Linked Influences Of Environmental Underwater Noise And Geomorphology On Larger Mass Strandings Of Odontocetes (Toothed Whales)

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ABSTRACT
The trigger for a few instances of larger mass strandings of odontocetes (toothed whales) involving 10+ animals have been attributed to underwater noise generated by manmade causes. It is believed that a flight response from sounds made by particular sonar devices or underwater explosions caused odontocetes to approach unfamiliar coastal environments, after which a stranding ensued, possibly because the animals were in a panicked state. In comparison to these events the role of natural ambient underwater noise in strandings has received little attention, but it may be a contributing factor in some cases. Perhaps the most obvious is that storm generated noise may mask the presence of coastline wave noise, causing odontocetes to inadvertently approach coasts in difficult conditions. Paradoxically however, the ultimate reason for some mass strandings may be lack of underwater noise generated at shores in times of calms, rather than enhancements. This condition can occur in conjunction with a particular coastal geomorphology which may also act to defeat or impair cetacean biosonar, increasing the risks of stranding. In this case the coastal geomorphology and acoustics are linked. Strandings at other types of sites are related to physical factors such as high tidal range and bathymetric configuration, and acoustics need not be invoked to explain them, although it may also be a contributing factor.

1 INTRODUCTION
Larger mass strandings of odontocetes (toothed whales) of 10+ animals receive much press and the causes are generally regarded as a mystery. Why should living creatures do this? Attention has been heavily focused on a few instances of mass strandings which appear to have been precipitated by manmade sound generated by underwater explosions or military sonar. These events are attributed to a flight response which inadvertently causes odontocetes to approach unfamiliar coastal environments. An example is the mass stranding of 35 pilot whales in the Kyle Of Durness, Scotland after underwater detonations to dispose of explosives (Brownlow *et al.* 2015). An event deep into an estuary at Antosohihy, Madasgascar is attributed to the melonhead whales running from a multibeam sonar survey (Southall *et al.* 2013). Acoustical factors initiated the strandings, but their actual cause was the fall of the tide. A stranding of 10 Cuvier's beaked whales in Kyparissiakos Gulf, Greece was attributed to military sonar (Frantzis, 1996), but this event occurred on open coastline, rather than an estuarine environment, something rather difficult to explain. However, Hamilton and Lindsay (2014) noted that this location had the form of a headland-bay, a type of coastal configuration which hosts over 90% of larger mass strandings around Australia. The similarity of site properties between Australia and Greece implies this stranding is ultimately related to coastal configuration, rather than any direct effect of acoustics on the animals.

Better knowledge of stranding locations and their properties could enable more informed comments on strandings and their causes, not a search for non-existent factors, or continued treatment of them as a mystery. This paper will first briefly outline work showing that many larger world mass strandings occur in association with particular coastal geomorphologies from continental to bay scales, to the point where it appears possible to routinely identify some types of potential stranding sites. This has obvious implications for offshore engineering or other activities near such sites. Relations of these geomorphologies to sonar propagation and ambient environmental noise conditions is then explored with respect to possible influence on strandings.

There are two suborders of cetaceans, the odontocetes or toothed whales (false killer, pilot, sperm whales for example), and the mysticeti or baleen whales (humpback, minke, blue whales). Odontocetes routinely strand in larger numbers, with about one world event of 10+ animals every 6 to 8 weeks. The baleens rarely do so, and when they do it is invariably attributed to the ingestion of poisonous algae. Consequently only odontocete strandings will be examined in this paper.

2 SPECIES IN LARGER STRANDINGS AND TYPES OF MASS STRANDING SITES

Worldwide mass strandings of open ocean odontocetes of 10+ animals were investigated with a compilation of 680 events occurring at over 400 sites. Near mass strandings (where whales enter shallow waters but do not actually strand) and whale drives (captures) were excluded. Beluga, false killer, long-finned pilot, melonhead, short-finned pilot, and sperm whales formed 95.5% of events, with beaked, killer, and pygmy killer whales forming the remainder (Hamilton 2017). Three-quarters (76%) of reasonably well located events were in bays, 16% in shallow topographically complex areas (estuarine environments, straits, keys, reef and coastal lagoons), 6% 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 made up 40%, spit-bays 20% (even though there are only four of them), indented bays 11% and unspecified bay types 5%. Nearshore slopes were less than 1^{o} for 94 of 105 sites having bathymetry information, with only two reaching or exceeding 3^{o}.

