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DR Schiel, PM Ross & CN Battershill

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INTRODUCTION

Environmental effects of the MV *Rena* shipwreck: cross-disciplinary investigations of oil and debris impacts on a coastal ecosystem

DR Schiel[a], PM Ross[b] and CN Battershill[b]

[a]Marine Ecology Research Group, School of Biological Science, University of Canterbury, Christchurch, New Zealand; [b]School of Biological Sciences, University of Waikato, Hamilton, New Zealand

ABSTRACT
The 2011 wreck of the MV *Rena* off the northeast coast of New Zealand, and subsequent impacts, has been called New Zealand's worst ever maritime environmental disaster. It is certainly one of the world's most complex as it involved a pollutant combination of oil and dangerous goods debris in a dynamic oceanic environment adjacent to a pristine coastline. Heavy fuel oil, shipping containers loaded with cargo, and a wide range of wreck debris and contaminants were spread along hundreds of kilometres of coastline of the Bay of Plenty. Much of this landed on sandy beaches and rocky shores. Broken containers released often toxic substances, and the wreck itself slid down the pinnacle of the wreck site at Astrolabe Reef (Otaiti). The reef remains heavily contaminated, with substantial remnants of the ship and its cargo present, and chemical effects still evident in some species. Here we present the background and timeline of events that unfolded after the grounding. The following articles contain the results of the ensuing chemical, toxicological and ecological studies of contamination and environmental recovery. At the time of writing, numerous legacy issues remain.

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Astrolabe Reef; environmental recovery; maritime environmental disaster; *Rena*; oil spill contamination

Introduction

Few maritime events elicit such outrage in the general populace as a nearshore oil spill. This is especially so in New Zealand, which prides itself on its relatively pristine marine environment and the bountiful cultural, recreational and economic benefits derived from its coastal waters. When the 38,788 tonne, 236 m long container ship MV *Rena* struck Astrolabe Reef approximately 12 nautical miles off shore (37°32′42″S, 176° 25′73″E; Figure 1) at 0214 h on 5 October 2011 there was no hint of the environmental impacts that would ensue. The incident began as a ship grounding, with primary concern and responses related to the safety of the crew and the removal of the ship from the reef. Five days of calm weather allowed divers to inspect the ship and it quickly became evident that there was serious damage to the hull, with a portion of the reef protruding through the keel. It was clear to salvors from the outset that recovery of the ship and cargo would be difficult. A storm brought 5–7 m swells during the evening

