Investigation into the long-finned pilot whale mass stranding event, Kyle of Durness, 22nd July 2011

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Abstract

Cetacean mass stranding events (MSEs) elicit much interest from both the public and scientific community but the underlying reasons largely remain a mystery. Live stranding events and more specifically mass live stranding events are extreme situations in which public safety, animal welfare and conservation science issues have to be managed with an extremely clear perception of priorities and under the constant pressure of emergency. Thorough investigation of these events usually requires the consideration of a number of natural and anthropogenic factors. In 2011 and 2012 two large mass strandings of long-finned pilot whales (*Globicephala melas*) occurred in Scotland. This report outlines the diagnostic and investigative pathways followed to investigate any potential causal or contributory factors for the 2011 mass stranding. It is in response to funding allocated by Defra and the Scottish Government as a variation to contract number MB0111 (CSIP cetacean strandings around the UK coast).

On Friday 22nd July 2011, a pod of approximately 70 long-finned pilot whales entered the Kyle of Durness, a shallow tidal inlet bordering Cape Wrath, northern Scotland. Herding the pod back towards open water was attempted using rigid inflatable boats and a team of Royal Navy divers from the Northern Diving Group, however approximately 35 animals stranded on the falling tide at the mouth of the estuary. A rapid reaction from local people and stranding response teams enabled the successful refloat of a large proportion of these animals on the following tide. Four additional animals stranded further upstream. These were also refloated but restranded and were euthanized on welfare grounds the following morning.

Nineteen animals were known to have died during the MSE from a combination of factors including hyperthermia, myositis and water aspiration. Sixteen animals, comprising eight males and eight females were recovered and necropsied on site by an investigation team from the UK Cetacean Stranding Investigation Programme (CSIP). Samples were collected according to standard protocols and investigations into potential trigger factors for the MSE were undertaken. The investigation included detailed pathological examination to quantify overall disease burden and specific diagnostics. This included microbiology, histopathology, morbillivirus (RT-PCR), and quantitative analyses for algal toxins (domoic acid and saxitoxin), organochlorine pesticides and 25 individual chlorobiphenyl congeners in blubber and metals concentrations in liver. External triggers, such as unusual climatic conditions and influences of underwater noise were also investigated. A request was made to the UK Ministry of Defence to establish the temporo-spatial distribution of military sources of underwater noise preceding the MSE. The investigation identified two main factors which would be plausible explanations for the stranding, navigational error in a complex, shallow

tidal zone, and acoustic impairment or a behavioural response to a series of underwater explosions conducted in the vicinity of the Kyle during the previous 24 hour period.

Section 1: Stranding summary and investigation outline

- Between 60-70 long-finned pilot whales entered the estuarine Kyle of Durness at high tide (11:20-12:20) on Friday 22nd July
- Bathymetry of area formed an effective 'whale-trap' for live cetaceans as the falling tide resulted in a braided network of shallow channels and sandbanks.
- Some animals were subsequently herded back out to sea on ebbing tide (13.15-16.00hrs) by divers from the RN Northern Diving Group, members of British Divers Marine Life Rescue and local volunteers
- 39 animals known to have live-stranded in two locations
- 15 died, 4 euthanized and about 20 were refloated
- Multiple site stranding, limited road access and requirement for boat support, kindly supplied by from Royal Navy and Coastguard, presented logistical issues with both refloat attempts and carcase recovery.
- No other cetacean species were reported stranded in this region around the time of this MSE

The investigation into the 2011 Kyle of Durness mass stranding aimed to assess a number of factors known or considered potentially influential in causing cetaceans to strand. Given the uncertainties in proving causation, this investigation did not seek to provide a definitive reason why this MSE occurred, but instead aimed to consider the plausibility that certain factors could have contributed to this stranding.

Three questions which could be asked about a pod of long finned pilot whales entering and subsequently stranding in the Kyle of Durness.

1. *Why was a pelagic species close to shore?*
2. *Given the pod was close to the coast, what caused the pod of animals to enter the shallow tidal Kyle?*
3. *Why were animals reluctant to leave the Kyle despite being herded by swimmers and small boats*

The report is organised into sections and each deals with a particular factor considered plausible at contributing to the mass stranding event. The relevance of each of these factors on the questions posed above is discussed followed by the overall conclusions from the investigation, recommendations and suggested future mitigation strategies.

Section 2: Ecology of long-finned pilot whales (*Globicephala melas*)

Long-finned pilot whales are one of the largest members of the dolphin family. Newborns are 1.6-2.0 m long and weigh approximately 100 kg. Adult males and adult females reach an average of 6.7 m and 5.7 m in length respectively. Males weigh up to 2,300 kg and females are smaller, seldom exceeding 1,300 kg.

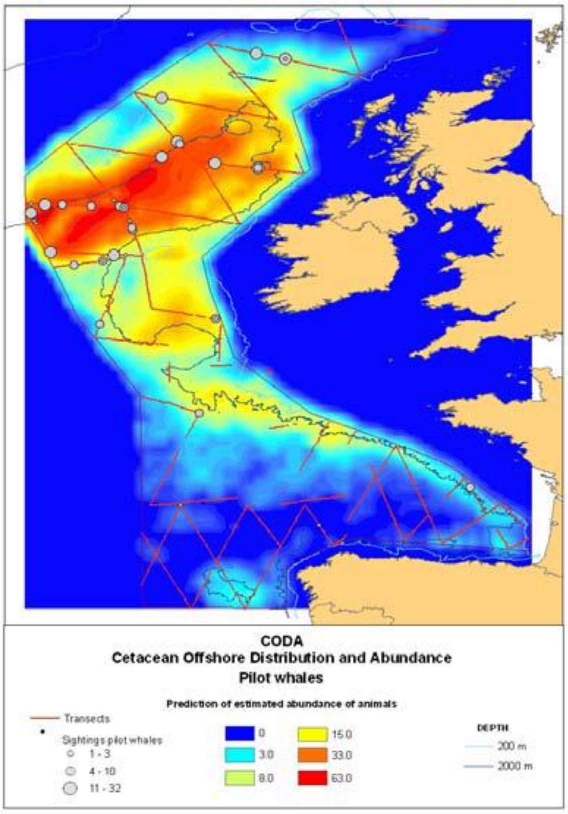


Figure 1: Surface maps showing predicted abundance of long-finned pilot whales based on sightings data[1]

Long-finned pilot whales occur in temperate and sub-Arctic regions of the North Atlantic. With a indicate a range between of 40° N and 80° N in the North Atlantic.[2] The species occurs mainly in deep waters (200-3,000m) and predominantly are sighted along the continental shelf edge (Fig 1 & 2). Primarily squid eaters, long-finned pilot whales will also take small medium-sized fish, such as mackerel, when available. They have also been observed to follow prey (squid and mackerel) inshore and into continental shelf waters during the summer and autumn[3]. Figures 1 & 2 show long-finned pilot whale distribution around the UK based on sightings data. The distribution map highlights a predominantly deep water habitat, with the species occurring in greatest numbers to the north of Scotland and south-east of the Faroes, as well as along the shelf edge from southern Ireland south to the Bay of Biscay. Off the north coast of Scotland the highest sightings rates occurred over deeper areas (500-2,000 m), however the species is known to venture into coastal waters in areas such as the Faroes, northern Scotland, western Ireland and the south-west approaches to the English Channel. There appears to be little seasonality in the pattern of sightings. Median group size ranged from 10-15 (maximum 200) between May and August, whereas for six out of eight months between September and April, it varied between 20 and 25 with a maximum of 1,000 individuals sighted [4] As with most cetacean population and abundance estimates, these distribution maps can suffer from low survey effort.

