

# **Documentation of depth-related migratory movements, localised movements at critical habitat sites and the effects of scuba diving for the east coast grey nurse shark population**

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Australia



August 2009

Industry & Investment NSW –  
Fisheries Final Report Series  
No. 112  
ISSN 1837-2112



**Industry &  
Investment**



**Australian Government**  
**Department of the Environment,  
Water, Heritage and the Arts**

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**Published By:** Industry & Investment NSW (now incorporating NSW Department of Primary Industries)  
**Postal Address:** Port Stephens Fisheries Institute, Locked Bag 1, Nelson Bay, NSW 2315  
**Internet:** [www.industry.nsw.gov.au](http://www.industry.nsw.gov.au)

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ISSN 1837-2112

*Note: Prior to July 2004, this report series was published by NSW Fisheries as the 'NSW Fisheries Final Report Series' with ISSN number 1440-3544. Then, following the formation of the NSW Department of Primary Industries the report series was published as the 'NSW Department of Primary Industries – Fisheries Final Report Series' with ISSN number 1449-9967. The report series is now published by Industry & Investment NSW as the 'Industry & Investment NSW – Fisheries Final Report Series' with ISSN number 1837-2112.*

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## ACKNOWLEDGEMENTS

A large number of people assisted with this research in the form of research funding, administrative support, on-going technical support, veterinary support, field studies, scuba diving and peer review. To each and everyone involved, we express our thanks.

### Funding

Funds for various aspects of the research described in this report were provided by: the New South Wales Department of Primary Industries (NSW DPI); the Sea World Research and Rescue Foundation Inc.; the Department of Environment, Water, Heritage and Arts (DEWHA); the Northern Rivers Catchment Management Authority (NRCMA); and the Southern Rivers Catchment Management Authority (SRCMA).

### Administrative Support

NSW DPI – Ian Powell, Karen Herrick, Michelle O’Leary, Polly Blayden, Kaylene Robertson, Pamela Gallagher and Richele West.

NRCMA – Darren Murray and Roger Stanley.

SRCMA – Michelle Perry and Nerida Loutit.

DEWHA – Ashley Leedman and Paul Anderson.

### On-going Technical Support

NSW DPI – Geoff Davies, Samantha Fenton and Kathy Bown.

Paul Nixon, Carla Beers, and Veronica Hutchison.

### ACEC and Veterinary Support

Rod Starr and staff from Port Stephens Veterinary Services.

NSW Animal Care and Ethics Committee, Geoff Allan and Jo Pickles.

### Field Studies

*NSW DPI* – Greg West, Bruce Pease, Peter Gibson, Roger Laird, Adrienne Burke, Natalie Morrison, Rob Carraro, Chris Gallen, Tony Fowler, Cristina Venables, Isabelle Thiebaud and Melanie Field. Fisheries Officers – Wayne Bennett, Mark Sherry and Andrew Boughton.

Dick and Pip Smith and the crew of *Ulysses Blue*

*UTS* – Emily Buckle

*Sea World* – Trevor Long and marine sciences staff, Master and crew of *Sea World I*.

*Sydney Aquarium* – Craig Sowden and the curatorial staff

*NSW Marine Parks Authority* – Andrew Read, Tracey Macdonald and Alan Jordan. Andrew Page and Matt Dasey (Cape Byron Marine Park), Max Haste (Port Stephens Great Lakes Marine Park), Hamish Malcolm, Brett Vercoe and Nicola Livingstone (Solitary Islands Marine Park), Frances Clements (Jervis Bay Marine Park), and Brendan Kelaher (Batemans Marine Park).

### Scuba Diving

John and Kathy Duggan (Action Divers, Tuncurry), Peter and Kev Hitchins (South West Rocks Dive Centre, South West Rocks), Wayne Smith, Andrew Phillips (National Diving Academy, Batemans Bay), Peter Huettner (Scuba Haven, Laurieton), Ron Hunter (Fishermans Wharf Dive Centre, Forster), Jack Cavazzini (Sundive, Byron Bay), Perry Bartholomew, Rob Dalton (Byron Bay Dive Centre, Byron Bay), Mike Davey (Jetty Dive, Coffs Harbour), Chris and Kate Connell (Dive Quest, Mullaway), Nick Heiniger (Forster Dive Centre, Forster), Chris and Pam Norman (ProDive, Nelson Bay), Peter Freeman (Dive, Skate and Ski, Newcastle), Rob Hughes (Aquazero Dive Centre, Swansea), Ron and Julie Duncan (Leisure Coast Dive, Shell Harbour), Michael Standen (Merimbula Diver’s Lodge, Merimbula), Herb Ilic (Palm Beach Dive Centre) and Peter Comerford (Tweed Sea Sports, South Tweed Heads). There are also a large number of scuba divers

who were not aware that they contributed to this research by simply diving with the grey nurse sharks.

**Peer Review**

Steve Kennelly, Bob Creese and Ashley Leedman.

**Research Approvals**

This research was done under NSW DPI research permit number P01/0059(A) and animal care and ethics research approvals – ACEC 99/14 and ACEC 03/04.

## NON-TECHNICAL SUMMARY

**Documentation of depth-related migratory movements, localised movements at critical habitat sites and the effects of scuba diving for the east coast grey nurse shark population**

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**OBJECTIVES:**

- Quantify the localised movements of grey nurse sharks at critical habitat sites along the east Australian coast;
- Quantify the depth-related migratory movements of grey nurse sharks along the east coast; and
- Quantify the effects of scuba diving on the behaviour of grey nurse sharks at aggregation sites along the east Australian coast.

**NON TECHNICAL SUMMARY:**

This project analysed data obtained from research carried out over six years. The study involved using the South-East Australian Coastal Acoustic Monitoring System (SEACAMS), active acoustic tracking studies and tagging studies with acoustic and pop-up archival satellite transmitters to document the localised movements of grey nurse sharks at NSW critical habitat sites and their migratory movements along the NSW coast, and to assess the impacts of scuba diving on the species.

Localised movements were documented by using dive boats, equipped with acoustic receivers, to actively track 9 grey nurse sharks tagged with continuously transmitting acoustic tags. The resulting information was then augmented with data from the SEACAMS acoustic listening stations. Analyses of the nine tracking studies showed that the tagged sharks spent almost 94% of their time within 500 metres of the critical habitat site and predominantly within 100 metres. The excursions away comprised only 6% of their time spent at a critical habitat site and occurred during the day and night. Data from 30 grey nurse sharks tagged with acoustic tags showed that the timing and duration of occupation of critical habitats by grey nurse sharks varied throughout the year. The timing of site occupation was correlated with water temperature, the sexual maturity of the shark and, in females, the stage of the reproductive cycle. Grey nurse sharks occupied critical habitat sites for varying lengths of time ranging from less than a day to in excess of six months, but averaged around 11 days.

Analyses of the data from 30 sharks tagged with acoustic transmitters and their associated detections on the SEACAMS acoustic listening stations, combined with the data from 15 sharks tagged with pop-up archival satellite tags identified the timing and duration of migratory movements; the migratory routes taken; the duration of occupation of sites in shallow and deep waters along the migratory routes and the duration of occupation of waters with particular depths and temperatures. Tagged, sexually-mature, male grey nurse sharks migrated north over the autumn and winter months reaching sites in the Capricorn Channel off southern Queensland. This was



followed by a southerly migration during spring and summer months during which they swam to sites in southern NSW waters including the Tollgate Islands and Wasp Island. Sexually-immature tagged grey nurse sharks migrated from southern NSW in autumn and winter months, occupying sites off the mid-north coast of NSW and did not participate in the lengthy migration north to southern Queensland waters. These migratory patterns are very similar to the results of previous studies by NSW DPI and CSIRO. During their migratory movements, the tagged sharks spent, on average, 74% of their time in waters not exceeding 40 metres and 95% of their time in waters less than 80 metres in depth. The tagged sharks also spent 95% of their time, on average, in waters with temperatures ranging from 17 to 24°C.

The effects of scuba diving on the localised movements and behaviour of grey nurse sharks was assessed using three field experiments across 15 sites from Julian Rocks (off Byron Bay) to the Tollgate Islands (off Batemans Bay). The sites used reflected the annual variation in abundance and distribution of the shark along the NSW coast. The data used in these experiments were obtained from the 30 grey nurse sharks tagged with acoustic tags and the SEACAMS network. Importantly, the acoustic tags used transmit at 69 kHz which is well outside the range of frequencies that can be heard by sharks. The numbers of detections received per hour by the listening stations were sorted according to tag number and then used to document the movements of the grey nurse sharks in the gutters at the various sites and at times when scuba divers were present and absent. To ensure that the behaviour of the scuba divers was not modified, no information concerning the aims, methods, sites used and/or timing of the experiments was provided to divers or the owner/operators of dive shops before or during these experiments.

None of the tagged grey nurse sharks left any of the sites in response to scuba diving and all remained for the duration of each experiment. Detailed statistical analyses of the acoustic detections showed that there were no effects of scuba diving on the movements or behaviour of the acoustically-tagged grey nurse sharks in the gutters across the 15 sites from Julian Rocks to the Tollgate Islands in each of the 3 experiments. Preliminary analyses of additional data from several sites indicate that there are unlikely to be any cumulative effects of more intense scuba diving on grey nurse sharks.

The results of this study have clear management implications for the recovery and long-term conservation of the grey nurse shark along the east coast of Australia. The localised movements of grey nurse sharks were restricted spatially and mostly occurred within the 200 metre wide critical habitats declared at key aggregation sites. Grey nurse sharks exhibited extensive migratory movements occurring predominantly along inshore coastal waters less than 80 metres in depth. The timing of these movements appears predictable and should be considered if any additional measures are taken to mitigate fishing-related interactions in the future. Scuba diving has negligible effects on the shark and this may be due, in part, to the observance of the grey nurse shark scuba diving code of conduct developed in cooperation with recreational divers.

## 1. BACKGROUND

### 1.1. General introduction

In the past, the grey nurse shark, *Carcharias taurus* Rafinesque, 1810, had a broad inshore distribution (Fig. 1.1a), primarily in sub-tropical to cool temperate waters on continental shelves off the coasts of eastern USA (Springer 1948, Bigelow & Schroeder 1948), Brazil (Sadowsky 1970, Sadowsky *et al.* 1989, Amorin *et al.* 1998), Uruguay (Marin *et al.* 1998), Argentina (Chiaramonte 1998), in the Mediterranean Sea (Compagno 2002), around the Canary Islands and to western equatorial South Africa (Cadenat 1956), in the Red Sea (Compagno 2002), off the east coast of South Africa (Bass *et al.* 1975, Compagno 2002), off the east to west coasts of Australia (Whitley 1940, Last & Stevens 1994), and in Japanese waters (Taniuchi 1970). As a result of overfishing, it is doubtful that sustainable populations of grey nurse sharks still exist in the Mediterranean Sea, around the Canary Islands and to western equatorial South Africa, the Red Sea and in Japanese waters. Consequently, the shark's distribution (Fig. 1.1b) is now likely restricted to the east coasts of North and South America (i.e., USA, Brazil, Uruguay and Argentina), the east coast of South Africa and, the east and west coasts of Australia.

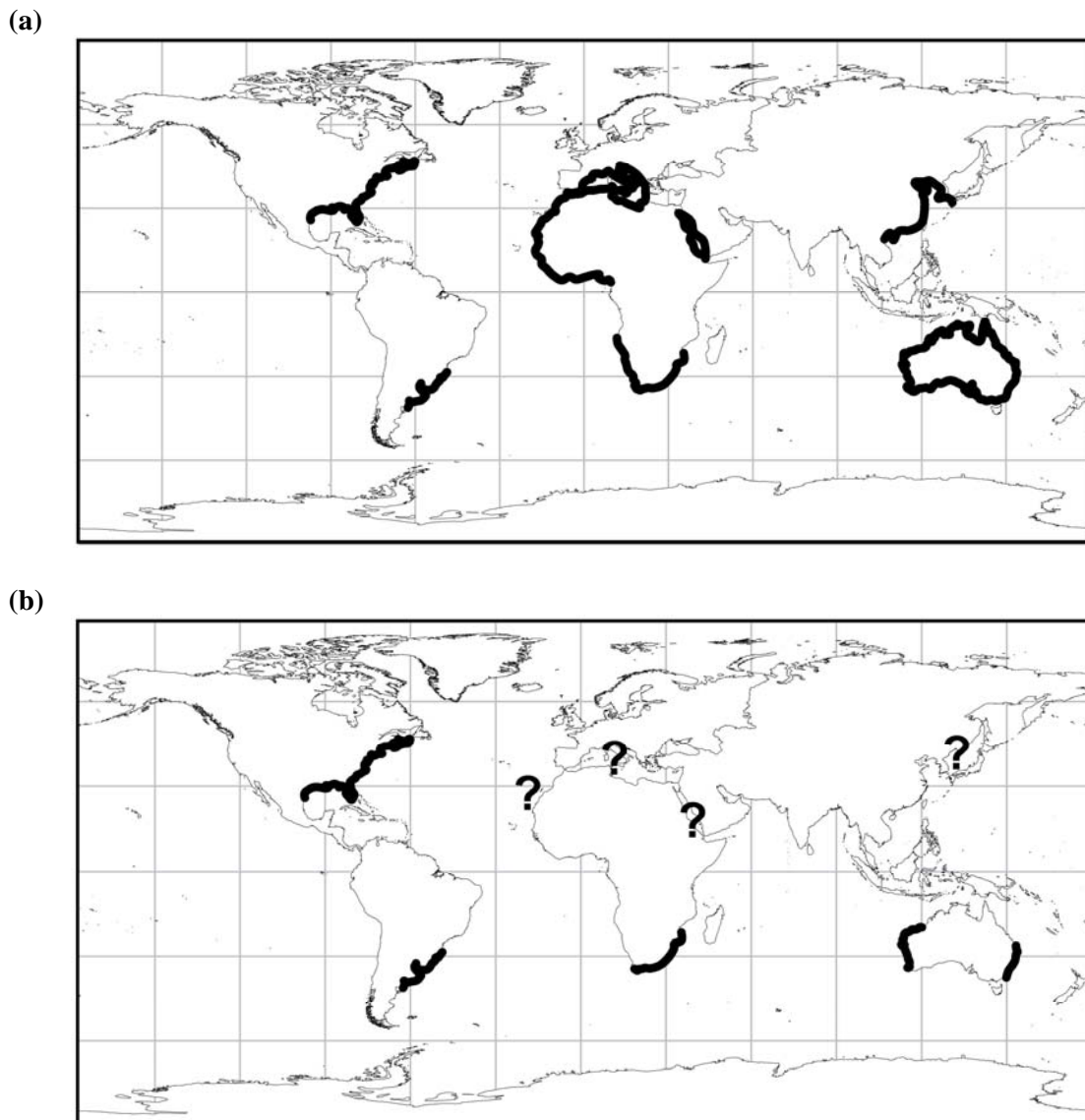
In Australia, *C. taurus* has, in the past, been recorded at various sites from Cairns on the Queensland coast around the southern half of the continent and northwards to Shark Bay in Western Australia (Last & Stevens 1994). The species has not been found in Tasmanian waters, but has been caught in the Arafura Sea on a few occasions (Read & Ward 1986). Over the past few decades, *C. taurus* has been restricted to two, separate and genetically distinct populations (Cavanagh *et al.* 2003; Stow *et al.* 2006) on the east and west coasts of Australia. The east coast population extends from Double Island Point (25° 55' S, 153° 12' E) in southern Queensland to Narooma (36° 15' S, 150° 12' E) in southern New South Wales (Cavanagh *et al.* 2003, Otway *et al.* 2003). The range of the west coast population is less well known, but the by-catch of commercial shark fisheries indicate that the species occupies sites from North West Cape (21° 46' S, 114° 09' E), around the south-western coastline and then east to the coastal waters south of Cocklebidly (32° 15' S, 126° 12' E) in the Western Australian section of the Great Australian Bight (McAuley *et al.* 2002, Cavanagh *et al.* 2003).

The shark is a slow, strong-swimming species that is often seen hovering motionless near the bottom in or near sandy-bottomed or cobble-filled gutters, overhangs or in rocky caves around inshore rocky reefs and islands at depths between 15 and 40 m, but may extend to 191 m (Pollard *et al.* 1996, Compagno 2002). Grey nurse sharks aggregate at these sites and feed on a wide range of bony fish, squid and occasionally on crustaceans (Bass *et al.* 1975, Compagno 2002, Schmid *et al.* 1990, Smale 2005).

The grey nurse shark population off eastern Australia has had a very chequered history (Otway 2001, 2004). In the late 1800s and early 1900s, they were harvested for their flesh for human consumption, liver oil for powering Sydney's streetlamps, and skin for leather and sandpaper (Whitley 1940, Roughley 1955). Grey nurse sharks were initially caught in large numbers in the NSW shark meshing program, but catches declined rapidly (Reid & Krogh 1992, Krogh 1994). They were also targeted by gamefishers from the 1930s until the late 1970s (Pepperell 1992). In the 1950s and 60s, they were wrongfully accused of the shark attacks off Sydney's beaches and again hunted (Stead 1963, Otway 2001). With the advent of the powerhead, numerous grey nurse sharks were killed by spearfishers in the 1960s and '70s (Cropp 1964, Byron 2000). Combined, these activities caused a substantial reduction in the grey nurse shark population. After much lobbying by various groups, the shark was declared a protected species in 1984 by the New South Wales government. With their numbers continuing to decline via inadvertent capture by commercial and

recreational fishers, the grey nurse shark was declared a threatened species in 1999 and is now listed as “critically endangered” on the east coast of Australia under the *New South Wales Fisheries Management Act (1994)*, the *Queensland Nature Conservation Act (1992)*, the *Environment Protection and Biodiversity Conservation Act (2001)* and by the IUCN (Cavanagh *et al.* 2003). In 2002, 10 aggregation sites in NSW waters were declared as critical habitat sites. Many of these sites have subsequently been incorporated within sanctuary zones within the multiple use marine parks declared at various locations along the NSW coast (Breen *et al.* 2003, Breen *et al.* 2004, Breen *et al.* 2005ab).

Like many elasmobranchs, the grey nurse shark exhibits late onset of sexual maturity (6 – 7 yr in males, 9 – 10 yr in females in the USA – Goldman *et al.* 2006), low fecundity with 2 pups born biennially following intrauterine cannibalistic and oophagous phases (Springer 1948, Gilmore *et al.* 1983) and longevity of about 35 years. Their habitat requirements and biology have made grey nurse shark populations extremely vulnerable to over-exploitation and they require decades to recover from anthropogenic reductions in their numbers (Smith *et al.* 1998, Otway *et al.* 2004).



**Figure 1.1.** Global distribution of the grey nurse shark, *Carcharias taurus* (a) past and (b) present.

## **1.2. Objectives**

The objectives of this study were to quantify:

1. the localised movements of grey nurse sharks at critical habitat sites along the east Australian coast;
2. the depth-related migratory movements of grey nurse sharks along the east coast; and
3. the effects of scuba diving on the behaviour of grey nurse sharks at aggregation sites along the east Australian coast.

## 2. LOCALISED MOVEMENTS

### 2.1. Introduction

The localised movements of fish and sharks have been determined using active and/or passive acoustic technology (Stasko & Pincock 1977, Sundstrom *et al.* 2001, Voegeli *et al.* 2001 for reviews). These approaches can provide detailed information on habitat use, distances travelled, water depths and temperature ranges for many species. The data can then be examined for relationships with shark size, gender, time of day, lunar cycle and salinity (e.g., Klimley *et al.* 1988, Bruce *et al.* 2005, Simpfendorfer *et al.* 2008, Werry *et al.* 2009). Various elasmobranchs including: great white sharks (Strong *et al.* 1992, Goldman & Anderson 1999); blue sharks (Sciarrotta & Nelson 1977, Carey & Scharold, 1990); scalloped hammerhead sharks (Holland *et al.* 1992, Holland *et al.* 1993); bigeye thresher sharks (Nakano *et al.* 2003); lemon sharks (Morrissey & Gruber 1993); nursehound sharks (Sims *et al.* 2005); leopard sharks (Ackerman *et al.* 2000); mako sharks (Sepulveda *et al.* 2004); Hawaiian and round stingrays (Cartamil *et al.* 2003; Vaudo & Lowe, 2006); and pacific angel sharks (Standora & Nelson 1977) have been actively tracked for short periods of time using continuous acoustic tags and a directional hydrophone and receiver.

Tracking sharks over longer periods of time requires the use of passive, acoustic tracking systems with receivers deployed at specific sites and the tagging of individuals with acoustic tags with battery lives of at least a year. The localised movements of various elasmobranchs including: blacktip whalers (Heupel & Hueter, 2001, 2002, Heupel *et al.* 2004, Heupel & Simpfendorfer 2005a), bonnethead sharks (Heupel *et al.* 2006; Ubeda *et al.* 2009); wobbegong sharks (Huvneers *et al.* 2006); lemon sharks (Wetherbee *et al.* 2007); scalloped hammerheads (Klimley *et al.* 1988); and cownose rays (Collins *et al.* 2007, 2008) have been documented using this technique.

Data on the localised movements of sharks can inform management agencies and help determine spatial and temporal fishing closures and/or marine protected areas to assist with the conservation of a conservation dependent, protected or threatened species (e.g., Cavanagh *et al.* 2003, Heupel & Simpfendorfer 2005b, Bruce *et al.* 2005, Chapman *et al.* 2005, Huvneers *et al.* 2006).

With this in mind, this study uses continuous acoustic tags to provide a detailed understanding of the localised movements of grey nurse sharks at critical habitat sites in coastal waters off the east Australia, including the percentage of time spent in waters of various depths; the percentage of time spent at various distances from the main habitat; and any possible relationships with shark size/age.

### 2.2. Materials and methods

#### 2.2.1. Sites studied

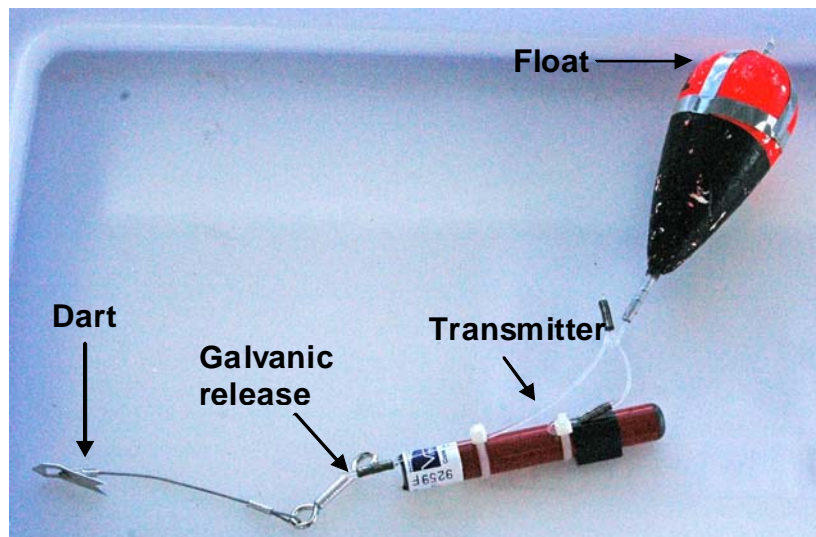
Continuous acoustic tracking studies were done at six sites: Julian Rocks (off Byron Bay); Fish Rock (off South West Rocks); Big Seal Rock (off Seal Rocks); Little Seal Rock (off Seal Rocks); Broughton Is. (to the north of Port Stephens); and the Tollgate Is. (off Batemans Bay).

#### 2.2.2. Acoustic tracking equipment

The acoustic tag used to track each grey nurse shark was a V16P-5H continuous telemetry transmitter (Vemco, Nova Scotia, Canada) equipped with a depth sensor operable to 204 m. The tag was 16 mm in diameter, 108 mm long and had a weight in water of 18 g (Fig. 2.1). The

continuous tags had a battery life of 60 days, interval coding, a pulse period of 1000 ms, a ping width of 10 ms and no delayed start.

To prevent chaffing of the shark's skin, the V16P-5H continuous transmitter was attached to a float providing positive buoyancy. A galvanic timed release (model A5 – Ocean Appliances, Emerald Beach, Australia) was then attached between the transmitter and a stainless steel dart to enable the transmitter to be released from the animal (Fig. 2.1). The corrosion of the galvanic release was dependent on seawater temperature and allowed maximum deployments of 16 – 18 hours.



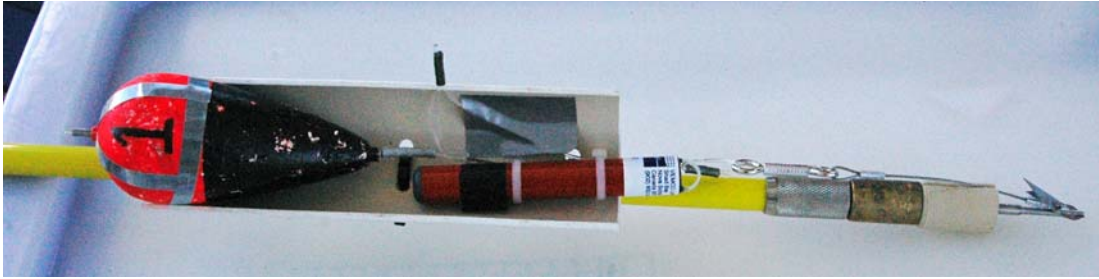
**Figure 2.1.** A V16P-5H continuous telemetry transmitter with associated float, galvanic release and dart.

The signal transmitted by the continuous acoustic tag was detected by a VH100 directional hydrophone fitted to a revolving, tracking pole (attached to the hull of the boat) which was, in turn, connected to a VR60 ultrasonic receiver (Vemco, Nova Scotia, Canada). A compass was also attached to the tracking pole to enable the bearing of the signal to be determined. The control panel of the VR60 receiver included a keypad for entry of transmitter specifications, a signal level meter and controls for gain, volume and channel selection. The signal level meter indicated the amplitude of each pulse received. Whilst tracking, the gain was controlled manually and set at one of 12 levels (0 – 66 dB) increasing in 6 decibel increments. The gain control was used in association with the signal level meter to estimate the distance between the transmitter (i.e., the shark) and the boat. The transmitter's frequency (e.g., 84 kHz) and the pressure sensor's slope and intercept were programmed into the VR60 to enable decoding of the shark's depth (in metres).

### 2.2.3. *Tagging and tracking*

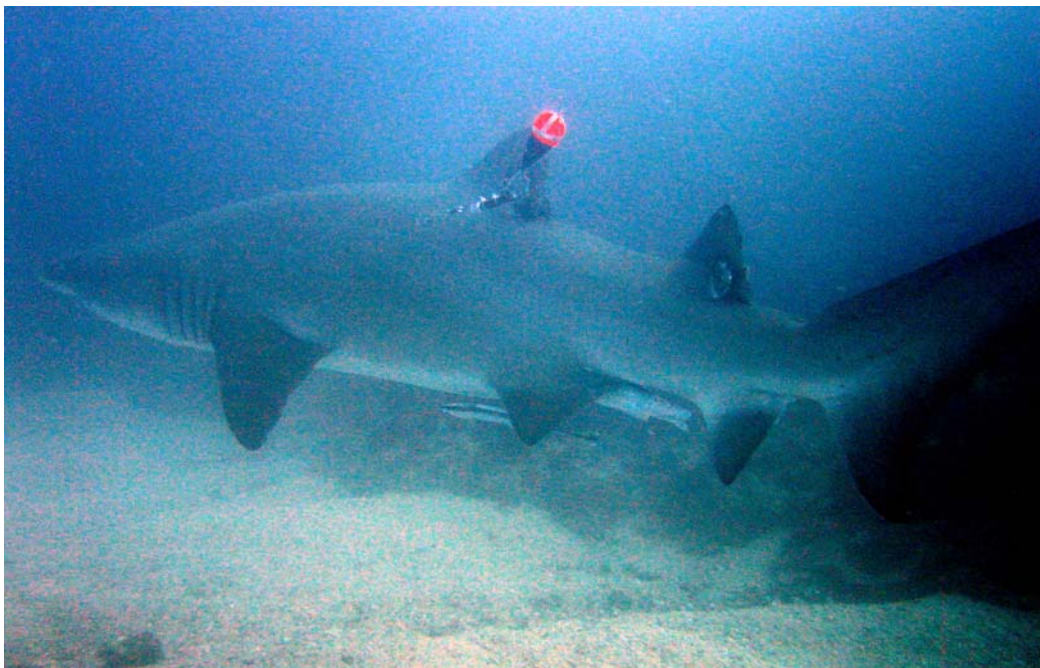
Grey nurse sharks were tagged using a dart tag attached to a modified hand spear with purpose-built cradle to hold the transmitter/float to tag the grey nurse shark (Fig. 2.2). Two scuba divers descended to the edge of the gutter where the sharks were aggregated and remained at this location for 5 minutes to observe the sharks' behaviour and select a target animal. The targeted shark was then approached from above and behind, and tagged in the dorsal saddle (epaxial muscle mass – Liem & Summers 1999; Stoskopf 1993) immediately adjacent to the first dorsal fin (Fig. 2.3). Following tagging, the divers observed the tagged shark for a further 10 minutes to confirm the shark's gender, estimate its total length (TL), record its swim pattern, and note the tag's position and hydrodynamics.