CONTACT David R Schiel ✉ david.schiel@canterbury.ac.nz

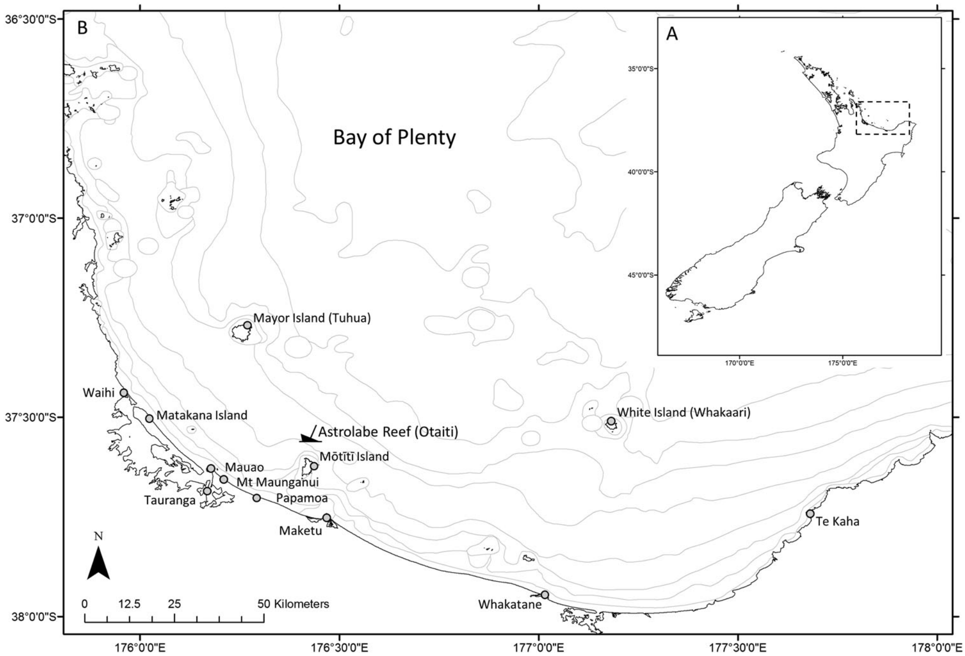

Figure 1. Locations associated with the MV *Rena* wreck. **A,** Map of New Zealand showing the location of the Bay of Plenty (dashed box); **B,** map of the Bay of Plenty showing the position of Astrolabe Reef (Otaiti), the wreck site of the MV *Rena*, and other key locations throughout the Bay of Plenty.

of 10 October, altering the ship's position on the reef and causing many of the 1368 containers (121 with perishable goods and 32 with 'dangerous goods') on board to break loose and cascade into the sea. A combination of diesel, hydraulic oil and heavy fuel oil (HFO 380) from the recently filled bunkers began to leak from the vessel through fractures in the hull (Figure 2). Up to 350 tonnes of HFO were eventually released into the sea (Murdoch 2013; Transport Accident Investigation Commission 2014), mostly during a series of mid-October storms. With strong onshore winds, most of the oil landed on sandy beaches and rocky promontories along 70 km of the western Bay of Plenty from Waihi to Maketu (Figure 1).

The oil spill itself was small by comparison to the world's worst oil spills, such as the *Exxon Valdez* oil tanker spill which released 36,000 tonnes of crude oil into the nearshore zone of Prince William Sound, Alaska in 1989 (Paine et al. 1996), or the Deepwater Horizon oil well blowout of 2010 that resulted in the loss of between 628,000 and 846,000 tonnes of crude oil into the Gulf of Mexico (Griffiths 2012). However, the *Rena* oil spill was by far the worst experienced in New Zealand in terms of volume spilled. The *Rena* recovery has proven to be one of the most expensive salvage and oil spill clean-up operations ever attempted. To date, over NZ$660 million in costs have been incurred through the clean-up of oil, the salvage of container debris, and the considerable difficulties experienced in removing the broken ship from a hostile and highly dynamic open ocean environment (Murdoch 2013; BECA 2014). It is estimated that 4593 tonnes of debris has been brought to the surface so far and over 17,376 tonnes of ship structure has been removed from the sea. At the time of writing (September 2015), however, much

Figure 2. MV *Rena* wedged on a rock outcrop on Otaiti (Astrolabe Reef). **A,** Listing to starboard following a storm; **B,** stern of the wreck seperated from the bow section on 8 January 2012 (Photographs: Maritime New Zealand).

of the broken hull, 259 broken containers, and a considerable debris field remain on and around Astrolabe Reef. An unknown quantity of material listed as 'dangerous goods' cargo also remains. The salvage operation continues.

Astrolabe Reef (also known by its Māori name Otaiti) rises from a depth of around 90 m and breaks the sea surface at mid to low tides. The reef is a pinnacle with a base circumference of about 1 km and an area of approximately 0.14 km^2 occupying waters shallower than 30 m. The reef is well marked on nautical charts and is 25 km northeast of the entrance to Port Tauranga, New Zealand's second-busiest but largest commercial port (Figure 1). The adjacent Bay of Plenty coastline has 259 km of New Zealand's finest beaches, together with several estuaries, headlands and nearshore islands. The prevailing swell is from the northeast and there is an average significant wave height (Hs, or the top third of wave heights) of around 2 m. The MV *Rena* hit the crest of Astrolabe Reef at full speed, travelling at around 17 knots. Once grounded, the ship remained stuck fast on the reef, eventually listing precariously to starboard before breaking in two, with the aft section sliding off the reef crest and settling on the northeastern slope of the reef across a depth range of 30 to 70 m (PM Ross, pers. obs.; Transport Accident Investigation Commission 2014). Estimates of HFO 380 (also called bunker C oil) lost to sea ranged from 200 to 350 tonnes (or 1300 to 2345 barrels; Murdoch 2013; Transport Accident Investigation Commission 2014). Although 1007 of 1368 containers aboard the *Rena* were recovered soon after the initial grounding, a substantial amount of cargo was lost into the sea. The vessel was considered a total loss on 11 October 2011, by which time a series of responses had been initiated by governmental and research agencies.