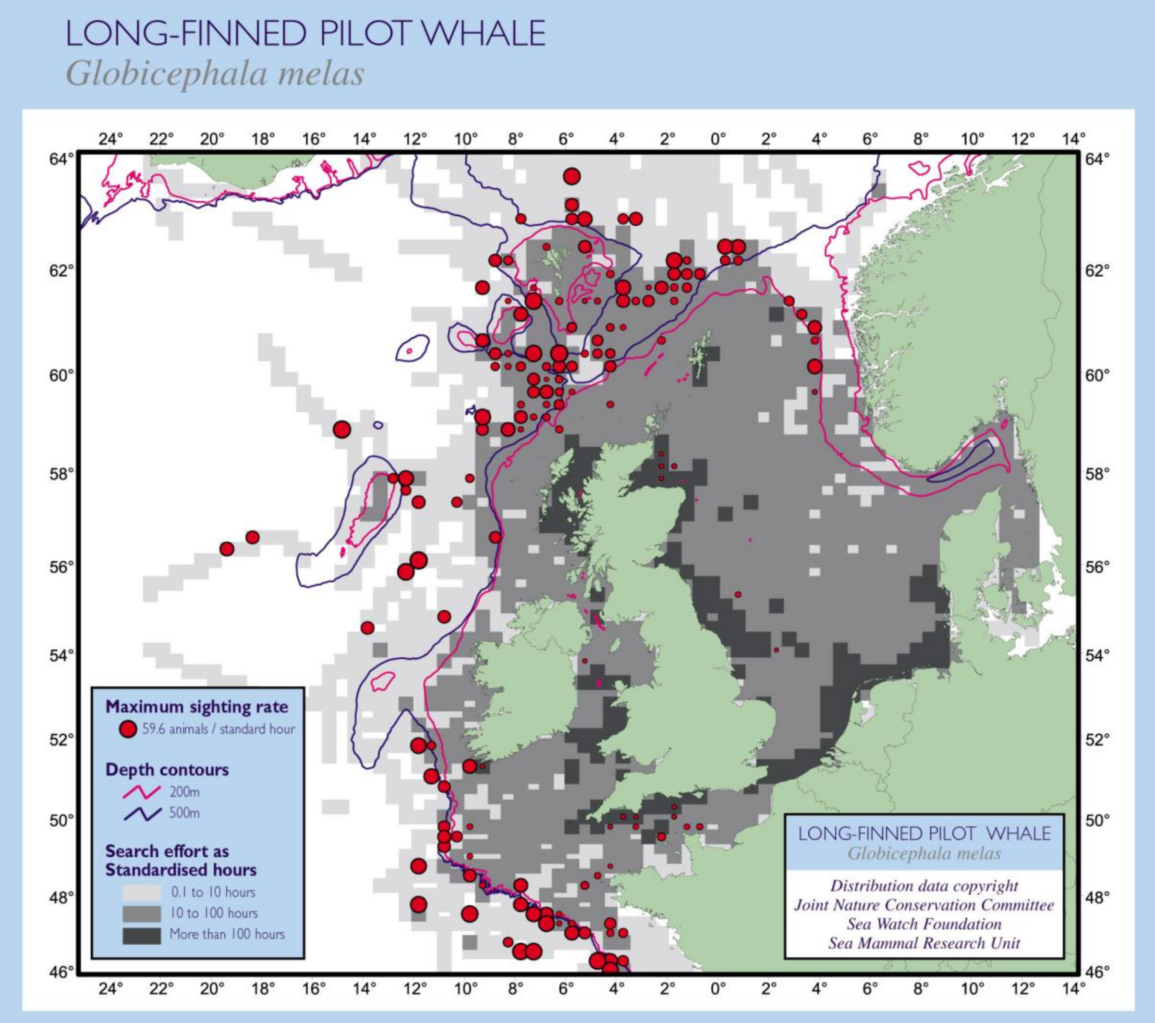


Figure 2: Distribution map of long-finned pilot whale sightings (from Reid, Evans & Northridge, 2003[5])

Section 3: Long-finned pilot whale strandings in Scotland

A mass stranding is defined as two or more animals found together excluding cow/calf pairs. Long-finned pilot whales are the species most prone to mass strand in the UK (CSIP data). Since 1913, there have been 29 long-finned pilot whale MSEs in the UK with an average of 21 individuals at each event. The largest MSE occurred in May 1950 in East Lothian and involved 148 individuals (NHM data). Figure 4 is a map showing the density of long-finned pilot whale strandings in Scotland since 1992. Hotspots for single strandings of this species are the Western Isles (n=74), North West Scotland (n=26), Orkney (n=20) and Shetland (n=22) which is explicable given this is the land closest to the normal shelf-edge foraging zones for this species. The Kyle of Durness mass stranding is also in this category, in contrast to the subsequent mass stranding in 2012 in Fife. Figure 3 shows the number of mass strandings by species in Scotland, and highlights the magnitude of the 2011 and 2012 pilot whale mass strandings and Figure 5 shows the location of all pilot whale MSE's since 1990.

