The relation of coastal geomorphology to larger mass strandings of odontocetes around Australia

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ABSTRACT

Sites of larger live mass strandings (10 to 250 individuals) for five selected odontocete (toothed whale) species around Australia are examined to see if they have any characteristics or properties which might be related to the strandings. Bays are the significant coastal unit in the 66 events reported over a 100 year period; only three events were not within bays but on open sandy coastlines. Species, species adult size and bay size do not appear to be factors in these larger stranding events. The reason for the association of bays with larger mass strandings is not obvious. Many of the bays have simple planform and uncomplicated bathymetry. However, they share some properties previously associated with strandings that are a consequence of the processes of bay formation. Coastal locations other than particular types of bays do not necessarily have all of these properties, potentially explaining why these bays dominate the Australian mass stranding record. A chain of geomorphological, physical, and biological factors can be constructed to explain the role of the bays in mass strandings. Regardless of this possible explanation, there is an observed correlation of particular site properties with larger live mass strandings about Australia which might be expected to have predictive power in indicating potential mass stranding sites. This is particularly apparent when key properties of stranding sites are defined and compared in terms of simple quantitative thresholds. The sites of herd strandings around New Zealand generally exhibit the expected properties.

KEYWORDS: AUSTRALASIA; AUSTRALIA; STRANDINGS; ODONTOCETE; PACIFIC OCEAN; SOUTHERN HEMISPHERE; TRENDS

INTRODUCTION

There are a wide variety of potential reasons for mass strandings of cetaceans (e.g see the review by Perrin and Geraci, 2009) including behavioural characteristics, disease, military sonar, and fishing activities but the focus of the present paper is whether or not live mass strandings are influenced by stranding site characteristics. Australian stranding sites for five selected odontocete (toothed whale) species were charted to examine this question, particularly sites of ‘larger’ live strandings (10+ animals, see below) and sites where strandings have occurred repeatedly. Continental scale spatial and seasonal stranding patterns for the five odontocete species are compared with Ziphiidae (beaked whale) and baleen strandings in Hamilton and Lindsay (2014).

DATA AND METHODS

Definitions used in this paper

Coincidental strandings of two or more cetaceans, alive or dead, excluding mother-calf pairs, are considered unusual and are commonly referred to as ‘mass strandings’, although there is no consensus definition as to how close strandings have to be in time and space to be considered related. D’Amico *et al.* (2009) define an ‘atypical’ mass stranding as two or more animals stranded within six days of each other and within a range of 74km, excluding mother-calf pairs. Such definitions are broad and potentially may lead to false categorisation of unrelated events as mass strandings in addition to correct categorisations.

A further confounding factor when examining potential causes is that the stranding of numbers of live and dead animals may have unrelated causes. For example, the drifting of incapacitated cetaceans into shore due to prevailing conditions may in some cases result in strandings being categorised as mass strandings (implying common cause), whereas a number of animals may have arrived at the stranding site within a few days simply by chance.

To provide unequivocal examples of mass strandings, the present paper initially considers only live strandings of ten or more animals. Such events are also often better publicised and documented, enabling details to be more easily verified. Dolphins and porpoises were excluded from the analysis as these smaller odontocetes are often resident or semi-resident in harbours, bays, and coastal areas, so may not have the stranding patterns of other odontocetes (Brabyn, 1990).

Australian data

Strandings database

A database was constructed by Hamilton and Lindsay (2014) of stranding records for five cetaceans chosen (Table 1) as being broadly representative of odontocete whale species, other than small coastal species (see above), found stranded in Australian waters (Fig. 1). Dolphins and porpoises sometimes stranded together with the five species, but are not included in the counts of animals. The five species were chosen as sometimes having large numbers of animals in a stranding (tens to hundreds) and a range of maximum adult sizes. This was to examine possible differences in stranding behaviour caused by size e.g. agility in shallower waters, habitat/feeding behaviour and efficiency and acoustic frequency of vocalisations.

The five species are from two separate families, Physeteridae and Delphinidae; all are socially cohesive and can occur in large, relatively stable groups. The primary source for the database are records from the Commonwealth of Australia (2010) repository.

Stranding records in the database for the selected species date back to 1868 for the sperm whale, and extend up to 2010 (143 years). Strandings of 10+ animals date from 1911 to 2009

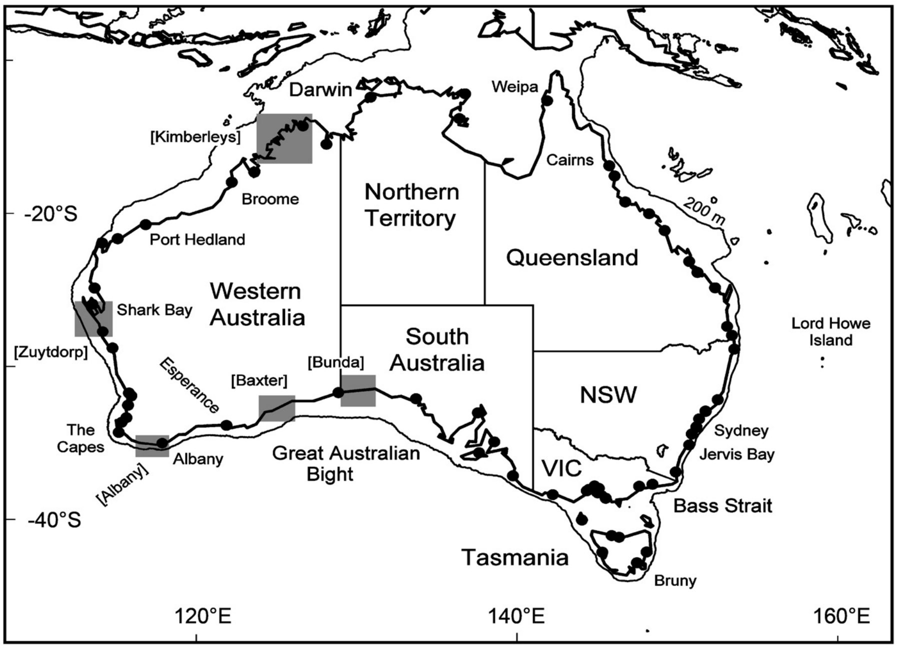

Fig. 1. The Australian coastline, Australian states, and selected population centres. Sea cliffs and rocky areas in Western Australia are outlined with rectangles and named in square brackets, for example [Baxter]. Cliff locations are adapted from Reader's Digest (1983) and Sharples *et al*. (2009).

Table 1

Five odontocete species considered in this study and number of larger stranding events of 10+ live animals (Hamilton and Lindsay, 2014) for which sufficient data on location are available. Numbers in brackets are the total number of strandings with two or more animals (including mother-calf pairs).

Species	Adult male length	Number of live[1] larger events (total 2+)	Maximum number in a single event
Physeteridae			
Sperm whale (*Physeter macrocephalus*)	*Ca* 18m	16 (27)	65
Delphinidae			
Killer whale (*Orcinus orca*)	*Ca* 9m	1 (2)	13
Long-finned pilot whale (*Globicephala melas*)	*Ca* 6.5m	32 (46)	200
False killer whale (*Pseudorca crassidens*)	*Ca* 5.5m	16 (20)	250
Melon-headed whale (*Peponocephala electra*)	*Ca* 2.8m	1 (3)	51
Total		66 (98)	

[1]Includes two cases where the animals were found dead but it was highly likely they had stranded alive.

(99 years), and more events have occurred since which are not included in the analysis. The data are temporally uneven, but this should not affect a spatial examination provided there are no temporal trends in either distribution of strandings or bias in reporting. Beaked whale (Ziphiid) strandings were also compiled and are discussed in Hamilton and Lindsay (2014). There were 35 beaked whale strandings of two or more individuals, with a maximum of 6 individuals in any one event. Not all beaked whale strandings are live events.

Stranding site properties

A range of relatively simple properties have been considered as a first step in determining whether or not sites of larger mass strandings have physical characteristics in common. Coastline configurations (primarily reported as bays or beaches in the database), bathymetric trends, slopes and sediments are basic properties used to describe the near shore environment. Quantitative measures of these and other parameters were collated where possible to enable comparisons between sites (e.g. see Table 2).

A bay is defined as a body of water partially enclosed by the inward curving of the land, with a wide mouth allowing access to the sea. This broad definition can be refined by classing bay geomorphology as one of three types:

(1) a headland and a gently curving planform;

(2) relatively deeply indented into the coastline with a headland often not prominent or absent; or

(3) either of the above two types with additional complexity such as that caused by interior coastline configuration (e.g. Cloudy Bay) or the presence of islands (Marion Bay).