**Figure 2.2.** A V16P-5H continuous telemetry transmitter in the purpose-built cradle of a modified hand spear.

The position of the shark relative to the boat's position was determined at 10 minute intervals via the VR60 acoustic receiver (i.e., transmitter depth, the gain and the signal strength, the compass bearing and the boat's position (via GPS) and water depth (via depth sounder).



**Figure 2.3.** A 2.6 m TL sexually-mature male grey nurse shark tagged with a V16P-5H continuous telemetry transmitter at Julian Rocks, NSW.

## 2.3. Results

### 2.3.1. *Tagging and tracking performance*

Between June 2005 and April 2008, 9 grey nurse sharks (4 males, 5 females) were tagged with continuous acoustic tags at Julian Rocks, Fish Rock, Big Seal Rock, Little Seal Rock, Little Broughton Is. and the Tollgate Is. (Table 2.1). The 4 male grey nurse sharks tagged had TL and TW of 1.50 – 2.60 m and 20 – 113 kg, respectively and 2 were sexually mature. The 5 female grey nurse sharks tagged had TL and TW of the 1.50 – 2.2 m and 20 – 66 kg, respectively and all were sexually immature.

Five of the tracking studies were of shorter duration than planned because of inclement weather. Gale force NE winds and associated rough seas occurred 4 times: twice at Fish Rock, once at Big Seal Rock and once at Little Seal Rock. Similarly, a southerly change with strong (20 – 25 knot) SE winds, rough seas and an increasing SE swell combined with rain and no moonlight meant that tracking had to be terminated ahead of schedule at Broughton Is.

**Table 2.1.** Details of 9 grey nurse sharks tagged with continuous acoustic tags at Julian Rocks (JR), Fish Rock (FR), Big Seal Rock (BS), Little Seal Rock (LS), Little Broughton Is. (LB) and the Tollgate Is. (TI). Tagging was done between April 2005 and April 2008. TL: Total Length; TW: Total Weight and estimated via the length weight curve  $y = 5.4511(x^{3.1716})$ , where y is TW in kg and x is TL in metres.

Track No.	Sex	TL (m)	TW (kg)	Sexual Maturity	Tagging Date	Tagging Location	Deployment Duration (Hours)
1	M	2.60	113	Mature	22.06.05	JR	15.50
2	M	2.50	100	Mature	24.06.05	JR	13.25
3	F	2.20	66	Immature	28.03.07	FR	6.63
4	M	2.00	49	Immature	29.03.07	FR	6.00
5	F	1.50	20	Immature	12.04.05	BS	15.75
6	F	1.70	29	Immature	20.02.07	BS	5.50
7	F	1.60	24	Immature	21.02.07	LS	6.63
8	M	1.50	20	Immature	14.02.06	LB	4.00
9	F	2.00	49	Immature	01.04.08	TI	18.43

### 2.3.2. Track narratives

#### 2.3.2.1. Julian Rocks

##### Track 1

This male grey nurse shark was tagged at 1530 on 22 June 2005 on the north side of Julian Rocks and tracking continued for 15.50 h (Table 2.1). Between the time of tagging and 1758, the shark swam at depths ranging between 13.1 and 20.5 m and remained close to the north side of Julian Rocks (Fig. 2.4a). At 1758, the shark swam towards a fishing boat situated slightly north of Julian Rocks. At 1850, this fishing boat headed closer to Julian Rocks and the shark headed in the same direction. The fishing boat anchored at 1910 and began to burley. The boat remained at anchor over the next hour with the shark's movements circling it (Fig. 2.4a). With the departure of the fishing boat, the shark swam back to Julian Rocks where it remained in close proximity for the remainder of the track. The last data were recorded at 0705, loss of signal occurred at 0712 and the tag was recovered at the surface at 0727 (Fig. 2.4a). The shark occupied a mean ( $\pm$ SD) depth of 15.06 (1.19) m during the 3 hours of daylight (Fig. 2.5a). At night, the shark swam at a mean depth of 16.10 (1.57) m, which was slightly deeper than during the day (Fig. 2.5a). However, the hourly mean depths did not vary greatly over the duration of the track (Fig 2.6a). Over the track, the shark swam to  $\approx$  700 m from Julian Rocks (Fig. 2.4a), spending  $\approx$  92% of its time in waters 10 – 20 m deep (Fig. 2.7e). The shark spent 97% of its time within 500 m and 3% of its time within 1000 m of Julian Rocks, respectively (Fig. 2.8a).



### Track 2

This male grey nurse shark was tagged at 0815 on 24 June 2005 on the northern side of Julian Rocks and tracking continued for 13.25 h (Table 2.1). From time of tagging until 1055, the shark remained close to the northern side of the rocks in depths ranging from 9.90 to 15.90 metres (Figs. 2.4b and 2.5b). Two dive boats arrived at 1035 and 1045, respectively and tied up on the same mooring to the northeast of Julian Rocks. At 1055, the shark changed direction and swam towards the dive boats and subsequently appeared to follow the bubbles of the divers that had entered the water from the dive boats. At 1104, two additional dive boats arrived, one to the north east of the rocks (near the original two boats) and one to the south side. The shark continued swimming in the direction of diver's bubbles or towards the dive boats until all dive boats had departed by 1215. From 1215 to 1700, the shark remained close to the northern side of Julian Rocks. However, when two dive boats arrived respectively at 1325 and 1340, the shark did not exhibit the behaviour (i.e., following diver's bubbles and swimming towards the boats) as it had done earlier in the day. Close to sunset (i.e., at 1700), the shark started to swim in a northerly direction and away from Julian Rocks. At 1720, a fishing boat passed the path of the shark and it changed direction towards this boat. Thereafter, the shark kept swimming in a northerly direction (following the 30 – 40 m bathymetric contours) until tracking ceased at 2100 with the passage of a cold front causing gale force winds, rough seas and increasing swell. During the sharks' passage north from Julian Rocks, it changed directions several times moving in an easterly or westerly direction, only to return to its original (northerly) path. The shark occupied a mean ( $\pm$ SD) depth of 14.70 (1.71) m during the 9 hours of daylight (Fig. 2.5b). At night, the shark swam at a mean ( $\pm$ SD) depth of 29.94 (10.25) m and this was substantially greater than that during the day (Fig. 2.5b) owing to the northerly movements (likely migratory) of the shark away from Julian Rocks. The hourly mean depths were similar throughout most of the track, but increased with the migratory movements away from Julian Rocks (Fig. 2.6b). During the track, the shark spent  $\approx$  90% of its time in waters 10 – 15 m deep (Fig. 2.7b). Prior to leaving Julian Rocks, the shark remained in the gutter (Fig. 2.4a). Incorporating the likely northerly, migratory movements, the shark spent  $\approx$  95% of its time within 500 m,  $\approx$  2% of its time within 500 – 1000 m and  $\approx$  3% of its time within 1000 – 1500 m of Julian Rocks (Fig. 2.8b).

#### 2.3.2.2. Fish Rock

### Track 3

This female grey nurse shark was tagged at 0902 on 28 March 2007 in the gutter at the deep entrance to Fish Rock cave and tracking continued for 6.63 h (Table 2.1) prior to its discontinuation. From the start to the end of tracking (i.e., from 0902 to 1540), the shark remained in a restricted area to the south-east of Fish Rock (Fig. 2.4c). The shark swam at depths varying between 18.40 and 28.90 metres (Fig. 2.5c) with a mean depth of 21.32 m. The hourly mean depths did not vary greatly over the duration of the track (Fig. 2.6c). During the track, the shark spent  $\approx$  95% of its time in waters 15 – 25 m deep (Fig. 2.7c). The shark remained within 45 m of the SE side of Fish Rock for the vast majority of the track (Fig. 2.4c) and spent 100% of its time within 500 m of Fish Rock (Fig. 2.8c).

### Track 4

This male grey nurse shark was tagged at 0852 on 29 March 2007 in the gutter at the deep entrance to Fish Rock cave and tracking continued for 6.00 h (Table 2.1) prior to its discontinuation. Over the duration of the track, the shark remained in a restricted area to the SE of Fish Rock (Fig. 2.4d). The shark swam at depths varying between 18.60 and 29.30 metres (Fig. 2.5d) with a mean depth of 21.47 m and the hourly mean depths did not vary greatly over the duration of the track (Fig. 2.6d). Moreover, the shark's movements were not affected by the scuba divers that entered the water at 0938 with the animal remaining in the same, restricted area of reef with the recreational

scuba divers. During the track, the shark spent  $\approx 95\%$  of its time in waters 15 – 25 m deep (Fig. 2.7d). The shark remained within 40 m of the SE side of Fish Rock for the vast majority of the track (Fig. 2.4d) and spent 100% of its time within 500 m of Fish Rock (Fig. 2.8c).

### 2.3.2.3. *Big Seal Rock*

#### *Track 5*

This female grey nurse was tagged at 1400 on 12 April 2005 and tracking continued for 15.75 h (Table 2.1). Between the time of tagging and 1548, the shark swam at depths ranging between 8.5 and 11.7 m and remained at a distance of between 5 and 80 m from Big Seal Rocks in an area predominantly to the northern tip of the rock. Between 1548 and 1742, the shark spent time in the same general area as the previous time period, except during the latter part when it moved to the north-eastern tip of the rock and then down the eastern side of the island approximately 65 m from the northern tip. Over this time period, the depth of the shark varied from 7.5 to 13.8 m with its distance off the rock varying from 2 – 62 m. At 1742, the shark was at the north-eastern tip of the rock within 7.5 m of the rock. The shark then moved to the southeast for a short period before travelling away from the rock to the northwest about 75 m from the northern tip. The shark then moved south and at 2013, the shark was on the western side of the rock, 35 m from the northern tip and 19 m away from the rocks. The depth of the shark during this time period ranged from 6 m to 13.8 m. Over the next 2 hours (2013 to 2222), the shark spent the majority of its time in the north-western corner within 67 m of the rock. At 2042, the shark moved to the northern tip, but the majority of the track was spent parallel to the western side of the rock. The depth range of the shark was narrow at between 8.5 and 9.9 m and the distance range from the rock was 14 to 67 m. From 2222, the shark spent the next two hours in a similar location to the previous time period, running parallel to the western side of the rock in the north western corner. The shark did venture further north to a distance of 74 m from the northern tip and also further south, ending up down the western side of rock, approximately 110m from the northern tip and 20 m away from the rock. During this period, the shark swam at depths ranging from 8.5 to 12.7 m at a range of 17 to 74 m from Big Seal Rock. Between 0017 and 0225, the movements of the shark were essentially identical to the previous time period. However, the shark did not swim as much beyond the tip of the island at a similar distance (111 m) south along the western side of the rock. The shark remained within 17 m to 42 m from the rock at depths ranging from 8.9 to 11 m. From 0225 to 0420, the shark remained on the western side of the rock within 14 m to 38 m from the rock. The shark never ventured beyond the northern tip and the furthest distance south from the northern tip was 115 m. The shark's movements are more closely associated than previous tracks. The depth of the shark ranged from 7.8 to 10.3 m. For the remaining 2 hours of the track, the shark maintained similar movements and position to the previous 2 hours, running parallel to the western side of the rock. The distance of the shark from Big Seal Rock varied from 12 to 35 m and the shark remained within 104 m from the northern tip of the rock. Over the entire track, the shark swam in depths varying between 8.2 to 10.3 m (Fig. 2.5e) with a mean depth of 9.61 m and the hourly mean depths did not vary greatly over the duration of the track (Fig. 2.6e). During the track, the shark spent  $\approx 75\%$  of its time in waters 5 – 10 m deep (Fig. 2.7e). The shark spent 73% of the tracking period in the north-western corner, 21% in the north-eastern corner and 6% in the south-western corner (Fig. 2.4e). Importantly, the shark spent 100% of its time within 500 m of Big Seal Rock (Fig. 2.8e).

#### *Track 6*

This female grey nurse shark was tagged at 0915 on 20 February 2007 on the north-western side of Big Seal Rock and tracking continued for 5.50 h (Table 2.1). Tracking commenced at 0923 and throughout the track (Fig. 2.4f), the shark swam at depths varying between 5.00 and 12.60 metres (Fig. 2.5f) with a mean depth of 9.61 m. The hourly mean depths did not vary greatly over the duration of the track (Fig. 2.6f). During the track, the shark spent  $\approx 83\%$  of its time in waters 5 – 10 m deep (Fig. 2.7f). The shark remained close to the north-western side of Big Seal Rock for the

vast majority of the track and tracking ceased following the last detection of the shark at 1450. Importantly, the shark spent 100% of its time within 500 m of Big Seal Rock (Fig. 2.8f).

#### 2.3.2.4. *Little Seal Rock*

##### *Track 7*

This female grey nurse shark was tagged at 0818 on 21 February 2007 to the west of Little Seal Rock and tracking continued for 6.63 h (Table 2.1) prior to its discontinuation due to gale force NE winds and rough seas. The shark initially swam south, but then changed direction and headed north to a position just south of where it was tagged (Fig. 2.4g). The shark then headed in a north-easterly direction towards a series of gutters on the north-eastern side of Little Seal Rock. The shark then occupied this area for the remainder of the track (Fig. 2.4g). Over the entire track, the shark swam at depths varying between 13.90 and 22.40 m (Fig. 2.5g) with a mean depth of 18.87 m. The hourly mean depths shallowed towards the end of the track at 1456 (Fig. 2.6g). During the track, the shark spent  $\approx 97\%$  of its time in waters 15 – 25 m deep (Fig. 2.7g). The shark spent 97.9% of its time within 100 m of Little Seal Rock and 100% of its time within 500 m of Little Seal Rock (Fig. 2.8g).

#### 2.3.2.5. *Little Broughton Island*

##### *Track 8*

This female grey nurse shark was tagged at 1630 on 14 February 2006 in a small, gutter on the eastern side of the Little Broughton Is. and tracking continued for 4.00 h (Table 2.1) prior to its discontinuation because of southerly change producing strong (20 – 25 knot) SE winds, rough seas and an increasing SE swell. These conditions combined with rain and no moonlight made navigation of the tracking vessel close to the shore extremely dangerous. Following tagging, the shark remained in the gutter until 17:20 when it moved out to the north, returning to the gutter by 1735 (Fig. 2.4h). The shark remained in the gutter until 19:00 when it again left the gutter and headed south following a path very close (i.e., within 20 m) of the island (Fig. 2.4h). The signal was lost at 20:30 as result of the inclement sea conditions and the sharks close proximity to the island and breaking waves. Over the entire track, the shark swam at a depths varying between 6.30 and 16.40 m (Fig. 2.5h) with a mean ( $\pm$ SD) depth of 8.56 (2.37) m. The hourly mean depths became greater towards the end of the track at 2030 (Fig. 2.6h). During the track, the shark spent  $\approx 89\%$  of its time in waters 5 – 10 m deep (Fig. 2.7h). The shark spent the majority of its time within 110 metres of Little Broughton Is. and 100% of its time within 500 m of the island (Fig. 2.8h).

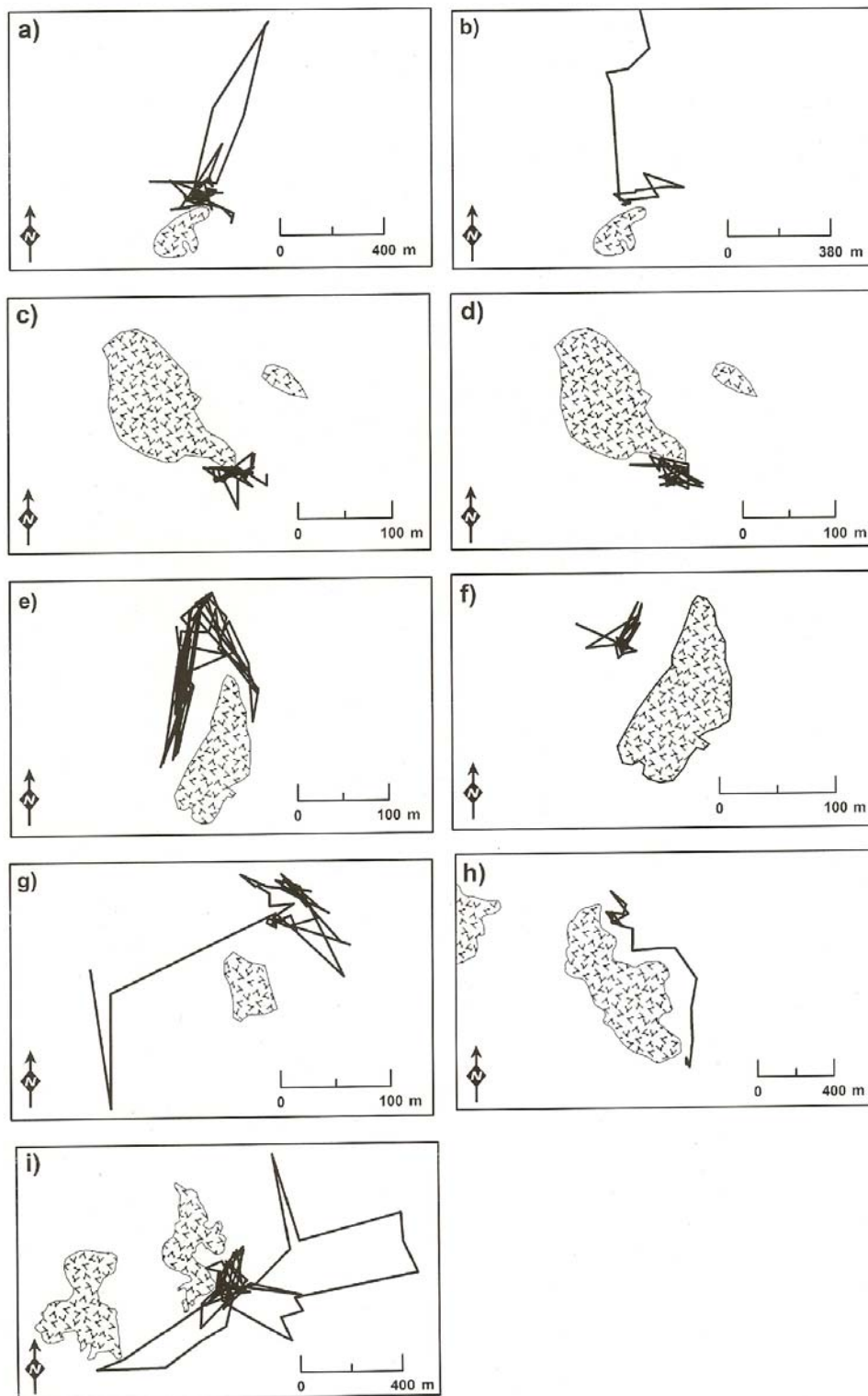
#### 2.3.2.6. *Tollgate Islands*

##### *Track 9*

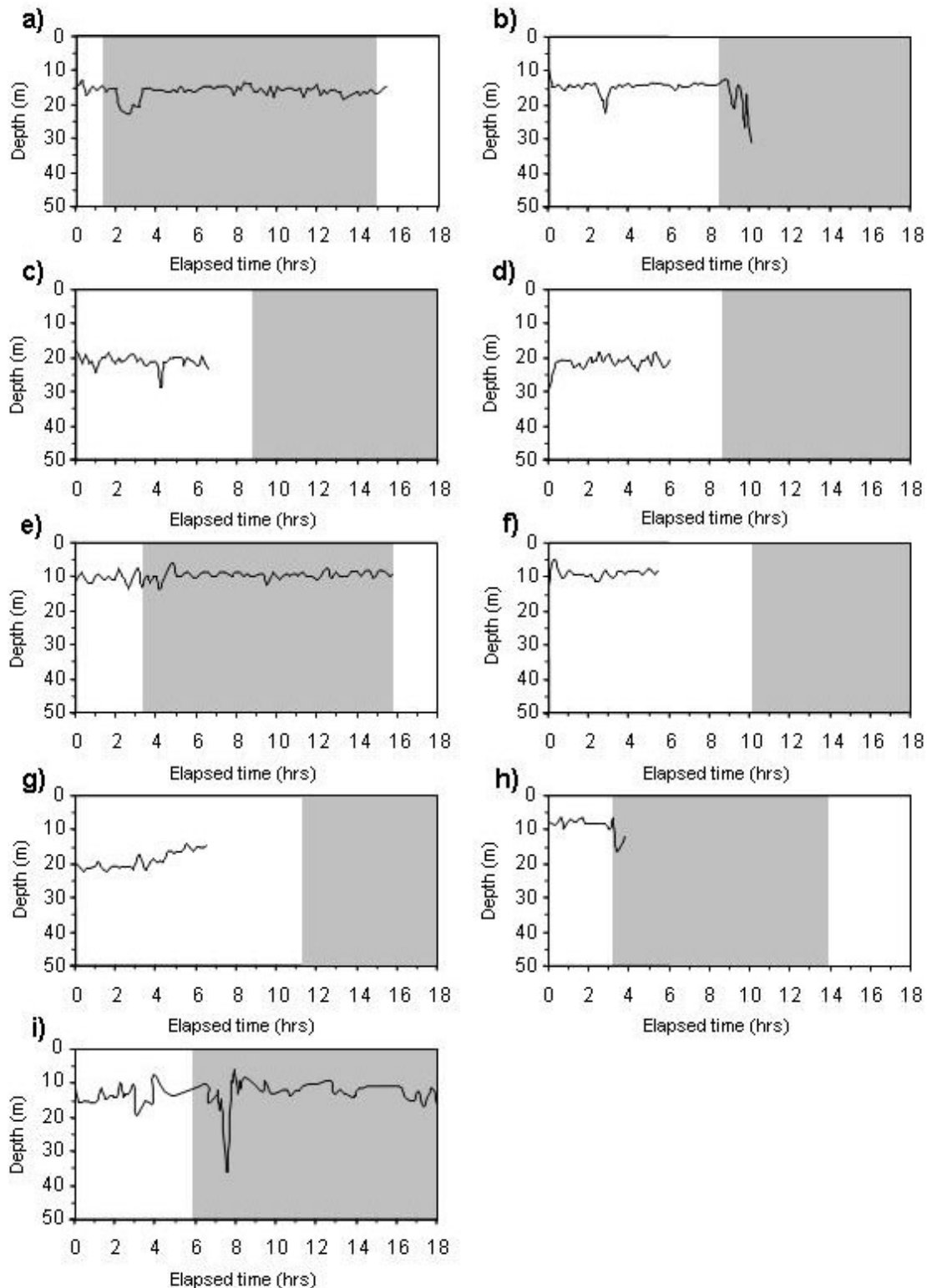
This female grey nurse was tagged at 1250 on 1 April 2008 in the main gutter on the eastern side of the Tollgate Is. and tracking continued for 18.43 h (Table 2.1). From 1250 until 2003, the shark remained close to the main gutter with a single excursion north around 1630 (Fig. 2.4i). During this time, the depth of the shark varied from 7.80 to 19.80 m. From 2003 to 2056, the shark left the gutter and swam in a north-easterly direction away from the island to a maximal distance of  $\approx 606$  m. The shark returned to the gutter at 2109, where it remained until 0100. From 0100 until 0145, the shark swam to the southern tip of the islands and then began swimming back towards the main gutter. The shark entered the main gutter at approximately 0230 and remained there until the track ended at 0700. The shark spent  $\approx 69\%$  of its time in waters 10 – 15 m in depth. During daylight hours, the shark occupied a depth range of 8.20 to 20.20 m with a mean ( $\pm$ SD) depth of 14.34 (2.51) m (Fig. 2.5i). At night, the shark occupied a depth range of 6.50 to 36.10 m with a mean ( $\pm$ SD) depth of 13.85 (5.70) m (Fig. 2.5i). The hourly mean depths fluctuated throughout the track and the changes were associated with the excursions away from the gutter during the night (Fig.

2.6i). During the track, the shark spent  $\approx 69\%$  of its time in waters 10 – 15 m deep and  $\approx 19\%$  of its time in waters 15 – 20 m deep (Fig. 2.7i). The shark spent the majority of its time within 100 metres of the Tollgate Is., swimming out to  $\approx 650$  m away on a couple of occasions (Fig. 2.4i). Overall, the shark spent 98% of its time within 500 m and 2% of its time within 1000 m of the island, respectively (Fig. 2.8i).

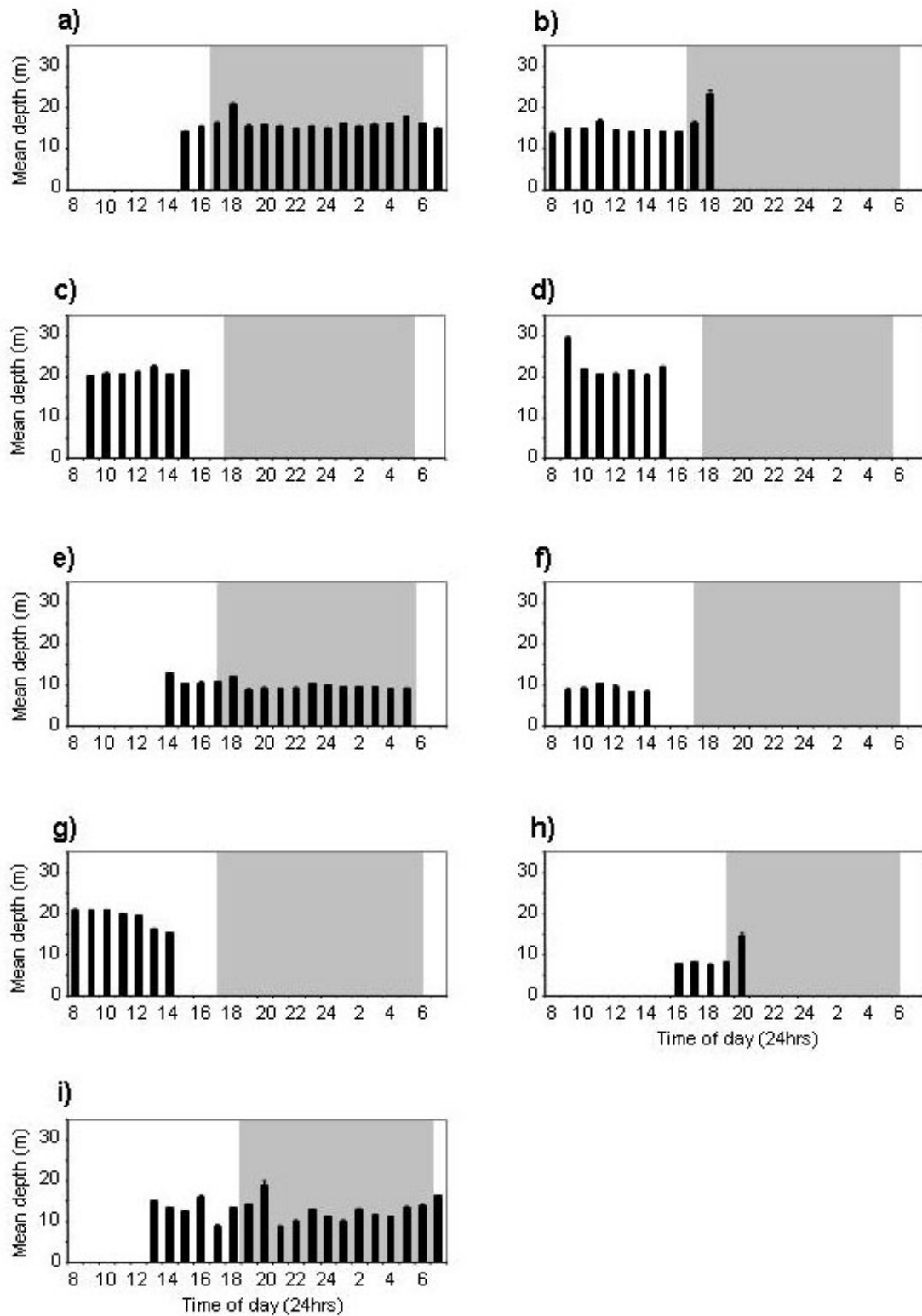
The total lengths of the grey nurse sharks tracked using continuous acoustic telemetry at critical habitat sites in NSW coastal waters were positively correlated with the maximal distance from the main gutter (Fig. 2.9a), negatively correlated with the percentage of time spent within 500 m of the habitat (Fig. 2.9b), and positively correlated with the percentage of time spent within 500 – 1000 m of the habitat (Fig. 2.9c).