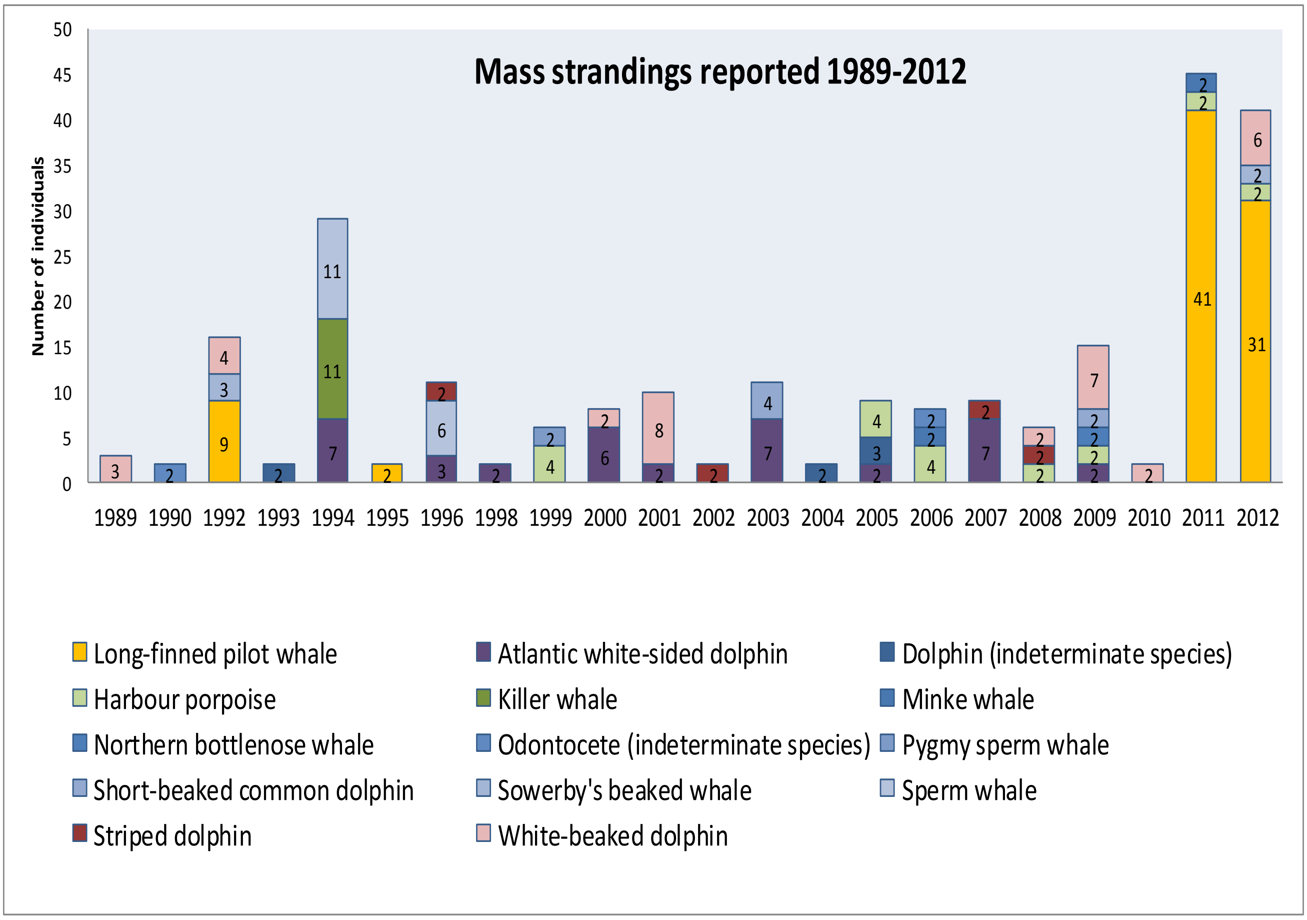


Figure 3: MSE's in Scotland 1989-2012

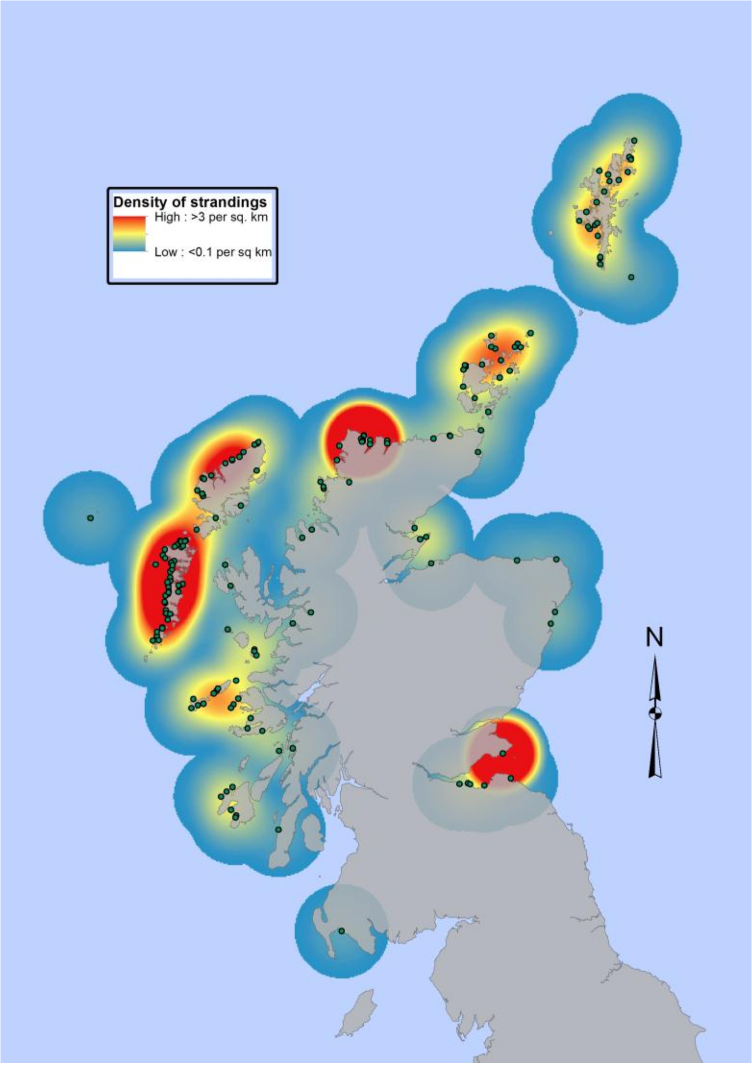


Figure 4: Density of pilot whale strandings 1992-2012

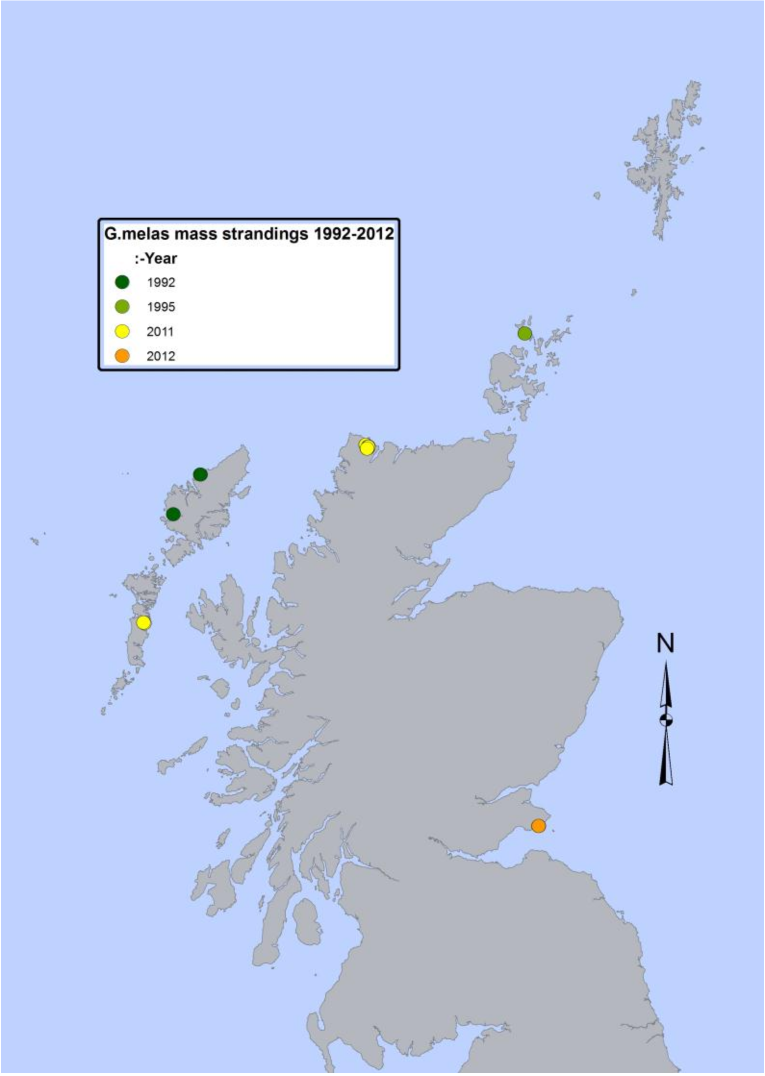


Figure 5: Pilot whale mass strandings 1992-2012

Section 4: Previous near mass-stranding events

There were three unusual long-finned pilot whale mass or near–mass strandings in the months prior to July 2011 (Figure 6). A near mass stranding can be defined as a group of animals close to shore exhibiting behaviour consistent with an attempt to strand, but prevented from becoming beached by human intervention or topography.

4.1 Uist near stranding 27th October 2010, Donegal mass stranding 6th November 2010

Loch Carnan, South Uist, (OS grid reference, NF 835 429). Approximately 40 long-finned pilot whales were seen very close to a rocky shore, packed in a tight group, milling and spyhopping. They were herded out to sea using small boats, however 10 days later (6th November 2010) 33 long-finned pilot whales mass stranded on Rutland Island, Donegal in the Republic of Ireland. This was a remote, relatively inaccessible location however the Irish Whale and Dolphin Group (IWDG) was able to confirm the mass stranding of 33 pilot whales in total, all which were found dead (http://www.iwdg.ie/article.asp?id=2422). Necropsies are not routinely carried out in Ireland, and without financial support from the Irish government it was not possible for a CSIP team to allocate UK funds to this work, so these cases were not examined. Photographic identification of dorsal fin images confirmed some animals were those which left Uist the previous week.

4.2 Uist stranding/near mass stranding 21st May 2011

Approximately six months later, in precisely the same region of Loch Carnan, South Uist, approximately 50 long-finned pilot whales were noted spyhopping. Many animals demonstrated head lacerations indicative of recent trauma, most likely from rock abrasions. No attempt was made to herd this pod out to sea. Two carcases were found, one recoverable for necropsy which showed a thin animal but without any significant pathology. After two days the rest of the pod left the area. No subsequent re-sighting in region was noted, and no confirmed reports of carcases were found elsewhere.

At both of these near stranding events, investigations were conducted by the charities BDMLR (British Divers Marine Life Rescue) and WDC (Whale and Dolphin Conservation) to identify any concurrent anthropogenic activity which may have led to the pod congregating in Loch Carnan. The Royal Navy stated the only vessel in the region of the first Uist stranding was 50 nm away (HMS Ramsay) and another MOD source stated that no royal Naval units were operating within 50 miles of the Irish stranding site and no sonar units within 100 nm. It was also stated that the vessel in nearest proximity to the first sighting at Uist was a minehunter vessel deploying low frequency sonar. The IWDG were contacted by a source who claimed to have deployed a hydrophone in ‘North west Scottish waters’ and picked up ‘extensive’ usage of mid-frequency sonar over a 7 day period approximately a fortnight before the first sighting in Uist on 27th October. This could not be corroborated however, and the lack of necropsies meant it was neither possible to investigate causes for these near mass strandings, nor the mass stranding itself in Ireland a week or so later. Loch Carnan itself does not appear topographically or bathymetrically unusual to the rest of the island, so it was not clear why two near mass strandings both occurred in this particular inlet. A subsea cable crosses Loch Carnan from a 11MW Oil-fired power station and consideration was given to the possible impact on cetacean navigation from any electromagnetic interference[6,7]. It is possible that naval activity may have had a contributory impact on the animals initial presence in Uist, although it isn’t clear though what may have triggered the mass stranding itself in Ireland. From the information provided, no anthropogenic activity or source of underwater noise could therefore be identified which would plausibly explain either of these stranding events.

4.3 Subsequent mass stranding events

On Sunday 2nd September 2012 a pod of approximately 35 long-finned pilot whales were reported as stranded or attempting to strand on the rocky coastline between Pittenweem and Anstruther, Fife. A large rescue and refloat attempt was launched and ten animals were refloated on the following tide. Twenty-one animals were either found dead by the rescue teams or died during the refloat. The carcases were recovered to an adjacent field and necropsied by veterinary pathologists and biologists from the CSIP, the Sea Mammal Research Unit (SMRU) and Moredun Research Institute (MRI). Investigation of this stranding event was funded by the Scottish Government and findings published in a separate report.

Figure 6: Map of *G. melas* mass or near mass stranding events (data © 2012 Google)

Section 5: Timeline of Kyle of Durness stranding

5.1 Friday 22nd July 2011

*numbers in brackets refer to locations on Figure 8

Uncorroborated accounts from a number of local people aiding the rescue suggested a number of large cetaceans had been sighted from the headland to the west of Durness on the evening of Wednesday 20th July. No marine mammal observer or sightings monitoring was operational during that time, so it was not possible to confirm these reports.

1. 11.20hrs: Between 50-70 long-finned pilot whales were seen at the end of a flow tide entering the shallow estuarine environment of the Kyle of Durness (**1).**
2. 12.03hrs: High water (3.5 m).
3. 12.20hrs: Report of two groups of pilot whales in inner Kyle with tide now ebbing, leaving both at risk of stranding**.**
4. 13.15hrs: Initial response by Royal Navy Divers (Northern Diving Group) with rigid inflatable boat. Four animals strand on falling tide **(2).**
5. 14.00hrs: Twenty-two animals seen in channel at south end of Kyle, twenty more in shallow water. Rest of pod remained in deeper water. Northern Diving Group used boats and divers in water to attempt to herd the entire pod towards Kyle entrance.
6. 15.45hrs: Approximately 60 whales were herded out to the Kyle mouth. Close to opening of Kyle pod reported to show agitated behaviour. Progress was slower as animals began milling activity and seemed reluctant to leave the Kyle. Pod split at this point and 35 animals headed to shore and were left stranded on sandbanks on the western side of Kyle **(3).**The remainder of the pod left the Kyle and were not sighted again.
7. 18.08hrs Low water (1.7 m).
8. 18.15hrs: Many volunteers now on site. Approximately 30 people ferried by boat to assist with refloat of main group on incoming tide.
9. 21.00-23.00hrs: Attempt to refloat animals on rising tide. Five animals were known to be dead by this time. Most of the remaining live animals were in lateral recumbency

and exhibited impaired use of the musculature on the side on which they had been lying. This is a familiar sequela to live stranding and is due poor perfusion of the dependent muscle groups due to the crushing effect of the animal's bodyweight out of the water. In addition, depressions created by the movement on a soft sand substrate appeared to impaired the animals' ability to right themselves and hence maintain the blowhole out of the water. Consequently, many animals required support to keep them in ventral recumbency and maintain the airway as the tide returned.

