Large mass strandings of selected odontocete species: statistics, locations, and relation to earth processes

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ABSTRACT

Larger mass strandings of open ocean odontocetes (toothed whales) of 10+ animals are examined with a compilation of 710 worldwide events. Six species form 96% of events (false killer, long-finned pilot, melon-headed, short-finned pilot, sperm and white whales), with beaked, killer, and pygmy killer whales forming 4%. Site type was determined for 630 events – three-quarters (76%) are in bays, 14% in shallow topographically complex areas (estuarine environments, straits, keys, reef and coastal lagoons), 8% on relatively unindented coasts, with ice entrapment (of killer whales) and miscellaneous categories being 2%. For the 76% of events in bays, sites with headland-bay character make up 42%, spit-bays 20% (even though there are only four of them), indented bays 9% and unspecified bay types 5%. Headland-bays and spit-bays become stranding sites through the properties endowed them by their mechanisms of formation and maintenance, but these mechanisms differ greatly for the two. Breakwaters, groyne series, tides, partial burial, and violent storms also appear as themes. Nearshore slopes are less than 1° for 94 of 105 sites having bathymetry information, with only two reaching or exceeding 3°. Some types of potential stranding sites can be identified by simple quantitative specifications for planform, sediment size, and seabed slope, although strandings will not necessarily occur there. There is an indication that larger strandings are globally correlated with areas of higher oceanic primary productivity near landmasses and oceanic islands, but quantitative studies are needed to clarify any such possible relationship. There is also an indication that larger strandings are associated with plate tectonics, with few events being seen on the steeper swell resistant active western margins of South America and South Island (New Zealand) in particular. In contrast several larger events are recorded for the relatively older passive margins of the south-eastern sides of these two landmasses, putatively because waves and swell have had time to construct stranding sites on them. Similarly, few larger events are seen for steeper shores adjacent to coastal highlands, such as those of South Africa and Brazil. These observations indicate previously unsuspected relations between the phenomenon of odontocete mass strandings and global scale earth and ocean processes, but they are essentially hypotheses in need of more quantitative examination.

KEYWORDS: STRANDINGS; TRENDS; BAIRD'S BEAKED WHALE; BLAINVILLE'S BEAKED WHALE; CUVIER'S BEAKED WHALE; FALSE KILLER WHALE; GRAY'S BEAKED WHALE; KILLER WHALE; LONG-FINNED PILOT WHALE; MELON-HEADED WHALE; PYGMY KILLER WHALE; SHORT-FINNED PILOT WHALE; SPERM WHALE; WHITE WHALE

INTRODUCTION

Hamilton and Lindsay (2014a) found that Australian mass stranding events of open ocean odontocetes (toothed whales) involving 10+ animals occurred dominantly in bays (63 of 66 events and 33 of 36 locations), especially bays with fine sandy sediments and offshore seabed slopes deeper than the wave base of less than 0.5º (this is a 1m vertical change over 100m horizontal distance). These conditions were observed to occur particularly in mature headland-bays. These have a distinctive half-heart or log-spiral shape (Fig. 1) sculpted behind headlands by waves and swell, with the shape forming to lessen wave action at the bay shore (Silvester and Ho, 1972). The striking geometrical regularity of mature headland-bay planforms enables ready identification of these coastal features. Most Australian headland-bays were sited south of 25°S on coastlines influenced by strong persistent Southern Ocean swell. The dominance of bays in Australian mass strandings of odontocetes had not previously been noted, nor had headland-bays been formally recognised in the stranding literature. These remarks exemplify just how little is known about mass strandings and possible relations to stranding site properties.

Remarkably, Hamilton and Lindsay (2014a) were able to express their findings quantitatively. They first used indentation ratio and planform to class stranding bays as having indented or headland-bay character. Strong similarities were noted between quantitatively defined ranges of site properties (coastal indentation, sediment size, seabed slopes) for Australian headland-bays which were attributed to their common mode of geomorphological origin and similar state of maturity. Developing headland-bays do not have all these property ranges. The similarities imply that particular site properties may be directly related to strandings. Possible reasons advanced were the gradually shallowing depths in headland-bays, which odontocetes may not be able to readily comprehend, sonar termination (Dudok Van Heel, 1962; 1966) in the low slopes and fine sands of mature headland-bays, the effect of the headland in then influencing odontocetes to turn onshore to danger or offshore to safety if unexpectedly encountered, and lesser wave action at the shore in times of calms in headland-bays compared to other bay types to alert whales to land. Whether or not these factors are involved in strandings is moot, but for Australia the observed correlation of particular site properties with larger live mass strandings provides predictive power in indicating other potential stranding sites, although this does not mean that strandings will occur there. In effect, the 'where' of strandings can be known without a perfect knowledge of the behavioural 'why', and if the 'where' is known, then the 'why' may follow.

An examination of worldwide sites of larger mass strandings was made using the quantitative framework of Hamilton and Lindsay (2014a) to see if they are also associated with particular geomorphologies or other physical factors. The data also provide indicative statistics on numbers of larger events for regions and species. Ultimately

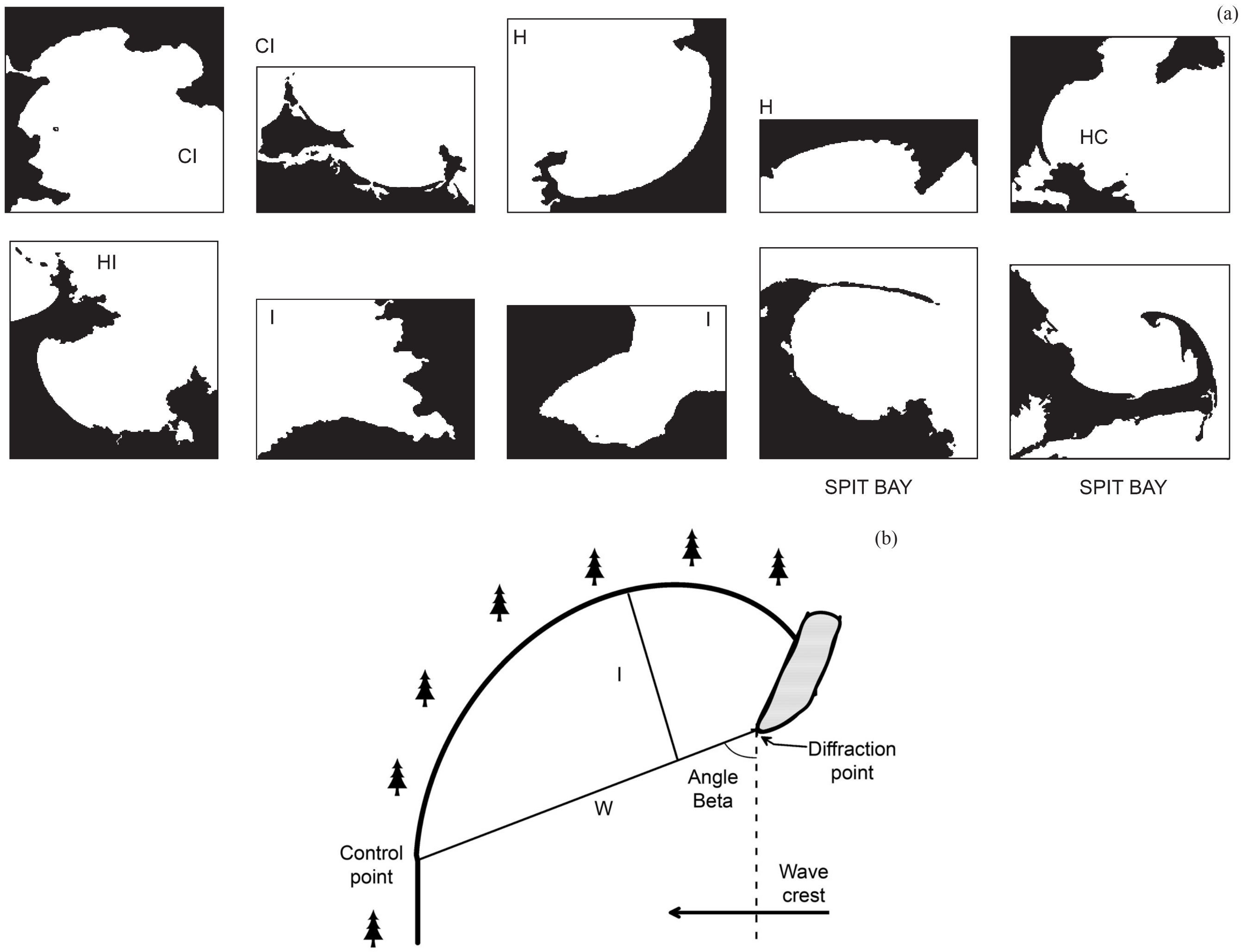

Fig. 1. Bay types (CI, H, HC, HI, I) and definitions. Coastal outlines from: *http://gadm.org/country*.

(a) Top panel: Bremer Bay – indented bay with complex character (three internal bays) (CI), Perkins Bay – indented bay with complex character (islands and channels in the west) (CI), Mason Bay – headland-bay (H), Wreck Bay – headland-bay (H), Marion Bay – headland-bay with complex character (HC) caused by northern island and channel. Lower panel: Doubtless Bay – headland-bay with indented character (HI), Doughboy Bay – indented bay (I), The Wash – indented bay (I), Golden Bay and Cape Cod Bay (spit-bays).

(b) Log-spiral headland-bay planform and characteristics. The control point is taken where the beach straightens from the log-spiral. W is headland-bay width. I is indentation distance. Bay indentation ratio (W:I) for classic log-spiral headland-bays is > 2. Swell direction is from right to left.

there are intriguing indications that many larger mass strandings are related to global earth and ocean processes in a rather straightforward but previously unrealised manner.

MATERIALS AND METHODS

Data

Details of larger mass strandings (10+ odontocetes per event) were sourced from online national databases, scientific papers and reports, newspapers, and internet sources (Table 1). The number 10 is chosen to reduce statistical noise, to obtain unequivocal examples of mass stranding events, and to obtain events expected to be active or live strandings, rather than passive. Active strandings are those where cetaceans are not impaired by factors such as injury or disease, which is unlikely for all animals in larger strandings. Passive strandings are those where sick, impaired, or dead individuals simply drift into shore under the action of wind, wave, and current. Active strandings are required if correlations of animal behaviour with properties of stranding locations are to be investigated.

A mass stranding is usually defined as two or more animals, excluding a single mother-calf pair (Brabyn, 1990; d'Amico *et al.,* 2009). Larger events are expected to provide more reliable statistics than this usage, because many smaller events will not be reported, an unknown number will not be live events, and details of larger events are typically better noted and verifiable. Whale drives, and cases where cetaceans entered bays or constricted waters, channels, or shallow coastal areas but did not actually strand are not included.

Dolphin and porpoise strandings are not examined, as these smaller cetaceans are often resident or semi-resident in ports and coastal areas, and may not have the same stranding patterns as other odontocetes, such as Physeteridae, Kogiidae, Ziphiidae, and selected species of Delphinidae (melon-headed, pygmy killer, false killer, killer, long-finned pilot and short-finned pilot whales) (Brabyn, 1990). The Arctic species, white whale (*Delphinidae leucas*) and Narwhal (*Monodon monoceras*) are included as dominantly being open ocean cetaceans, although both spend time in estuaries. Baleen whales are not examined because they seldom mass strand in larger numbers.

Table 1.
Summary of information on sites with large mass strandings of 10 or more animals per event.

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
ALASKA										
Knik Arm		E	0	0	0.0				M	
Susitna River		E	0	0	0.0				M	2
Turnagain Arm		E	0	0	0.0				M	20
ARGENTINA										
Bahia Bustamante		I	5522	4682	1.2	0.11			Sa	
Bahia San Sebastian		Spit-bay	17192	22945	0.8	0.063			M	5
Caleta Malaspina		I	4495	9150	0.4				R, St	
Caleta San Mauricio, Peninsula Mitre		HC	2026	1105	1.8				m.Sa	
Comodoro Rivadavia		X	0	0	0.0					
Mar del Plata		HB	2473	432	5.7	0.26	0.16	0.06	f.Sa, Sa.Sh	
Punta Norte, Peninsula Valdes		Small indent south of peninsula	1068	342	3.1					
Punta Tafor		HC	1532	512	3.0					
Punta Tombo, 2km south of		HB	1068	342	3.1				R, Sa, St	
AUSTRALIA										
Arthurs Bay, Flinders Island	Tas	HB	7801	2660	2.9					
Aurukun	NT	X	0	0	0.0					
Blackman Bay	Tas	HB	877	365	2.4					
Blooming Beach, Maria Island	Tas	HI	3800	1810	2.1	0.3				
Butlers Beach, Bruny Island	Tas	HB	709	161	4.4					
Cape Grim	Tas	I	600	750	0.8		0.4	0.2	R	
Cheynes Beach, Albany	WA	HB	1100	524	2.1	0.3	1.1	1.5		
Cloudy Bay, Bruny Island	Tas	CI	5400	6000	0.9		0.7	0.2	Sa	
Crowdy Head	NSW	S	0	0	0.0	1.9	1.1	0.1	Sa	2
Darlington Bay, Maria Island	Tas	HB	800	333	2.4	1.2	0.5	0.3		
Doubtful Island Bay	WA	HB	23600	9440	2.5	0.2	0.1	0.03		6
Dundowran	Qld	HB	21000	7241	2.9	0.06			Sa	
Elcho Island, eastern end	NT	X	0	0	0.0					
Flinders Bay, Augusta	WA	HB	30088	7510	4.0	0.14	0.06		Sa	2
Eurong Beach, Fraser Island	Qld	S	0	0	0.0					
Friendly Beaches	Tas	HB	10358	2164	4.8					
Geographe Bay	WA	HB	63000	24231	2.6	0.2	0.08	0.07	Sa	4
Greens Pt Beach, Marrawah	Tas	HI	2900	1526	1.9					
Gunnamatta Beach	Vic	S	0	0	0.0	0.8	0.6	0.4	f.Sa	
Hamelin Bay	WA	HC	4650	1560	2.2	0.24	0.2		Sa	2
Jigaimara Point, Howard Island	NT	X	0	0	0.0					
Koombana Bay, Bunbury	WA	HB	0	0	0.0					
Lighthouse Beach, Seal Rocks	NSW	HI	2200	917	2.4	1.3	0.9	0.6		
Mann's Beach	Vic	E	0	0	0.0					
Marion Bay	Tas	HC	14800	6435	2.3	0.5	0.2		f.Sa	6
McIntyre's Beach, Falmouth	Tas	HB	1700	607	2.8	0.5	0.5	0.3		
Merdayerrah to Eucla	SA	HB	0	0	0.0				S	
Moreton Island, SW corner	Qld	HI	5700	2280	2.5	0.2	0.9	0.1	M.Sa,Sa	
Naracoopa Beach, King Island	Tas	HB	0	0	0.0					
Newman's Beach, Koonya, Tasman Peninsula	Tas	I	1700	1545	1.1	0.24	0.08		M, Sa	
Ninety Mile Beach, near Port Albert	Vic	E	0	0	0.0					
North Bay, Two Mile Beach, Dunalley	Tas	HB	4600	2875	1.6	1.6	1	0.7		2
Ocean Beach	Tas	HB	18500	6852	2.7	0.4	0.2	0.5	S	7
Pardoe Beach, Devonport	Tas	HB	4700	1880	2.5	0.4	0.3	0.2	Sa	
Parry Inlet, Walpole	WA	HB	7634	2441	3.1					
Patriarch Beach (NE Flinders Island)	Tas	HB	31664	7505	4.2					4
Perkins Bay, Stanley	Tas	CI/Spit-bay	18000	12000	1.5	0.17	0.03		Sa	8
Petrel Point to Island Point (Port Hicks beach)	Vic	S	0	0	0.0	0.8	1.3	2	Sa, Sa.Sh	
Picanniny Point, north of Seymour	Tas	HB	0	0	0.0					
Pieman River Heads	Tas	I	2000	1176	1.7					
Point Charles	WA	HB	0	0	0.0					
Point Hibbs	Tas	HI	5000	2632	1.9	0.3	0.07	0.07	R	
Port Prime, St Vincent Gulf	SA	HB	7600	4471	1.7	0.07	0.2	0.04	Sa, M	
Port Welshpool	Vic	E	0	0	0.0				Sa	
Rheban Beach	Tas	HB	2811	853	3.3				Sa	
Richardsons Beach, Coles Bay, Great Oyster Bay	Tas	I	0	0	0.0	0.9	0.7	0.4		
Sandy Cape	Tas	HB	10600	3028	3.5				R	2
Sawyer Bay, Stanley	Tas	HB	11435	3932	2.9	0.2	0.2	0.1	Sa	5
Sea Elephant Beach, King Island	Tas	HB	10400	3852	2.7	0.5	0.1	0.13	Sa.Sh	2
Seal Bay, King Island	Tas	HB	339	178	1.9					
Seal Rocks	NSW	HI	0	0	0.0					
Sellar Point, Flinders Island	Tas	HB	21000	5676	3.7	0.14	0.07	0.05	S	
Small rocky island near Centre Island	NT	X	0	0	0.0					
St Alban's Bay, Bridport	Tas	HB	5600	3111	1.8	0.4	0.35	0.12	Sa	
Stephen's Beach, Port Davey	Tas	HI	3300	1941	1.7	1				
Stokes Pt, Barrow Island	WA	X	0	0	0.0					
Treachery Beach, Seal Rocks	NSW	HI	2200	579	3.8	1.7	1.1		Sa.Sh	2
Wreck Bay	NSW	HB	9111	3822	2.5	0.3	0.25	0.3	Sa	
Yabooma Island	NT	X	0	0	0.0					

