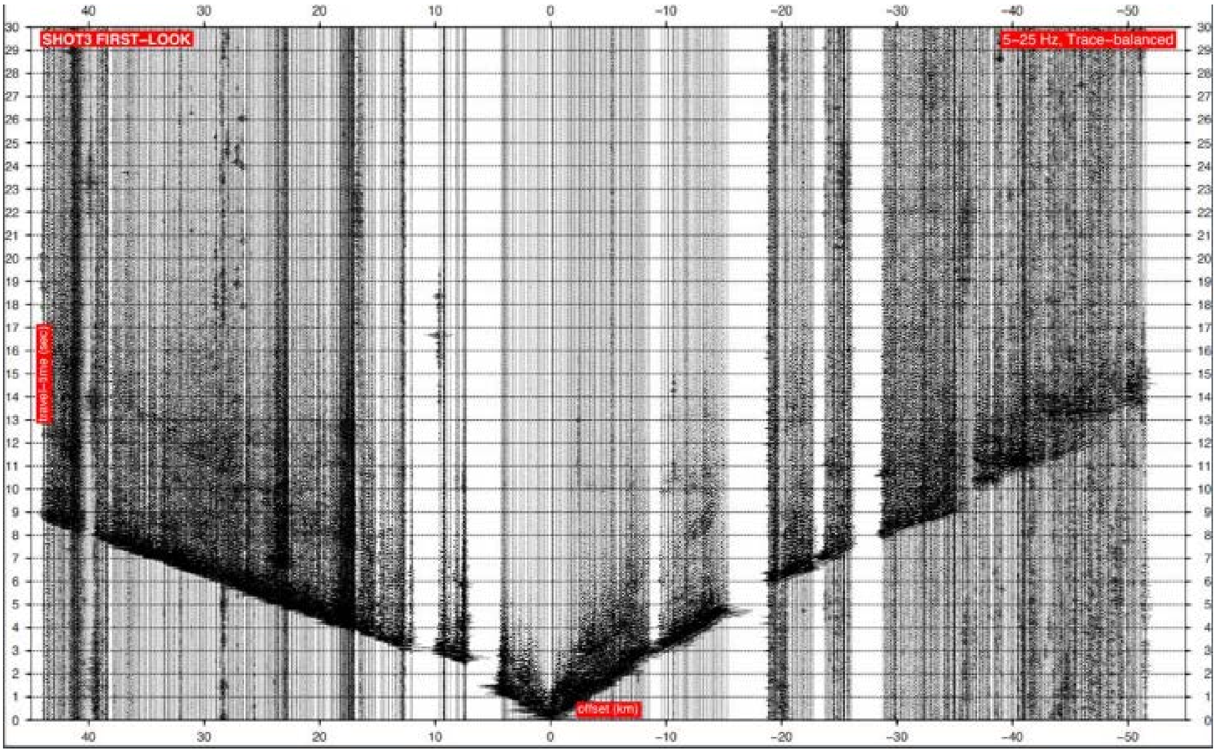


Figure 3.11 Source point gather from explosion at Site 3, located in the Mangatu Forest, near the centre of the transect. Traces are nominally 150 m apart and displayed with offset (km) along the horizontal axis and time (seconds) since explosion on the vertical axis. Gaps are where we could not locate instruments along the transect.

3.8.2 Onshore-Offshore Supergather

The two phases of SHIRE I and II field seasons come together in the assembling of 'supergathers' (Okaya et al. 2002). Onshore-onshore receiver gathers provide crustal velocity and wide-angle imaging beneath the coastline, and the land explosion data provide velocity imaging beneath the land array. Figure 3.12 illustrates from west to east the supergather wide-angle phases received from profile MC03, in the Bay of Plenty; source gather for Site 4; and energy from profile MC10, offshore Gisborne. The combined supergather can be viewed as a split-spread shot gather, i.e. as if the explosion source was at station 565 and receivers at each marine airgun source point. To the west, strong wide-angle PmP reflections are identified as Moho of the Australian plate. Clear diving waves, Pg, in the crust are visible to offsets of 100 km. A few seconds later than Pg are observed reflections that may bounce off the top-of-subducting plate reflection (PtopP) and identified at offsets <60 km. Energy from MC10, offshore Gisborne, propagates as Pn phases travelling in the mantle of the Pacific Plate.

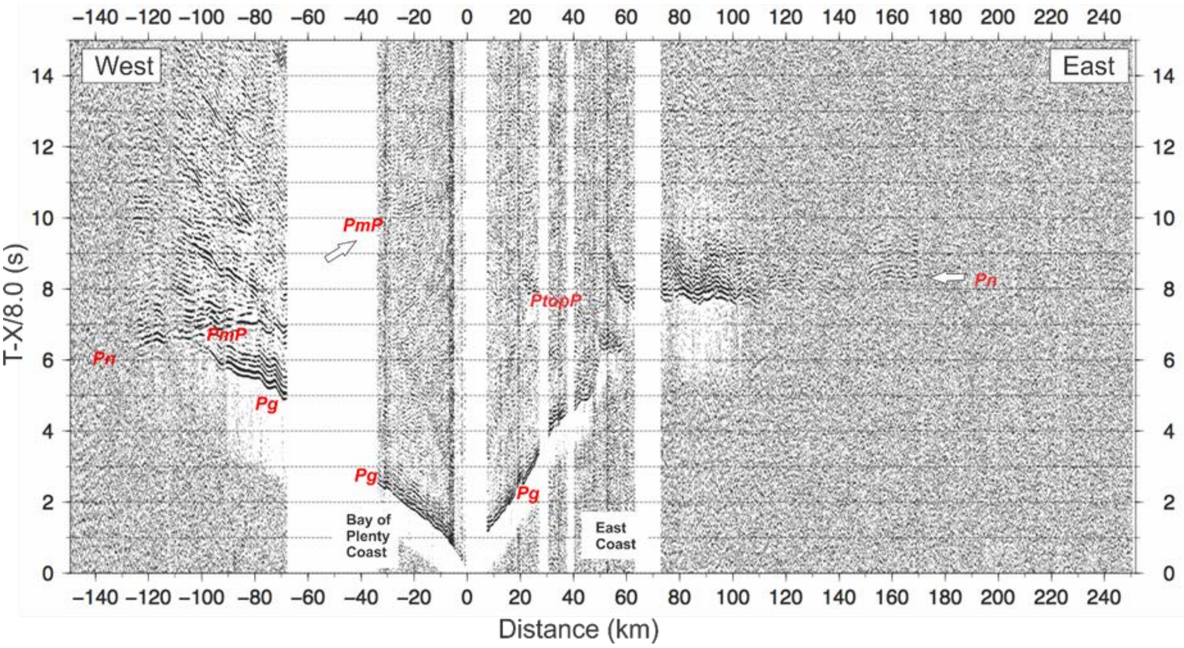
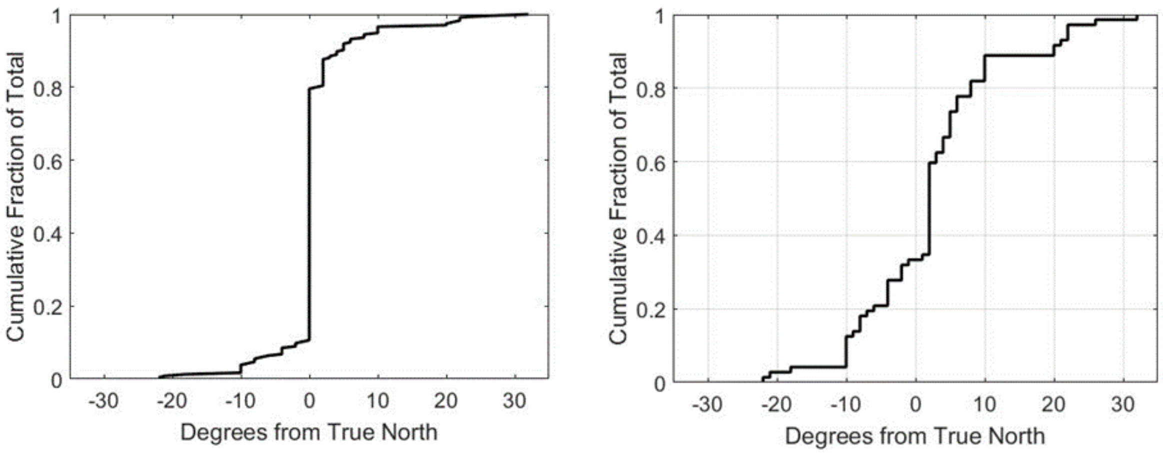


Figure 3.12 Combined onshore-offshore gather at station 565 near source point Site 4 produces a 350-km-wide ‘supergather’ (Okaya et al. 2002). Receiver gather from profile MC03, in Bay of Plenty, has strong wide-angle PmP reflections identified to be base of the Australian plate crust. On the source gather for Site 4, clear turning waves, Pg, in the crust are observed and a top-of-subducting plate reflection (PtopP) is identified on offsets <60 km. Energy from MC10, offshore Gisborne, propagates as Pn phases.

3.8.3 Comment on Orientations

Just under 90% (235/269) of 3C Texan sites had recorded orientations on the retrieval field deployment sheets (see Section 3.6.4). Of the reported orientations, roughly 70% (162/235) reported correct True North orientations (Figure 3.13). Out of the reported orientations, most are well oriented to True North, with 85% within +/-5 degrees of True North. The distribution of orientations shows that most are well oriented with a subset of ~5%, likely due to an incorrect interpretation of the magnetic declination (~22 degrees). The distribution of orientations indicates the horizontal component data should require relatively little rotation processing before use.



a) b)

Figure 3.13 Cumulative distribution of measured orientations of instruments on retrieval from the field. a) 235 3C transect stations with reported orientations. b) Subset of the 73 non-zero reported orientations.

3.8.4 Passive Sources

In the 20 days that the SHIRE II 2D array was deployed, 173 earthquakes were located by GeoNet (Figure 3.14). A list of local and global earthquakes during that time is located in Appendix 9. Four earthquakes with M > 6.0 occurred between 16 Feb 2019 and 8 March 2019 when the 2D seismometer array was deployed. Based on UTC origin times, it is unlikely that any of these M > 6.0 earthquakes occurred during the Texan array recording windows (Table 3.4).

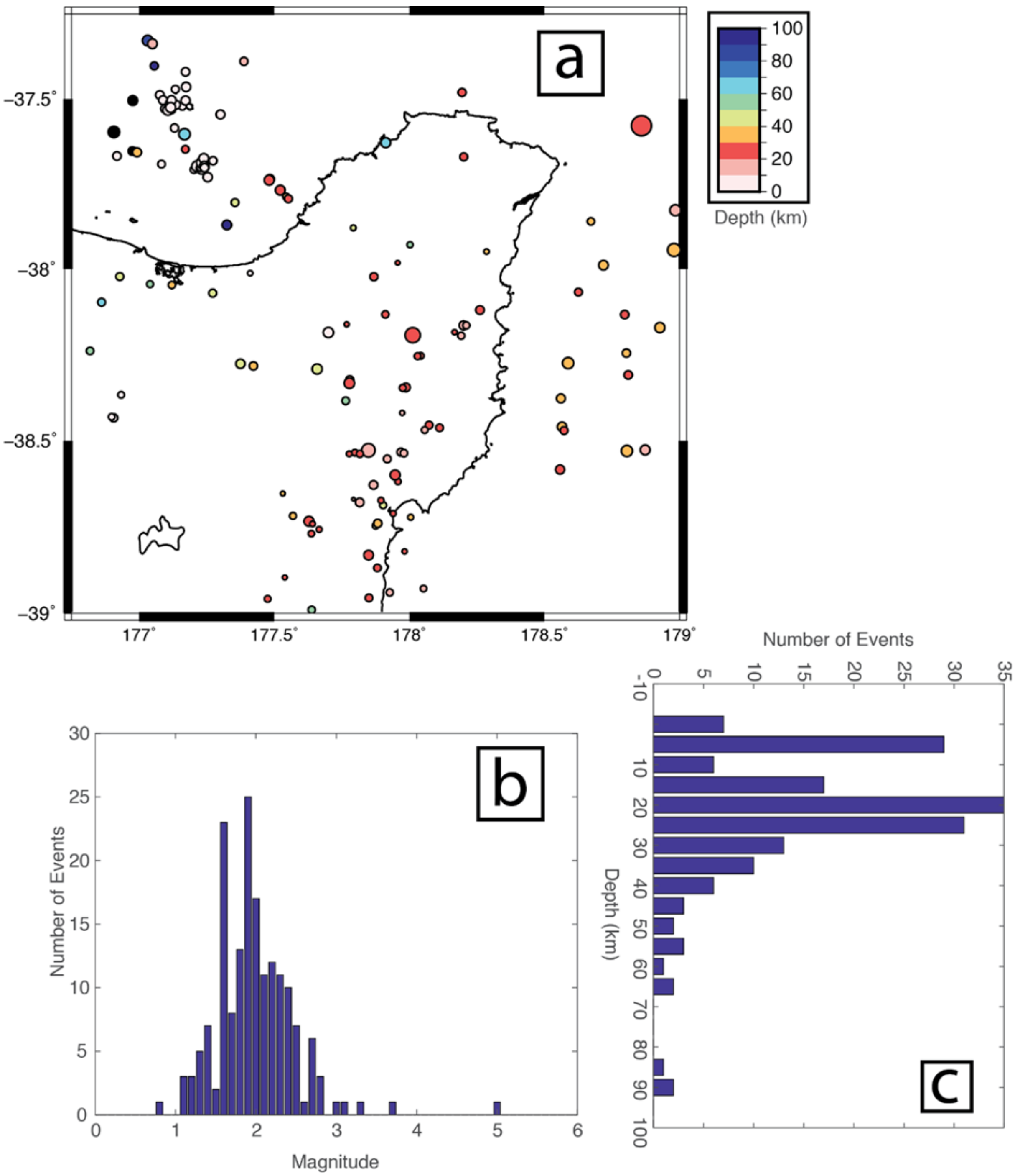


Figure 3.14 SHIRE II earthquake a) locations, colour-coded by depth; b) magnitude histogram; and c) depth histogram.

4.0 COMMUNICATION AND OUTREACH

The controlled source component of the SHIRE project (SHIRE II) created more interest and solicited more questions from landowners. For that reason, most of the outreach and engagement efforts were focused in the second phase of the project. Due to attention related to the offshore seismic acquisition and Integrated Ocean Drilling Program (IODP) scientific drilling project, the project team put together a series of factsheets and educational material. Several factsheets had been developed for the ancillary IODP scientific drilling, and a separate matching seismic factsheet was developed to accompany the SHIRE I project (Appendix 9).

Although the detonations tend to be much less dramatic than the images conjured up when people hear the word ‘explosion’, they still had the potential to be of interest to the public. Two factsheets were created for SHIRE II (Appendix 9). One was specifically designed for landowners to provide relevant information as part of the July 2018 borehole explosion site scouting trip. Another more general factsheet, in the style for SHIRE I, was provided as part of the series related to the Hikurangi Subduction Margin Earthquakes and Slip Behaviour projects.

Through the permitting process, we established communication with iwi and hapū groups and distributed information on the SHIRE II purpose and operations. Iwi contacts were added to the email list of weekly updates. Initially, the postings were used for GNS Science internal updates to department management, but later broadened to include council and community groups. The weekly updates allowed everyone to keep abreast of the evolving schedule.

A further list of notifications undertaken for SHIRE II included:

- a public notice to newspapers
- emails to SHIRE I and NZ3D landowners in the region of explosion sites
- an in-person visit to Gisborne Police Station
- a notice to Civil Defence
- notification to GeoNet of planned times/locations of borehole explosions, and
- individual landowner communication.

The visit and notification to police received positive feedback for being proactive, as we undertook these days in advance. However, a delay in submitting the public notice to media and newspapers caused concern to some communities, which we took extra communication effort to allay. We recommend that future notifications for controlled source activities should be made well in advance. Table 4.1 lists SHIRE media releases and public information.

Table 4.1 List of media releases and other public information links.

GNS Science Media Releases
GNS Science SHIRE I – October 2017
GNS Science SHIRE II – Preview 25 Feb 2018
GNS Science – Hikurangi Road Show
Other Media
TVNZ News SHIRE I – 23 Oct 2017
Stuff Preview SHIRE II work – Nov 2018
Gisborne Herald SHIRE II – 26 Feb 2019
NZ Herald M 5.0 East Cape and SHIRE II – 1 Mar 2019
Other Links
GNS Science Hikurangi Information page
East Coast Life at the Boundary (LAB) SHIRE project page
University of Texas Institute for Geophysics Hikurangi page

5.0 REFERENCES

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APPENDICES

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APPENDIX 1 ACKNOWLEDGEMENTS

A number of people are acknowledged in the tables that follow (Tables A1.1 and A1.2). However, the list of people and organisations that made SHIRE possible is much larger, and we recognise the assistance and many acts of kindness and support that contributed to the success of the project.

SHIRE is primarily funded by the US National Science Foundation; the New Zealand Ministry of Business, Innovation & Employment; JAMSTEC; and the Earthquake Research Institute, University of Tokyo. Participating organisations are GNS Science, the University of Texas, JAMSTEC, Imperial College London, Penn State University, the University of Southern Mississippi, the University of Southern California, California State Polytechnic University, Victoria University of Wellington and the University of Tokyo. The *R/V Marcus G. Langseth* is owned by the US National Science Foundation and operated by the Lamont-Doherty Earth Observatory of Columbia University in New York. Seismic instruments were provided by IRIS through the PASSCAL Instrument Center at New Mexico Tech and the Earthquake Research Institute, University of Tokyo.

The general interest in science and willingness to support scientific projects makes data collection in New Zealand both enjoyable and rewarding. We are grateful to individual landowners and companies who enabled the data collection by hosting seismograph sites on their properties; allowing us access to their land; and helping us navigate the landscape, sometimes under challenging weather conditions. We are grateful to you all. We would also like to thank the Tairāwhiti/Raukumara communities for engaging with us, particularly the three major iwi involved in the project for guiding us and helping us to better understand your interests and needs. We will continue to work on incorporating your advice in future projects and look forward to bringing you the results of this work as they develop.

In particular, we would like to acknowledge the following organisations: Bay of Plenty Regional Council, Chorus, Ernslaw One, Gisborne District Council, Hawke's Bay CDEM, Hawke's Bay Regional Council, Heritage New Zealand Pouhere Taonga, Hikurangi Forest Farms, Honnor Welldrillers Ltd, the IRIS PASSCAL Instrument Center, Mccannics, Ngāti Rua Hapū, Ōpōtiki District Council, Orica, the Paikea-Whitireia Trust, PF Olsen, Sedna D&B, staff at Ngata College, Tairāwhiti CDEM, the Whakatōhea Māori Trust Board, Whakatōhea Taumata Kaumātua and WSP. Staff at GNS Science helped advise and logistically assist the SHIRE project at various times. We are particularly grateful to Ellen Fransen, Tania Gerrard, Diane Bradshaw, Jenny Woodward, Peter Royle, Roger Williams, Lianne Brejnakowski, Nida Templenuevo, Bevan Hunter and the GNS Science Health and Safety team.

Table A1.1 SHIRE team field personnel.

Organisation	Name	SHIRE I	SHIRE II
GNS Science	Stuart Henrys	x	x
	Katie Jacobs	x	x
	Jenny Black	x	x
	Dan Barker	x	x
	Dan Bassett	-	x
	Rory Hart	x	x
	Jess Hillman	x	-
	Richard Kellett	x	x
	Regine Morgenstern	x	x
	Vaughan Stagpoole	x	x
	Wanda Stratford	x	x
	Emily Warren-Smith	x	-
	Sapthala Karalliyadda	-	x
Victoria University of Wellington	Kenny Graham	x	-
	Pasan Herath	x	-
	Bimaya Herath	x	-
	Chet Hopp	x	x
	Laura Hughes	x	x
	Megan Kortink	x	x
	Marcel Lanz	-	x
	Daniel Lindsay	x	-
	Konstantinos Michailos	x	-
	Damian Orr	x	-
	Martha Savage	x	-
	Weiwei Wang	x	-
	Hubert Zal	x	-
University of Texas Institute of Geophysics	Harm Van Avendonk	-	x
	Jennifer Harding	x	-
	Andrew Gase	x	x
	Kelly Olsen	-	x
	Dominik Kardell	-	x
University of Southern California	David Okaya	x	x
	Thomas Luckie	x	x
University of Canterbury	Sam Davidson	x	x
IRIS/PASSCAL	Lloyd Carothers	-	x
	Alissa Scire	x	x

Table A1.2 SHIRE I and II external partners.

Name	Organisation and Position
Noël Barstow	IRIS/PASSCAL, Senior Staff Scientist / Lead Logistics
Kate Boersen	East Coast Life at the Boundary, Project Leader
Pene Brown	Chairman Te Aitanga ā Māhaki Trust, Deputy Chairman Mangatu Blocks
Lloyd Carothers	IRIS/PASSCAL, Senior Staff Scientist / Field Engineer
Murry Cave	Gisborne District Council, Principle Scientist
Jo Cranswick	Bay of Plenty Regional Council, Consents Officer
Campbell Dewes	Tarere 2 Station Trust, Chairman
Jackie Gonzales	IRIS/PASSCAL, Senior Associate / Trade Compliance and Logistics
Kate Graham	WSP, Senior Planner
Willy Haenga	Farm Care Services, Agricultural and Forestry Manager
Dionne Hartley	Gisborne District Council, Senior Resource Consents Officer
Mark Ivamy	Bay of Plenty Regional Council, Natural Hazards Advisor
Owen Lloyd	Mangatu Marae, Chairman
Pnina Miller	IRIS/PASSCAL, Senior Staff Scientist / Logistics and Instrumentations
Paul Murphy	Gisborne District Council, Team Leader: Water and Coastal Resources
Lisa Pearse	Hawke's Bay CDEM Group, Team Leader: Hazard Reduction
Danny Paruru	Whakatōhea Māori Trust Board, Iwi Development Projects Manager
Pia Pohatu	Ngati Porou
Julia Russell	Gisborne District Council, Senior Regional Compliance and Monitoring Officer
Mo Ruru	Gisborne District Council, Traffic Management Coordinator
Alisa Scire	IRIS/PASSCAL, Data Group Supervisor / Filed Engineer, data archive
Olivia Steven	Gisborne District Council, Water and Coastal Resources Officer (Environmental Scientist)
Paul Stuart	Tairāwhiti CDEM, Civil Defence Training Assistant
Tui Warmenhoven	Ngati Porou

APPENDIX 2 DEPLOYMENT DETAILS

Deployment timing details are shown in the tables below for all SHIRE I sites and SHIRE II 2D sites. As the SHIRE II transect site Texan recorders record on fixed time windows (see Table 3.3), their actual deployment and pick-up dates do not affect the amount of available data.