Figure 7: Refloat operation, rising tide 18:00hrs 22/07/11

10. Several calves were also present in the group and corralling them together in the deeper water appeared to encourage adult animals to follow.

11. Approximately 20 animals refloated from this main group.

12. 22.30hrs: Four animals refloated from secondary group **(2).** Close to road so British Divers Marine Life Rescue's inflatable pontoon used in this case.

Figure 8: Image showing strandings locations described above. Only the east, (right), shoreline was accessible from a road. Image © Google 2012

5.2 Sat 23rd July 2011

13. 00.08hrs: High water (3.6 m).

14. 06.00hrs: Five stranded appeared moribund. Difficult location to access due to soft sand **(4).**
15. 06.49hrs: Low water (1.6 m).
16. 09.00hrs: Safe access to sandbank achieved. One animal already dead, remaining assessed by veterinarian and euthanized with Immobilon L.A. (Etorphine 2.45 mg/ml plus Acepromazine 10 mg/ml) on welfare grounds.
17. Sat pm: Recovery of carcases by the Ministry of Defence's Northern Diving Group (NDG), coastguard and members of the public to site at head of Kyle for necropsy and burial **(5).**

5.3 History of cetacean sightings and strandings in the region

Figure 9 & Figure 10 shows long-finned pilot whale strandings around the NW coast of Scotland between1990-2011. It can be seen that several individuals were reported over this period but the largest cluster by far was this mass stranding in July 2011. With the exception of one case (an Atlantic white-sided dolphin, January 1997), no strandings were previously recorded in the Kyle of Durness. In contrast, strandings are more commonly reported in the area north of the Kyle at Balnakeil bay. This is a large sandy beach with good public access, onto which dead strandings tend to be funnelled by the prevailing winds. Figure 11 shows long-finned pilot whale sightings reported to Seawatch between 1980-2010 and it can be seen that the species has been sighted close to shore, albeit usually further east around the Pentland Firth and Orkney[8].

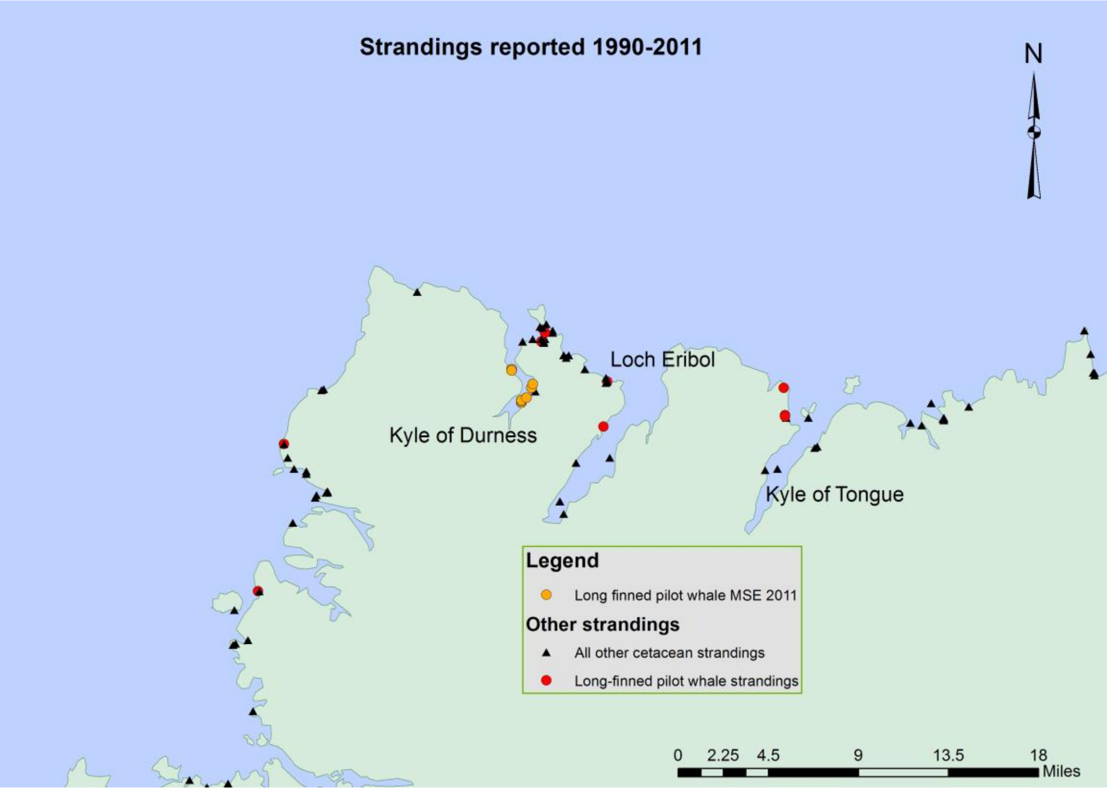


Figure 9: Strandings reported to the CSIP 1990-2011

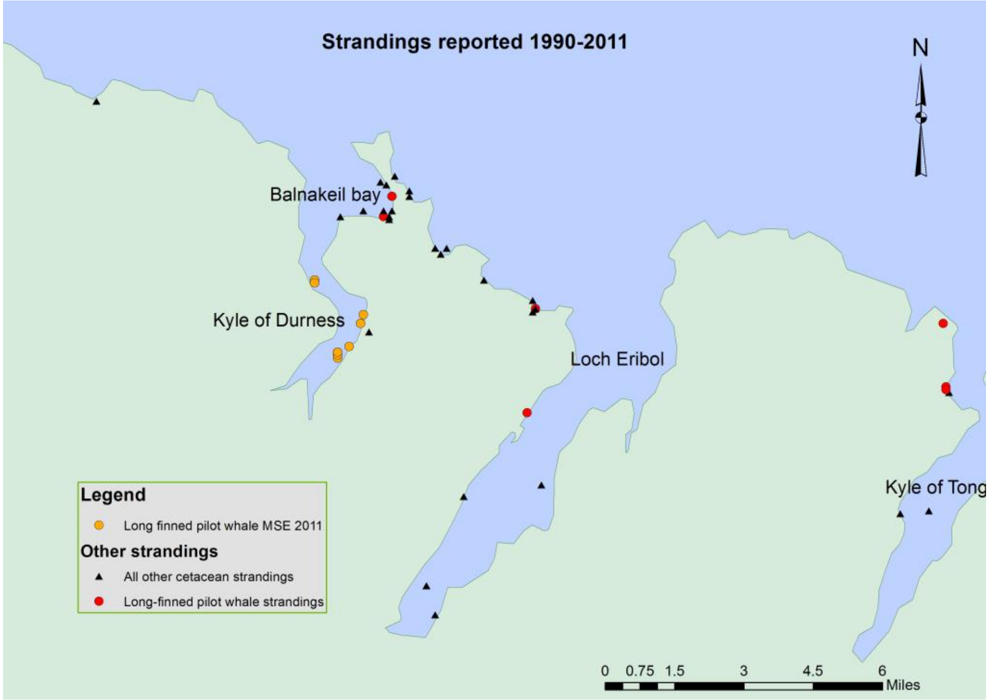


Figure 10: Close up of Kyle of Durness region

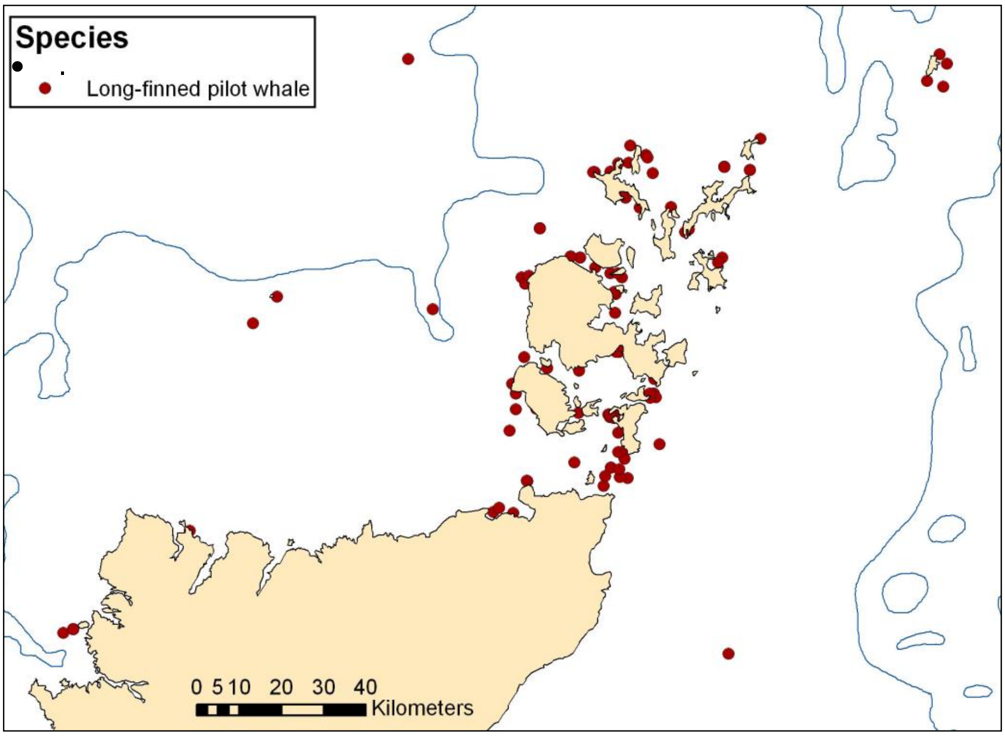


Figure 11: Sightings of pilot whales 1980-2010. (data Evans and Baines 2010)

Section 6: Topography of Kyle of Durness

The Kyle of Durness is a sinusoidal shallow tidal inlet containing two major bends, the more southerly of which is almost a right angle. It is approximately 7 km long and on average 800 m wide, narrowing to 490 m at the main bend. There is a large tidal range of the order of 4.8 m at spring tides (UK Hydrographic Office) with the result that at low water the upper 6.5 km empties to form a series of braided channels and extensive areas of exposed sand. To that end it is effectively a 'whale trap' as the complex, sinusoidal and shallow topography are likely to make navigation difficult. Consequently animals entering the Kyle at high water risk becoming stranded by the receding tide. Access to the eastern shore of the Kyle from the public road is straightforward; however the lack of any paths or roads along the western shore, sandbanks and rapid tidal streams necessitates boat access in most situations.