Table 1 (*continued*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
BRAZIL										
Bojuru beach, Rio Grande de Sul		S	0	0	0.0					
Piracanga		S	6048	1138	5.3	0.4	0.5	0.3	Sa, Rf	
Rio Grande Do Sul, 51 km Of Beach Opp. Lagoa Mangueira		X	0	0	0.0					
Sao Miguel do Gostoso		Salient-Island	0	0	0.0					
Upanema, Areia Branca		HB	8195	1757	4.7	0.3	0.4	0.2		
BRITISH VIRGIN ISLANDS										
East End, Anegada Island		X	0	0	0.0					
CANADA										
Bayfield, Antigonish	Nova Scotia	HB	4322	2267	1.9	0.11	0.08	0.12		
Beach between Boulder Pt and Estevan Pt		S	0	0	0.0				Bo	
Bedeque Bay, Lower Bay, Near Summerside, PEI		HB	0	0	0.0					
Bonavista Bay, Charleston		CI	0	0	0.0					
Borden, Prince Edward Island (PEI)		X	0	0	0.0					
Cape Kildare (near to), PEI		HB	0	0	0.0					
Cow Head, St Pauls Bay		B	0	0	0.0					
Cumberland Sound, saltwater lake at head of		I	77722	220860	0.4					
Ellesmere Island, near to	Nunavut	X	0	0	0.0					
Fortune Bay, Burin Peninsula	Newfoundland	B	0	0	0.0					
Glace Bay, Cape Breton Island		X	0	0	0.0					
Grand Beach, Burin Peninsula		HB	0	0	0.0					
Grand Etang, Breton Island	Nova Scotia	HB	7118	2290	3.1					
Grant Suttie Bay, Foxe Basin		Ice	0	0	0.0					
Guysborough County	Guysborough	X	0	0	0.0					
Lamaline Bay, Point au Gaul beach, Burin Peninsula		HB	0	0	0.0					
Malpeque Bay, Cabot Beach and south side of Hog Island, PEI		E	0	0	0.0					
Metis to Riviere Blanche, St Lawrence Estuary		E	0	0	0.0					
Miquelon Island, Between Goulet De Langlade & Pointe Aux Alouettes		X	0	0	0.0					
Musgrave Harbor	Newfoundland	I	0	0	0.0					
Near Inukjuak, eastern shore of Hudson Bay	Quebec	Ice	0	0	0.0				Ice	
Notre Dame Bay		I	0	0	0.0					2
Percival (and Enore) River, PEI		B	29050	13578	2.1					
Port Maitland		HB	4724	1004	4.7					2
Sable Island region		Island crescent	35479	6135	5.8					2
Saint Mary's Bay	Newfoundland	I	0	0	0.0					
Saint Pierre		X	0	0	0.0					
St Georges Bay, Judique, Cape Breton Island		HB	4945	1172	4.2				R	
Sturgess Bay, beach across Masset Sound from Old Masset (Haida Gwaii, BC)	BC	I	44733	13588	3.3	0.08	0.03	0.01	R	
Trinity Bay, New Melbourne	Newfoundland	Ice	0	0	0.0					
Trois Pistoles, S Shore of St. Lawrence opp. Saguenay River		E	0	0	0.0					
Yarmouth, Pinkney, South Point	Nova Scotia	X	0	0	0.0					
CANARY ISLANDS										
Ginijinamar	Fuerteventura Island	HI	730	362	2.0					
Las Colorados, Playa Blanca, Lanzarote		HI	798	357	2.2				St, Sa	
SE Fuerteventura		X	0	0	0.0					
CAPE VERDE										
Bahia de Sal Rei		HB	3671	1254	2.9	1	0.25		Sa	2
Calheta Funda (and Praia de Jorge Fonseca), Sal		I	412	260	1.6				R	
Maio (northern shore of)		X	0	0	0.0					
Parda to Kite Beach, Sal		HB	233	103	2.3					
Pedra de Lume (south of)		HI	0	0	0.0					2
Ponta Rica (de Porto Cais), Maio		X	0	0	0.0					
Ponta Sino, Sal		HB	3304	1011	3.3					
Praia de Abrolhal & Praia de Carvao, Boa Vista		HB	0	0	0.0				Sa	2
Praia de Boa Esperanca, Boa Vista		S	12488	3086	4.0					
Praia de Monte Leao, Sal		B	0	0	0.0					
Praia do Canto, Boa Vista		HB	6021	1537	3.9				Sa	
Praia do Coqueiro, Cancelo, Santa Cruz, Ilha de Santiago		B	1110	653	1.7				Pb, St	
Praia dos Achados, Santa Luzia		HB	3038	971	3.1				Sa, R	
Praia dos Balejos, Boa Vista		HB	1450	348	4.2					
Santa Maria beach, Sal Island		HB	2180	567	3.8					
CHILE										
Bahia Posesion, Rio Duck to Rio Butterfly		B	0	0	0.0					
Bahia Windhond, Isla Navarino		I	11900	12687	0.9					
Holger Islets, Beagle Channel		E	0	0	0.0					
Isla San Clemente, a small bay		I	1020	916	1.1				Sa.M	
Los Choros, Coquimbo		X	0	0	0.0					
Magellan Strait		E	0	0	0.0				M	3

Table 1 (*continued*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
CHINA										
Shidao		X	0	0	0.0					
COLOMBIA										
San Andres Island		X	0	0	0.0					
COSTA RICA										
Playa Tambor		I	4531	4329	1.0					
CUBA										
Bahia de Nipe, Holguin (south of)		B	0	0	0.0					
Cayo Saetía		S	0	0	0.0					
DENMARK										
Bay Of Kiel Islands		X	0	0	0.0					
Jammerbugten, West Jutland		E	0	0	0.0				Sa	
Lakolk Beach, Romo Islands		E	0	0	0.0					2
ECUADOR										
Ancon, Santa Elena Peninsula	Guayas	HB	10592	2659	4.0					
Chanduy, provincia del Guayas	Guayas	HB	3040	755	4.0					
FALKLAND ISLANDS										
East Bay settlement, Philomel Harbor		E	0	0	0.0					
Fish Creek		X	0	0	0.0					2
Foul Bay		B	14379	9260	1.6					2
Pleasant Roads		I	1970	1913	1.0	0.4	0.5	0.1		
Ruggles Bay, Danson Harbour		I	1550	1162	1.3					
Speedwell Island, west side		I	708	530	1.3					
Teal Inlet, Bay of San Salvador		E	0	0	0.0					
FIJI										
Suva, beaches at		X	0	0	0.0					
FRANCE										
Anse de Cabestan, Rivage de Primelin		HI	1288	376	3.4				Sa	
Bay of St Vaast, Morsalines	Manche	HB	21366	6527	3.3					
Calais		S	0	0	0.0				Sa	
Carantec	Finistere	X	0	0	0.0					
Gulf of St Tropez		I	1986	1170	1.7					
Ker-Chalon beach, l'Ile-d'Yeu		B	1212	520	2.3					
L'estuaire du Jardy, La Roches-Derrien (Bois Du Renard)		E	0	0	0.0					
Paimpol	Cotes-Du-Nord	E	0	0	0.0					
Pleubian		X	0	0	0.0					
Port-la-Nouvelle, Aude (Le Barcares, Pyrenees Oriental)		Salient/Straight	0	0	0.0					
GALAPAGOS ISLANDS										
Puerto Villamil (near to), Isabela Island		HB	0	0	0.0				Sa	
Wreck Bay, Puerto Baquerizo beach, Moreno, San Cristobal		I	1498	956	1.6				Sa	
GERMANY										
Elbe river mouth, Neuwerk, Ritzebuttel		E	17227	22117	0.8				Sa	
GREECE										
Kypariassiakos Gulf		HB	57254	18883	3.0	0.6	0.6	1.2	Sa	
HAWAII										
Anini beach, Kauai		Reef lagoon	1422	348	4.1	0.13	1.2	2.9		
Kalihi beach, Kauai		I	1219	830	1.5	0.5	0.6	1.1		
Keomuku beach, Lanai		Reef lagoon	1049	107	9.8	0.3	0.3	3.5		
Waikiki, Oahu		HB	0	0	0.0				Sa	
HOLLAND										
Goeree beach, Sint Annaland, Zeeland		E	0	0	0.0					
Ouddorp, Goedereede Island		E	0	0	0.0				M	
Ter Heijde		E	0	0	0.0					
ICELAND										
Innri-Njar'vík (near to)		I	0	0	0.0					
Rif Harbour		Breakwater	4853	786	6.2					2
Thorlakshofn		HB	7673	2449	3.1	0.8	0.7		Sa.M	
INDIA										
Elizabeth Bay, Andaman Is		I	0	0	0.0				Sa	
Manapad		HB	0	0	0.0	0.1	0.04	0.4	Sa	2
Salt Lake (Serampore), Hooghly River, Calcutta		E	0	0	0.0				M	

Table 1 (*continued*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
INDONESIA										
Ancol Beach, Banyuwangi, East Java		X	35578	15376	2.3					
Banyuwangi, East Java		S	0	0	0.0					
Deme Village, Savu Island, East Nusa Tenggara Timur		S	0	0	0.0				Sa	
Dringu, Gending, Bentar beaches, Probolinggo, East Java		B	0	0	0.0					
Kali River mouth, Besuki, Mllandingam, Madura Strait		E	0	0	0.0				Sa	
Kampong Nias, near Sabang, Weh Island		X	0	0	0.0					
Lhokseumawe, NE Sumatra		HB	10788	4320	2.5					
Ponggeran beach, Sulawesi		I	15811	11881	1.3					
Ujong Kareung beach, Aceh Besar		S	0	0	0.0					
IRELAND										
Ballyness beach, Falcarragh strand	Donegal	HB	0	0	0.0				cs.Sa	
Bay of Fethard, Fethard strand		HB	0	0	0.0					
Brandon Bay, Cloghane, Kerry		HI	6890	5575	1.2					
Dunfanaghy	Donegal	E	0	0	0.0					
Little Burrow, Fethard, Wexford		X	0	0	0.0					
Rutland Island, Donegal		X	0	0	0.0					
Tralee Bay		I	8693	7963	1.1				Sa	2
ITALY										
Calvi, Corsica		X	0	0	0.0					
Ligurian Sea		B	0	0	0.0					2
Near Mazaro del Vello, Sicily		X	0	0	0.0					
JAPAN										
Aoshima beach		HB	7902	1802	4.4					
Arikawa Bay, Shinkamigoto	Nagasaki-ken	I	0	0	0.0					
Beppu Bay, Oita City, Seto Inland Sea		I	13950	18150	0.8					
Choshi-shi, Chiba-ken		HB	72530	11040	6.6					3
Eshima Beach (between Kaedagawa & Aoshima)	Miyazaki	HB	0	0	0.0					
Fukuroi-shi, Shizuoka-ken		X	0	0	0.0					
Hannan-shi, Osaka-fu		I	0	0	0.0	0.7	0.2	0.1		
Ibaraki coast		HB	73064	11057	6.6					8
Ichinomiya-Cho, Chosei-gun, Chiba		HB	0	0	0.0					
Iioka coast, Asahi line, Chiba		HB	58667	15465	3.8					
Isumi-shi, Chiba-ken		X	0	0	0.0					
Kamakura-shi, Kanagawa-ken		I	2481	1188	2.1	0.08	0.7	0.6		
Kurikepura, Hirasawa-cho, Akita-ken		HB	0	0	0.0					
Menashi-Tomari, Esashi-Cho, Esashi-gun	Hokkaido	Ice	0	0	0.0	0.6	0.3	0.22		
Minamiboso-shi, Chiba-ken, Awa-gun		B	2511	1495	1.7					
Nachikatsuura-Cho, Higashimuro-gun, Wakayama-ken		X	0	0	0.0					
Nakatane town, Nagahama coast, Kagoshima-ken, Tanegashima Island		HB	23916	4348	5.5	0.7	0.25	0.9		
Near Aidomari Port, Rausu-Cho, Menashi-gun	Hokkaido	Ice	0	0	0.0					
Near Awa, Kagoshima		X	0	0	0.0					
Oura (dike), Minamisatsuma-shi, Kagoshima		HB	36798	17892	2.1					
Sado-shi, Niigata-ken		X	0	0	0.0					2
Sagami Bay, Odawara City, Kozu to Hayakawa		I	40500	20283	2.0					
Tanne-moy, Etorofu Island		Ice	0	0	0.0					
Tarama-Son, Minna island, Miyako-gun, Okinawa-ken		X	0	0	0.0					
Tatsugo-Cho, Oshima-gun, Kagoshima-ken		I	0	0	0.0					
Tsutsugajou beach, Iki-shi, Nagasaki-ken		X	0	0	0.0					
LESSER ANTILLES										
Butler's Area, NE Side Of Nevis island		S	0	0	0.0				R	
LOYALTY ISLANDS										
Saint-Joseph, Ouvea (Ohounou)		Reef lagoon	0	0	0.0					
MADAGASCAR										
Antsohihy, Loza Lagoon		E	0	0	0.0					
MEXICO										
Amortajada Bay, San Jose Island		HB	7490	2862	2.7	0.3	0.6	0.8	St, Sa	
Bahia de La Paz		HC	0	0	0.0					3
Bahia de San Rafael	BCN	HB	28098	9185	3.1					
Bahia Guadalupe, N of Bahia de los Angeles		HB	860	322	2.7					
Dzilam Bravo (24 km E of), Xpet Ha	Yucatan	X	0	0	0.0					
Holbox Island		X	64975	9482	6.9					
Huatabampito, Sonora		HB	16754	2446	6.8					
Punta Bufeo		HB	5704	1795	3.2					
Rio Lagartos, Yucatan	Yucatan	X	0	0	0.0					
San Bruno, 15km north of Mulege	BCS	X	0	0	0.0					
Tenabo, Campeche state	Campeche	X	0	0	0.0					
NEW CALEDONIA										
Baie d'Oro, sandy beach in front of a hotel		B	0	0	0.0				Sa	