Bay complexity may also arise due to the presence of reefs and irregular bathymetry within bays. Perkins Bay, for example, has extensive shallow sand bars, islands and channels in the southwest and west.

Type 1 bays are formally known as 'headland-bays' (Fig. 2). A headland-bay is a geomorphological unit where the harder more resistant headland controls the bay shape through eroding effects of diffracted and refracted swell waves on the adjacent downswell coastline. An archetypal headland-bay has only one headland, and a long, curving bay with a characteristic shape, often modelled as a log-spiral or

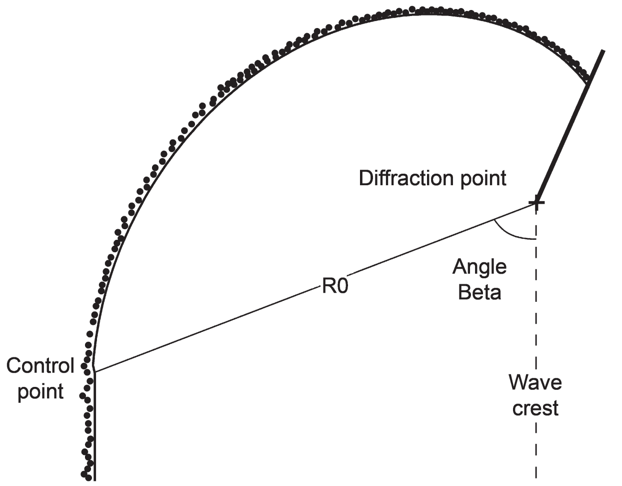

Fig. 2. Schematic of headland-bay geometry. Swell direction is from right to left. Distance R0 and angle Beta define the bay shape. Line R0 extends from the Diffraction point (usually a headland) to the point on the coastline where the beach shape changes from curved to straight. Beta is the angle between the dominant swell and line R0 (Moreno and Kraus, 1999).

zeta spiral (Moreno and Kraus, 1999). They are also termed zetaform, log-spiral, half-heart, or crenulate bays (Krumbein, 1944). Particular Australian examples are Geographe Bay, Ocean Beach, and Wreck Bay (Fig. 3). Modelling and observation indicate the log-spiral bay shape forms in response to the dominant swell direction in order to reduce wave action in the bay compared to other shapes (Silvester and Ho, 1972). The term 'hooked bay' is also used in the literature, but does not necessarily refer to a log-spiral shape or imply that a headland is present. The term headland-bay is used in the present paper to indicate that a headland is present and that this headland played a part in creating the shape of the bay.

Many of the bays have a headland at one or both ends. Bay width was measured from headland to beach end for the single headland case (Fig. 2), and headland to headland when two were present. Bay indentation distance was measured as the maximum value from shore perpendicular to the line specifying the bay width. Indentation ratio was computed as the ratio of bay width to bay indentation distance. We observed that a ratio of bay width to bay indentation of 2:1 could broadly be used to separate archetypal *log-spiral headland-bays* (ratio greater than 2) from *indented bays* (ratio less than 2). An indentation ratio >2 does not automatically specify a log-spiral bay (see Green Point and Treachery Beach (Fig. 3) which are rectangular bays), but a ratio <2 normally means that it is not a classic log-spiral bay, although it may still have significant log-spiral character. Twenty of the 35 sites (57%) have ratios >2, 12 of 35 (34%) have ratios <2 and the ratio was not able to be defined for three cases (9%) (Gunnamatta and Petrel Point in Victoria, and Crowdy Head in New South Wales).

Classification of sites in this paper

Table 2 summarises all of the sites considered bays referred to in the text by classification as follows:

CI: bay with indented character also with additional coastline or bathymetric complexity;

H: log-spiral headland-bay;

HC: log-spiral headland-bay with additional coastline or bathymetric complexity;

HI: log-spiral headland-bay with indented character;

I: indented bays without prominent headlands.

A beach is a coastal deposit of mobile material, often of sand size particles, in dynamic interplay with waves and currents. Royal Australian Navy (RAN) Hydrographic Office nautical charts were used to examine the morphology of stranding sites and to obtain descriptions of the seabed. All 18 sites for which RAN seabed indicators were available had

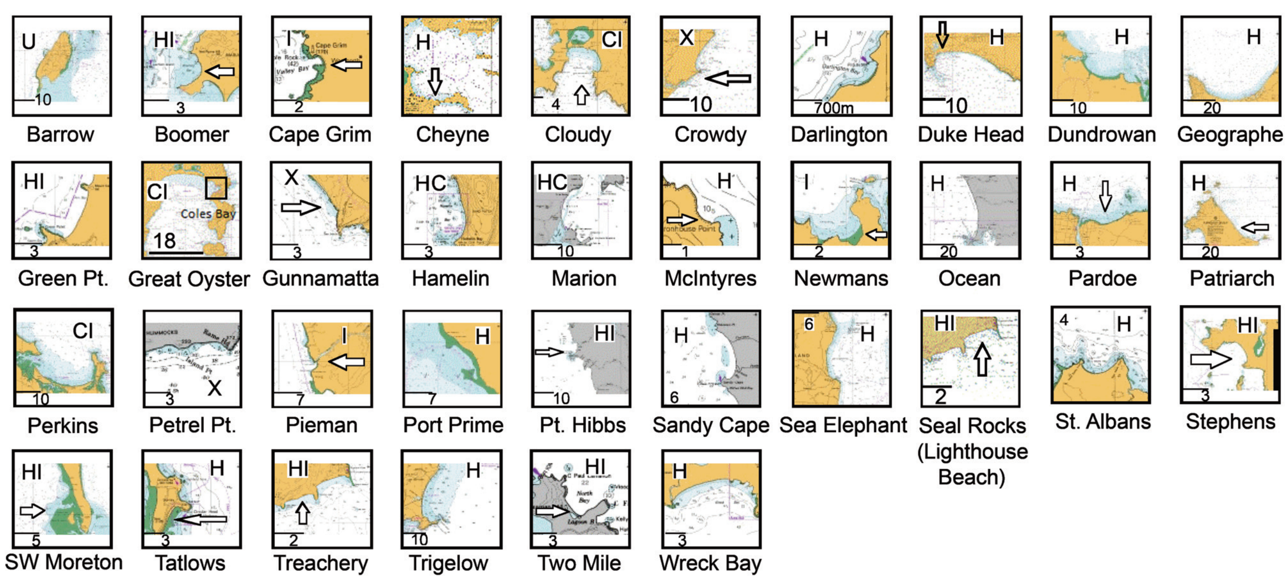

Fig. 3. Planforms of Australian sites of mass strandings of 10+ individuals. The actual stranding site on Barrow Island is unknown, but it is recorded as being in the bay at the south of the island. Symbols: H shows a log-spiral headland-bay, HI shows a log-spiral headland-bay with indented character, I shows an indented bay, U means the exact stranding site (on Barrow Island) is unknown. For HC (one site) and CI (two sites) the H and I have the meanings already given, and the C denotes additional coastline or bathymetric complexity. X shows coastline configurations which are not bays (three cases). Map scales (km) differ for the thumbnails.

dominantly sandy seabed, sometimes noted as fine sand. The descriptions were obtained by visual and tactile examination of fresh, wet samples. Hamilton (1999) has shown they are generally reliable indicators of sandy sediments with respect to the Udden-Wentworth sediment grain size and classification scheme (Wentworth, 1922). Sands have grain size diameter from 0.065–2mm. The divisions are: 0.065–0.125mm (very fine); 0.125–0.25mm (fine); 0.25–0.5mm (medium); 0.5–1mm (coarse); and 1–2mm (very coarse). Particles of diameter less than 0.065mm (e.g. silts and clays) are collectively termed muds and particles with diameter greater than 2mm (termed gravel) range from granules to boulders.

Bathymetric cross-sections were constructed from the RAN bathymetry charts for shore perpendicular transects (generally perpendicular to trends of depth contours). More transects were constructed for sites with larger geographical dimensions. These sections showed that sites tend to have either two or three regions of near constant seabed slope, with slopes decreasing with distance from the shore. With respect to Lowest Astronomical Tide (LAT) these are: nearshore slopes at 0–10m (an extension of the lower beach face in the wave or surf zone); a second slope from 10–20m (a transition zone for wave influence); and a third slope from 20–40m (with lesser seabed wave action than inshore areas).

Beach slope generally increases with grain size (Wiegel, 1965). This dependence is a function of sediment size, density, shape and wave exposure, particularly the higher wave energy available to move coarser sediment landward in times of storms and other major events. Fine sand beaches generally have slopes of about 1°, coarse sand and gravel beaches have slopes of 4 to 17°, and shingle beaches can attain slopes over 30° (Gilluly *et al.*, 1975).