Figure 12: Stranding, low water, site (2) (photo BDMLR)

6.1 Loch Eribolll and Kyle of Tongue

Loch Eribolll is situated 10 km to the east of the Kyle of Durness and is different to the other inlets along the north coast. Loch Eribolll is a deep water sea loch reaching 63 m depth within the loch and 75 m at the mouth. An additional 10 km further west is the Kyle of Tongue, another shallow inlet with extensive areas of exposed sand at low water. A number of cetacean species, including minke and long-finned pilot whales have been recorded in Loch Eribolll, whereas there are very few sightings of cetaceans in the shallower inlets[8].

Section 7: Pathology

The aim of gross pathological examination of carcases is twofold. Primarily, necropsy allows the condition and health of stranded animals to be assessed and pathology, disease burden and life history parameters to be assessed. This can identify many traumatic, infectious or metabolic processes which may be contributory to the stranding. Secondly, necropsy procedures permit the collection of samples for subsequent analysis and archiving.

Carcases were recovered by boat and volunteers and floated to a site at the south end of the kyle where necropsy and subsequent burial could be undertaken. Due to the logistics of accessing, moving and examining a large number of carcases in a very tidal area, necropsy examination did not begin until the evening of Sat 23rd July with most necropsies occurring on the 24th and 25th July. Additionally, some necropsies were performed in-situ at the stranding site on the eastern bank of the Kyle and carcases moved for disposal afterwards.

All post-mortem investigations were conducted using standard procedures[9,10]. Ambient temperature was14–21°C during the necropsy period. Sexual maturity was determined from gonadal material and, where possible, teeth were obtained from lower mandible for subsequent age estimation.

In summary, the animals were examined in right lateral recumbency and basic morphometric data were collected. The carcase was opened and organs were systematically examined and tissue samples collected for virological, microbiological, histopathological and toxicological analysis. Any observed lesions were also sampled for further diagnostic tests, depending on the suspected aetiology. Ears were collected from the two freshest cases, M168.4 and M168.10. Due to the time after death and assumed autolysis of hair cells, it was not considered that ear analysis would be of diagnostic value in the other cases and therefore they were not collected.

Sixteen long-finned pilot whale carcases, comprising 2 sexually immature males, 2 sexually immature females, 6 sexually mature females and 6 sexually mature males were retrieved from the MSE for necropsy. All dead long-finned pilot whales were in freshly dead condition when initially recovered. The time between death and necropsy varied, hence the state of decomposition at necropsy was fresh (n=2); fresh-slight decomposition (n=4); slight decomposition (n=8) and slight-moderate decomposition (n=2). The main gross and microscopic findings were similar in all cases, with the exception of SW2011/303.5 which is described below. All long-finned pilot whales appeared to be in good nutritional condition and showed no significant evidence of acute physical injury or disease. No acute traumatic lesions characteristic of by-catch or boat impact [11] were seen.

With the exception of case 5 detailed below, the observed pathology in other cases could be attributed to subclinical parasitism or that associated with the process of live stranding. Most cases showed multiple excoriations and bruising associated with the stranding process. Some animals exhibited trauma consistent with serial strandings, and several had aspirated seawater and sand particles in the lungs indicating they had drowned. This was consistent with observations during the rescue attempt where animals refloating on the rising tide appeared to exhibit muscle cramp and required support to maintain the blowhole out of the rising water. Low intensity parasitic infestations were typical, most frequently in the lungs, and these were associated with relatively mild host tissue reactions which are commonly found in stranded cetaceans in UK waters. One female was pregnant and close to term.

Section 8: Stomach contents analysis

Recent studies of stomach contents of *G.melas* stranded along the coasts of Scotland showed a dominance of oceanic prey species[12] This is in agreement with studies from schools around the Faroe Islands where oceanic cephalopods as *Todarodes sagitattus* and *Gonatus* sp. were seen as the main prey present in pilot whale stomach contents In the case of this MSE, the stomachs were observed to be free of recently-ingested prey and cephlapod beaks in all but one case. Case 3, a close to term pregnant female, had fish lenses and squid beaks in the cardiac stomach. No animals however showed evidence of recently ingested prey and several showed refluxed bile in the pyloric stomach. This indicates the pod had not been recently feeding and therefore does not support the theory that the animals' presence close to shore was due to hunting or feeding behaviour. Analysis of necropsy data from other *G. melas* single and mass strandings seldom reported digesta in the stomachs of stranded animals.

Section 9: Teeth aging

The straightest and least worn teeth were selected for age estimation using the wax embedding technique outlined in[13]. This consisted of fixing teeth in 10% neutral buffered formalin for at least two weeks, decalcifying using the rapid decalcifier RDO_, and using standard histological processing techniques teeth were dehydrated, embedded in paraffin wax, sectioned at 5 mm using a microtome and stained using 60% Harris's haematoxylin. The slides were analysed by two independent trained researchers and a final age derived from the average (Table 1).

ID	Reader 1 age estimation	Reader 2 age estimation	Final age estimation (years)
SW2011/303.01	14	>13	14
SW2011/303.02	1.5	1 nearly 2	1.5
SW2011/303.03	20	20	20
SW2011/303.04	15	13	13-15
SW2011/303.05	25	25+	25+
SW2011/303.06	18+	ca. 25-27	ca. 25-27
SW2011/303.08	8	8 nearly 9	8
SW2011/303.09	27	22 (24?)	ca. 22
SW2011/303.11	5	4	5
SW2011/303.12	ca. 20	ca. 17-18	ca.18
SW2011/303.13	20-24	20	20
SW2011/303.14	18	18	18
SW2011/303.16	ca. 22	max 24	22+

Table 1: Teeth ages of necropsied animals (years)

Section 10: Bacteriology

Tissue samples or swabs of selected tissues, including liver, kidney, lung and brain, were taken aseptically for bacteriological examination and incubated under aerobic, anaerobic and capnophilic conditions according to standardised methods. Any organisms recovered were identified using conventional methods including growth characteristics, colony morphology, staining properties and biochemical characterisation using the API identification system (bioMérieux, France). Culture methods and identification of *Brucella* species isolated from tissues utilised standardised methodologies similar to those described by Foster et al [14] and were confirmed as *Brucella ceti.* With the exception of the case outlined below, no other significant bacterial pathogens were isolated from any of the animal examined.

Section 11: SW2011/303.5 (case 5)

One adult male, SW2011/303.5 was found to have a septic left shoulder joint (Fig 11). This was severe enough for it to be assumed the animal had impaired use of the joint. This animal was however in good body condition. It was however thinner than cohort animals of similar size. (Mean blubber thickness for case 5 34.3 mm, blubber thickness by length ratio 6.48. Mean blubber thickness for all strandings 36.7 mm, blubber thickness by length ratio 8.4, variance 0.94, S.D 0.97) It was therefore thinner than cohort animals, but demonstrated adequate blubber reserves, suggesting the animal was still able to forage successfully.

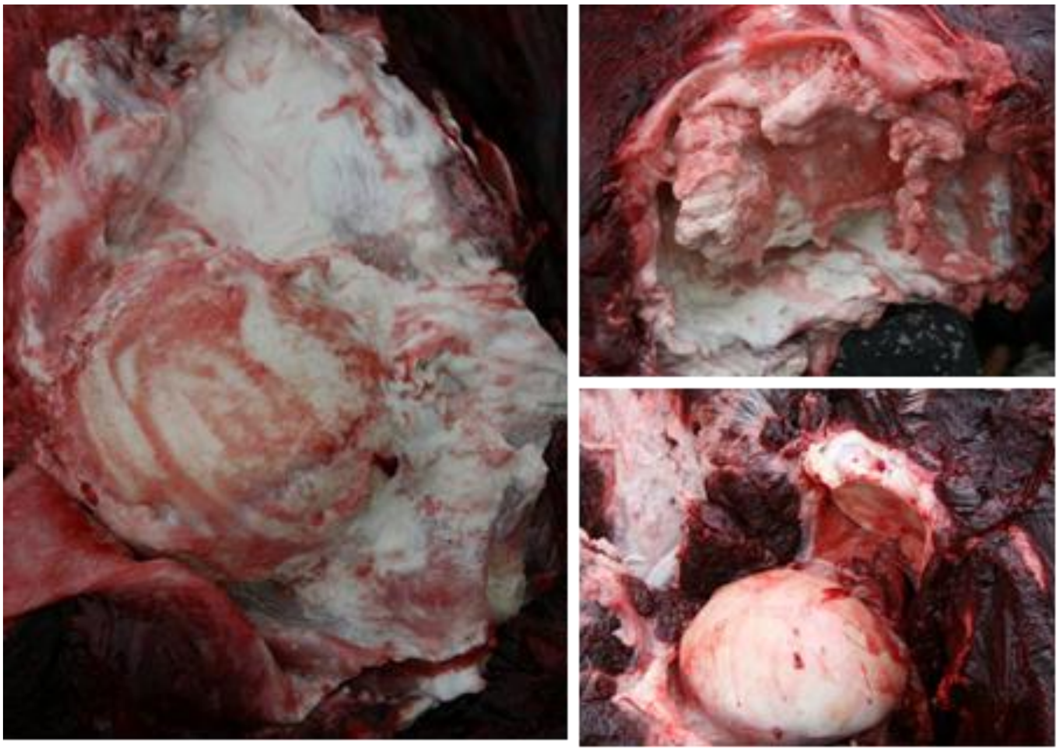


Figure 13: SW2011/303.5 Left shoulder joint showing septic arthritis. Lower right image shows normal contralateral joint.