The strandings (Figure 1) were spatially correlated with areas of higher oceanic primary productivity near landmasses and oceanic islands, including biologically productive western boundary currents (Figure 2), but generally only for coastlines having particular geomorphologies. Plate tectonics (Figure 3) on the active western margins of South America and South Island (New Zealand) has produced steeper swell resistant coastlines not associated with strandings, whereas the south-eastern sides of these landmasses are relatively older passive margins, on which waves and swell have had time to construct stranding sites (usually bays). These observations provide a new perspective to the phenomenon of odontocete mass strandings and their relations to global scale earth and ocean processes.

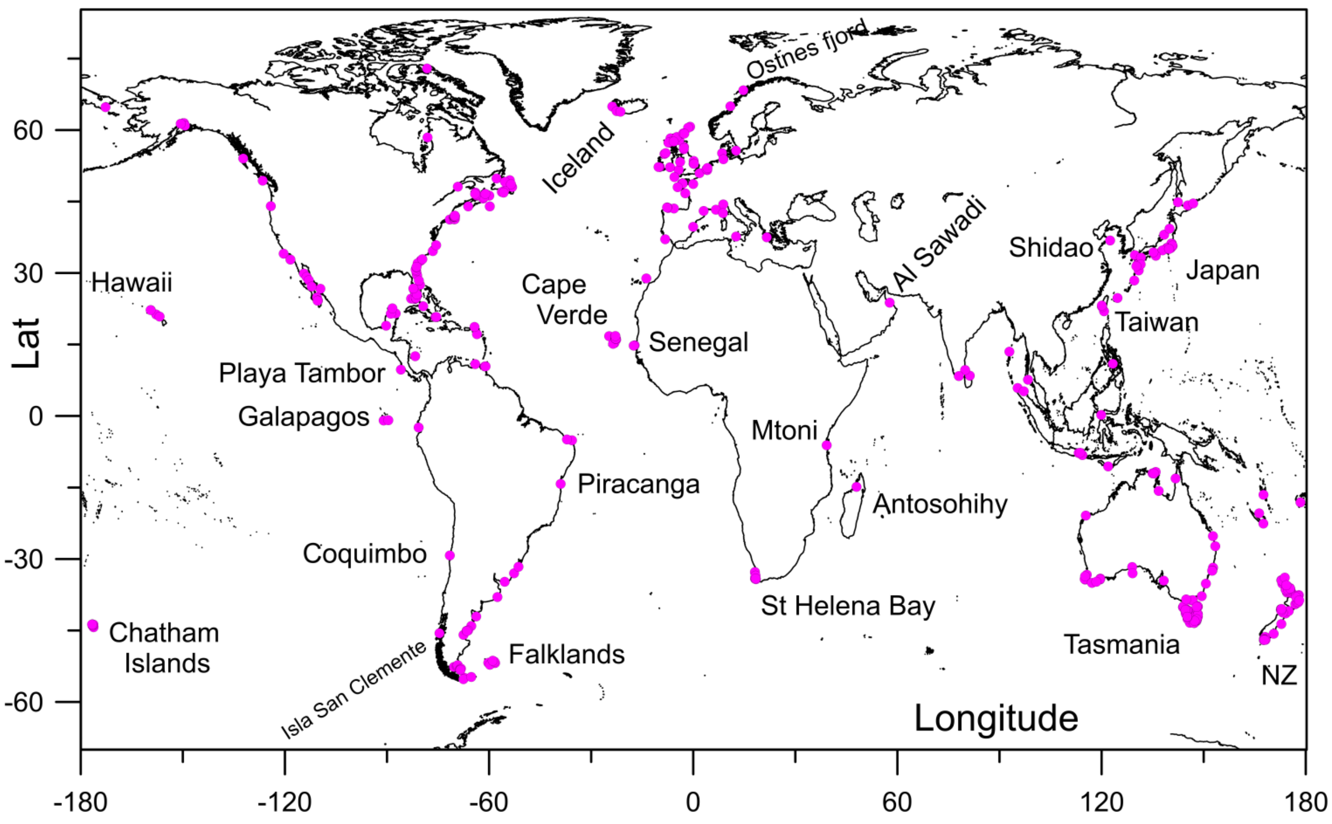

Figure 1. Worldwide distribution of larger mass strandings of odontocetes involving 10+ animals.