Two techniques are often used to measure beach slopes (Jennings and Schulmeister, 2000). The first measures 'beachface slope' as an average from the top of the highest storm berm to low tide. Grain size is averaged over this distance. The second measures 'active profile slope' as the average from high tide to low tide on the day of survey, with average grain size assessed in the swash zone. Beachface slope can be higher than active profile slope because the coarsest material can be marooned above high tide level for long periods. These two slope measures would usually be higher than slopes at 0–10m LAT. The two measurements of beach slope describe different aspects of the environment and ideally both measures or beach profiles would be obtained together with offshore bathymetry profiles and slopes. Cetaceans venturing inshore will experience offshore seabed slopes before they encounter beach slopes.

Data from New Zealand

Properties of sites of New Zealand 'herd' strandings, defined as 2+ animals, excluding mother-calf pairs, were analysed by Brabyn (1990) and Brabyn and McLean (1992).

RESULTS

Australia

The 66 live larger mass strandings considered here occurred at 35 different sites (Tasmania 21, Western Australia 5, New South Wales 4, Victoria 2, Queensland 2, South Australia 1) spanning the width of the Australian continent south of 25°S (Fig. 4 and Table 2). The sites cover a wide latitude and longitude range of inhabited and uninhabited coasts with different geographic aspects, geomorphology, oceanography and scale. Therefore, we believe that any reporting bias caused by proximity to towns and settlements resulting in particular locations being over represented is unlikely to affect the broad conclusions.

Twelve of the 35 sites (34%) had more than one stranding of 10+ individuals. If smaller (1–9 animals) strandings of sperm whales, long-finned pilot whales, and beaked whales are included, then 20 of the 35 locations have more than one stranding event. The repetition of both large and small stranding events at sites with strandings of 10+ individuals suggests that site properties may be related to the strandings, not coincidence or other factors. Repeat stranding sites may thus be archetypes for characteristics of stranding sites, if such archetypes exist.

Morphology of stranding sites (see Table 2)

Thirty-two of the 35 sites (with 63 of the 66 events) refer to bays (Table 2 and Fig. 3). Bay widths ranged from 600m to 64km. Three sites, each with one live mass stranding event, depart from this general pattern: the coastline at Petrel Point (Victoria) has only a relatively slight indentation, while Gunnamatta Beach (Victoria) and Crowdy Head (NSW) are associated with a long almost straight coastline, not a bay. At least 28 of the 32 bays have a headland or headland-equivalent, as do Gunnamatta Beach and Crowdy Head. Headland-equivalents are formed more by the configuration of shallow bathymetry than coastline configuration, examples being Pardoe Beach (Tasmania) and Port Prime (South Australia). Sites without prominent or protruding headlands are the indented Cape Grim Bay, Cloudy Bay (although it has interior headlands), Great Oyster Bay, and Pieman Heads, all in Tasmania, and each has one 10+ stranding event.

A large proportion of the bays (at least 26 of 32) were visually assessed by the authors as having significant log-spiral character (those labelled H, HC, HI) (Table 2, Fig. 3). These account for 50 of 66 (76%) of strandings of 10+ individuals. The 18 more classically shaped or archetypal of these 26 bays (those classed H, HC) incorporate 40 of the 66 events (60%).

There are three rectangular bays (Green Point (Marrawah), Lighthouse Beach, Treachery Beach) that have an indentation ratio and bathymetric configuration matching the bays with a gently curving planform. They have been classified here as headland-bays with indented character.

Five bays have complexity in coastline configurations or bathymetry (Cloudy, Great Oyster, Hamelin, Marion and Perkins bays). Hamelin Bay is a sandy headland bay with interior reef structures. Cloudy, Great Oyster and Perkins bays are indented (classified as CI in Table 2 and Fig. 3). Cloudy Bay has several interior bays and headlands. The western side of Perkins Bay is made up of sandbanks, islands, and channels. Marion Bay (classified as HC in Table 2 and Fig. 3) is a zetaform headland-bay with complexity in coastline configuration to its north caused by a large island near the coast. Cloudy Bay and Great Oyster Bay have 1 strandings of 10+ individuals, Homelin Bay has 2, Marion Bay has 4 and Perkins Bay has 8 (Fig. 3). 'Classic' log-spiral

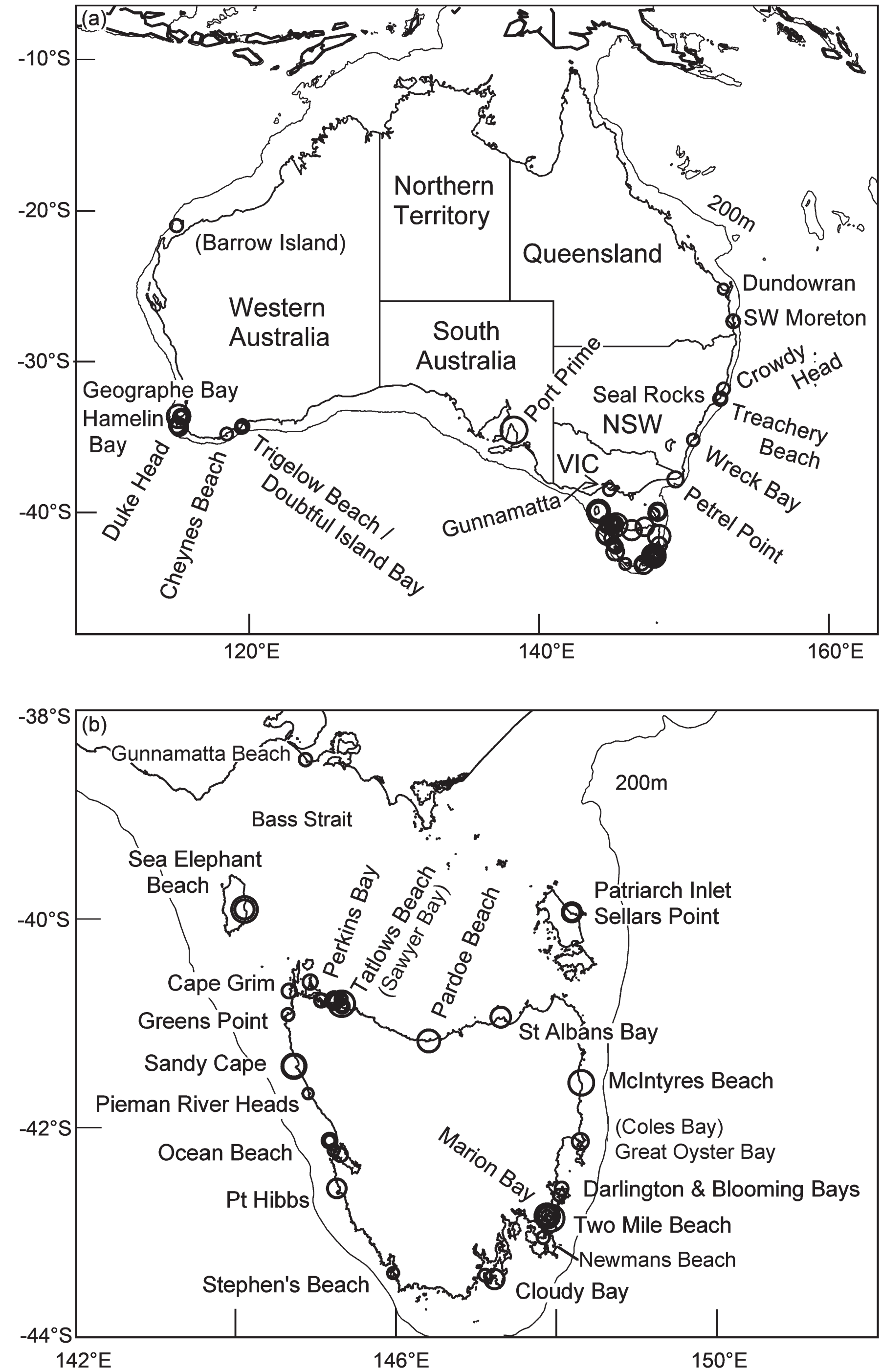

Fig. 4. Distribution of strandings of ten or more individuals for false killer, killer, long-finned pilot, melon-headed, and sperm whales. The maximum in a stranding is 250. (a) Australia; (b) Tasmania.

headland-bays have a maximum of five events at both Ocean Beach (Tasmania) and Trigelow Beach (Western Australia).