Table 1 (*continued*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
NEW HEBRIDES										
Ravallec Bay		HI	1713	1926	1.6	0.2	0.1	0.3	Sa	
NORWAY										
Brossoya (in a strait), north of Borgan, Vikna		E	0	0	0.0					
Laupstad, Austnesfjord (Ostnesfjord)		E	0	0	0.0					
NEW ZEALAND										
Aotea Harbour, north of		S	0	0	0.0					
Bay Of Plenty region		HB	29384	10329	2.8					4
Blind Bay, Great Barrier Island		CI	1736	2053	0.8					
Bream Bay		HI	20918	11386	1.8	0.22	0.04	0.2		11
Cape Campbell		HB	0	0	0.0					
Cloudy Bay		B	23181	10144	2.3	0.8	0.3	0.1		
Colville Beach, Coromandel Peninsula		I	0	0	0.0	0.03	0.09	0.1	M	
Dargaville		S	0	0	0.0					2
Doubtless Bay		HI	10600	13876	0.8	0.33	0.35	0.11		6
Doughboy Bay, Stewart Island		HI	6815	4980	1.4	0.16	0.34	0.86		2
Golden Bay		Spit-bay	0	0	0.0	0.4	0.04	0.13		37
Hanson Bay, Chatham Island		HB	28517	13509	2.1	0.6	0.9	0.2		14
Hawke Bay		HB	22139	6862	1.7	0.4	0.13	0.07	f.Sa	8
Houhora Bay, Northland		HB	1707	888	1.9					
Kaipara coast		S	0	0	0.0	0.3	0.1	0.15	Sa	4
Karepiro Bay, Wade River (Weiti River)		B	8758	1579	5.5				Sa	
Karikari Beach	North Island	S	0	0	0.0	0.9	0.2	0.3		2
Katherine Bay, Great Barrier Island		B	0	0	0.0					
Kawau Bay, Snells Beach	North Island	HB	1983	543	3.7					
Kuaotunu Bay, Matarangi Beach	North Island	HI	11848	3586	3.3					
Long Beach, Auckland		HI	24260	19874	1.2				Sa	
Lyall Bay, Cook Strait		I	1506	2170	0.7				Sa	
Mahurangi		X	0	0	0.0					
Mairangi, Wharekauri Beach, Chatham Island		HB	0	0	0.0					
Mangawhai Estuary		E	0	0	0.0					
Manukau Harbor, On Poutawa Bank		E	0	0	0.0					
Mason Bay, Stewart Island		HB	81505	7254	11.2	0.5	0.6	0.5		2
Maunganui, NW Chatham Island		HB	13787	4129	3.3	0.45	0.13	0.32		3
Muriwai		S	13439	4411	3.0	0.6	0.4	0.3		3
Napier Beach		X	0	0	0.0	0.5	0.1	0.1		
Ngawai Bay		HB	749	310	2.4					
Northland		X	0	0	0.0					
Ocean Beach, Old Sand Neck, Stewart Island		HI	728	338	2.2	0.8	0.9	0.5	Sa	
Paraparamau beach		HB	0	0	0.0	0.8	0.33	1	Sa	
Parengarenga, Northland		X	0	0	0.0					
Petre Bay, Long Beach, Chatham Island		HB	0	0	0.0	0.4	0.4	0.3		12
Port Levy, Banks Peninsula, South Island		CI	2085	6600	0.3	0.3	0.2	0.1		2
Radio Station beach, Pt Weeding, Chatham Island		HB	390	145	2.7					
Ruapuke Island, small beach near east end		HB	464	223	2.1					
Sandy Bay, Nelson		I	3262	2100	1.6					
Shipwreck Bay (near to) (Ahipara, Northland)		HB	77506	15229	5.1	0.9	0.26	0.13		
Spirits Bay		HB	16000	4050	4.0	0.9	0.3	0.2		
Stingray Bay, Great Mercury Is		B	0	0	0.0					
Tararewa River mouth, 2km east of		S	0	0	0.0					
Tasman Bay		B	0	0	0.0					
Te Paki, 90 Mile Beach		HB	2663	685	3.9					
Thames		I	10569	14035	0.8	0.02	0.03	0.04		
Titirangi Point, North Cape		X	0	0	0.0					
Tryphena Harbor, Great Barrier Island, Puriri Bay, Goosebury Flats		I	2638	3160	0.8	0.8	1	0.3		
Waianakarua River mouth, on rock platform		Reef, rock	0	0	0.0					
Waihau Bay, Orouiti Beach, Waihau Bay East		HB	4755	1639	2.9					
Waihere Bay, Pitt Island		HI	1871	1104	1.7					3
Waikuku Beach, North Cape		HB	11047	3120	3.5					
Wainui beach (Okitu), Tatapouri Point, Gisborne		HB	5480	917	6.0	0.8	0.5	0.14		
Waitangi West Beach, Chatham Island		HI	4820	2780	1.7					
Warrington (Okahau)		B	0	0	0.0	0.6	0.2	0.13		2
West Ruggedy Beach, Stewart Island		HB	2640	678	3.9	0.25	2.3	1.1		
Whale Bay/Hendersons Bay		HB	4425	1082	4.1					
Whangaparaoa Bay		HB	2944	982	3.0	0.24	0.1	0.08		2
Whangaumu Bay, Ngunguru		HI	1269	513	2.5					
Whatipu beach, West Auckland		S	608	365	1.7					
Whitianga Bay		CI	3645	5100	0.7					
Wooding Bay, Maori Beach, Stewart Island		HI	941	848	1.1	0.3	0.4	0.4		
OMAN										
Al Sawadi beach		HB	13649	1932	7.1	0	0.34	0.3		
PHILIPPINES										
Cadiz city, Negros Occidental province		X	11747	1946	6.0					

Table 1 (*continued*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
PORTUGAL										
Albufeira, Algarve coast		HB	2590	555	4.7					
SCOTLAND										
Backaskaill Bay, Sanday, Orkney		HB	1950	828	2.4				Sa	
Bay Of Tafts, Twinness, Westray (South Side, Wastbis Farm)		HB	791	471	1.7					
Buddon Ness and Barry Sands east		E	0	0	1.5				Sa	
Dornoch Firth		E	0	0	0.0				M, Sa	
Isle Of Lewis		X	0	0	0.0					
Kyle of Durness		E	0	0	0.0	0	1	1.9		
Loch Carnan, South Uist		E	0	0	0.0					
Loch Torridon		E	0	0	0.0					
Pittenweem, Fife		S	0	0	0.0				Sa, R	
Point of Cott, Westray, Orkneys		I	0	0	0.0				St	
Staffin, Isle of Skye		HB	0	0	0.0					
Thorntonloch Beach, East Lothian		S	0	0	0.0					
Uyeasound, Shetland		I	0	0	0.0					
SENEGAL										
Yoff		HB	0	0	0.0	0.9	0.4	0.2		6
SEYCHELLES										
La Digue Island		X	0	0	0.0					
SOUTH AFRICA										
False Bay, Cape Peninsula		CI	0	0	0.0					
Grotto Bay, Seaspray, Mamre		HB	0	0	0.0				Sa	
Long Beach, Kommetjie		HB	1643	395	4.2				Sa	2
Melkboss Strand		S	0	0	0.0					
Morgan Bay		HB	1525	411	3.7					
Nordhoek beach		HB	4176	1049	4.0					
St Helena Bay		HB	53473	20284	2.6	0.14			Sa	3
Walkers Bay, Die Kelders		HI	22396	10809	2.1					
SPAIN										
Arbeyal beach, Gijon		B	1395	1580	0.9				Sa	
Bahia de Alcudia, Majorca		HI	16370	12830	1.3					
Bares Bay		HB	895	463	1.9					2
Burela (near to)		X	0	0	0.0					
La playa de Cobas, Vivero		I	1934	4860	0.4					
La playa de San Antonio, Nueva, Llanes		B	76	142	0.5					
La playa de Zumaya		B	750	393	1.9					
San Lorenzo beach, Gijon		HI	1039	562	1.8					
SRI LANKA										
Koddiyar Bay		HI	7934	9360	0.8				M	2
Shallow inlet near Kambanturai at Kayts, Velenai, Kayts Island		B	0	0	0.0				M, Sa	
TAIWAN										
Anping Harbour (near to), Tainan		Breakwater	0	0	0.0	0.4	0.4	0.1		
Chin-Shan fishing port (a beach near)		Breakwater	0	0	0.0	0.5	0.2	0		
Heng Chun		HB	12227	4723	2.6					
Tseng Wen River mouth		E	19722	3105	6.4	0.3	0.2	0.13		
Xingda port, Kaohsiung, Tainan		X	0	0	0.0					
THAILAND										
Batok Bay, Racha Yai Island		I	689	826	0.8				Sa	
TRINIDAD										
Cocos Bay, Manzanilla beach		HI	20720	4345	4.8				Sa	
UNITED KINGDOM										
Beaumaris Bay, Conway Estuary, Caernarvon	North Wales	I	4960	2802	1.8				Sa, M	
Birchington	Kent	S	0	0	0.0					
Donna Nook	Lincolnshire	E	0	0	0.0				Sa	
Eday	Orkney	X	0	0	0.0					
Hillswick, Urafirth, Shetland (Saint Magnus Bay)		E	0	0	0.0					
Holland Bay, Stronsay	Orkney	I	2356	3578	0.7					
Holmpton to Easington	East Riding Of Yorkshire	S	0	0	0.0					
Mounts Bay, Eastern Green beach, Penzance		HB	0	0	0.0	0.5	0.3	0.2	Sa	
The Wash, Haven River mouth, Boston, Norfolk		I	17745	26104	0.7					2
Whiteford Sands beach, Carmarthen Estuary (NE side of Whiteford Pt)	Wales	E	0	0	0.0					
URUGUAY										
Jaureguiberry		HB	9939	1225	4.9	0.6	0.11	0.3		

Table 1 (*concluded*).

COUNTRY / SITE NAME	DISTRICT	SITE TYPE	WIDTH (m)	INDENT (m)	W:I	SLOPE1 (Degrees)	SLOPE2 (Degrees)	SLOPE3 (Degrees)	SUBSTRATE	LARGE EVENTS
USA										
Avalon Beach State Park	FL	Lagoon	0	0	0.0					
Baldhead Island	NC	X	0	0	0.0					
Bayou Lafourche, West Of Pass Fourchon	Louisiana	E	0	0	0.0					
Bull Island	SC	X	0	0	0.0					
Cape Canaveral (near the lighthouse)	FL	X	0	0	0.0				Sa	
Cape Cod Bay	MA	Spit-bay	32380	36657	0.9	0.8	0.4	0.9		74
Cape Lookout		HB	154900	35222	4.4					
Cape Sable region, Everglades		S	0	0	0.0					2
Coquina beach (Bodie Island, N of ramp 2)	NC	E	0	0	0.0					
Corolla, Ocean Beach	NC	S	0	0	0.0					
Cow Cove, Block Island		B	1440	303	4.8					
Cumberland Island	SC	X	0	0	0.0					
Daytona Beach, Between South Daytona and New Smyrna Beaches	FL	S	0	0	0.0					
Flagler Beach (5 Miles South Of)	FL	S	0	0	0.0				Sa	
Florida Keys	FL	Key	0	0	0.0					11
Fort Myers Beach	FL	Lagoon	45624	13868	3.3					
Fort Pierce to Vero beach		Lagoon	0	0	0.0					
Highland Beach, Everglades	FL	S	86140	19175	4.5	0.06	0.02	0.03		
Hog Key, Everglades		X	0	0	0.0				M	
Jacksonville, N Of Little Talbot Is, Nassau Sound, Bird Is.	FL	E	0	0	0.0					
Kiawah Island		S	16938	2655	6.4	0.11	0.07	0.02		2
Lewis Bay, Hyannis, Barnstable		B	0	0	0.0					
Little Gasparil, Gum, S End Little Gasparilla Is	FL	Key	0	0	0.0					
Little St Simons Island, beach midway down island	SC	X	0	0	0.0					
Loggerhead Key, Dry Tortugas		Key	0	0	0.0					
Manasota Key & Gasparilla Island		Key	0	0	0.0					
Marco Island (Marco River/Factory Bay)	FL	X	0	0	0.0					
Mayport		E	0	0	0.0					
Melbourne, 11 Miles South Of	FL	X	0	0	0.0					
Naples	FL	X	0	0	0.0					2
Nantucket Island region		X	0	0	0.0					3
Pass-a-Grille beach, Pinellas county	FL	X	0	0	0.0					
Pavilion Key, West Coast Of Florida	FL	Key	0	0	0.0					
Ponte Vedra	FL	S	0	0	0.0					
Port Everglades National Park, NW Tip Of Sable Island	FL	X	0	0	0.0					
Pyramid Cove, San Clemente Island		HB	4518	1355	3.3	3.3	2.9	2.7	Sa, R	2
Richardson Creek, Georgia	GA	X	0	0	0.0					
Siesta Key	FL	S	0	0	0.0					
Simonton Cove, San Miguel Island		HB	4428	1271	3.5	1.2	0.4	0.3		
Siuslaw (Florence, 2.3Km S Of Jetty)	OR	Breakwater	0	0	0.0	0.4	0.8	1	Sa	
Squaw Island (near Kennedy Compound), Hyannis Port	MA	Breakwater	0	0	0.0	1.3	2.6			
St Augustine Beach	FL	S	0	0	0.0				Sa	
St Simons Island, South End Of		X	0	0	0.0					
Upper Captiva Island, Pine Island Sound, Lee	FL	E	0	0	0.0					
VENEZUELA										
Bahia Guamache, Margarita Island		HB	6009	2493	2.4				Sa	
ZANZIBAR										
Mtoni beach		HB	4584	1096	4.2				f.Sa, M	

Key: Type: B = bay of unspecified type; CI = bay with indented character and additional coastline or bathymetric complexity; E = estuary; HB = 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 = unknown (see Fig.1 for examples of bay types). W:I = Indentation ratio. Slope: 1 = nearshore; 2 = intermediate; 3 = offshore. Substrate: particle sizes, f = fine, m = medium, cs = coarse; Bo = boulder, M = mud, MS = mud and sand, Pb = pebble, R = rocky, S = sand, SSh = sand with shell fragments, St = stones (see Hamilton (1999) for information on this seabed characterisation scheme). Large events: number of live events with 10+ animals.

A representative total of 710 events resulted, including 74 events in Cape Cod Bay (USA) and 37 in Golden Bay (New Zealand). The data are described as representative because detailed records are typically only available for about 100 years at most, some areas do not have records, not all events are noted, and not all recorded events will have been discovered for this analysis. These factors are expected to be offset by the widespread geographical distribution of events (Fig. 2). Accurate descriptions of site types and characteristics are dependent on good positioning information. Geographic co-ordinates are often not included in the literature or databases, or are too broad to be useful. Positions for explicitly named or photographed locations such as beaches and bays were extracted from charts. Good locations could not always be found for sites described as being 'near to' some beach, population centre, or other feature. All 710 events were used for general statistical information on numbers and species in larger strandings, and for broader geographical distribution of events, but not all could be used for site specific analyses. Brabyn and McLean (1992) regarded each New Zealand herd stranding (2+ animals) as having a separate location, even if on the same beach. In the present paper, coastal features such as bays are regarded as one site only, whether one or many strandings occurred in them, resulting in 402 separate sites.