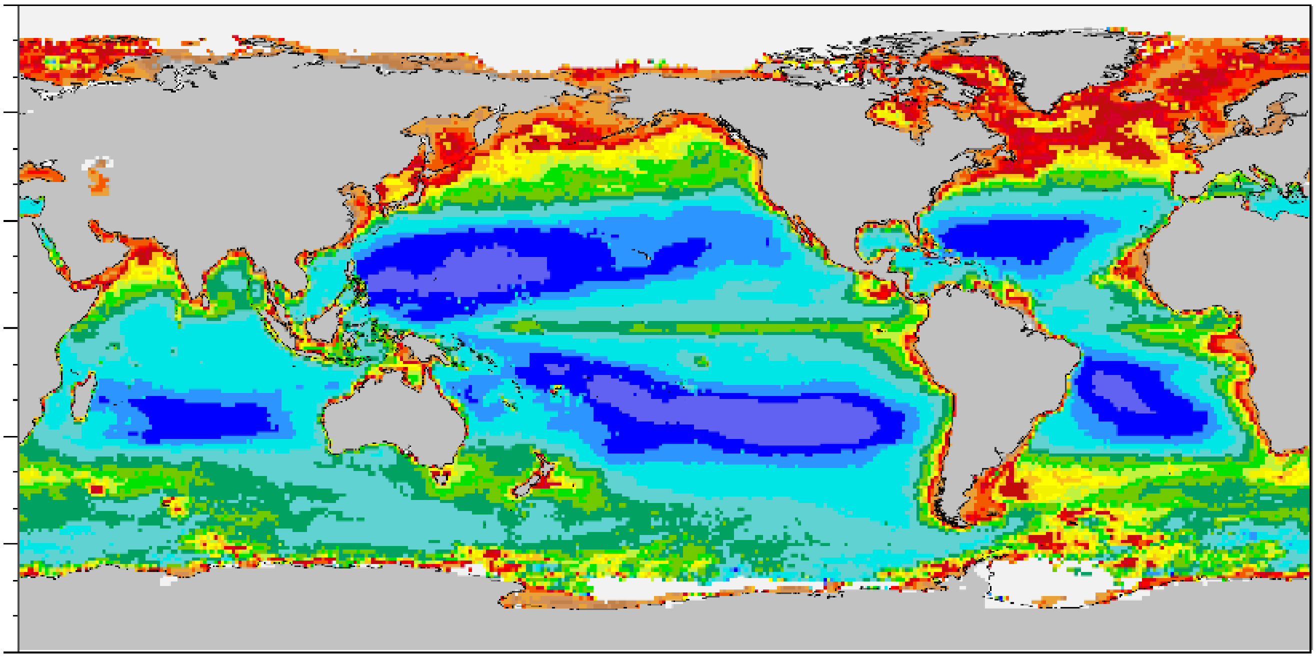

Figure 2. Worldwide primary productivity 1998 (from Figure 2 of Gregg *et al.* (2005)). Red is high productivity, blue is low.