Of the 19 events with 100+ individuals in a stranding (see Table 2), 12 were in log-spiral headland-bays (H in Fig. 3), 2 were in log-spiral headland-bays with indented character (HI), none were in an indented bay (class I), and 5 were in three bays with complex character (Cloudy, Perkins, Marion Bays). Cloudy and Perkins bays (CI) each had one stranding of 100+ individuals, and Marion Bay (CH) has three.

Seabed sediments and gradients

As noted under methods, the 18 sites for which seabed type indicators are shown on RAN Hydrographic Office nautical charts all had dominantly sandy seabeds, sometimes noted as fine sand. However, as discussed below, there are three examples of mass strandings in rocky locations within bays in Tasmania.

From the RAN bathymetry charts, many of the sites tend to have either two or three regions of near constant seabed slope, with slopes decreasing with distance from the shore. Only 4 of 92 seabed slopes calculated for 29 of the 35 sites (some at different locations within the same bay) had slopes greater than 1°, all were for 0–10m, with 1.6 and 1.7° at Treachery Beach and Two Mile bays, and 1.9° at Crowdy Head. The outer slopes were usually less than 0.5°. Slope calculations for 0–10m represent a broad average, as sand

Table 2

Summary of the information on Australian sites with good position information with live large mass strandings with 10 or more animals per event (for details see text). *The position of the Barrow Island site is unknown. It is shown because it is the northernmost site, but it is not included in analyses. **Key:** Type: CI = bay with indented character and additional coastline or bathymetric complexity; H = log-spiral headland-bay; HC = log-spiral headland-bay with additional coastline or bathymetric complexity; HI = log-spiral headland-bay with indented character; I = indented bays without prominent headlands; and X = not bays. IR = Indentation ratio. Slope: N1 = nearshore; N2 = intermediate; N3 = offshore. Substrate: fS = fine sand, M = mud, MS = mud and sand, R = rocky, S = sand, SSh = sand with shell fragments. Large events: number of live events with 10+ animals (number with 100+ animals in parentheses). Small events: number of events (live and dead) of 1–9 animals for long fin pilot and sperm whales only. Beaked whales: number of beaked whale stranding events (of 1 or more animals).

Site	State	AUS chart	Type	Width (km)	IR	Slope (degrees)			Substrate if known	Large events	Small events	Beaked whales
						N1	N2	N3				
**Barrow Island*	*WA*	*742*	*?*	–	–	–	–	–	–	*1**	–	–
Boomer Bay	Tas	170	HI	3.8	2.1	0.3				1		
Cape Grim	Tas	790	I	0.6	0.8		0.4	0.2	R	1	2	
Cheyne Beach	WA	110	H	1.1	2.1	0.3	1.1	1.5		1	1	1
(in Frenchmans Bay)			*(I)*	*(5.6)*	*(1.8)*	–	–	–				
Cloudy Bay	Tas	795	CI	5.4	0.9	–	0.7	0.2		1 (1)	1	6
Crowdy Head	NSW	811	X	X	X	1.9	1.1	0.1	S	1	1	
Darlington	Tas	170	H	0.8	2.4	1.2	0.5	0.3		1		
Duke Head	WA	757	–	–	–	0.14	0.06		S	2(1)	1	
(Flinders Bay)			H	31.5	2.1	–	–					
Dundowran	Qld	817	H	21	2.9	0.06			S	1		
Geographe Bay	WA	755	H	63	2.6	0.2	0.08	0.07	S	4(1)		1
Great Oyster Bay	Tas	766	CI	18	0.7	0.2	0.1	0.1		1		1
Greens Point	Tas	791	HI	2.9	1.9	–	–	–		1		1
Gunnamatta	Vic	150	X	X	X	0.8	0.6	0.4	fS	1		
Hamelin Bay	WA	756	HC	7.3	2.2	0.24	0.2		S	2		
Marion Bay	Tas	169	HC	14.8	2.3	0.5	0.2			4 (3)	1	2
McIntyres Beach	Tas	766	H	1.7	2.8	0.5	0.5	0.3		1(1)	2	1
Newmans Beach	Tas	171	I	1.7	1.1	0.24	0.08		M, S	1		
Ocean Beach	Tas	353	H	18.5	2.7	0.4	0.2	0.5	S	5	7	6
Pardoe Beach	Tas	164	H	4.7	2.5	0.4	0.3	0.2	S	1(1)		
Patriarch Inlet and Sellars Point	Tas	800	H	21	3.7	0.14	0.07	0.05	S	2(1)	1	1
Perkins Bay	Tas	790	CI	18	1.5	0.17	0.03		fS, S	8 (1)	3	1
Petrel Point	Vic	359	X	X	X	0.8	1.3	2	S, SSh	1		
Pieman River Heads	Tas	791	I	2	1.7	–	–	–		1		1
Port Prime	SA	781	H	7.6	1.7	0.07	0.2	0.04	S	1(1)		
Point Hibbs	Tas	353	HI	5	1.9	0.3	0.07	0.07	R	1(1)		
Sandy Cape	Tas	353	H	10.6	3.5	–	–	–	R	2(2)		1
Sea Elephant Beach	Tas	789	H	10.4	2.7	0.5	0.1	0.13	SSh	2(2)		
Seal Rocks (Lighthouse Beach)	NSW	219	HI	2.2	2.4	1.3	0.9	0.6		1		
St Albans Bay	Tas	798	H	5.6	1.8	0.4	0.35	0.12	S	1(1)		
Stephen's Beach	Tas	176	HI	3.3	1.7					1		
SW Moreton	Qld	236	HI	5.7	2.5	0.2	0.9	0.1	MS, S	1(1)		
Tatlows Beach (Sawyer Bay)	Tas	790	H	18.8	2.7	0.2	0.2	0.1		5(1)	1	3
Treachery Beach	NSW	219	HI	2.2	3.8	1.7	1.1		SSh	1		
Trigelow Beach	WA	337	H	23.6	2.5	0.2	0.1	0.03		5	2	
Two Mile Beach	Tas	169	HI	4.6	1.6	1.6	1.0	0.7		2(1)	1	1
Wreck Bay	NSW	807	H	8.9	2.5	0.3	0.25	0.3	S	1		
Number of sites:			**35**				**Number of larger events:**			**66(20)**		

bars and smaller features do not appear on charts. However, slope estimations are consistent in trends across all sites. Slopes for waters deeper than 10m are usually well defined.

Australian repeat stranding sites

If site properties influence live mass strandings, then sites where strandings have occurred more than once may have similar properties, irrespective of numbers in a stranding. To investigate this, strandings of 1–9 animals, both live and dead, for beaked, sperm and long-finned pilot whales were examined. There are about 100 sites in the database that have two or more such stranding events. However, restricting the search to well-documented sites and reports, 15 locations were found to have three or more strandings events of 1–9 animals, all of which were bays (Fig. 5 and Table 3).

South Australia had only one event (Port Prime) with 10+ animals, but several repeat stranding sites. Streaky Bay (with 6 events) is an indented headland-bay with complexity in planform in the south and shallow sand ridges. Anxious Bay (3 events) has headland-bay structure in both north and south. Coffin Bay (7 events) is an indented headland-bay with coastline and bathymetric complexity in the south. The Coorong (with 21 events) is a wide sandy headland-bay open to the southwest. Kangaroo Island acts to extend the action of the headland. Port Fairy (3 or more events) is a log-spiral headland-bay, with a secondary headland. D'Estrees Bay (3 events) is a log-spiral headland-bay on Kangaroo Island. Rivoli Bay (5 events) is a twin headland-bay.