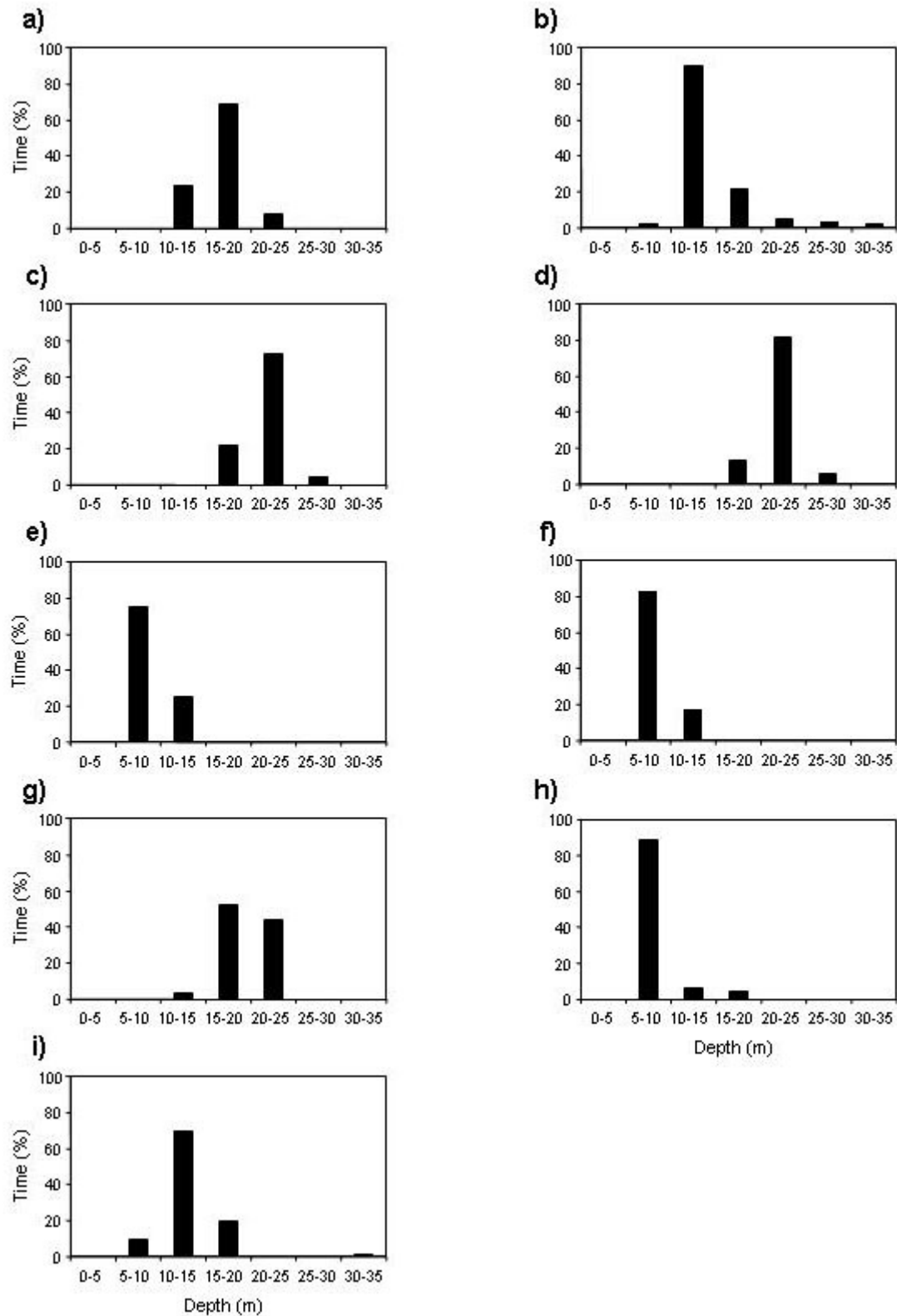
**Figure 2.4.** Tracks of localised movements obtained via continuous acoustic telemetry of grey nurse sharks tagged at: (a, b) Julian Rocks; (c, d) Fish Rock; (e, f) Big Seal Rock; (g) Little Seal Rock; (h) Little Broughton Island; and (i) Tollgate Islands.



**Figure 2.5.** Depths of tagged grey nurse shark during tracks of localised movements obtained via continuous acoustic telemetry at: (a, b) Julian Rocks; (c, d) Fish Rock; (e, f) Big Seal Rock; (g) Little Seal Rock; (h) Little Broughton Island; and (i) Tollgate Islands. Shading denotes hours of darkness.

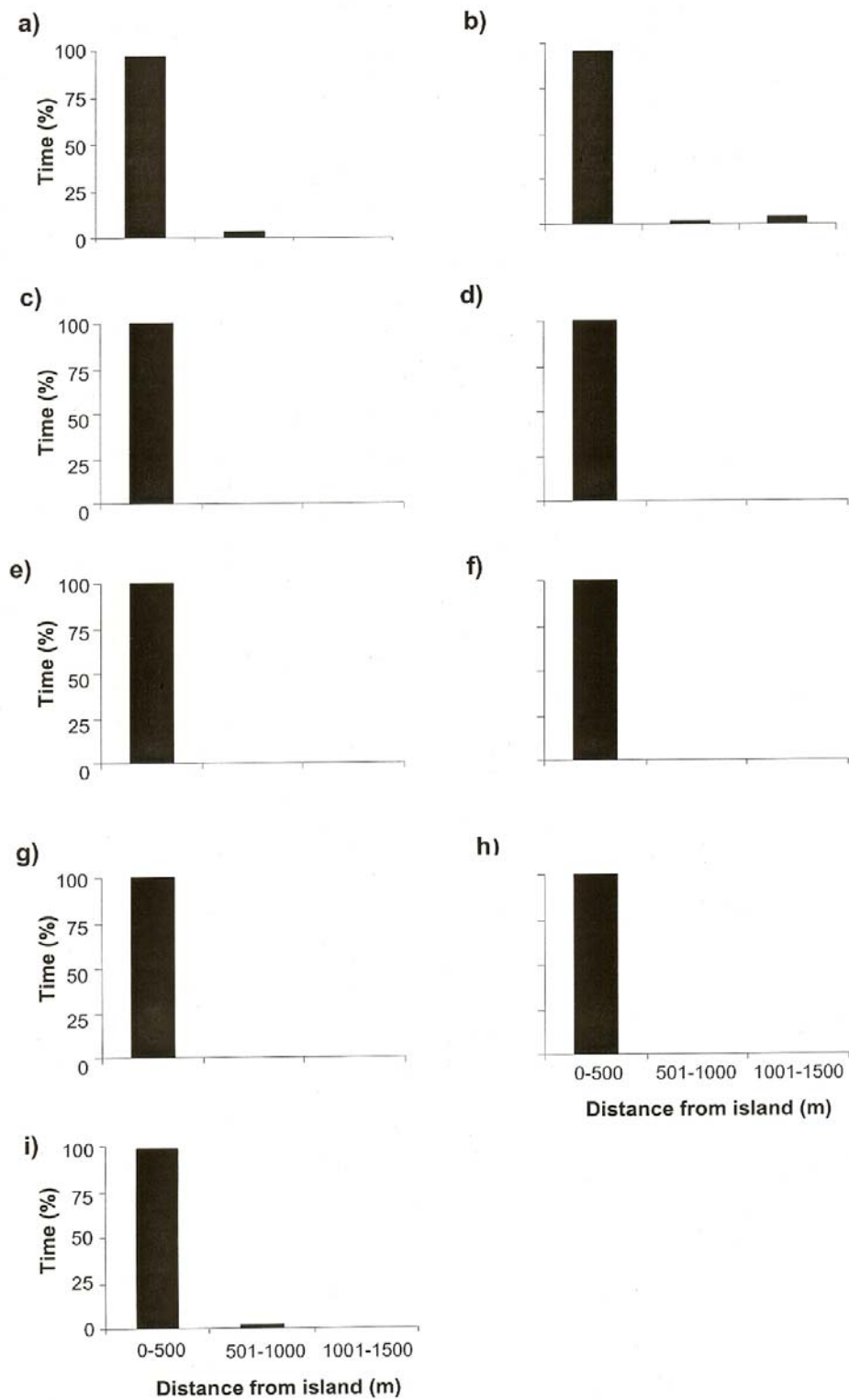


**Figure 2.6.** Mean ( $\pm$  SE) hourly depths of tagged grey nurse shark during tracks of localised movements obtained via continuous acoustic telemetry at: (a, b) Julian Rocks; (c, d) Fish Rock; (e, f) Big Seal Rock; (g) Little Seal Rock; (h) Little Broughton Island; and (i) Tollgate Islands. Shading denotes hours of darkness.

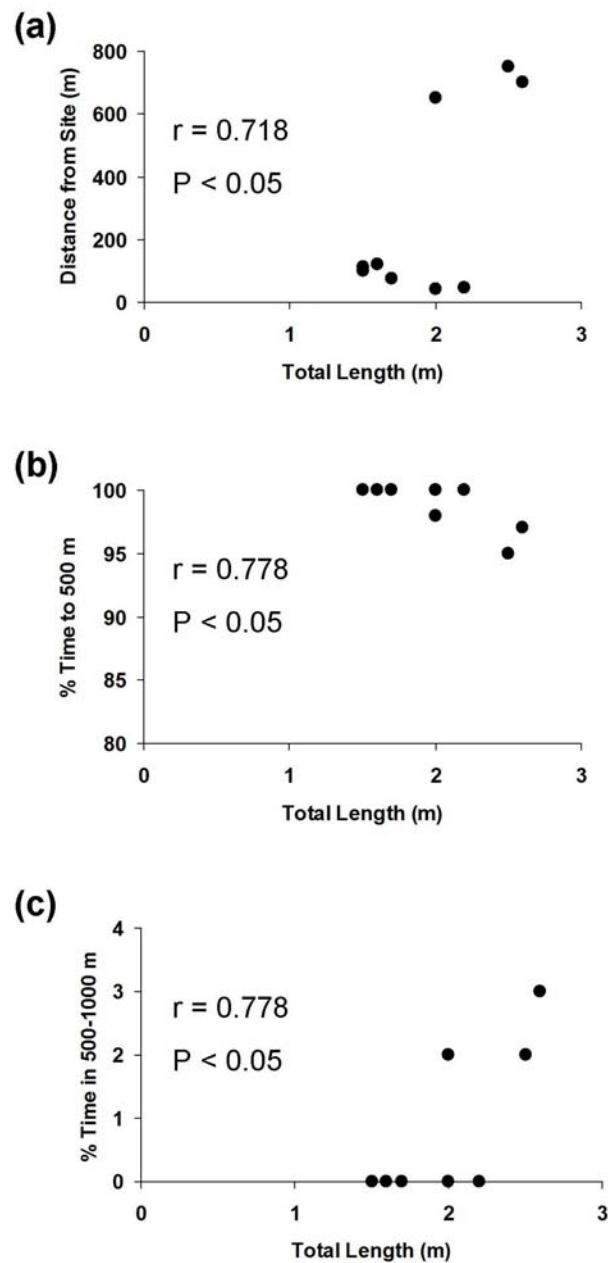


**Figure 2.7.** Percentage of total track duration spent at various depths by grey nurse shark when tagged at: (a, b) Julian Rocks; (c, d) Fish Rock; (e, f) Big Seal Rock; (g) Little Seal Rock; (h) Little Broughton Island; and (i) Tollgate Islands.





**Figure 2.8.** Percentage of total track duration spent at 0 – 500, 501 – 1,000 and 1,001 – 1,500 metres from the main gutter occupied by the grey nurse shark when tagged at: (a, b) Julian Rocks; (c, d) Fish Rock; (e, f) Big Seal Rock; (g) Little Seal Rock; (h) Little Broughton Island; and (i) Tollgate Islands.



**Figure 2.9.** Relationships between the total length of the grey nurse sharks tracked using continuous acoustic telemetry and (a) maximal distance from the main gutter, (b) the percentage of time spent within 500 m of the habitat, (c) the percentage of time spent within 500 – 1000 m of the habitat for critical habitat sites in NSW coastal waters.

## 2.4. Discussion

As has been the case in previous studies (e.g., Carey & Scharold, 1990, Strong *et al.* 1992, Holland *et al.* 1993, Goldman & Anderson 1999 Nakano *et al.* 2003, Sims *et al.* 2005), tracking using continuous acoustic telemetry proved to be a reliable means for obtaining detailed information concerning habitat usage, activity space, diel patterns of behaviour and swimming depths of grey nurse sharks at critical habitat sites in NSW coastal waters. The use of this technique was, however, dependent on safe, navigable sea-conditions, especially when we were generally in very close proximity to the rocky outcrops and islands where the sharks inhabit gutters, overhangs and caves.

The grey nurse sharks tracked at the six sites, from Byron Bay to Batemans Bay, exhibited similar patterns of movement characterised by extensive periods patrolling back and forth in the gutters at these sites, interspersed with periods of greater activity involving excursions around and/or away from the particular site. The sharks generally remained close to the bottom, but this varied during excursions away from the site when the sharks moved over a range of depths. These results are consistent with a previous study by Bruce *et al.* (2005) that also involved tracking studies in QLD (i.e., Flat Rock – off North Stradbroke Is.) and NSW (i.e., South Solitary Is., Fish Rock and the Tollgate Is.) coastal waters. Three of the sharks tracked during our study did not, however, undertake any excursions. On each of these occasions, the tracks had to be terminated because of inclement weather (i.e., gale force winds and associated rough seas). It is possible that these tagged sharks also undertook excursions around and/or away from the sites, but we were unable to record these events because of our forced absence.

It is important to recognise that, like previous researchers (e.g., Sciarrotta and Nelson 1977, Morrissey & Gruber 1993, Sepulveda *et al.* 2004, Werry *et al.* 2009), we were constrained by the prevailing sea-conditions and thus, the range of localised movements described in this study may not be completely representative of the behaviour and localised movements of grey nurse sharks. The sharks may exhibit different localised movements and behaviour during periods of heavy swell and rough seas. Clearly, continuous acoustic tracking is not possible under such circumstances, especially given the close proximity to the rocky outcrops and islands required to track these sharks. However, data acquired via the R-coded, acoustic tags and SEACAMS (Chapter 3) will allow some insight, albeit based on analyses of datasets with reduced spatial information, into the localised movements and behaviour of grey nurse sharks during periods of heavy swell and rough seas occurring at varying spatial and temporal scales along the SE Australian coast (Trenamen & Short 1987).

The results obtained during this study, together with those of Bruce *et al.* (2005) at Flat Rock, South Solitary Is., Fish Rock and the Tollgate Is., clearly show that grey nurse sharks spend a vast majority of their time (mean ( $\pm$ SD) = 93.7 (10.9)%) in the waters within 0 – 500 m of an aggregation site. The excursions further away from the site that extend to waters 500 – 1000 m and 1000 – 1500 m contributed only 4.0 (7.2)% and 2.3 (4.0)% of the shark's time, respectively when tracked at these 8 sites. However, given, the significant correlations between the total length of the tracked grey nurse sharks and the maximal distance from the main gutter and the percentage of time spent within 500 – 1000 m of the habitat, it is likely that the frequency and duration of excursions away from the site, and the spatial extent of the movement may vary among sites possibly reflecting the local population size-structure. Combined, these results provide further evidence of the restricted movements of grey nurse sharks when they occupy aggregation sites.

### 3. Migratory movements

#### 3.1. Introduction

In the past, the migratory movements of sharks have been documented using conventional (e.g., streamer, rototag) tags (Kohler & Turner 2001 for a review, Otway & Burke 2004, Queiroz *et al.* 2005). Two long-term studies involving the tagging of grey nurse sharks with conventional tags have provided substantial information on the species' migratory movements off the east coasts of the USA (Kohler *et al.* 1998) and South Africa (Davies & Joubert 1966). The National Marine Fisheries Service Cooperative Shark Tagging Program has tagged sharks on the east coast of the USA and over the period 1962 – 1993 (i.e., 31 years), 562 grey nurse (sandtiger) sharks (257 males, 242 females and 63 sex unknown) have been tagged. Of the 31 recaptured individuals, the maximum distance travelled was 1172 km with a maximum time at liberty of 3.2 years and a mean recapture rate of 0.18% per annum.

The Oceanographic Research Institute in Durban (South Africa) has also tagged grey nurse (spotted ragged-tooth) sharks for over 30 years (Davies & Joubert 1966). From 1964 to 1995, 1637 grey nurse sharks were tagged with 79 individuals (4.8%) being recaptured giving a mean recapture rate of 0.15% per annum. The maximum distance travelled by grey nurse sharks along the east coast of South Africa was 1416 km. These large-scale, migratory movements of grey nurse sharks off the east coasts of the USA and South Africa have been linked to water temperatures and the sharks' reproductive cycle (USA – Gilmore *et al.* 1983, Gilmore *et al.* 2005, South Africa – Cliff 1989, Dicken 2007).

Preliminary data on the migratory movements of grey nurse sharks along the east coast of Australia have been obtained using: underwater visual census techniques (Otway & Parker 2000, Otway *et al.* 2003); cattle ear tags (Otway and Burke 2004); pop-up archival satellite tags (Otway 2004); and some initial acoustic tagging (Bruce *et al.* 2005). These studies have suggested a northerly migration of grey nurse sharks over autumn/winter followed by a southerly migration in spring/summer.

The rapid improvement in acoustic and satellite tagging technologies have enabled similar advances in migratory studies. Acoustic receivers deployed in arrays or curtains have provided detailed information on the migratory movements of acoustically-tagged fish (e.g., Cod – Comeau *et al.* 2002, Atlantic Salmon – Lacroix & McCurdy 1996, Finstad *et al.* 2005, Lacroix *et al.* 2005, Pacific Ocean Salmon – Welch *et al.* 2003, Rockfishes – Starr *et al.* 2000, Squid – Stark *et al.* 2005, Pecl *et al.* 2006) and sharks (e.g., Whale sharks – Eckert & Stewart 2001, Hsu *et al.* 2007, White sharks – Dewar *et al.* 2004, Weng *et al.* 2007, Tiger sharks – Heithaus *et al.* 2007, School sharks – West & Stevens 2001, Sandbar sharks – Casey *et al.* 1985). Archival tags have been used to document the migratory movements of sharks (e.g., West & Stevens 2001) and rays (e.g., Hunter *et al.* 2005). Smart positioning or temperature transmitting (SPOT – [www.wildlifecomputers.com](http://www.wildlifecomputers.com)) tags are commonly attached to the first dorsal fins of sharks that regularly frequent the sea-surface. Location data are transmitted while the shark is swimming at the surface with the tag's antenna exposed to the atmosphere. This enables the movements of the shark to be tracked in real time. Unfortunately, these tags cannot be used with grey nurse sharks because the species spends little time at the sea-surface (Otway 2004). However, pop-up archival satellite tags provide an ideal solution as they are pre-programmed to release from the shark after a given period of time and transmit the archived data to satellites. These tags have been used on a range of elasmobranchs including stingrays (Le Port *et al.* 2008), white sharks (Dewar *et al.* 2004, Weng *et al.* 2007), and whale sharks (Eckert & Stewart 2001).

With this in mind, pop-up archival satellite tags and R-coded acoustic tags used in conjunction with NSW DPI's South East Australian Coastal Acoustic Monitoring System (SEACAMS) permitted a more detailed documentation of the migratory movements of grey nurse sharks in coastal waters off the east coast of Australia. The data allowed us to quantify the: migratory routes; distances travelled; timing of arrival at and departure from sites; duration of occupation of sites; and percentage of time spent in waters with various depths and temperatures.

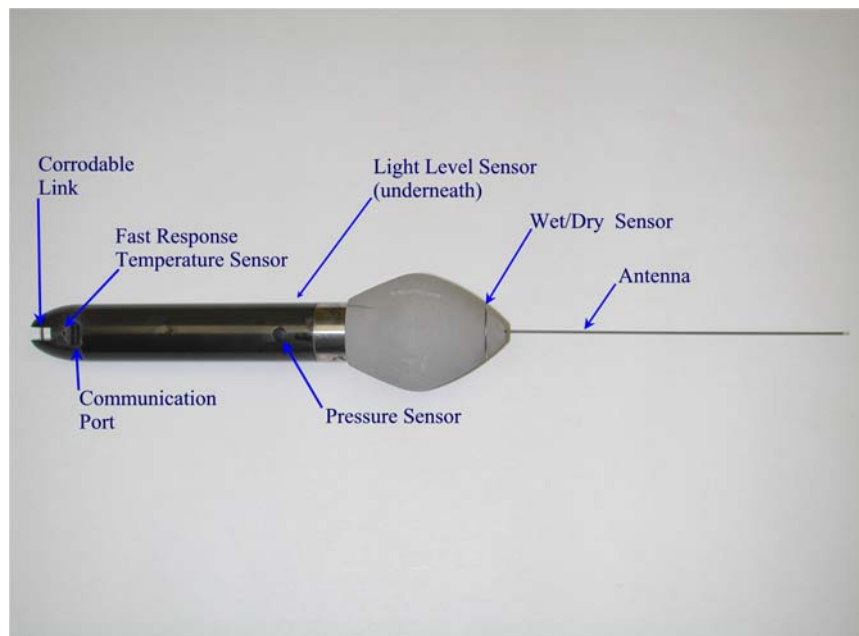
## 3.2. Materials and methods

### 3.2.1. Pop-up archival satellite tags

#### 3.2.1.1. Tags

These "state of the art", computerised tags (Fig. 3.1) are programmed to measure conductivity, water temperature, depth and light levels at user-defined intervals. This information is then stored in the tag's memory. Each tag is pre-programmed to leave the shark on a given date and once free, the tag floats to the sea's surface where the archived data are transmitted via the ARGOS system to NOAA satellites and thence to receiving stations on earth. The information is then emailed to NSW DPI where it is decoded and analysed using computer software provided by the tag's manufacturer, Wildlife Computers.

The pop-up tags were programmed with a range of deployment durations (Table 3.1) for several reasons. First, rough seas can greatly affect the transmission of data to the NOAA satellites because the tag's aerial becomes submerged with breaking waves. Second, the different deployment durations enable better geolocation information to be obtained along the migratory route.



**Figure 3.1.** Photograph of a pop-up archival satellite tag manufactured by Wildlife Computers with various features labelled.

Prior to deployment, the pop-up archival satellite tags were painted with 2 coats of antifouling paint to prevent the settlement and growth of sessile marine organisms (particularly barnacles) that has been documented with other tags used on sharks (Davies & Joubert 1967ab, Dicken *et al.* 2006, Otway unpubl. data). Importantly, the presence of fouling organisms on pop-up archival satellite tags can reduce the tag's buoyancy and prevent it from surfacing following pop-off. The tag was then attached to  $\approx 10$  cm of monofilament line with an intra-muscular dart made of surgical plastic.

### 3.2.1.2. Tagging procedures

Grey nurse sharks were lassoed around the caudal peduncle by scuba divers, brought to the surface and into a semi-submerged stretcher attached to the side of a boat where each animal was placed in dorsal recumbency to induce tonic immobility (Gruber 1981, Henningsen 1994). Each shark was then rolled into left or right lateral recumbency. As *Staphylococcus epidermidis*, together with other bacteria, are common on the skin of sharks (Smith 1992, Mylniczenko *et al.* 2007), the skin at the base of the dorsal fin was cleansed with a non alcohol-based surgical scrub prior to a 10 mm incision being made. The plastic dart was inserted into the musculature using a purpose-built, sterile stainless steel, applicator. The sex of the shark was determined via the presence of claspers in males, the calcification of which was used to indicate sexual maturity. Sexual maturity in females was identified via total length. The total length (TL) of each shark, with tail in a depressed position (Compagno 2002, Bass *et al.* 1975), was measured to the nearest cm prior to releasing the animal. The TL was used to estimate the total weight (TW) of the shark to the nearest kg via a length weight curve developed from necropsies of grey nurse sharks over the past 10 years.



**Figure 3.2.** Grey nurse shark restrained in right lateral recumbency in a stretcher next to the boat. Note skin of shark is still bronze-brown in colour and there is no evidence of pallor following capture by a lasso around the caudal peduncle.

### 3.2.1.3. *Monitoring of possible capture stress*

Whilst each shark was held in the stretcher, staff routinely monitored the animal for signs of stress by observing the buccal pumping rate, skin colour, skin turgor and pupillary reflexes. Grey nurse sharks can use either ram ventilation or buccal pumping to ensure water passes over their gills. Buccal pumping is used when the animal requires additional oxygen for its metabolic processes. During capture, sharks often resort to anaerobic metabolism which can increase the lactate concentrations in blood (Smith 1992). The additional oxygen demand is caused by the aerobic breakdown of lactate occurring in the liver.

Sharks that are stressed often become much lighter in colour due to vasoconstriction of peripheral blood vessels (in the skin) in response to catecholamines (e.g., adrenalin). While this ensures the maintenance of good blood flow to the essential organs, it simultaneously provides a reliable, visual indicator of a stressed shark (Stoskopf 1990).

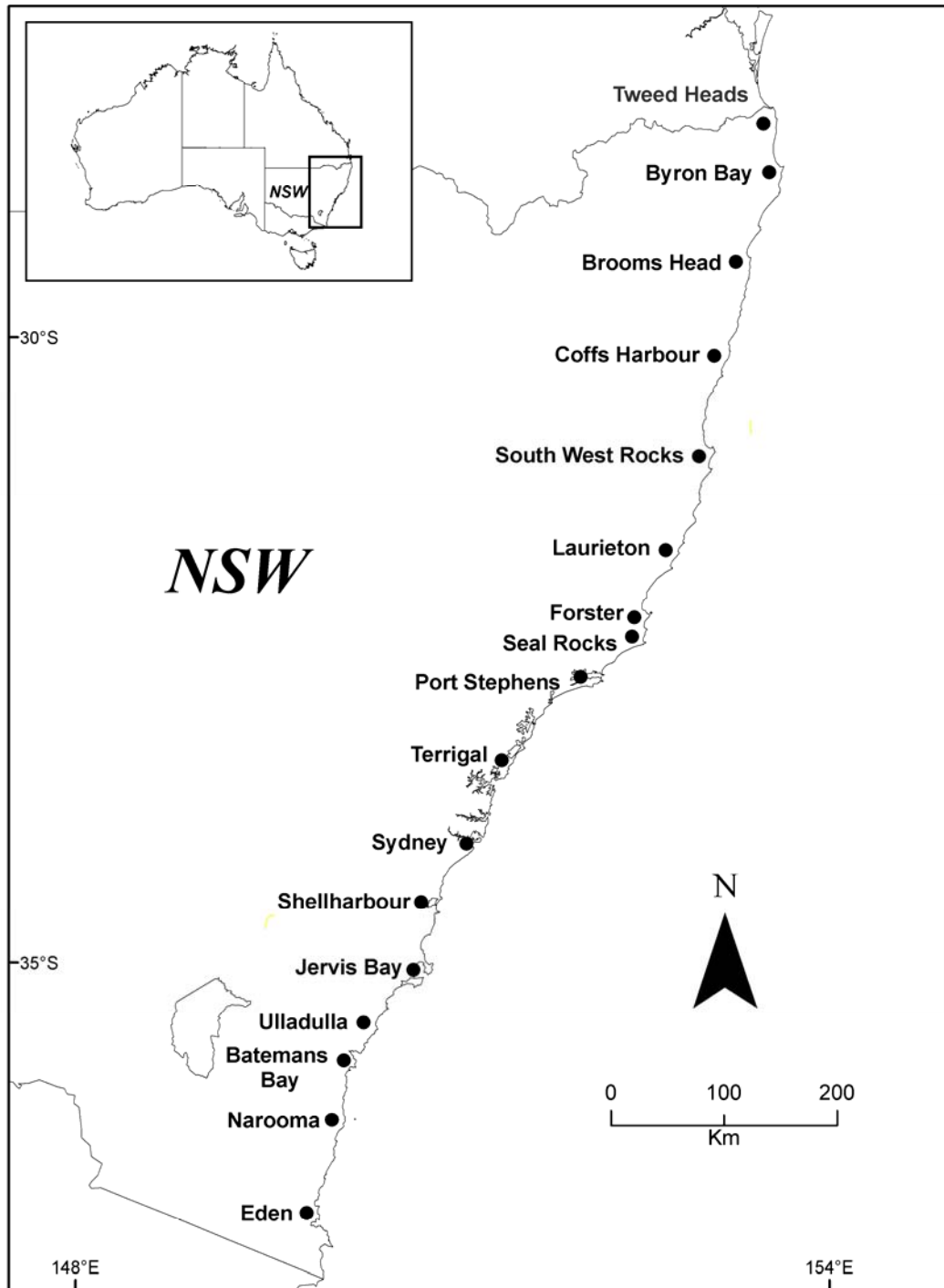
Sharks held captive and restrained for long periods of time exhibit a stiffening (rigidity) of the muscles that progresses from the caudal peduncle (near the tail) towards the head (Gruber 1980, Gruber & Keyes 1981, Martini 1978, 2004). The duration of restraint used by NSW DPI was less than 15 minutes and therefore, not sufficient for the onset of this condition in grey nurse sharks. Nevertheless, we took a precautionary approach and monitored for the development of this condition by assessing the skin turgor at various points along the body while the shark was restrained in the stretcher.