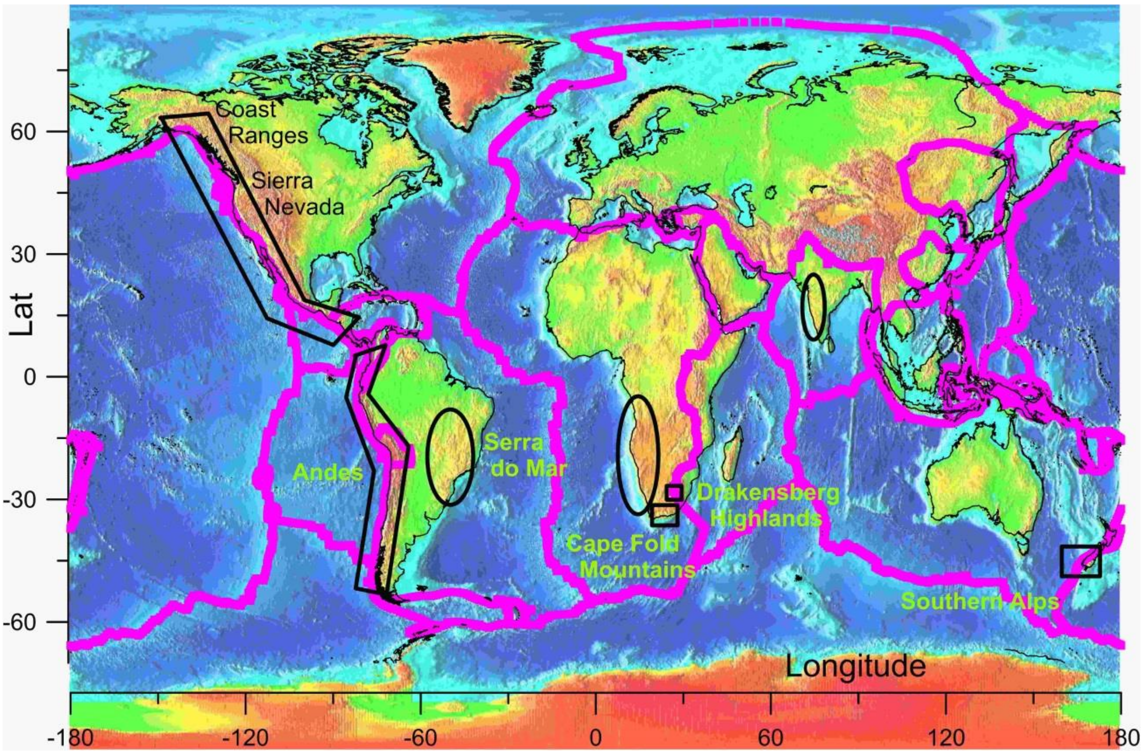

Figure 3. Tectonic plate boundaries and selected high ground in coastal regions. Note the plate boundaries parallel to the western coasts of South America and South Island, New Zealand. Compare these and high ground adjacent to coasts with the distribution of strandings in Figure 1. Digital tectonic plate boundary data and the background topography map are from http://earthquake.usgs.gov.

3 THE POSSIBLE ROLE OF ACOUSTICS IN MASS STRANDINGS

Both active and passive acoustics may play roles in mass strandings. Noise in the littoral zone from breaking waves or living creatures (fish, snapping shrimp, sea urchins) may indicate the presence of land to offshore cetaceans. The use of active and sophisticated biosonar for navigation or avoidance of obstacles by odontocetes has long been accepted. Some odontocetes (beaked whales and sperm whales) use a lower frequency to hunt prey and a higher frequency to localise the final approach and take of fish and squid. It has been proposed that biosonar may be rendered ineffective by various environmental factors.

3.1 Sonar termination

Acoustic propagation into shore over low slopes can be severely attenuated by multiple seabed and sea surface interactions (Figure 4), leading to reberberation and a weak distorted return, or no return at all. This could cause odontocetes using biosonar to navigate may infer the way ahead is open ocean when they are heading into shore (Dudok Van Heel, 1962). This attenuation is known as the sonar termination effect. Chambers and James (2005) modelled it as likely to occur at 0.5^0 but not at 5^0. If sonar termination does act then whales unexpectedly encountering a headland may turn landwards or seawards to avoid it, giving them a 50/50 chance of surviving the effect.