In detail, a large volume of yellow-white purulent turbid to caseous fluid was found within the left scapulo-humoral joint. The synovial membrane appeared distended and the articular surface of the ball and socket joint was rough and irregular in areas. This suggested the lesion was chronic in duration and it is likely that this animal had this pathology for the order of several weeks. Similar inspissated lesions were noted in the left testis. A mixed growth of bacteria, including *Brucella ceti* was isolated from both the shoulder and testis. The other organs were unremarkable although gross and histopathology was hampered by autolysis.

In some cases multiple site isolates can represent a systemic *Brucella* infection, although there was no indication of this in this animal. In specific *Brucella* was not isolated from the brain. The carcase appeared more decomposed than the other animals from the mass stranding which were examined at post mortem. It is possible that the animal was one of the first to die, contributing to the increased decomposition code. Equally, it is possible that the animal may have had an elevated temperature prior to death which increased the rate of decomposition. Given the severity of the infection, it could be considered a contributory factor in this individual's live stranding and subsequent death.

Section 12: Contaminant burden analysis

12.1 Organic pollutant analysis

Marine mammals are exposed to a range of potentially toxic chemicals in their environment as some lipophilic and persistent organic compounds bioaccumulate to very high levels, particularly in top predators. Polychlorinated biphenyls (PCB) have the potential to cause immunosuppression and morbidity and also impair reproduction in populations with highest exposure. PCB levels in UK-stranded bottlenose dolphins and killer whales currently greatly exceed levels associated with infectious disease mortality in harbour porpoises[15,16]. Although long-finned pilot whales feed at lower trophic levels than these other odontocetes, assessment of levels within members of a single pod was considered necessary given the known impact in other populations. Female cetaceans can offload the majority of their PCB burden to their first offspring during pregnancy and lactation, whereas males have no significant mechanism to offload the contaminant burden[17]. In order to reduce analysis costs it was considered reasonable to mainly focus analysis of PCB congeners on adult male animals.

12.2 PCB assay methods

All tissue samples were collected using standard methodology and stored at –20°C prior to preparation and analysis. Wet weight concentrations (mg/kg) of 25 individual chlorobiphenyl congeners (IUPAC numbers: 18, 28, 31, 44, 47, 49, 52, 66, 101, 105, 110, 118, 128, 138, 141, 149, 151, 153, 156, 158, 170, 180, 183, 187, 194) and a range of organochlorine pesticides and metabolites were determined in blubber samples according to previously established and validated protocols using internationally standardized methodologies[18]. The sum of the concentrations of the 25 CB congeners (Σ25CBs) and organochlorine pesticides tested was determined and were then converted to a lipid basis (mg kg^{-1} lipid) using the proportion of hexane extractable lipid (%HEL) in individual blubber samples. For all analyses, appropriate quality control materials (certified or laboratory reference materials) were analysed within each sample batch in order that the day-to-day performance of the methods could be monitored.

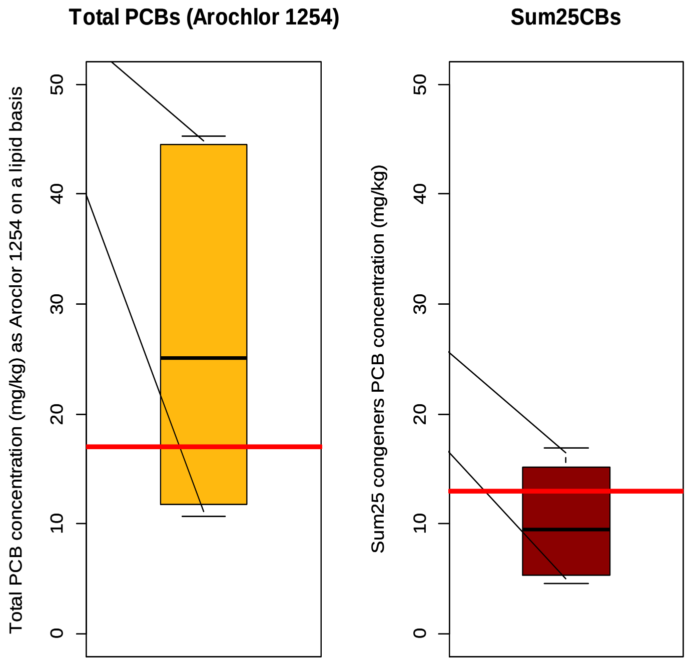


Figure 14: Box and whisker plot showing median and range of PCB burden in screened animals. Horizontal red line indicates minimum threshold for pathology[19].

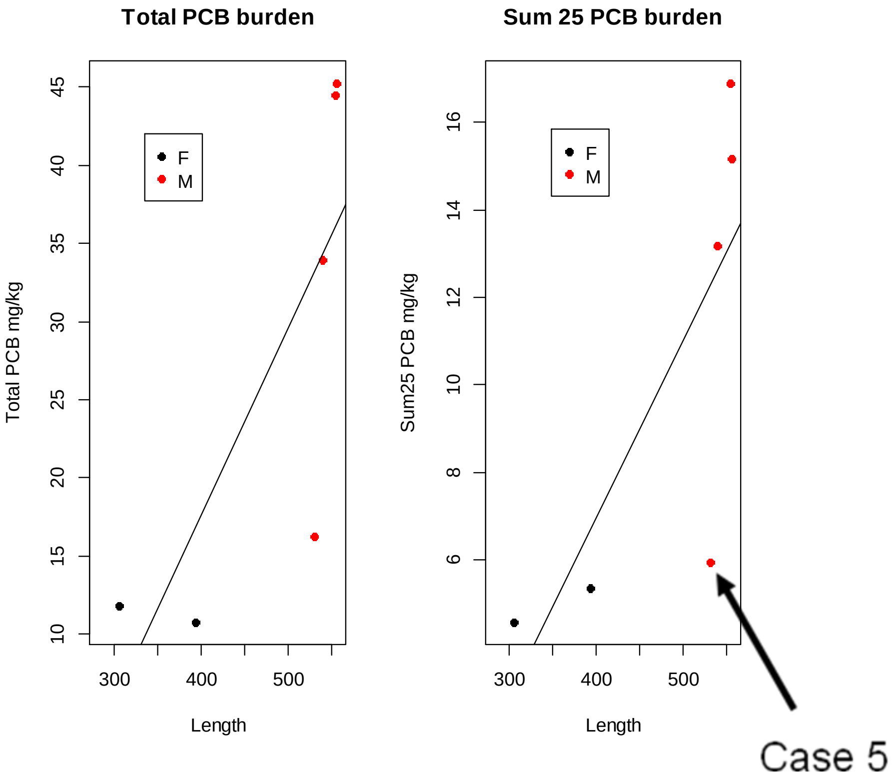


Figure 15: Regression plot showing relationship between total PCB burden and body length, by sex

National Reference	Case number	Sex	Length	Age, years	Euthanased?	Cause of Death	Length cm	Girth cm	Dorsal Blubber mm	Lateral Blubber mm	Ventral Blubber mm	Total PCB concentration (mg/kg	SUM25Congeners mg/kg
SW2011/303.5	5	M	530	>25	NO	Live stranding underlying pectoral abscess, Brucella isolated	530	300	35	31	37	16.2812	5.938
SW2011/303.7	7	M	554	Unknown	YES	Live stranding and hyperthermia	554	328	70	40	49	44.5387	16.912
SW2011/303.9	9	M	555	22	YES	Live stranding and euthanasia	555	280	58	37	37	45.2907	15.186
SW2011/303.10	10	F	393	Unknown	NO	Live stranding and subsequent drowning	393	250	51	28	36	10.7321	5.365
SW2011/303.11	11	F	305	5	NO	Live stranding and drowning	305	170	37	24	29	11.7693	4.57
SW2011/303.15	15	M	539	Unknown	NO	Live stranding capture myopathy	539	280	68	42	39	33.9728	13.185

Table 2: Results from animals screened for organic pollutants

Table 2 shows the results of PCB analysis. Four animals had a total PCB burden above 17mg/kg. In experimental situations pathology becomes evident above this threshold [19]. Whilst it is possible that some animals were experiencing PCB mediated immunotoxicity, levels were not as high as those demonstrated in studies of this[20,21] or other[22,23] cetacean species. It is therefore considered unlikely that PCB burden was having a significant detrimental effect on this pod.