Sharks are similar to mammals and can vary the size of the pupil via changes to the iris in response to differing light levels (Moss 1984). This provides a simple and effective means of assessing possible nervous dysfunction. Moreover, sharks with bacterial sepsis or meningitis frequently exhibit reduced visual responses (Stoskopf 1990). Consequently, we monitored the responses of eyes to stimulation by light while the shark was restrained in the stretcher.

Following the animal's release, divers monitored the swimming behaviour of the tagged shark for 10 – 15 minutes.

### 3.2.2. *South East Australian Coastal Acoustic Monitoring System*

A South East Australian Coastal Acoustic Monitoring System (SEACAMS) has been set up by the NSW Department of Primary Industries. The entire system comprises 70 acoustic listening stations deployed at various sites along the NSW coast, from the Victorian to Queensland borders (Fig. 3.3). Each listening station consists of an acoustic receiver and temperature logger attached to a bottom-set mooring deployed within a gutter utilised by grey nurse sharks in the past or present (Fig. 3.4). The number of listening stations deployed at any given site varies depending on a number of factors including the usage of the site by grey nurse sharks, depth, currents and topography.



**Figure 3.3.** Map showing locations of acoustic listening stations comprising SEACAMS.



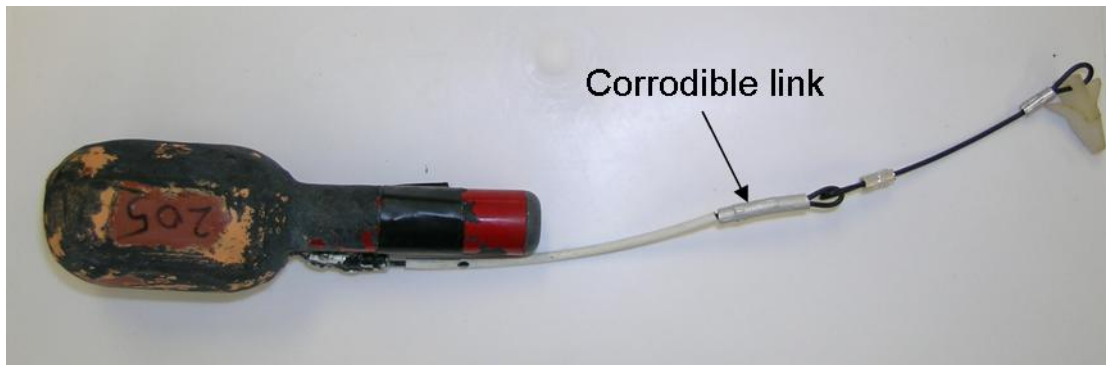


**Figure 3.4.** Photograph of SEACAMS listening station comprising VR2 acoustic receiver and temperature logger.

### 3.2.3. *R-coded acoustic tags*

The electronic components of the V16TP R-coded acoustic tag are set in a non-toxic, hard, plastic resin. Externally, the acoustic tag has a diameter of 16 mm and is 100 mm long, and this produces weights of 36g and 16g in air and water, respectively. R-coded tags are individually identified by a unique pulse string encoded in the signal that is transmitted at a frequency of 69.0 kHz at pre-programmed intervals with a silent period occurring at randomly-spaced intervals to reduce code collisions. The signals from the R-coded tag are recorded by the network of underwater acoustic listening stations (SEACAMS). The tags uniquely identify the tagged shark and transmit the depth at which the animal is swimming and the surrounding water temperature.

To prevent skin abrasions, the tags were inserted into small floats that were coated with antifouling paint to prevent the settlement and growth of sessile marine organisms (particularly barnacles). The tag was then attached to  $\approx 10$  cm of monofilament line with a corrodible link and an intra-muscular dart made of surgical plastic or stainless steel (Fig. 3.5). The tags were inserted into the musculature of each shark at the base of first dorsal fin by one of two methods. Tags with metal darts were fitted to free-swimming grey nurse sharks by scuba divers using a modified hand spear, with a purpose-built cradle to hold the transmitter. Tags with plastic darts were fitted to grey nurse sharks that had been lassoed by scuba divers and placed in a semi-submerged stretcher attached to the side of a surface vessel (see Section 3.2.1).



**Figure 3.5.** A V16TP R-coded acoustic tag embedded within a float for buoyancy attached to a corrodible link and an intra-musculature dart made of surgical plastic.

### 3.3. Results

#### 3.3.1. *Tagging and performance of pop-up archival satellite tags*

Between October, 2003 and July, 2008, 15 grey nurse sharks (8 males, 7 females) were tagged with pop-up archival satellite tags (Table 3.1). Fourteen sharks (8 males, 6 females) were tagged at Fish Rock off South West Rocks and one, a 2.97 m TL female, was tagged at Julian Rocks off Byron Bay (Fig. 3.3). The male grey nurse sharks tagged had TL and TW of 1.80 – 2.45 m and 35 – 94 kg, respectively and 7 were sexually mature with fully calcified claspers. The female grey nurse sharks tagged had TL and TW of 2.20 – 2.97 m and 57 – 172 kg, respectively and 6 of the 7 were assessed as sexually immature. The sexually mature female tagged at Julian Rocks was captured to remove a fishing gaff from the animal's oesophagus.

Two of the 15 pop-up archival satellite tags failed to surface upon release (Table 3.1). The first tag was deployed on a 2.40 m TL male grey nurse shark at Fish Rock on 23 October, 2003 with a programmed deployment of 180 days (Table 3.1). The shark was observed by scuba divers at Big Seal Rock about 1 week prior to the tag's scheduled release. The divers also reported seeing several barnacles growing on the tag's float. Therefore, it is highly likely that the tag was released as programmed, but did not float to the surface because of the reduced buoyancy attributable to the barnacle growth. The second tag was deployed on a 2.38 m TL female grey nurse shark at Fish Rock on 1 December, 2006 with a programmed deployment of 120 days (Table 3.1). In the absence of information to the contrary, we can only presume that the tag either failed to pop-up or, more likely was unable to transmit following pop-up because of reduced buoyancy attributable to barnacle growth.

**Table 3.1.** Details of 15 grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock (FR) and Julian Rocks (JR) between October, 2003 and July, 2008. TL: Total Length; TW: Total Weight and estimated via the length weight curve  $y = 5.4511(x^{3.1716})$ , where y is TW in kg and x is TL in metres.

Tag No.	Sex	TL (m)	TW (kg)	Sexual Maturity	Tagging Date	Tagging Location	Deployment Duration (Days)	Tag Pop-up (Y/N)
1	M	2.25	75	Mature	29.04.05	FR	150	Y
2	M	2.26	76	Mature	11.11.03	FR	120	Y
3	M	2.40	92	Mature	23.10.03	FR	180	N
4	M	2.20	66	Mature	22.05.07	FR	77	Y
5	M	2.45	94	Mature	22.05.07	FR	70	Y
6	M	2.40	92	Mature	22.05.07	FR	84	Y
7	M	2.15	62	Mature	01.12.06	FR	120	Y
8	M	1.80	35	Immature	01.12.06	FR	122	Y
9	F	2.40	92	Immature	11.11.03	FR	90	Y
10	F	2.25	71	Immature	01.12.06	FR	121	Y
11	F	2.40	92	Immature	22.05.07	FR	55	Y
12	F	2.37	84	Immature	01.12.06	FR	40	Y
13	F	2.10	57	Immature	22.05.07	FR	54	Y
14	F	2.38	85	Immature	01.12.06	FR	120	N
15	F	2.97	172	Mature	16.07.08	JR	38	Y

### 3.3.2. *Monitoring of possible capture stress*

None of the sharks caught by scuba divers using a lasso placed around the caudal peduncle became noticeably stressed while restrained in the stretcher for tagging. None of the sharks began to buccal pump, nor did any individual animal become noticeably lighter in colour. Furthermore, the pupillary reflexes and skin turgor remained unchanged in all the sharks tagged.

Diver observations, photographs and video footage indicated that the swimming behaviour of the tagged sharks did not differ from that of the remaining sharks following their release. Furthermore, divers observed the sharks tagged with pop-up archival tags on numerous occasions at other sites including the Cod Grounds, South Solitary Is, North Solitary Is, Julian Rocks and Flat Rock (in southern QLD waters). Reports and photographs from various scuba divers indicated that the sharks were swimming normally and clearly unaffected by the presence of the pop-up archival satellite tags.

### 3.3.3. *Movements of sharks tagged with pop-up archival satellite tags*

#### *Shark 1*

This sexually-mature, 2.25 m TL male grey nurse shark was tagged at Fish Rock on 29 April, 2005 (Table 3.1). This shark remained at Fish Rock until mid-May, 2005 when it left and headed north. The shark travelled via South and North Solitary Is., Pimpernel Rock and then to Flat Rock (off North Stradbroke Is.) where it remained for 10 days. The shark was observed and photographed by divers on 27 July 2005 and then headed further north passing Fraser Is. in mid-August, 2005. The shark then continued further north and had entered the Capricorn Channel by the beginning of September, 2005. The shark then began its southward journey in mid-September, 2005 travelling relatively rapidly to reach Shag Rock (off North Stradbroke Is.) where the pop-up archival satellite tag was released on 29 September, 2005. During this migratory route, the shark travelled  $\approx 700$  km, spent  $\approx 91\%$  of its time in water depths  $< 60$  m and did not exceed 100 m. Moreover, the shark spent most of its time in waters  $> 50$  m whilst migrating north from Fraser Is. and into the Capricorn Channel and then again on its return journey (Fig. 3.11f). The shark spent 98% of its time in waters  $19 - 23^\circ\text{C}$  (Fig. 3.12f). The shark's migratory path was very similar to Shark 6 whose route is described below.

#### *Shark 2*

This sexually-mature, 2.26 m TL male grey nurse shark was tagged at Fish Rock on 11 November, 2003 (Table 3.1). After tagging, the shark remained at Fish Rock for  $\approx 3$  weeks and then migrated south. The shark continued to travel south to the waters off Jervis Bay where it remained from 24 to 28 January, 2004. The shark then migrated further south, arriving at the Tollgate Islands on 13 February, 2004. The shark remained at this site until its pop-up archival satellite tag was released on 11 March, 2004. During this migratory route, the shark travelled  $\approx 650$  km, spent  $\approx 92\%$  of its time in water depths  $< 60$  m and did not exceed 125 m (Fig. 3.11c). The shark occupied waters with a wide range of temperatures along its migratory path, spending  $\approx 15.5\%$  of its time in waters  $< 18^\circ\text{C}$  and 75% of its time in waters  $18 - 25^\circ\text{C}$  (Fig. 3.12c). The shark's migratory path was very similar to Shark 7 whose route is described below.

#### *Shark 3*

This sexually-mature, 2.40 m TL male grey nurse shark was tagged at Fish Rock on 23 October, 2003 (Table 3.1). The shark remained at Fish Rock for about 1 week and then left. Over the ensuing weeks, the shark travelled south and was observed by divers at Big Seal Rock on 15/4/04 about 1 week prior to the tag's scheduled release. As noted earlier, this pop-up archival satellite tag apparently failed to surface upon release.

#### *Shark 4*

This sexually-mature, 2.20 m TL male shark was tagged at Fish Rock on 22 May, 2007. The shark remained at Fish Rock and surrounding areas until early July, 2007. Throughout July, the shark migrated north via South Solitary Is. (5/7/07), North Solitary Is. (7/7/07), Pimpernel Rock (9/7/07), Riordan Shoals (12/7/07), and Windarra Banks (21/7/07). The shark passed through the waters off the Gold Coast on 25 July, 2007. The shark continued to travel north and was at Flat Rock off North Stradbroke Is. from 1 to 5 August, 2007. The shark reached Henderson Rock (off Moreton Is.) where the pop-up archival satellite tag was released on 7 August, 2007 (Fig. 3.6). During its migration north, the shark travelled  $\approx 450$  km, spent  $\approx 96\%$  of its time in water depths  $< 60$  m and did not exceed 80 m (Figs. 3.10a and 3.11d). While the temperature of the water ranged from  $18 - 22.8^\circ\text{C}$  along its migratory path, the shark spent  $\approx 95\%$  of its time in waters  $20 - 22.8^\circ\text{C}$  (Fig. 3.12d).

### *Shark 5*

This sexually-mature, 2.45 m TL male shark was tagged at Fish Rock on 22 May, 2007, where it remained for 5 days following tagging. The shark then migrated north via South Solitary Is. (30/5/07), Buchanan's Rock (1/6/07), North Woody Head (2/6/07) and Riordan Shoals (3/6/07). The shark was at Julian Rocks from 4 to 7 June, 2007 and at Flat Rock (off North Stradbroke Is.) from 1 to 12 July, 2007. The shark continued migrating north to Fraser Is. where the pop-up archival satellite tag was released on 31 July, 2007 (Fig.3.7). During its migration north, the shark travelled  $\approx 700$  km, spent  $\approx 90\%$  of its time in water depths  $< 60$  m and did not exceed 128 m (Figs. 3.10b and 3.11a). While the temperature of the water ranged from 18.4 – 23.6°C along its migratory route, the shark spent  $\approx 88\%$  of its time in waters 20 – 23°C (Fig. 3.12a).

### *Shark 6*

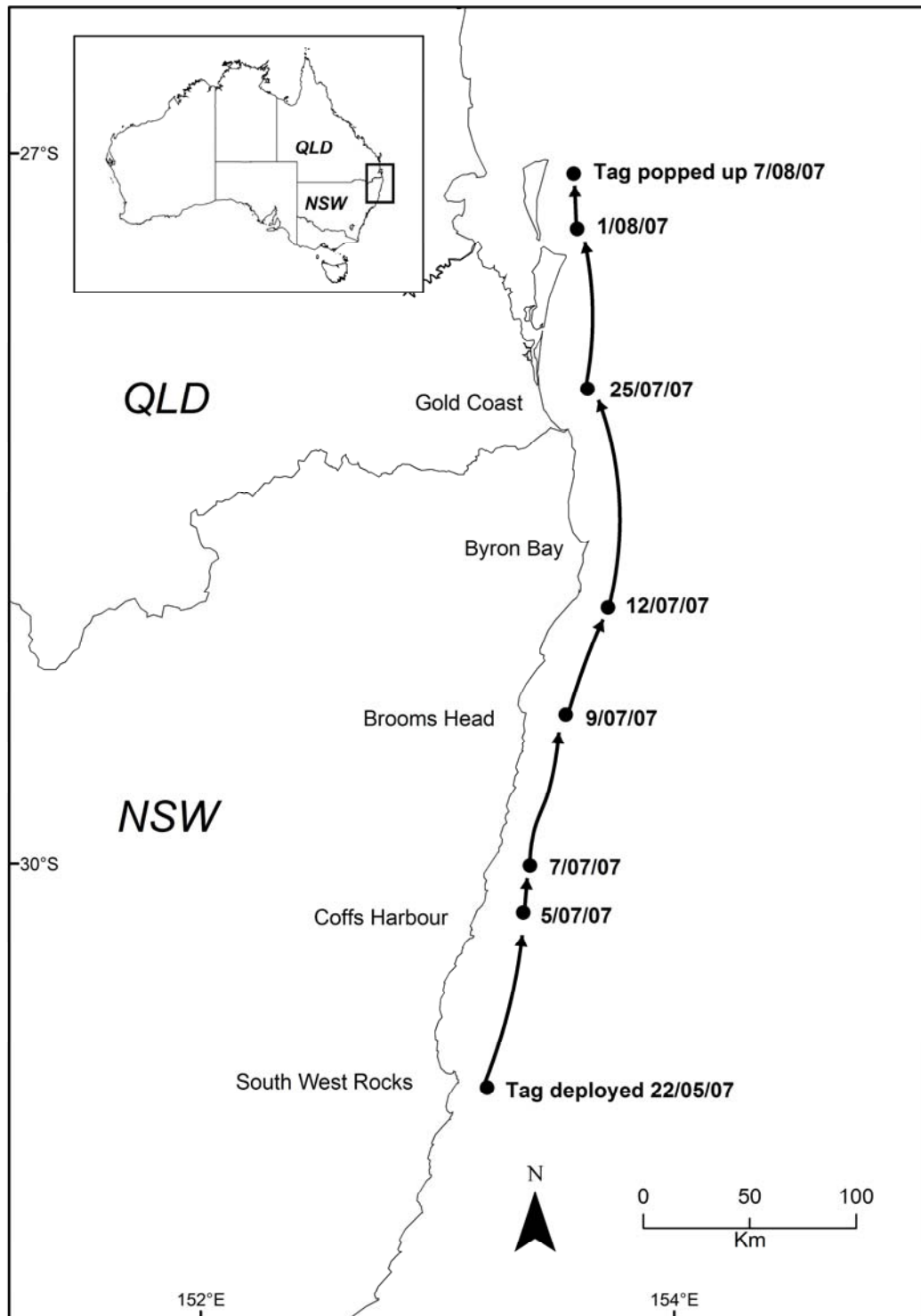
This sexually-mature, 2.40 m TL male shark was tagged at Fish Rock on 22 May, 2007 (Table 3.1). The shark migrated north, was at South Solitary Is. from 27 May, 2007 to 9 June, 2007 and then at Pimpernel Rock from 12 to 16 June, 2007. The shark continued to travel north via Riordan Shoals (19/6/07), Flat Rock (off North Stradbroke Is. (29/6/07), and Moreton Is. (7/7/07), reaching the northern end of Fraser Is. towards the end of July, 2007. The shark then continued further north and entered the Capricorn Channel. Its pop-up archival satellite tag was released off Guthrie Shoal in the southern Great Barrier Reef on 14 August, 2007 (Fig. 3.8). During this migratory route, the shark travelled  $\approx 1000$  km, spent  $\approx 49\%$  of its time in water depths  $< 60$  m and did not exceed 136 m (Figs. 3.10c and 3.11e). The shark spent most of its time in waters  $> 50$  m whilst migrating north from Fraser Is and into the Capricorn Channel. While the temperature of the water ranged from 17.4 – 23.2°C along its migratory route, the shark spent  $\approx 92\%$  of its time in waters 21 – 24°C (Fig. 3.12e).

### *Shark 7*

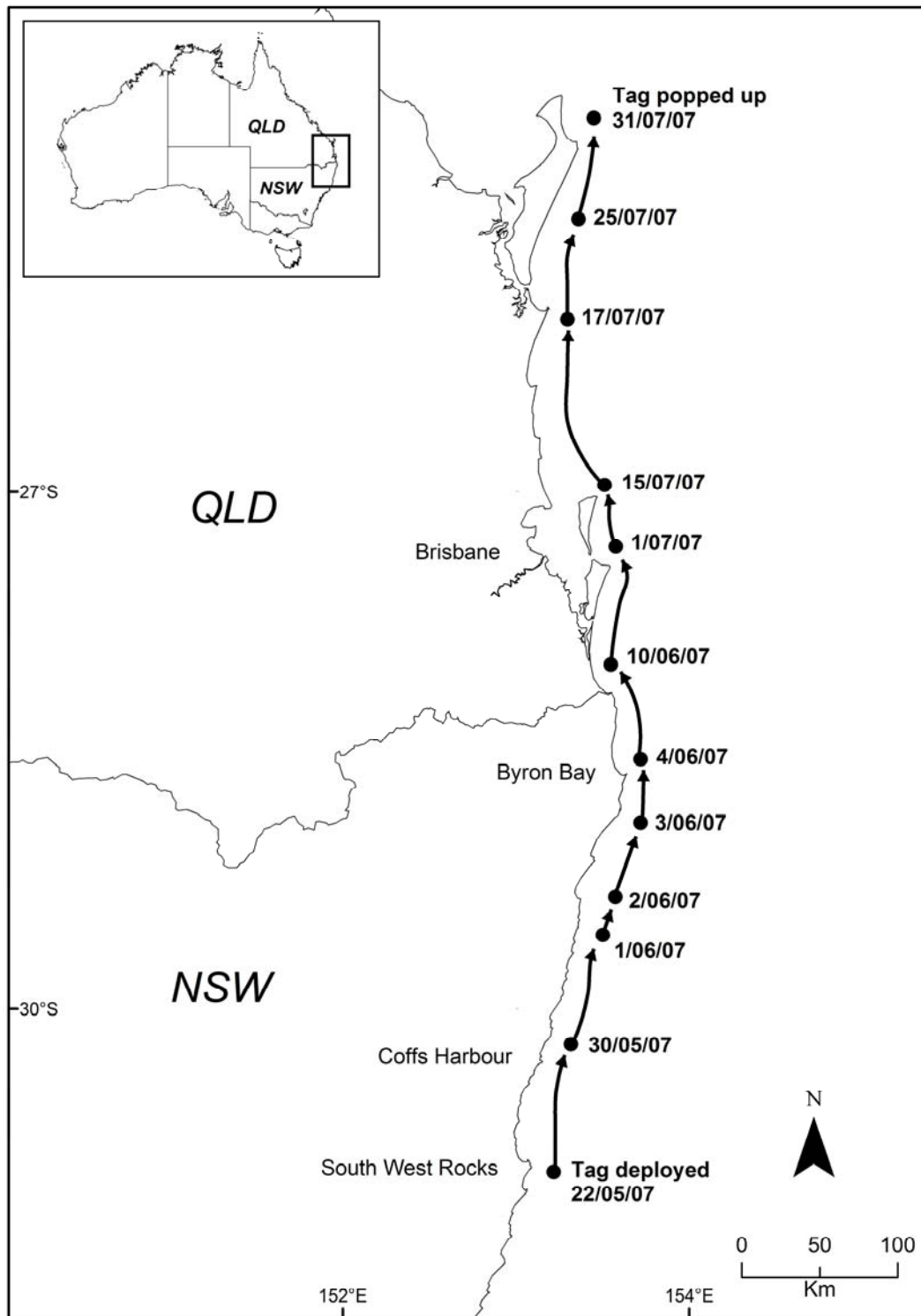
This sexually-mature, 2.15 m TL male shark was tagged at Fish Rock on 1 December, 2006. The shark remained at Fish Rock until 28 December, 2006 and then migrated south. From 14 to 15 January, 2007, the shark was at Latitude Rock, off Forster and then at Broughton Island, off Port Stephens, from 20 to 21 January, 2007. The shark continued to migrate south to the waters off Jervis Bay where it remained from 24 to 28 January, 2007. The shark then migrated further south to Wasp Island, north of Bateman's Bay, where its pop-up archival satellite tag was released on 1 April, 2007 (Fig. 3.9). During its migration south, the shark travelled  $\approx 640$  km, spent  $\approx 93\%$  of its time in water depths  $< 30$  m and did not exceed 72 m (Figs. 3.10d and 3.11b). The shark occupied waters with a wide range of temperatures (i.e., 13.8 – 24.8°C) along its migratory route, spending  $\approx 10\%$  of its time in waters  $< 18^\circ\text{C}$  and 90% of its time in waters 18 – 25°C (Fig. 3.12b).

### *Shark 8*

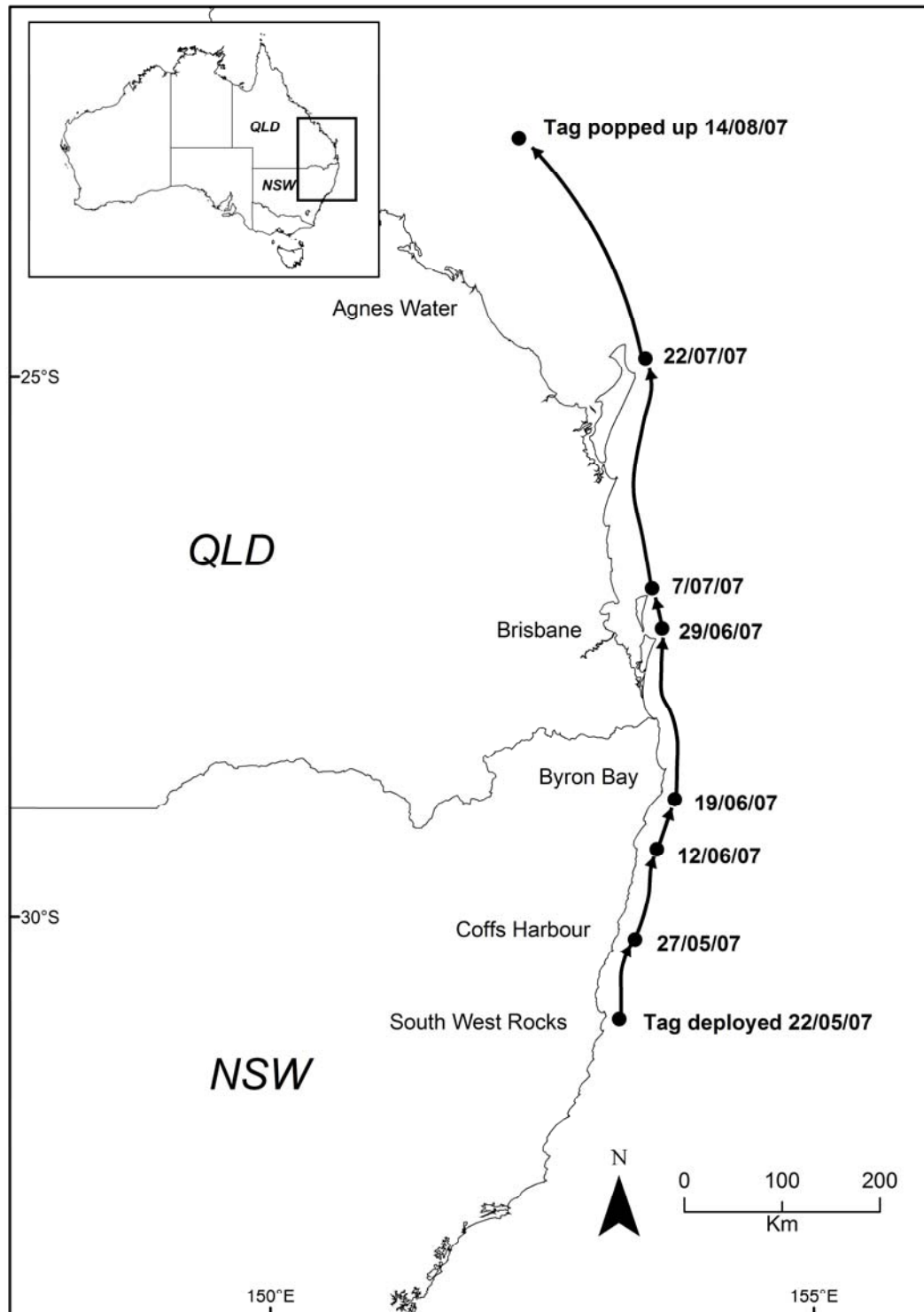
This sexually-immature, 1.80 m TL male shark was tagged at Fish Rock on 1 December, 2006. The shark remained at Fish Rock for the entire period of the tag's deployment and was observed and photographed by scuba divers on numerous occasions. The pop-up archival satellite tag was released on 2 April, 2007 at Fish Rock. During the shark's occupation of the waters around Fish Rock, it spent  $\approx 91\%$  of its time in water depths  $< 60$  m and did not exceed 100 m. Its occupation of Fish Rock was very similar to that of a female grey nurse shark (Shark 13 – Table 3.1) that also remained, as described later, at Fish Rock for the duration of her tag's deployment.



**Figure 3.6.** Migratory movements of a 2.20 m TL sexually-mature, male grey nurse shark (Shark 4, Table 3.1) tagged with a pop-up archival satellite tag at Fish Rock in May, 2007. Note: distances offshore have been exaggerated and are not representative of the recorded depths.