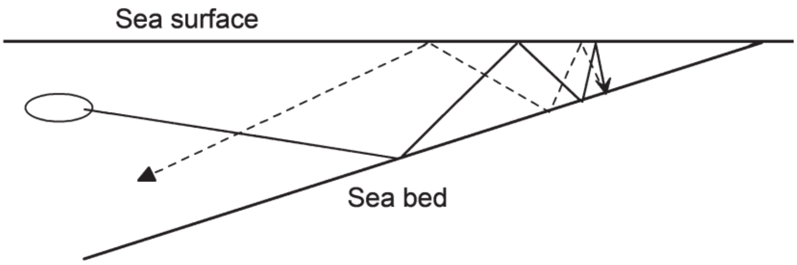

Figure 4. Schematic of sonar termination. An acoustic signal directed into a wedge may experience many seabed and sea surface reflections, becoming greatly attenuated and distorted before, and if, it returns to the transmitter.

3.2 Surf Noise

Beach slope and sediment size increase together (Wiegel 1965), and are a function of wave energy (wave height), particle shape, and porosity. Fine sands can have beach slopes less than 1^0, and shingle beaches can reach slopes over 30^0 (Gilluly *et al.* 1975). Seabed slope determines the breaker type. Finer sediments (with lower slopes) are generally dissipative of incoming wave energy and produce low noise spilling breakers. Coarser beach sediments with higher slopes produce plunging breakers with more noise than spilling breakers for the same incoming wave conditions. Surf noise from wave heights of 0.5-0.8m from pebble coasts has been observed at underwater distances well over 10km seaward of the surf zone (Bardyshev, 2008). Rock cliffs also produce plunging breakers, and a few measurements indicate source levels are 5 to 15 dB higher for the same incoming wave heights than plunging breakers over coarse sediments (Cho and Choi 2010). There is a link between beach sediment, beach slope and surf zone noise, which in principle could influence strandings by alerting cetaceans to the presence of the shore at some times and not at others. This assumes that odontocetes are sensitive to surf noise acoustic frequencies, which are typically less than 4kHz in the far field of the surf zone, and broad-band in the surf zone.

3.3 Violent Storms

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”. 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. Storm conditions may generate high levels of waves, air and water borne sound, including wave and rain noise, suspended sediment, and bubbles, causing poor sonar transmission conditions, and confusing the odontocetes. In this situation surf zone noise may be masked by storm noise, or mistaken as a continuation of open ocean, leading to strandings.

4 THE ROLE OF BAYS IN LARGER STRANDINGS

Three-quarters of all larger strandings in reasonably known locations were in bays. Headland-bays and spit-bays accounted for 60%. A particular question here is whether or not sonar transmission or ambient noise conditions are involved in the mass strandings in these two types of locations.

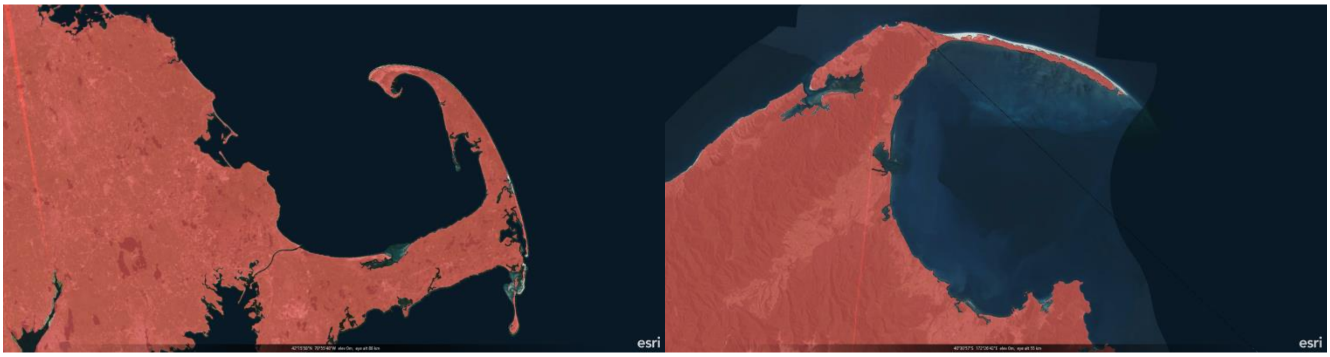

Figure 5. Spit-bay examples. Cape Cod Bay (USA), Golden Bay (New Zealand). Coastal outlines from http://gadm.org/country. Displayed with ESRI ArcGIS Earth.