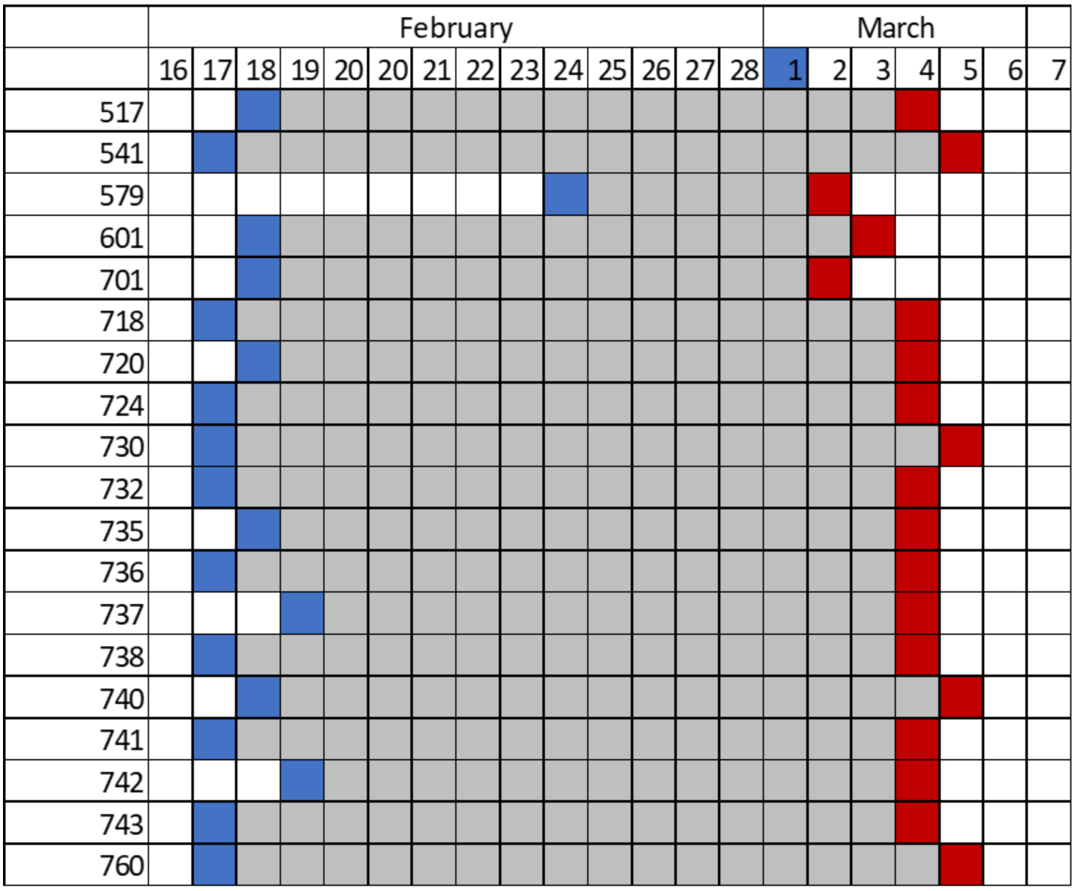

Figure A2.1 SHIRE II 2D array deployment table. Blue indicates deployment date and red indicates pick-up date. All dates are given in NZDT. Grey fill shows the dates when a station was operational. Detonation of borehole explosions occurred between 26 February 2019 and 28 February 2019 (Table 3.4).

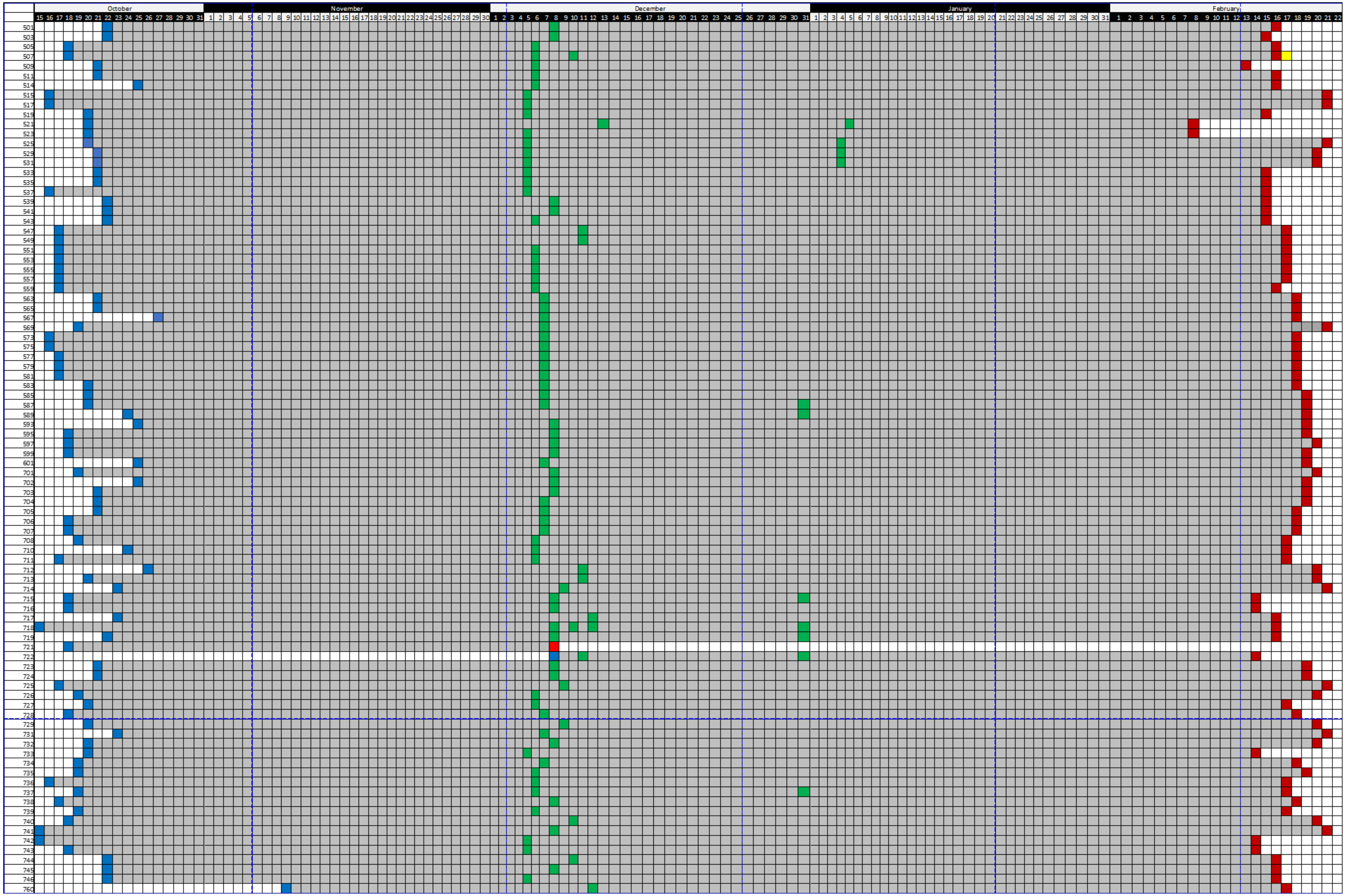

Figure A2.2 SHIRE I deployment table. Blue indicates deployment date; green indicates service date and red indicates pick-up date. All dates are given in NZDT. Grey fill shows the dates when a station was operational. Sites with multiple services often indicate GPS replacement (see Appendix 7 for more details).

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APPENDIX 3 PERMIT AND CONSENT APPLICATIONS

This appendix contains details of the permissions and consenting process with various organisations. Both resource consent and traffic management issues continue to evolve, and care should be taken to consult current regulations for any future project.

A3.1 Resource Consent for Gisborne District Council

Resource consent was one of the most time-consuming parts of the active source SHIRE II project. The consent documents themselves are long and mostly applicable to the individual councils. For that reason, they are not given in full here. A summary of points to consider when lodging consent applications are listed briefly below, along with a record of correspondence to give an indication of timelines, efforts and information required.

- Establish early contact with local iwi and hapū to ensure good communication throughout the consent process and project.
- Where the project is compared to specific regulations within the consent document, also include the relevant Iwi Management Plans for the region.
- Do not submit consent to discharge – as the explosives are completely consumed, there is no physical discharge that occurs in this experiment set-up. A consent to discharge can trigger remediation rules not applicable to this type of research activity (only applicable to extracting or pumping of groundwater and disposal wells).
- Undertake geotechnical assessments once intended sites are identified. For desktop studies, assessments of extra sites do not take much additional time. Therefore, the geotechnical assessment should be undertaken at the same time as land access agreements for all possible sites.
- In general, it is recommended that additional information, such as comparisons between explosion size and earthquake magnitude, should not be submitted in the primary consent document. The regulations and evaluation of consents do not require this level of detail and including it can complicate the consent application. However, as these details are of interest, it is recommended that documents that include an overview of this information and comparisons with similar past projects be prepared for reference if requested. Such information can also be shared at initial council information sessions.

Table A3.1 documents most of the communication between GNS Science and councils to communicate timelines and information required for consenting.

Table A3.1 Record of submission and correspondence regarding Resource Consent Application for Drilling to Gisborne District Council.

Date	From	Role	To	Role	Regarding
1/11/2018	-	-	service@gdc.govt.nz	-	Lodging GNS Science Resource Consent Application, as advised by telephone.
	Polly Wilson	Environmental Services Support Officer	-	-	Application will not be lodged until form is filled out (attached).
	-	-	Polly Wilson	Environmental Services Support Officer	Reply: Form is filled out and in the submitted consent document on page 45.
	Polly Wilson	Environmental Services Support Officer	-	-	Reply: Consent application will be lodged tomorrow.
	Kimberly Morete	-	rcadmin@gdc.govt.nz	-	Request for Admin to lodge the application and invoice GNS Science.
	Paul Murphy	Team Leader: Water and Coastal Resources	rclodgements@gdc.govt.nz	-	New consent application attached.
5/11/2018	Polly Wilson	Environmental Services Support Officer	water.info@gdc.govt.nz	-	Request to vet the application and allocate to someone.
6/11/2018	Polly Wilson	Environmental Services Support Officer	-	-	Request to update the application form, which is missing a printed name and date by a signature.
	-	-	Polly Wilson	Environmental Services Support Officer	Reply: Updated application attached. Request who to contact about the invoice.
	Polly Wilson	Environmental Services Support Officer	-	-	Reply about who to contact regarding invoice: accounts@gdc.govt.nz
	-	-	accounts@gdc.govt.nz	-	Request for invoice regarding lodgement fee.
7/11/2018	rcadmin@gdc.govt.nz	-	Kate Graham	Senior Planner	Question regarding whether the lodgement deposit has been paid for the application.
	Kate Graham	Senior Planner	rcadmin@gdc.govt.nz	-	-
	rcadmin@gdc.govt.nz	-	Kate Graham	Senior Planner	Link to payment for application.

Date	From	Role	To	Role	Regarding
8/11/2018	rcadmin@gdc.govt.nz	-	Kate Graham	Senior Planner	Confirmation that payment has been received for lodging the application.
21/11/2018	-	-	-	-	Site visits with consenting team.
22/11/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Notice to hold under Section 37 of RMA until amendment to application is received that includes both new primary and back-up sites to be used.
28/11/2018	-	-	Dionne Hartley	Senior Resource Consents Officer	Amended application with all updated locations.
29/11/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Section 92 RMA request for more information on four points.
5/12/2018	-	-	Dionne Hartley	Senior Resource Consents Officer	Section 92 RMA response, including geologic assessment.
12/12/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Clarification question as to whether a particular slip is covered in the geologic assessment.
	-	-	Dionne Hartley	Senior Resource Consents Officer	Map and photos sent showing slip is at a location that was not in revised application.
	Dionne Hartley	Senior Resource Consents Officer	-	-	Request to confirm whether we are requesting to apply for land disturbance permit as required for borehole site 2 under Rule C7.1.6(30), as predicted volume of borehole is 10 m^3 and only 6 m^3 are allowed at that site without a permit.
13/12/2018	-	-	Dionne Hartley	Senior Resource Consents Officer	Reply with answers and further questions around the land disturbance
17/12/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Reminder to apply for land disturbance.
	-	-	Dionne Hartley	Senior Resource Consents Officer	Reply requesting land disturbance.

Date	From	Role	To	Role	Regarding
19/12/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Notice that combined notification and decision report recommending approval of the consent would be reviewed to be finalised the following day.
	Kate Graham	Senior Planner	Dionne Hartley	Senior Resource Consents Officer	Request to see Draft Conditions before consent approval.
	Dionne Hartley	Senior Resource Consents Officer	-	-	Reply to request for draft conditions. Conditions included and request for feedback, if any.
	-	-	Dionne Hartley	Senior Resource Consents Officer	Reply to Draft Conditions requesting changes.
20/12/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Draft conditions version 2 sent.
	-	-	Dionne Hartley	Senior Resource Consents Officer	Reply to version 2 draft conditions. Request a few more minor changes.
21/12/2018	Dionne Hartley	Senior Resource Consents Officer	-	-	Consent granted and signed off.
7/01/2019	rcadmin@gdc.govt.nz / Dionne Hartley	Senior Resource Consents Officer	-	-	Notification of intent to start work and an Environmental Management Plan (for drilling).
22/01/2019	Reginald Profit	-	-	-	Notice of approval of Environmental Management Plan.
13/02/2019	-	-	Dionne Hartley	Senior Resource Consents Officer	Submitted Emergency Management Plan, Blast Management Plan and Chemical data sheets for Explosives and Primers (fulfilment of conditions 3 and 4 of granted consent).
15/02/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Acknowledgement of receipt of plans; forwarding for approval.
22/02/2019	-	-	Dionne Hartley	Senior Resource Consents Officer	Prompt to check on status of approval of additional work plans submitted 13/2/2019.

Date	From	Role	To	Role	Regarding
22/02/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Orica Emergency Management Plan accepted and approved.
25/02/2019	Reginald Profit	-	-	-	Official notification of acceptance of Emergency Management Plans.
27/02/2019	Julia Russell	Compliance Monitor	-	-	Touching base about notification to start works. When? Site visits possible next week?
	-	-	Julia Russell	Compliance Monitor	Update on progress and invitation to attend remaining three shots. Followed up with phone call and it was decided site visits were not necessary.
18/03/2019	-	-	Dionne Hartley	Senior Resource Consents Officer	Notification of successful project; request for clarification on ability to leave Site 1 un-remediated and who is considered 'qualified' to remediate.
3/04/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Forwarded response to remediation questions from Olive Stevens, stating initial approval to leave Site 1, if landowner agrees, and that the driller who installed the borehole is likely the one who should remediate.
18/04/2019	-	-	Dionne Hartley	Senior Resource Consents Officer	Compliance Report sent to Gisborne District Council showing site remediation, etc.
23/04/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Acknowledgement of receipt of remediation report. Team members that need to approve are away so there could be delay.
21/05/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Reply around compliance report questions, groundwater encountered and remediation.
28/05/2019	-	-	Dionne Hartley	Senior Resource Consents Officer	Reply to compliance / groundwater questions.
7/06/2019	Dionne Hartley	Senior Resource Consents Officer	-	-	Final compliance approval, including the okay to leave Site 1 un-remediated.

Table A3.2 Record of submission and correspondence regarding Resource Consent Application for Drilling to Bay of Plenty Regional Council.

Date	From	Role	To	Role	Regarding
30/08/2018	-	-	Jo Cranswick	Consents Officer	Request copy of Whakatōhea Iwi Management Plan (IMP).
3/09/2018	Jo Cranswick	Consents Officer	-	-	Reply to request of Whakatōhea IMP.
15/10/2018	-	-	regulatoryadmin@boprc.govt.nz	-	Submission for consent to drill and discharge.
8/11/2018	Jo Cranswick	Consents Officer	-	-	RMA Section 92 request for more information (especially as regards IMP).
15/11/2018	-	-	Jo Cranswick	Consents Officer	Reply letter addressing request from 8/11/2018.
21/11/2018	Jo Cranswick	Consents Officer	-	-	Draft Conditions; note change of wording 'bore' to 'borehole' to distinguish it from holes that are constructed for the purpose of accessing, taking or using groundwater.
4/12/2018	-	-	Jo Cranswick	Consents Officer	Reply to Draft Conditions; no changes and happy to proceed as proposed.
5/12/2018	Cassandra Hastie	-	-	-	Non-notified consent granted (drilling only, not discharge as originally applied for).
7/01/2019	-	-	compliance_data@boprc.govt.nz	-	Bore log for GNS Science Hole #5.
14/01/2018	-	-	compliance_data@boprc.govt.nz	-	Notice to start drilling.
21/02/2018	-	-	Jo Cranswick / Jason Laurent	Consents Officer / Senior Regulatory Compliance Officer	Notification of shot loading/firing time.
	Jason Laurent	Senior Regulatory Compliance Officer	-	-	Approval to proceed; request to advise them if help is needed.
18/04/2018	-	-	compliance_data@boprc.govt.nz	-	Site plan for borehole, as required to complete consent.

A3.1.1 Tairāwhiti Roads

Tairāwhiti Roads was a branch of the Gisborne District Council and participated in a programme called 'beforeuDig'. This allowed organisations to lodge generic traffic management plans (TMPs) to the council online in an effort to speed up the approval process.

RCA consent (eg CAR/WAP) and/or RCA contract reference	

TRAFFIC MANAGEMENT PLAN (TMP) – SHORT FORM						
Complete short form if simple activity and RCA permits. Refer to the NZ Transport Agency's Traffic control devices manual, part 8 Code of practice for temporary traffic management (CoPTTM), section E, appendix A for a guide on how to complete each field.						
Organisation/ TMP reference	**TMP reference:**	**Contractor (Working space):**	**Principal** *(Client)*: GNS Science			
		Contractor (TTM): GNS Science	**RCA:**			
Location details and road characteristics	**Road names and suburb**		**House no. / RPs** *(From and to)*	**Road level**	**Permanent speed**	**AADT/Peak flows**
	Throughout Gisborne District, various roads including. *RCA to be contacted with daily location times and dates*		.	1		
	Including Waiomoko, Wharekiri, Waimata Valley, Kanakania, Bruce, Armstrong, Te Hau, Wairere, Motu, Motu Falls and other similar roads in the district			1		

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RCA consent (eg CAR/WAP) and/or RCA contract reference	

Description of work activity	Installation and removal of small seismic equipment. Each site will be dug into the ground ~30 cm and will be covered completely. Equipment will be left for 7-10 days and then a similar work schedule will remove all equipment. Work will involve spending ~20-30 minutes at each site and up to 6 teams may be active in different areas of the region at one time. All sites will be outside of the live lane and within the road reserve. **Prior to leaving the office and arrival on site:** ● The inspector to familiarize himself / herself with the inspection site and carry out a risk assessment of the proposed work area ● Notify the nominated STMS of the intended site visits and proposed locations ● Carry out the following equipment check: o a rotating flashing beacon to be fitted to the roof of the vehicle, tested for operational efficiency and be visible from all approaches to the vehicle o a Road Works or Road Inspection sign to be fitted to the rear of the vehicle or placed on a stand giving CSD warning of the activity for the road users o the inspector to wear orange and reflective high visibility clothing ***INSPECTIONS ONLY – Outside of Live Lane – Up to 10 m from edge line.*** **Arrival at the work site:** o When approaching the inspection site the driver of the vehicle will switch on the vehicles' rotating beacon to indicate the intention to leave the carriageway, indicate, slow down and move into the shoulder/parking area. o Once outside the live lane the vehicle will be parked at the furthest lateral position from the edge line o Beacon to remain on and indicator lights in hazard mode used, if required, for extra warning **On site - vehicle requirement:** **The vehicle is to be parked upstream from inspection site giving advanced warning of the activity:** o outside the edge line of the road on a shoulder or roadside area at the furthest lateral position available away from the live lane o in a designated parking lane or parking space **On site – Inspector activity:** **The inspector will:** o when outside of the vehicle on foot, remain on either the shoulder or roadside area. o remain downstream and a minimum 10m from the vehicle o seek and position himself / herself behind a roadside barrier if available for added protection. ***Additional notes:*** ● *Vehicle to display TV3 Road inspection sign, flashing amber beacon + hazard warning lights(when vehicle is parked)* ● *Vehicle to be parked clear of the live lane at warning distance ahead of inspection OR* ● *Static Road Inspection sign to be placed at warning distance if vehicle creates poor visibility for oncoming traffic* ● *All inspections to be carried out outside of the edge line and clear of the live lane* ● *If at any time existing temporary traffic management is in place the inspector will identify themselves to the "in control" person and ask permission to work within the requirements of the existing set up* ● STMS to brief TC and other site personnel on the requirements of this TMP prior to commencement of work

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RCA consent (eg CAR/WAP) and/or RCA contract reference	

Planned work programme							
Start date	February 15 2019	Time	8:00	End date	June 1 2019	Time	18:00

Consider significant stages, for example: • road closures • detours • no activity periods.	**No closures, detours or delays expected for this work.** **This is a Generic application for repetitive work activities carried out over several weeks. RCA to be contacted by site personnel with daily location times and dates and/or supplied to RCA prior to entry into the region.**
Alternative dates if activity delayed	**This is a Generic application for repetitive work activities carried out on an, as required basis.** Main phase of the work is planned for mid-end February. If everything goes ahead, the work would be done by March. There could be delay to the work and so we have made the generic TMP for a longer time period. RCA to be advised on days when work is planned and also when work has been completed.

Road aspects affected *(delete either Yes or No to show which aspects are affected)*

Pedestrians affected?	No	Property access affected?	No	Traffic lanes affected?	No
Cyclists affected?	No	Restricted parking affected?	No	Delays or queuing likely?	No

TSL/ Diagram *(see TSL decision matrix for guidance)*	**TSL details as required** Approval of Temporary Speed Limits (TSL) are in terms of Section 6 of Land Transport Rule: Setting of Speed Limits 2017, Rule 54001/2017 *(List speed, length and location)*	**Times** *(From and to)*	**Dates** *(Start and finish)*	**Diagram ref. no.s** *(Layout drawings or TMDs)*
Attended day/ night	A temporary maximum speed limit of km/h is hereby fixed for motor vehicles travelling over the length of m situated between (House no./RP) and (House no./RP) on (street or road name)	n/a	n/a	n/a
Unattended day/ night	A temporary maximum speed limit of km/h is hereby fixed for motor vehicles travelling over the length of m situated between (House no./RP) and (House no./RP) on (street or road name)	n/a	n/a	n/a
TSL duration	Will the TSL be required for longer than 12 months? *If yes, attach the completed checklist from section I-18: Guidance on TMP Monitoring Processes for TSLs to this TMP.*			No

Contingency plan

If long queues form or delays exceed 5mins *(or any other period required by RCA)*, site to be disestablished or additional lanes made available.	Adjust TMD to suit unforeseen circumstances *(eg weather or site overlaps with another work site).*	Emergency services will be accommodated and access provided through the site as required.

Add additional contingencies:

RCA consent (eg CAR/WAP) and/or RCA contract reference	

Add additional contingencies:

Contact details

	Name	24/7 contact number	CoPTTM ID	Qualification	Expiry date
Principal	Stuart Henrys	0272264627	53977	L1 STMS	L1 STMS
TMC					
Engineers' representative					
Contractor					
STMS	Stuart Henrys	0272264627	53977	L1 STMS	L1 STMS
TC	Various			TC and L1	various
Others as required					

TMP preparation (or approval if STMS delegated authority to approve TMPs)
Delete the option that does not apply (either prepared or approved)

Prepared	Stuart Henrys	1/2/2019	S. Henrys	53977	L1 STMS R	16/06/2020
	Name	*Date*	*Signature*	*ID no.*	*Qualification*	*Expiry date*
This TMP meets CoPTTM requirements attached			**Number of diagrams**			
TMP returned for correction						
	Name	*Date*	*Signature*	*ID no.*	*Qualification*	*Expiry date*

Engineer/TMC to complete following section when approval or acceptance required

Approved by TMC or engineer *(delete one)*						
	Name	*Date*	*Signature*	*ID no.*	*Qualification*	*Expiry date*
Acceptance by TMC *(only required if TMP approved by engineer)*						
	Name	*Date*	*Signature*	*ID no.*	*Qualification*	*Expiry date*

Qualifier for engineer or TMC approval

Approval of this TMP authorises the use of any regulatory signs included in the TMP or attached traffic management diagrams.
This TMP is approved on the following basis:

1. To the best of the approving engineer's/TMC's judgment this TMP conforms to the requirements of CoPTTM.
2. This plan is approved on the basis that the activity, the location and the road environment have been correctly represented by the applicant. Any inaccuracy in the portrayal of this information is the responsibility of the applicant.
3. The TMP provides so far as is reasonably practicable, a safe and fit for purpose TTM system.
4. The STMS for the activity is reminded that it is the STMS's duty to postpone, cancel or modify operations due to the adverse traffic, weather or other conditions that affect the safety of this site.