Description of sites

Where possible, site properties were characterised quantitatively by coastal indentation, seabed slopes, and

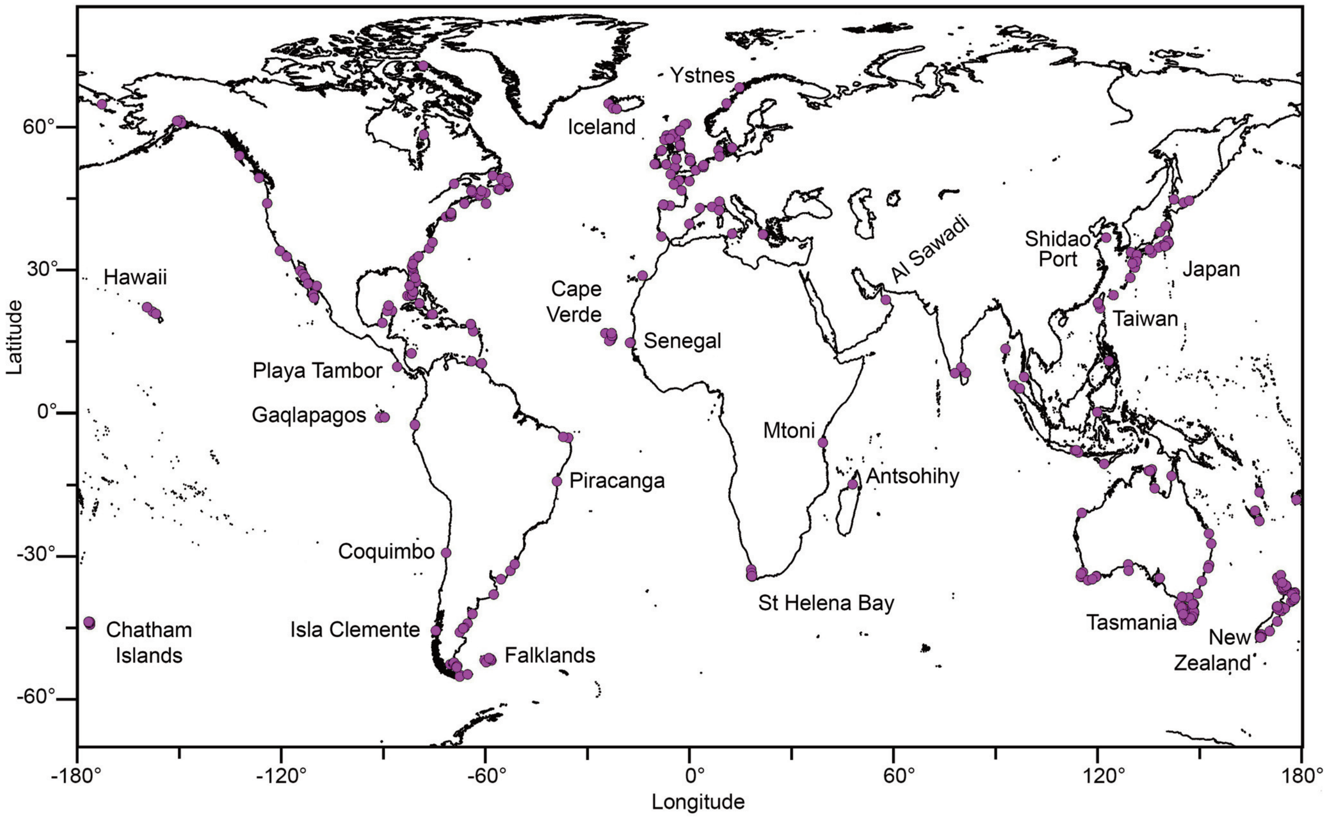

Fig. 2. Worldwide sites of larger strandings of odontocetes (toothed whales).

sediment grain size, following the approach of Hamilton and Lindsay (2014a). Planforms of coastal configurations were compiled as indications of the larger geomorphological environments of sites (for example bays, estuaries, lagoons), together with indications of complexity caused by reefs, islands, and convoluted coastlines. Some bays have a headland at both ends. Bay width (W) was measured from headland to headland when two were present, and from headland to beach end or to where the beach straightens for the single headland case (Fig. 1(b)). Bay indentation distance (I) was measured as the maximum value to shore perpendicular to the line specifying the bay width. Indentation ratio (W:I) is the ratio of bay width to bay indentation distance, and is a useful proxy for coastline curvature (Hamilton and Lindsay, 2014a).

Bays are separated into indented bays and headland-bays using planform and indentation. Headland-bays have indentation ratio greater than 2:1 and a characteristic log-spiral shape, and indented bays have ratio less than 2:1, although indented bays may have headland-bay character and vice versa (Fig. 1). The ratio of 2:1 was initially used by Hamilton and Lindsay (2014a) as an empirical value which separated Australian bays of a similar regular shape (subsequently identified as headland-bays), regardless of their sizes, from those of irregular shapes. It was found that coastal engineering studies had identified the value of 2 as the lower bound for indentation ratio approached by mature headland-bays (Silvester and Ho, 1972), giving the empirical findings a physical basis. Indented bays can have a variety of planforms, seabed slopes, and geomorphological origins such as wave formed, or drowned topography. Headland-bays are formed by the eroding effects of waves and swell on coastlines of relatively softer materials interspersed by harder materials which become headlands. The eroded material may range from block and boulder size to fine sands, depending on the state of maturity of the bay. Larger sizes are broken into smaller by continued attrition and abrasion. Finer sediments (silts and clays) are generally winnowed out by waves and currents. Headland-bays are often associated with a stream running along the bay side of the headland, which may supply additional sediments.

Bays were classed as follows (see Fig. 1): headland-bays with a gently curving half-heart planform (H); indented bays with a headland often not prominent or absent (I); headland bays with indented character (HI). Bay types H and I with additional complexity (C) caused by topographical or bathymetrical configuration are classed as HC and CI. Bay (B) is used for bays without a specific name or location. Other classes are estuary (E) (estuary, firth, fjord, forth, coastal lagoon), reef lagoon, relatively unindented or straight coasts, entrapment in ice, and unknown (X) for general locations specified for example as ‘St Andres Island’. The presence of breakwaters and groyne series are also noted. Spit-bays are also recognised as a particular indented bay type.

Seabed indicators on hydrographic charts were the primary source of sediment descriptions. These descriptions are made by charting agencies from visual and tactile examinations of fresh wet surficial samples. Hamilton (1999) has shown they are generally reliable and consistent assessments of non-cohesive sediments in particular with respect to the quantitative Udden-Wentworth sediment grainsize 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 (silts and clays) are collectively termed muds and particles with diameter greater than 2mm (termed gravel) range from granules to boulders.

Seabed slopes were measured for shore perpendicular transects for 105 sites for which quality information was available, nominally from shore to deeper than the usual wave base (30m depth). The slopes are measured perpendicular to shore along bay axes, not over low gradient areas or in enclosed areas such as estuaries. Digital charts were used for Australia, New Zealand (LINZ – Land Information New Zealand, *http://www.linz.govt.nz*), the USA, and parts of Japan and South America (Digital Nautical Charts from NGA Maritime Division). Elsewhere any available information was used. Seabed topography and coastal configuration can change markedly with time for some locations (river deltas, ports and harbours in particular), but older charts were seldom available.

RESULTS

Number of events by species

The 710 larger strandings are for long-finned pilot (*Globicephala melas*) (218), short-finned pilot (*Globicephala macrorhynchus*) (103), pilot whales of undetermined species (160), false killer whales (*Pseudorca crassidens*) (75), sperm whales (*Physeter macrocephalus*) (58), melon-headed whales (*Peponocephala electra*) (28), white whales (24), blackfish (these are unidentified odontocete species excluding dolphins and porpoises) (16), killer whales (*Orcinus orca*) (15), beaked whales (11) [Cuvier's (*Ziphius cavirostris*) (6), Baird's (*Berardius bairdii*) (1), Blainville's (*Mesoplodon densirostris*) (1), Gray's (*Mesoplodon grayi*) (3)], pygmy killer whales (*Feresa attenuata*) (3). Twelve long-finned pilot whale events of 200+ animals for the Falklands mentioned by Otley (2012) are not in these figures.

Numbers in a stranding

Maximum numbers in a stranding were for 'pilot' whales (1,000), false killer whales (835), long-finned pilot whales (500), melon-headed whales (265), short-finned pilot whales (200), white whales (186), sperm whales (72), pygmy killer whales (28), killer whales (25), Gray's beaked whale (28), Cuvier's beaked whale (15), Baird's beaked whales (10), Blainville's beaked whales (10). The figure of 835 for Mar del Plata, Argentina was well reported (Marelli, 1953). The figure of 1,000 pilot whales at Chatham Island is from the New Zealand Department of Conservation Tea Ara website (*http://TeAra.govt.nz*). Cape Cod Bay has historical drives of more than 1,400 pilot whales, but maximum in strandings of 500.

Areas with high numbers of strandings

Many events occur south of 30°S and north of 15–20°N (Fig. 2), coinciding with the known distributions of several odontocete species. Higher numbers of events are seen on the southern coast of Australia, particularly around Tasmania (Hamilton and Lindsay 2014a); the eastern coastlines of New Zealand (McCann, 1964; Brabyn and McLean, 1992); the southeastern coastline of South America (Goodall, 1989); and the far southwest of South Africa. In the northern hemisphere, the Ibaraki coast on eastern Honshu, Japan figures prominently, along with the British Isles, the east coast of North America (including the eastern interior shorelines of Cape Cod Bay; McFee, 1990; 1991), and the Gulf of California on the west coast. Islands such as Cape Verde (18 events), Chatham (26), Falklands (9), Galapagos (2), Hawaii (4) appear over represented compared to their size.

Regions of larger strandings by species

White whale strandings sometimes occur during lower low tides at Susitna River and Turnagain Arm in the muddy Cook Inlet, Alaska, with and without mortality (Fig. 3). These events are included as being similar to those associated with tides in locations such as Cape Cod Bay and elsewhere. Entrapments under ice with limited access to breathing holes ('savsats') occur for both white whale and narwhal (Porsild, 1918). At least 17 savsats are known for both species, with more than half in Disko Bay, Alaska, but they are not included in the database, as details are often lacking. Savsats sometimes involve hundreds of animals. A narwhal ice entrapment in Greenland in November 2008 yielded 629 animals (hauled out of 3 ice holes by Eskimo), with one white whale savsat of 260 animals in November 2015.

All six Cuvier's beaked whale events are in the northern hemisphere, three being in the Mediterranean (Fig. 3). New Zealand has three Gray's beaked whale events. A Baird's beaked whale event occurred at Isla San Jose, Mexico. An unconfirmed Blainville's event is recorded for the Canary Islands. No Australian beaked whale strandings of more than 6 animals appear in a 100-year record of 331 events (Hamilton and Lindsay, 2014b).

Blackfish events are widely spread (Fig. 3), indicating no particular bias to results except for New Zealand. False killer events are seen particularly around Japan, the British Isles, the Gulf of Mexico, and south of 30°S (Fig. 4). Melon-headed whales (*Peponocephala electra*) are a tropical pelagic species (Findlay *et al.,* 1992; Jefferson and Barros, 1997) and events lie between 40°N and 30°S, particularly for the Cape Verde Islands and eastern Japan, the latter geographically associated with the warm Kuroshio western boundary current (Fig. 5).

Pilot whale events occur particularly on the North American east coast, the British Isles, Japan, and south of 30°S (Figs 6 and 7). Most short-finned pilot events are in the northern hemisphere (Fig. 6). Short-finned and long-finned pilot strandings overlap to some extent on the eastern coast of North America from 35°N to 45°N, as noted by Abend and Smith (1999) for live sightings, and around the British Isles. Long finned pilot (Fig. 6) and killer whales (Fig. 4) have much the same geographical stranding patterns of north of 30°N and south of 30°S. The three pygmy killer strandings (Fig. 4) were on the southwest coast of Taiwan (Tzeng-wan river mouth and Ching-shan fishing port; Brownell *et al.,* 2009), and Xingda port. Sperm whale events are noted round the Gulf of California, the North Sea (Europe), eastern Japan (but not the Sea of Japan, and Nishimura [1965] notes an almost complete absence of sightings in this area), and south of 30°S (Fig. 5).

Site details

Site type was determined for 627 events. Three-quarters (76%) occurred in bays, with 14% in shallow topographically complex areas (estuarine environments

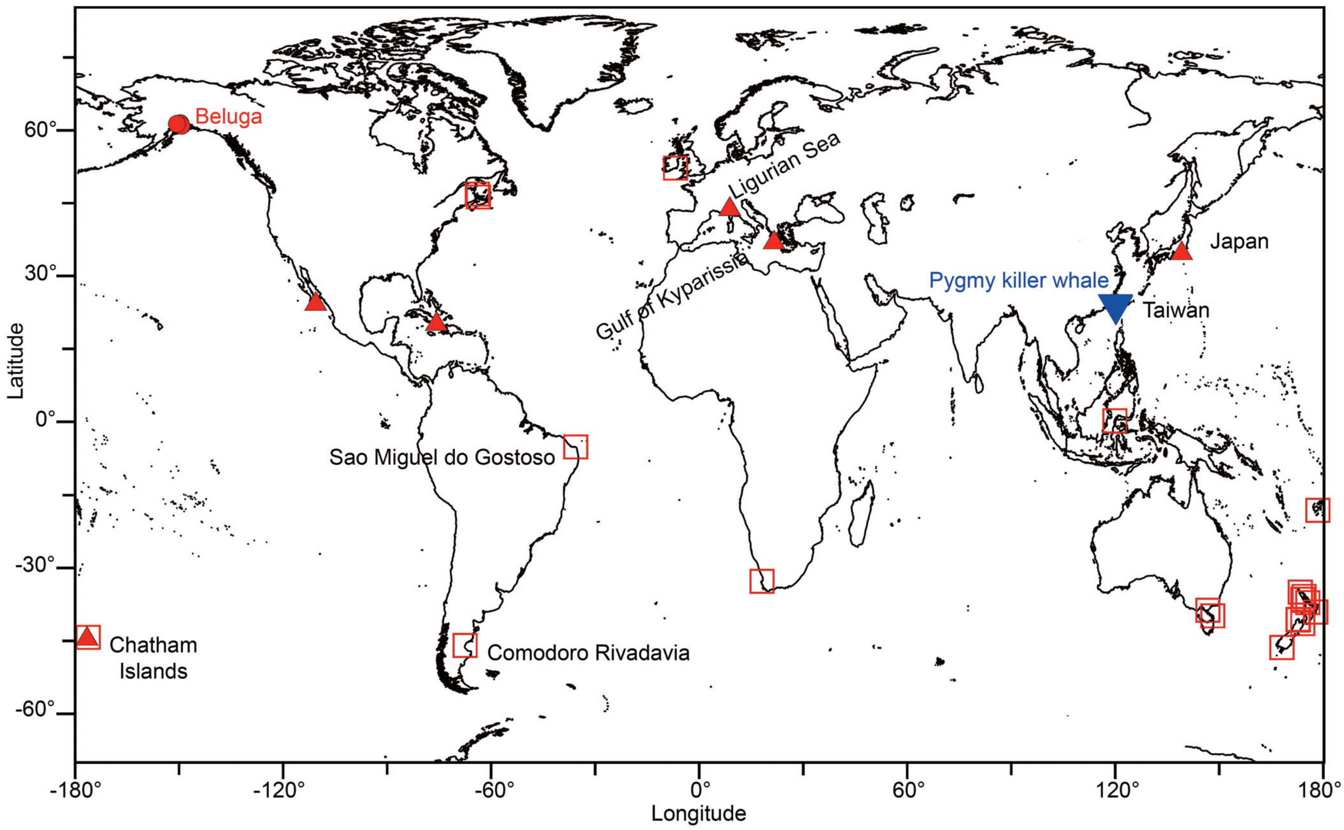

Fig. 3. Beaked (▲), Blackfish (unidentified odontocete species excluding dolphins and porpoises) (□), Pygmy Killer (▼),White whale (●) strandings.