Males showed higher levels than females and this would be consistent with previous observations in other species [16,23]. It is interesting to note that case 5 was the only animal showing evidence of pathology. This adult male had significantly lower levels of PCB than other males (Figure 15).

12.3 Metal analysis

Frozen liver samples were assessed for total element analysis of metals (arsenic, mercury, lead, zinc, selenium, copper, cobalt plus other trace metals). Metal analysis is a proxy for environmental contaminants, but also serves to assess nutritional status of the animals regarding essential elements like zinc or selenium. Analyses of these tissues enabled an assessment of the exposure and load of individual animals with toxic metals, and served as a proxy for the health status of the animals. Analysis was undertaken using high-resolution inductively coupled argon plasma mass spectrometry (ICP-MS) after total digestion, providing an accurate trace and main element analysis over most elements of the periodic table.

12.4 Methylmercury / mercury speciation analysis

Mercury is a very toxic element and in its chemical form of methylmercury can be a potent neurotoxin. Methylmercury accumulates naturally through the food web, with top predators and old individuals showing the highest concentration. There is high correlation between mercury (Hg) and selenium (Se) in the organs of marine mammals. The formation of Hg–Se complexes appears to be part of the detoxification process leading to the fossilization of Hg and Se in the form of non-biodegradable compounds. The hepatic molar Hg:Se ratio is therefore a useful calculation for assessing the potential detrimental effect of biological active mercury species [24–26]. The size and longevity of long-finned pilot whales potentially leads to significant accumulations of methylmercury during their life. In most mammalian species, mercury intoxication impacts the nervous system and may be a cause of disorientation or unexplained behaviour. Therefore, the determination of methylmercury and mercury in the animal tissues can provide a proxy for mercury impacting their health.

Analysis of Hg and Se were conducted on 5 different biological tissues; liver, kidney, muscle, blubber and skin. Cold vapour atomic fluorescence spectrometry and ICP-MS were used for analysis of total Hg and Se, respectively.

The Hg concentrations in adult kidney and blubber, and the Se concentration in adult liver were significantly higher than in the juvenile whales. There was a strong correlation with Hg and Se in liver and muscle, reflecting a concentration ratio of ~1:1.

This is in line with other observations, hinting to the proposed detoxification mechanism of methylmercury with selenium compounds. A correlation was found in kidney, but not the molar relationship and no correlation was found in blubber.

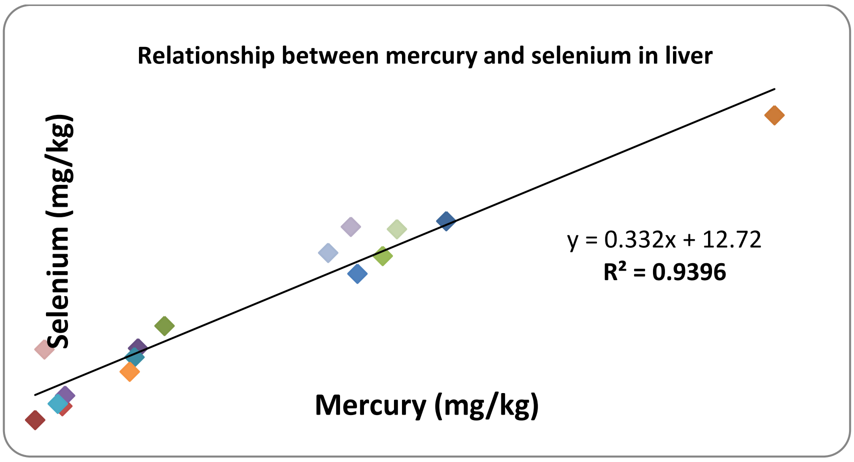


Figure 16: Relationship between mercury and selenium levels in liver tissue

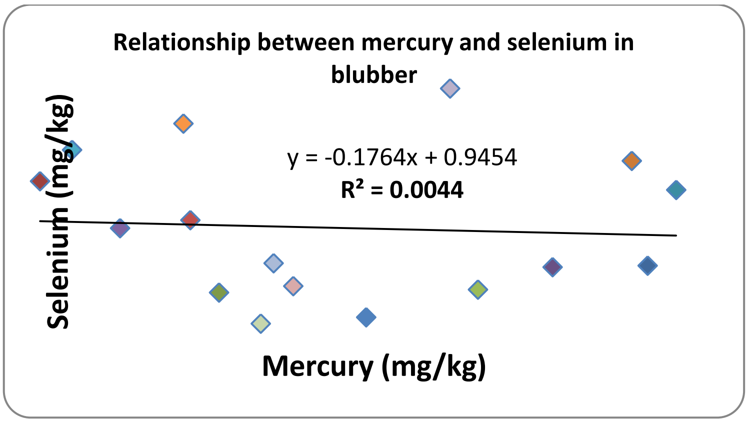


Figure 17: Relationship between mercury and selenium levels in blubber tissue

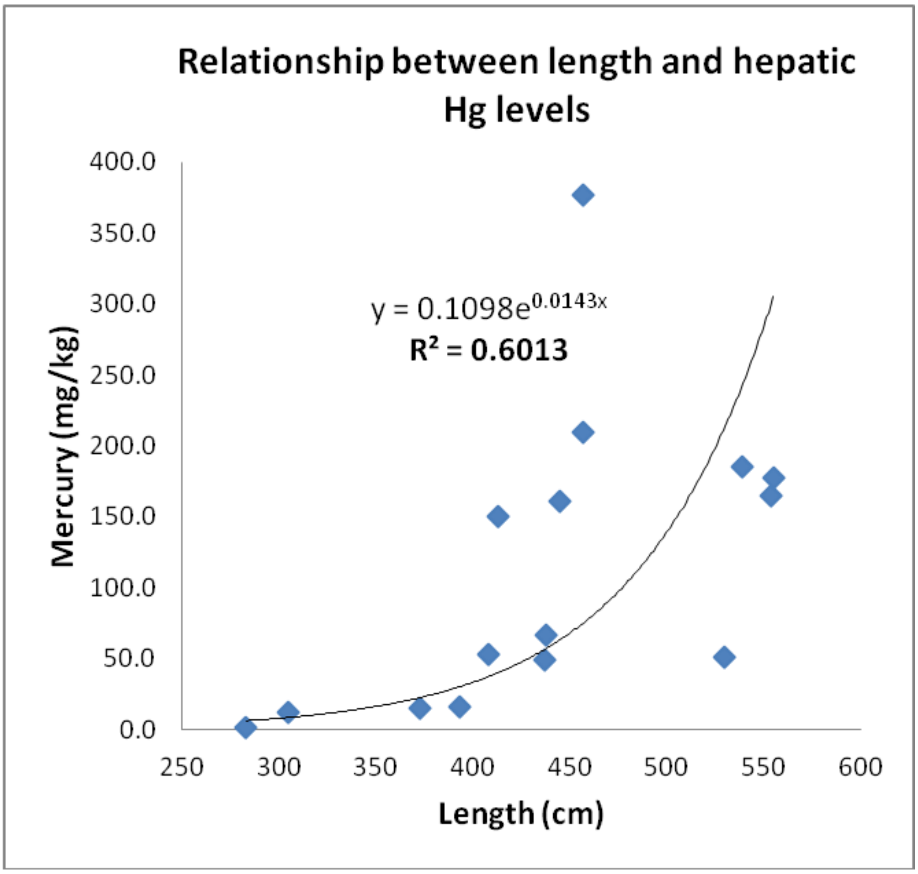


Figure 18: Relationship of liver mercury burden by length of animal

Mercury concentrations in liver are strongly correlated to animal length (a proxy for age), which is a clear sign for bioaccumulation. The correlation factors show a gender difference, possibly because male long-finned pilot whales are larger animals.

Section 13: Algal toxins

Harmful algae are phytoplankton that produce toxins at certain times in their life cycle. These toxins are well recognized as causing severe health impacts in humans and animals. Among marine mammals, domoic acid (DA), a neurotoxin produced by the diatom *Pseudo-nitzschia spp,* has caused mortality events since 1998 particularly in California sea lions (*Zalophus californianus*)[27] . The impact of cetacean exposure to DA is still unclear, although there is concern exposure may have detrimental effects at the level of both individual health and, through reproductive failure, populations [28,29] In Scotland limited research has been conducted on DA but the toxic diatoms are regularly found in Scottish waters, and DA is found in fish, crustaceans and cephalopods[30] and these species act as DA vectors, screening in this species was considered appropriate. Pilot whales (*Globicephala melas*) are known to feed on cephalopods and levels as high as 241,700 ng / g have been reported in the digestive glands of this prey species [31].

A direct competitive enzyme linked immunosorbent assay (ELISA) (ASP assay kits, Biosense, Norway) was used to determine biotoxin concentration in long-finned pilot whale tissue. This assay has been widely used to detect demoic acid in various matrices including shellfish tissue, urine and faeces from marine mammals [32,33]. The samples were analysed at the Sea Mammal Research Unit (SMRU), University of St. Andrews. Long-finned pilot whale kidney, liver and stomach contents (4 g) were homogenized in a 1:4 dilution of 50 % methanol and centrifuged at 3000 x g for 10 min. Supernatants were retained for the ELISA method and further diluted to 1:200. All samples were tested in duplicate.