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TMP or generic plan reference	

ON-SITE RECORD On-site record must be retained with TMP for 12 months.			Today's date	
Location details	Road names(s):	House number/RPs:	Suburb:	

Working space

Person responsible for working space		
	Name	*Signature*
Where the STMS/TC is responsible for both the working space and TTM they sign above and in the appropriate TTM box below		

TTM

STMS in charge of TTM					
	Name	*TTM ID Number*	*Warrant expiry date*	*Signature*	*Time*
Worksite handover accepted by replacement STMS					
	Name	*ID Number*	*Warrant expiry date*	*Signature*	*Time*
	Tick to confirm handover briefing completed				

Delegation

Worksite control accepted by TC/STMS-NP					
	Name	*ID Number*	*Warrant expiry date*	*Signature*	*Time*
	Tick to confirm briefing completed				

Temporary speed limit

Street/road name (RPs or street numbers):	TSL action	Date:	Time:	TSL speed:	Length of TSL (m):
	TSL installed				
	TSL remains in place				
From: To:	TSL removed				

Street/road name (RPs or street numbers):	TSL action	Date:	Time:	TSL speed:	Length of TSL (m):
	TSL installed				
	TSL remains in place				
From: To:	TSL removed				

Street/road name (RPs or street numbers):	TSL action	Date:	Time:	TSL speed:	Length of TSL (m):
	TSL installed				
	TSL remains in place				
From: To:	TSL removed				

Street/road name (RPs or street numbers):	TSL action	Date:	Time:	TSL speed:	Length of TSL (m):
	TSL installed				
	TSL remains in place				
From: To:	TSL removed				

TMP or generic plan reference	

Worksite monitoring

TTM to be monitored and 2 hourly inspections documented below.

Items to be inspected	TTM set-up	2 hourly check	2 hourly check	2 hourly check	2 hourly check	2 hourly check	TTM removal
High-visibility garment worn by all?							
Signs positioned as per TMP?							
Conflicting signs covered?							
Correct delineation as per TMP?							
Lane widths appropriate?							
Appropriate positive TTM used?							
Footpath standards met?							
Cycle lane standards met?							
Traffic flows OK?							
Adequate property access?							
Add others as required							
Time inspection completed:							
Signature:							

Comments:

Time	Adjustment made and reason for change

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A3.1.2 Ōpōtiki District Council

Ōpōtiki District Council did not participate in the beforeUdig website. The generic TMP below was lodged, and we were required to email in the morning of each day that we intended to be using it. Compliance was delegated to the Traffic Controller in the local field team.

The TMP was identical to the one lodged with Tairāwhiti Roads (A2.3.1), with the exception of the road names and obvious regional differences, so is not listed separately here.

A3.2 Heritage New Zealand Pouhere Taonga

HERITAGE NEW ZEALAND
POUHERE TAONGA

Heritage New Zealand Pouhere Taonga Archaeological Discovery Protocol

In the event that an unidentified archaeological site is located during works, the following applies;

1. Work shall cease immediately at that place and within 20m around the site.
2. The contractor must shut down all machinery, secure the area, and advise the Site Manager.
3. The Site Manager shall secure the site and notify the Heritage New Zealand Regional Archaeologist. Further assessment by an archaeologist may be required.
4. If the site is of Maori origin, the Site Manager shall notify the Heritage New Zealand Regional Archaeologist and the appropriate iwi groups or kaitiaki representative of the discovery and ensure site access to enable appropriate cultural procedures and tikanga to be undertaken, as long as all statutory requirements under legislation are met (*Heritage New Zealand Pouhere Taonga Act*, *Protected Objects Act*).
5. If human remains (koiwi tangata) are uncovered the Site Manager shall advise the Heritage New Zealand Regional Archaeologist, NZ Police and the appropriate iwi groups or kaitiaki representative and the above process under 4 shall apply. Remains are not to be moved until such time as iwi and Heritage New Zealand have responded.
6. Works affecting the archaeological site and any human remains (koiwi tangata) shall not resume until Heritage New Zealand gives written approval for work to continue. Further assessment by an archaeologist may be required.
7. Where iwi so request, any information recorded as the result of the find such as a description of location and content, is to be provided for their records.
8. Heritage New Zealand will determine if an archaeological authority under the *Heritage New Zealand Pouhere Taonga Act* 2014 is required for works to continue.

It is an offence under S87 of the *Heritage New Zealand Pouhere Taonga Act 2014* to modify or destroy an archaeological site without an authority from Heritage New Zealand irrespective of whether the works are permitted or a consent has been issued under the Resource Management Act.

Heritage New Zealand Regional archaeologist contact details:

Figure A3.1 Basic Accidental Discovery Protocol used by field teams. Additional iwi-specific contacts were added where requested. Contact details of Heritage New Zealand and that are site-specific are left out here for privacy reasons. The field coordinator name and phone number were included to ensure that coordinated and appropriate response was taken.

A3.3 Land Access Agreements

The generic land access agreements used for SHIRE II are below. Note that these should be reviewed before being used in a new project and also require a title search when submitted to the council for consent. Something recommended for future agreements, which was not in the agreement below, is a clause that would allow access for both iwi and scientific observers.

Seismogenesis Hikurangi Integrated Research Experiment -2
LAND USE and ACCESS AGREEMENT
and PRIVACY ACT CONSENT

1 Fairway Drive
Avalon
PO Box 30 368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600
www.gns.cri.nz

Between

Institute of Geological and Nuclear Sciences Limited (GNS Science)

And

Full names of landowners taken from a recent title search

1. The Landowner owns the land at ***physical address*** contained in Certificate of Title ***title reference*** (Land).

2. The Landowner agrees to allow GNS Science to ***access and drill a cased borehole to a depth of 50 meters and to let off an explosion in that borehole*** at the location on the Land shown on the attached map being an area of ~15 square metres (Site). The borehole, explosion, and recording of that explosion are all for research purposes only and will not be used for commercial endeavours.

3. The Landowner permits GNS Science employees, agents and sub-contractors to cross the Land to access and work on the Site at any time in the ***8-month period*** from the date of this agreement, (from September 1 2018 through April 2019) subject to notification per clause 5.

4. The parties are responsible for meeting their respective health and safety obligations at law and must as far as reasonably practicable consult, co-operate and co-ordinate activities with each other and any subcontractors or other parties on the Land or working on the Site

5. GNS Science will give the Landowner reasonable prior notice each time the Land is accessed under this agreement. On receipt of that notice, the Landowner will inform GNS Science of any health and safety risks that may exist that might affect that access occasion and the parties will work together to modify their existing health and safety plans in light of that risk.

6. GNS Science agrees to remediate the site, to the extent reasonably determined by GNS Science, in the month following the explosion (March 2019), including cutting the casing at ground level. Furthermore, GNS Science also agrees to provide ongoing remediation, to the extent reasonably determined by GNS Science, if further change to the site occurs through collapse at depth or other issues associated with the original borehole for a period of up to ten years.

7. Where the Privacy Act 1993 applies, and subject to that Act:

    a. the Landowner consents to GNS collecting, storing and using the Landowner's personal information for the purpose of ***GNS Science, contractors and subcontractors*** contacting them for access and for general research purposes;

    b. GNS Science may disclose that information to third parties or publish it in scientific reports and journals to achieve that purpose or disclose it to comply with New Zealand law or to protect and/or enforce its legal rights or interests, including defending any claim;

c. the Landowner may request access to and correction of the information;
d. GNS Science will destroy the information when it is no longer needed.

8. All communications between the parties shall be via the contact details below.
9. This agreement may be signed in counterparts including electronically.

SIGNED by the Landowner

Date: ______________________________

SIGNED by the Institute of Geological and Nuclear Sciences Limited by its authorised signatory ***Name and Position***

Date: ______________________________

SIGNED by the Landowner

Date: ______________________________

SIGNED by the Landowner

Date: ______________________________

Contact details for Landowner:	Contact details for GNS Science:
Name: ***Email address:*** ***Phone number:*** ***Cell phone number:*** ***Mailing address:***	***Stuart Henrys*** ***Email:** s.henrys@gns.cri.nz* ***Phone number:** 04-570-4812* ***Or*** ***Katie Jacobs*** ***Email:** k.jacobs@gns.cri.nz* ***Phone number: 04-570-4605*** ***Cell phone number: 0212462347*** ***Mailing address GNS SCIENCE:*** PO Box 30-368, Lower Hutt 5040

Map: Location of Site

A3.4 Temporary Equipment Importing

IRIS/PASSCAL instruments for SHIRE I and II were imported under a temporary import agreement. These allow equipment to be imported without paying any import duty and require the complete packing list (with values) and an agreement that equipment will be exported from the country again within twelve months. A letter stating that the person signing the Temporary Import Agreement (TIA) has the financial authority to sign the form on behalf of the organisation (GNS Science) should be included with the TIA. As most shipments are prepared well in advance, these forms should also be ready prior to equipment arrival. The form used for SHIRE was NZCS 233A, with a most recent update of October 2018. Consult with importing freight companies to ensure that an up-to-date form is used.

APPENDIX 4 GEOTECHNICAL ASSESSMENT AND DRILL LOGS

This section contains geological formation description from the drilling of the holes, as well as location information. A separate desktop geological and geomorphologic study of the proposed drill sites was commissioned and completed as an internal report (Bruce 2018). That assessment was submitted in response to a request from Gisborne District Council related to the resource consent application and questions over the effects of the shaking produced on the immediate site and surrounding morphology. To help inform the relevant spatial scale important to the assessment, and to further inform the council, we modelled the accelerations expected using the formulas generated from empirical testing in California during the LARSE project (Fuis et al. 2001; see Figure 3.3, Section 3.3).

Table A4.1 Final drill locations and detonation times (see Section 3.6.5 and Appendix 5 for more information on timing). All dates refer to February 2019.

Shot	Longitude	Latitude	NZTM_E	NZTM_N	Julian Day	UTC	hh:mm:ss.sss	Elev. (m)
SP-1	178.1715	-38.4762	2051233	5728654	058	Feb-27	17:49.7	240
SP-2	177.8686	-38.4276	2025074	5735504	058	Feb-27	12:26.7	175
SP-3	177.7391	-38.2736	2014637	5753195	057	Feb-26	13:19.3	394
SP-4	177.6144	-38.2384	2003918	5757651	059	Feb-28	25:31.1	491
SP-5	177.4213	-38.0284	1988122	5781798	057	Feb-26	22:51.4	58

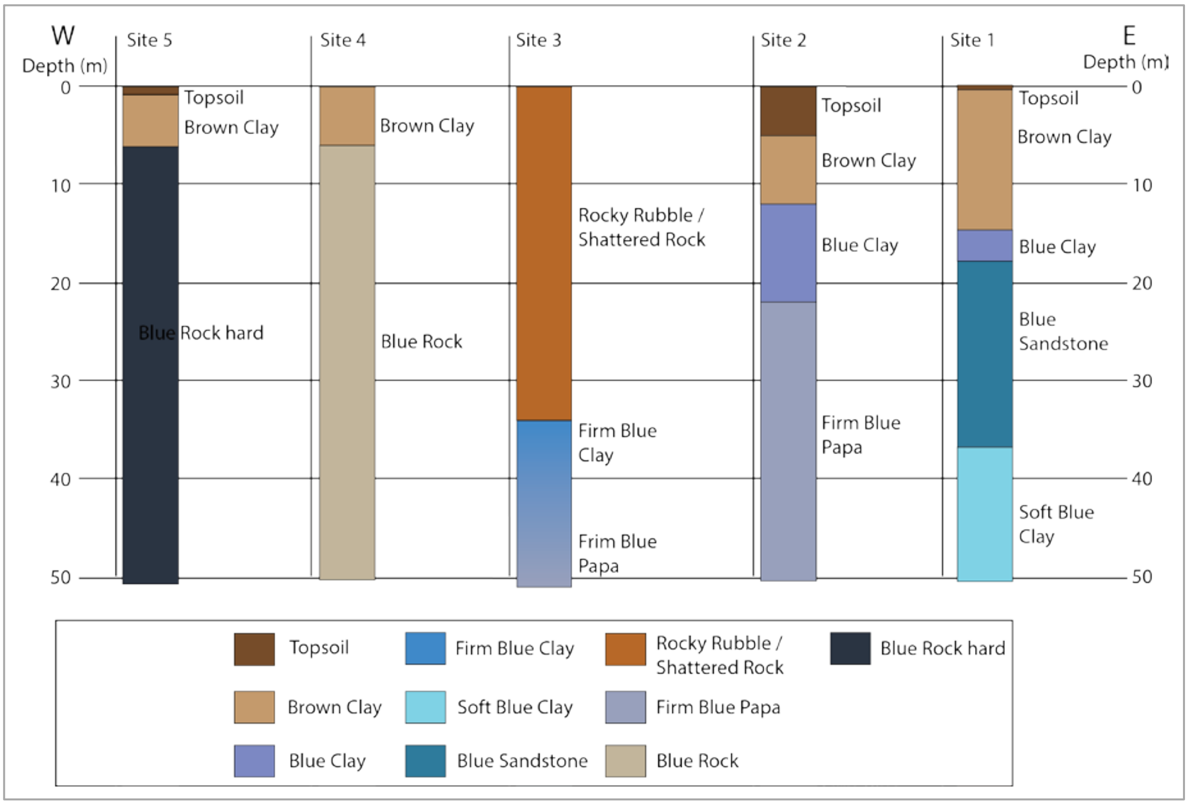


Figure A4.1 Illustration of the drill logs for the five boreholes from west (5) to east (1).

Table A4.2 Logs from drilling at borehole sites.

Site 1: Panikau Road	
Depth (m)	**Description**
0	Topsoil
0.5	Brown Clay
6	Brown Clay
15	Blue Clay
18	Blue Sandstone – airlift 2LPS SWL 10.5 m
37	Soft Blue Clay
Site 2 : Rangatira	
Depth (m)	**Description**
0	Topsoil
5	Brown Clay
12	Blue Clay
22	Firm Blue Papa
Site 3: Mangatahu	
Depth (m)	**Description**
0	Rocky Rubble / Shattered Rock
34	Firm Blue Clay turning to Papa
Site 4: Waitangarua	
Depth (m)	**Description**
0	Brown Clay
6	Blue Rock
Site 5: Hermanson	
Depth (m)	**Description**
0	Topsoil
0.5	Brown Clay
6	Blue Rock Hard

APPENDIX 5 SEDNA D&B FIELD REPORT

A5.1 Project Details

The aim of this project was to measure and report the firing times, to millisecond accuracy, of five seismic blast holes (Figure A5.1) fired one by one over several days across the Raukumara Peninsula in New Zealand by GNS Science, in collaboration with national and international partners.

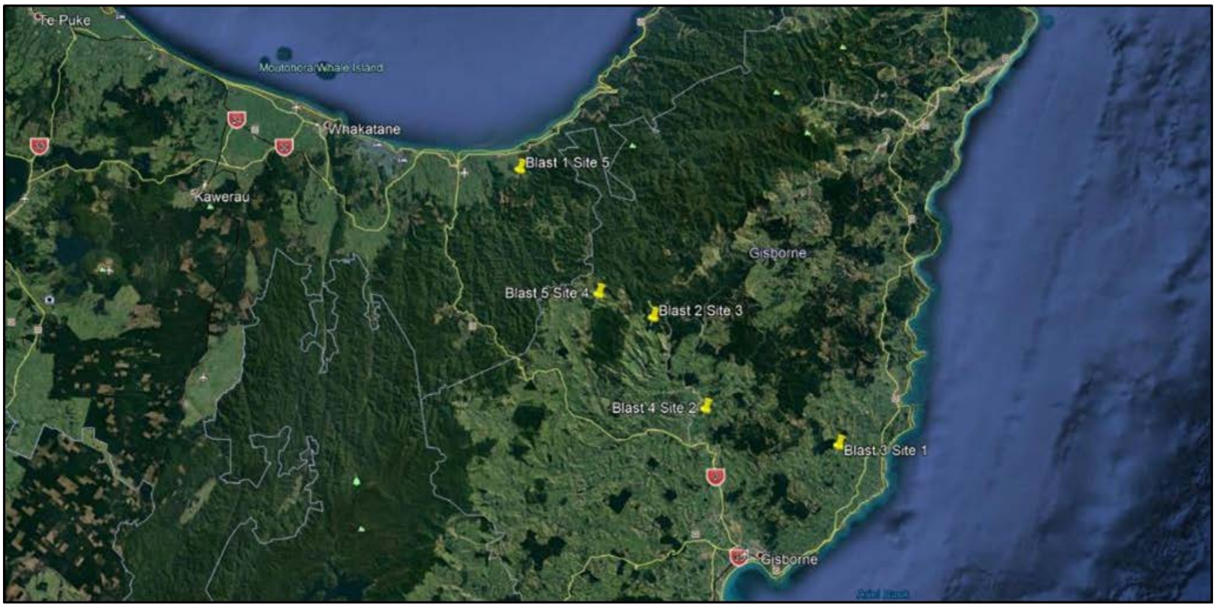


Figure A5.1 Map showing sites. Site number corresponds to the number used by the SHIRE project, and blast number refers to the order of firing.

A5.2 Trial Equipment

The primary monitor selected for the project was a ShotTrack VOD 305 unit (Figure A5.2a).

Sedna typically uses this device to measure the surface and in-hole Velocity of Detonation (VOD) of various explosives. It has the following relevant features:

- Detects the firing of the explosives to within a millisecond.
- Uses GPS for establishment of UTC time and coordinates.
- Can deploy very tough RG6 cable within the blast hole.
- Has a simple set-up.
- Has a proven track record in test firing.

Considering the project deliverables, it was decided to employ a back-up unit as well, in order to provide redundancy in the measurement and data collected. The unit selected was a ShotTrack Vib unit (Figure A5.2b). This device is used to measure ground vibration. Relevant features included:

- A wire-break circuit to detect the firing of the explosives to within a millisecond.
- Use of GPS for establishment of UTC time and coordinates.
- Compatible with a variety of cables.
- Simple set-up.

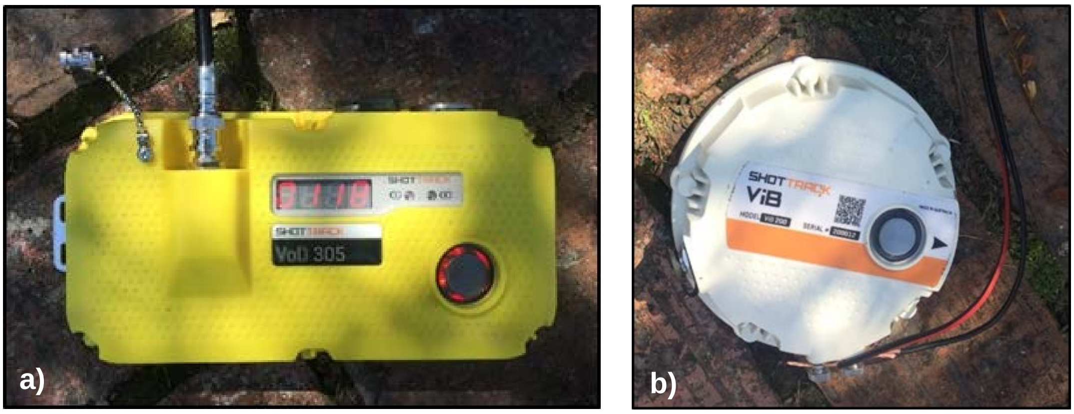


Figure A5.2 Timing devices. a) ShotTrack VOD 305. b) ShotTrackVIB.

A5.3 Monitoring Wire

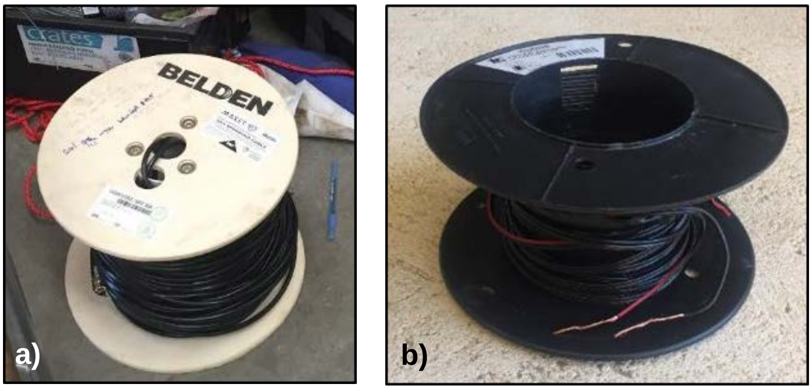


Figure A5.3 Timing wires. a) VOD cable: Belden Coax RG6 18 AWG solid copper-covered steel wire break cable (305 m reel). b) Tycab Twin Speaker: Flex 0.75 mm (100 m reel).

A5.4 Testing and Calibration

Prior to shipping the equipment to New Zealand, the units were set up side by side in Perth to check GPS reception, connectivity to the laptop and general functionality over a series of test simulations. The 305 unit was also calibrated to RG6 cable. A set of project field instructions were completed.

A5.5 Blast Hole and Loading Details

All shot-firing duties were performed by the Orica team (including priming, loading, stemming, blast control and firing). Orica selected the following products:

- Detonators: Davey Bickford DaveyDet® instantaneous electric, 50 m lead length. Three per hole.
- Boosters (Figure A5.4): Dyno Nobel TROJAN® GEOPRIME® dBX® pentolite seismic explosives, 1 kg unit. Three per hole.
- Bulk Explosives: Orica Centra Gold, at target 1.15 g/cm^3 average in-hole density. Nominal charge of 500 kg per hole.

Figure A5.4 Photo from 'SOP for dBX Assembly top with Anchors' by Global Seismic Solutions.

To maximise the detonation shock wave transmitted downwards into the ground, for best seismic monitoring results, the holes were designed to be top-primed.

Before loading, each hole was dipped for depth and the height of the standing water (Table A5.1). A small amount of aggregate backfill was added to the hole to seal off the bottom, with the aim of reducing the propensity of the casing to be ejected during detonation.

The holes were loaded over two days and fired over three. They were fired in a different order to which they were loaded; for example, the last hole to be loaded on Day 2 was then fired that same evening (Table A5.1). The preferred schedule for detonating the holes was to aim for early morning and early evening, when conditions were as still practicable (least wind, traffic noise, etc.).

As detailed in Table A5.1, challenges were encountered during loading. These included needing to bottom load the product in very deep, wet holes while top priming, together with successfully positioning the two monitoring instrument wires. Orica undertook a very professional job of continuously improving the process to adapt to the difficult conditions. A summary of the issues and recommendations are presented below, in case they are of use to future controlled-source projects.

Table A5.1 SHIRE II borehole loading information.

Site ID	Load Order	Blast Order	Date Loaded (NZ Time)	Initial Hole Depth	Depth after Backfilling	Water Level (from Collar)	Amount of Water	Mass of Explosives	Top of Explosives Column (from Collar)	Explosive Column Length	Loading Notes
1	2	3	25-Feb-2019	50.4 m	49.5 m	11.1 m	39.3 m	507 kg	39.2 m	10.3 m	VOD cable taped to rock and placed at bottom of hole before loading commenced. After loading 450 kg, paused while 3 primers lowered: 1 caught, 2 floated. Hose blocked even with only this slight pause.
2	3	4	26-Mar-2019	50.7 m	50.0 m	48.1 m	2.6 m	609 kg	37.4 m	12.6 m	VOD cable taped to rock, and 1 primer taped on at 11.5 m up from bottom; assembly lowered into hole before loading commenced. Remaining 2 primers lowered once 300 kg reached, without stopping hose. 1 caught, 1 floating, which was caught during washout.
3	1	2	25-Feb-2019	51.2 m	50.2 m	31.1 m	20.1 m	603 kg	-	-	VOD cable taped onto primer and loom taped every 2 m up to top. Lowered that and the other 2 primers after loading 450 kg or product. Re-used loading but floated and tangled the det leads twice, leading to blocking the delivery hose while it was sorted out. Wire too easy to catch when slightly slack. The longer 75 m hose is easier to block than normal if loading is paused.