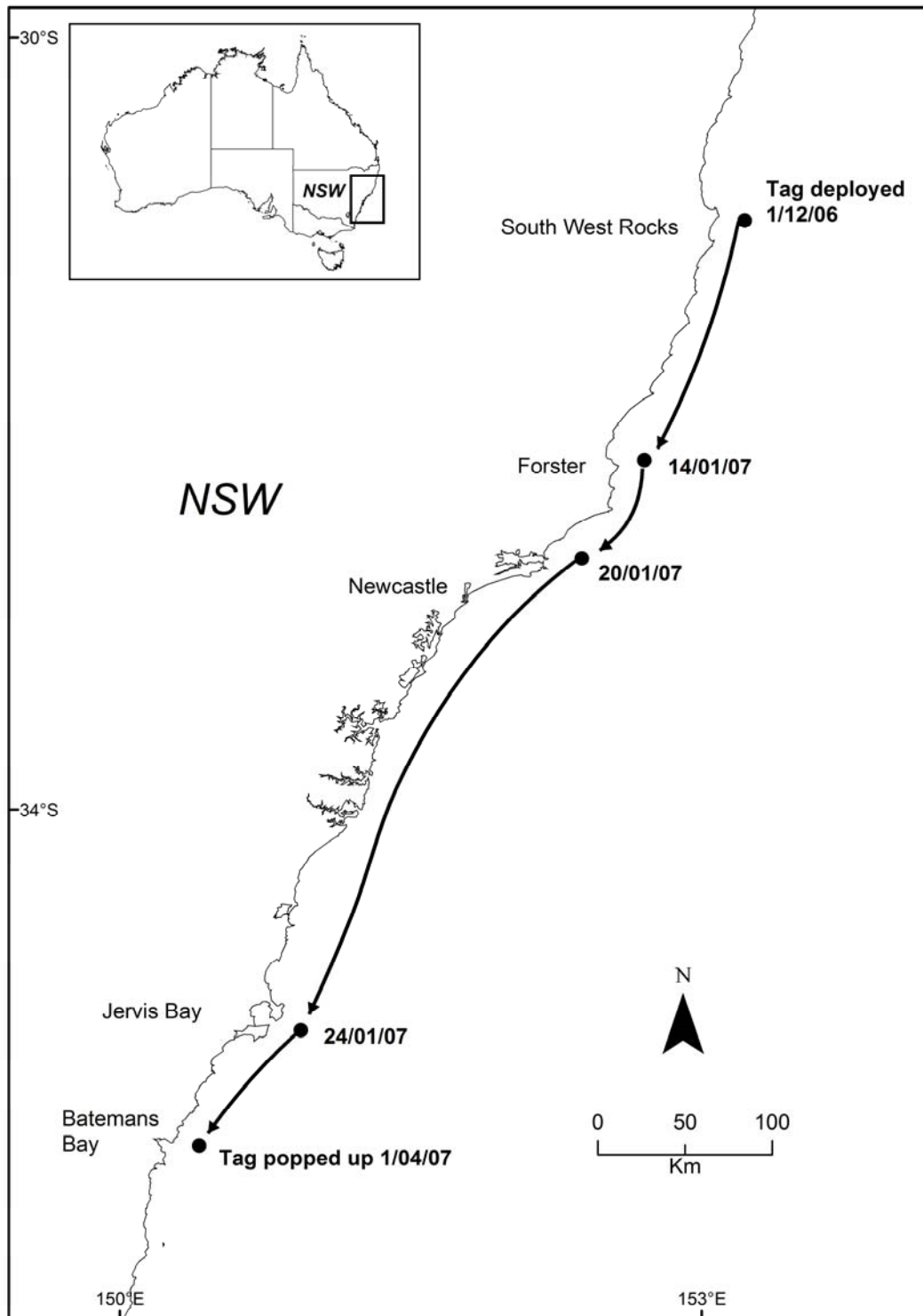


**Figure 3.7.** Migratory movements of a 2.45 m TL sexually-mature, male grey nurse shark (Shark 5, Table 3.1) tagged with a pop up archival satellite tag at Fish Rock in May, 2007. Note: distances offshore have been exaggerated and are not representative of the recorded depths.

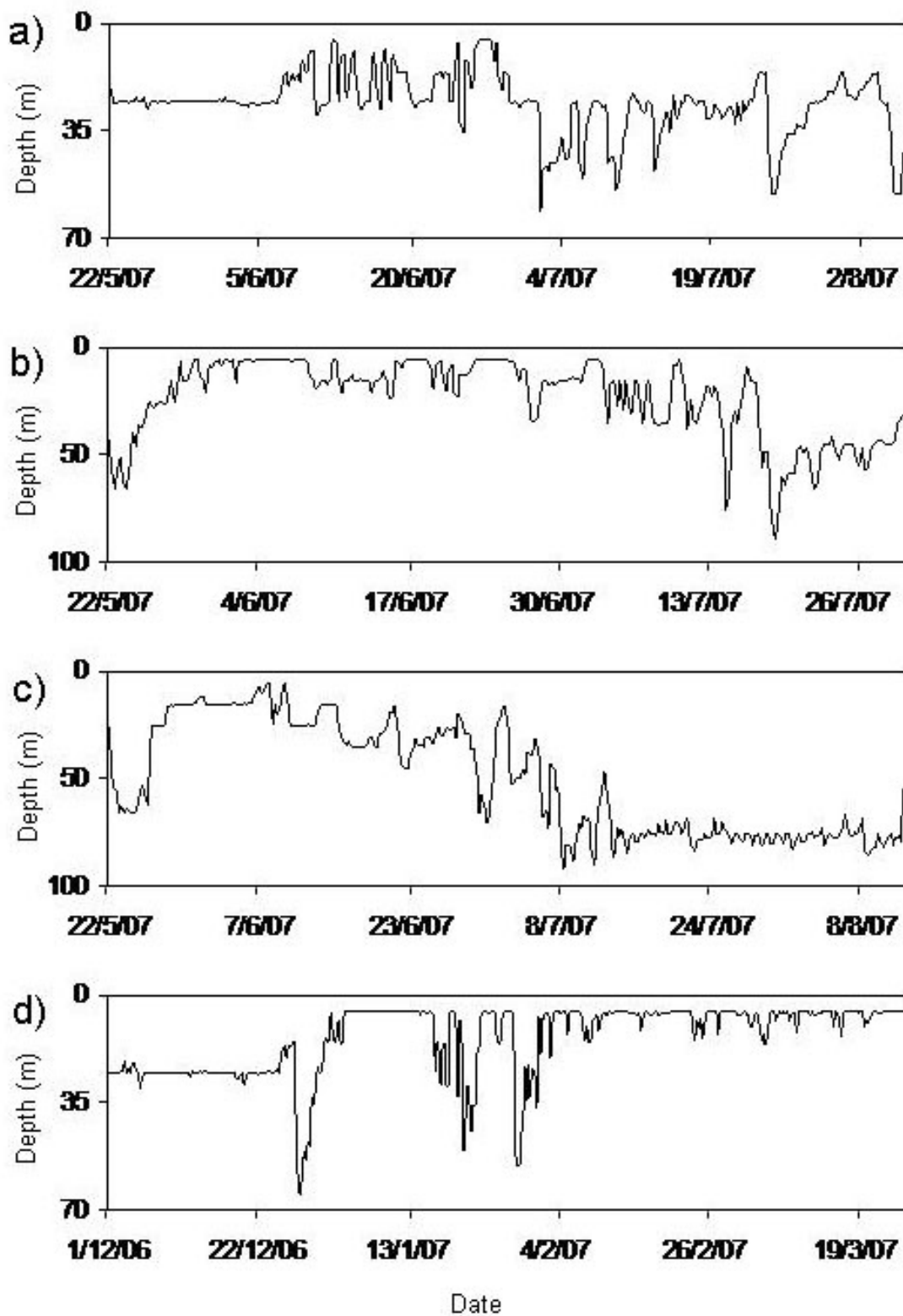


**Figure 3.8.** Migratory movements of 2.40 m TL sexually-mature, male grey nurse shark (Shark 6, Table 3.1) tagged with pop-up archival satellite tag at Fish Rock in May, 2007. Note: distances offshore have been exaggerated and are not representative of the recorded depths.

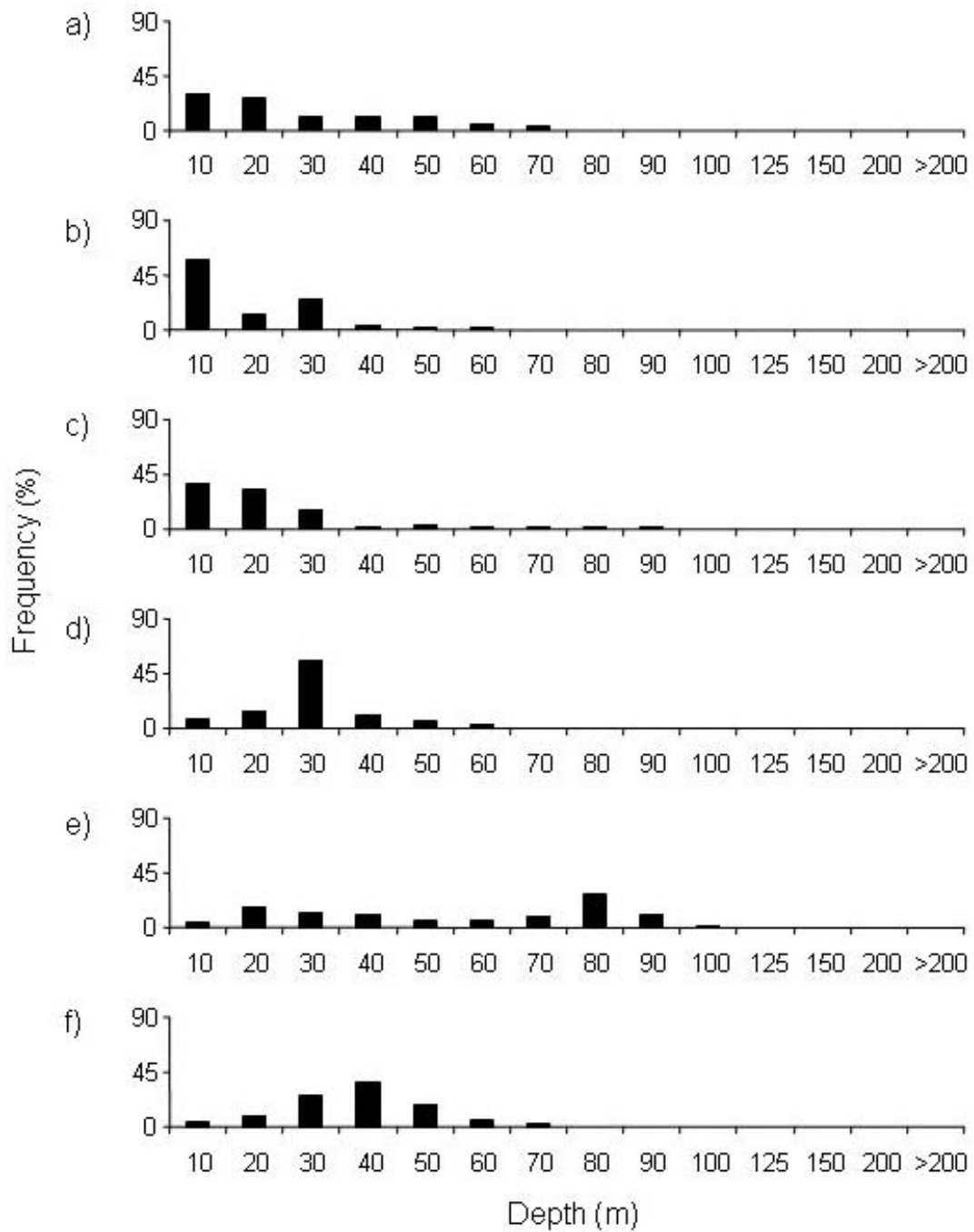




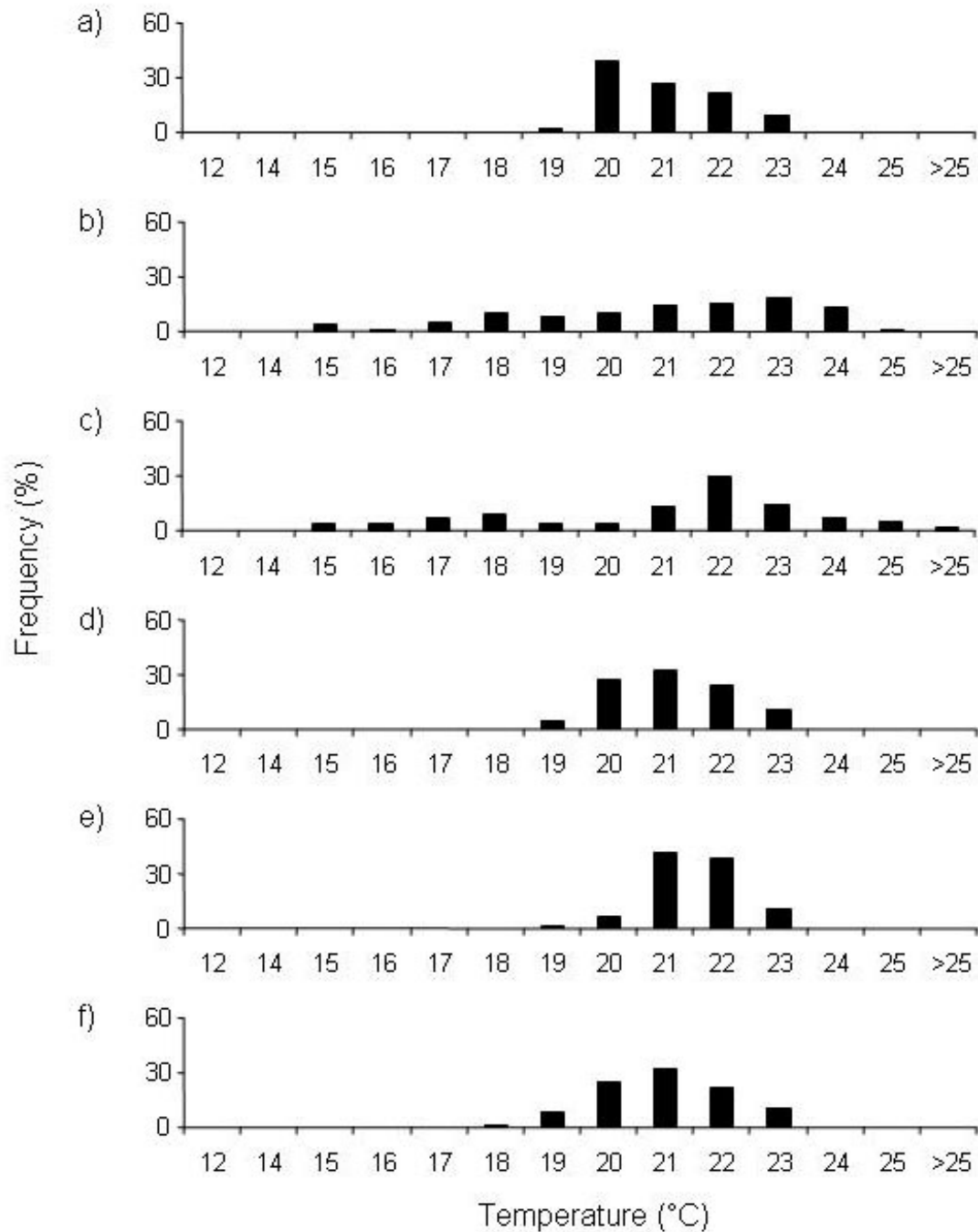
**Figure 3.9.** Migratory movements of a 2.15 m TL sexually-mature, male grey nurse shark (Shark 7, Table 3.1) tagged with a pop-up archival satellite tag at Fish Rock in December, 2006. Note: distances offshore have been exaggerated and are not representative of the recorded depths.



**Figure 3.10.** Depth profiles of four male, migrating grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock. (a, Shark 4; b, Shark 5; c, Shark 6; d, Shark 7).



**Figure 3.11.** Percentage of time spent at various depths for six, migrating male grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock. (a, Shark 5; b, Shark 7; c, Shark 2; d, Shark 4; e, Shark 6; f, Shark 1).



**Figure 3.12.** Percentage of time spent at various temperatures for six male, migrating grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock. (a, Shark 5; b, Shark 7; c, Shark 2; d, Shark 4; e, Shark 6; f, Shark 1).

### *Shark 9*

This sexually-immature, 2.40 m TL female shark was tagged at Fish Rock on 11 November, 2003. Following tagging, this shark migrated south and finally reached Crowdy Head. The shark's pop-up archival satellite tag was released off Harrington Inlet (just to the south of Crowdy Head) on 11 February, 2004. During its migration south, the shark travelled  $\approx 100$  km, spent  $\approx 78\%$  of its time in water depths  $< 60$  m and did not exceed 80 m (Fig. 3.17f). The shark occupied waters with a wide range of temperatures (i.e.,  $15 - 26^\circ\text{C}$ ) along its migratory path, spending  $\approx 26\%$  of its time in waters  $< 18^\circ\text{C}$  and  $\approx 74\%$  of its time in waters  $18 - 25^\circ\text{C}$  (Fig. 3.18f).

### *Shark 10*

This sexually-immature, 2.25 m TL female shark was tagged at Fish Rock on 1 December, 2006 and remained there for the next 15 days. Over the following month, the shark migrated north to Coffs Harbour (16/1/07) and then travelled south, reaching the waters off Morna Point (near Port Stephens) in late January, 2007 (Fig. 3.13). The shark's pop-up archival satellite tag was released off Morna Point on 1 April, 2007. During its migratory path, the shark travelled  $\approx 400$  km, spent  $\approx 96\%$  of its time in water depths  $< 60$  m and did not exceed 100 m (Figs. 3.16a and 3.17d). While the temperature of the water ranged from  $14 - 26^\circ\text{C}$  along its migratory route, the shark spent  $\approx 90\%$  of its time in waters  $19 - 26^\circ\text{C}$  (Fig. 3.18d).

### *Shark 11*

This sexually-immature, 2.40 m TL female shark was tagged at Fish Rock on 22 May, 2007. The shark migrated north and was observed at South Solitary Is. from 9 June, 2007 to 19 July, 2007 and then at North Solitary Is. from 23 to 26 July, 2007 (Fig. 3.14). The shark's tag was released off North Solitary Is. on 26 July 2007. During its migration north, the shark travelled  $\approx 130$  km, spent  $\approx 75\%$  of its time in water depths  $< 60$  m and, on one occasion, swam to 232 m where it spent  $< 17$  minutes (Figs. 3.16b and 3.17b). While the temperature of the water ranged from  $15 - 26^\circ\text{C}$  along its migratory route, the shark spent  $\approx 91\%$  of its time in waters  $19 - 24^\circ\text{C}$  (Fig. 3.18b).

### *Shark 12*

This sexually-immature, 2.37 m TL female shark was tagged at Fish Rock on 1 December, 2006. In the month following tagging, this shark migrated south, passing through various locations including Hat Head (2/12/06), Crescent Head (5/12/06), Point Plummer (7/12/06), Grant's Head (19/12/06), the Cod Grounds (23/12/06), Diamond Head (25/12/06), Mermaid Reef (31/12/06) and finally reaching Crowdy Head (Fig. 3.15). The shark's pop-up archival satellite tag was released off Harrington Inlet (just to the south of Crowdy Head) on 27 January, 2007. During its migration south, the shark travelled  $\approx 100$  km, spent  $\approx 97\%$  of its time in water depths  $< 30$  m and did not exceed 64 m (Figs. 3.16c and 3.17c). While the temperature of the water ranged from  $15.4 - 23.2^\circ\text{C}$  along its migratory route, the shark spent  $\approx 92\%$  of its time in waters  $18 - 22^\circ\text{C}$  (Fig. 3.18c).

### *Shark 13*

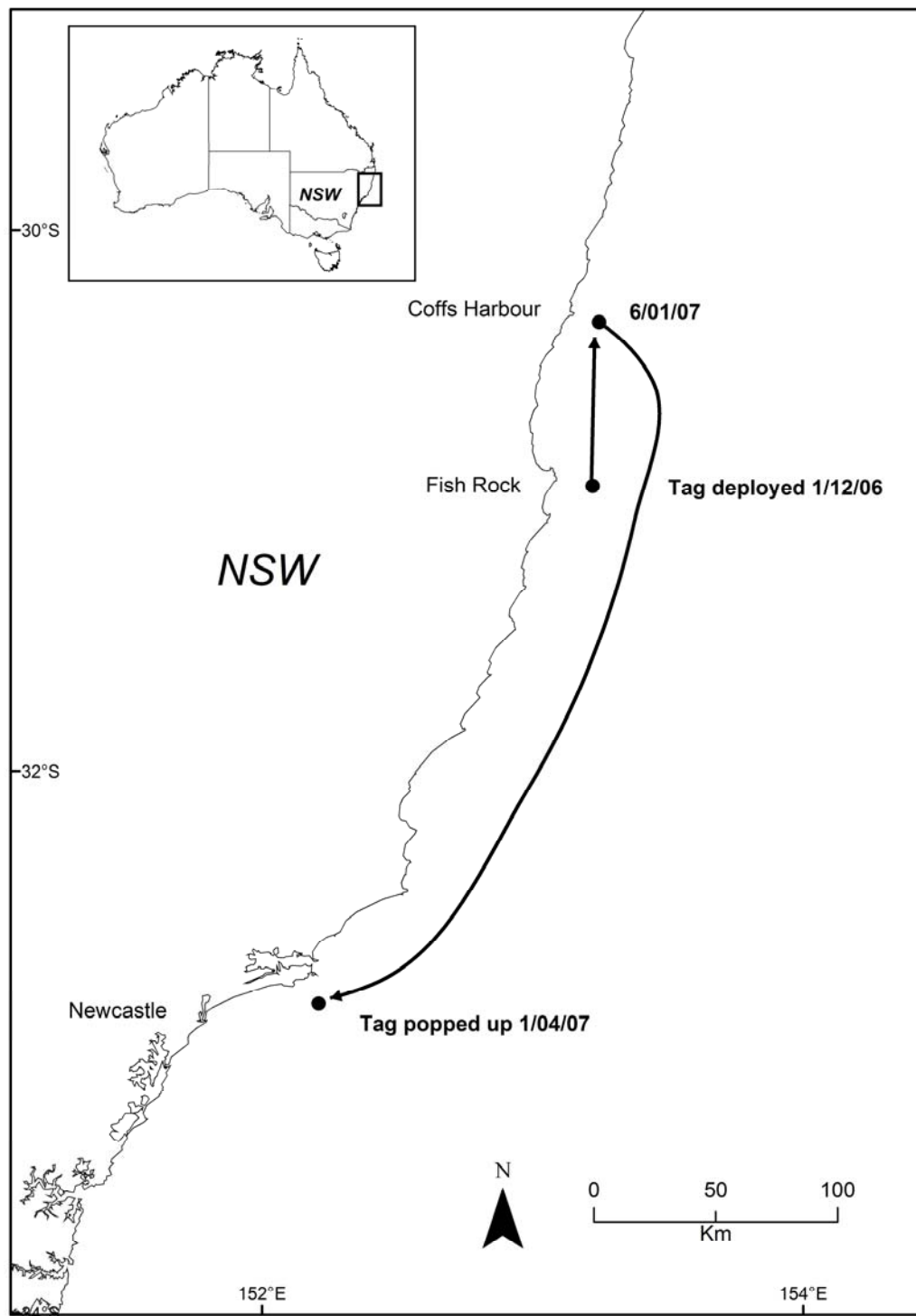
This sexually-immature, 2.10 m TL female shark was tagged at Fish Rock on 22 May, 2007. The shark remained at Fish Rock for the entire period of the tag's deployment and was observed and photographed by scuba divers on numerous occasions. The pop-up archival satellite tag was released at Fish Rock on 15 July, 2007. During the shark's occupation of the waters around Fish Rock, it spent  $\approx 94\%$  of its time in water depths  $< 40$  m and did not exceed 60 m (Figs. 3.16d and 3.17a). While the temperature of the water ranged from  $18 - 24^\circ\text{C}$  at Fish Rock, the shark spent  $\approx 99\%$  of its time in waters  $20 - 24^\circ\text{C}$  (Fig. 3.18a).

*Shark 14*

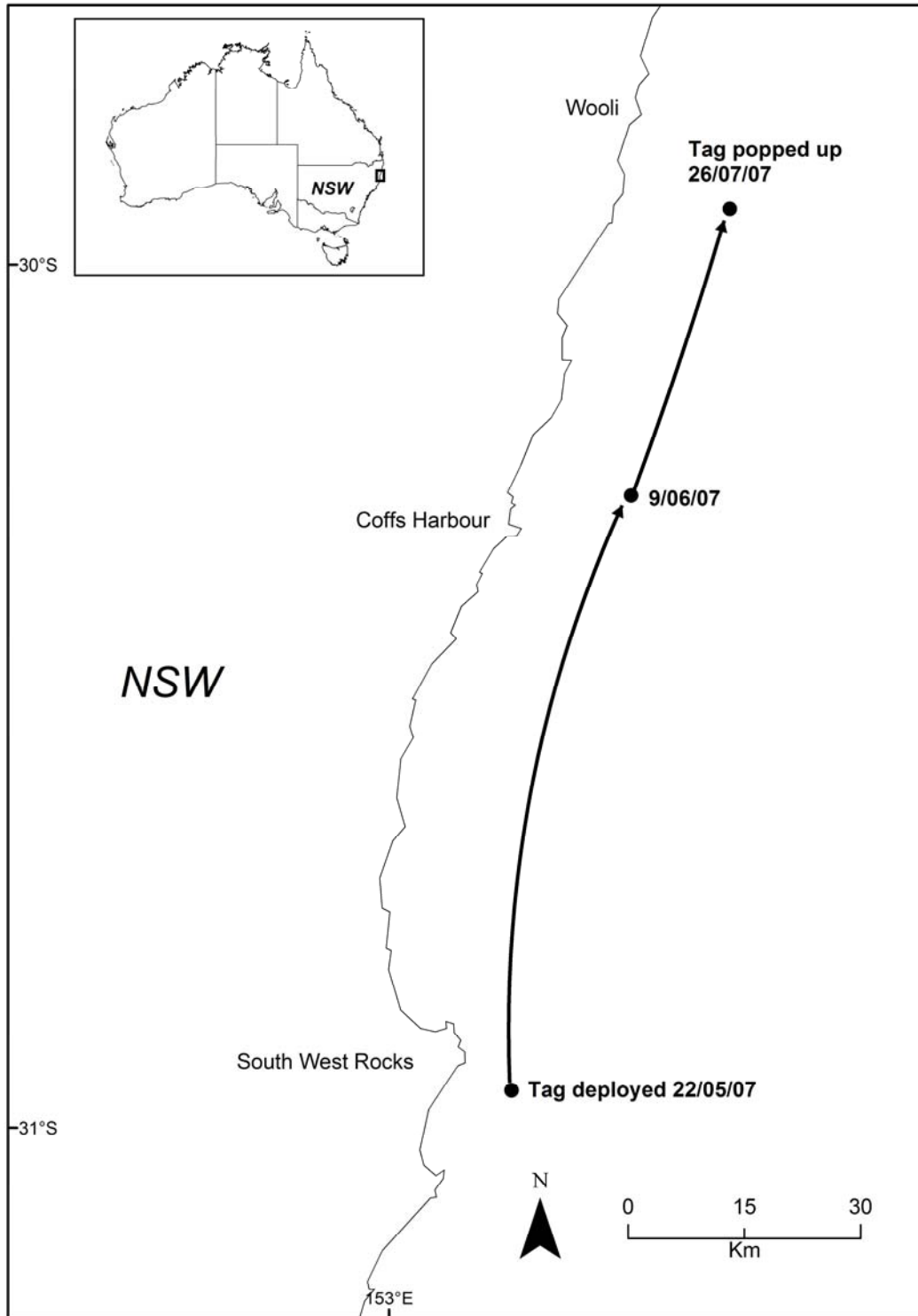
This sexually-immature, 2.38 m TL female grey nurse shark was tagged at Fish Rock on 1 December, 2006 (Table 3.1). As noted earlier, this pop-up archival satellite tag apparently failed to surface upon release.

*Shark 15*

This sexually-mature, 2.97 m TL female shark was tagged at Julian Rocks on 16 July, 2008. Following tagging, this shark migrated south to Urunga off the NSW mid-north coast and then travelled north, reaching the southern waters of the Cape Byron Marine Park in mid-August, 2008. The shark's pop-up archival satellite tag was released off Lennox Head on 23 August, 2007. During its migratory path, the shark travelled  $\approx 400$  km, spent  $\approx 37\%$  of its time in water depths  $< 30$  m,  $\approx 61\%$  of its time in waters 40 – 80 m in depth, but did not exceed 100 m (Fig. 3.17e). While the temperature of the water ranged from 18 – 23°C along its migratory route, the shark spent  $\approx 92\%$  of its time in waters 19 – 22°C (Fig. 3.18e).