4.1 Spit-bays

Only four of the 400 different sites are spit-bays (Figure 5), but they own 20% of all 680 larger events, 15 times more than expected if strandings occured equally often at all sites. Cape Cod Bay (USA) has over 70 recorded events, Golden Bay (New Zealand) has over 20, Perkins Bay (Australia) has 9, Bahia San Sebastian (Argentina) has 5 known events.

No explanation for the disproportionately high numbers of mass strandings in spit-bays has ever been given. However, the explanation is rather straightforward. The seawards sides of Cape Cod Bay, Golden Bay, and Bahia San Sebastian are extended curving sand and gravel spits built up by waves and currents. 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).

Whales in the bay seeking to move back to open water by tracking north along the east coast of Cape Cod Bay 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, which is where the strandings occur (McFee 1990, 1991). The actual stranding mechanism is likely large tidal range caused by the constricting action of the spit on water flow (4.7 m spring tide at Wellfleet, 4.5 m in Golden Bay, 10 m in Bahia San Sebastian, 3 m in Perkins Bay). Partial burial in the soft sediments may also be a factor. Planform, tides, complex shallows, and fine sediments make spit-bays highly effective natural traps, with their properties arising from the bay configuration and method of formation. There is no need to invoke sonar or noise conditions to explain mass strandings in spit-bays, but these may also contribute.

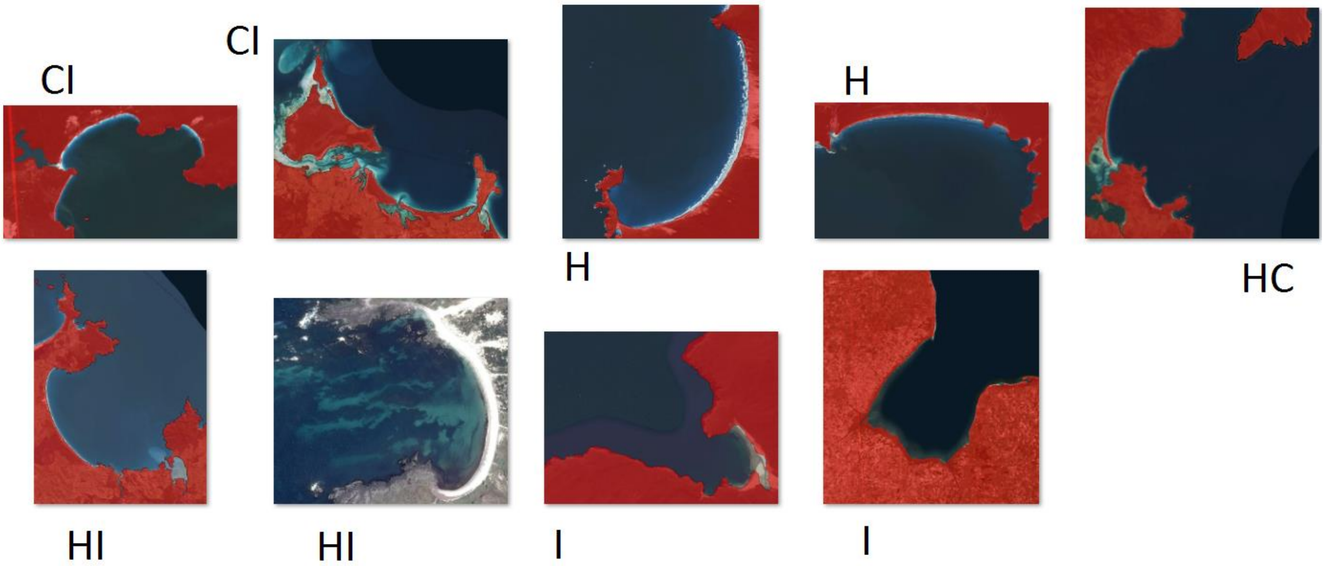

Figure 6. Examples of headland-bays and indented bays. Coastal outlines from http://gadm.org/country. Displayed with ESRI ArcGIS Earth. CI - indented bay with complex character, H - headland-bay, HC - headland-bay with complex character, HI - headland-bay with indented character, I - indented bay. See Hamilton and Lindsay (2014) for other examples.