Because the MV *Rena* was a cargo ship and not an oil tanker, the oil that came from it was used for propulsion. At the time of the grounding, the ship carried 1700 tonnes of heavy fuel oil and 200 tonnes of marine diesel (Marshall 2014). A small number of its containers were also carrying hazardous and ecotoxic goods including trichloroisocyanuric acid (TCCA, 12 tonnes), ferro silicon (96 tonnes), DA-HFP (27 tonnes), cryolite (sodium hexafluoroaluminate, 543 tonnes) and granulated copper (clove grade, 21 tonnes). As the ship broke up, this potentially toxic mixture of substances combined with HFO 380, hydraulic oil, lighter oil for generators, and a great amount of debris from the ship, containers and their contents. Although the oil spillage was the major initial environmental concern at the time of grounding, the *Rena* incident unfolded over several months into a multi-layered investigation of a combination of impacts. The timeline of main events is relevant to the clean-up and recovery operations (Table 1). Oil began landing on the beaches along the Bay of Plenty coast on 10 October 2011, 5 days after the grounding. Strong onshore winds that night resulted in oil being driven to shore and spreading along the bay. Drifting and semi-submerged containers lost overboard posed navigational hazards, and as they split open they spilled debris along the coastline. Maritime New Zealand had jurisdictional control of the wreck from the time of its grounding. Other agencies were involved, such as the Bay of Plenty Regional Council (responsible for managing the coastline and shipping channels), the Department of Conservation, and the Ministry for the Environment. Research providers, especially from the University of Waikato and Bay of Plenty Polytechnic (environmental surveys) and MetOcean Solutions Ltd (wind and current modelling) quickly became involved in the response process.

Benchmarking of the potentially affected environment before oil and debris arrived was a priority for researchers. Marine ecologists and environmental chemists combined with colleagues from the region versed in mātauranga (Māori traditional knowledge), to review what was known about the region likely to be affected. A fast response monitoring plan was established to fill in gaps. Long term datasets such as the work emanating from the University of Canterbury biodiversity programme (e.g. Blanchette et al. 2009; Rilov & Schiel 2011) and Bay of Plenty Regional Council was especially useful. There was 'pre-*Rena*' information for much of the region's coastline, particularly beaches and estuaries, but information about the ecological character of offshore rocky reefs near Astrolabe Reef was scarce and largely anecdotal. Pre-impact subtidal surveys were therefore initiated just after the grounding and before oil hit the shore. These were intended to provide a baseline against which to measure changes in the event of oil impacts. Once oil made it to shore, however, the prime activity was its removal.

Passions ran high in the region, and numerous public meetings allowed open discussion about the unfolding events and the response of Maritime New Zealand. After some consultation, Maritime New Zealand decided to use the populace to help with the clean-up (Figure 3). Volunteers crawled along the coastline removing oil from the surface of beaches, rocks and tide pools by hand. For the most part, heavy machinery was not allowed onto sandy beaches, because experience in Australia had shown that oil can be driven deep below the surface with vehicle activity (AMSA 2009). The Ministry for the Environment outlined the 'Rena Long-Term Environmental Recovery Plan' in December 2011. The goal of the *Rena* Recovery Plan was to 'restore the mauri of the affected environment to its pre-*Rena* state' (Ministry for the Environment 2011). Mauri is a key component of Māori spirituality and is the life force or the life essence contained in

Table 1. Timeline of major events for the MV *Rena* wreck.