Site ID	Load Order	Blast Order	Date Loaded (NZ Time)	Initial Hole Depth	Depth after Backfilling	Water Level (from Collar)	Amount of Water	Mass of Explosives	Top of Explosives Column (from Collar)	Explosive Column Length	Loading Notes
4	4	5	26-Mar-2019	50.2 m	49.9 m	48.9 m	1.3 m	580 kg	35.7 m	14.2 m	VOD cable and primer at 11.5 m assembly, as per Site 2. Remaining 2 primers lowered from top during loading and caught without stopping hose.
5	5	1	26-Feb-2019	50.1 m	49.5 m	2.9 m	47.2 m	589 kg	36.9 m	12.6 m	VOD cable and primer at 11.5 m assembly, as per Site 2. Due to primers sinking slowly with all the water, the other 2 primers were lowered mid-way down the hole before pumping commenced. After loading 450 kg, primers lowered all the way to product and caught, without stopping hose.

A5.5.1 Top Priming

Top priming holes is rare in the blasting industry. Most conventional blasting operations employ bottom priming and only use a booster at the top as an additional back-up/insurance primer. Bottom priming is preferred as firing a blast hole from the bottom upwards promotes toe breakout, improves confinement and reduces fly rock. The associated loading method is relatively straightforward: the primer is lowered to the bottom of the hole, the charging hose is inserted and, once sufficient bulk explosives have been added to the hole, the primer is pulled up into good product by its lead wires. When holes are wet, the hose can be lowered almost all the way to the bottom of the holes, and when the product is pumped it displaces the water upwards (and sometimes right out of the top of the hole).

Top priming is significantly more challenging, particularly for wet holes. During loading, with the charging hose and column of bulk explosives starting below the primer and steadily rising up the hole, there is a tendency for the top of the column to 'float' the primer and keep pushing it upwards. A floating primer is detected when its lead wires stay slack, showing there is no weight on the booster. To rectify, the charging hose is normally removed from the product, the booster is dropped down to below the hose level and charging recommences. However, fixing a floating booster this way can trap some water in the explosives column. As noted above, top priming was required on this project so that the holes could be fired from the top downwards to maximise the seismic benefits.

For streamlining top priming, some operations prefer to use two long-lead wire detonators and start with both on the bottom of the hole. After loading has been completed, the top primer can be pulled up through the product until it is just near the top of the column. Another strategy is to assemble two primers together on the surface, with the shorter top primer's lead wires taped onto the longer bottom primer's lead wires in the desired position. Once the bottom primer is trapped in product during loading, the top primer cannot be easily floated. However, none of these particular options were applicable to this project as there was no bottom primer.

A5.5.2 Hose Blockages

The depth of the holes and the presence of water in all of them required the holes to be loaded from the bottom up; this requires the charging hose to be first inserted down the hole until it rests on the bottom. On typical bulk explosives trucks, the hose length is limited to 50 m for most operations; however, for this project, the team required a 70+ m hose to ensure sufficient length for a) any access issues positioning the truck near the collar of the hole and b) to reach the bottom of the 50 m holes. The major disadvantage to running extra-long hoses is the increased propensity for blockages (see Figure A5.5) caused by increased friction (requiring higher pumping pressures) and issues with the explosives product expanding within the hose. The product is designed to expand as a means of providing sensitivity (chemical gassing agents react with the product ingredients, transforming the mixture from dangerous goods into explosives. This is affected by the addition of tiny voids created by the formation of gas bubbles). This 'gassing' process is continual, starting just after the product is manufactured and mostly finishing within one hour (most of the gassing is targeted to occur in the first 20 minutes). However, this can cause issues whenever charging is paused and the delivery hose cannot be quickly emptied out and flushed clean. 'Washing out' the hose produces a lot of waste material of explosives mixed with water and cannot be easily dealt with; dumping onto the surface causes contamination issues relating to release of nitrates and diesel into the environment, while pumping out into an incompletely loaded blast hole places a mess of water/explosives mixture in between sections of good product and also occupies space intended for good product.

Figure A5.5 Site 1: second blast hole to be loaded. Hose is in the process of being unblocked into a bucket.

The normal strategy is to deal with any loading interruptions (floating primers, adding new primers, checking column heights) as efficiently as possible to lessen the time that the product sits static in the hose. When necessary, or whenever the hose has become blocked, the hose can be flushed out into a bucket or carefully onto the stemming pile, and, after loading has finished, this waste can be manually placed back into the top of the hole where it will be consumed in the forthcoming explosion.

The normal process after loading is complete is to wash out the hose into the hole so that the waste sits on top of the explosives column. Aggregate placed in the hole for stemming then seals it in. Both the issues with floating primers and the washing out contribute to increasing the reported totals of explosives loaded per hole beyond the initial 500 kg for the target column.

A5.5.3 Primer Shape, Detonator Spools and Monitor Wire

The combination of the number of primers (three), the shape of the boosters (Figure A5.4), the detonator lead wires and all of the monitoring wire certainly added to the challenge. These seismic boosters are several times longer than typically used boosters, and their special pointed nose cones might have inclined them to sit diagonally in the hole (Figure A5.4). Thus, it is expected that when two or three of these primers were lowered down onto the product during loading, they may have taken up a significant portion of the cross-sectional area of the hole, exacerbating the tendency to float one or more of them.

The detonators are boxed and packaged on plastic spools featuring very small diameter shafts. This imparts a pronounced 'memory' in the lead wires when unspooled. Provided tension can be maintained on the primers while in the hole, the leads stay largely straight. However, should the boosters start to float, any slackness in the lead wires results in an immediate helical spiral: perfect for wrapping around and ensnaring the charging hose.

Finally, the monitoring wires; a thick rigid RG6 coaxial cable and a thinner braided cable (Figure A5.3) were also present in the blast hole. For the first hole loaded, these monitoring wires were taped onto one of the primer's lead wires and joined all the way to the top with electrical tape to make a loom, which is the usual method for assembly and loading. However, when combined with the other challenges of top priming and deep wet holes, this did not prove to be a practical or satisfactory method. As soon as the first booster started to float, the loom became badly entangled in the loading hose.

On the second hole to be loaded (Site 1), the monitoring wires were tied to a rock and placed at the bottom of the hole, where they were easily trapped just after loading commenced. This allowed tension to be maintained in the monitoring wires and kept out of the way of the detonator lead wires and charging hose. However, this method still required the stop-start method of loading the majority of the explosives column, pausing to lower the three primers and then trying to catch them in the rising explosives column when charging recommenced. The outcome was blocking the hose and floating two of the three boosters (Figure A5.5).

On the third hole (Site 2), one of the primers was taped onto the monitoring wires at 11.5 m so that it would be able to be trapped in the hole by the rock at the bottom and be reliably positioned just at the desired point near the top of the final explosives column. This left just two primers to be lowered during loading, decreasing potential interruptions with the charging hose.

The fifth hole (Site 5) was very wet, which caused the primers to sink more slowly. To compensate for this, the last two primers were lowered down the hole before loading commenced so that they were within a few metres of the target location. This method allowed continual loading without a need to stop the hose at all.

Critical to success for the final method of deploying monitoring wiring was found to be:

1. Accurately measuring the hole depth and depth to water first.
2. Putting the assembly together on the surface in a neat straight line to avoid tangles.
3. Using a sizable rock, heavier than the booster, to allow determination of the rock hitting the bottom of the hole versus the booster reaching the water level during priming of the hole.
4. Using electrical tape to mark the position of the hole collar on all three wires so that, when primed, the mark is visible at the top of the hole to indicate the loom is sitting in the right place.
5. Not taping the monitor wires or the lead wires together (except once, where the booster is joined to the coax only) so that they can be individually checked for tension during loading.
6. Having a dedicated person to keep tension on the wires during loading.

A5.6 Results

A5.6.1 Blast 1 (Site 5)

The VOD 305 monitor was connected to the laptop, GPS fixed and time verified, and the unit set to monitor mode.

The back-up ViB unit was not able to be deployed, as testing of the in-hole monitoring wire prior to the blast had shown it had gone ‘open circuit’. The wires may have been damaged during priming, loading and/or stemming.

The hole was ready to fire just on sunset. Blast guards were installed, and site clearance was completed just before dusk. When the blast was initiated, a great deal of water/steam/gravel was ejected from the hole immediately upon firing. The material travelled mostly upwards and fell back down to within an approximate 10 m radius of the hole. Some landed on the site where the seismic monitors were located. The GoPro placed next to the hole has a clear audio track but otherwise is in darkness, except for the Shotfirer's headlights and silhouette during the after-blast inspection.

The VOD 305 monitor successfully recorded the hole detonating with GPS timestamp (Table A5.3).

A5.6.2 Blast 2 (Site 3)

The day started perfectly, with dawn breaking just as the team arrived at the blast site. This hole had been loaded two days before, and, to secure the detonator lead wires, they had been stowed within the hole's steel casing and a sturdy padlock applied to the cap. A gas bag had been inserted into the hole below the wires to guard against the hole slumping and/or the wires becoming irretrievable. All lead wires and test wires were recovered from the hole and successfully tested for continuity.

Following the events of the previous night, with the ejection at the time of firing, additional stemming was placed on and around the collar of this hole to reduce throw.

The VOD 305 and ViB monitors were connected to the laptop, GPS fixed and time verified, and the units set to monitor mode.

The hole fired with a decent ground thump, with only minor lifting of the stemming pile at the collar. There was no further visible activity until 47 seconds after firing, when the GoPro video then starts to show visible de-gassing (probably water vapour mixed with post-detonation gasses) from the collar of the hole. Then suddenly, five seconds later, stemming rises from the hole followed by the top gas bag, more stemming and then a violent ejection of water / steam / stemming / blast gases. Once this ejection subsides 28 seconds later, the hole can be seen to continue to visually de-gas for several minutes. (See still frames from the GoPro video in Figures A5.6 and A5.7).

Inspection of the hole after the blast shows that the steel casing has been lifted upwards a short distance (approximately 300 mm). The video shows that this happened immediately upon the hole detonating. Checking with a mirror shows that the casing inside the hole had ruptured further down and that the hole was mostly empty. It was possible to get the dip tape to a depth of 44 m, passing a few obstructions before reaching what felt like a blocked section.

Downloading of the VOD 305 monitor showed that it had not found a GPS fix during its blast set-up and, furthermore, that its internal real-time clock had inaccuracy (drift) of over five minutes (Table A5.3). These findings were forwarded to the manufacturer in Australia for review and comment.

The ViB monitor was triggered during the blast and the results downloaded. It had found a GPS fix and reported the wire-break. So, although the primary monitor had failed, the back-up looked to have captured the blast result (Table A5.3).

Unfortunately, it was subsequently determined, when the seismic monitors deployed by GNS Science were returned from the field after the end of the project, that the time recorded by the ViB was almost one minute later that when the hole actually fired (Table A5.3; see also Table 3.4). It is suspected that the unit did not record a wire-break event for the detonation of the booster and explosives column but rather when the wire assembly was ejected out of the hole along with the stemming / steam / blast gases. These findings have been forwarded to the manufacturer in Australia for review and comment.

Figure A5.6 Site 3, Blast 2: before firing and at point of detonation.

Figure A5.7 Site 3, Blast 2: a) ejection in full progress 55 seconds after detonation and b) degassing at 1 minutes 20 seconds.

A5.6.3 Blast 3 (Site 1)

This night-time shot proceeded well: Orica had recovered the lead wires and monitoring cable and built even more protection around the collar of the hole with a tub filled with stemming.

As per previous blasts, the VOD 305 and ViB monitors were connected to the laptop, to verify that they were receiving GPS fixes and were displaying accurate times, before being set to monitor mode.

The hole was fired and threw the tub to one side; stemming rose into the air a few metres. There was no further observable activity until 28 seconds later, when water, stemming and the top gas bag were pushed out of the hole, followed closely by more stemming and then a geyser of water / steam / stemming / blast gases. This lasted for 31 seconds, followed by a lengthy period of slow, visible de-gassing lasting over eight minutes (Table A5.2).

The after-blast inspection showed that the steel casing had been lifted slightly upwards, approximately 100 mm. The video suggests that the casing rose a little further than this during the hole detonating, then subsided slightly during ejection and degassing.

Downloading of the VOD 305 monitor showed that it once again failed to find a GPS fix during its blast set-up. In addition, the real-time clock still had the large drift present, despite (apparently) being verified as correct at the pre-blast set-up (Table A5.3). Emails from the manufacturer suggested a field procedure to improve obtaining the GPS fix: rather than undertaking a pre-blast check, it was advised that the monitor should be turned on for 10 minutes prior to the blast and then the monitoring wire attached when it was required for the monitor to set (arm) itself. It was understood then that the problem with a pre-blast check was that, when the monitor was turned back on for blast time, its software only allowed one minute to re-establish the GPS fix, which was considered not to be reliably long enough. This new method kept the monitor on continually, with the sequence proceeding to set itself once the cable was attached, without requiring a power down.

The ViB monitor was triggered during the blast and the results downloaded. We have yet to verify its time with that of GNS Science seismic array.

A5.6.4 Blast 4 (Site 2)

This early morning shot went according to plan, with all leads and wires tested, until the time of firing, when there was a misfire (nothing happened when the firing button was pushed). After the required five-minute stand-down, the detonator circuit was re-checked for continuity from the firing point, the Stinger 100 re-energised and the shot fired successfully. Most likely, the fault was due to an imperfect attachment of the firing cable to the Stinger 100 terminal screws. Part of the re-firing process involved the testing of the circuit using the Stinger 100 itself rather than a separate blaster’s ohmmeter. This is a better method that should greatly reduce imperfect terminal attachments going undetected.

The hole fired with a pronounced ground thump, and the casing was lifted upwards by approximately 400 mm. There was no ejection of water / steam / stemming / blast gases after the initial detonation event. The blast exclusion zone was kept closed for an extended period after the blast, in case the ejection event was merely delayed. After the blast guards were brought in to a reduced zone, the hole was observed for one-hour post-blast. Apart from the sound of water trickling in/through the hole, there was no other observable activity. No visible degassing was picked up by the GoPro (however, its field of view was poor due to the blast shock wave moving the camera angle).

After firing four blasts with varying amounts of standing water, it was postulated that there may be a relationship between the amount of water present in holes and the onset of ejection events: potentially immediate when the hole is full (Blast 1), delayed by a short amount when more than quite full (Site 1: Blast 3 = 28 seconds), delayed by a longer interval when less than half full (Site 3: Blast 2 = 52 seconds) and some uncertainly when there was only a few metres of water in the bottom (Site 2: Blast 4 = no event or very long delay?). See Table A5.2 for full details.

The new VOD 305 procedure proved successful; the monitor had a valid GPS fix for the blast and captured the blast firing time.

The ViB monitor did not trigger/capture the blast via the wire-break. It only triggered well after the blast via its ground vibration threshold, when the famer and his tractor used the nearby access track after the blast zone was opened.

A5.6.5 Blast 5 (Site 4)

This final blast required a Weka-resistant fence around the blast hole area.

All wires tested successfully. Stemming aggregate was placed around the base of the steel casing, and the top was painted fluorescent orange to improve visibility for the drone pilot.

The blast was fired as the sun was setting. With the driest of the three holes, there was a thump and the stemming was thrown upwards into the air several metres. The steel casing had risen approximately 300 mm. No other visible effects were observed by the drone's camera, and no ejection events or visible de-gassing occurred.

As this was the driest hole, and the blast exclusion zone included a public road, it was decided to keep the area closed for an extended period of time. Once the zone was brought in at one hour after firing, observers watched the hole for a further 30 minutes. After the end of this period, the hole was cautiously approached; observations were that, apart from the first 300 mm, the hole was still full of stemming. There was a definite sound emanating from deeper in the hole (described as similar to holding a shell next to one's ear, but louder) and a very subtle presence of slightly warm gas rising out of the hole as detected by holding a hand above the remaining stemming.

Potentially, the lack of water in this hole reduced the propensity for violent ejection events in favour of a gradual and not readily detectable depressurisation of the trapped blast gases (Table A5.2).

Table A5.2 Blast ejection delays.

Site ID	Blast Order	Delay until Ejection	Ejection Duration	Standing Water Height in Hole before Loading
1	3	0 min 28 sec	0 min 31 sec	39.3 m
2	4	No ejection	-	2.6 m
3	2	0 min 51 sec	0 min 28 sec	20.1 m
4	5	No ejection	-	1.3 m
5	1	0 min 00 sec	0 min 27 sec	47.2 m

The VOD 305 monitor successfully recorded the GPS firing time of the hole (Table A5.3).

The backup ViB unit did not trigger. When it was recovered after the blast, it was found to be still in 'Set' mode, with a blue flashing light indicating that it was awaiting a wire-break trigger (Table A5.3).

A5.7 Preliminary Detonation Times

Table A5.3 SHIRE II preliminary blast detonation times.

Site ID	Blast Order	Date Fired UTC (dd-mmm-yyyy)	Time at Detonation UTC (hh:mm:ss.000)	Monitor Unit	Monitor GPS Latitude	Monitor GPS Longitude	Comments
1	3	27-Feb-2019	06:17:49.736	ShotTrack ViB	38° 28.57371' S	178° 10.29094' E	Yet to be confirmed with GNS Science seismographs.
2	4	27-Feb-2019	18:12:26.692	ShotTrack 305	38° 25.65443' S	177° 52.11668' E	Yet to be confirmed with GNS Science seismographs.
3	2	26-Feb-2019	18:14:17.516	ShotTrack ViB	38° 16.41506' S	177° 44.34368' E	Recorded time is the ejection event, not the detonation time of the hole.
4	5	28-Feb-2019	06:25:31.073	ShotTrack 305	38° 14.30559' S	177° 36.86278' E	Yet to be confirmed with GNS Science seismographs.
5	1	26-Feb-2019	07:22:51.430	ShotTrack 305	38° 01.70387' S	177° 25.27799' E	Yet to be confirmed with GNS Science seismographs.

A5.8 Learnings and Recommendations for Future Projects

A5.8.1 Steel Casing

- The internal diameter of the steel casing is needed to allow calculation of the column height of the explosives charge.
- Backfill the blast hole 0.5–1.0 m prior to loading explosives in order to reduce potential for casing to be ejected from the hole.

A5.8.2 Product Selection: Detonators

- Electronic detonators are preferred. They permit testing for leakage and continuity. Suggested properties: suitable for deep / high water pressure environments, lead lengths equal depth of hole plus 5 m, packaging incorporates a large diameter spool to reduce 'memory'. Ideal product is Orica's i-kon III RX 60 m unit (or Orica i-kon Extreme, should these become available in the required lead length). Suggested deployment: top primer programmed at 1 ms, mid primer positioned 5 m below the top primer and programmed at 3 ms, bottom primer positioned 1 m up from the bottom of the hole and programmed at 6 ms (a successful top-firing hole will consume the mid and bottom primers just before these detonators fire themselves).
- Electric detonators are not preferred, as they require additional hazard management (stray currents, mobile phones, radios, other electrical devices) and require additional steps in the blasting process (testing only from a point of safety). Most of the time only instantaneous electric detonators (no inbuilt delays) can be sourced; these are difficult to use with redundant primers.

A5.8.3 Production Selection: Boosters

- Cast Pentolite boosters of mass 400 g, or equivalent, are preferred. These are cheap, readily available, reliable (det locks in the wells) and compact.
- Seismic cast/packaged explosives are not preferred; these are expensive, difficult to supply and stock and their shape hinders deployment (Figure A5.4, Table A5.1).

A5.8.4 Production Selection: Bulk Explosives

- The Orica product appeared well suited to the project. Load at lowest density recommended by the supplier, based on gassing and hydrostatic head charts.
- During the pre-site inspection, determine exactly how close the truck can be positioned to each blast hole to allow pre-determination of the maximum length of charging hose required. Minimising the hose length will reduce the propensity for blocking the hose as far as practicable.
- Carry an additional full roll of charging hose in case truck access changes (e.g. inclement weather).

A5.8.5 Production Selection: Stemming

- The 13–15 mm crushed aggregate used for this project was an ideal choice for stemming material. It does not contain any fines (which helps it sink quickly in water-filled holes and prevents bridging), is kind on detonator lead wires (if falling from a great height when there is no water present, and also via abrasion at the collar of the hole) and is ideal for manual handling (product pours well and consistently when added by bucket or shovelled).
- Allow 100% wastage factor and use the product's loose density (approximately 1.4 to 1.65 t/m^3) when calculating quantities.

A5.8.6 Site Security

- Sleeping loaded holes overnight was easily facilitated by the lockable steel covers on the steel casing.
- Create sufficient room at the top of the hole so that all lead wires and measurement cables can be hidden inside the locked casing. A gas bag can be used to ensure the wires are not sucked down the hole should the stemming or column below collapse.

A5.8.7 Stemming Height

- Wet holes should be stemmed all the way from the top of the explosives column to within a metre of the top of the casing.
- Dry holes should be stemmed at least 10 m height on top of the explosives column. A gas bag can be added at 4 m from the top of the hole to permit use of a top stemming deck, leaving the last 1 m empty.

A5.8.8 Blast Videoing

- A GoPro in close proximity to the blast, e.g. 10–15 m, will require firm anchoring to the tripod and ground to resist shockwaves from airblast and ground vibration. It will probably avoid being hit by stemming at 10 m but may be doused with water and mud.
- A drone camera can be extremely useful for after-blast inspections, particularly if anticipating post-blast ejection events.

A5.8.9 Firing Times

- Morning blast windows: aim to get to site as the sun comes up (to minimise slips and trips on the uneven terrain) in order to shoot as early as practicable.
- Evening blasts: aim to fire 30 minutes before dusk so that there is time to clear the area and still troubleshoot any misfires or other issues before total darkness sets in.

A5.8.10 Waiting Times and Exclusion Zones After Firing

- Large explosives charges buried relatively deeply (excessively confined) can lead to water / steam / stemming / blast gas ejection events at unpredictable intervals post-detonation, as observed on this and in other projects. There may be very little warning, if any, of impending ejection events. Sedna's past experience includes a maximum of 36 minutes post-detonation ejection in soft sedimentary units. Treat with utmost caution.

- Fully wet steel-cased holes can eject shortly after firing. As the amount of water decreases, the delay until ejection may increase. On this project, the longest delay was 51 seconds (Site 3, Table A5.2).
- Dry holes may delay ejection further or not eject at all (Table A5.2). Reducing the stemming amounts may better facilitate controlled de-gassing.
- Recognise that trapped blast gases may migrate to the collar of the hole and depressurise the hole slowly, whether there was an ejection event or not. Such de-gassing may be visible if it contains sufficient amounts of water vapour. Consider employing a gas monitoring unit, such as a personal CO monitor, on future blasts to aid in quantification and clarification.
- Consider each site for the pros and cons of controlling ejection events versus maintaining blast exclusion zones and guarding for extended durations.

Richard Sullivan
Specialist D&B Engineer
Sedna D&B

13th March 2019

APPENDIX 6 INSTRUMENT LOCATIONS

During the SHIRE 1 deployment, instruments were deployed roughly every 2 km on the main transect across the Raukumara Peninsula. Table A6.1 lists the locations and serial numbers of the instruments deployed in the Transect and 2D Arrays.

Table A6.1 List of SHIRE I onshore locations deployed on Transect and 2D Array. Station numbers between 501–601 are located on the Transect; station numbers starting with 7 are the 2D Array sites. Sensor orientation is given in degrees east of True North.