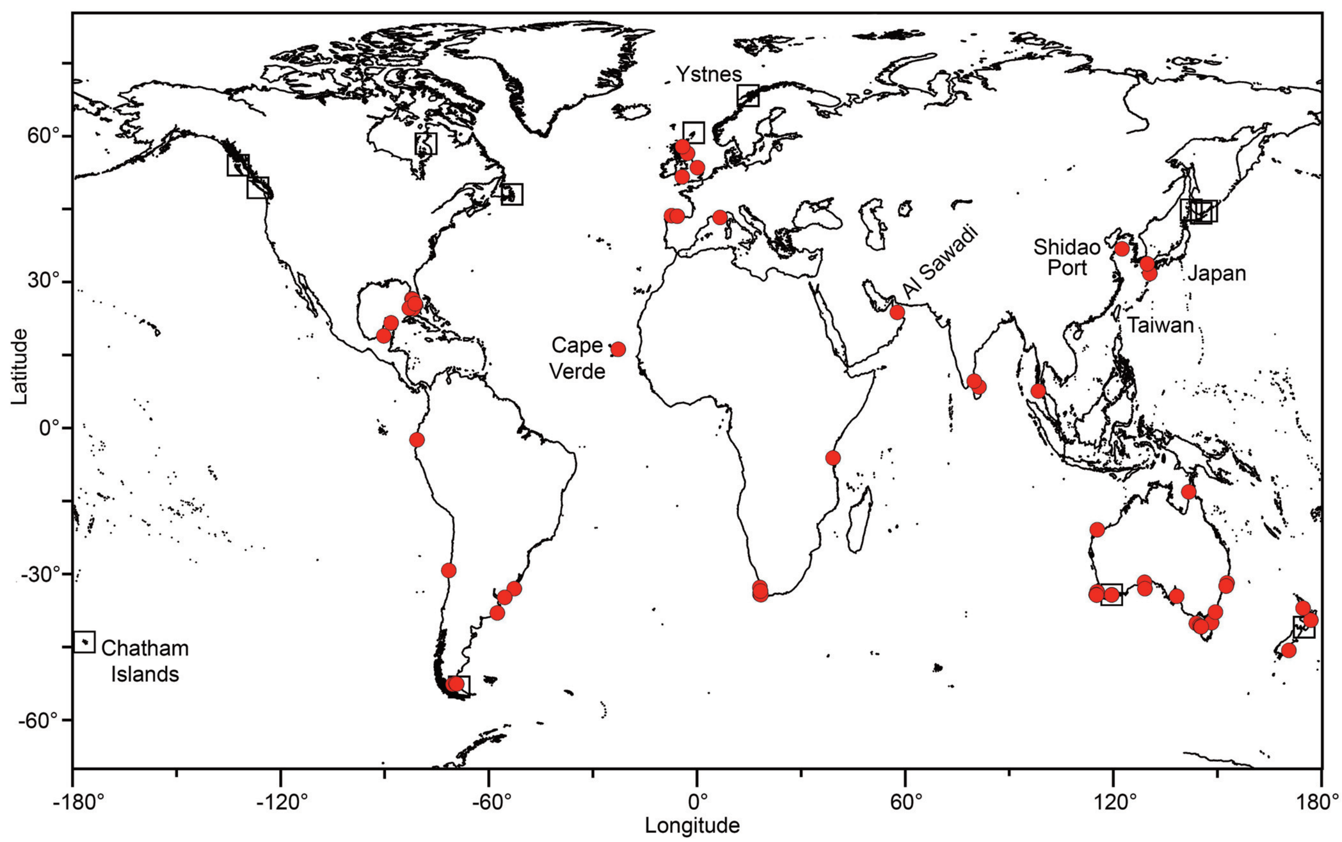

Fig. 4. False killer (●), Killer (□) whale strandings.

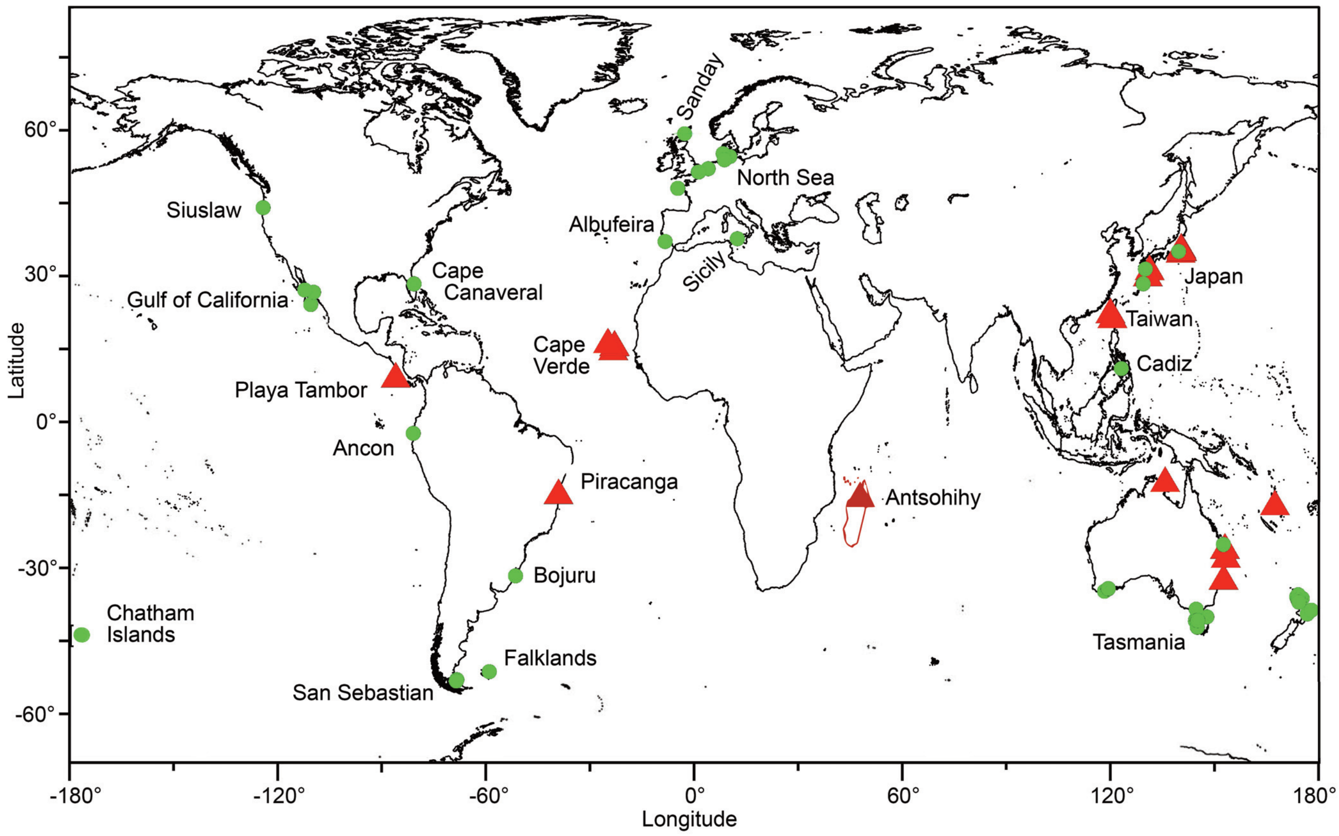

Fig. 5. Melon-headed whale strandings (▲) and sperm whale strandings (●).

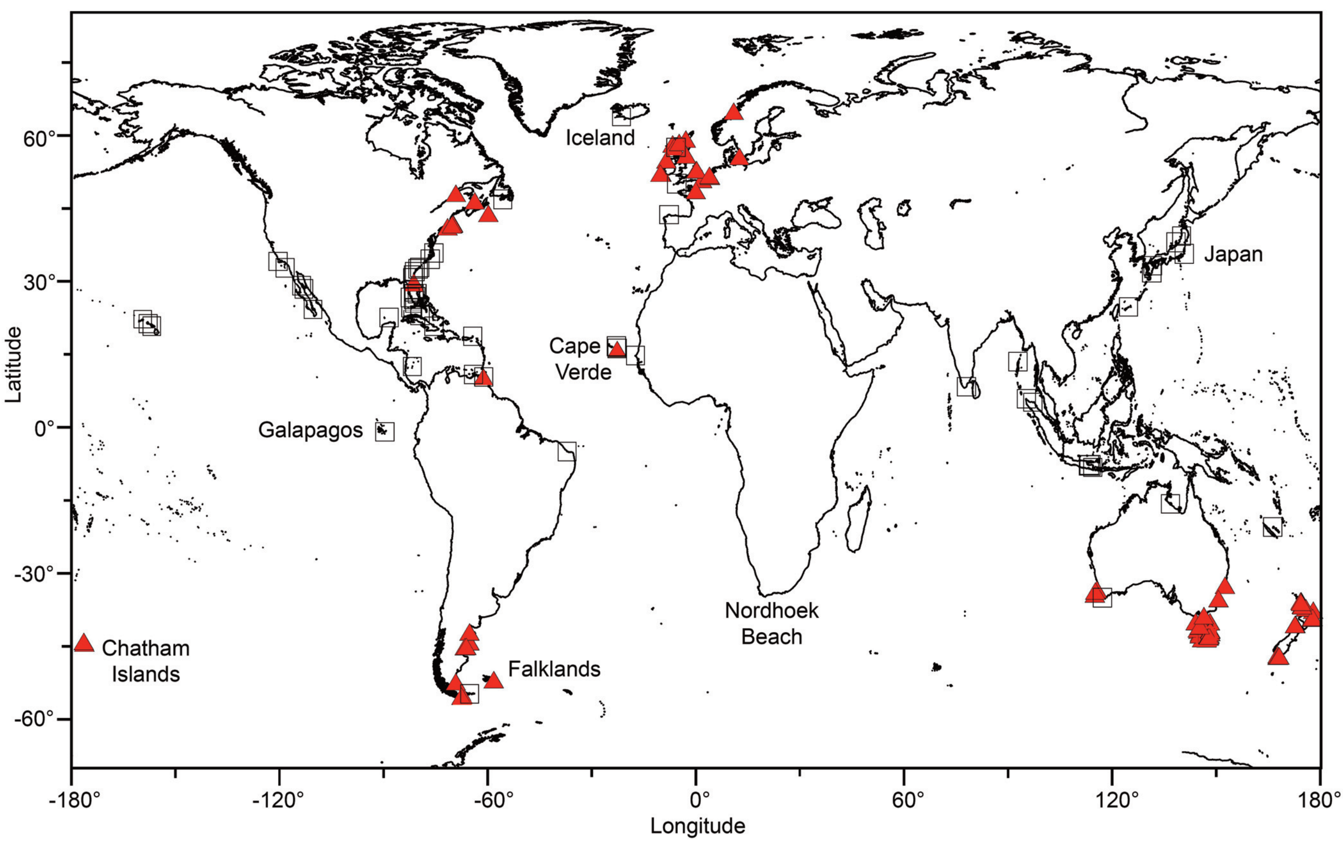

Fig. 6. Long-finned pilot (▲), Short-finned pilot (□) whale strandings.

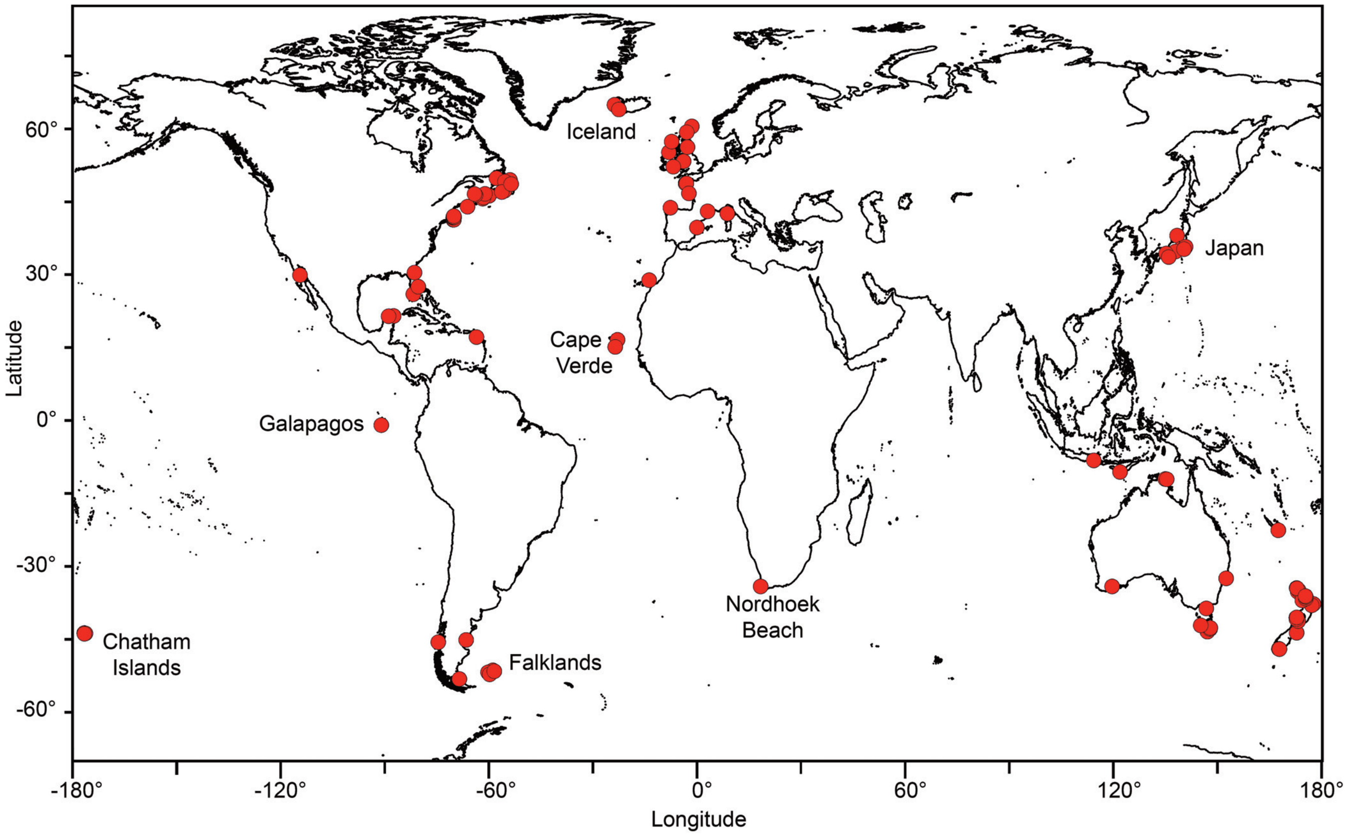

Fig. 7. Pilot whale strandings of undetermined species.

including firths, forths, fjords, straits, and keys, reef and coastal lagoons), 8% on relatively unindented coasts, with ice entrapment (of killer whales), breakwaters, and miscellaneous categories being 2%. For the 76% of bays, sites with headland-bay character have 42% of events, spit-bays 20% (even though there are only four of them), indented bays 9% and 5% are unspecified bay types. The shallow topographically complex areas include locations with restricted entry/egress, such as: (a) the long stretches of shore parallel shallow coastal lagoons of south-eastern USA, which are connected to the open ocean by occasional channels, (b) reef lagoons, (c) locally extensive shallow open ocean platforms with highly complex island and reef topography, channels and islands (Florida Keys, Okinawa Islands), and (d) estuaries, including firths, fjords, Magellan Strait, Denmark and Netherlands delta areas.

The 710 events occurred at 402 sites, 335 with one event only, and 67 (9%) with 2 to 74 events. Of the 67 sites with multiple events, 72% are bays, 12% are straight coasts, and 8% are in estuarine environments. These figures are within 4 to 6% of those in the previous paragraph for the 627 events with known site type, indicating an internal consistency of results and trends. Thirty-seven (37) sites have 2 events, eight sites have 3 events, five sites have 4, two sites have 5, four sites have 6, one site has 7, three sites have 8, Bream Bay and Florida Keys have 11, Petre Bay has 12, Hanson Bay has 14, Turnagain Arm has 20, Golden Bay has 37, and Cape Cod Bay has 74. Cape Cod Bay and Golden Bay (spit-bays) and Turnagain Arm (an estuary) have large tidal ranges and fine sediments.

Six events are in proximity to harbour breakwaters (Thorlakshofn and Rif, Iceland; Siuslaw, Oregon; Squaw Island, USA: An-ping and Ching-shan, Taiwan). Some sites have numerous groynes and groyne series (for example Mar del Plata, Argentina, and the Ibaraki coast, Japan). Also noted are river mouths with extensive shallow seawards sediment buildups (Bodri stream, Indonesia; Delsman, 1923); large bays with width over 30km, W:I < 2 and extensive interior shallows or estuaries (Cape Cod Bay, USA; Golden Bay, New Zealand; Perkins Bay, Australia; Tralee Bay, Ireland; Bahia San Sebastian, Argentina); and inland seas with shallow island platforms (Seto Sea, Japan).

DISCUSSION

The high numbers often observed in open ocean odontocete strandings are ascribed to their social nature and the formation of large pods of hundreds and even thousands of animals for some species. As noted by Hamilton and Lindsay (2014a) for Australia, odontocete species, species adult size, and bay size do not appear to be factors in worldwide larger stranding events. The species involved have adult sizes from 3m (melon-headed) to 18m (sperm whales). Bay sizes range from hundreds of m to 55km or more.