For Tasmania, in addition to the eight repeat sites for large events (see Table 2), there were three additional repeat sites that included no large events. Adventure Bay (5 events, none of 10+) is a log-spiral headland-bay with a secondary headland. The log-spiral shape is interrupted by more resistant material northwest of the primary southern

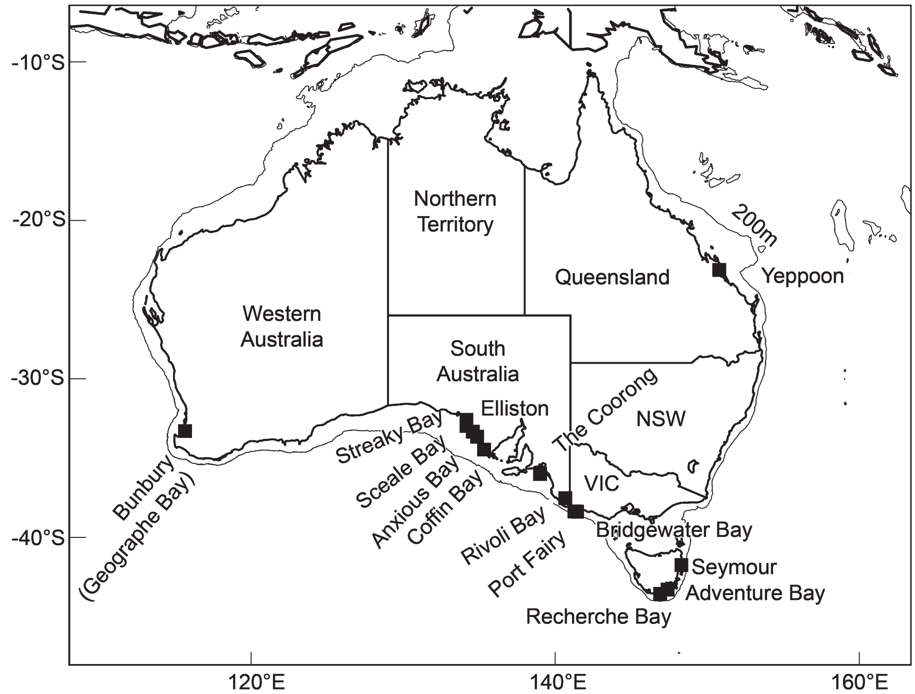

Fig. 5. Location of Australian sites with good position information with three or more smaller strandings (1–9 animals, alive or dead, including mother-calf pairs), and no events with 10+ animals in a stranding. For beaked whales, long-finned pilot whales, and sperm whales only

Table 3

Summary of the information on Australian sites with good position information with three or more smaller strandings (1–9 animals, alive or dead, including mother-calf pairs), and no events with 10+ animals in a stranding. For beaked whales, long-finned pilot whales (LFP), and sperm whales only. For key to column headings and symbols see Table 2.

Site	State	AUS chart	Type	Width (km)	IR	Slope (degrees)			Substrate if known	Number of events		
						N1	N2	N3		Sperm	LFP	Beaked whale
Adventure Bay	Tas	173	HI	1.9	1.9	1.1	0.4	0.1	S		1	2
Anxious Bay	SA	121	HI	58	2.5	1.2	0.5	0.1				4
Bridgewater Bay	Vic	140	HI	12	2.4	0.4	0.2	0.5		1	1	2
Bunbury	WA	115	H	9.3	3.9	1.6	0.4	0.5	S			3
Coffin Bay	SA	342	HC	31	2.3	0.1	0.3	0.1	fS, MS, S	1	3	5
Coorong	SA	347	H	283	2.3	0.3	0.4	0.1	fS, S, SSh	9	3	9
D'Estrees Bay	SA	346	H	15	2.8	0.5	0.2	0.2			1	2
Elliston	SA	121	I	1.6	1.1	–	–	–	fS	1		3
Port Fairy	Vic	141	H	3.9	2.0	0.7	0.3	–	fS		3	4
Recherche Bay	Tas	174	CI	2.4	1.0	0.7	1.0	0.6	S			3
Rivoli Bay	SA	127	HC	11	2.8	–	–	–	fS, M, S	3		2
Sceale Bay	SA	342	I	10	1.2	0.5	0.2	0.7	S			3
Seymour	Tas	766	H	13	3.8	1.2	0.5	0.1			2	3
Streaky Bay	SA	121	CI	27.7	1.0	–	–	–	S	1	2	4
Yeppoon	Qld	820	HC	12	3.2	–	–	–	S			3

headland. Recherche Bay (3 events) is an indented bay with complex planform and interior headlands. Seymour has a prominent headland (Long Point). The western side of Bridgewater Bay (3 events) in Victoria has log-spiral headland-bay structure, and a prominent eastern headland also provides log-spiral character to its eastern side.

Hamilton and Lindsay (2014; Fig. 2) found that all 13 sites with 3 or more beaked whale strandings were bays, with 9 (63%) having strong headland-bay character. Four of these were bays not in the above lists: Bunbury (Western Australia), Elliston and Sceale Bays (South Australia), and Yeppoon (Queensland). Elliston is a small indented bay and the other three have log-spiral character (Table 3).

Relation of Australian mass stranding sites to the surrounding coastline

As noted above, 95% (n = 63) of the strandings of 10+ individuals for Australia occurred in bays. By comparison, non-sandy coasts comprise 39% of South Australia's, 34% of Victoria's and 60% of Tasmania's coasts (Short, 2006a). Neglecting other factors, one would expect at least 15 (33%) of the 46 mass strandings in these three states, or alternatively, at least 8 of their 24 stranding sites, to occur on non-sandy coastlines.

In fact, from the available information, large stranding events may have occurred once each at three rocky locations in Tasmania (Pt Hibbs, I; Sandy Cape, H; Cape Grim, CI); although in bays, the actual stranding site within the bay may not have been sandy. Short (2006b) provides some description of all 1,596 beaches and coastlines for Tasmania and its major islands. From Short (2006b), it is observed that the 21 stranding bays in Tasmania generally have completely different characteristics from their neighbouring coastlines (e.g. rock or reef flats, or steep, with cobbles or boulders, when the bay beaches and bay floor are clear of these descriptions). Apart from the three cases above, nine of the bays have no mention of sediments other than sands, nor of rock, or reefs whilst for the remaining nine bays there was no mention of rock or reef.

Short (2006b) described the three rocky sites as having rocks or reef areas on the bay floor. The Pt Hibbs stranding (110 long-finned pilot whales) was discovered 7–10 days after death, so the actual stranding site may not be certain. The Sandy Cape live stranding (155 long-finned pilot whales) occurred on a rocky shore in the south of the bay; 32 other animals were trapped in an offshore channel among reefs, and were guided to safety. The Cape Grim stranding (58 sperm whales) occurred on a rocky platform in a 'reef locked shallow bay', and 'putrefaction was well under way' when the whales were examined (Guiler, 1978). The presence of reefs and reef channels give the latter two bays complex bathymetric character, potentially explaining their possible strandings on non-sandy areas. These bays can be considered a type of topographic trap.

There is a correlation between absence of stranding records (for single strandings upwards) for the five species and the presence of sea cliffs on the coasts of Western Australia and South Australia (the Zuytdorp, Baxter and Bunda cliffs; Fig. 1). The entire coastline of southern Australia from 123°58'E to 132°23'E is smooth. There are only four recorded strandings (two single beaked whale events, and two single false killer whale events) in this longitude range. There are few beaches in these high-cliffed areas and the Bunda cliffs run unbroken for hundreds of kilometres; one hypothesis is that wave noise may alert animals to the presence of the cliffs (see below). However, conditions there mean that even if whales do strand along these areas, it is unlikely they would be noticed.

Comparison with New Zealand mass stranding sites

New Zealand has coastlines with many sediment types, geomorphologies, geographical aspects and oceanography as well as a long, well-maintained stranding record which makes it appropriate for comparison with Australia. Brabyn and McLean (1992) examined New Zealand mass ('herd') stranding sites (2+ animals, excluding mother-calf pairs) of 11 odontocete species, each with four or more such stranding events across all sites (Brabyn 1991, p.3). They reported 95 events at 41 sites, although several sites were in the same locality or the same bay. Details were not specified in that paper but table 7 of Brabyn (1990) reported 82 events in 12 locations (excluding Chatham Island, which has two major stranding bays). The majority of sites were where pilot whales had stranded.

Sites with two or more events were typically associated by Brabyn and McLean (1992) with 'long, gently sloping[1] beaches' with an adjacent protruding section of coastline, either a headland or a sand spit ('sandy bay beaches protected by a hook'). The only exception was Kaipara on the northwest of North Island, where five strandings were associated with 'low seabed slopes', but not coastline protrusions according to the authors. However, we note that headland-equivalents are present in the form of sandbanks <3m depth which extend 3.7km seawards from Kaipara Harbour; slopes of 0.3–0.1° from shore to the 30m contour were estimated here, which is 11km out to sea.

Half (21) of the 41 herd stranding sites examined for the 11 species were on beaches with low tide slopes generally <1°, with 83% on low tide beach slopes <3°. Slopes for herd stranding sites were significantly less than those of random sites where strandings were not recorded. Brabyn and McLean (1992) randomly selected 26 sites within 100 km of the 41 herd stranding sites to make these determinations. Only one of 95 herd strandings (of 12 killer whales) was recorded on a beach steeper than 4.4°. Bays with 16 of 34 pilot whale events had width to indentation ratios >2. Only 1 of 31 pilot whale stranding sites was on a beach with a sediment coarser than sand. No herd strandings of any species were recorded on shingle or boulder beaches, which are steeper than sand and gravel beaches. Excluding dolphins, no herd strandings of any species were recorded on rocky coasts. Brabyn and McLean (1992) concluded that whales do not strand at random locations.