5 October 2011	The 37,000 tonne cargo ship MV *Rena* hit Otaiti (Astrolabe) Reef at 0214 h. On board were 1760 tonnes HFO; 200 tonnes marine diesel, 1368 containers. By 0700 h, Maritime New Zealand had declared a tier 3 emergency, the highest level of response to an oil spill, and mobilised the National Response Team for oil spill response. Maritime New Zealand also activated its Maritime Incident Response Team to monitor and respond to the situation.
6 October 2011	A small amount of oil was found to have leaked overnight prompting aerial deployment of oil dispersant. Environmental monitoring survey team deployed to provide a 'pre-*Rena*' fast response environmental assessment.
9 October 2011	Salvors began removing the estimated 1350 tonnes of oil in various tanks on *Rena* but were hampered by bad weather, equipment breakdown and hazardous and changeable conditions. Environmental stakeholders assessed response options.
10 October 2011	Oil discovered on Mt Maunganui beach. Clean-up teams commenced collecting oil from beaches.
11 October 2011	Storm overnight resulted in loss of an estimated 350 tonnes of oil from *Rena* (Maritime New Zealand). 5 km slick surrounded *Rena*. Oil washed up at various points along Bay of Plenty coastline.
12 October 2011	Approximately 30 containers fell into the sea. Beaches closed from Mt Maunganui to Maketu. A significant amount of oil washed up on Papamoa Beach.
13 October 2011	Ship on 20° list, 88 containers lost overboard, 20 came ashore, and 14 recovered at sea.
14 October 2011	*Rena* cracked apart, but held intact on the reef. More than 220 tonnes of oiled sandy waste collected from the beaches and taken to the transfer station.
22–23 October 2011	A further 5–10 tonnes of oil lost from vessel overnight. Oil spill response personnel and volunteers, including large numbers of locals, worked to clean oiled beaches and recover debris from the containers. Wildlife experts from the National Oiled Wildlife Response Team treated oiled birds, including little blue penguins (*Eudyptula minor*) and pied shags (*Phalacrocorax varius varius*), and pre-emptively caught 60 rare New Zealand dotterel (*Charadrius obscurus aquilonius*) to prevent them becoming oiled. (These birds were later re-released back into cleaned environments in a staged release programme.)
15 November 2011	Over 1300 tonnes of HFO were eventually recovered from *Rena*, with all accessible oil removed.
16 November 2011	Container removal operations from *Rena* began once all of the oil had been removed.
December 2011	Bad weather caused more oil to leak, more debris. By 26 December, 341 containers removed from *Rena*.
8 January 2012	*Rena* separated into two pieces.
10 January 2012	Stern section sank. An estimated 200–300 of the c. 830 remaining containers were lost overboard: at least 49 containers were identified floating in the sea, 25 of which washed ashore. Container debris retrieved between Waihi Beach and Maketu comprised mainly plastic beads, milk powder and some meat products.
24 January 2012	497 containers processed on shore—441 lifted off the wreck and 56 collected at sea or from beaches.
February/March 2012	Coastal clean-up continued.
4 April 2012	Stern section sank completely in severe weather.
May 2012	815 containers retrieved and seabed recovery of debris commenced.
June 2012	Accessible containers removed from the submerged stern section; 944 containers have been processed ashore.
July 2012	*Rena* owners and representatives met with community groups and leaders. Collection of container scrap from the seabed surrounding the *Rena* wreck; 20 containers have now been hoisted from the ocean floor with 986 containers landed and identified.
August 2012	986 containers salvaged.
September 2012	High winds and rough seas result in c. 25 m of fore section, weighing around 250 tonnes, being ripped free from the aft portside and falling to the sea bed. 999 containers salvaged.

resources both animate and inanimate. Mauri therefore encompasses the environment holistically as one interlinked and interrelated system (Love et al. 1993).