Site Number	Latitude	Longitude	Elv. (m)	Sensor Orientation	REFTEK Number	Sensor Number	Sensor Type
501	-38.56903	178.22658	28	0	A123	2522	L-28
503	-38.55253	178.22132	64	0	9E0F	G308	L-28
505	-38.53784	178.19566	39	0	9AFA	483-L	L-22
507	-38.50645	178.17420	72	1	9338	230-L	L-22
509	-38.51643	178.16344	220	0	9BB4	736-L	L-22
511	-38.51049	178.15140	211	-2	944D	740-L	L-22
514	-38.49620	178.11764	305	0	9293	482-L	L-22
515	-38.49652	178.09852	195	0	9292	486-L	L-22
517	-38.47988	178.08534	165	0	9D7A	225-L	L-22
519	-38.48055	178.05840	265	4	9E3C	222-L	L-22
521	-38.45677	178.05618	476	0	9DF0	L220000010	L-22
523	-38.43222	178.04783	545	0	91F7	L220000108	L-22
525	-38.42854	178.03636	439	-2	91F4	741-L	L-22
529	-38.40701	177.98123	154	-8	9911	238-L	L-22
531	-38.41044	177.95356	76	-8	9892	494-L	L-22
533	-38.37183	177.96692	391	-5	AAA3	733-L	L-22
535	-38.35950	177.94804	249	0	991C	241-L	L-22
537	-38.34429	177.93466	118	3	9D6E	1007232	L-22
539	-38.38504	177.85708	89	2	A091	K4/1009277	L-28
541	-38.37597	177.83907	86	0	98EC	L220000121	L-22
543	-38.36550	177.82469	96	-4	989C	K114	L-28
547	-38.31723	177.81186	343	-10	9738	1504-L	L-22
549	-38.28755	177.81644	459	0	9D9D	1000838	L-22
551	-38.29277	177.77525	357	0	929E	506-L	L-22
553	-38.28834	177.75427	462	0	AB13	1001237	L-22
555	-38.27695	177.73991	420	0	98000000	1008615	L-22
557	-38.26860	177.72065	599	0	967D	1003263	L-22
559	-38.26316	177.69143	736	10	91EA	447-L	L-22
563	-38.24333	177.66414	518	-2	9DFC	1503L	L-22
565	-38.24262	177.63014	637	0	9851	L220000128	L-22

Site Number	Latitude	Longitude	Elv. (m)	Sensor Orientation	REFTEK Number	Sensor Number	Sensor Type
567	-38.22509	177.61377	457	-14	92A6	245-L	L-22
569	-38.20014	177.60074	469	0	9696	452-L	L-22
573	-38.17668	177.56000	431	-7	939E	743-L	L-22
575	-38.18543	177.52680	467	-6	9DAC	472-L	L-22
577	-38.12213	177.57424	354	0	978F	L220000103	L-22
579	-38.11937	177.55388	343	-10	939D	L220000110	L-22
581	-38.10935	177.52954	361	-10	944E	468-L	L-22
583	-38.11113	177.50738	365	-2	A120	1487L	L-22
585	-38.09951	177.48584	389	0	92A2	L220000115	L-22
587	-38.09036	177.48611	463	5	9000000	727-L	L-22
589	-38.05599	177.45733	74	0	969E	5004113	L-22
593	-38.01820	177.44774	136	-6	929C	748-L	L-22
595	-38.03205	177.39681	67	0	9AF8	957-L	L-22
597	-38.01755	177.38270	81	0	92B6	963-L	L-22
599	-38.01505	177.34869	60	0	9670	451-L	L-22
601	-38.00735	177.33299	45	0	92CE	1001244	L-22
701	-37.97644	177.49037	28	-20	967F	L220000127	L-22
702	-37.87676	177.60151	19	0	9.00E+41	777-L	L-22
703	-37.82680	177.63671	88	3	92D9	956-L	L-22
704	-37.73744	177.67348	12	-5	930D	480-L	L-22
705	-37.67755	177.77826	24	0	9464	0239-L	L-22
706	-37.64652	177.88739	73	0	9.00E+39	497-L	L-22
707	-37.55102	178.03174	178	6	9298	954-L	L-22
708	-37.56053	178.16197	144	0	98F3	950-L	L-22
710	-37.75649	178.41753	39	6	9DFD	1007600	L-22
711	-37.67977	178.35517	51	4	9313	973-L	L-22
712	-37.87278	178.40441	47	0	9912	1003585	L-22
713	-37.89299	178.32417	69	0	953D	7-096	L-22
714	-38.00633	178.32500	147	2	929D	1508-L	L-22
715	-38.12143	178.25566	172	0	9243	964-L	L-22
716	-38.21499	178.19052	365	0	9BB3	745-L	L-22
717	-38.29517	178.26892	13	6	92B7	744-L2	L-22
718	-38.38730	178.26022	6	8	98000	969-L	L-22
719	-38.51198	178.25079	47	-8	91F8	1495-L	L-22
721	-38.18418	178.09595	536	0	9389	243-L	L-22
722	-38.18545	178.09667	553	-5	9389	243-L	L-22
723	-38.26079	178.05010	567	-8	9678	250-L	L-22

Site Number	Latitude	Longitude	Elv. (m)	Sensor Orientation	REFTEK Number	Sensor Number	Sensor Type
724	-38.38283	178.12247	92	0	920000	487-L	L-22
725	-37.95372	178.17519	163	5	92D1	463-L	L-22
726	-37.68644	178.24495	290	0	9AB6	955-L	L-22
727	-37.85836	178.08512	361	0	9E2A	1505-L	L-22
728	-37.66499	178.06360	84	3.5	AB2B	473-L	L-22
729	-38.04862	178.04997	565	-2	98DC	951-L	L-22
731	-38.38998	177.64013	343	-2	9517	448-L	L-22
732	-38.47828	177.60398	651	4	9DFE	5004106	L-22
733	-38.56982	177.47808	580	0	9544	453-L	L-22
734	-38.25664	177.54158	480	-5	9793	642-L	L-22
735	-38.08370	177.36884	31	-10	A197	967-L	L-22
736	-38.30136	177.33715	143	0	9782	744-L	L-22
737	-38.11488	177.15622	67	0	986B	1003793	L-22
738	-38.40106	177.45426	596	-5	A090	496-L	L-22
739	-38.20665	177.10367	88	-12	9AB2	L220000106	L-22
740	-38.61769	178.10636	203	0	938B	1001256	L-22
741	-38.49025	177.91775	20	-1.5	9E4A	456-L	L-22
742	-38.62895	177.85299	25	-1	98C6	242-L	L-22
743	-38.52472	177.72211	117	-1	A195	L220000112	L-22
744	-38.75050	177.88683	95	9	9E5D	0236-L	L-22
745	-38.72121	177.71483	514	2	9407	1506-L	L-22
746	-38.63718	177.58234	245	0	9BC6	732-L	L-22
760	-38.19673	177.79244	899	-2	9E+58	L220000126	L-22

Table A6.2 List of SHIRE II onshore locations deployed on Transect and 2D Array. Station numbers between 501–601 are located on the Transect; station numbers starting with 7 belong to the 2D Array. Sensor orientation is given in degrees east of True North.

Site Code	Latitude	Longitude	Elevation (m)	Sensor Orientation	Sensor Serial Number	DAS Serial Number
517	-38.4807	178.08522	160	-10	9071	92B4
541	-38.3759	177.83888	83	0	2484	92A3
579	-38.1094	177.52956	358	0	5-068	9480
601	-38.0072	177.33266	20	0	G162	9260
701	-37.9765	177.49014	28	0	G356	91EC
718	-38.3873	178.26017	14	0	G361	AB22
720	-38.5821	178.01251	118	-16	9360	92CC
724	-38.3828	178.12246	100	0	2437	A207
730	-38.3548	177.73312	312	-	2562	9D6B
732	-38.4794	177.60419	389	0	2576	91F5
735	-38.0829	177.36833	28	-	G048	9516
736	-38.3022	177.33459	150	-	5085	9457
737	-38.1149	177.15625	59	-	2590	9391
738	-38.4017	177.45641	622	0	G383	9DE2
740	-38.6186	178.10619	202	0	G313	92E7
741	-38.4902	177.91775	36	0	2503	98F5
742	-38.629	177.85301	42	0	K195	930A
743	-38.5247	177.72207	125	0	G217	9491
760	-38.1967	177.79249	841	0	G223	940A

Table A6.3 List of SHIRE II Texan 1C and 3C site locations deployed on Transect and perpendicular lines. Line numbers 1–10 are the main Transect segments and lines 21, 21, 26, and 29 are perpendicular lines with 1C stations only. Sensor orientation is given in degrees east of True North.

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
1	10101	1824	1875	745	-38.5519	178.2129	12	-10
1	10102	1520	-	-	-38.5513	178.2104	16	-
1	10103	2118	2910	3983	-38.5503	178.2088	19	-10
1	10104	1686	-	-	-38.5501	178.2081	19	-
1	10105	2708	2186	2158	-38.5497	178.2062	20	4
1	10106	2991	-	-	-38.5493	178.2046	21	-
1	10107	2881	4045	1818	-38.5478	178.2031	38	-
1	10108	2310	-	-	-38.5467	178.2025	38	-
1	10109	2062	3875	3832	-38.5455	178.2016	34	-
1	10110	2321	-	-	-38.5451	178.2001	67	-
1	10111	1313	1769	2641	-38.5461	178.1966	24	-
1	10112	1729	-	-	-38.5447	178.196	30	-
1	10113	3679	2906	3678	-38.5432	178.1951	25	-
1	10114	3855	-	-	-38.5419	178.1945	23	-
1	10115	1304	3841	1874	-38.5403	178.1938	27	-
1	10116	2187	-	-	-38.5384	178.1937	26	-
1	10117	1595	3791	2581	-38.5355	178.1937	33	-
1	10118	2138	-	-	-38.5344	178.1936	30	-
1	10119	719	2695	2226	-38.5317	178.1936	30	-
1	10120	1971	-	-	-38.529	178.1954	37	-
1	10121	759	878	2335	-38.5267	178.1956	46	-
1	10122	3865	-	-	-38.5248	178.1954	37	-
1	10123	2261	1951	1180	-38.5235	178.1942	30	-
1	10124	1002	-	-	-38.5226	178.1933	32	-
1	10125	3571	1799	4041	-38.5221	178.1918	33	-
1	10126	1989	-	-	-38.5213	178.1902	44	-
1	10127	3720	2320	738	-38.5198	178.1897	38	-
1	10128	2193	-	-	-38.5181	178.1891	39	-
1	10129	2880	2389	1064	-38.5166	178.1885	37	-
1	10130	2353	-	-	-38.5157	178.1877	32	-
1	10131	3683	1013	1165	-38.515	178.1858	35	-
1	10132	3641	-	-	-38.5139	178.1846	39	-
1	10133	3964	2361	4016	-38.5133	178.183	46	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
1	10134	1605	-	-	-38.5125	178.1821	47	-
1	10135	668	2365	2295	-38.5109	178.1813	40	-
1	10136	1742	-	-	-38.5105	178.1799	42	-
1	10137	1112	4019	2103	-38.5097	178.1775	42	-
1	10138	2505	-	-	-38.5092	178.1764	51	-
1	10139	3688	3681	1008	-38.5081	178.1746	45	-
1	10140	726	-	-	-38.5065	178.1755	55	-
1	10141	1713	2544	4008	-38.5048	178.1744	53	-
1	10142	1105	-	-	-38.5033	178.1731	54	-
1	10143	1047	1192	1011	-38.5026	178.1722	55	-
1	10144	2388	-	-	-38.5032	178.1701	64	-
1	10145	3710	1267	1136	-38.5018	178.1692	57	-
1	10146	2387	-	-	-38.5011	178.167	57	-
1	10147	1023	877	852	-38.5	178.1657	56	-
1	10148	3843	-	-	-38.4981	178.1661	74	-
1	10149	2460	2912	2096	-38.4969	178.1649	52	2
1	10150	2486	-	-	-38.4955	178.1645	58	-
1	10151	739	2628	3985	-38.4945	178.1634	61	5
1	10152	4036	-	-	-38.4923	178.1634	62	-
1	10153	3757	2052	2530	-38.4908	178.1622	59	-
1	10154	3992	-	-	-38.4899	178.1615	62	-
1	10155	850	830	3921	-38.4893	178.16	66	-
1	10156	2459	-	-	-38.489	178.1584	73	-
1	10157	959	2760	2663	-38.4874	178.1577	60	-
1	10158	2174	-	-	-38.4868	178.1566	61	-
1	10159	3848	2739	2987	-38.4855	178.1551	71	-
1	10160	2474	-	-	-38.4858	178.1533	81	-
1	10161	2098	2542	2802	-38.4855	178.1505	80	2
1	10162	2467	-	-	-38.4844	178.1494	78	-
1	10163	3772	2430	3713	-38.4855	178.145	110	-
1	10164	1685	-	-	-38.4847	178.1447	133	-
1	10165	3729	1815	988	-38.484	178.1427	157	-
1	10166	1931	-	-	-38.4833	178.1417	186	-
1	10167	3906	3817	2007	-38.4818	178.1408	182	2
1	10168	1864	-	-	-38.481	178.1395	182	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
1	10169	712	777	1887	-38.4801	178.1382	158	-
1	10170	2270	-	-	-38.4793	178.137	177	-
1	10171	3661	2255	791	-38.4786	178.1356	182	5
1	10172	1014	-	-	-38.4783	178.1337	187	-
1	10173	2073	3978	2298	-38.4776	178.1325	210	-
1	10174	1160	-	-	-38.4774	178.1304	217	-
21	12101	2102	-	-	-38.4786	178.1291	218	-
21	12104	2767	-	-	-38.4823	178.1286	203	-
21	12107	3891	-	-	-38.4862	178.1261	208	-
21	12110	2548	-	-	-38.4887	178.125	221	-
21	12113	2447	-	-	-38.4924	178.1229	253	-
21	12116	2672	-	-	-38.4948	178.1195	301	-
21	12119	2928	-	-	-38.4974	178.1169	280	-
21	12122	1263	-	-	-38.5011	178.1168	257	-
21	12125	1871	-	-	-38.5035	178.1197	227	-
21	12127	3947	-	-	-38.5049	178.1215	230	-
2	10201	1903	1312	2422	-38.5189	178.0942	240	-
2	10202	999	-	-	-38.5184	178.0921	196	-
2	10203	1679	2304	2384	-38.5176	178.0909	191	-
2	10204	3508	-	-	-38.5165	178.0896	176	-
2	10205	2870	2216	1945	-38.515	178.0884	152	-
2	10206	3798	-	-	-38.5144	178.0875	138	-
2	10207	1583	3761	2412	-38.513	178.0863	155	-
2	10208	3592	-	-	-38.5121	178.0855	155	-
2	10209	747	1650	2545	-38.5108	178.0846	161	-
2	10210	2112	-	-	-38.5096	178.0837	143	-
2	10211	2126	1857	3919	-38.5085	178.083	164	-
2	10212	3953	-	-	-38.5071	178.082	169	-
2	10213	2612	3765	766	-38.505	178.0816	157	-
2	10214	4081	-	-	-38.5044	178.0807	177	-
2	10215	4096	4010	1803	-38.5044	178.0784	143	-
2	10216	1741	-	-	-38.5036	178.077	146	-
2	10217	2722	3749	1003	-38.502	178.0761	141	-
2	10218	4068	-	-	-38.5012	178.0751	133	-
2	10219	2166	1862	2807	-38.5041	178.0691	104	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
2	10220	2648	-	-	-38.505	178.0668	87	-
2	10221	3707	1901	875	-38.5054	178.0629	76	-
2	10222	2151	-	-	-38.505	178.061	78	-
2	10223	3655	2652	2129	-38.5041	178.0595	84	-
2	10224	2872	-	-	-38.5035	178.0587	81	-
2	10225	4086	2590	3722	-38.5023	178.0569	94	-
2	10226	4003	-	-	-38.5015	178.0562	89	-
2	10227	676	958	4011	-38.4987	178.0561	105	-
2	10228	2426	-	-	-38.497	178.0565	142	-
2	10229	2167	2348	3959	-38.4928	178.0568	174	-
2	10230	1984	-	-	-38.4918	178.0579	181	-
2	10231	2609	2196	3909	-38.4896	178.0572	186	-
2	10232	1959	-	-	-38.4887	178.0568	183	-
2	10233	2688	1029	2707	-38.4873	178.0559	178	-
2	10234	2268	-	-	-38.4866	178.0547	180	-
2	10235	2919	1712	1608	-38.4838	178.0557	226	-22
2	10236	2525	-	-	-38.481	178.0569	240	-
2	10237	2830	1932	2758	-38.4787	178.0561	274	-4
2	10238	2257	-	-	-38.4798	178.0537	274	-
2	10239	3682	3989	1954	-38.479	178.0517	302	-18
2	10240	1507	-	-	-38.4784	178.0506	298	-
2	10241	1529	2661	2282	-38.4766	178.0497	282	-4
2	10242	1134	-	-	-38.4751	178.0481	339	-
2	10243	1694	2836	2668	-38.4733	178.0495	325	-
2	10244	1998	-	-	-38.4704	178.0513	376	-
2	10245	1744	4161	1832	-38.468	178.0506	370	-
2	10246	3627	-	-	-38.4668	178.05	401	-
2	10247	3006	2616	1026	-38.4635	178.0512	389	-8
2	10248	3955	-	-	-38.4614	178.0514	410	-
2	10249	2810	2702	2701	-38.4596	178.0511	408	-
2	10250	863	-	-	-38.4571	178.0519	409	-
2	10251	1710	1812	1200	-38.4563	178.0504	409	-
2	10252	811	-	-	-38.4553	178.0487	421	-
2	10253	3666	1654	1615	-38.4525	178.0492	445	-4
2	10254	2305	-	-	-38.452	178.0479	437	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
2	10255	1202	2837	2356	-38.4505	178.0475	480	-4
2	10256	3776	-	-	-38.4483	178.0474	483	-
2	10257	2114	3730	3914	-38.4462	178.0472	498	-4
2	10258	1838	-	-	-38.4447	178.0476	486	-
2	10259	967	1121	2515	-38.4428	178.0474	475	-
2	10260	3634	-	-	-38.4389	178.0482	516	-
2	10261	3998	2751	2908	-38.4338	178.0505	555	-6
2	10262	2940	-	-	-38.4323	178.051	522	-
2	10263	2117	1735	2354	-38.4312	178.0508	491	8
3	10301	2301	1900	2748	-38.4309	178.0498	487	-
3	10302	3878	-	-	-38.4305	178.0479	525	-
3	10303	2403	1880	3839	-38.4305	178.0457	509	2
3	10304	1044	-	-	-38.4307	178.0428	490	-
3	10305	1859	1725	3799	-38.4309	178.04	442	-
3	10306	1699	-	-	-38.4304	178.0387	437	-
3	10307	2935	2941	2623	-38.4299	178.037	452	2
3	10308	3769	-	-	-38.4292	178.0354	490	-
3	10309	1567	733	2601	-38.4292	178.0331	502	-
3	10310	2288	-	-	-38.4285	178.0316	433	-
3	10311	1910	2045	1571	-38.4279	178.03	477	2
3	10312	3851	-	-	-38.4277	178.0277	458	-
3	10313	3895	2523	3885	-38.4271	178.0265	433	2
3	10314	2317	-	-	-38.4263	178.0249	462	-
3	10315	2373	1785	2309	-38.4249	178.024	441	2
3	10316	2454	-	-	-38.4239	178.023	424	-
3	10317	2920	790	1265	-38.4226	178.022	420	5
3	10318	965	-	-	-38.4217	178.0208	424	-
3	10319	720	3717	3869	-38.4207	178.02	435	-
3	10320	1028	-	-	-38.4195	178.0187	417	-
3	10321	2470	2352	1939	-38.4184	178.0178	413	2
3	10322	2478	-	-	-38.4172	178.0167	396	-
3	10323	4087	736	2199	-38.4158	178.016	379	-
4	10407	854	1577	2223	-38.4062	177.9856	247	-
4	10408	4014	-	-	-38.4046	177.9845	259	-
4	10409	2137	1661	2065	-38.4059	177.9813	186	2

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
4	10410	1678	-	-	-38.4077	177.9756	148	-
4	10411	1858	1692	2658	-38.4083	177.9741	126	-
4	10412	3968	-	-	-38.4124	177.9716	117	-
4	10413	1965	2212	3611	-38.4123	177.9683	86	-
4	10414	808	-	-	-38.4127	177.9661	78	-
4	10415	2937	1854	2809	-38.4123	177.9647	82	-
4	10416	2229	-	-	-38.4118	177.9629	73	-
4	10417	1152	1004	1652	-38.411	177.9601	75	22
4	10418	2008	-	-	-38.4104	177.9601	92	-
4	10419	2191	3640	2207	-38.4093	177.9588	81	5
4	10420	774	-	-	-38.4089	177.9568	74	-
4	10421	2132	2006	2035	-38.4081	177.9557	69	4
4	10422	1568	-	-	-38.408	177.9541	69	-
4	10423	2583	1754	2604	-38.4079	177.9522	70	10
24	12401	2557	-	-	-38.4064	177.9538	135	-
24	12404	1814	-	-	-38.4036	177.9536	180	-
24	12407	2893	-	-	-38.4001	177.9559	253	-
24	12410	2149	-	-	-38.3964	177.9559	309	-
24	12414	1122	-	-	-38.3913	177.958	341	-
24	12416	3952	-	-	-38.3903	177.956	352	-
24	12419	2813	-	-	-38.3867	177.9567	329	-
24	12422	2415	-	-	-38.3823	177.9597	352	-
24	12425	2692	-	-	-38.38	177.9636	362	-
24	12428	3965	-	-	-38.3771	177.9662	374	-
24	12431	2086	-	-	-38.374	177.9686	401	-
5	10501	1645	2514	2917	-38.3719	177.9677	405	-
5	10502	1844	-	-	-38.37	177.9674	389	-
5	10503	2145	1821	2163	-38.3681	177.9668	393	2
5	10504	2990	-	-	-38.3674	177.965	381	-
5	10505	1726	3937	2865	-38.368	177.9624	358	-9
5	10506	785	-	-	-38.3683	177.9597	361	-
5	10507	1933	1130	2084	-38.3679	177.9585	356	-
5	10508	3764	-	-	-38.3667	177.9573	343	-
5	10509	2296	2143	1081	-38.3657	177.9556	316	-
5	10510	2289	-	-	-38.3653	177.9542	329	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
5	10511	2942	828	2063	-38.3643	177.9534	317	-
5	10512	4006	-	-	-38.363	177.9524	256	-
5	10513	3904	2733	2676	-38.3619	177.9514	297	-
5	10514	2395	-	-	-38.3606	177.9506	299	-
5	10515	1914	2079	2831	-38.3602	177.9482	257	-
5	10516	1656	-	-	-38.3593	177.9466	256	-
5	10517	2921	3587	1904	-38.3595	177.9445	238	2
5	10518	2399	-	-	-38.3571	177.9457	190	-
5	10519	2892	2247	1610	-38.3573	177.9426	169	-
5	10520	730	-	-	-38.3575	177.9395	124	-
5	10521	1162	2843	2691	-38.3582	177.9367	120	-
5	10522	2741	-	-	-38.3553	177.938	110	-
5	10523	2508	1593	1139	-38.3515	177.9395	107	6
5	10524	2602	-	-	-38.3503	177.9393	119	-
5	10525	1825	2911	1790	-38.3487	177.9386	114	-
5	10526	2244	-	-	-38.3476	177.9377	118	-
5	10527	1191	1994	924	-38.3464	177.9363	115	6
5	10528	3671	-	-	-38.345	177.9365	117	-
6	10601	3905	3801	3705	-38.2973	177.9122	520	-
6	10602	2636	-	-	-38.298	177.909	482	-
6	10603	1997	2662	1574	-38.2982	177.9069	473	-
6	10604	2521	-	-	-38.298	177.9041	466	-
6	10605	1958	2768	2669	-38.2971	177.9028	470	3
6	10606	1647	-	-	-38.2962	177.9018	462	-
6	10607	1590	4071	679	-38.2954	177.9004	463	-
6	10608	4095	-	-	-38.2953	177.8982	449	-
6	10609	2495	2550	3828	-38.2952	177.8961	452	4
6	10610	2381	-	-	-38.2943	177.8946	435	-
6	10611	1057	1783	2262	-38.294	177.8924	408	8
6	10612	2080	-	-	-38.2932	177.8911	392	-
6	10613	1114	3833	1834	-38.2927	177.8896	438	10
6	10614	1804	-	-	-38.2922	177.8883	418	-
6	10615	836	4089	2281	-38.2922	177.8857	391	8
6	10616	2299	-	-	-38.2921	177.8834	367	-
6	10617	1083	1585	1065	-38.2921	177.8814	360	20