DISCUSSION

The analysis presented here has shown that over the last 99 years, reported Australian large (10+ animals) live mass strandings for the five odontocete species considered here, occurred largely within bays (95% of the 66 well documented examples compiled for this examination) and particularly in sandy headland-bays. Many of the stranding bays are sheltered areas with simple planform and simple bathymetric configuration and would appear to have no inherent perils for odontocetes. The presence of a headland does not change this.

By contrast, the most commonly stranding baleen whale, the humpback whale was found to strand (usually singly) almost anywhere, not exclusively in bays (Hamilton and Lindsay, 2014).

The following discussion first lists properties of live mass strandings locations around Australia, then explores possible roles of headland-bays in mass strandings.

Stranding site properties

The broad qualitative terms generally used to describe stranding sites in the literature (e.g. 'wide', 'large', 'long', 'gently curving', 'sandy', 'gently sloping', 'shallow') hinder comparisons of site properties; consistent quantitative terms are needed.

Bay types and bay size

'Wide bays' with respect to strandings were up to 50–65km in width with indentation of 15–25km. The smallest bay width was 600m. Three prototype bay forms were noted, indented bays, headland-bays, and headland-bays with indented character. These are differentiated by planform, by indentation ratio and the presence or absence of an upswell headland.

[1]Beach slopes were measured by them from low tide to 20 paces up the beach.

Indentation ratio and coastline curvature

The authors observed that an indentation ratio of 2 separated indented bays from archetypal log spiral bays. A physical basis for this observation was found in Silvester and Ho (1972) and Kim and Lee (2009; see fig. 2); 2 is the lower bound to the ratio approached by log spiral bays in equilibrium at higher values of wave incident angle. The ratio is >2 for lower wave angles and during initial bay development when coastline indentation is slight. Indentation ratio can therefore act as a quantitative proxy for coastline curvature in terms of log-spiral geometry. Archetypal log-spiral headland-bays have indentation ratios >2 and, away from the headland, are 'gently curving'. Indented bays have ratios <2, although they may still have a headland-bay character. Of the 32 Australian bays with 10+ in a stranding, the three (9%) highest indentation ratios are between 3.5–3.8 (see Table 2).

Depths and gradients

The terms 'shallow bay' and 'deep bay' have no particular meaning unless specified through a bathymetric chart, or as a depth and distance offshore when they represent a broad slope measure. It should be noted that what is 'shallow' to a sperm whale may not be shallow to smaller species. From Brabyn and McLean (1992) for New Zealand herd strandings of 2+ animals, a gently sloping beach has low tide slope less than 1 to 3°. However, the beach is the last feature a cetacean encounters in a stranding and offshore properties and slopes may be more important than beach slope. Seabed slope determinations for Australian sites were made from bathymetric cross-sections constructed perpendicular to shore. Slopes for 0–10m chart depths are usually < 1° whilst offshore slopes (deeper than the limits of the wave base in bays) were <0.5°.

Complexity

Complexity applies to coastline and bathymetric configuration, including factors such as the presence of islands and obstacles, reefs, channels, passages and sand bars. Coastline curvature for simpler situations can be quantified usefully by the bay indentation ratio (see above), but an assessment of overall complexity of the stranding location is also required, particularly for indented bays and re-entrant coastlines. We recommend diagrams of planform and bathymetry as the simplest way to provide information on these assessments.

Beaches and sediments

Short (2006a; 2006b; 2006c) has established a widely used system for characterisation of sandy beaches. In terms of wave energy and steepness, beach types range from flatter, fine sandy beaches ultra-dissipative of wave energy, to steeper, energetic, coarse sand forms. Other salient features are bars and rips. Jennings and Schulmeister (2002) classify mixed sand and gravel beaches in a simple tripartite scheme.

The analysis uses sediment types taken from RAN bathymetry charts. As noted under methods, these chart descriptions are reliable, especially for sandy sediments, but an analysis of sediment samples for grain size distribution is recommended; beach sediment samples could be easily undertaken by scientists attending strandings.

Relation of bays to strandings

Except for Barrow Island at around 20°S, all the larger mass stranding sites for the five odontocete species occur south of 25°S (Fig. 4). However, only the long finned pilot whale is not known to occur north of 25°S[2], so that species range does not appear to explain this.

An important consideration in this is that the long period and energetic swell of the Southern Ocean is favourable to formation of headland-bays around Australia south of 25°S. Low wave energy generally occurs north of 25°S except for occasional tropical cyclones and storms. The northwest of Australia is protected from Southern Ocean swells by coastline orientation and a wide shelf. The northeast of Australia is protected by a wide shelf and the Great Barrier Reef (Fig. 1). From the southern reaches of Western Australia to west of Tasmania, perennial energetic Southern Ocean swell arrives from the southwest, resulting in formation of bays located to the north of headlands on west facing coasts, and on the eastern side of headlands on zonal coastlines. On the east and west coasts of Tasmania, bays are typically formed north of headlands (see Marion Bay and Ocean Bay). The shallow Bass Strait (80–200m) between Tasmania and Australia receives swell from both west and east.

There are many rock or reef-lined coasts across northern Australia, for example the entire Kimberly coast of northwest Australia is shown as rocky in Sharples *et al.* (2009) and no strandings of any size there appear in the database. Short (2006a) describes laterite rocks and reef flats as common along the Northern Territory coast and coral reef structures are located immediately seaward of at least 1,430 beaches from the Kimberleys to Cape York, Queensland. Most have large areas of barrier reef backed by a lagoon and lower energy beaches. Only 16% of the bedrock-dominated Kimberley coast is sandy (Short, 2006a). Elsewhere in Australia sandy beaches occupy between 38–66% of each state coastline.

It is easy to postulate how whales become trapped in deeply indented bays such as Cloudy Bay and Great Oyster Bay (Fig. 3). Deeply indented bays and bays complex in planform or bathymetry can be interpreted as topographic traps, in which odontocetes may possibly become confused or lost and be unable to find their way out. This is the general stranding mechanism postulated for 'hooked bays' in New Zealand by Brabyn (1990). Strandings in long tapering fjords and larger inlets in Europe represent a similar situation. However, this does not explain mass strandings at sites such as Booming Bay or Newmans Beach (Table 2, Fig. 3), where the indentation does not appear geometrically difficult. Neither indentation nor coastline complexity can explain mass strandings in large, gently curving bays with simple log-spiral shapes and simple bathymetry such as Geographe Bay and Wreck Bay (Fig. 3). These two bays lie perpendicular to overall coastline orientation, but the majority of bays do not, seemingly eliminating bay orientation as a major factor. Sites such as Crowdy Head, Dukes Head, Ocean Beach (Fig. 3) occur in log-spiral bays which are more hook shaped than Geographe Bay at the headland end and geometrically present greater difficulty. However, stranding sites are often towards the centre of the

[2]Department of the Environment, Australian Government (website at http://www.environment.gov.au/cgi-bin/sprat/).

bay shoreline, not at the headland end. The question remains why live mass strandings should occur in so many of the seemingly innocuous log-spiral bay shapes and simple bathymetric configurations of Fig. 3. Potential explanations related to the manner in which odontocetes are believed to navigate, simple geometry and the possible inability of odontocetes to interpret gradually shallowing depths are considered below.

Odontocete navigation

Odontocete echolocation skills are well known (e.g. Au, 2009) and they can potentially use echolocation for a number of purposes including navigation and exploration of their environment (e.g. to locate the seabed, obstacles, objects and shorelines); mysticetes are not known to use this method. Beaked whales, sperm whales and other odontocetes are known to use echolocation when hunting their prey (e.g. Johnson *et al.*, 2004; Miller *et al.*, 2004). Their echolocation capabilities in feeding suggest that they could also use echolocation to locate the seabed. Miller *et al.* (2004) note that echoes from both surface and seafloor are regularly detected on acoustic recorders attached to sperm whales producing regular clicks. This indicates sperm whale clicks display suitable intensity for using echolocation to detect seabeds. The same is noted for reception of seafloor echoes for tagged Blainville's beaked whales within 750m of the seabed (Arranz *et al.*, 2011).

Based on the premise that odontocetes use echolocation for at least local navigation and avoidance of obstacles, two different mechanisms have been proposed for active cetacean sonar to become ineffective near coastlines, leading to strandings. One is a sonar propagation condition called sonar termination (Dudok van Heel, 1966), and the other relates to coastline shape (Sundaram *et al.*, 2006).