To achieve the restoration of the Bay of Plenty environment to its pre-*Rena* state, a partnership (Te Māori Moana) was set up between research providers, including tertiary institutions from throughout the Bay of Plenty, New Zealand and Germany, Māori researchers and one of the Māori iwi groups most seriously affected by the oil spill (Figure 4). Specific research projects were designed to address two key questions of concern to the public: what was the impact of the oil, and how long would it take for the marine environment to recover? Addressing these questions involved assessments of

Figure 3. Volunteers cleaning oil and debris from the shoreline of the Bay of Plenty. **A,** Moving along a beach removing oil by hand (Photograph: Maritime New Zealand); **B,** raking debris from a beach (Photograph: New Zealand Defence Force).

the organic and inorganic chemistry related to the spilled oil and debris, the ecological and physiological impacts on habitats and key organisms, the impact of the oil spill on mauri, the efficacy of methods used to clean oil from the coast and, finally, the identification of potential legacy effects of the grounding and oil spill (Battershill et al. 2013). The series of articles contained within this volume is the result of these collaborations and provides an account of the key findings of the scientific, cultural and operational work that ensued after the *Rena* grounding. The volume is assembled so that sequential articles address

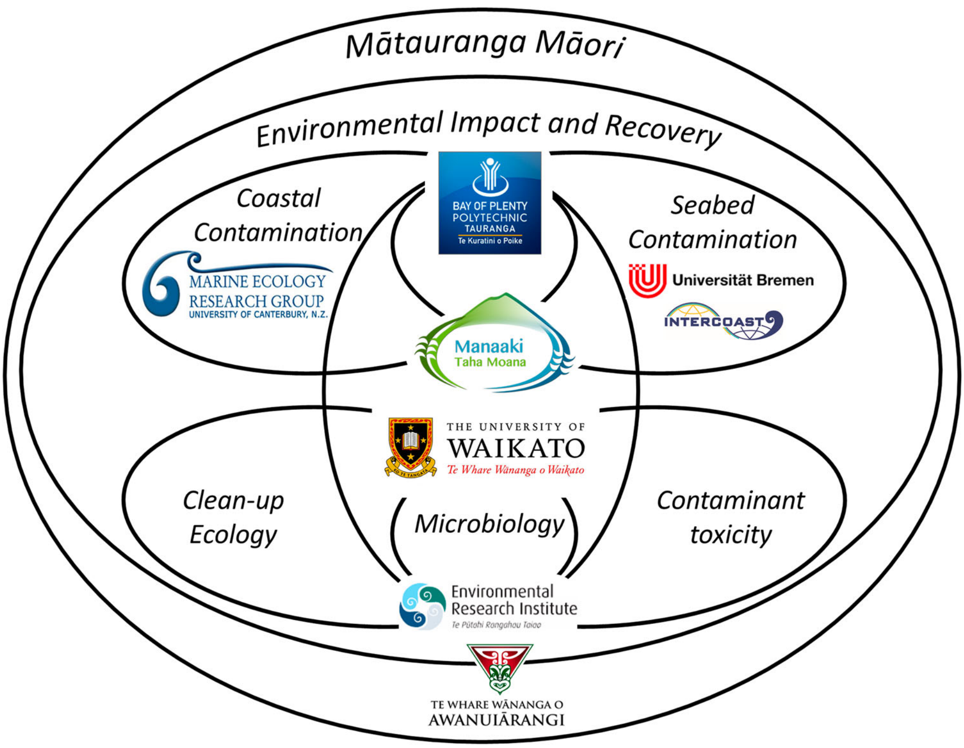

Figure 4. Summary of the work and partnership programme of the *Rena* Long-Term Recovery Plan (2011).

the oil spill and operational responses, the fate of contaminants in the environment, and the ecotoxicological effects of *Rena*-derived contaminants and oil dispersants on native marine biota.

In the first article, Jones, Bryan, Poot, Mullarney and de Lange compare the outputs of hydrodynamic and particle tracking models with observations of oil accumulation following the *Rena* grounding to examine the utility of open-source modelling software for predicting the dispersal of spilled oil (Jones et al.). Lockwood, Weaver, Munshi and Simpson then explore the phenomenon of self-organising youth volunteers during crisis events (Lockwood et al.). This article focuses on how 'volunteering' was conceptualised by youth involved in the *Rena* oil spill clean-up, and the process of communication and self-organisation during this crisis. Smith, Inglis, Wilkens, Buckthought and McDonald examine the biosecurity risks posed by vessels participating in the *Rena* salvage operation, which were commissioned rapidly from international ports (Smith et al.). They document responses to the detection of non-indigenous species (new to New Zealand) on the hulls of two salvage vessels, including vessel treatment, surveillance and marine pest identification training of personnel involved in the salvage and environmental recovery.