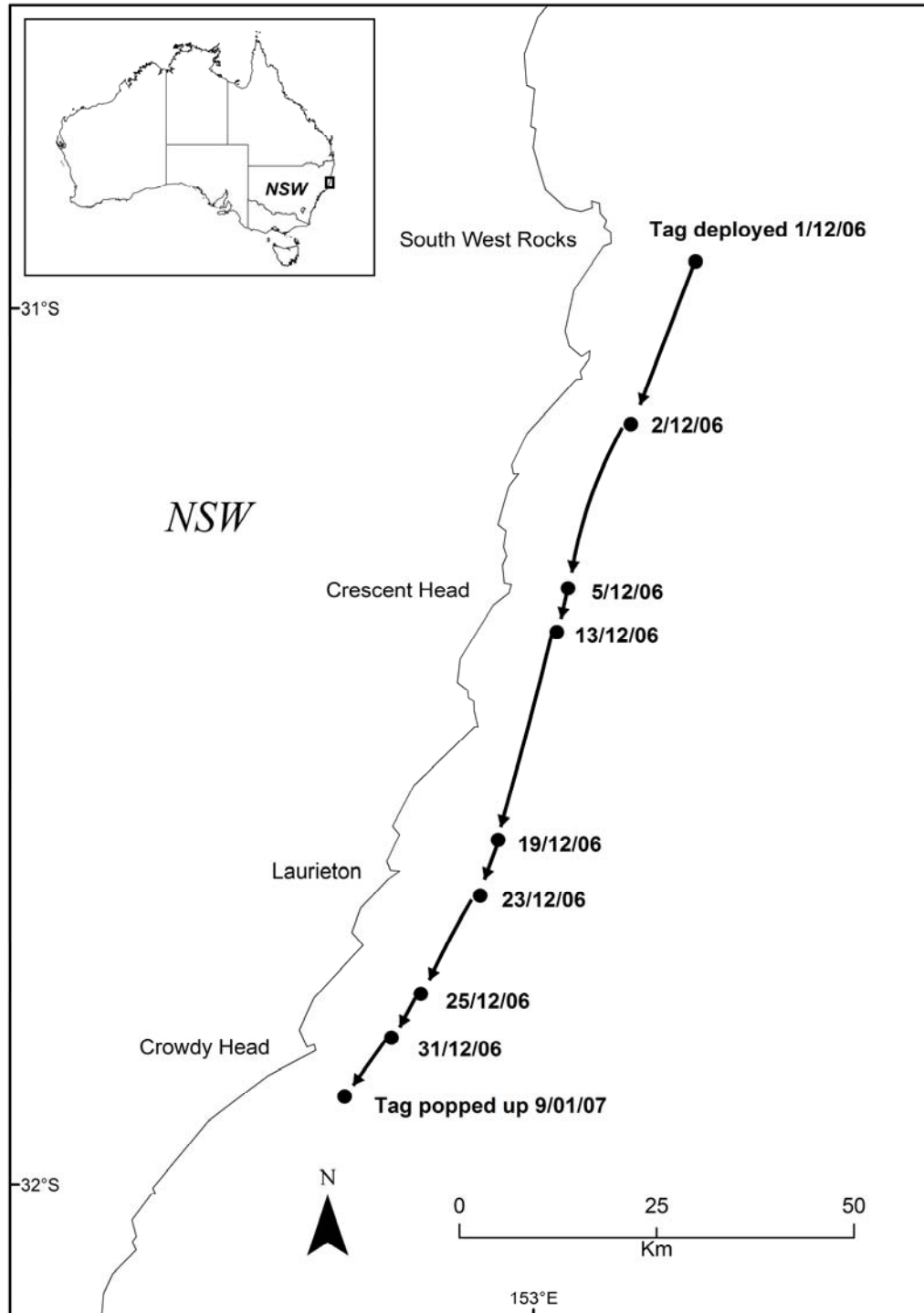


**Figure 3.13.** Migratory movements of a sexually-immature, 2.25 m TL female grey nurse shark (Shark 10, Table 3.1) tagged with a pop-up archival satellite tag at Fish Rock in May, 2007. Note: distances offshore have been exaggerated and are not representative of the recorded depths.

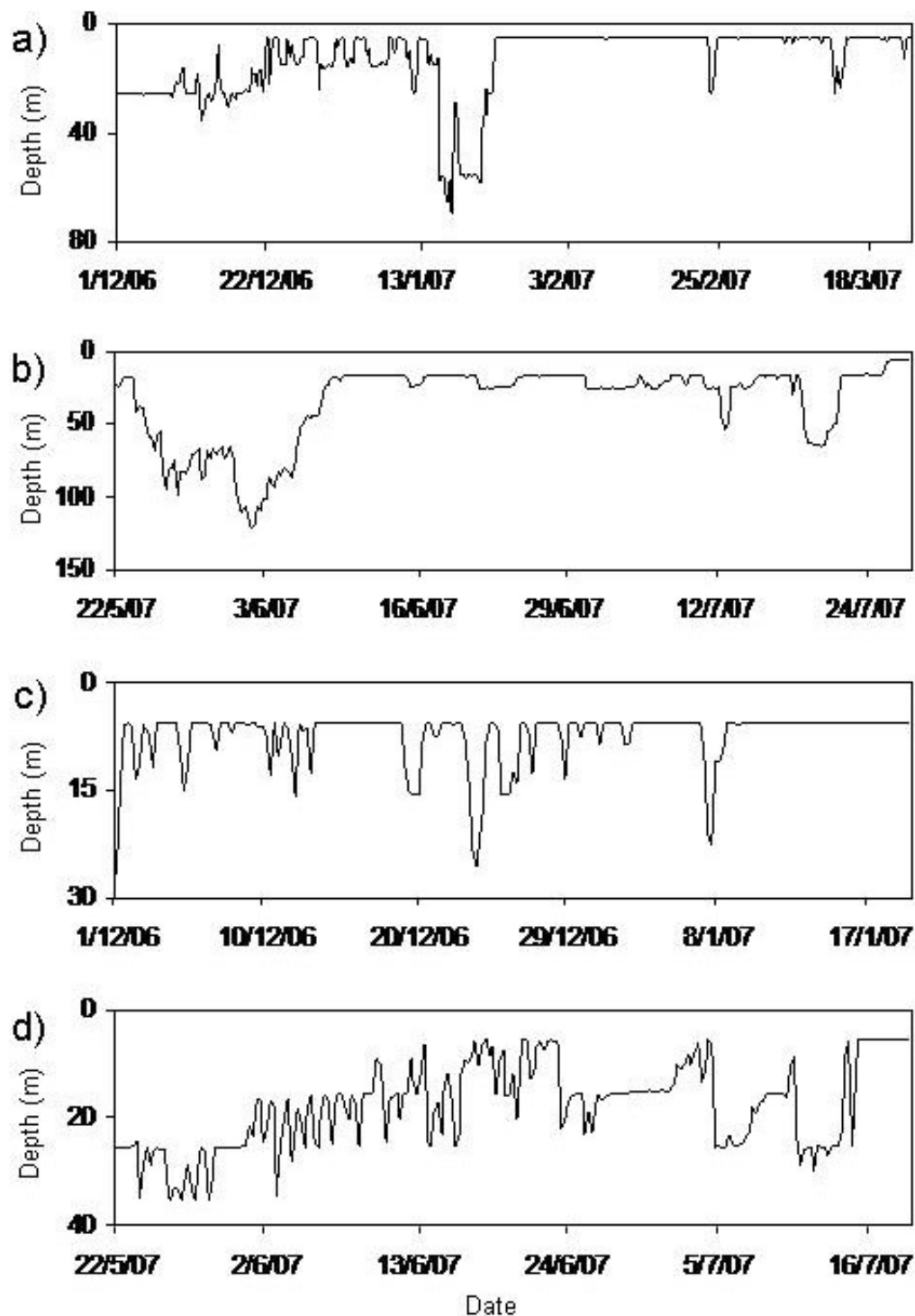


**Figure 3.14.** Migratory movements of a 2.40 m TL female grey nurse shark (Shark 11, Table 3.1) tagged with a pop-up archival satellite tag at Fish Rock in December, 2006. Note: distances offshore have been exaggerated and are not representative of the recorded depths.

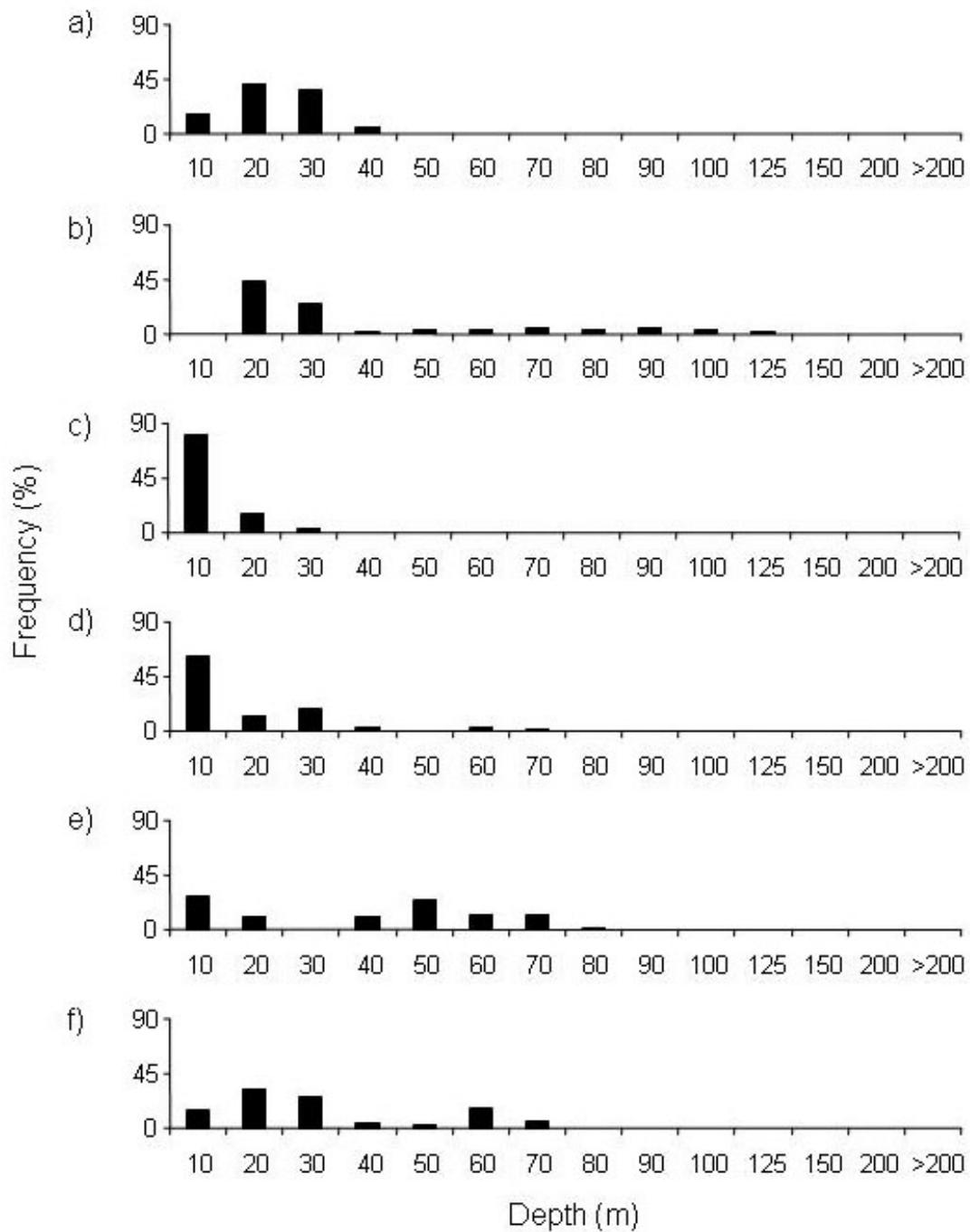




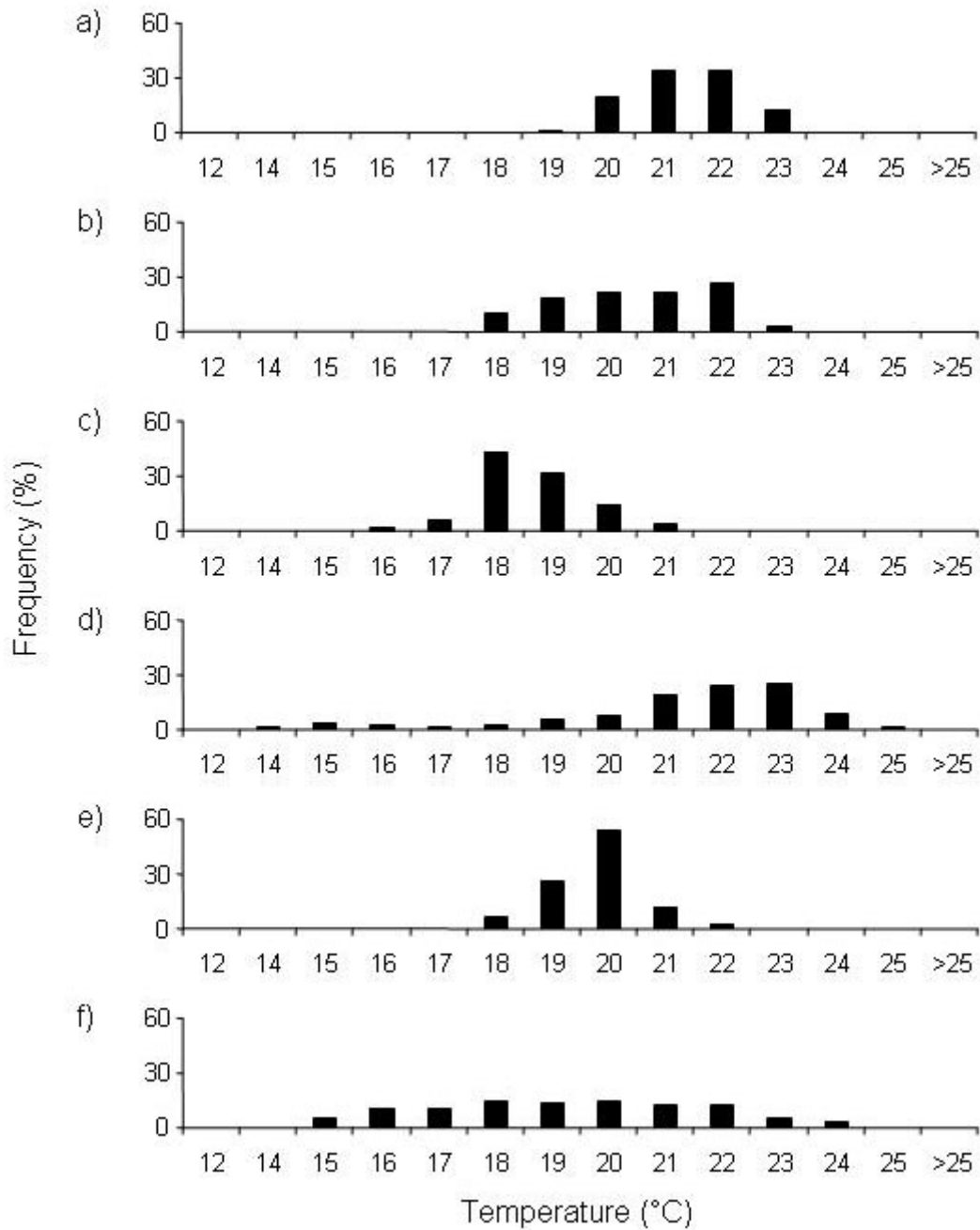
**Figure 3.15.** Migratory movements of a 2.37 m TL female grey nurse shark (Shark 12, Table 3.1) tagged with a pop-up archival satellite tag at Fish Rock in December, 2006. Note: distances offshore have been exaggerated and are not representative of the recorded depths.



**Figure 3.16.** Depth profiles of four female grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock. Note: sharks in (a) through (c) exhibited migratory movements, whereas shark in (d) remained at Fish Rock for the entire deployment of the pop-up tag (i.e., 60 days). (a, Shark 10; b, Shark 11; c, Shark 12; d, Shark 13).



**Figure 3.17.** Percentage of time spent at various depths for six, female grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock (a–d, f) and Julian Rocks (e). (a, Shark 13; b, Shark 11; c, Shark 12; d, Shark 10; e, Shark 15; f, Shark 9).



**Figure 3.18.** Percentage of time spent at various temperatures for six, female grey nurse sharks tagged with pop-up archival satellite tags at Fish Rock (a–d, f) and Julian Rocks (e). (a, Shark 13; b, Shark 11; c, Shark 12; d, Shark 10; e, Shark 15; f, Shark 9).

### 3.3.4. *Depth and temperature-related occupation of se australian coastal waters*

The results of the successful pop-up archival satellite tagging studies were pooled and used to provide estimates of the mean ( $\pm$ SE) percentage of time that male ( $n = 7$ ), female ( $n = 6$ ) and all grey nurse sharks (i.e., sexes combined,  $n = 13$ ) grey nurse sharks spent in waters of various depths and temperatures.

Male and female grey nurse sharks exhibited similarities in the percentages of time spent in waters of various depths. On average, male grey nurse sharks spent  $\approx 71\%$  of their time in waters  $< 40$  m and  $\approx 94\%$  of their time in waters  $< 80$  m (Table 3.2). On average, female grey nurse sharks spent  $\approx 78\%$  of their time in waters  $< 40$  m and  $\approx 97\%$  of their time in waters  $< 80$  m, respectively (Table 3.2). On average, both sexes combined spent  $\approx 74\%$  of their time in waters  $< 40$  m and  $\approx 95\%$  of their time in waters  $< 80$  m (Table 3.2).

Male and female grey nurse sharks also exhibited similarities in the percentages of time spent in waters of various temperatures. On average, male grey nurse sharks spent  $\approx 95\%$  of their time in waters  $17 - 24^\circ\text{C}$  (Table 3.3). On average, female grey nurse sharks spent  $\approx 96\%$  of their time in waters  $17 - 24^\circ\text{C}$  (Table 3.3).

**Table 3.2.** Mean ( $\pm$ SE) percentage of time spent at various depths for male ( $n = 7$ ), female ( $n = 6$ ) and all grey nurse sharks (sexes combined,  $n = 13$ ) tagged with pop-up archival satellite tags.

Depth (m)	% time spent at depth		
	Males	Females	Sexes Combined
10	28.77 (9.47)	33.34 (11.71)	30.88 (7.75)
20	21.01 (3.97)	26.24 (5.59)	23.42 (3.58)
30	21.10 (6.49)	17.95 (5.20)	19.65 (4.37)
40	10.46 (4.54)	4.22 (1.36)	7.58 (2.71)
50	6.59 (2.39)	5.24 (3.75)	5.97 (2.26)
60	3.22 (0.86)	5.99 (2.51)	4.50 (1.38)
70	2.62 (1.15)	4.41 (1.96)	3.45 (1.18)
80	4.23 (3.74)	0.88 (0.60)	2.68 (2.10)
90	1.66 (1.39)	0.79 (0.71)	1.26 (0.84)
100	0.31 (0.16)	0.45 (0.42)	0.38 (0.23)
125	0.01 (0.01)	0.41 (0.38)	0.20 (0.20)
150	0.00 (0.00)	0.05 (0.05)	0.03 (0.03)
200	0.00 (0.00)	0.03 (0.02)	0.01 (0.01)
>200	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

**Table 3.3.** Mean ( $\pm$ SE) percentage of time spent at various temperatures for male (n = 7), female (n = 6) and all grey nurse sharks (sexes combined, n = 13) tagged with pop-up archival satellite tags.

Temperature (°C)	% time spent at temperature		
	Males	Females	Sexes Combined
12	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
13	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
14	0.09 (0.06)	0.20 (0.20)	0.14 (0.10)
15	0.95 (0.60)	1.35 (0.88)	1.13 (0.52)
16	0.81 (0.58)	2.34 (1.69)	1.52 (0.86)
17	1.74 (1.15)	3.07 (1.81)	2.35 (1.05)
18	3.01 (1.48)	12.52 (6.45)	7.40 (3.37)
19	4.89 (1.05)	15.98 (4.70)	10.01 (2.77)
20	16.83 (5.38)	21.61 (6.72)	19.04 (4.28)
21	24.32 (4.53)	16.95 (4.15)	20.92 (3.29)
22	24.62 (2.88)	16.39 (5.62)	20.82 (3.24)
23	13.28 (1.39)	7.39 (3.95)	10.56 (2.14)
24	6.56 (3.65)	2.00 (1.38)	4.46 (2.18)
25	2.68 (1.84)	0.18 (0.13)	1.53 (1.07)
>25	0.22 (0.22)	0.02 (0.02)	0.13 (0.12)

### 3.3.5. *Movements of sharks tagged with R-coded acoustic tags*

Thirty grey nurse sharks were tagged with acoustic R-coded acoustic tags across 5 sites spanning 915 km from 29 April, 2005 to 1 April, 2008. Twenty-six of these sharks were detected within 1 year of tagging at sites distant from the initial site of tagging indicating substantial mixing of tagged sharks with the untagged population. Examples of the movements of grey nurse tagged with R-coded acoustic tags are provided below and illustrated in Figure 3.19.

#### *Shark 1*

This sexually-mature, 2.50 m TL male grey nurse shark was tagged at Julian Rocks on 5 September, 2006. The shark remained at Julian Rocks and surrounding areas on the day of tagging. The shark migrated south and was at Big Seal Rock on 9 December, 2006 and then migrated north and was at North Solitary Is. from 6 to 7 January, 2007. The shark was next detected south of this location, at the Cod Grounds, on 29 January, 2008.

#### *Shark 2*

This sexually-immature, 2.10 m TL female grey nurse shark was tagged at Fish Rock on 14 November, 2006. The shark remained at Fish Rock until 6 December, 2006. The shark then migrated south and was at Big Seal Rocks from 7 to 8 December, 2006, before migrating north

again to Fish Rock where it remained during December, 2006. Throughout June, 2007, the shark was at South Solitary Is.

#### *Shark 3*

This sexually-immature, 2.20 m TL female grey nurse shark was tagged at Fish Rock on 14 November, 2006. The shark remained at Fish Rock and surrounding areas until 16 April, 2007. The shark migrated north and was at South Solitary Is. from 9 June, 2007 to 16 July, 2007 and at North Solitary Is. on 23 July, 2007. The shark then migrated south and was at Fish Rock on 6 August, 2007.

#### *Shark 4*

This sexually-immature, 1.80 m TL male grey nurse shark was tagged at Broughton Is. on 23 February, 2007 where it remained until 15 July, 2007. The shark migrated north and was present at the Cod Grounds from 22 July, 2007 to 26 September, 2007. The shark then migrated south, was at The Pinnacle on 5 October, 2007 and then back at Broughton Is. from 15 October, 2007 to 6 February, 2008.

#### *Shark 5*

This sexually-mature, 3.20 m TL female grey nurse shark was tagged at Fish Rock on 30 January, 2007. The shark remained at Fish Rock until 5 March, 2007 before migrating south to the Cod Grounds where it remained from 22 to 24 April, 2007.

#### *Shark 6*

This sexually-immature 2.10 m TL female grey nurse shark was tagged at Big Seal Rock on 7 December, 2006. The shark remained at Big Seal Rock and Little Seal Rock for 8 days following tagging. The shark then migrated north, was at The Barge on 28 December, 2006 and then at Fish Rock on 19 February, 2007.

#### *Shark 7*

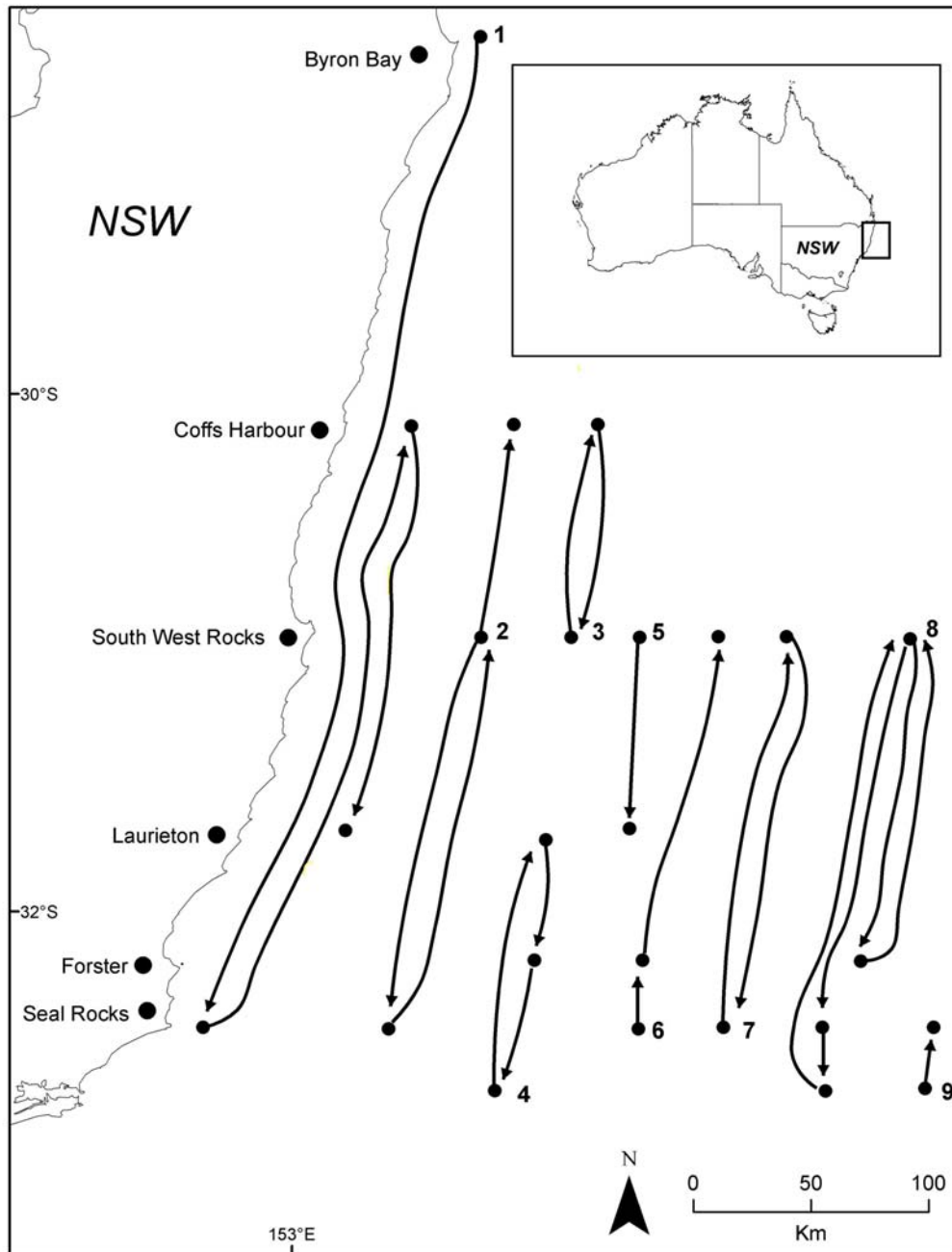
This sexually-immature 2.00 m TL male grey nurse shark was tagged at Big Seal Rock on 7 December, 2006 where it remained for 4 days following tagging. The shark then migrated north and was at Fish Rock in late December 2007 before migrating back south to Big Seal Rock where it remained from 12 to 13 January, 2007.

#### *Shark 8*

This sexually-immature 2.10 m TL female grey nurse shark was tagged at Fish Rock on 14 November, 2006. The shark remained at Fish Rock and surrounding areas until 8 December, 2006. The shark migrated south, was at Big Seal Rock on 12 December, 2006 and at Broughton Island on 15 December, 2006. The shark returned north to Fish Rock on 19 December, 2007 before again migrating south to Latitude Rock on 26 December, 2006. The shark then migrated north via The Barge and was at Fish Rock from 29 December, 2006 to 4 August, 2007.

#### *Shark 9*

This sexually-immature 1.70 m TL female grey nurse shark was tagged at Broughton Is. on 23 February, 2007. The shark migrated north and was at Seal Rocks from 24 February, 2007 to 31 March, 2007.