Ray tracing

Sundaram *et al.* (2006) applied simple ray tracing to actual bay shapes associated with mass strandings, with the coastline treated as a lossless reflector and with a depth of zero (a planar calculation). Their results indicated that odontocetes may experience acoustic dead spots within the bays; this would imply that strandings might be expected at or near these sites. However, we note that the modelling amounts to saying that portions of coastline which present a convex shape to sound rays arriving from the cone of 20° Sundaram *et al.* (2006) use for odontocete acoustic emissions will not be detected as well as coastline portions that present a concave shape. Locally convex features could be expected to be harder portions of coastline more resistant to erosion (e.g. Wreck Bay, Australia has such areas, see Fig. 3), which is why they have curvature opposite to the concave curvature generally shown by beaches within bays. However, the present investigation finds that odontocetes generally strand on concave rather than convex sections of the coastline. The ray tracing inferences of Sundaram *et al.* (2006) do not appear applicable to explaining odontocete strandings on experimental or theoretical grounds.

Sonar termination

Woodings (1995) and Chambers and James (2005) postulated mass strandings of false killer whales in Western Australia to be caused by sonar termination, where acoustic transmissions directed into a gently sloping, sandy shore are returned at low signal strength, masking the presence of shallow depths (Fig. 6). This had been suggested earlier (e.g. see Dudok van Heel, 1966) and was referenced by Brabyn and McLean (1992) as a possible cause of New Zealand strandings. Through the attenuating effects of coastal micro-bubbles and multiple sea surface and seabed reflections in shallow sandy seabeds of low slope, returns may be distorted or reverberating signals of insufficient strength or fidelity relative to the output signal to be reliably detected, or may not be returned at all. Under these circumstances a whale may not know that unsafe shallow waters are up ahead. Gravel and rock typically provide stronger returns than sands.

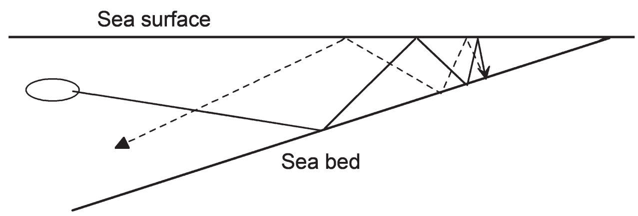

Fig. 6. Schematic of sonar termination in a wedge. An acoustic signal propagating shorewards can turn seawards before it reaches shallow depths, and experiences enhanced attenuation through multiple reflections from the sea surface and the seabed.

The emission and hearing frequency range of false killer whales is 2–120kHz, with highest sensitivity for 30–80kHz (Chambers and James, 2005). Using the frequency response for 20–120kHz, and with bay waters modelled as a wedge, their model predicted sonar termination to occur at slopes less than 1°. Slopes >5° were highly likely to be detected at a safe distance. This is consistent with the Australian examples examined here as well as the measured low tide beach slopes of 1–3° of Brabyn and McLean (1992) for New Zealand strandings. Although Chambers and James (2005) describe their modelling as a simplified indication of possible sonar termination, it appears realistic, as they couple the hearing response of a particular odontocete species with real mass stranding situations.

Gradually changing depths

With or without navigation by sonar, and quite apart from sonar termination, odontocetes may simply not recognise that a headland-bay or other location is gradually shallowing to unsafe depths as a purely geometrical effect. An offshore slope of 0.5° equates to a gradual decrease in depth of 1m every 100m, and this may simply not be noticed. When normally offshore odontocetes find themselves in shallow water, confusion may occur.

Sediment type, seabed slope and wave noise

The sonar termination hypothesis would not be consistent with large numbers of mass strandings associated with sediments coarser than sands or with slopes higher than those estimated for sonar termination. This is not the case for either Australia or New Zealand, despite the fact that mixed sand and gravel beaches, although generally relatively rare, are a common feature of the New Zealand coastline (Dawe, 2001; Jennings and Shulmeister, 2002).

The New Zealand data of Brabyn and McLean (1992) for herd strandings of 2+ animals occurred predominantly (83% of 41 events) on sandy beaches with low tide beach slopes less than 3°. Excluding dolphins, only one herd stranding (of 12 killer whales) was noted for a low tide slope greater than 4.4° (Brabyn and McLean, 1992). Only one herd stranding of ≥2 animals occurred on a gravel beach, with none on shingle and boulder beaches (Brabyn and McLean, 1992). No herd strandings have been reported anywhere on the steeper west coastline of South Island, New Zealand (Brabyn, 1990, p.38).

Log-spiral headland-bays and crenulate beaches are not limited to sandy sediments. Sediment size distribution in zetaform bays is a function of factors such as wave climate, the angle between the headland and dominant swell direction, erodability and physical properties of the coastline material, and sediment supply. Crenulate cobble and boulder beaches occur around Australia (Short, 2006a). Gravel and boulder beaches are much shorter on average than sand beaches in Australia (Short, 2006a), which could be a factor in the lack of reported mass strandings in those environments. There are no recorded larger mass strandings on gravel beaches in our database, even though they comprise more than one sixth of beaches in Tasmania. Tasmania experienced three mass strandings found on rocky platforms within bays with reefs and reef channels (Cape Grim, Point Hibbs, Sandy Cape).

In examining possible explanations for mass strandings, Chambers and James (2005) proposed that calm conditions may prevent coastline wave noise from alerting whales to the presence of shallow water. In addition, the particular log-spiral shapes of headland-bays apparently reduce wave action along the shore compared to other shapes (Silvester and Ho, 1972). A reduction in wave action on log-spiral Australian beaches was noted by Short (2006a; 2006c). This hypothesis assumes that odontocetes are sensitive to surf noise acoustic frequencies, which are typically less than 4kHz in the far field of the surf zone, and broad-band in the surf zone. Surf noise is a function of beach and seabed slope, sediment size, and incident wave energy. Seabed slope determines the breaker type, with plunging breakers producing more noise than surging and spilling breakers. Coarser beach sediments produce higher slopes and plunging breakers. Rock cliffs also produce plunging breakers. There is a link between beach sediment, beach slope and wave noise, which in principle could influence strandings. Although there is insufficient evidence to determine a causal effect, it is noteworthy that headland-bays associated with strandings produce planforms, sediments, and slopes which all combine to reduce wave noise.

Direct relation of headlands to mass strandings

If sonar termination does affect odontocete navigation, then it has been postulated that headlands can mechanically influence stranding behaviour. Odontocetes may change course to landwards or seawards to avoid headlands when they are unexpectedly encountered after having been masked by sonar termination. This would then give them no better than a 50/50 chance of surviving the sonar termination effect on their echolocation navigation facilities (e.g. Hans Wapstra of the University of Tasmania; quoted in Montgomery, 1998).

Sperm whale strandings, Tasmanian strandings, and species size

Long-finned pilot whale strandings are recorded at 19 of the 21 Tasmanian sites (Fig. 2b). Cape Grim and Greens Point in Tasmania have sperm whale strandings only. Sperm whales also stranded in Tasmania at Ocean Beach and Perkins Bay. Sperm whales had the widest range in type of mass stranding sites. Of the eight larger sperm whale stranding sites for Tasmania and mainland Australia, Gunnamatta is not embayed, Greens Point has four areas of rock and inner reefs, the indented Cape Grim has rock and reef areas within the bay, and Dundowran is the northmost site on the eastern coast. No other notable relations of stranding site with species or species size were observed.

Key geomorphological factors relevant to mass strandings

The following factors may explain why so many larger Australian mass strandings occur in headland-bays with log-spiral character and sandy sediments.

(1) The presence of a resistive headland causes a bay with log-spiral character to be formed downswell of the headland in less resistive coastline – if the resistive headland material was not present, the bay would not be present, nor would the log-spiral shape.

(2) Persistent wave and swell action acts to produce (fine) sandy sediments in headland-bays from the continued attrition and breakdown of less resistive coastline material. Finer sediments (silts and clays) are winnowed out by wave and current action. Grain sizes in headland-bays are not restricted to sandy sediments, however, these are the sediments associated with larger Australian mass strandings.

(3) Fine sandy sediments generally produce offshore headland-bay slopes less than 0.5° around southern Australia.

(4a) The combination of (fine) sands and seabed slopes less than 1° is highly favourable to the sonar termination effect (Chambers and James, 2005); or

(4b) alternatively, in the presence of seabed slopes less than 0.5°, odontocetes may simply not comprehend they are gradually heading into shallow water;

(5) If a headland is encountered in a headland-bay, whales may (perhaps randomly) turn seawards or shorewards to avoid it. Turning shorewards may expose them to the sonar termination effect and/or to gradually shallowing depths, making them susceptible to stranding; and

(6) In calmer conditions, the reduced wave action in log-spiral headland bays compared to other bay shapes may prevent coastline wave noise from alerting whales to the presence of shallow water (increased acoustic attenuation in shallow water propagation paths experiencing multiple sea surface and seabed reflections could enhance this effect).