4.2 Headland-bays

Headland-bays have a distinctive half-heart or log-spiral shape (Figure 6) sculpted in softer material behind headlands by waves and swell, and are easily recognised in coastal charts. Developmental headland-bays can have sediments up to block and boulder size, but their swell driven dynamics eventually produce (fine) sandy sediments from the continued attrition and breakdown of larger material, with finer sediments (silts and clays, or muds) winnowed out by wave and current action. This mechanism of formation and maintenance is opposite to the accretionary environment of spit-bays. During initial formation the ratio of bay width to indentation distance is high. As the bay matures this ratio approaches a lower limit of 2 (Silvester and Ho, 1972).

The high number of stranding events in headland-bays is somewhat puzzling, because many have relatively simple planform and bathymetry. The presence of a headland does not change this, especially as strandings generally occur towards the bay centre, not at the headland. Hamilton and Lindsay (2014) advanced three possible reasons for the role of headland-bays in strandings. One is purely geometrical. They found that mature headland-bays typically have nearshore seabed slopes of 1 to 2^0, and offshore slopes less than 0.5^0 (a depth change of 1 m over 100 m). 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 for recovery. A second possible reason is sonar termination in low slopes and fine sands. In conjunction with this it has been conjectured that the specialized high frequency sounds used by some odontocetes to hunt small prey may not be effective for navigation by biosonar (Dudok van Heel 1962). A third reason is that the log-spiral planform and low slopes of headland-bays act to reduce wave action at the shore compared to other shapes (Silvester and Ho, 1972), which may prevent whales from being alerted to the presence of the shore in times of calms.

When odontocetes find themselves in shallow water, they may become disorientated and not know the direction of deeper water. Milling behaviour, indicating confusion, is often observed with individuals occasionally darting off and returning in apparent exploratory behaviour, then a mass stranding sometimes caused by ‘follow the leader’ behaviour. This leads to another possibility. Confused whales in shallow water may interpret any wave noise at the beach as coming from the familiar sea, rather than from a shore, and may head shorewards. It appears quite likely that headland-bays provide platforms for mass strandings because of sonar transmission conditions and their lower surf noise.

5 Sediments and Slopes

Herd strandings (2+ animals) and larger mass strandings are seldom observed on beaches coarser than sand (Dudok van Heel (1962), Brabyn and McLean (1990), Hamilton and Lindsay (2014), Hamilton (2017)). The equivalent statement is that these events do not occur for nearshore slopes greater than 3° or so. The relatively new coastlines of the west coasts of South America and South Island (New Zealand) are steeper and smoother than coastlines on older passive margins. There are few potential stranding sites on these types of coasts compared to passive margins, because waves and swell have not acted on them for long enough to create mature headland-bays and other types of stranding sites. Higher wave noise on these steeper coasts may also be a factor. A further possibility is that odontocetes may be able to extricate themselves from slopes greater than, but not less than, about 3°. Chinook salmon swimming upstream can manoever off slopes greater than about 4°. There is little information on this point for odontocetes, apart from the deliberate strandings of killer whales as a way to catch seals, and similar behaviour by one dolphin group in southern USA to catch fish in estuaries.

6 CONCLUSIONS

It appears that mass strandings in spit-bays need not necessarily involve acoustics. There is little mystery about strandings in Cape Cod Bay and other spit-bays once the mechanisms of formation and maintenance which give rise to their properties are recognized. In other environments factors such as geomorphology, surf zone noise, and possibly sonar transmission conditions are linked, and may influence mass strandings. It is not possible to separate the effects of acoustics and other environmental factors on mass strandings without more information. What is clear, however, is that odontocetes strand in particular types of sites to the extent that other potential stranding sites throughout the world (particularly spit-bays and headland-bays) can be identified by quantitatively specified properties (planform, slopes, sediments). This type of knowledge should enable more informed comments on strandings and their causes.

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