Species in larger mass strandings of odontocetes

Six species (false killer, long-fin pilot, melon-headed, short-fin pilot, sperm and white whales) contribute 96% of the mass strandings of 10+ animals, the remainder being killer whales, beaked whales, and pygmy killer whales. Some events for the latter three species appear to represent extreme cases or outliers. One of 15 killer whale events is at the head of a Norwegian fjord, and is attributed to chasing fish, and four are entrapments in ice. One of 11 Ziphiid events was associated with naval sonar activities (Frantzis, 2004).

Charging the beach

Eyewitnesses sometimes describe active mass strandings of an extreme nature. Robson and Van Bree (1971) describe sperm whales in a Gisborne, New Zealand event during a violent storm as 'charging the beach'. In a stranding at Duke Head beach, Flinders Bay, Western Australia, two large false killer whales broke away from a milling herd and 'sped ashore' (Leatherwood *et al.,* 1989). At The Grotto, Mamre, South Africa, false killer whales 'came ashore at a run, making determined efforts to strand themselves' (Leatherwood *et al.,* 1989). Birkby (1935) describes the false killer whales as 'rushing the shore', possibly in association with a 'furious southeaster'.

This behaviour implies the animals did not know what land was, or could not tell they were near land. In some cases, it is possible that surf zone noise may be misinterpreted as a continuation of open ocean. Further candidates to explain such behaviour are sonar termination or poor sonar transmission conditions, and simple confusion, particularly when storm conditions generate high levels of air and water borne sound, waves, wave and rain noise, suspended sediment, and bubbles. Suspended sediment may irritate whales and distract them. To partly discount the sonar termination hypothesis, Geraci (1978) stated that suspended particles offer no impediment to the transmission of underwater sound. Suspended sediments do attenuate sound through backscattering and viscous dissipation effects, but as a strong function of frequency and particle size. Attenuation is minimal at tens of kHz in usual circumstances, but sediment clouds are sometimes observed in side scan sonar imagery at hundreds of kHz. Resonant scattering by air bubbles in coastal waters (Dudok van Heel, 1962; Chambers and James, 2005) has potentially far greater effect on disrupting cetacean acoustic transmissions than suspended sediments.

Violent storms

Lacépède mentioned 17 sperm whales beached in 1723 in the mouth of the Elbe, Germany during a violent storm (van Beneden, 1888). New Zealand events at Gisborne (sperm whales) and Opoutama (long-finned pilot whales) occurred during violent storms (Robson and van Bree, 1971). Murata (2004) describes a stormy sea for a sperm whale stranding at Oura, Japan. An event near the Port Albert boat harbour entrance, Victoria, Australia was thought to occur when storms forced blackfish over a sandbar they could not recross (*The Age* newspaper, 1946). A Donna Nook, United Kingdom event has a similar report to Port Albert (Peacock *et al.,* 1936). Separate to the remarks in the previous section, these reports imply that whales sometimes founder on shores during storms in the same way as shipping, by simple misadventure.

Salients, Breakwaters, Groyne Series

Mazzucca *et al.* (1999) associated salients with strandings, rather than headlands, for three Hawaiian Island events. These are actually for odontocetes trapped in small sandy bays inside long fringing reefs with a constricted entry channel, and site complexity seems the important factor. However, other events perhaps do merit description as salients, such as Donna Nook (Fraser, 1936). Coastline configuration for a stranding at Tzeng-Wan river mouth, Taiwan also appears as a minor salient, but sediment buildup extends 4km seawards immediately north of the river mouth as a remnant subaqueous delta of less than 6 to 8m depth (Liu *et al.,* 2000). Delsman (1923) described an event at the mouth of the Bodri River, northern Java where sediment buildup extended seawards. The river mouth has changed considerably since, but previous configurations indicate an arrowhead delta projecting seawards from the river mouth. Three events in proximity to seawards extending breakwaters (Siuslaw, USA and An-Ping and Chin-Shan, Taiwan) have sediment buildups forming shore parallel ramps rising up to the breakwaters on both sides. Another event occurred in extensive shallow sediments west of the breakwater at Squaw Island (USA). The sediment ramps caused by the breakwaters may lead to the strandings, rather than the breakwaters themselves. The Ibaraki coast, Japan (8 events) is a fine sandy immature headland-bay of low curvature (W:I of 6.5) and nearshore slopes less than 1° which faces east into the Pacific Ocean. Complexity is introduced by occasional salients, streams, and shore perpendicular sandbars, plus several sets of T-shaped groynes (about 35 in total) of length 170 to 930m and 1km apart, and a series of 20 more of length 65m and 120m spacing. At Mar del Plata, Argentina 835 false killer whales stranded over 6km of coastline with W:I of 5.4. The coastline is fronted by an extended series of T-shaped groynes at 100 to 850m spacing, indicating site complexity as a factor.

Odontocetes and estuaries

Some recent apparently anomalous strandings in estuarine situations have been attributed to anthropogenic causes. An event in the Kyle of Durness, Scotland is believed to have been precipitated by panicked whales fleeing from underwater explosions (Brownlow *et al.,* 2015). An event at Antosohihy, Madasgascar is attributed to whales running from a multibeam sonar survey (Southall *et al.,* 2013). Estuaries in these circumstances form a particular type of topographic trap akin to deeply indented bays. Odontocetes also frequent estuaries in entirely natural circumstances, although perhaps not very often. There are records of tens of false killer whales being found swimming far into the Qiantung, Guanhe, and Yangtse (Chiangjiang) rivers in China (upstream distances of 30, 50, 220–300km respectively) (Leatherwood *et al.,* 1989). A killer whale was observed over 30km from the sea in the River Foyle at Londonderry, Ireland in November 1977 (*Daily Mail* Australia, 2016). In 1647 two cetaceans were observed near Cohoes Falls, Saratoga County, New York, over 225km from their presumed entry at New York (Sylvester, 1878). False killer whales stranded 65 and 120km into Magellan Strait, South America and 23km upstream in Dornoch Firth, Scotland. Eyewitness descriptions of a stranding of hundreds of pilot whales in Teal Inlet, Falkland Islands, 22km from the sea, imply a mass stampede of panicked animals (Hewlett, 1897), but the reason for the whales being there is unknown. For Norway, killer whales chasing fish stranded 12km from open water at Laupstad in Ostnesfjord, and pilot whales stranded in a strait north of Brossoya. In July 1852, 20+ short finned pilots stranded at Salt Lake, Calcutta, about 125km from the sea (Silas, 2010).

Sediments and seabed slopes

New Zealand has many gravel beaches but Brabyn and McLean (1992) found that about 80% of 41 New Zealand pilot whale herd strandings (2+ animals) generally occurred on sediments no coarser than sands and on beach slopes less than 3°. Hamilton and Lindsay (2014a) noted that one implies the other, since beach slope and sediment size increase together (Wiegel, 1965). Fine sands can have beach slopes less than 1°, and shingle beaches can reach slopes over 30° (Gilluly *et al.,* 1975). Similarly to New Zealand, none of 21 larger Tasmanian events occurred on gravel beaches, even though they make up more than one-sixth of the 1,596 Tasmanian beaches (Hamilton and Lindsay, 2014a). Fine sands were noted for many Australian sites (Hamilton and Lindsay, 2014a). The present analysis examines nearshore slopes with respect to Lowest Astronomical Tide, not beach slopes. They are less than 1° for 94 of 105 world sites, including 33 for New Zealand, and only two reach or exceed 3° (Pyramid Cove, USA, and Anini, Hawaii). Offshore slopes deeper than the wave base were typically less than 0.5°. Whether the sediment/slope observations for strandings is a physical phenomenon related to whale biology or other factors is unknown. It is common to all odontocete species with 10+ in a stranding regardless of species size.

Tides, shallow water and partial burial

Peacock *et al.* (1936) and Fraser (1936) associated ebbing tides with mass strandings. Fraser (1936) noted that the coast in several English events was characterised by a more or less extensive area of shoal exposed at low tide. Donna Nook, Lincolnshire for example had a wide sand and mud-flat extending seawards for about two miles, in which the struggling cetaceans had embedded themselves in silty sand. Recent photographs of events in Golden Bay (New Zealand), Calais (France) and elsewhere also show partial burial, and this can occur in mobile sediments by scour processes even if animals do not move if waves and currents are sufficiently strong to suspend sediment. In softer sediments, the weight of the animals may be sufficient to cause seabed deformation and initiate partial burial. Partially buried animals with restricted movement may be hampered from moving offshore as tides recede.

Falling tides are noted as involved in strandings for Cape Cod Bay (USA), Golden Bay (New Zealand), Bahia San Sebastian (Argentina), Magellan Strait (Chile), Penzance (England), the Kyle of Durness (Scotland), An-Ping (Taiwan), the Hooghly River (Salt Lake, India) and other locations. Some of these events were in confined areas, compounding the difficulty, and tides were not always the only cause of the strandings. At An-Ping the melon-headed whales were reported as trapped against the coast by the presence of several hundred offshore oyster cages (Wang *et al.,* 2001). The cages extend for 6km on both sides of An-Ping harbour. Cetaceans are believed to have entered the Kyle of Durness after being spooked by underwater explosions. The Hoogly river was in flood, and the cetaceans were 125km upstream when the water level fell.

Relation of strandings to coastal topography

In agreement with Dudok Van Heel (1962), Brabyn and McLean (1992) suggested that New Zealand herd strandings (2+ animals) did not happen at random locations. They described the majority of New Zealand stranding sites as 'gently sloping sandy beaches with an adjacent protruding section of coastline', where gently sloping meant less than 3°. Hamilton and Lindsay (2014a) showed that bays rather than beaches dominated larger Australian strandings (63 of 66 events and 33 of 36 sites), particularly mature headland-bays. The headland and downswell bay do not occur together by coincidence (Hamilton and Lindsay, 2014a), something not realised in previous stranding studies. Bays form the platforms for three-quarters of all the 627 generally well located world events, to which headland-bays contribute 42%. The protruding sections of coastlines for New Zealand also include spits. Bays associated with spits have very different character to other indented bays and headland-bays.

Spit-bays

Cape Cod Bay (USA) (74 events) and Golden Bay (New Zealand) (37 events) (Fig. 1a) have disproportionately high numbers of events compared to adjacent coastlines and other sites. They are large indented bays (15–30km width) partially enclosed by spits. An initial explanation for their high number of strandings presents no difficulty. The orientation and width of Cape Cod Bay place it directly in the path of any animals coming from the north parallel to the general trend of the coast. Whales in the bay seeking to move back to open water by tracking north along the east coast may move into the two south opening interior spit-bays (Provincetown and Wellfleet), and difficult to navigate mudflats, sand bars, shallows and low slopes of the eastern bay, where the strandings dominantly occur. They may come to difficulties there, or choose to rest in the sheltered, shallow area inside the spit. Tides at Wellfleet up to 4.7m and partial burial in silty sediments can then leave them stranded.

Similarly, Golden Bay has tides up to 4.5m, and 1km wide mudflats along 25–30km of its northern spit interior where the strandings occur. Strandings of 416 and 240 pilot whales occurred on the spit interior in February 2017 during a king tide. Bahia San Sebastian (Argentina) (5 events), originally a low relief valley formed by glaciers, is partially enclosed in the northeast by a 20km long attached south pointing gravel spit (Bujalesky, 2007). It has gravel shorelines in the south, but its five events are associated with mudflats in the northwest or with the spit. Goodall (1989) describes a 10.8m tide that recedes at walking pace over 10km (nominally a slope of 0.057°, matching the chart value of 0.063°), with the rapidly falling tide and low slopes leading to strandings.

The seawards sides of these bays are extended curving sand and gravel spits built up by waves and currents, not a headland of rocky material as for headland-bays. The sheltering effect of the spit extension modifies the depositional environment within the bay, allowing fine sediments (silts and clays ('muds') and fine sands) to accumulate on the landwards or inner side of the spit, including contributions from wave overtopping (Friedman *et al.,* 1992). A further characteristic is that large tides are caused by the constricting action of the spit on water flow. The result is that static factors (size, orientation, fine sediments, low slopes, and bathymetric and topographic complexity), couple with dynamic factors (large tides) to make spit-bays highly effective natural traps.

Perkins Bay (Australia), another notorious stranding site forms a related example. It has headland-bay structure in the east, extensive shallows, sandbars, islands, and channels in the west, and tidal range of 3m. The western side of Perkins Bay is not a spit, but is similarly constructed as a topographically and bathymetrically complex buildup of sand pushed eastwards into Bass Strait by currents and Southern Ocean swell.

Indented bays

Spit-bays are indented bays of a particular type. Other indented bays arise from drowned topography or irregular antecedent coastal shapes. These can have a variety of planforms, slopes, and sediments. Some larger indented bays may become stranding sites through size and interior bathymetric and coastline complexity, including estuaries, shallows, and interior bays. Cloudy Bay, Tasmania was cited as an example by Hamilton and Lindsay (2014a). The Wash, England (Fig. 1a) is a large indented rectangular bay (width 25km and W:I of 0.72) fed by several streams, with complex bathymetry, including extensive shallow saltmarsh, mudflats, sand bars, and channels, particularly in the south and west. Spring tidal range is 6.3m and neap is 3m.

Headland-bays

Headland-bays form the platform for 42% of 630 reasonably well located larger world events. Indented bays contribute 9%, spit-bays 20%, and bays of unknown type 5%. The ratio of 4.7:1 for headland-bays to indented bays (not including spit-bays) is somewhat puzzling, because many headland-bays have relatively simple planform and bathymetry, and seemingly have little reason to be stranding sites (Hamilton and Lindsay, 2014a). Indented bays would by their very nature be expected to be more difficult locations than headland-bays. There is no particular reason for odontocetes to strand in bays of relatively benign shape and bathymetry simply because they have a headland, especially as strandings generally occur towards the bay centre, not on the headland.

This points to factors other than coastline complexity, and Hamilton and Lindsay (2014a) advanced two possible reasons. One is purely geometrical. In their recognition and subsequent investigation of the role of headland-bays in strandings Hamilton and Lindsay (2014a) noted that mature Australian headland-bays shared a set of common properties apart from planform and indentation ratio, conditions occurring in mature headland-bays worldwide. They typically have fine sands of diameter less than 0.25mm, offshore slopes less than 0.5° (a depth change of 1m over 100m), and nearshore slopes of 1 to 2°. It is possible that odontocetes may not comprehend this gradual change in depth and may simply not realise they are heading into shallow water until it is too late, following which confusion and panic can occur. 'The action of the animal was described as frantic', eyewitness accounts for an event at Greens Point beach, Marrawah, Tasmania in Evans *et al.* (2002).

Another possibility is that acoustic propagation into shore over the low seabed slopes seen in headland-bays can be severely attenuated and distorted by multiple seabed and sea surface interactions, so that odontocetes using biosonar to navigate may infer the way ahead is open ocean when they are heading into shore. The attenuation of acoustic signals directed into a wedge is known as the sonar termination effect, and it was proposed by Dudok Van Heel (1962) as a possible cause of strandings. It has been noted that if sonar termination does occur then whales unexpectedly encountering a headland may turn landwards or seawards to avoid it, giving them a 50/50 chance of surviving the effect. Chambers and James (2005) modelled sonar termination as likely to occur at 0.5° but not at 5°, also noting that reduced wave noise in calm conditions may prevent whales from being alerted to the presence of the shore. Hamilton and Lindsay (2014a) noted this as especially likely in headland-bays, as their log-spiral planform acts to reduce wave action at the shore compared to other shapes (Silvester and Ho, 1972), as do their low beach and offshore slopes, which dissipate wave energy. Wave noise increases with beach slope, as breaker type changes from spilling to plunging.