When odontocetes find themselves in shallow water, they may become disorientated and not know the direction of deeper water. Milling behaviour, indicating confusion, is often observed with individuals occasionally darting off and returning in apparent exploratory behaviour, then a mass stranding sometimes caused by 'follow the leader' behaviour (for example, strandings at Duke Head in Western Australia and Sandy Cape and Greens Beach in Tasmania). Confused whales in shallow water may interpret any wave noise at the beach as coming from the familiar sea, rather than from a shore, and may head shorewards.

Headlands may therefore be implicated in strandings at different time scales, and for different reasons. If there were no resistive headland, there would be no bay formed with sands and resultant low seabed slopes. The bay and the headland are intimately related, a factor seemingly previously unknown to stranding studies. Without a headland there might be no mass movement towards shore to subject odontocetes to sonar termination or confusion with a simple geometry (gradually shallowing depths) they are unable to comprehend. If wave noise were not reduced in log-spiral headland bays, odontocetes might be alerted to the presence of the shore. The formation of headland-bays leads to coastline configurations, seabed sediments, and seabed slopes which may combine to defeat or impair the echolocation and comprehension abilities of odontocetes, both passive and active.

Other factors in strandings

Coastal configuration and bathymetric trends, with or without sonar termination, are not the only factors in live strandings. For example, Brabyn (1990; 1991) lists many theories on mass stranding, believing some more plausible than others. Some of the more likely factors contributing to strandings of whales are attempted escape from predators (other whales and sharks), predation on animals that flee close to the coast, disease, age, epimeletic behaviour, bad weather, cyclones (hurricanes), storm surge, starvation, and tidal change in water levels. In themselves, these theories cannot explain the observed prevalence of headland-bays in larger Australian mass strandings and we do not further discuss them.

Species such as killer whales which often live close inshore seldom strand. That strandings occur of cetaceans which are usually found offshore may indicate that many offshore cetacean species have not evolved mechanisms to cope with inshore conditions (for example Brabyn, 1990; Klinowska, 1985). Pod sizes and social cohesion are used to explain the large numbers in strandings of odontocetes (e.g. Whitehead, 2003).

We believe it implausible that mass strandings can be normally explained in terms of the drifting of large numbers of incapacitated cetaceans into shore. For the live large stranding events considered here, this would require groups of 10 to 250 live animals to all become incapacitated at the same time and place, near a headland bay, into which they then all drift. Strong swimming accompanied by milling behaviour has been observed prior to several Australian mass strandings (for example Evans *et al.*, 2002) and milling nearshore is recognised as a sign of an imminent stranding. Cetaceans engaged in milling behaviour may be confused, but their swimming is not observed to be incapacitated, and rescues have subsequently been performed. Incapacitation may explain single strandings of sick individuals, but to extend this to larger numbers is implausible; although it is plausible that one or a few animals may be incapacitated in some way and that social cohesiveness/epimeletic behaviour may cause others to follow and get into difficulty. At least 20 of the 66 Australian strandings of ≥10 animals in the Commonwealth of Australia (2010) database were noted as being active events, as opposed to simply being live events, although we are unable to verify this information.

It remains unclear whether there is a single or predominant mechanism that can consistently cause simultaneous incapacity in large numbers of cetaceans near shore and near a headland-bay (although sonar termination is a candidate). Hurricanes or stronger storms might in a few cases, and perhaps contaminated food intake in a few others, but this leaves most cases unaccounted for. Underwater earthquakes and seismic events ('subterranean upheavals') have long been mooted as damaging or stunning cetaceans and causing strandings (for example, *Rockhampton Morning Bulletin*, 22 August 1946). However, if cetaceans were affected by this mechanism they would likely strand anywhere, not preferentially in headland-bays, and a case could be made that baleens should also be affected. However, baleens rarely strand other than singly, even when undertaking seasonal mass migrations for long distances along the Australian and New Zealand land masses (Hamilton and Lindsay, 2014; Brabyn, 1991).

SUMMARY AND CONCLUSIONS

(1) The bay usually appears the significant coastal unit in Australian mass strandings. Bays form the platforms for the majority of stranding sites around Australia. Brabyn and McLean (1992) noted that New Zealand strandings consistently occurred at particular locations within some bays, indicating the actual stranding site properties are important. However, the stranding site exists only because the bay exists, and its properties are largely a function of the processes of bay formation.

(2) Sandy log-spiral headland-bays form the dominant bay type for large Australian mass strandings. The formation of these bays from Southern Ocean swell endows many of them with properties which appear conducive to stranding (a headland, concave coastline curvature, sandy sediments, low seabed slopes, lower wave noise).

(3) Quantitative measures and thresholds are required to examine site properties relevant to strandings (planform and coastline curvature – through indentation ratio or more rigorously the geometry of the log-spiral, sediment sizes, seabed slopes); a suggested schema has been developed in this paper. This provides a simple framework for comparison of sites differing in size by orders of magnitude. An assessment of site complexity is also required, for example, the ratio of coastline length within the bay to the bay width, provided the length is measured in a consistent matter for different chart scales. Complexity is also introduced by the presence of sand banks, reefs, or islands within bays, and deep indentation.

(4) The observed correlation between larger mass strandings and quantitatively specified site properties for Australia

has predictive power, and should be further tested against observations from Australia and elsewhere. It appears likely that sandy headland-bays with low seabed slope will dominate the mass stranding record for larger events compared to other sections of a coastline.

Headland-bays have a distinctive and easily recognised log-spiral planform. Thus sites where odontocetes are more likely to strand can be predicted from coastline configuration (sediments and slopes are also important). This may allow measures to be developed to enable offshore activities to minimise possible disturbance of cetaceans that might lead to strandings.

The analysis presented here, whilst not conclusive, is consistent with the sonar termination hypothesis (e.g. Dudok van Heel, 1966; Woodings, 1995; Chambers and James, 2005). Ineffectiveness of active and passive cetacean biosonar arising through geometrical and physical properties associated with zetaform headland-bays appears a natural mechanism to explain why larger Australian mass strandings occur in them, and not the adjoining coastline, and why particular zetaform headland-bays experience repeated strandings and larger strandings.

If sonar termination and/or inability to comprehend simple wedge geometry with low seabed slopes are responsible for mass strandings of odontocetes, then the presence of a headland is not required for strandings to occur. The principal requirements for sonar termination are low seabed slopes (less than 5° from Chambers and James, 2005; and experimentally <1° in particular), fine to medium sands or finer sediments, and a shoreline or bay width of sufficient distance for the sonar termination effect to act for long enough during the passage of cetaceans to lead to a stranding. In this scenario, log-spiral headland-bays are simply coastal locations where these conditions are more likely to occur, with the additional complexity of a headland. Coastline complexity undoubtedly plays a part in mass strandings around Australia. Particular examples are Perkins Bay, Cloudy Bay, and Marion Bay in Tasmania, which have recorded repeated larger mass strandings. However, mass strandings of odontocetes could also be expected on any coastline with fine sediments and low seabed slopes. This could explain why non-embayed locations with these properties such as Petrel Point (Victoria) and Kaipara (North Island, New Zealand) are mass stranding sites.

Regardless of sonar termination, the Australian findings indicate that the physical circumstances of headlands and swell which shape portions of coastlines into the form of zetaform headland-bays can be expected to lead to conditions unfavourable to odontocetes if the bays have matured to produce sands or finer sediments. The New Zealand data of Brabyn and McLean (1992) and Brabyn (1990; 1991) support this inference although they concentrated on stranding sites as beaches, rather than bays. The only explicit mention we have found on bays other than remarks associated with indented bays and coastline complexity are by Kemper and Ling (1991). They noted that strandings in South Australia (for all dolphin and whale species, for single strandings upwards, for dead, live, or unknown status) were not evenly distributed along the coast, but were frequent in regions with 'large bays'.

The relationship of headland-bays to larger strandings is likely to be universal, not uniquely Australasian and it is recommended that the geomorphology of mass stranding sites for other regions be examined. For example, we note that the well-known mass stranding sites of Kyparissiakos Gulf (Greece) and St. Helena Bay (South Africa) have log-spiral headland bay character.

To facilitate such a comparison and other potential analyses, stranding sites require more quantitative characterisation than is usually made, and more note of the larger scale environment in which they are situated. The emphasis has been on beach properties to the extent that offshore properties and coastline geomorphology have been largely neglected. This might explain why headland-bays are not formally recognised in the stranding literature in the context of mass strandings.

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