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
6	10618	762	-	-	-38.2917	177.8794	354	-
6	10619	2245	2029	3834	-38.2912	177.8773	339	22
6	10620	1197	-	-	-38.2912	177.8752	350	-
6	10621	3009	3685	1156	-38.2912	177.8733	340	20
6	10622	2890	-	-	-38.2896	177.8725	299	-
6	10623	4028	1182	2929	-38.2887	177.8715	305	22
6	10624	2205	-	-	-38.2885	177.8689	283	-
6	10625	1621	1782	2481	-38.2889	177.8667	311	32
6	10626	4048	-	-	-38.2883	177.8646	314	-
6	10627	1667	2350	2835	-38.2879	177.8628	263	26
6	10628	1144	-	-	-38.2877	177.8604	256	-
6	10629	2756	3673	2131	-38.2866	177.8596	235	-
6	10630	848	-	-	-38.2873	177.8572	218	-
6	10631	1671	3723	3507	-38.2866	177.8551	186	-1
6	10632	2664	-	-	-38.2851	177.8549	159	-
6	10633	4005	2047	1698	-38.2858	177.8513	190	6
6	10634	4078	-	-	-38.2874	177.848	175	-
26	12601	2894	-	-	-38.2833	177.8476	210	-
26	12604	2650	-	-	-38.2849	177.843	263	-
26	12607	3644	-	-	-38.2884	177.8419	266	-
26	12610	2546	-	-	-38.2923	177.8419	283	-
26	12613	1518	-	-	-38.2955	177.8376	279	-
26	12616	3933	-	-	-38.2962	177.8335	301	-
26	12619	3881	-	-	-38.2963	177.8285	334	-
26	12622	770	-	-	-38.2973	177.8248	343	-
26	12625	1956	-	-	-38.3001	177.8241	318	-
26	12629	2236	-	-	-38.3002	177.8181	304	-
26	12631	2713	-	-	-38.3022	177.815	332	-
26	12634	3782	-	-	-38.3056	177.8125	360	-
26	12637	1060	-	-	-38.3091	177.8102	345	-
26	12640	3608	-	-	-38.313	177.809	328	-
26	12643	3763	-	-	-38.3158	177.8066	319	-
7	10701	1767	2286	2139	-38.3199	177.8171	318	-8
7	10702	2673	-	-	-38.3197	177.8153	325	-
7	10703	3938	806	1639	-38.3187	177.8135	304	2

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
7	10704	2190	-	-	-38.3179	177.8124	324	-
7	10705	2686	2263	2420	-38.3186	177.8102	325	-
7	10706	2674	-	-	-38.3178	177.8083	320	-
7	10707	3825	2135	2194	-38.3167	177.8071	319	-
7	10708	3771	-	-	-38.3173	177.8048	299	-
7	10709	2747	3783	3784	-38.321	177.7985	300	-8
7	10710	2456	-	-	-38.325	177.7902	269	-
7	10711	3894	1548	2613	-38.323	177.7898	250	-2
7	10712	2108	-	-	-38.3224	177.7892	204	-
7	10713	3625	1819	1697	-38.3206	177.7889	185	-
7	10714	2563	-	-	-38.3195	177.7876	199	-
7	10715	3913	2569	1961	-38.3195	177.7864	169	-
7	10716	4088	-	-	-38.3182	177.7853	155	-
7	10717	3976	4034	2561	-38.3172	177.7837	173	-
7	10718	3738	-	-	-38.3167	177.782	182	-
7	10719	1128	2345	769	-38.3161	177.7813	182	-
7	10720	2498	-	-	-38.3137	177.7804	234	-
7	10721	1879	1113	2095	-38.3128	177.7796	244	-
7	10722	4055	-	-	-38.3112	177.7784	266	-
7	10723	2745	2675	722	-38.3094	177.7788	277	-
7	10724	4094	-	-	-38.3074	177.7787	278	-
7	10725	3805	1072	1629	-38.3062	177.7774	280	-
7	10726	1734	-	-	-38.3042	177.7777	280	-
7	10727	1966	1902	2685	-38.3026	177.777	332	-
7	10728	1974	-	-	-38.3023	177.7755	361	-
7	10729	3889	2889	1599	-38.3002	177.7756	333	-
7	10730	4029	-	-	-38.2975	177.7761	291	-
7	10731	3645	2552	1115	-38.2955	177.7754	350	-
7	10732	1791	-	-	-38.2939	177.7753	339	-
7	10733	1891	2898	833	-38.292	177.7757	344	-
7	10734	2689	-	-	-38.2915	177.774	377	-
7	10735	3742	2385	3752	-38.291	177.7716	389	-
7	10736	2400	-	-	-38.2901	177.7708	388	-
7	10737	2528	2562	1835	-38.2892	177.7699	415	-
7	10738	2850	-	-	-38.2877	177.7688	410	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
7	10739	2427	1817	2449	-38.2873	177.7677	421	-
7	10740	3898	-	-	-38.2866	177.7658	423	-
7	10741	1706	2939	2720	-38.2856	177.7646	424	-
7	10742	1793	-	-	-38.2853	177.763	376	-
7	10743	2593	4015	3639	-38.2849	177.7604	388	-
7	10744	3753	-	-	-38.285	177.7583	383	-
7	10745	3616	3888	2455	-38.2845	177.756	428	-
7	10746	1674	-	-	-38.2883	177.7497	455	-
7	10747	4021	2808	1681	-38.2876	177.7488	479	-
7	10748	3628	-	-	-38.2864	177.7472	495	-
7	10749	2334	2300	725	-38.286	177.7456	517	-
7	10750	3778	-	-	-38.2849	177.7445	512	-
7	10751	2509	1553	2405	-38.2837	177.7431	500	-
7	10752	3797	-	-	-38.28	177.7454	503	-
7	10753	1570	1665	2871	-38.2787	177.7451	470	-
7	10754	3803	-	-	-38.2771	177.744	442	-
7	10755	2731	2323	3872	-38.2762	177.743	422	-
7	10756	1889	-	-	-38.2754	177.741	404	-
7	10757	3792	3899	1627	-38.2755	177.7396	401	-
7	10758	1886	-	-	-38.2744	177.7383	401	-
7	10759	4083	2902	3748	-38.2743	177.7363	398	-
7	10761	3631	2500	3596	-38.2704	177.736	399	-
7	10762	3744	-	-	-38.2682	177.7354	402	-
7	10763	3785	2993	1845	-38.2679	177.7329	397	-
7	10764	2665	-	-	-38.267	177.7329	388	-
7	10765	1043	2408	2398	-38.2656	177.7321	435	-
7	10766	717	-	-	-38.2668	177.7284	491	-
7	10767	1040	2927	2366	-38.2657	177.7259	523	-
7	10768	4063	-	-	-38.2661	177.7226	561	-
7	10769	3927	1701	2378	-38.2678	177.7205	596	-
7	10770	2487	-	-	-38.2683	177.7175	623	-
7	10771	1953	2923	1840	-38.2696	177.7136	595	-
7	10772	1305	-	-	-38.27	177.7109	590	-
7	10773	1731	723	3609	-38.2697	177.7088	616	-
7	10774	3677	-	-	-38.2717	177.7046	693	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
7	10775	813	578	1707	-38.2709	177.703	701	-
7	10776	2811	-	-	-38.2702	177.7016	714	-
7	10777	2571	2287	1575	-38.2712	177.6978	729	-
7	10778	1720	-	-	-38.2706	177.6966	729	-
7	10779	1982	753	3615	-38.2699	177.6953	719	-
7	10780	2201	-	-	-38.2682	177.6943	724	-
7	10781	862	853	1778	-38.2671	177.6938	717	-
7	10782	2473	-	-	-38.2656	177.693	707	-
7	10783	962	839	2319	-38.2643	177.6923	739	-
8	10824	3709	-	-	-38.2438	177.6072	456	-
8	10825	2104	3932	2090	-38.2465	177.6064	472	-
8	10826	1823	-	-	-38.2506	177.5979	467	-
8	10827	2324	1747	792	-38.2494	177.5965	495	1
8	10828	3977	-	-	-38.2491	177.5954	530	-
8	10829	1638	2435	1870	-38.248	177.5939	478	-
8	10830	2116	-	-	-38.2471	177.5919	476	-
8	10831	873	2101	3850	-38.2505	177.5883	476	-
8	10832	3656	-	-	-38.251	177.5854	475	-
8	10833	2133	2742	3721	-38.253	177.5809	471	-
8	10834	2705	-	-	-38.2547	177.5767	473	-
8	10835	3004	689	3900	-38.2559	177.5734	485	-
8	10836	2424	-	-	-38.2593	177.5668	484	-
8	10837	2931	1640	2985	-38.2593	177.5645	480	-
8	10838	3814	-	-	-38.2587	177.5633	473	-
8	10839	2326	847	861	-38.2586	177.561	483	-
8	10840	2845	-	-	-38.2582	177.5596	484	-
8	10841	864	1970	2743	-38.2577	177.5572	506	-
8	10842	840	-	-	-38.2569	177.5557	470	-
8	10843	4051	2302	3873	-38.2565	177.5544	480	3
8	10844	3939	-	-	-38.2559	177.5526	473	-
8	10845	3967	755	2981	-38.2556	177.5502	468	-
8	10846	3796	-	-	-38.2535	177.5461	477	-
8	10847	2684	2769	1673	-38.2521	177.5449	479	-
8	10848	2943	-	-	-38.2513	177.5437	484	-
8	10849	3836	3676	1779	-38.2508	177.5421	483	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
8	10850	2746	-	-	-38.2498	177.5408	495	-
8	10851	2579	2698	2891	-38.2485	177.54	502	-
8	10852	2618	-	-	-38.2476	177.5388	502	-
8	10853	3925	715	3706	-38.2465	177.5376	515	-
8	10854	2556	-	-	-38.2454	177.5369	515	-
8	10855	2089	3882	799	-38.2439	177.5362	522	-
8	10856	2081	-	-	-38.2427	177.5353	552	-
8	10857	2172	2574	2243	-38.2407	177.534	570	-
29	12901	3866	-	-	-38.2411	177.5412	565	5
29	12904	2759	-	-	-38.2373	177.5442	613	-
29	12907	1849	-	-	-38.2341	177.5456	672	-
29	12910	1967	-	-	-38.2313	177.5486	712	-
29	12913	3638	-	-	-38.2306	177.5533	734	-
29	12916	1625	-	-	-38.2271	177.5546	719	-
29	12919	1630	-	-	-38.2235	177.5534	738	-
29	12922	3973	-	-	-38.2203	177.5547	727	-
29	12925	1728	-	-	-38.2177	177.5574	709	-
29	12928	1952	-	-	-38.2134	177.5582	733	-
29	12931	1110	-	-	-38.2114	177.5592	771	-
29	12934	742	-	-	-38.2078	177.5572	778	-
29	12937	2915	-	-	-38.2043	177.5566	744	-
29	12940	2339	-	-	-38.2009	177.5563	735	-
9	10901	4044	4002	1780	-38.1985	177.5558	750	-
9	10902	1853	-	-	-38.1974	177.5549	744	-
9	10903	1709	2469	1619	-38.1962	177.5526	745	-
9	10904	1922	-	-	-38.1957	177.5519	750	-
9	10905	767	2078	1690	-38.1951	177.55	735	-
9	10906	1877	-	-	-38.195	177.5482	717	-
9	10907	1768	1178	2374	-38.1944	177.5466	721	-
9	10908	3996	-	-	-38.1948	177.5445	709	-
9	10909	3789	-	-	-38.1955	177.5409	711	-
9	10910	4032	-	-	-38.1953	177.5391	700	-
9	10911	4082	1863	2214	-38.1946	177.5382	673	2
9	10912	2982	-	-	-38.1932	177.536	648	-
9	10913	2249	3613	1614	-38.1915	177.5355	582	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
9	10914	3595	-	-	-38.1913	177.5345	634	-
9	10915	2170	1664	4077	-38.1911	177.5329	616	-
9	10916	4085	-	-	-38.1904	177.5299	587	-
9	10917	2727	746	1591	-38.1905	177.5282	608	-
9	10918	1526	-	-	-38.1895	177.5266	621	-
9	10919	2916	1628	2726	-38.1892	177.5257	621	-10
9	10920	1646	-	-	-38.1884	177.5242	641	-
9	10921	2804	3920	3951	-38.1876	177.5227	596	2
9	10922	1962	-	-	-38.1866	177.5213	620	-
9	10923	3963	2738	820	-38.1855	177.5204	620	-
9	10924	3948	-	-	-38.1846	177.5188	619	-
9	10925	3852	2621	3660	-38.184	177.5179	607	-2
9	10926	1670	-	-	-38.1827	177.5162	594	-
9	10927	3804	1644	2393	-38.1822	177.5155	598	-
9	10928	3602	-	-	-38.1831	177.5124	548	-
9	10929	671	3830	2120	-38.1792	177.5135	599	-
9	10930	2433	-	-	-38.1782	177.5135	597	-
9	10931	2087	3942	2536	-38.1768	177.5117	537	-
9	10932	2360	-	-	-38.1754	177.5111	514	-
9	10933	3633	981	1049	-38.1733	177.512	464	-
9	10934	2592	-	-	-38.1706	177.5124	484	-
9	10935	1264	3980	1988	-38.1709	177.5099	507	-
9	10936	2242	-	-	-38.165	177.5142	461	-
9	10937	2316	3966	4043	-38.1627	177.5144	509	-
9	10938	2097	-	-	-38.1613	177.5133	491	-
9	10939	2598	1573	1708	-38.1595	177.5131	541	2
9	10940	1950	-	-	-38.1576	177.5132	504	-
9	10941	1921	3818	4040	-38.1557	177.513	579	10
9	10942	1204	-	-	-38.1543	177.5126	549	-
9	10943	779	1046	3999	-38.1542	177.5103	642	-
9	10944	1669	-	-	-38.1531	177.509	639	-
9	10945	3883	1775	2181	-38.1523	177.508	639	-
9	10946	2176	-	-	-38.1506	177.5075	575	-
9	10947	1695	2418	1589	-38.148	177.5083	596	-21
9	10948	1992	-	-	-38.1465	177.5077	589	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
9	10949	2643	3601	2048	-38.1446	177.5073	600	21
9	10950	1810	-	-	-38.1429	177.5073	626	-
9	10951	966	1015	1617	-38.141	177.5062	628	2
9	10952	1151	-	-	-38.1403	177.5049	626	-
9	10953	2211	775	2231	-38.1394	177.5033	678	2
9	10954	992	-	-	-38.139	177.5015	610	-
9	10955	1796	2897	2235	-38.1384	177.5003	565	-
9	10956	1603	-	-	-38.1398	177.4965	478	-
9	10957	2761	3903	2558	-38.1389	177.4954	615	-
9	10958	3993	-	-	-38.138	177.4941	526	-
9	10959	1612	2011	2322	-38.1339	177.497	526	-2
9	10960	1915	-	-	-38.1221	177.5079	374	-
9	10961	2833	2502	1682	-38.1269	177.5069	379	-
9	10962	3812	-	-	-38.1187	177.5071	374	-
9	10963	4072	1308	1885	-38.1165	177.5072	383	-
9	10964	1801	-	-	-38.1149	177.5065	384	-
9	10965	1019	2750	975	-38.1133	177.506	380	-
9	10966	3008	-	-	-38.1105	177.5072	361	-
9	10967	4092	4066	1703	-38.1088	177.5066	350	-
9	10968	1161	-	-	-38.1078	177.5056	349	-
9	10969	1147	4157	3718	-38.1072	177.504	376	-
9	10970	2189	-	-	-38.107	177.5021	378	-
9	10971	3979	2854	1980	-38.1065	177.5004	376	-
9	10972	1941	-	-	-38.1058	177.4995	413	-
9	10973	2549	2801	2377	-38.105	177.4972	358	-
9	10974	3695	-	-	-38.1037	177.4968	392	-
9	10975	1795	2925	1869	-38.1028	177.4952	387	-10
9	10976	2225	-	-	-38.1036	177.4918	372	-
9	10977	1623	732	1774	-38.1029	177.4904	412	-10
9	10978	1764	-	-	-38.102	177.4898	448	-
9	10979	2367	2913	4061	-38.1012	177.4877	384	-
9	10980	718	-	-	-38.1007	177.4863	391	-
9	10981	2160	1085	2368	-38.0993	177.4857	391	-
9	10982	3821	-	-	-38.0974	177.4856	379	-
9	10983	1704	3820	2228	-38.095	177.4857	397	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
9	10984	2344	-	-	-38.0933	177.4856	396	-
9	10985	2839	3731	1572	-38.0904	177.4863	472	-
9	10986	2312	-	-	-38.091	177.4835	515	-
9	10987	2737	4020	3974	-38.0905	177.482	396	-
9	10988	1897	-	-	-38.0903	177.4801	390	-
9	10989	2624	2159	2512	-38.0882	177.4796	358	-
9	10990	3620	-	-	-38.0876	177.4784	451	-
9	10991	2279	2519	2148	-38.0864	177.4773	307	-
9	10992	2240	-	-	-38.0845	177.4774	303	-
9	10993	1884	1032	845	-38.0827	177.4775	288	-
9	10994	1771	-	-	-38.081	177.4763	259	-
9	10995	2677	1969	2518	-38.0797	177.4763	208	-
9	10996	701	-	-	-38.0783	177.4753	188	-
9	10997	1655	1528	1626	-38.0769	177.4741	229	-
9	10998	2494	-	-	-38.0753	177.4737	201	-
9	10999	4079	2806	3701	-38.074	177.4733	191	-
9	11000	3737	-	-	-38.072	177.4732	167	-
9	11001	749	1602	1740	-38.0716	177.4716	192	-
9	11002	1927	-	-	-38.0707	177.47	184	-
9	11003	2599	4027	1048	-38.0685	177.4701	181	-
9	11004	856	-	-	-38.0671	177.4692	157	-
9	11005	2127	1582	3962	-38.0666	177.4672	153	-
9	11006	2812	-	-	-38.0659	177.4667	111	-
9	11007	763	1186	1557	-38.064	177.4659	183	-
9	11008	1581	-	-	-38.0628	177.4657	102	-
9	11009	1210	2446	2570	-38.0618	177.4643	110	-
9	11010	2077	-	-	-38.059	177.4648	107	-
9	11011	860	2203	2475	-38.0587	177.4628	77	-
9	11012	1205	-	-	-38.058	177.4615	85	-
9	11013	3971	744	1037	-38.0568	177.4605	99	-
9	11014	771	-	-	-38.0557	177.4597	78	-
9	11015	2161	2642	2066	-38.0545	177.4577	123	-
9	11016	1270	-	-	-38.0535	177.4568	72	-
9	11017	2690	2327	2472	-38.0523	177.4593	160	-
9	11018	4026	-	-	-38.0511	177.455	92	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
9	11019	1653	2735	3727	-38.0519	177.4525	105	-
9	11020	4070	-	-	-38.0518	177.4506	97	-
9	11021	2220	3617	3910	-38.0497	177.4492	91	10
9	11022	1266	-	-	-38.0478	177.4501	81	-
9	11023	2712	2277	1973	-38.0467	177.4495	81	-
9	11024	1111	-	-	-38.0459	177.4476	71	-
9	11025	1896	2832	2402	-38.0447	177.4469	53	-10
9	11026	803	-	-	-38.0439	177.4455	54	-
9	11027	2238	1766	2372	-38.0428	177.4447	75	-
9	11028	2578	-	-	-38.0412	177.4444	69	-
9	11029	2538	4046	3940	-38.0396	177.4436	87	-
9	11030	2895	-	-	-38.039	177.4421	82	-
9	11031	3922	4064	1637	-38.0375	177.4414	55	-
9	11032	1752	-	-	-38.0335	177.4432	56	-
9	11033	1761	1714	4058	-38.033	177.4413	58	-
9	11034	1150	-	-	-38.0318	177.4407	67	-
9	11035	2666	3745	2275	-38.0294	177.4409	59	-
9	11036	2715	-	-	-38.0283	177.4407	50	-
9	11037	685	1805	2457	-38.0269	177.4395	29	-
10	11101	787	2646	1194	-38.0207	177.4411	40	-
10	11102	2202	-	-	-38.0197	177.4407	55	-
10	11103	2369	2687	716	-38.0186	177.4402	98	-
10	11104	1836	-	-	-38.017	177.4392	99	-
10	11105	1203	672	3779	-38.0158	177.4384	93	-
10	11106	2522	-	-	-38.0143	177.4377	87	-
10	11107	1311	961	1154	-38.0135	177.4363	80	-
10	11108	4075	-	-	-38.0133	177.4347	76	-
10	11109	2867	3747	3822	-38.0126	177.433	70	-7
10	11110	2331	-	-	-38.0117	177.4317	52	-
10	11111	1588	2560	1183	-38.0106	177.4304	51	-
10	11112	758	-	-	-38.0095	177.4294	61	-
10	11113	2264	3802	879	-38.0087	177.4278	58	-
10	11114	2647	-	-	-38.0082	177.4262	60	-
10	11115	2359	2409	2749	-38.0079	177.4248	51	-
10	11116	2413	-	-	-38.0076	177.4228	57	-

Line	Site Number	T-V	T-N	T-E	Latitude	Longitude	Elev. (m)	Sensor Orientation
10	11117	2614	2860	2248	-38.0071	177.4205	56	-
10	11118	2150	-	-	-38.0074	177.4187	40	-
10	11119	2814	3766	2162	-38.0066	177.4166	16	-
10	11120	2510	-	-	-38.0056	177.4161	30	-
10	11121	3675	2458	4076	-38.0161	177.4063	22	-
10	11122	2859	-	-	-38.0151	177.4044	15	-
10	11123	702	2611	1987	-38.0146	177.4029	31	-
10	11124	1691	-	-	-38.014	177.4012	39	-
10	11125	1120	1843	2696	-38.0133	177.3994	25	-
10	11126	2762	-	-	-38.0121	177.3985	13	-
10	11127	3862	4053	2577	-38.0107	177.3983	31	-
10	11128	3774	-	-	-38.0093	177.3977	16	-
10	11129	1609	2144	2269	-38.0078	177.3966	19	-
10	11130	3893	-	-	-38.0059	177.3961	12	-
10	11131	724	1784	2221	-38.0044	177.3959	11	-
10	11132	3590	-	-	-38.0016	177.3976	17	-
10	11133	2693	2539	4073	-37.999	177.3977	11	10
10	11134	2093	-	-	-37.9982	177.3964	8	-
10	11135	2115	2699	2111	-37.9972	177.395	10	-
10	11136	1867	-	-	-37.9969	177.3945	10	-
10	11137	3725	1552	1718	-37.9955	177.3923	8	-
10	11138	1918	-	-	-37.9956	177.3898	8	-
10	11139	782	2417	2924	-37.9941	177.3898	9	-
10	11140	2566	-	-	-37.9917	177.3886	9	-
10	11141	3674	1616	3664	-37.9896	177.3898	6	-

APPENDIX 7 SITE ISSUES AND PROBLEMS

A7.1 General Site Design and Issues

A7.1.1 Fencing

For site set-up (see Section 2.4.2.3), two methods of fencing were employed by teams during deployment:

- Driving waratahs at the four corners of a polygon enclosure and then stretching fence around the corners, tightening, stretching and securing each side with wire in turn.
- Threading waratahs through fencing, arranged at corners of a square enclosure, and driving them into the ground.

Method 2 was thought to be quicker and more efficient by some deployment teams. Although this method meant that the fencing could not be pushed or pulled away from the waratahs, it did not stop the enclosure fence being breached by cattle. In general, Method 1 seemed to provide tighter fences that were more secure and required less repair. In general, this method is standard practice on most farms in the region.

A distance of 1–1.5 m between waratah posts was used at most sites (typically measured by the waratah length itself). This provided enough strength and tension in the fence for most sites. 1.3 m waratahs were used for most sites. Fencing wire was ~0.9 m high, so there was no need for longer waratahs, and previous experience in the SAHKE project showed that waratahs driven deeply into the ground were difficult to remove, even with waratah pullers. Waratah pullers were utilised for SHIRE and come highly recommended to speed up site removal and avoid the need to re-visit sites if fences cannot be removed manually.