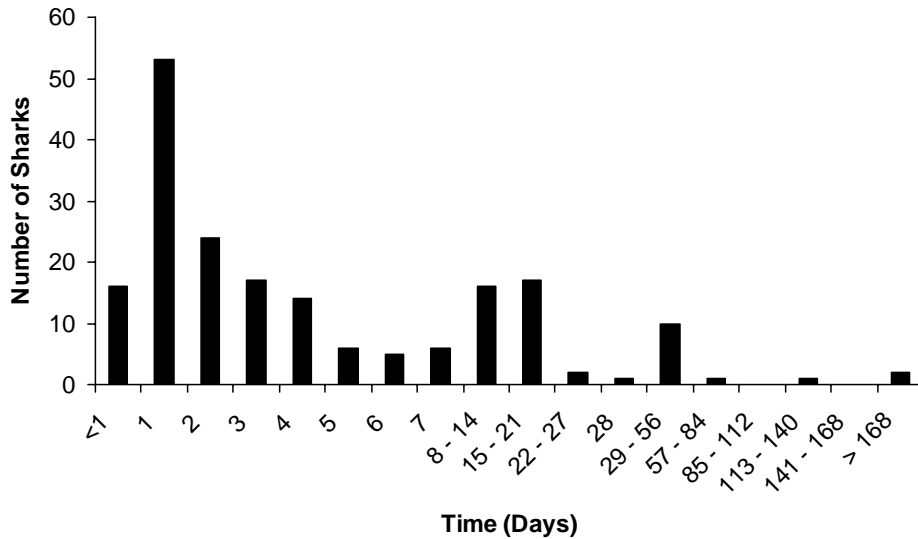


**Figure 3.19.** Examples of migratory movements of grey nurse sharks tagged with V16TP R-coded acoustic tags (tagging site is numbered).

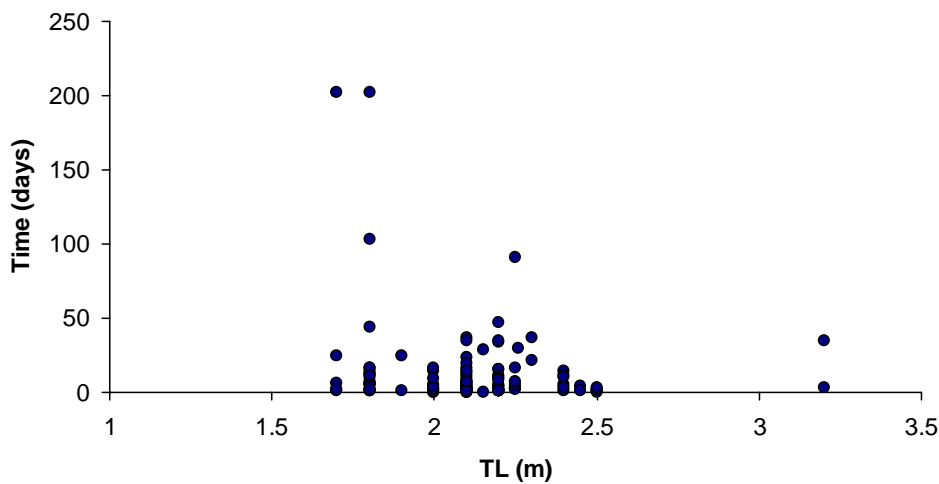


**3.3.6. Timing and duration of occupation of sites**

The timing of occupation of sites by grey nurse sharks tagged with R-coded acoustic tags varied throughout the year along the east coast. Site occupation was correlated with water temperature, the shark’s sexual maturity and, when sexually mature, its stage in the reproductive cycle. Grey nurse sharks occupied aggregation sites for varying lengths of time ranging from less than 1 day to in excess of 6 months with a mean ( $\pm$  SD) of 10.61 (3.60) days (Fig. 3.20). Moreover, the duration of occupation was not significantly correlated with the shark’s total length (Fig 3.21).



**Figure 3.20.** Frequency of occupation of aggregation sites of differing durations by grey nurse sharks tagged with R-coded acoustic tags (n = 191 observations).



**Figure 3.21.** The frequency of occupation of aggregation sites of differing durations for grey nurse sharks of varying total lengths tagged with R-coded acoustic tags Correlation coefficient not significant (n = 136, r = 0.1712, P > 0.05).

### 3.4. Discussion

The tagging of grey nurse sharks with pop-up archival satellite tags and R-coded acoustic tags enabled the large-scale, migratory movements of sexually-mature males and sexually immature females to be documented. A northerly migration of males occurred over the autumn/winter period and these results were consistent with previous studies (Otway *et al.* 2003, Otway 2004, Otway and Burke 2004, Bruce *et al.* 2005). The unidirectional distances travelled by the sexually-mature males varied from 450 to 1000 km and included migratory paths from Fish Rock (off South West Rocks, NSW) north to the Capricorn Channel off Yeppoon (southern QLD) and various sites in between. The northern migratory movements of sexually-mature males mainly occurred in shallower waters (i.e., 30 – 40 m) until just north of Fraser Is. The sharks then moved into deeper waters (i.e., 60 – 70 m) continuing their migratory path north.

A southerly migration of sexually-mature males and sexually immature males and females occurred over the spring/summer period and was consistent with previous studies (Otway *et al.* 2003, Otway 2004, Otway and Burke 2004, Bruce *et al.* 2005). These southern migrations occurred rapidly and were punctuated with periods of time spent at site along the migratory route. The unidirectional distances travelled by the sexually-mature males and sexually immature males and females varied, but reached magnitudes of  $\approx$  640 km. Moreover, when migrating south, the sharks swam in deeper waters (i.e., 80 – 100 m) and their movements were likely assisted by the southerly-flowing East Australia Current.

Twenty six of the 30 grey nurse sharks tagged with R-coded acoustic tags across 5 sites spanning 915 km were detected within 1 year of tagging at sites distant from the initial site of tagging (e.g., Shark 1 – Julian Rocks to Seal Rocks, Section 3.3.5) and indicated substantial mixing of tagged sharks with the untagged population. Consequently, the movements of the tagged individuals documented in this study, to date, are most likely representative of the untagged population. The substantial mixing of the tagged and untagged grey nurse sharks was also evident with grey nurse sharks tagged with cattle ear tags (Otway 2004, Otway and Burke 2004). Given the spatial dispersion of acoustic listening stations comprising SEACAMS (Fig. 3.3), a re-sighting rate of 86.7% within 1 year is a simple and compelling statistic that indicates that the sharks were not greatly affected by the tagging techniques used. This re-sighting rate is also very similar to the results of two previous tagging studies that obtained re-sighting rates of 83.3% and 76.2% using Roto tags (Otway and Burke 2004) and R-coded acoustic tags (Bruce *et al.* 2005), respectively. All of these re-sighting rates far exceed the mean annual recapture rates reported in previous studies (e.g., Olsen 1953, Casey *et al.* 1985, Smith & Abramson 1990, Kohler *et al.* 1998, Stevens *et al.* 2000). For example, the highest annual recapture of 15% per annum was achieved by West & Stevens (2001) whilst working with the school shark *Galeorhinus galeus*.

The timing of occupation of sites by grey nurse sharks tagged with R-coded acoustic tags varied throughout the year along the east coast. Site occupation was dependent on water temperature and, in part, on the sexual maturity of the shark. Juvenile males (i.e., < 2.1 m TL) and juvenile females (i.e., < 2.6 m TL) remained for a large part of the year in the coastal waters between South Solitary Is. and Magic Pt. off Sydney. Over this period the sharks moved among numerous sites. With increased water temperatures over summer and autumn, male and female grey nurse sharks (i.e., immature and sexually-mature individuals) extended their range by migrating to southern NSW where they were observed by numerous scuba divers at sites including Bass Point, the Tollgate Is. and Montague Is. Site occupation was correlated with water temperature, sexual maturity and the stage in the reproductive cycle. On average, grey nurse sharks occupied aggregation sites for  $\approx$  11 days, but this varied substantially with occupations of less than 1 day to some in excess of 6 months. Finally, the duration of occupation of aggregation sites was not correlated with the shark's total length.

Male and female grey nurse sharks exhibited similar patterns when it came to the percentage of time spent in waters of various depths and temperatures. On average, male and female grey nurse sharks spent  $\approx 71\%$  and  $\approx 78\%$  of their time in waters  $< 40$  m, respectively. On average, both sexes combined spent  $\approx 74\%$  of their time in waters  $< 40$  m and  $\approx 95\%$  of their time in waters  $< 80$  m and this was consistent with the results of Otway (2004). Male and female grey nurse sharks also exhibited similarities in the percentages of time spent in waters of various temperatures. On average, male and female grey nurse sharks spent  $\approx 95\%$  and  $\approx 96\%$  of their time in waters  $17 - 24^\circ\text{C}$ , respectively and these results are consistent with those documented by Otway (2004). The occupation of deeper depths was mainly evident during migratory movements north and south. Again, the large proportion of time spent in waters  $< 40$  m emphasises the occupation of relatively shallow, inshore coastal waters of the east Australian continental shelf where much of the offshore, recreational fishing occurs.

Tagging of grey nurse sharks with pop-up archival satellite tags also enabled the collection of additional morphometric, physiological and biochemical data and tissue samples for DNA analyses. Results of the genetic work to date have shown that the South African population is isolated from Australian populations off the east and west coasts and that these are effectively isolated from each other with little, if any, migration between them. More importantly, the east Australian population has significantly less genetic variation (i.e., a single mitochondrial haplotype) than the other populations. Negligible genetic variation in a population predisposes it to an erosion of its evolutionary potential and enhances the risk of extinction through inbreeding. Analysis of the DNA samples (Ahonen & Stow 2009) has confirmed the earlier results in Stow *et al.* (2006). Their study also modelled the consequences of barriers to migration (and hence gene-flow) and provided an initial estimate of effective population size of  $\approx 126$  individuals, suggesting a total population on Australia's east coast of 1000 – 1500 individuals.

## 4. Effects of scuba diving

### 4.1. Introduction

Given that elasmobranchs possess a superb array of sensory organs that are well-adapted to their environment (Gilbert 1962, Bleckmann & Hofmann 1999, Maruska 2001, Myrberg 2001, Montgomery and Walker 2001, Tricas 2001), it's not surprising to learn that many sharks have distinctly larger brains (i.e., brain to body weight ratios) than many bony fish, amphibians and reptiles (Northcutt 1978, Moss 1984, New 2001). In this regard, the grey nurse shark has the largest brain within the Order Lamniformes (Demski & Northcutt 1996). Furthermore, the behavioural repertoire of an animal has often been used to estimate the complexity of the brain (e.g., Graeber 1978 for sharks) and in this respect, bony fish respond in characteristically predictable ways and have stereotyped behaviour. Sharks, in contrast, are notoriously unpredictable and the resulting richness of responses often masks the limited stereotypical behaviour that is displayed. Interestingly, several authors (e.g., Moss 1984, Hofmann 1999) have pointed out that this degree of behavioural complexity had been argued in the older scientific literature as evidence for considering sharks as primitive animals. Recent research (see below) clearly shows that this is not the case with many studies now demonstrating evidence of very complex, social and predatory behaviour.

In studying shark behaviour, most authors have focused on the behaviours associated with: swimming (including localised and migratory movements) (e.g., Thomson 1976, Holland *et al.* 1992, Eckert & Stewart 2001, Sundström *et al.* 2001); diurnal and longer-term activity rhythms (e.g., Tricas *et al.* 1981, Klimley *et al.* 1988, West & Stevens 2001); courtship and reproduction (e.g., Klimley 1980, Tricas 1980, Gordon 1993, Pratt & Carrier 2001, Pratt & Carrier 2005); social groups and aggregations (e.g., Springer 1967, Parker & Bailey 1979, Klimley 1981, Klimley & Nelson 1981); feeding (e.g., Moss 1984, Motta & Wilga 2001, Klimley *et al.* 1996); and the defence of territories (e.g., Johnson & Nelson 1973, Nelson 1981, Nelson *et al.* 1986). Behavioural research on the interactions between humans and sharks has, for obvious reasons, been dominated by studies focussing on shark attacks and various measures for their prevention (e.g., Nelson *et al.* 1986, Burgess & Callahan 1996, Levine 1996, West 1996). Consequently, there are few quantitative data on the effects of human activities on the behaviour of sharks.

With the advent of shark ecotourism, there has been substantial debate, with support for (e.g., Kroese 1998) and against (e.g., Bartlett 1998, Burgess 1998), the practice of burleying (chumming) the water to attract white sharks for cage diving (e.g., Strong *et al.* 1992 1996) and/or the operation of regular feeding stations for sharks, predominantly from the Order Carcharhiniformes. Both of these commercial shark feeding activities are operated at numerous locations worldwide including the USA, South Africa, Australia, the Maldives and the Bahamas (Michael 1993, Taylor & Deacon 1997). These shark feeding operations provide varying degrees of protection for the participating divers and these include metal cages with white sharks, to chain mail suits with pelagic species such as the oceanic white-tip and blue shark, through to absolutely nothing with many whaler species. While shark tourism, and particularly scuba diving with sharks, plays a very important role in supporting policy and legislation favouring shark conservation, badly-managed, unregulated shark ecotourism activities can result in: harm to scuba divers and other water-users via attacks or loss of fish; marked alterations to local shark populations; unforeseen damage to the marine environment; and ultimately, affect the local economy (Burgess 1998). Conflicts among competing dive operators have also exacerbated this situation and local management agencies have had to take various steps to mitigate the disputes (Bartlett 1998, Kroese 1998). Despite this, the putative impacts on the marine environment and shark populations *per se* still remain to be addressed.

In Australia, shark ecotourism has a similar focus, but also includes activities with more placid shark species. Cage diving with white sharks occurs mainly in South Australia (Bruce 1995). Regular shark feeding enterprises focussing mainly on carcharhinid whalers operate at various locations in the Great Barrier Reef. Expanding ecotourism operations catering for scuba divers and snorkellers have taken advantage of the seasonal aggregations of whale sharks in Ningaloo Marine Park, WA (Colman 1998). Finally, numerous dive operators in NSW and southern QLD take scuba divers to various sites where they can dive with grey nurse sharks. Given their protected status, conservation and/or fisheries management agencies have taken steps to mitigate possible impacts of divers (snorkellers and scuba divers) on the whale shark (Colman 1998) and the grey nurse shark (Otway *et al.* 2003, Talbot *et al.* 2004).

As stated earlier, numerous scuba divers enter the water for the sole purpose of observing, photographing and/or filming grey nurse sharks as part of a diving ecotourism industry that also caters to divers from overseas (Otway *et al.* 2003, Hayward 2003). In the past, grey nurse sharks have, on occasions, also been fed by divers (Cropp 1964, Ireland 1984), but this practice is no longer permitted in critical habitat sites declared under state (NSW – *Fisheries Management Act*, QLD – *Nature Conservation Act*) and federal laws (*Environment Protection and Biodiversity Conservation Act*). There have been few, if any, studies that directly focus on the effects of scuba divers on sharks and especially the grey nurse shark. However, when studying aggregations of scalloped hammerhead sharks swimming close to the sea surface, Klimley (1981) noted that the sharks moved rapidly away from scuba divers, presumably in response to their conspicuous air bubbles. These initial observations were not, however, subjected to any experimental testing at a later date.

Two previous studies (Hayward 2003, Bennett & Bansemer 2004) have attempted to quantify the impacts of scuba diving. Both of these studies used similar sampling protocols involving a scuba diver making observations of the interactions between grey nurse sharks and other scuba divers. Given that sharks have an enviable array of sensory organs functioning interactively, it is highly likely that all the scuba divers (including the diver making the observations) during these studies would have been detected by the sharks present. Consequently, there was no independent means of quantifying whether observed behaviour of the grey nurse sharks was directly attributable to the scuba divers under observation or the cumulative effect of all divers present. Data collected in this manner risk producing equivocal results, lack sufficient statistical power to detect important changes and confound any subsequent assessment of the impact (Otway 1992, Underwood 1997). Moreover, sampling methods reliant on video-cameras or similar equipment (remotely-operated or otherwise) will also confound interpretations if the shark's behaviour is influenced by the electronic signals emanating from the equipment.

An unconfounded assessment of the putative impacts of scuba diving on grey nurse sharks will, therefore, depend on identifying a sampling technique that permits the collection of unequivocal data. While this may appear, at first glance, to be an insurmountable problem, recent technological advances in the acoustic tracking of sharks and fish with R-coded tags (Stasko & Pincock 1977, Voegeli *et al.* 2001 for reviews) provide an ideal means of obtaining diver-independent data. Previous research has shown that sharks can hear sounds with frequencies of 40 Hz to  $\approx$  800 Hz (Myrberg 2001 for a review). Importantly, R-coded acoustic tags transmit at 69 kHz and thus, are outside the acoustic reception range of sharks. Hence, transmissions from R-coded tags are benign and unlikely to contribute to behavioural changes in grey nurse sharks. R-coded acoustic tags, in conjunction with SEACAMS, provide a cost-effective, diver-independent means of quantifying the impacts of scuba diving on grey nurse sharks.

## 4.2. Materials and methods

### 4.2.1. Experimental sites

Field experiments assessing the putative effects of scuba diving on grey nurse sharks were done at 15 sites: Julian Rocks, Pimpnel Rock, North Solitary Is., South Solitary Is., Green Is., Fish Rock, Black Rock, the Cod Grounds, the Barge, Latitude Rock, Big Seal Rock, Little Seal Rock, North Rock, Broughton Is. and the Tollgate Is. (Fig. 4.1). These sites reflect the annual variation in distribution of grey nurse sharks with a more year-round occupation of northern NSW coastal waters and the generally seasonal (summer/autumn) usage of southern waters associated with warmer sea temperatures.

### 4.2.2. Acoustic tagging

The data used in the experiments were obtained from the acoustic detections on the SEACAMS listening stations of the 30 grey nurse sharks tagged to document their localised and migratory movement as described earlier in this report. While the R-coded tags used in this study had a maximum signal range of  $\approx 500$  m in coastal waters with normal oceanographic conditions, the underwater topography around rocky reefs can markedly alter the signal range. With this in mind, the listening stations were placed on the bottom of the gutters occupied by grey nurse sharks at each site. Given the underwater topography associated with these gutters, this ensured that grey nurse sharks tagged with R-coded tags were only detected when they were actually in the gutter. Furthermore, the signal transmission frequency is pre-programmed into the tag and cannot be affected by the behaviour of the shark.

The detections from each VR2/VR2W acoustic receiver were downloaded onto a computer and sorted by tag number. Once sorted, the number of detections received per hour for each tagged grey nurse shark was calculated for the entire duration of the shark's occupation of the site. The hourly detections were then linked to the activities of divers in the 3 experiments described below.

### 4.2.3. Experimental protocols

Operators of dive shops in NSW have provided observations of grey nurse sharks at the sites they regularly dive to NSW DPI. This information includes details of sharks tagged with pop-up archival satellite tags and/or R-coded acoustic tags together with information concerning diver usage of the sites. These observations were recorded and readily linked to the detections received on the respective, SEACAMS acoustic listening stations.

Three experiments were done to assess the putative effects of scuba diving on grey nurse sharks. Importantly, the sites chosen represent a random sample of the total population of sites along the east coast of Australia that are subjected to scuba diving activities with grey nurse sharks. Consequently, the results of the experiments assessing the putative impacts of scuba diving on grey nurse sharks can be generalised to all sites occupied by grey nurse sharks and subjected to contemporaneous scuba diving. Each of the experiments incorporated numerous scuba divers (i.e., at least 6 divers per dive per site) with wide-ranging scuba diving skills, experience and familiarity with the sharks. To ensure that the behaviour of recreational scuba divers was not modified, potentially biasing the results, no *a priori* information concerning the aims, methods, sites, timing and duration of these experiments was provided to recreational scuba divers or the owner/operators of the dive shops.

### *Experiment 1*

Given that individual grey nurse sharks exhibit a range of behaviours at different spatial and temporal scales, it is important that these potential sources of variation are incorporated into field experiments done to assess the putative impacts of scuba diving on the species. To this end, it was important to ensure that sampling was done “before, during and after scuba diving” and that this was replicated on different occasions. Sampling would also need to be done at multiple sites and include replicate sharks. Moreover, it is possible that grey nurse sharks may detect the presence of divers prior to their entry into the water because of the noise and vibrations associated with anchoring, mooring, and gearing-up (i.e., noise and vibrations associated with the bumping of the boat’s hull by scuba tanks and weight belts, etc.). If this were the case, then the behaviour of grey nurse sharks on days when diving occurs could differ from days when divers are not present irrespective of whether the divers enter the water. For example, if the shark’s behaviour were to change markedly on sensing the arrival of a dive boat and the associated noise and vibrations prior to the divers entering the water, it is plausible that a comparison of the data collected before, during and after scuba diving would not differ. This would then result in the erroneous conclusion that scuba diving has no impact on grey nurse sharks. To ensure that such conclusions were not made required the incorporation of an additional temporal scale involving sampling on the day before scuba diving, the day of scuba diving, and the day after scuba diving. Comparisons among these situations would then enable an assessment of possible changes in the grey nurse shark’s behaviour attributable directly to scuba diving and distinct from those associated with the noise and vibrations of anchoring and/or mooring the dive boat and the divers gearing-up. Therefore, in this experiment we partitioned the total variation into that between sharks and time periods, and among sites, days (the day before scuba diving, day of scuba diving, day after scuba diving) and treatments (before, during and after scuba diving), and finally among the replicate number of hourly detections.

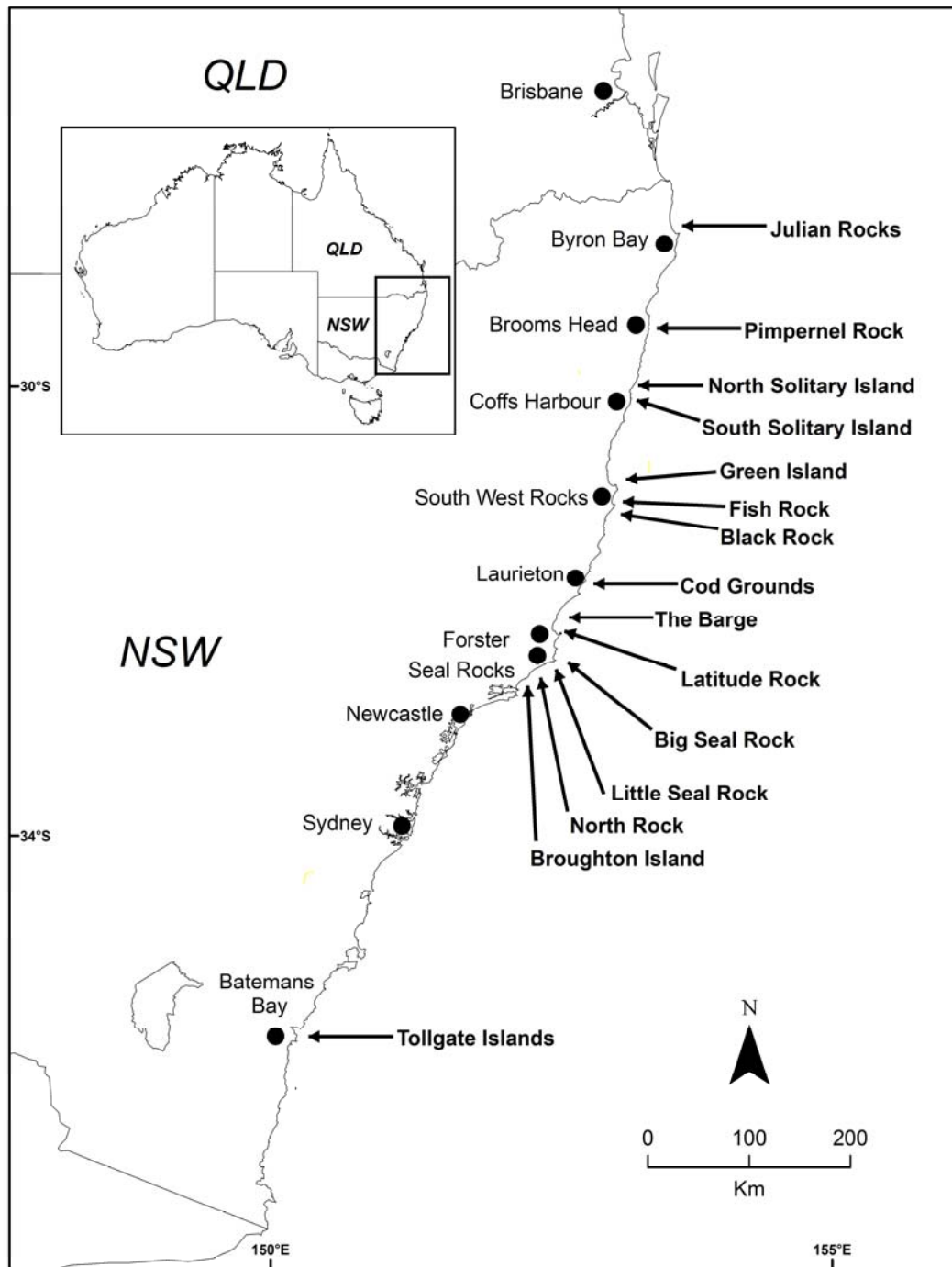
This extremely comprehensive field experiment involved monitoring the behaviour of 10 acoustically-tagged grey nurse sharks (2 sharks per site) on 2 separate time periods each comprising 3 days (i.e., the day before scuba diving, the day of scuba diving, the day after scuba diving) and on each day for 3 hours before, during and after scuba diving had occurred at each of 5 sites (South Solitary Is., Fish Rock, the Cod Grounds, Big Seal Rock and Broughton Is. – Fig. 4.1). The spatial coverage of this experiment was large as the most northerly site at South Solitary Is. was separated from the most southerly site at Broughton Is. by 325 km.

### *Experiment 2*

The second field experiment involved monitoring the behaviour of 24 acoustically-tagged grey nurse sharks (3 sharks per site) for 4 hours before and after scuba diving had occurred at each of 8 sites (Julian Rocks, Pimpernel Rock, North Solitary Is., South Solitary Is., Fish Rock, the Cod Grounds, Big Seal Rock and Broughton Is., Fig. 4.1). The spatial coverage of this experiment was even larger as the most northerly site at Julian Rocks was separated from the most southerly site at Broughton Island by 490 km.

### *Experiment 3*

This field experiment involved monitoring the behaviour of 15 acoustically-tagged grey nurse sharks (one shark per site) for 3 hours before, during and after scuba diving had occurred at each of 15 sites (Fig. 4.1). This experiment maximised the spatial coverage of sites along the NSW coast with the most northerly site at Julian Rocks being separated by 915 km from the most southerly site at the Tollgate Is.



**Figure 4.1.** Map showing locations of dive sites used to assess the impacts of scuba diving on grey nurse sharks.



#### 4.2.4. Statistical analyses

##### *Implications of Type I and Type II errors*

Statistical tests are subject to two types of defined error (Table 4.1). The first is a Type I or “ $\alpha$ ” error, which is the probability of falsely concluding that an impact has occurred (i.e., the null hypothesis ( $H_0$ ) is rejected in favour of the alternative hypothesis indicating that impact has occurred). The second is a Type II or “ $\beta$ ” error, which is the probability of falsely concluding that an impact has not occurred (i.e., the null hypothesis ( $H_0$ ) is accepted). To date, most studies have been preoccupied with Type I errors with  $\alpha$  being set, by scientific convention, at  $P = 0.05$ . Put simply, it means that there is a 1 in 20 chance of incorrectly concluding that an impact has occurred. In contrast, Type II errors have largely been ignored, a matter which should be of some concern. This is especially the case with experiments purporting to assess impacts of anthropogenic activities. Importantly, the probability of a Type II error is directly linked to the power (Pr) of a statistical test to detect differences between means via the relationship:  $Pr = 1 - \beta$ . With this in mind, it is important to ensure a priori that the experimental sampling design will enable a statistical test that has sufficient power to detect a change of a biologically important magnitude.

**Table 4.1.** Relationships between the real world situation and the outcomes of statistical tests for identifying impacts and their Type I ( $\alpha$ ) and Type II ( $\beta$ ) errors.

Biological Reality	<u>Outcome of Statistical Test</u>	
	No Impact ( $H_0$ : Accepted)	Impact ( $H_0$ : Rejected)
No Impact ( $H_0$ : True)	CORRECT	Type I Error
Impact ( $H_0$ : False)	Type II Error	CORRECT

##### *Experiment 1*

The data were analysed using a partially-nested, partially-orthogonal 5-factor analysis of variance (Table 4.2) with the factors: Sites (a random factor); Sharks nested in Sites (a random factor); Time Periods nested in Sharks and Sites (a random factor); Days (a fixed factor); and Treatments (a fixed factor).

##### *Experiment 2*

The data were analysed using a partially-nested, partially-orthogonal 3-factor analysis of variance (Table 4.6) with the factors: Sites (a random factor); Sharks nested in Sites (a random factor); and Treatments (a fixed factor).

##### *Experiment 3*

The data were analysed using an orthogonal 2-factor analysis of variance (Table 4.7) with the factors: Sites (a random factor); and Treatments – Before, During and After (a fixed factor).