The fate of oil and other contaminants in the marine environment is addressed in five articles. Ross, Fairweather, Culliford, Parke, Pilditch and Battershill investigate the in situ uptake and depuration of *Rena* oil in surf clams on Bay of Plenty beaches (Ross et al.). De Lange, de Groot and Moon then explore the fate of oil on Bay of Plenty beaches through the examination of sediment cores to assess oil burial depths and degradation rates (De Lange et al.). Schiel, South and Lilley describe the spatial and temporal distribution of oil on intertidal rocky reefs and assess the impact of oil on ecological communities (Schiel et al.). Ross, Battershill and Loomb (Ross et al.) focus on Astrolabe Reef and nearby Mōtītī Island where they examine the fate of hydrocarbons, metals and antifouling-derived organotins in the environment and biota. Dempsey, Ross, Hartland and Battershill explore the use of diffusive gradients in thin film (DGT) passive samplers for assessing trace metal concentrations in the water column adjacent to the *Rena* shipwreck (Dempsey et al.).

The lethal and sublethal effects of contaminants (HFO, dispersants and dangerous goods) on native marine biota are assessed in two articles. Muncaster, Jacobson, Taiarui, King and Bird examine the effects of *Rena* HFO 380 and the dispersant Corexit 9500 on the development and survival of the early life stages of yellowtail kingfish (Muncaster et al.). Similarly, Webby and Ling evaluate sublethal effects of HFO, Corexit 9500 dispersed HFO and the water soluble fraction of cryolite on the haematology of sub-adult and adult fish and rock lobster (Webby & Ling). A concluding article identifies knowledge gaps and makes suggestions for future research to address uncertainties so that future responses to similar events can be improved (Ross et al.).

The longer term impacts of the *Rena* are now mostly concerned with the continued presence of ship and cargo debris on Astrolabe Reef and residual chemical effects, especially from a deposit of copper clove on the northeastern slope of the reef, and tributyltin (TBT)-based antifouling paint that has been recorded in sediments and biota across much of Astrolabe Reef. These issues are not fully resolved. The fate of the remnants of the *Rena* have been subject to a Resource Consent hearing, where the environmental effects of the *Rena* and the feasibility of further wreck and debris removal were considered. The costs of the salvage operation have mounted considerably, and many challenges were identified about fulfilling the mission of the *Rena* Recovery Plan to bring Astrolabe Reef back to its pre-*Rena* state. A consent was granted (26 February 2016) by the Bay of Plenty Regional Council to abandon the remaining ship parts and cargo debris where they lie. It is anticipated there will be appeals to the granting of the consent. As this Special Issue shows, there are some legacy effects that will take time to ameliorate through natural processes.

By world standards, the *Rena* oil spill barely rates as a major event. In New Zealand, however, the spill and its concomitant contamination from debris and associated toxicants stand as a testament to what can go wrong in a country whose economy is based largely on shipping goods around the world. The then Minister for the Environment, the Hon. Nick Smith, declared the *Rena* wreck New Zealand's worst ever maritime environmental disaster. The story continues, with a considerable part of the *Rena* still on Astrolabe Reef, the scattered debris field (of about 10,000 m^2) continuing to affect reef biota and salvors continuing their removal work. The owner and insurer of the *Rena* have applied for a consent to abandon what is left of the ship on the reef. There is considerable opposition to this, however, and a desire in many quarters for all remnants of the *Rena* to be removed. At this stage, complete wreck removal looks to be increasingly unlikely.

Disclosure statement

Phil Ross is a Research Fellow at the University of Waikato. During the time that this research was conducted, Ross was contracted both by the Bay of Plenty Regional Council and by the owner (Daina Shipping Co.) and insurer (P & I Services) of the MV *Rena* to conduct environmental monitoring and report on monitoring results. Ross was called as an expert witness for the owner and insurer of the MV *Rena* at the Resource Consent hearing in November 2015.

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