There was some effort to make sure that the sensor was a small distance, i.e. ~0.5–1 m, apart from the PASSCAL-supplied quick deploy boxes (QDS; see Section 2.4.2.3) so that we could minimise any potential noise sources. However, to minimise the fence size, this often meant that the QDS box was positioned close to the perimeter of the fence. This sometimes resulted in stock being able to reach the solar panel. See site-specific problems at Sites 575 and 722, for example.

It was also noted that, in paddocks with large numbers of stock present, connecting the station to an existing fence made deployment easier (could be just three-sided) and tended to be less affected by stock. At sites where this was not possible, due to landowner request or GPS requirements, future projects could consider adopting sturdier and larger fences (see 722 site issues below).

Figure A7.1 Examples of SHIRE site fencing. a) Site 714; waratah enclosure fencing adjoining existing fence and deployment of QDS box. A tarpaulin was used in front of the solar panels and was effective for keeping down vegetation growth. Tarpaulins were not deployed at all sites, and no power loss was attributed to blocked solar panels. b) Site 595; stock have bent the fencing slightly, but it is largely intact. Note how the fencing wire is tucked into the top hook on the waratah to minimise sagging and prevent the wire from sliding down. c) Site 715; isolated fencing enclosure. Extra waratahs and a non-rectangular shape used to increase strength and distance between fence and solar panel.

Figure A7.2 Managing vegetation growth at sites. a) Site 716 showing the effects of the tarpaulin to keep vegetation growth down. b) Extreme summer growth at Site 505 required extra tarpaulins.

A7.1.2 Animals

Cattle were the main problem for SHIRE sites. We did not see any evidence that goats took any interest in or damaged any of the sites, in spite of seeing many wild goats throughout the scouting and deployment. Horses were tall enough to reach into the fences, and, in the sites where this occurred (714 and 531), it was found to be no issue, as they simply ate the grass around the equipment. Cattle, and especially bulls, were more problematic, as they used the waratahs as scratching posts and were keen to chew through wire. In future projects in regions where cattle are present, site selection should take this into account and consideration should be given to moving the site, if possible, or to creating a larger site footprint coupled with the use of sturdy fencing to protect equipment from the reach of animals.

The QDS boxes used in SHIRE I were water-tight and very efficient to deploy. However, the water-tight seals did not prevent insects and spiders from getting inside the cases. Cockroaches, ants and earwigs seemed particularly prevalent in the QDS boxes. Although this did not directly affect the site operation, it took a considerable amount of time and effort to prepare the boxes for return to PASSCAL and meet customs regulation standards (Figure A7.3). A seal on the box and box lining may prevent some difficulty in cleaning, or more-open boxes would be easier to clean in areas where insects are an anticipated problem.

Figure A7.3 Decontaminating the QDS boxes prior to shipping back to PASSCAL. Insects found a home in the QDS boxes during the four-month-long SHIRE I deployment.

A7.1.3 Wind

Many of the sites in the middle of the transect along the Raukumara ranges, and some of the coastal sites, were known windy spots. The low profile of the QDS boxes was robust at most of these sites, and only tightening of straps was necessary for sites during service. However, one coastal site was found knocked over by wind. The weight of the battery held the boxes down at most sites. Boxes could be further pegged down, but this may mean widening the enclosure fence.

A7.1.4 GPS and Disk Problems

As discussed in Section 2.4.2.3, nearly 25% of SHIRE I sites encountered some form of GPS problem during the deployment. Some were fixed, others were intermittent, and some were not remediated. Table A7.1 below lists problems that were flagged during service and demobilisation, as well as any replacement antennae, and whether disks were removed with or without a lock (if known).

Table A7.1 Sites with GPS and disk problems. Only sites with known issues are listed. Red fill indicates locking problem on the order of days, yellow fill indicates hours only. Black box with 'DOA' indicates that the site was not operating on arrival. Sites with timing issues recorded at the service may not have recorded the SHIRE I active source survey properly. Similarly, sites with timing issues at demobilisation may have incorrect timing for the NZ3D active source survey. Where a GPS lock was attained prior to disk removal ('back time stamp'), it may be possible to apply a phase shift correction. The back time stamp is only noted where it is known to have been achieved. Where GPS was changed, or back time stamp achieved, the box is coloured in the respective column.

Station	Last Lock Service	Back Time Stamp	GPS Changed	Last Lock Demob.	Back Time Stamp	Service Disk Problem	Demob. Disk Problem
507	17 days			-	-	-	-
511	-	-	-	22 days		-	-
517	-	-	-	9 hours	-		
519	-	-	-	1.5 hours	-		-
521	46 days	-		-	-	-	-
523	-	-	-	79 days*		-	-
529	32 days	-		-	-	-	-
535	-	-	-	7.5 hours		-	-
547	-	-	-	-	-		-
553	37 days		-	-	-	-	-
555	2 hours	-	-	-	-	-	-
557	12 days	-	-	109 days		-	-
575	51 days		-	DOA	-	-	-
581	-	-	GPS off on arrival?			-	-
587	1+ hour			-	-	-	-
706	-	-	-	9 hours		-	-
711	-	-	-	13 days		-	-
715	-	-		-	-	-	-
718	30 days	-		-	-	-	-
719	27 days	-		-	-	-	-
728	-	-	-	11 hours		-	-
729	-	-	-	-	-	-	
734	-	-	-	2 hours	-	-	-
737	38 days			-	-	-	-
741	9 hours		-	1 hour	-	-	-
743	1+ hour		-	-	-	-	-

* This was the time recorded by the field team but is longer than the prior service visit. Earlier timing may also be affected.

A7.2 Specific Site Problems

Most of the problems listed below are descriptions of why sites may have had trouble or stopped recording. Some are transcriptions of pick-up sheets from the site service.

A7.2.1 Site 557

Fence pushed over, sensor buried ~15 cm below ground, cord below sensor.

A7.2.2 Site 575

Solar panel flat (but facing upward) on arrival at December 2017 service. Ropes had been detached, likely by stock. Site 575 was one of the most remote transect sites and had no cell phone coverage. When it was visited during the December 2017 service, young calves had bent the fence and the station had GPS trouble. The fence was repaired, but not altered otherwise. Its remoteness meant that it was not practical to replace the GPS when spare units arrived. When the site was demobilised, the calves had continued to be interested in the site and had grown significantly, increasing their ability to infiltrate the site. They had chewed through the solar panel power cable. As the team had no spare equipment, they were unable to re-power the site before collection.

Figure A7.4 Site 575. a) Jenny Black with collapsed solar panel at service in December 2017. Fence is relatively small and could have been expanded to further protect the site. b) Solar panel face-up, so battery was still charging.

A7.2.3 Site 708

Box was found tipped over (forward onto solar panel) on arrival at February 2018 pickup. The cause could be wind or stock. The lack of further chewing suggests that it could have been wind, but the fence has also been substantially damaged.

Figure A7.5 Site 708 at February 2018 pickup. a) Site view. b) A closer view.

A7.2.4 Site 721/722

Site 722 was deployed in a field with cattle. At the December 2017 service, the site was found to be severely damaged. The fence and solar panel were also badly damaged. There was a reserve that bordered the paddock, and a decision was made to move the site to the reserve, where the cattle would not be able to damage it. Due to the change of location, although small, this site was renamed 721 to accurately reflect both sets of coordinates for the data archive. The new location was less disturbed but was also within ~1 m of an electric fence.

Figure A7.6 Damage at Site 722 at December 2017 service. a) Fence completely separated from waratahs. b) Closer image, showing damaged solar panel. Solar panel glass was also smashed, probably from being stepped on by the cattle.

A7.2.5 Site 725

Fence was destroyed by a small bull on the property; however, the bull had not touched the equipment. It appeared to have been motivated by the long grass that had grown up inside the fence. The site was still running and, apart from the fence, nothing else seemed to be damaged.

A7.2.6 Site 728

Although the fence was strengthened, and the site intact, the farmer had built a sturdier fence around the station at some point that was present when the team went to pick it up in February 2018. The team noted that the sensor was outside of the new fence, so it may have been subject to animals walking directly on it.

A7.2.7 Site 729

Acquisition OFF on arrival. RAM full. Disk 1 causing problems? Disk 1 removed. RAM written to Disk 2 (4 MB).

APPENDIX 8 IN-FIELD MAPPING APPLICATION

This section contains two documents that were created to help the field team download and use the OSM+ phone application for maps and GPS locations. During SHIRE II, the app was mostly used to locate sites, but a few teams also used it to record locations. We recommend uptake of this method in the future, as it was an easy way to check hand-recorded metadata and was easier to download than the gpx files from the handheld GPS units. The handout below describes the download and set-up (map acquisition) of the application; the next document describes its use in the field.

Installing and setting up OsmAnd+

The app is free and opensource, and if you install it on android via f-droid (see below) you get the full open source version giving you unlimited maps (across the world) and contours lines for NZ. It uses Open Street Map mapping (https://www.openstreetmap.org/).

OsmAnd+ works off-line, but you need an internet connection to install it, download the maps and install plugins (steps 1-4 below).

1. Download and install f-droid - https://f-droid.org/en/

f-roid allows you to install free and open source apps on your android phone. You will need to chose "allow" to allow the app to download to your phone.

2. Install OsmAnd+ from the f-droid app

You will need to chose "allow" to allow the app to download to your phone.

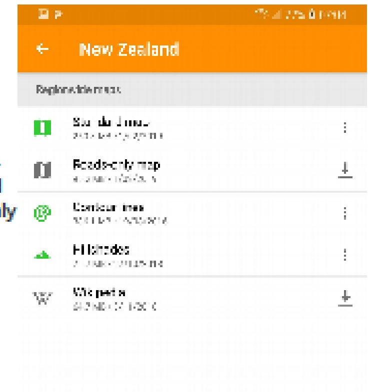
For more info see: https://f-droid.org/en/packages/net.osmand.plus/

Once it is installed, run OsmAnd+. It will probably prompt you to donwload the map, you can do this now, or skip it and follow the steps below.

3. Install plugins

From the hamburger menu (bottom left), hit "Plugins" and choose "Contour Lines" to facilitate display of contour lines and hillshades (this will take a minute or two to install), then "Trip Recording".

4. Download maps for NZ



Run the OsmAnd+ app, hit the hamburger menu (bottom left) and choose "Download maps", it will have a look for all the possible maps, then give you a list of them sorted by region.

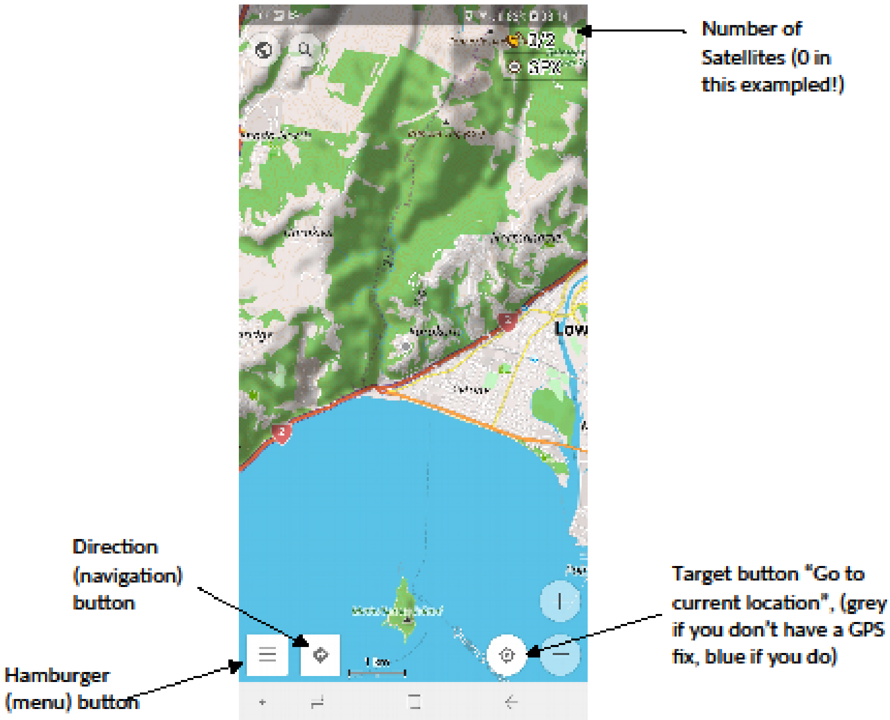
From the "ALL DOWNLOADS" tab choose: "Australia and Oceania" then "New Zealand" and download the "Standard map", "Contour lines" and "Hillshades". These will each take a ~10 minutes to install (depending on your internet speed), and total 712MB. If you have limited space on your phone, then only install the standard map (contour lines and hillshades are not essential, but nice).

If "Contour lines" does not have a download button next to it, close the app and start it again.

From now on, you can do everything you need off-line.

5. Configure OSMAND+

From the hamburger menu, choose "configure screen", scroll down and add "GPS info" and "altitude" (this will add info to the top right of your screen, telling you the number of satellites you can see, and once it has a fix, the altitude).



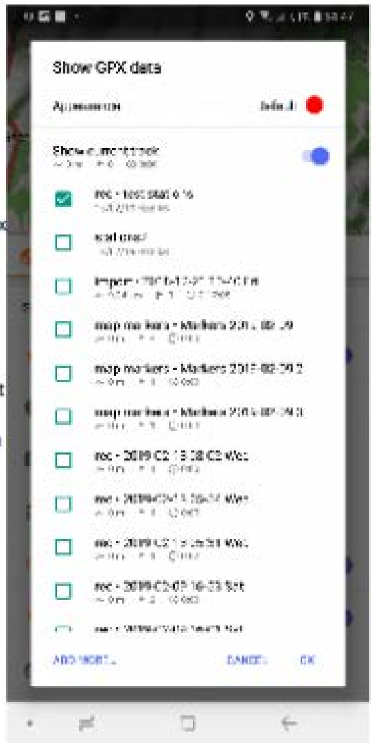
Using OsmAnd+ in the field

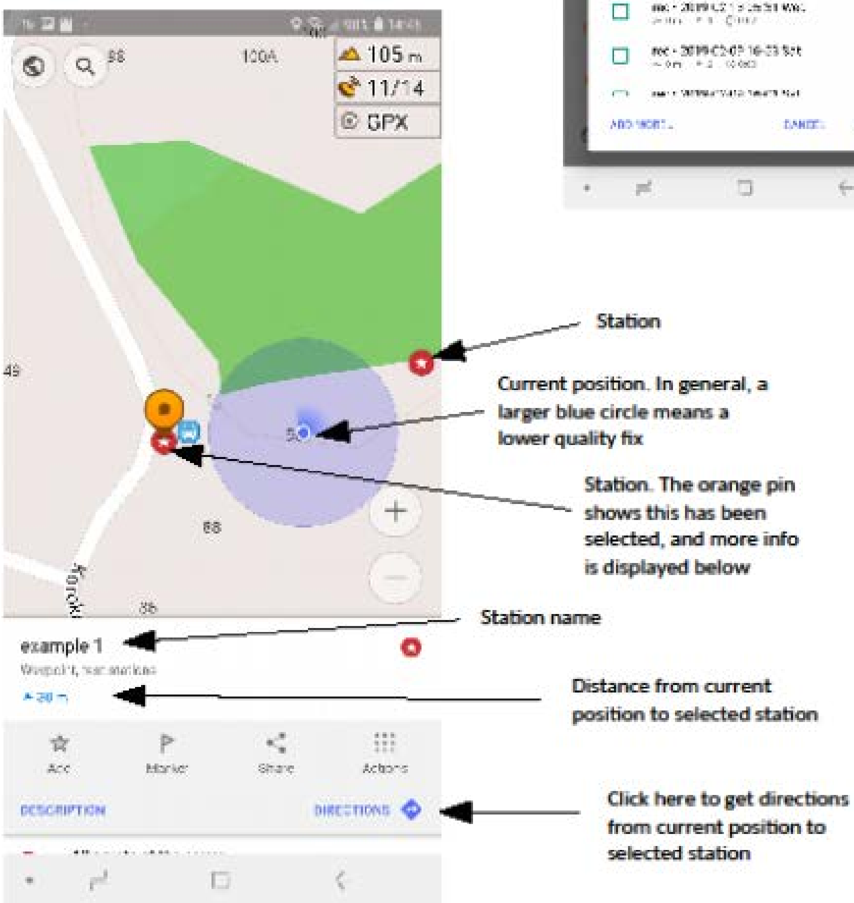
Load in station locations

Copy gpx file of station locations to your phone (e.g. via USB cable, email, etc). You can choose to put it anywhere on the phone, but OsmAnd+ will find it automatically if you put it in: Phone/Android/data/net.osmand.plus/files/tracks/rec/

Display your new gpx file on the map: from the hamburger menu (bottom left) choose "Configure map" then "GPX files…". Your gpx file should be at the bottom of the list (if you saved it somewhere else, hit "ADD MORE..." and navigate to where it is). Press the box to the left of the file to turn it on (a tick means it will be displayed on the map).

The stations will be marked by a white star in a red circle. If you click on a station you will see the station name and the distance it is away from you. If you hit "Directions" you can navigate form your current location to the station, either by roads (if the car icon is orange), or on foot (if the person icon is orange).





Create a waymark for a new station

Check you have good satellite coverage (ideally >10 satellites, displayed at top right)

Hit the target button to zoom to your current location (bottom right)

Click on the blue triangle/circle (i.e. your current position)

A pop up will appear at the bottom of the screen saying "My position". If you are close to other waypoints, they will also appear in the list. Your current location is called "My position" and has a little blue dot on the right.

Click on the "My position" pop up and you will see your location in lat/long. You can also hit the share button to copy it to the clipboard if you want to paste it in to anything.

Click "Actions", "Add GPX waypoint" and select "Currently recording track", edit the station name and hit "save". Your point should appear on the map.

DO NOT create the waypoints with "Add" or "Marker, neither of these write both the station name and timestamp to the final file.

At the end of the day, hit the "GPX" button (top right) and "save current track". It doesn't matter if you do this multiple times in the day, you will just get multiple files.

The file can be found it Phone/Android/data/net.osmand.plus/files/tracks/rec/[year]-[month]-[day]-[hour]-[min]-[day].gpx

This can be imported to qgis as a vector file, choosing "waypoints".

APPENDIX 9 OUTREACH MATERIALS

This section contains three handouts that were used to distribute information to landowners, stakeholders and community members. The first and third handouts were designed to match an existing IODP Hikurangi series produced by GNS Science. The second handout is less formal and was designed to be used during the scouting to give landowners of potential explosion sites more information about the project and our contact details.

Ka āla te papaneke moana o Te Moana-nui-a-Kiwa ki raro tonu i papaneke paparahi o Te Pāpaka-a-Māui ki te paenga papaneke o Hikurangi, ki waho nei i te moana o Te Tai Rāwhiti. He āinga whakararo taua rohe. Nā te āinga whakararo e pērā ana ko tētahi momo hapa, ā, he nui ngā rū whenua me ngā tai āniwhaniwha ka hua ake, pērā me Sumatra i te tau rua mano mā whā, pērā me Hiri i te tau rua mano mā tekau, pērā hoki me Hapani i te tau rua mano tekau mā tahi. Ka whakamahia ngā tirohanga rū whenua e te whakatakanga rangahau o Hikurangi Subduction Earthquakes and Slip Behaviour ki te whai mārama i tēnei ripa hapa kia taea ai e ngā hapori o Te Tai Rāwhiti te whakarite i te pai.

The Hikurangi plate boundary, off the East Coast of New Zealand's North Island, is where the Pacific tectonic plate dives beneath the Australian plate. This boundary is called a subduction zone. Subduction zones develop a type of fault that are responsible for the largest and most powerful earthquakes and tsunamis in the world, such as Sumatra 2004, Chile 2010, and Japan 2011. The Hikurangi Subduction Earthquakes and Slip Behaviour research project will use seismic surveys to understand this large fault, so local communities can be better prepared.

WHY USE SEISMIC SURVEYS AS A TOOL FOR SCIENCE?

The only way to determine which sections of the subduction zone are more prone to large earthquakes is by collecting detailed images of layers beneath the seafloor using sound waves. These seismic images reveal the internal structure of the Hikurangi subduction zone fault off the East Coast - allowing us to understand the processes that control earthquakes and tsunamis. Seismic surveys complement the data collected from scientific drilling and evidence of older earthquakes and tsunamis onshore.

THE HIKURANGI SEISMIC SURVEYS

The U.S. Marcus G. Langseth (R/V Langseth) is specially designed to conduct the Hikurangi seismic surveys. The vessel tows an array of individual sound sources that are tuned and combined to radiate a sound wave downward to the seafloor. These sources expel compressed air from cylindrical chambers – a bit like inflating and collapsing a large balloon.

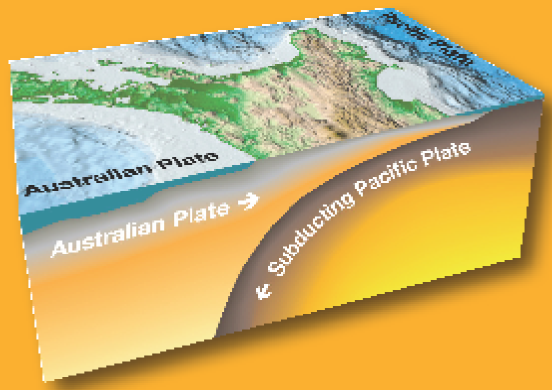
The sound source is generated approximately every 50 m along a ship track (i.e. once every 20–30 seconds). The echoes that bounce back from layers in the earth are recorded on a streamer towed behind the vessel and on sensitive seismographs located onshore and on the seabed. Scientists process all the recorded echoes to construct an image, like a medical sonogram, of the layers within the earth.

WHAT PRECAUTIONS WILL BE TAKEN TO PROTECT MARINE ANIMALS?

Mitigation strategies will exceed internationally accepted standards and are based on input from marine mammal and fish science experts. The surveys will comply with all regulations, including the U.S. Marine Mammal Protection Act, U.S. Endangered Species Act, and NZ's Department of Conservation's *Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Operations* (see More information below). Protection strategies include:

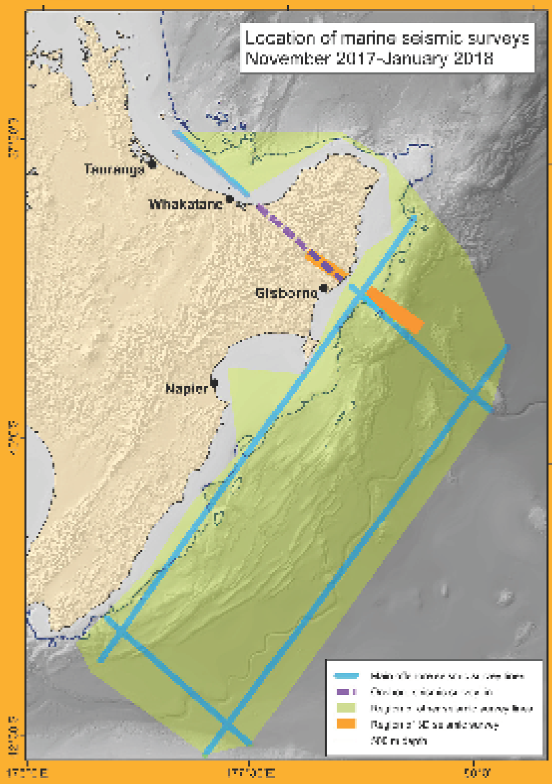
1. At the beginning of each survey the sound source will be increased very slowly over a period of thirty minutes, giving animals time to move away from the area if disturbed.
2. Qualified marine mammal observers will be on board to continuously record species occurrence, abundance, and behaviour, and to give the alert to stop the survey if a marine mammal enters the exclusion zone.
3. A Passive Acoustic Monitoring (PAM) system will operate 24 hours a day during the survey. PAM is a combination of sophisticated listening devices and computer software to filter and identify marine mammal noises. It listens for vocalisations of marine mammals so the sound source can be immediately shut down if necessary.
4. The R/V Langseth and other research vessels have completed more than a decade's worth of academic/government seismic surveys without any marine mammal stranding or disruption to fishing.