Comparison of spit-bays and headland-bays

Headland-bays and spit-bays have different dynamic processes governing fine sediment deposition, and physically are very different environments. Headland-bays are wave and swell driven, and finer sediment in them is typically winnowed out by wave action and alongshore residual current, leaving fine sands and coarser sediments. In contrast, spit-bays accumulate finer sediments along the sheltered interior of the spit. Seabed slopes in the silt, clay, and sand flats of spit-bays can be much lower than the wave maintained values of 0.5 to 1° observed for fine sands in mature headland-bays, and the resulting bathymetry and topography much more complex. Spit-bays and headland-bays can therefore acquire quite different properties. Both can grow in size over time, but unconstrained headland-bays widen, and move towards a lower limit of 2 for indentation ratio, whereas spit-bays become more indented, and may eventually close. Spit-bays form a more difficult topographic and bathymetric hazard for odontocetes than headland-bays, these difficulties being compounded when occuring in conjunction with the high tidal ranges generated in spit-bays. Only 4 of 402 sites (1%) are spit-bays (Bahia San Sebastian, Cape Cod Bay, Golden Bay, and nominally Perkins Bay), but they own 20% of all 710 larger stranding events.

The passive influences of coastal topography and coastline orientation in spit-bays become especially hazardous to cetaceans through the dynamic assist of tides, storms, and by softer or mobile sediments not being able to support the weight of resting or stranded animals without deformation or scour. Strandings in these circumstances can be viewed as simple misadventure due to unfamiliarity not only with the coastal environment, but with the particularly unusual conditions in spit-bays. This also appears to be the case to some extent for headland-bays, but they do not generally have the muddy soft bathymetrically complex sediment deposits of spit-bays, or the obvious trap configuration of indented bays and estuaries with convoluted or funnel shaped coastlines. It also appears that tides are not necessarily a primary agent of strandings in headland-bays, as many of the Australian headland-bays with larger events are in micro-tidal regimes, not the macro-tidal environments of spit-bays.

Global scale stranding patterns

Ocean temperatures and currents

In the northern hemisphere, concentrations of events on the eastern coasts of North America and Japan (Fig. 2) are spatially correlated with the presence of warm polewards flowing biologically productive western boundary currents (the Gulf Stream and the Kuroshio). Extensions of the Gulf Stream to northwards of the British Isles and beyond lead to warmer seas than similar northern latitudes elsewhere, ameliorating the northern European climate, and hindering ice formation. This extends the northern range of marine mammals (see Christensen *et al.*, 1992, for remarks on Norwegian whale sightings and strandings), and larger stranding events are seen in Norway north of 65°N. In contrast the northern reaches of the eastwards flowing arm of the warm Kuroshio current east of Japan have a quasi-zonal flow restricted to south of 36–38°N (Hamilton, 2013), and winter ice forms around northern Japan. Several killer whale strandings on northern Hokkaido (44°N) are entrapment in ice near shore, rather than actual shore strandings. In the southern hemisphere Antarctic ice does not reach north to major landmasses.

Primary productivity

Widely separated oceanic islands such as Cape Verde (18 events), Chatham (26), Falklands (12+), Galapagos (2), Hawaii (4) have more larger stranding events than their sizes would indicate. Estimates of productivity (the amount of carbon per cubic metre of seawater) from satellite data show enhanced values about these islands, although to a much lesser extent around Hawaii (Fig. 8, from fig. 2 of Gregg *et al*., 2005). The Falklands and Chatham Islands lie in a generally more productive regime between 30 to 50°S associated with the Subtropical Front. Topographic (or island mass effect) upwelling stimulated by the island platforms further enhances local productivity and food supply. Local enhancement is also seen around the Galapagos, which additionally experience upwelling from the divergent equatorial current system flowing westwards along the equator (Fig. 8). It is inferred that locally enhanced food supply about the islands attracts higher numbers of odontocetes, leading to more strandings.

Much of the entire distribution of larger world strandings (Fig. 2) is also strongly correlated with regions of higher ocean productivity shown in Fig. 8, for example for the southern hemisphere south of 30°S. In particular, events in isolated locations such as Al Sawadi (Oman), Manapad (India), and Playa Tambor (Nicaragua) occur in conjunction with locally enhanced areas of productivity. It would perhaps be strange if a relationship of strandings with productivity did not exist, and the islands and isolated regions do point to such a relation. Many regions of higher productivity occur in upwelling areas near land, potentially explaining why odontocetes are in these areas, but not why they strand there. However, higher productivity regions along the western coasts of South America and South Island (New Zealand) have few to no strandings. This apparent anomaly is examined in the next section.

Continental scale coastal geomorphology

Notably few strandings compared to other areas are seen on the western coasts of South America, South Africa, Western Australia, and South Island (New Zealand), although productivity indicated in Figure 8 is high for all but Western Australia. Explanations for lack of strandings in some of these areas are routine. For example, the most westerly portion of Western Australia from 27 to 29°S is comprised of the Zuytdorp cliffs, and the 100m high Baxter and Bunda cliffs run unbroken for hundreds of kilometres in the smooth unindented southern coastline of Western Australia between latitudes 124°E to 132°20’E. These hard rocky cliffed coastlines are not favourable to stranding, and it is unlikely that strandings would be noticed even if they did occur.

The western coasts of South America, South Africa, and South Island have relatively smooth and steep coastlines running parallel to coastline trending rocky mountain chains or highlands (the Andes, the Southern Highlands, the Southern Alps), while the Drakensberg Highlands border the southeast coast of South Africa (Fig. 9). Few potential

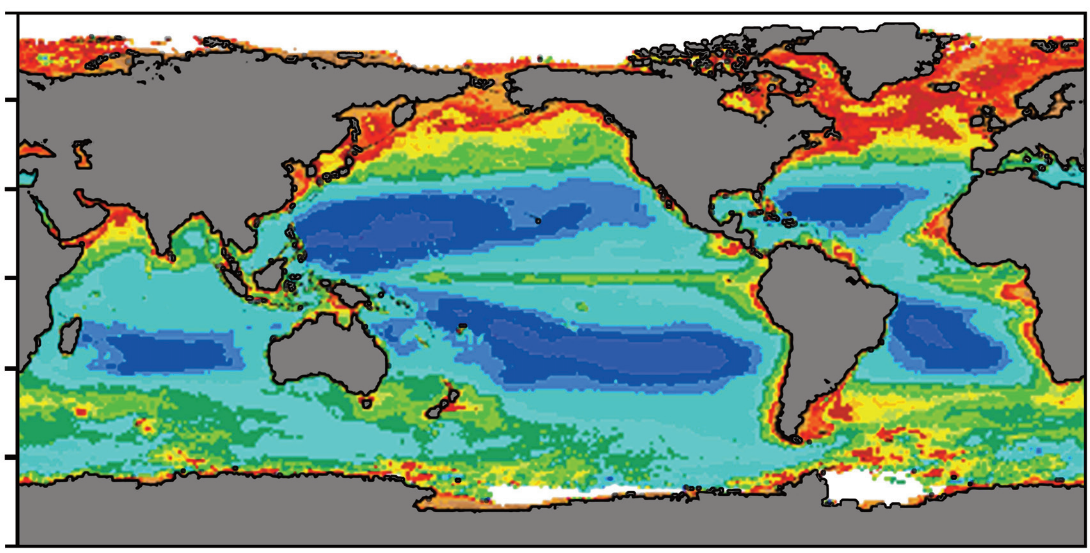

Fig. 8. Ocean primary productivity – SEAWIFS chlorophyll concentrations (mg m^{-3}) for 6-year annual best fit 1998 (this is the middle panel of fig. 2 of Gregg *et al.*, 2005).

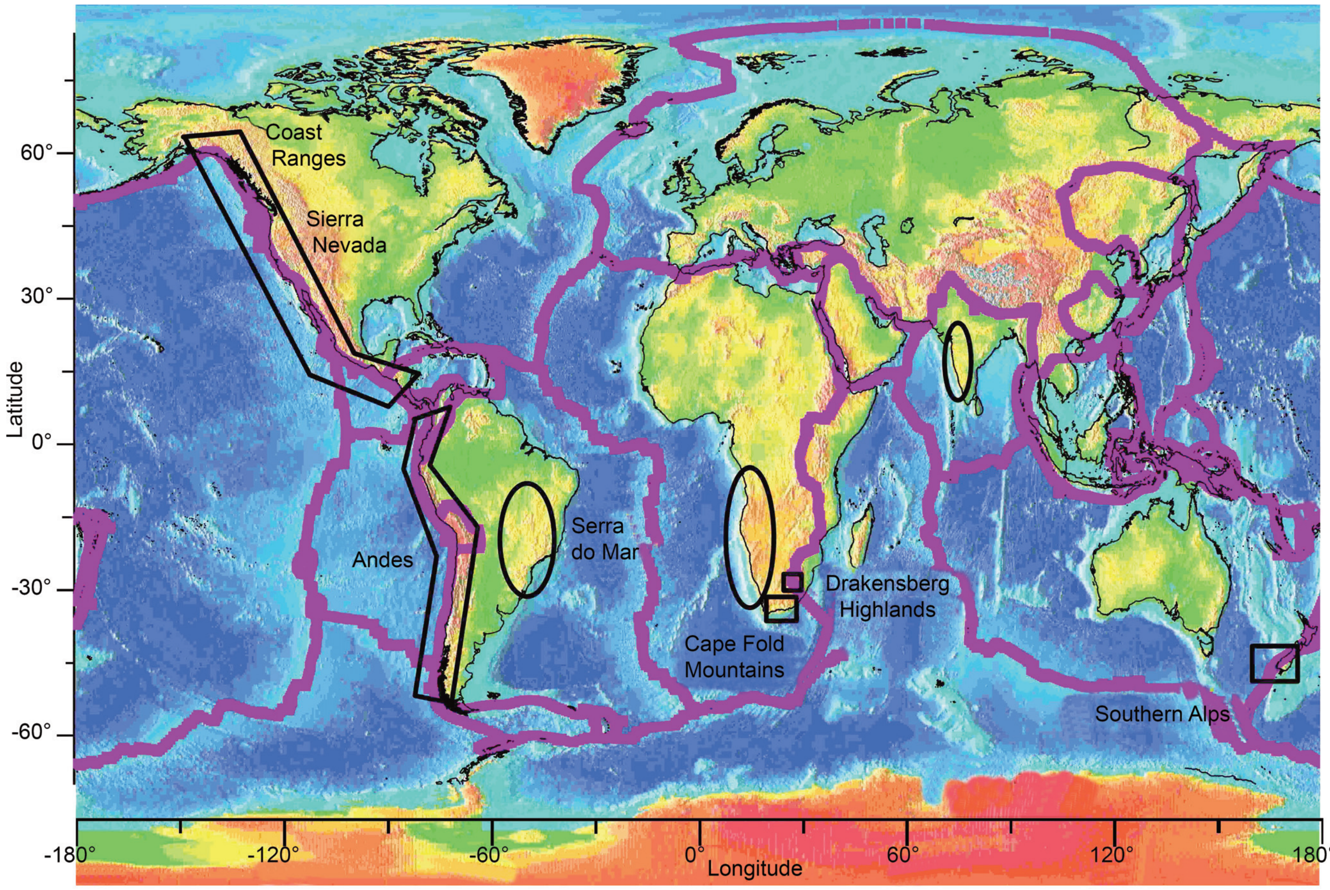

Fig. 9. Tectonic plate boundaries. Subduction of ocean tectonic plates under continental plates constructs mountain ranges such as the Andes of South America, and associated narrow continental shelves and steep shores. Comparison with Figs. 2 and 8 shows a general lack of larger stranding events along these steep shores, even in areas of enhanced primary productivity. Particular subduction zones are shown with polygons and rectangles. Ellipses show high ground near coasts. [Tectonic plate data and background topography from: *http://earthquake.usgs.gov*]

stranding sites such as mature headland-bays are seen in these areas. For example Harris *et al.* (2011) note that less than 2km of the 671km South African east coast is dissipative beach with respect to wave action (the type of low gradient beach found in mature headland-bays), whereas 19% (170km) of the 900km wave dominated southwest coast is dissipative sandy beach. This is apparently reflected in the number of sites in these areas with larger strandings. Morgan Bay hosts the only larger event on the African east coast south of 15°S, whereas there are six locations in the far southwest (False Bay, Long Beach, Melkboss Strand, Nordhoek Beach, St Helena Bay and Walkers Bay).

The spatial relationship of steeper smooth coasts adjacent to mountain chains is the result of plate tectonics. The mountain chains parallel to the western coastlines of South America and New Zealand are thrown up by the actions of tectonic plates subsiding under the continental landmasses, forming relatively new coasts which typically have narrow continental shelves and steep shores, with deep trenches close to shore (Gates and Lynn, 1990). Tectonic plate boundaries lie directly along the steeper western coastlines of South Island (New Zealand) and South America (Fig. 9). This situation would provide more time for wave and swell to sculpt potential stranding sites in the passive margins on these two landmasses than on their geologically newer steeper active western margins. This potentially explains the longstanding observations of McCann (1964) and Brabyn and McLean (1992) that herd strandings of two or more animals were not observed on the steeper west coast of South Island, New Zealand. In this respect it is noted that New Zealand has a longstanding well maintained stranding record so that the lack of recorded events on the west coast of South Island is unlikely explained by low observer effort.

Odontocete and baleen biosonar

Odontocetes regularly mass strand in large numbers, but with a very few exceptions baleens do not, even when forming large aggregates in feeding or in long migrations along world coastlines such as eastern and western Australia (Hamilton and Lindsay, 2014b). It is often said that baleens do not use biosonar, and there is some evidence for this (Beamish, 1978). This would mean they would not strand from susceptibility to the sonar termination effect. However, baleens make low frequency sounds (Stimpert *et al.*, 2007), and at least some baleens may receive sound with the same fatty sound reception mechanism as odontocetes (Yamato *et al.,* 2012). Low frequency sounds propagate further and more efficiently than high frequencies of the same energy, and it is possible that baleen sounds are more efficient at detecting the seabed or coastlines than the specialised high frequency odontocete sounds used to find and then localise small prey such as fish and squid (Dudok Van Heel, 1962). Further insights on odontocete mass strandings may well come from studies of baleen acoustics.

SUMMARY AND CONCLUSIONS

Stranding site properties, primary productivity and tectonic plates

Some investigators considered there were no convincing explanations linking site properties or coastal configuration to strandings. This is certainly not true for spit-bays, which generate both passive and active conditions (fine sediment flats of low slopes and complex bathymetry, high tidal ranges) conducive to stranding. Given that larger live strandings generally occur for nearshore slopes less than 3°, then it is not true for mature headland-bays either, in the sense that their mechanisms of formation and maintenance typically generate fine sands and nearshore slopes less than 1°. To discount the possible effect of coastal configuration and site properties on strandings, Sergeant (1982) regarded animals about to strand as being 'drift bottles' in a passive, moribund state, carried to the shoreline by currents. Eyewitness reports of strong swimming and milling behaviour prior to larger strandings in several countries do not support this view, particularly those described as 'charging the beach' mentioned earlier. Geraci (1978) saw no significance in strandings occurring on gently sloping beaches, arguing that no other physical configurations would be suitable for strandings, certainly not fjords, or sheer rock faces, or any other barrier, however small, 'In other words, whales do not strand where they cannot strand.' This statement makes a fair point, but provides no actual information. Where is it that they cannot strand? Odontocete strandings are of a random nature, and can be initiated by many factors, including simple misadventure, large tidal ranges, disorientation caused by storms, ingestion of poisonous algae, chasing prey, and attempt to escape from predators. This should arguably lead to strandings occurring on coastlines with a wide range of properties. However, the work of Dudok Van Heel (1962), Brabyn and McLean (1992), Hamilton and Lindsay (2014a) and the present paper shows that despite all other possible complicating agents, particular types of coastal locations with sets of properties (planform, sediments, seabed slopes) able to be specified quantitatively dominate larger live mass strandings worldwide. This allows some types of potential stranding sites to be identified by quantitative indicators.

The world geographical distribution of larger strandings is noticeably correlated with areas of locally higher primary productivity, potentially indicating why the odontocetes are near land. Pursuit of prey or search for calm conditions can then bring them to coastal areas, or they may simply approach coasts by chance. Once there for whatever reason, unfamiliarity with the inshore environment, particularly with shallows and low slopes, and dynamic factors such as tides and currents may confuse and confound them. Even the simple act of following the coast can bring disaster in spit-bays and features with trap or maze-like orientations. Sonar termination does not have to be invoked in these explanations, but forms a further possible cause, particularly for the relatively benign environments of many headland-bays. It is also possible that the effect of headland-bay configuration and properties in lowering surf zone noise in times of calms may prevent odontocetes from being alerted to the presence of land. Once in a panicked situation nearshore however, any wave noise might be taken as indicating open ocean, leading to strandings. In a similar mechanism, strandings might also occur as a result of surf zone noise during violent storms being taken as a continuation of open ocean.