Where possible, terms that were not significant at  $P = 0.25$  in the initial analysis of variance were pooled with the residual to enable more powerful tests of the remaining terms. Following the analyses of variance, significant interaction terms were interpreted using post-hoc comparisons (SNK tests – Underwood 1997) to identify significant differences among means.

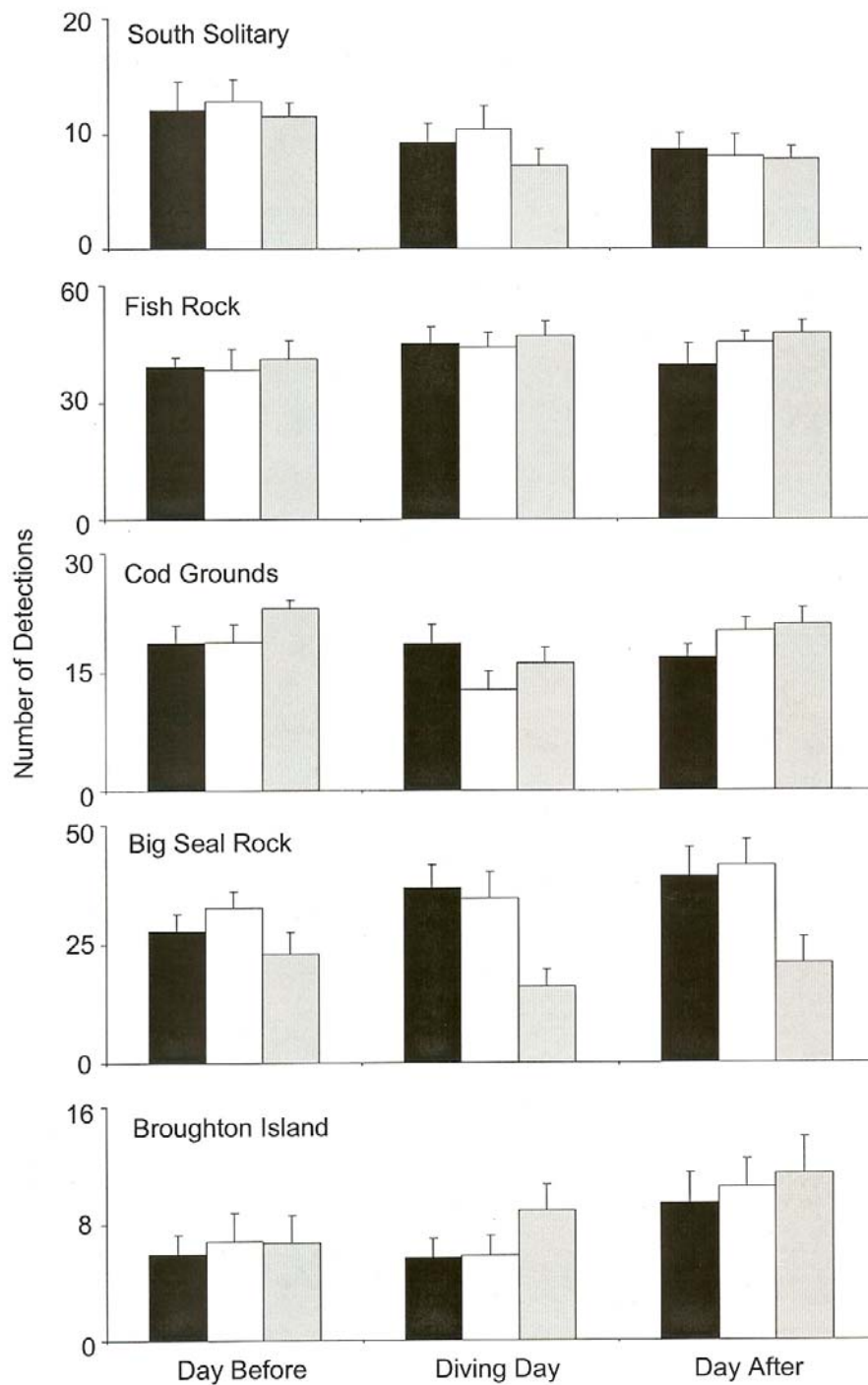
### 4.3. Results

The results of each of the 3 experiments showed that scuba diving had no impact on grey nurse sharks at any of the 15 sites studied. Details of the results of each experiment are provided below.

#### *Experiment 1*

The 2 grey nurse sharks tagged with R-coded, acoustic tags remained at each of the 5 sites throughout the duration of the experiment. More importantly, none of the sharks left the sites during or after the scuba diving occurred at these sites (Fig. 4.2). Statistical analysis showed that there was variation in the mean number of hourly acoustic detections between Sharks and Time Periods and among Sites, Days and Treatments as evidenced by the significant Time Period(Sharks(Sites)) x Days x Treatments interaction (Table 4.2). Results of *post-hoc* SNK tests (Tables 4.3 and 4.4) showed that there were no significant differences in the mean number of acoustic detections before, during and after scuba diving in 80%, 95% and 95%, respectively of the comparisons among the means. There was only one occasion at Big Seal Rock in Time Period 1 when the mean number of acoustic detections of one shark (i.e., Diving Day, Shark 8, Table 4.3) was significantly less while scuba divers were in the water compared to before and after. Moreover, there were no significant differences in the mean number of acoustic detections before, during and after scuba diving on the day before and day after scuba diving. This same shark, however, did not show any change in behaviour in Time Period 2 as the mean number of acoustic detections did not differ significantly before, during and after scuba diving on the day before diving, the diving day and the day after scuba diving (Tables 4.3 and 4.4). Interestingly, significantly fewer acoustic detections at the time when scuba diving occurred (i.e., during diving) compared to before and after were also evident with one shark on a single occasion on the day before diving at the Cod Grounds in Time Period 2 (i.e., Shark 5, Table 4.3). The number of detections was significantly less at the time when scuba divers would have been in the water compared to before and after. Moreover, there were no significant differences in the mean number of acoustic detections before, during and after scuba diving on the diving day and the day after diving.

The SNK tests showed that there were also significant differences in the mean number of acoustic detections among Time Periods and these most likely contributed greatly to the significant Time Period(Sharks(Sites)) x Days x Treatments interaction (Table 4.2). The individual outcomes of these SNK tests varied between Sharks among Sites, Days and Treatments and were most evident at Fish Rock where the mean number of acoustic detections was greater in Time Period 1 in 88.9% of the comparisons (Table 4.5).



**Figure 4.2.** Mean (+SE) number of hourly detections of grey nurse sharks tagged with R-coded acoustic tags received on SEACAMS listening stations before (■), during (□), and after (▒) times of scuba diving on the day before diving, the day of diving and the day after diving at 5 sites in NSW coastal waters. Means calculated by pooling over  $n = 2$  Sharks and  $n = 2$  Time periods with  $n = 3$  replicate hourly samples in each treatment (Before, During, After).

**Table 4.2.** Partially-nested, partially orthogonal 5-factor analysis of variance assessing the impacts of scuba diving on grey nurse sharks ( $n = 2$ ) at 5 sites and at 3 different temporal scales: Time Periods (weeks apart), Days (Day Before, Diving Day, Day After) and Treatments (Before, During & After).

Source of variation	df	MS	F	P
Sites = Si	4	27877.20	6.49	0.0325
Sharks(Sites) = Sh(Si)	5	4297.67	3.37	0.0484
Time Periods(Sharks(Sites)) = P(Sh(Si))	10	1276.94	37.46	0.0001
Days = D	2	240.68	0.97	0.4203
Treatments = T	2	365.36	3.94	0.0645
Si x D	8	248.63	0.55	0.7971
Si x T	8	92.78	1.88	0.1732
Sh(Si) x D	10	453.69	4.12	0.0034
Sh(Si) x T	10	49.42	1.13	0.3873
P(Sh(Si)) x D	20	110.10	3.23	0.0001
P(Sh(Si)) x T	20	43.63	1.28	0.1886
D x T	4	100.93	1.52	0.2444
Si x D x T	16	66.54	0.99	0.5006
Sh(Si) x D x T	20	67.15	1.01	0.4678
P(Sh(Si)) x D x T	40	66.17	1.94	0.0009
Residual	360	34.09		
Total	539			

**Table 4.3.** Results of SNK tests ( $P = 0.05$ ) examining the differences among means in the significant Time Periods (Sharks(Sites)) x Days x Treatments interaction with Treatments – B: Before, D: During, A: After scuba diving; and Days – Day before diving, Diving day; and Day after scuba diving.

Dive Site	Outcome of SNK test			
	Day Before	Diving Day	Day After	
South Solitary Island				
<i>Shark 1</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	B=D=A
<i>Shark 2</i> –	Period 1	B>A=D	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	B=D=A
Fish Rock				
<i>Shark 3</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	B=D=A
<i>Shark 4</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	A=D>B
Cod Grounds				
<i>Shark 5</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=A>D	B=D=A	B=D=A
<i>Shark 6</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	A=D>B
Big Seal Rock				
<i>Shark 7</i> –	Period 1	A>D=B	B=D=A	B=D=A
	Period 2	A>D=B	B=D=A	B=D=A
<i>Shark 8</i> –	Period 1	B=D=A	B=A>D	B=D=A
	Period 2	B=D=A	B=D=A	A=D>B
Broughton Island				
<i>Shark 9</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	B=D=A
<i>Shark 10</i> –	Period 1	B=D=A	B=D=A	B=D=A
	Period 2	B=D=A	B=D=A	A=D>B

**Table 4.4.** Results of SNK tests ( $P = 0.05$ ) examining the differences among means in the significant Time Periods (Sharks(Sites)) x Days x Treatments interaction with Treatments – Before, During and After scuba diving; and Days – DB: Day before diving, DD: Diving day, DA: Day after diving.

Dive Site	Outcome of SNK test		
	Before	During	After
South Solitary Island			
<i>Shark 1</i> – Period 1	DB=DD=DA	DB=DD=DA	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DB=DD=DA
<i>Shark 2</i> – Period 1	DD=DA<DB	DB=DD=DA	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DB=DD=DA
Fish Rock			
<i>Shark 3</i> – Period 1	DB=DD=DA	DB=DD=DA	DB=DD=DA
Period 2	DB=DD=DA	DD=DA>DB	DB<DD=DA
<i>Shark 4</i> – Period 1	DB=DD=DA	DB=DD=DA	DB=DD=DA
Period 2	DB=DD>DA	DB=DD=DA	DA=DD>DB
Cod Grounds			
<i>Shark 5</i> – Period 1	DB=DD=DA	DB=DD=DA	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DB=DD=DA
<i>Shark 6</i> – Period 1	DB=DD=DA	DB=DA>DD	DB=DA>DD
Period 2	DB=DD=DA	DB=DA>DD	DB=DD=DA
Big Seal Rock			
<i>Shark 7</i> – Period 1	DA=DD>DB	DA>DB=DD	DB=DD=DA
Period 2	DB=DD=DA	DA=DD>DB	DB=DA>DD
<i>Shark 8</i> – Period 1	DB=DD=DA	DB=DA>DD	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DB=DD=DA
Broughton Island			
<i>Shark 9</i> – Period 1	DA>DD=DB	DA>DD=DB	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DA>DB=DD
<i>Shark 10</i> – Period 1	DB=DD=DA	DB=DD=DA	DB=DD=DA
Period 2	DB=DD=DA	DB=DD=DA	DB=DD=DA

**Table 4.5.** Results of SNK tests ( $P = 0.05$ ) for Time Periods: P1 and P2 in the significant Time Periods (Sharks(Sites)) x Days x Treatments interaction.

Dive Site	Outcome of SNK test		
	Day Before	Diving Day	Day After
South Solitary Island			
Before – <i>Shark 1</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 2</i>	P1 > P2	P1 = P2	P1 = P2
During – <i>Shark 1</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 2</i>	P1 < P2	P1 = P2	P1 < P2
After – <i>Shark 1</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 2</i>	P1 = P2	P1 = P2	P1 = P2
Fish Rock			
Before – <i>Shark 3</i>	P1 > P2	P1 = P2	P1 > P2
<i>Shark 4</i>	P1 > P2	P1 > P2	P1 > P2
During – <i>Shark 3</i>	P1 > P2	P1 = P2	P1 > P2
<i>Shark 4</i>	P1 > P2	P1 > P2	P1 > P2
After – <i>Shark 3</i>	P1 > P2	P1 > P2	P1 > P2
<i>Shark 4</i>	P1 > P2	P1 > P2	P1 > P2
Cod Grounds			
Before – <i>Shark 5</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 6</i>	P1 = P2	P1 = P2	P1 = P2
During – <i>Shark 5</i>	P1 > P2	P1 = P2	P1 = P2
<i>Shark 6</i>	P1 = P2	P1 = P2	P1 = P2
After – <i>Shark 5</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 6</i>	P1 = P2	P1 = P2	P1 = P2
Big Seal Rock			
Before – <i>Shark 7</i>	P1 > P2	P1 = P2	P1 = P2
<i>Shark 8</i>	P1 = P2	P1 = P2	P1 = P2
During – <i>Shark 7</i>	P1 = P2	P1 < P2	P1 = P2
<i>Shark 8</i>	P1 = P2	P1 < P2	P1 > P2
After – <i>Shark 7</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 8</i>	P1 = P2	P1 = P2	P1 = P2
Broughton Island			
Before – <i>Shark 9</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 10</i>	P1 = P2	P1 = P2	P1 = P2
During – <i>Shark 9</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 10</i>	P1 > P2	P1 = P2	P1 = P2
After – <i>Shark 9</i>	P1 = P2	P1 = P2	P1 = P2
<i>Shark 10</i>	P1 > P2	P1 = P2	P1 = P2

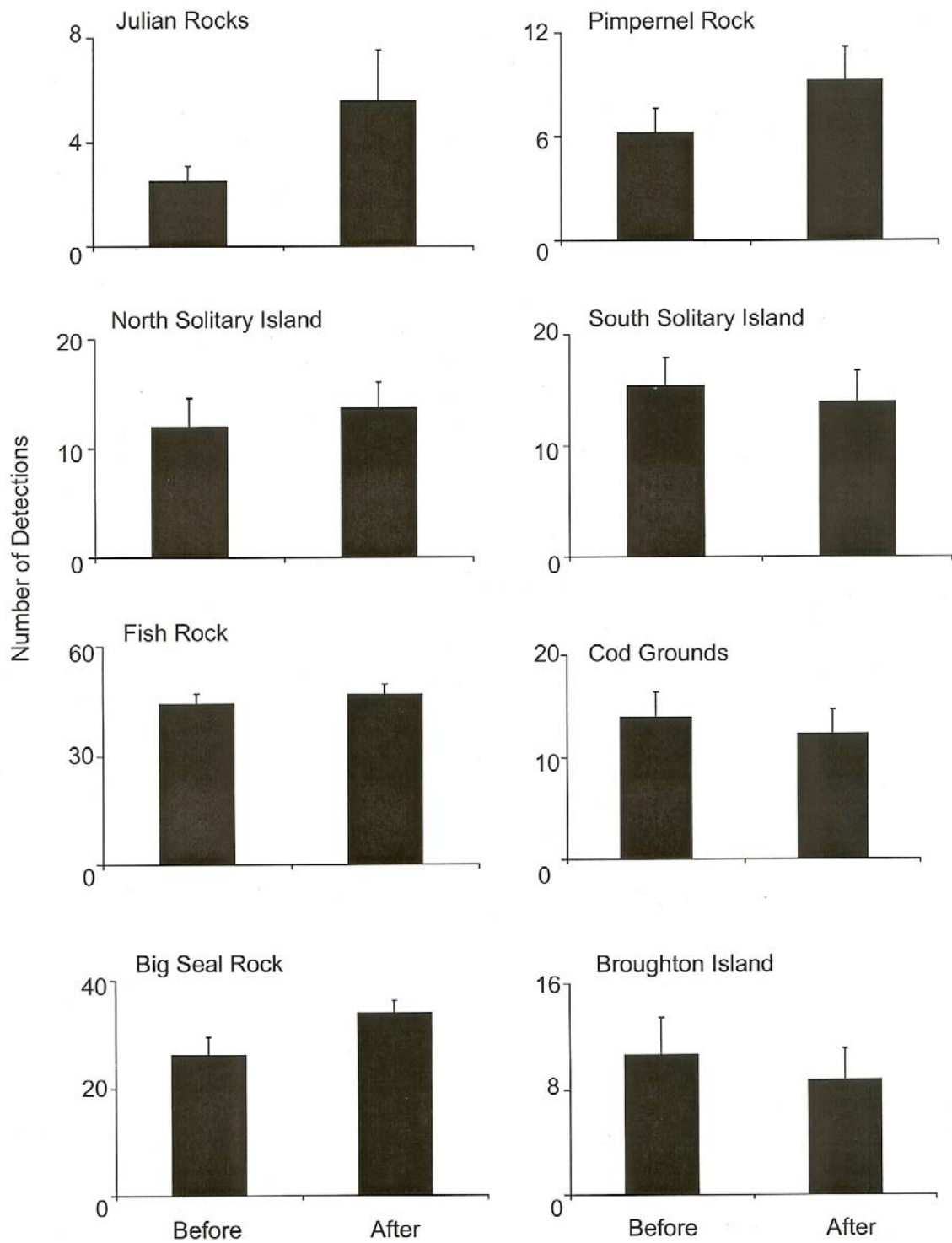
*Experiment 2*

The 3 grey nurse sharks tagged with R-coded, acoustic tags remained at each of the 8 sites throughout the duration of the experiment. There was no obvious evidence of an impact as none of the sharks left the sites after scuba diving occurred (Fig. 4.3). Statistical analysis showed that there was significant variation in the mean number of hourly acoustic detections among Sites and Sharks within Sites (Table 4.6) indicating that the behaviour of the grey nurse sharks differed among sites and individuals. More importantly, none of the remaining terms in the analysis (i.e., B vs A, Sites x B vs A and Sharks(Sites) x B vs A) were significant (Table 4.6) and clearly demonstrated that scuba diving had no impact on grey nurse sharks.

**Table 4.6.** Partially-nested, partially orthogonal 3-factor analysis of variance assessing impacts of scuba diving on grey nurse sharks. Three sharks were sampled before and after scuba diving at each of 8 sites.

Source of variation	df	MS	F	P
Sites	7	4587.62	13.33	0.0001
Sharks(Sites)	16	344.10	9.08	0.0001
Before vs After = B vs A	1	53.10	1.97	0.2028
Sites x B vs A	7	64.20	1.00	0.4657
Sharks(Sites) x B vs A	16	64.15	1.69	0.0542
Residual	144			
Total	191			





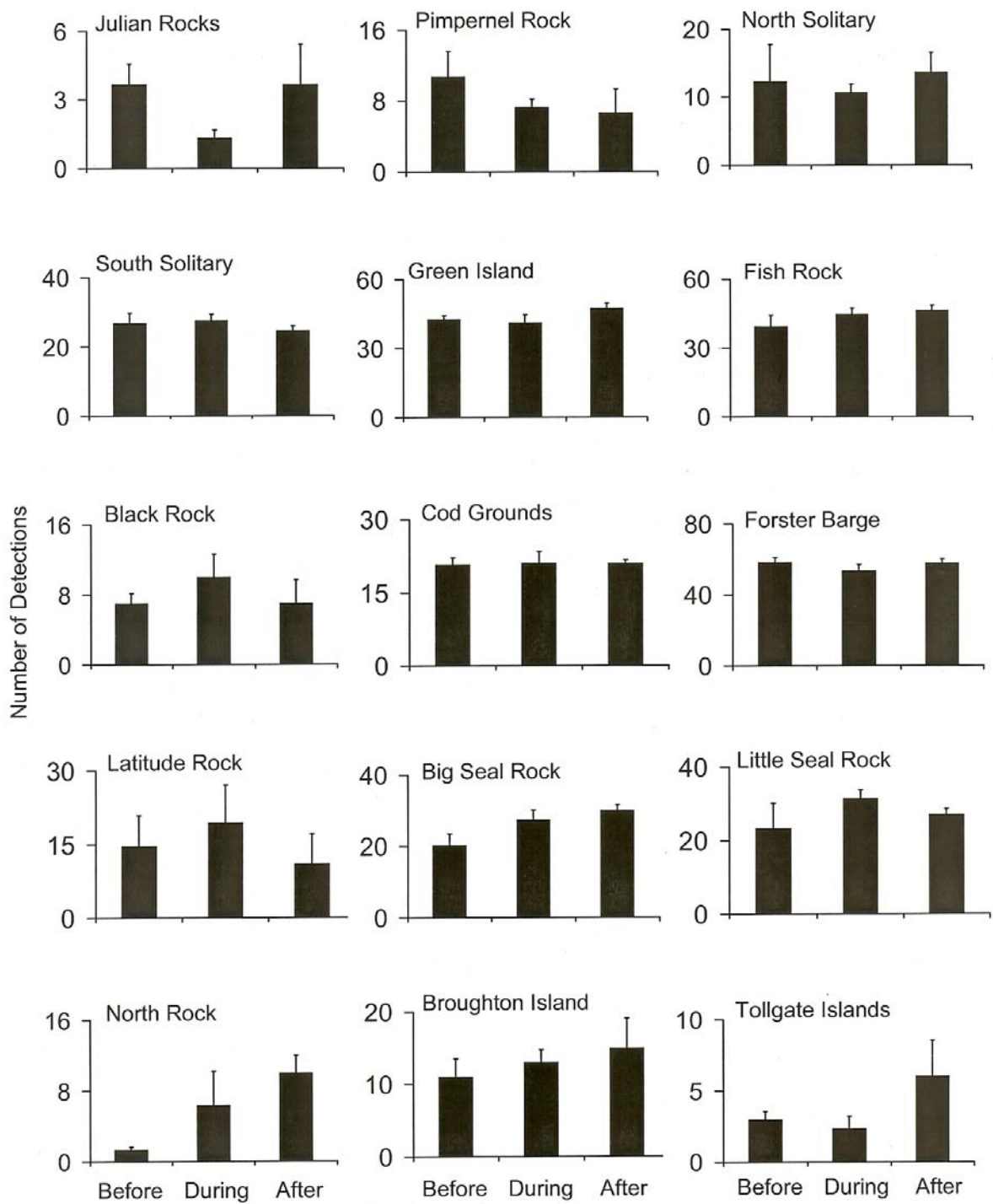
**Figure 4.3.** Mean (+ SE) number of hourly detections of grey nurse sharks tagged with R-coded acoustic tags received on SEACAMS listening stations before and after scuba diving at 8 sites in NSW coastal waters. Means for “before” and “after” pooled across 3 replicate sharks at each site and 4 replicate hourly samples.

### Experiment 3

The 15 grey nurse sharks tagged with R-coded, acoustic tags remained at each of the 15 sites throughout the duration of the experiment. There was no obvious evidence of an impact as none of the sharks left the sites following scuba diving (Fig. 4.3). Statistical analysis showed that the Sites x Treatments term was not significant ( $P > 0.25$ ) and was, therefore, pooled with the Residual to permit a more powerful test of the Treatments term (Table 4.7). The mean number of hourly acoustic detections did not differ significantly before, during and after scuba diving (Table 4.7) demonstrating that there was no impact of scuba diving on grey nurse sharks.

**Table 4.7.** Two-factor analysis of variance assessing the impacts of scuba diving on grey nurse sharks at 15 sites in NSW coastal waters. N = 3 replicate hourly acoustic detections were obtained for each of the 3 Treatments (Before, During and After scuba diving)

Source of variation	df	<u>Before Pooling</u>			<u>After Pooling</u>			
		MS	F	P	df	MS	F	P
Sites = S	14	2410.41	84.70	0.0001	14	2410.41	84.70	0.0001
Treatments = T	2	53.10	2.20	0.1295	2	53.10	1.94	0.1100
S x T	28	24.13	0.85	0.6827				
Residual	90	28.46			118	27.43		
Total	134				134			



**Figure 4.4.** Mean (+SE) number of hourly detections of grey nurse sharks tagged with R-coded acoustic tags received on SEACAMS listening stations before, during and after scuba diving at each of 15 sites in NSW coastal waters with n = 3 replicate hourly samples.

#### 4.4. Discussion

Sharks have an array of sensory organs that function interactively enabling them to detect most of the stimuli in their immediate environment including scuba divers entering the water to observe, photograph and/or film them (Gilbert 1962, Bleckmann & Hofmann 1999, Maruska 2001, Myrberg 2001, Montgomery and Walker 2001, Tricas 2001). To assess the impacts of scuba divers, previous studies have relied on a scuba diver making observations of other scuba divers interacting with sharks. Unfortunately, such an approach confounds logic and leads to equivocal data which when combined with poor experimental designs and sampling protocols, does not permit a reliable assessment of the impacts of scuba divers on the behaviour of sharks, thus leaving outcomes open to debate and scrutiny (Otway 1992).

In contrast, this study used SEACAMS together with grey nurse sharks tagged with R-coded acoustic tags to provide a cost-effective, diver-independent means of unequivocally quantifying the putative impacts of scuba diving on the species. Furthermore, as the R-coded acoustic tags transmitted their signals at 69 kHz, they were completely outside the acoustic reception range of sharks (i.e., 40 Hz to  $\approx$  800 Hz – Myrberg 2001) and did not cause any behavioural changes in the grey nurse sharks.

The three experiments done across 15 sites from Julian Rocks (near the NSW/QLD border) to the Tollgate Is. (off Batemans Bay in southern NSW) clearly showed that scuba diving had no impacts on grey nurse sharks at a spatial scale encompassing an entire gutter. Moreover, by sampling at several spatial and temporal scales it was also possible to demonstrate conclusively that scuba divers did not cause changes in the behaviour of grey nurse sharks following the arrival of the divers at a site nor before divers entered the water.

Assessing the putative impacts of scuba divers on grey nurse sharks at even smaller spatial scales within a gutter (e.g., 0 – 5 m) using video-cameras and/or similar equipment (remotely-operated or otherwise) would still not produce unequivocal data because the electronic signals emanating from the equipment or the physical presence of the diver operating the equipment would still contribute to the overall shark's behaviour and confound any assessment of impact. However, the use of a radio-acoustic positioning system (VRAP – Stasko & Pincock 1977, Voegeli *et al.* 2001) permits the monitoring of shark behaviour/movements at an even finer resolution (i.e.,  $\pm$  2 m – Klimley *et al.* 2001) and could be used to assess the possible changes associated with scuba divers. While such studies are possible as NSW DPI has this equipment, it is important to question the cost-effectiveness of doing such research given the more deleterious impacts posed by the capture of grey nurse sharks by commercial and recreational fishers.

## 5. GENERAL DISCUSSION

The research described in this report has provided a substantial increase in the understanding of the localised and migratory movements of sexually-mature male and sexually immature male and female grey nurse sharks. There is, however, a gap in knowledge for sexually-mature females. The possible northward and southward migrations of sexually-mature female grey nurse sharks needs to be addressed to test hypotheses concerning: the paths taken; the timing and duration of movements; and the time spent in waters of various depths and temperatures. This information will greatly assist in the development of demographic models incorporating spatial components and enable more accurate predictions concerning the viability of the east coast grey nurse shark population.

This will require the extension of SEACAMS to various sites in QLD waters and further tagging with pop-up archival satellite tags and R-coded acoustic tags.

The experiments used to quantify the impacts of scuba diving on grey nurse sharks clearly showed that divers had no impacts at the scale of an entire gutter. It is questionable as to whether further research in this area is warranted given the substantially more deleterious impacts posed by the accidental capture of grey nurse sharks by commercial and recreational fishers. It would likely be more cost-effective to focus future research efforts on better quantifying rates of mortality, especially those associated with commercial and recreational fishing. A shift of emphasis away from the impacts of scuba diving, would also permit a greater focus on the near absence of reporting, by fishers, of accidental captures and/deaths of grey nurse sharks.

The research outlined, to date, would also benefit from information concerning the population age/size structure of grey nurse sharks along the east Australian coast. This information would greatly assist the development of more precise demographic models. The population size-structure can now be quantified precisely using an underwater photogrammetry system developed and tested over the past few years (Otway *et al.* 2008). The use of this system will, however, require the identification of a cost-effective sampling regime incorporating spatial and temporal components to ensure that a representative sample of the east coast grey nurse shark population is obtained. Vertebral samples have been obtained via necropsies of grey nurse sharks and these, when processed and validated could provide estimates of the age-structure of the east coast grey nurse shark population. Combined, these two approaches could also be used to calculate rates of growth and mortality. The results of which could also be used in demographic models to monitor the viability of the east coast grey nurse shark population. This information will be important in assessing the efficacy of present and future management strategies aimed at the long-term conservation and recovery of the grey nurse shark population in the coastal waters off SE Australia.

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