Loud noise is known to cause behavioural responses in marine mammals, and could potentially result in physical harm if an animal was close enough to the seismic source. Therefore, an exclusion zone is constantly monitored and the source is immediately shut down if animals are seen close.

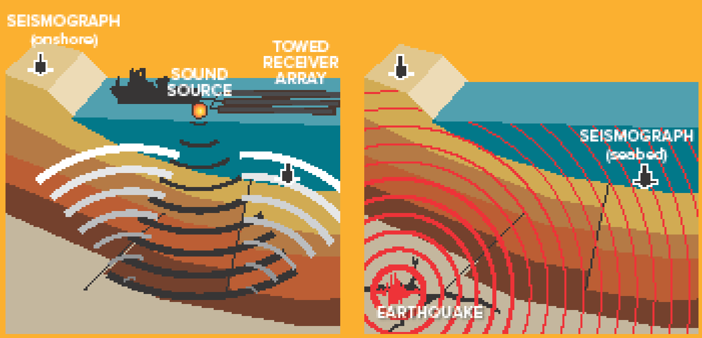


Slice through the North Island of New Zealand showing the Pacific tectonic plate diving beneath the Australian plate. The contact between these plates is called the Hikurangi subduction zone fault.

IMAGE BY DARREN D'CRUZ, GNS SCIENCE.



Map of the East Coast of NZ's North Island showing the location of the seismic surveys planned for November 2017 to January 2018. The onshore seismic survey line indicates the location of seismographs that will be installed to record marine sound sources and naturally occurring earthquakes.



The marine seismic survey (left) involves a sound source and a towed array of sensors which record waves that have bounced off sub-surface layers. Onshore and seabed seismic instruments record the boat's sound source as well as naturally occurring earthquakes (right)

IMAGES BY DARREN D'CRUZ, GNS SCIENCE.

WHEN AND WHERE WILL THE HIKURANGI SEISMIC SURVEYS HAPPEN?

The seismic data will be collected offshore of the East Coast of the North Island and Bay of Plenty in late 2017, and then collected in a small region offshore Gisborne in early 2018. Onshore, there will be land stations (seismographs) in a line from Opotiki to Gisborne from November 2017 to March 2018. Seismographs are highly sensitive measuring devices which will collect data from marine seismic surveys and local earthquakes.

DO SEISMIC SURVEYS CAUSE EARTHQUAKES?

No. The sound and energy sent to the seafloor could not trigger an earthquake, as they do not have enough energy to affect the stresses in the Earth's crust, which are the forces that cause earthquakes. As a comparison, the sound emitted during these scientific seismic surveys is less than the sound made by a lightning strike on the sea surface.

WILL THE DATA COLLECTED BE AVAILABLE TO THE PUBLIC?

Yes. The data collection will be complete early in 2018 and then analysed. Reports and data will be available in public archives in the U.S, New Zealand and the U.K in mid to late 2019.

WHO IS FUNDING THIS WORK?

The Hikurangi seismic data collection is funded by the U.S. National Science Foundation (NSF) and the Natural Environment Research Council (NERC), and will involve scientists from universities in the US, Japan, U.K, and New Zealand. New Zealand scientist participation is supported by funding from the Ministry of Innovation and Employment (MBIE) Endeavour Fund - the *Hikurangi Subduction Earthquakes and Slip Behaviour Research* project. The Hikurangi seismic project is not associated with or funded by any oil exploration company.

MORE INFORMATION

To read more about the Department of Conservation's Seismic Code of Conduct:
www.doc.govt.nz/our-work/seismic-surveys code-of-conduct

For more information on administration of the U.S. Marine Mammal Protection Act and Endangered Species Act visit:
www.nmfs.noaa.gov/pr/laws/mmpa/ and
www.nmfs.noaa.gov/pr/laws/esa/

For more information on this project visit:
www.gns.cri.nz/hikurangi

CONTACT

If you have questions please email:
hikurangi.surveys@gns.cri.nz

INSTITUTE FOR GEOPHYSICS

Imperial College London

USC University of Southern California

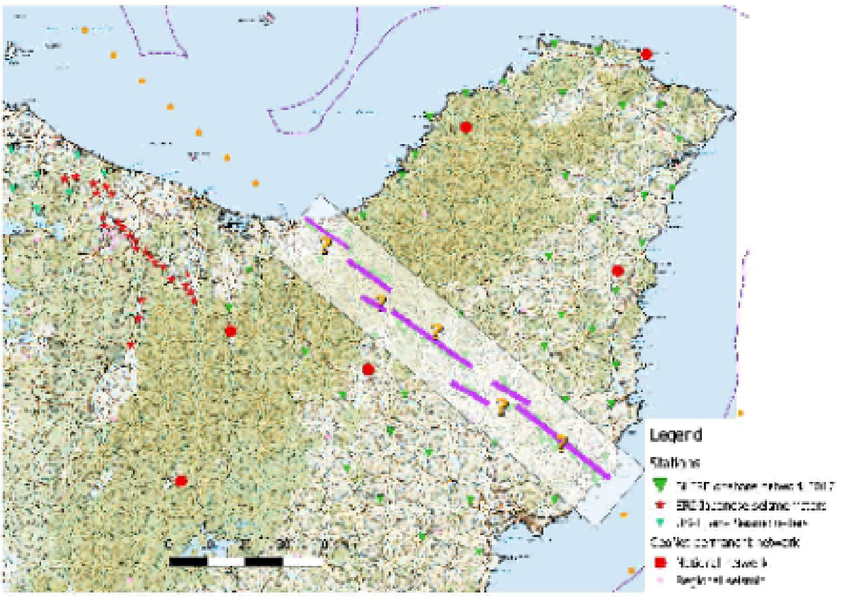
The Shire Project

MECHANICS OF AN EARTHQUAKE ENGINE

SHIRE: Seismogenesis at Hikurangi Integrated Research Experiment

This project is part of several large research projects working to better understand the Hikurangi subduction zone that lies off the East Coast of the North Island. This is where the Pacific tectonic plate subducts (or moves) under the Australian tectonic plate. Scientists are trying to learn more about the structure of the subduction zone will learn more about the structure to find out more about how these two tectonic plates behave as they move past each other

Part 1. October 2017-February 2018	Part 2 October 2018 and February 2019
The seismometers out during that time recorded local, regional, and teleseismic earthquakes in addition to sound energy from a ship offshore. This allowed scientists to image the deeper structures associated with the subduction zone in this region of New Zealand.	A line of seismometers will record signals from controlled underground explosions . This data will allow scientists to produce a high-resolution image of the shallow structures, such as faults, zones of stress build-up, and zones of weakness, within the region.



What does this research involve? Scientists will be installing around 1000 seismometers stations roughly every 150 meters in a line between Gisborne and Opotiki. These instruments will record energy waves provide by controlled underground explosions at locations across the Raukumara Peninsula (similar to those used in quarry and forestry operations). Data obtained from these stations will allow accurate models of the material and structures to be produced as both time and location of the source is known

Why this region? The region along the East Coast of the North Island from Hawke's Bay up through Gisborne and north to Te Araroa hosts slow slip events (SSEs) in addition to regular earthquakes. Slow Slip Events have motion similar to earthquakes but happen over weeks to months instead of the seconds to minutes of earthquakes. Because they happen so slowly they can't be felt and are only recorded by continuous position monitoring using GPS technology. Slow Slip Events do not occur off the Wairarapa coast and scientists want to understand why these regions behave so differently and whether that means that the regions have different hazards for future large earthquakes. GNS Science undertook a similar experiment in the lower North Island in 2010 and 2011. Data collected from this experiment will be used to contrast to the data gathered in the Wairarapa and Kapiti regions. The image this new data will provide will help us to determine rock properties beneath Gisborne and Opotiki and help us to better understand the connection between slow slip events and large earthquakes on the Hikurangi plate boundary subduction zone. Improved mapping of the material and structures of this region will also allow us to more accurately locate earthquakes and improve future hazard models.

What will the data collected show? The data recorded at the stations will provide a large amount of information regarding the about the rocks through which the energy travelled between controlled underground explosions and the station. The structural and rock property information is also important for building up more reliable earthquake shaking and tsunami models. This information can be used to create a "CAT-scan" like image to help locate subsurface faulting, rock boundaries, and regions of high stress.

Controlled detonations of underground land-based explosions

Where will the explosions occur? The controlled detonations of land based explosions will occur at five pre-identified locations across the Raukumara Peninsula. At each site a borehole will be drilled 40-60m below the ground to place the explosives into. The exact depth is dependent on the geology at each site. The locations of seismic boreholes are chosen with care and must meet this criteria:

1. Have minimal impact on local communities and be as far as possible from buildings, man-made structures and steep tomography (minimum 1 km)
2. Be accessible by a 3-axle truck as a truck is needed for both drilling and loading explosives

Why use explosives?

The explosives act like a small earthquake and release waves of energy. Scientists want to learn how these waves travel through solid, unfractured rock, known as bedrock. This experiment will provide scientists with information about the rocks through which the energy travelled between the blast and the sensor and will help to understand more about the Hikurangi subduction zone. Earthquakes can also be used to do these kinds of studies. Explosions have two main advantages over earthquakes 1) We can control and know the exact time and place of the energy. While we can roughly determine the location of an earthquake, how well we know that location is dependent on how well we know the material between where it happened and where it was recorded. For an explosion we know the exact time and choosing the location allows us to study a particular region of interest rather than relying on where an earthquake happens to occur. 2) Because we cannot predict when an earthquake will occur we cannot put out stations ahead of time to record it. There is a national network (https://www.geonet.org.nz/data/network/sensor/map) of stations, but to determine smaller scale structures we need a much denser array of recorders. It is not practical to put out dense arrays in hopes of catching an earthquake, except in exceptional circumstances such as recording aftershocks of a large earthquake.

Who will be managing the detonations?

A fully trained team will manage the entire detonation process including health and safety. These will be qualified explosive professionals and they will comply with all legal requirements including council consents and health and safety legislation.

When will the explosions occur?

The detonation of the shots will take place at night, as the road traffic and other noise sources are at a minimum allowing 'clean' signal to be recorded at each station. Blasting will occur either on the hour mark or the 30 min mark at various times during the night. There will be five explosions total and they will happen over the course of several nights.

Will we hear or feel the explosions?

The shots are designed to move downwards so that the energy ends up in the ground. The further away you are to the shot the least likely you are to feel it. For example, if you were standing within a few 100m you would feel the vibration of the explosion and a booming sound but if you were standing 2km the experience might be similar to a truck was driving past. Atmospheric and weather conditions also contribute to how far sound from the explosion will travel. The sound might be heard 10-20 km away but at a relatively low volume.

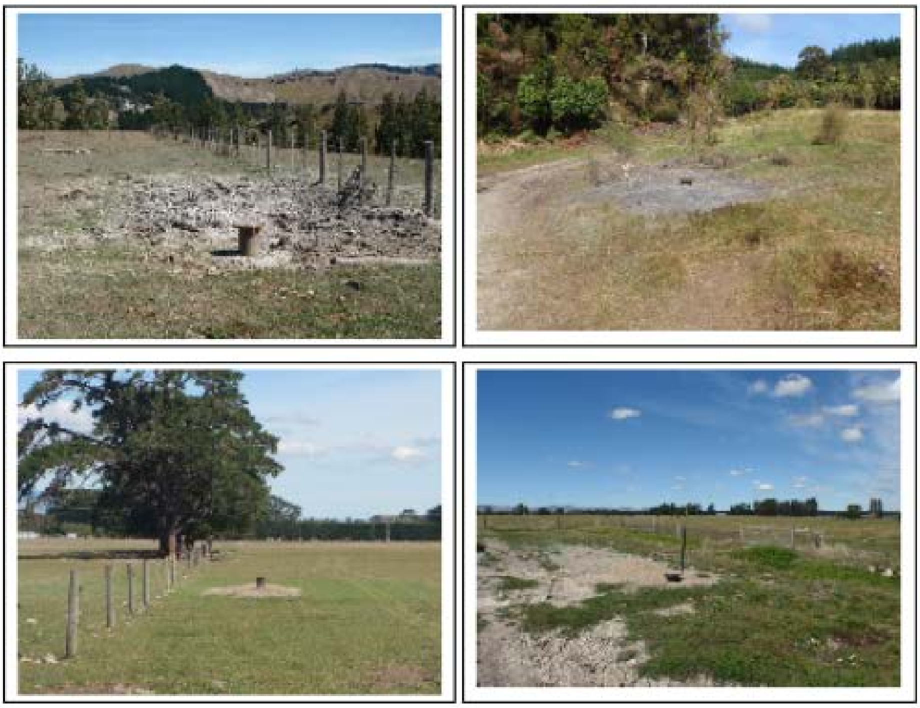
Will the explosions cause any damage?

The explosions have an energy equivalent less than a magnitude 2 earthquake. There were over 14000 $M \leq 2.0$ earthquakes in New Zealand in 2017. Most of these small earthquakes aren't felt or noticed, and typically earthquakes don't cause damage until they are magnitude 5.0 or greater (equivalent to 32000 tons of Explosive, 64 times bigger than what we're planning!). In previous experiments we have found that any damage done by the blast is minor and very localised. For example some of the gravel used to backfill the boreholes has been ejected during the blast. We will undertake remedial work to clean up any mess that this creates and to remove any casing that sits above ground. The blast may create a small cavity a few meters wide at depth at the bottom of the borehole. GNS will maintain responsibility to remediate any later collapse or problem related to the borehole for up to 10 years following the explosion.

What will we need from you?

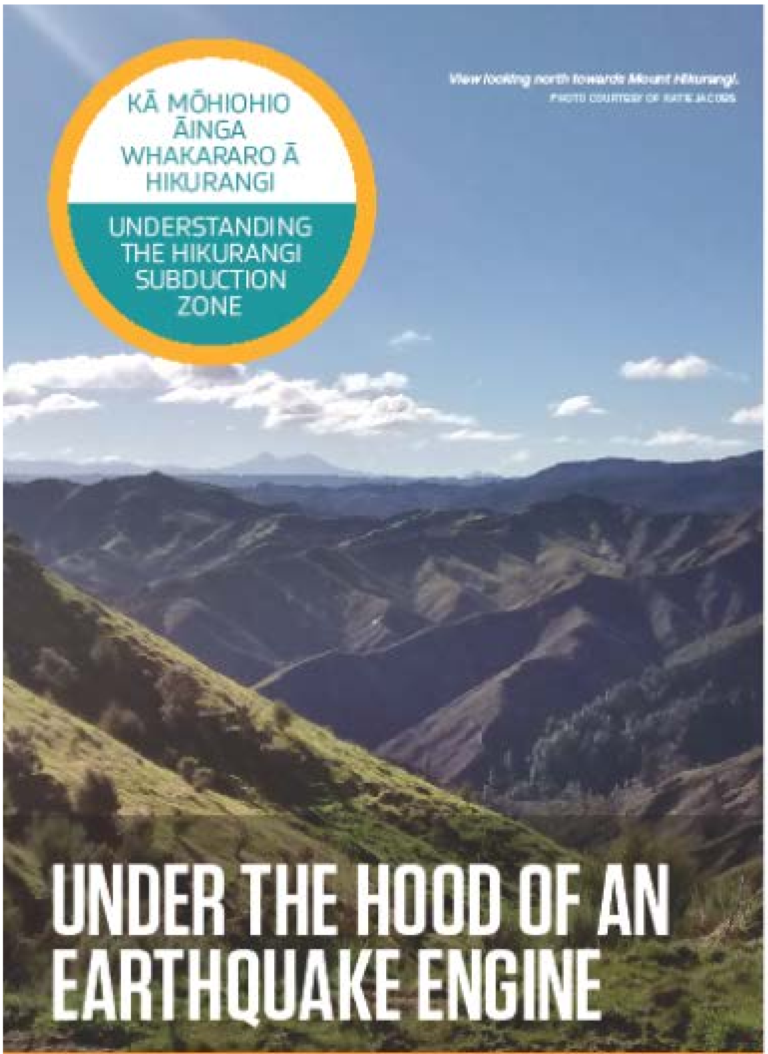
The main thing we need from you is consent to go ahead with the drilling and explosion. If you agree we will ask you to sign a land-use agreement that will formalize your acceptance that we can use your land for this time and our responsibility to contact you before we come and to clean up when the experiment is finished. The land-use agreement will be for a period of months, but the work itself will happen in several bursts that will likely be only a few days each. The drilling usually takes 1-2 days to complete. An explosives truck will also come 1-2 weeks prior to the explosion to load the explosives. There will not be a detonator on site and we will ensure that there are safety measures in place while the borehole is there. The usual safety measure is a locked lid at the top of the borehole. The explosives are pumped to the bottom of the hole and then backfilled with gravel. This process will take another 1-2 days and will happen weeks or a couple months after the hole is drilled. Then we will be on site for 1-2 nights in mid-late February to let off the explosion. Access will be needed for another 1-2 days following the explosion to clean up the site and return it to its original condition.

Past Borehole sites after the explosion has been detonated



Please contact Katie or Stuart with any questions:

Katie Jacobs: k.jacobs@gns.cri.nz ph. *04-570-4605* *cell ph. 0212462347*
Stuart Henrys: s.henrys@gns.cri.nz ph. *04-570-4812*



View looking north towards Mount Hikurangi.
PHOTO COURTESY OF KATIE JACOBS

KĀ MŌHIOHIO ĀINGA WHAKARARO Ā HIKURANGI

UNDERSTANDING THE HIKURANGI SUBDUCTION ZONE

UNDER THE HOOD OF AN EARTHQUAKE ENGINE

SHIRE: SEISMOGENESIS AT HIKURANGI INTEGRATED RESEARCH EXPERIMENT

PHASE 1: COMPLETE

The seismometers deployed during phase one recorded local, regional, and global earthquakes in addition to sound energy from a ship offshore. This allowed scientists to image the deeper structures associated with the subduction zone in this region of New Zealand.

PHASE 2: PLANNED

A line of seismometers will record signals from controlled underground explosions. This additional data will allow scientists to produce a high-resolution image of the shallow structures, zones of weakness (such as faults), and material properties within the region.

WHAT IS A SUBDUCTION ZONE?

Off the East Coast of New Zealand's North Island the Pacific tectonic plate dives beneath the Australian plate forming the Hikurangi Subduction Zone. Subduction zones are regions where one tectonic plate is forced beneath another. Subduction zones develop a type of fault that is responsible for the world's largest and most powerful earthquakes and tsunamis. The SHIRE project and other scientific projects focused on the Hikurangi Subduction Zone are using multiple techniques to understand this large fault, so local communities can be better prepared.

WHY STUDY THE HIKURANGI SUBDUCTION ZONE?

We know that the Hikurangi subduction zone can produce large earthquakes and tsunamis, and that these events have occurred in the past. We want to discover how often these earthquakes happen, how large they can be, and where they are most likely to occur.

The Hikurangi Subduction Zone is also home to the shallowest slow slip events in the world (also referred to as "slow earthquakes" or "silent earthquakes"). This makes the East Coast one of the best places in the world to learn more about why slow slip events occur. Studying this region will help us continue to refine our understanding of earthquake and tsunami hazards and the risks they pose to coastal communities.

HOW WILL THE EXPERIMENT WORK?

In February 2019, scientists are planning to set off explosives that act like a small earthquake, creating waves of radiating energy while temporary sensors record the Earth's response. Recording the variation in when the energy arrives at each sensor will provide scientists with information about the rock types and structures between the blast and the sensor.

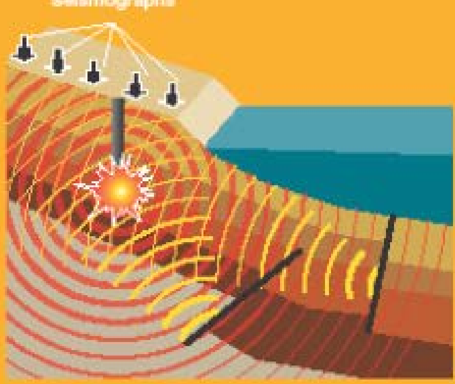
WILL THE EXPLOSIVES CAUSE ANY DAMAGE?

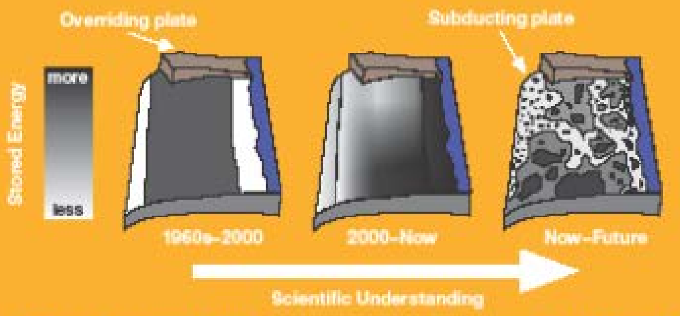
Any damage done by the blast is minor and very localized to the site. For example in previous experiments, the gravel used to backfill the boreholes has been ejected during the blast. At the bottom of the borehole, the explosion may create a small hole a few meters wide. There is not expected to be any damage from the explosion at the surface. In the unlikely even that damage does occur, each site will be remediated and returned to its original condition.

WHY DO WE NEED THIS DATA?

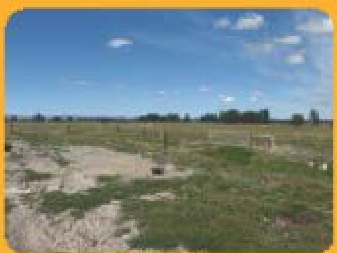
Scientists already know a lot about earthquakes, and the potential effects of tsunami events along the East Coast. The data collected for the SHIRE project will be used to build on our current understanding and improve our knowledge of the environments in which earthquakes occur. For example, the picture over the page shows how our understanding of the subduction zone earthquake potential is evolving with time. To understand earthquake behaviour we need much more detailed pictures of where energy is stored, and how stored energy is used up during earthquakes. The data from this project will give us a more focused picture of earthquake habitats within the Hikurangi Subduction Zone.

The energy from explosions travels out evenly in all directions. The time the energy arrives at each seismograph sensor should mostly depend on the distance from the explosion. Differences in the expected arrival time of the energy at each sensor are caused by structures, like faults, and changes in rock type that act as boundaries that change the direction and total travel time of the energy waves.





As we uncover more details of the Hikurangi Subduction Zone we can learn more about where energy is stored, and how the location of stored energy relates to where earthquakes start and how they develop.




Examples of previous boreholes.

WHY USE EXPLOSIVES?

Controlled explosions have two main advantages over earthquakes for these studies:

1. CONTROL - We can control and know the exact time and place of the energy source. Choosing the location allows us to study a particular region of interest rather than relying on where earthquakes happen to occur.
2. DENSITY – The density of recording seismographs is essential for identifying and mapping smaller structures and variations. The national network of seismic stations is focused on earthquake location and has a limited density with 20–40 km between stations in the region (www.geonet.org.nz/data/network/sensor/map). To record the explosions we will deploy a temporary network of up to 1000 stations which is about 100 times more dense than the permanent network.

WILL WE HEAR OR FEEL THE EXPLOSIONS?

The controlled source explosions, planned for February 2019, direct energy downwards so that the energy ends up in the ground. The further away you are to the explosion the less likely you are to feel it. For example, if you were standing within a 100 meters you would feel the vibration of the explosion and the experience might be similar to that of a truck driving past nearby. Atmospheric and weather conditions also contribute to how far sound from the explosion will travel. The sound might be heard up to 4 km away but at a very low noise level. Each explosion will take place on private land with owner's cooperation.

MORE INFORMATION

For more information on SHIRE and the other Hikurangi focused projects visit:
www.gns.cri.nz/hikurangi

EAST COAST LAB (Life At the Boundary):
www.eastcoastlab.org.nz

Be Prepared. Its your Best Defence:
www.happens.nz

If you have any questions or want to learn more, please contact:

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USC University of Southern California

Kirk McIntosh at Site 518, 23 February 2017. Photo courtesy of Stuart Henrys.

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