There is a notable scarcity of strandings on some active continental margins, even in the presence of higher productivity, the western coastlines of South America and South Island, New Zealand being prime examples. Active margins have narrow continental shelves and relatively smooth and steeper swell resistant shores, caused by more geologically recent tectonic plate action. It is likely that swell action has not had time to construct as many coastal configurations and conditions associated with strandings on the active margins as on the older passive margins. This potential relation of strandings to large scale and long term earth and ocean processes is remarkable in its scale, and seemingly underscores the role that geomorphological mechanisms ultimately play in strandings.

Conclusions

It can be said that the 'where' of larger mass strandings of odontocetes is generally well known, and is even largely understood in a mechanical sense, even if the biological factors remain elusive. Odontocetes tend to strand on particular coastlines and in particular types of locations at global to local spatial scales. The beginnings of this view date back 55 years to the qualitative descriptions and insightful observations of Dudok van Heel (1962), and 25 years to the quantitative descriptions of New Zealand beach slopes and sediments of Brabyn and McLean (1992). These works were extended by recognition and explanation of the role of headland-bays in constructing stranding sites (Hamilton and Lindsay, 2014a). The present paper further defines the values of seabed slopes and sediment sizes associated with larger strandings, and explains the magnified role of spit-bays. It then proceeds to note presence and absence of larger mass strandings on some continental coastlines as the possible outcome of a chain of physical causes (plate tectonics, wave and swell action, locally enhanced regions of primary productivity near coasts with particular geomorphologies). However, while these largescale relations seem entirely plausible they are subject to the vagaries of very different rates of observer effort throughout the world and a range of other factors and must be regarded as working hypotheses.

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REFERENCES

Abend, A.G., Smith, T.D. 1999. Review of distribution of the long-finned pilot whale (*Globicephala melas*) in the North Atlantic and Mediterranean. US Department of Commerce, NOAA Technical Memorandum NMFS NE 117. 22pp.

Beamish, P. 1978. Evidence that a captive humpback whale (*Megaptera novaeangliae*) does not use sonar. *Deep-Sea Res.*: 25, 469–72.

Birkby, C. 1935. Two hundred killer whales hurl themselves ashore. *The Illustrated London News* 187 (5044), 1124–25. 21 December 1935. [Noted in Leatherwood *et al.,* 1989]

Brabyn, M.W. 1990. An analysis of New Zealand whale strandings. MSc Thesis in Zoology, University of Canterbury, New Zealand.

Brabyn, M.W. and McLean, I.G. 1992. Oceanography and coastal topography of herd-stranding sites for whales in New Zealand. *J. Mammal.* 73(3): 469–76.

Brownell, R.L., Yamada, T.K., Mead, J.G. and Allen, B.M. 2006. Mass strandings of melon-headed whales, *Peponocephala electra*: a worldwide review. Paper SC/58/SM8 presented to the IWC Scientific Committee, May 2006, St. Kitts and Nevis, West Indies (unpublished). 12pp. [Paper available from the Office of this Journal]

Brownell, R.L., Yao, C.J., Lee, C.S. and Wang, M.C. 2009. Worldwide review of pygmy killer whales, *Feresa attenuata*, mass strandings reveals Taiwan hot spot. Paper SC/61/SM1 presented to the IWC Scientific Committee, June 2009, Madeira, Portugal (unpublished). 20pp. [Paper available from the Office of this Journal]

Brownlow, A., Baily, J., Dagleish, M., Deaville, R., Foster, G., Jensen, S-K., Krupp, E., Law, R., Penrose, R., Perkins, M., Read, F. and Jepson, P.D. 2015. Investigation into the long-finned pilot whale mass stranding event, Kyle of Durness, 22nd July 2011. Report to Defra and Marine Scotland. 60pp.

Bujalesky, G.G. 2007. Coastal geomorphology and evolution of Tierra del Fuego (Southern Argentina). *Geologica Acta* 5(4): 337–362. [Available at: *http://www.geologica-acta.com*].

Chambers, S. and James, R. 2005. Sonar termination as a cause of mass cetacean stranding in Geographe Bay, south-western Australia. pp. 391–398. *In* T. McMinn (Ed.) *Proceedings, Australian Acoustical Society, Annual Conference 2005. Acoustics 2005: Acoustics in a Changing Environment, Busselton, Western Australia.* [Available at: *http://www.acoustics.asn.au/divisions/WA/2005-proceedings.php*: Australian Acoustical Society].

Christensen, I., Haug, T. and Øien, N. 1992. Seasonal distribution, exploitation and present abundance of stocks of large baleen whales (*Mysticeti*) and sperm whales (*Physeter macrocephalus*) in Norwegian and adjacent waters. *ICES J. Mar. Sci.* 49:341–55.

Commonwealth of Australia. 2010. Department of Environment, Water, Heritage and the Arts. National Whale and Dolphin Sightings and Strandings Database. Retrieved February 11, 2010 [Available at: *http://data.aad.gov.au/aadc/whales/*].

Daily Mail. 2016. Whale nicknamed ‘Dopey Dick’ after swimming up a river in Northern Ireland to find salmon 39 years ago is spotted off coast of Scotland. *Daily Mail* Newspaper article, 2 April 2016, Melbourne, Australia.

D’Amico, A., Gisiner, R., Ketten, D.R., Hammock, J.A., Johnson, C., Tyack, P.L. and Mead, J.G. 2009. Beaked whale strandings and naval exercises. *Aquat. Mamm. Sci.* 35(4), 452–72.

Delsman, H.C. 1923. Een stranding in straat Maduren. *De Tropische Natuur*. 12(3):33–9.

Dudok Van Heel, W.H. 1962. Sound and cetacea. *Neth. J. Sea. Res.* 1: 407–507.

Dudok Van Heel, W.H. 1966. Navigation in Cetacea. pp.597–606. In: Norris K.S. (Ed.), *Whales Dolphins and Porpoises*. University of California Press, Berkeley.

Evans, K., Morrice, M., Hindell, M. and Thiele, D. 2002. Three mass strandings of sperm whales (*Physeter macrocephalus*) in southern Australian waters. *Mar. Mammal Sci.* 18(3):622–43.

Ferreira, I.M. 2008. Growth and reproduction in false killer whales (*Pseudorca crassidens* Owens, 1846). MSc Thesis, University of Pretoria, USA.

Findlay, K.P., Best, P.B., Ross, G.J.B.and Cockcroft, V.G. 1992. The distribution of small odontocete cetaceans off the coasts of South Africa and Namibia. *Afr. J. Mar. Sci.* 12:237–70.

Frantzis, A. 2004. The first mass stranding that was associated with the use of active sonar (Kyparissiakos Gulf, Greece, 1996). pp.14–20. *In*: Proceedings of the workshop: ‘Active Sonar and Cetaceans’, 8 March 2003, Las Palmas, Gran Canaria. ECS newsletter 42 (special issue):

Fraser, F.C. 1936. Recent stranding of the false killer whale, *Pseudorca Crassidens*, with special reference to those found at Donna Nook, Lincolnshire. *Scott. Nat*. 220: 105–14.

Friedman, G.M., Sanders, J.E. and Kopaspa-Merkel, D.C. 1992. *Principles of Sedimentary Deposits*. McMillan, New York. 717pp.

Gaskin, D.E. 1968. The New Zealand Cetacea. Fisheries Research Bulletin No. 1. Fisheries Research Division, New Zealand Marine Department.

Gates, P.J. and Lynn, N.M. 1990. *Ships, Submarines and the Sea*. Brassey’s Sea Power: Naval Vessels, Weapons Systems and Technology, Series. 2. Brassey’s (UK) Ltd., London. 178pp.

Geraci, J.R. 1978. The enigma of marine mammal strandings. *Oceanus* 21(2): 38–47.

Gilluly, J., Waters, A.C. and Woodford, A.O. 1975. *Principles of Geology*. Fourth edition. W.H. Freeman and Company, San Francisco, USA. 527pp.

Goodall, R.N.P. 1989. The lost whales of Terra del Fuego. *Oceanus* 32(1): 89–95.

Gregg, W.W., Casey, N.W. and McClain, C.R. 2005. Recent trends in global ocean chlorophyll. Geophys. *Res. Lett.* 32(3): L03606.

Hamilton, L.J. 1999. Classification, grainsize relations, and sediment distributions inferred from visual sediment descriptions on RAN Hydrographic Office bathymetry charts of the northern Great Barrier Reef lagoon. *Aust. J. Earth Sci.* 46(4): 501–14.

Hamilton, L.J. 2013. Statistical clustering of drifting buoy trajectories around Japan and off Fukushima to identify Lagrangian circulation features. *Methods in Oceanography* 6: 16–32.

Hamilton, L.J. and Lindsay, K. 2014a. The relation of coastal geomorphology to larger mass strandings of odontocetes about Australia. *J. Cetacean Res. Manage.* 14(1): 176–84.

Hamilton, L.J. and Lindsay, K. 2014b. Beaked whale strandings on the coast of Australia in comparison to those of other cetaceans. *J. Cetacean Res. Manage.* 14(1): 1–14.

Harris, L., Nel, R. and Schoeman, D. 2011. Mapping beach morphodynamics remotely: A novel application tested on South African sandy shores. *Estuar. Coast. Shelf Sci.* 92: 78–89.

Hewlett, G. 1897. Stranding of whales at the Falkland Islands. *Launceston Examiner* 20 March 1897, p.11.

Jefferson, T.A. and Barros, N.B. 1997. *Peponocephala electra*. *Mamm. Species* 553: 1–6.

Leatherwood, S., McDonald, D., Baird, R.W. and Scott, M.D. 1989. The false killer whale, *Pseudorca crassidens* (Owen, 1846): a summary of information available through 1988. Oceans Unlimited Technical Report 89-001. 114pp.

Liu, J.T., Huang, J-S., Hsu, R.T. and Chyan, J-M. 2000. The coastal depositional system of a small mountainous river: a perspective from grainsize distributions. *Mar. Geol.* 165: 63–86.

Marelli, C.A. 1953. Documentos iconograficos sobre cetaceos de las costa Argentina. *Anales del Museo de Nahuel Huapi* 3:133–43.

Mazzuca, L., Atkinson, S., Keating, B. and Nitta, E. 1999. Cetacean mass strandings in the Hawaiian Archipelago, 1957–1998. *Aquat. Mamm.* 25(2): 105–14.

McCann, C. 1964. A coincidental distributional pattern of some of the larger marine animals. *Tuatara* 12(2) 119–24.

McFee, W.E. 1990. An analysis of mass strandings of the long-finned pilot whale, *Globicephala melas* on Cape Cod. MSc Thesis, Center for Vertebrate Studies, Northeastern University, Boston, Massachusetts. 96pp.

McFee, W.E. 1991. Common names applied to the long-finned pilot whale, *Globicephala melas*. *Can. Field Nat.* 105(4):564–66.

Murata, T. 2004. Detailed report on the mass stranding of sperm whales. Ship and Ocean Newsletter, Institute for Ocean Policy, Ship and Foundation. Selected Papers 4:12–13.

Mustika, P.L.K., Hutasoit, P., Madusari, C.C., Purnomo, F.S., Setiawan, A., Tjandra, K. and Prabowo, W.E. 2009. Whale strandings in Indonesia, including the first record of a humpback whale (*Megaptera novaeangliae*) in the Archipelago. *Raffles B. Zool.* 57(1):199–206.

Nishimura, S. 1965. The zoogeographical aspects of the Japan Sea. Part 1. Publications of the Seto Marine Biological Laboratory, Sirahama, *Departmental Bulletin* 13(1): 35–79.

Otley, H. 2012. The composition of the cetacean community in the Falkland (Malvinas) Islands, southwest South Atlantic Ocean. *Revista de Biología Marina y Oceanografía* 47(3)3: 537–51.

Peacock, A.D., Comrie, L. and Greenshields, F. 1936. The false killer whales stranded in the Tay estuary. *The Scottish Naturalist* 220: 93–104.

Porsild, M.P. 1918. On ‘Savssats’: A crowding of Arctic animals at holes in the sea ice. *Geogr. Rev.* 6(3):215–28.

Robson, F.D. and Van Bree, P.J.H. 1971. Some remarks on a mass stranding of sperm whales, *Physeter macrocephalus* Linnaeus, 1758, near Gisborne, New Zealand, on March 18, 1970. *Sonderdruck aus zeitschrift fur Sangetierkunde* 36(1): 55–60.

Sergeant, D.E. 1982. Mass strandings of toothed whales (odontoceti) as a population phenomenon. *Sci. Rep. Whales Res. Inst.* 34: 1–47.

Silas, E.G. 2010. Inaugural address. Workshop on Marine Mammal Stranding. held at CMFRI from 21–23 January 2010 under the auspices of CMFRI, NOAA, USA and Indo-US Science Forum, New Delhi Inaugural Function in Cochin, India.

Silvester, R. and Ho, S.-K. 1972. Use of crenulate shaped bays to stabilise coasts. *Coast. Eng.* 13: 1,347–65. [Available at: *http://journals.tdl.org/ICCE/article/viewFile/*, accessed 22 September 2012].

Southall, B.L., Braun, R., Gulland, F.M.D., Heard, A.D., Baird, R.W., Wilkin, S.M. and Rowles, T.K. 2006. Hawaiian melon-headed whale (*Peponocephala electra*) mass stranding event of 3–4 July 2004. NOAA Technical Memorandum NMFS-OPR-31. 73pp.

Southall, B.L., Rowles, T., Gulland, F., Baird, R.W. and Jepson, P.D. 2013. Final report of the Independent Scientific Review Panel investigating potential contributing factors to a 2008 mass stranding of melon-headed whales (*Peponocephala electra*) in Antsohihy, Madagascar. 75pp. [Available at: *https://iwc.int/2008-mass-stranding-in-madagascar*]

Stimpert, A.K., Wiley, D.N., Au, W.W.L., Johnson, M.P., and Arsenault, R. 2007. 'Megapclicks': acoustic click trains and buzzes used during nighttime foraging of humpback whales (*Megaptera novaeangliae*). *Biology Letters* 3(5): 467–4

Sylvester, N.B. 1878. *History of Saratoga County, New York.* Everts and Ensign, Philadelphia, Press of J.B. Lippincott and Company Philadelphia. 514pp.

The Age. 1946. Stranded on island. 140 whales off Port Albert. *The Age* newspaper 1 April 1946, Melbourne, Victoria.

Urban-Ramirez., J., Cardenas-Hinojosa, G., Gomez-Gallardo, A., Gonzalez-Peral, U., del Toro-Orozco, W. and Brownell, R.L. 2007. Mass stranding of Baird's beaked whales at San Jose Island, Gulf of California, Mexico. *Lat. Am. J. Aquat. Mamm.* 6(1):83–8.

Van Beneden, P.-J. 1888. Le Cachalot (*Physeter macrocephalus*). Mémoires couronnés et autres Mémoires publiés par l'Académie Royale de Belgique.

Vos, D.J. and Shelden, K.E.W. 2005. Unusual mortality in the depleted Cook Inlet beluga (*Delphinapterus Leucas*) population. *Northwest Nat.* 86:59–65.

Wang, J.Y., Yang, S-C. and Liao, H-C. 2001. Records of melon-headed whales, *Peponocephala electra* (Gray, 1846), from the waters of Taiwan. *Bull. Natl. Mus. Nat. Sci. Ser. A Zool.* 14:85–92.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *J. Geol*. 30: 377–92.

Wiegel, R.L. 1965. *Oceanographical Engineering*. Prentice-Hall. 531pp.

Yamato, M., Ketten, D., Arruda, J., Cramer, S. and Moore, K. 2012. The auditory anatomy of the minke whale (*Balaenoptera acutorostrata*): A potential fatty sound reception pathway in a baleen whale. *Anat. Rec.* 295: 991–8.