The LOD (limit of detection) for the direct competitive ELISA method used to measure concentrations of DA in marine mammal excreta has been set to >2 ng/ml DA in urine and >5 ng/g DA in faecal extracts (Table 3). Of the 15 pilot whales analysed, all showed a low level of DA in tissues, with all but three animals below the LOD. This indicates acute high level DA toxicosis could be ruled out as a cause of the stranding, although a low level of exposure was found. It was therefore concluded that exposure to domoic acid biotoxin was unlikely to be a contributory cause of this MSE.

Case ID	**SW2011/303.01**	**SW2011/303.02**	**SW2011/303.03**	**SW2011/303.04**	**SW2011/303.05**	**SW2011/303.06**	**SW2011/303.07**	**SW2011/303.08**	**SW2011/303.10**	**SW2011/303.11**	**SW2011/303.12**	**SW2011/303.13**	**SW2011/303.14**	**SW2011/303.15**	**SW2011/303.16**
DA ng/g	1.30	0.35	1.01	1.97	0.00	0.93	1.93	1.37	8.07	0.59	5.26	0.49	5.61	2.21	3.26

Table 3: Mean domoic acid levels in sampled cases

Section 14: Morbillivirus

Distemper, caused by cetacean morbillivirus is a known cause of mortality in cetaceans and an epizootic in a group of animals would have a significant impact on health. A common dolphin mass mortality event in 1994 in the Black Sea was linked to cetacean morbillivirus infection and it was therefore a differential in this mass stranding event.

Total RNA was extracted from sections of frozen (-80°C) lung (n=16) samples and the presence of morbilliviral RNA was tested using reverse transcriptase polymerase chain reaction targeting the conserved N terminus of the morbillivirus N gene [34]. All reactions were conducted in duplicate.

No lesions consistent with distemper were found in any of the cases and no evidence of morbillivirus nucleic acid was detected in any of the screened samples. Distemper was therefore ruled out as a contributory factor in this MSE.

Section 15: Conclusion from pathological investigation

Necropsy examination by veterinary pathologists from the CSIP was possible on 16 of the 19 animals known to have died or which were euthanized during the MSE. In general all animals were healthy, in good condition and, with one exception, showed no evidence of underlying infectious disease. One adult male had a large purulent abscess in the left scapulo-humoral joint. A few *Brucella ceti* bacteria were isolated from this material. The significance of this is not totally clear, as the animal in question was largely in good condition, however it is plausible that this degree of pathology caused a fitness cost on its ability to forage and swim. All other biological indicators, analysis of contaminant burden and screening for pathological agents suggest that the pod was healthy and was not suffering from any underlying infectious, metabolic or toxic process which would account for the stranding.

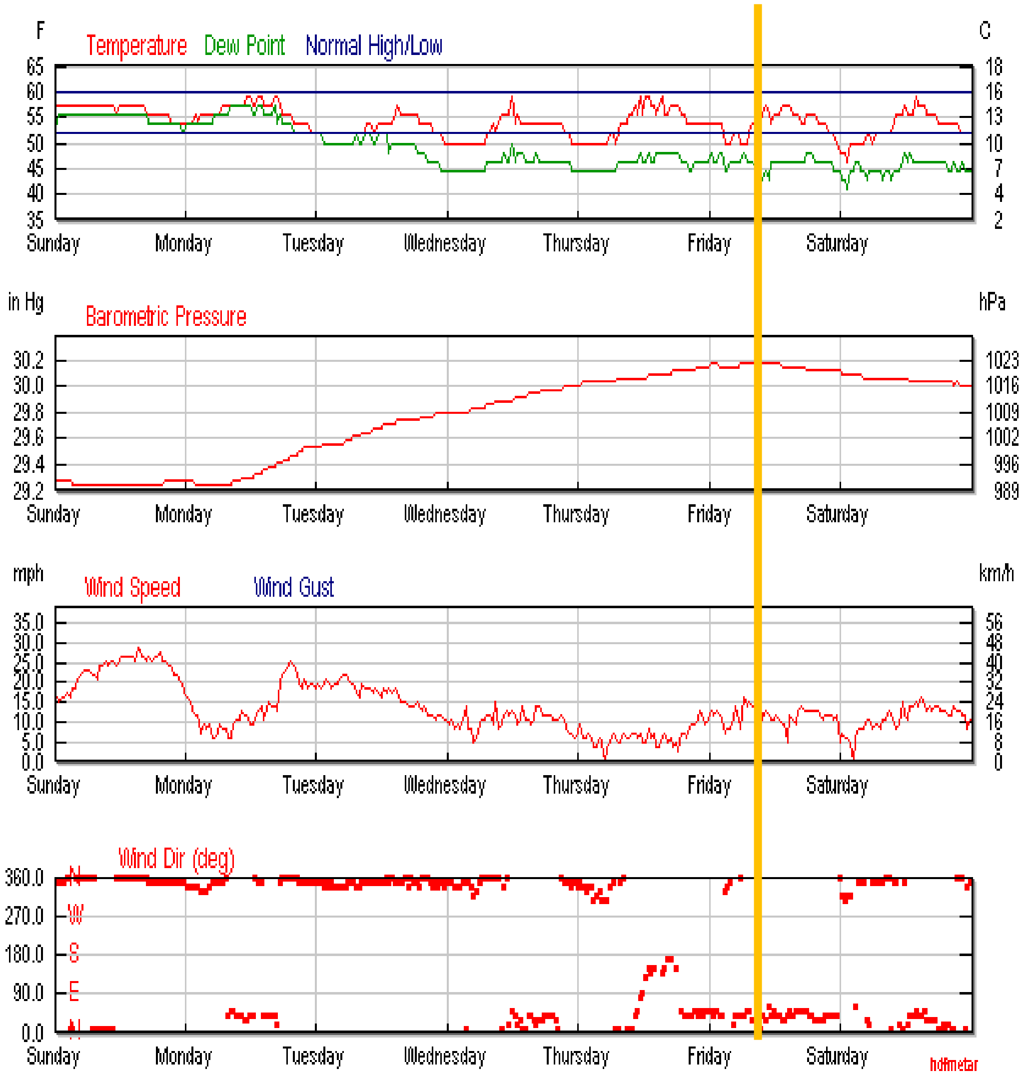


Figure 19: Weather from proximal meteorological station (58.21N, 6.33W) for period 17th-23rd July 2011 (via http://www.wunderground.com) Yellow line marks beginning of MSE

No severe weather events were recorded in the locality during the previous week. Wind was recorded as northerly, gusting 5-6 on 19-20th July, decreasing to force 3-4 the day prior to the stranding. Good visibility, tides were decreasing slightly from a spring high on 20th July.

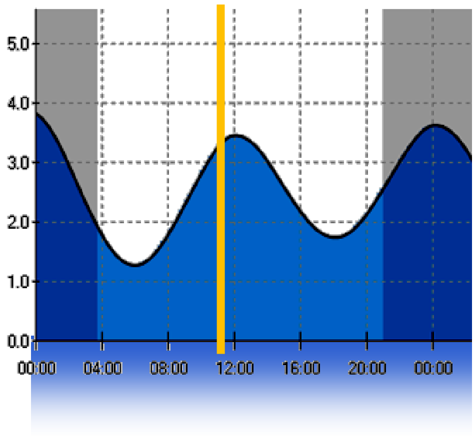


Figure 20: Tide cycle at Durness 22nd July 2011. Line shows beginning of MSE

Section 17: Natural seismic activity

Natural seismic events are recorded by the British Geological Survey and can be queried at http://www.earthquakes.bgs.ac.uk. The closest earthquake recorded was magnitude 3.5 on the 21st July 2011 in the North Sea. Given the distance and intervening landmass, it was not considered that acoustic disturbance from earthquakes was likely to be a significant factor in the stranding.

Section 18: Fisheries activities

The north-west of Scotland has an active fishing industry although it is small compared to the fleets of the east coast. Local communities involved in the rescue attempt and local fisheries compliance offices were questioned as to the magnitude and extent of fishing activity ongoing in the region. Information received from these sources did not suggest the period running up to the mass stranding exhibited any unusual activity. It was commented that boats fishing squid tended to operate closer to shore during periods of dry weather, with the anecdotal explanation that fresh water runoff pushed squid further offshore. Although the potential existed for a fisheries interaction to disturb cetaceans in the vicinity, there was no evidence that that occurred in this case.

Section 19: Marine renewables and anthropogenic seismic activity

The closest site developing or operating marine renewable energy equipment was the European Marine Energy Centre (EMEC) Farr Point wave test site 26 km to the east of the Kyle of Durness. This was not in operation however at the time of the MSE. The UK Department of Energy and Climate Change (DECC) confirmed that no geophysical surveys, including surveys involving seismic methodologies, were licensed to take place within a 100 km radius of Cape Wrath either immediately prior to or during the stranding event.

Section 20: Shipping and naval activity

Waters to the north of the Kyle of Durness are relatively busy with shipping traffic from the northern North Sea, Orkney and Shetland heading down the Minch. Over the preceding 48 hours of the MSE there was no unusually heavy activity based on data received from vessels broadcasting with an AIS (Automatic Identification System) transponder:- (http://www.marinetraffic.com/ais/). Following a request to the Royal Navy, UK naval activity history was stated as follows:

> "We can also confirm that the only Royal Naval unit within 50 nm (circa 90 km) of the incident and up to 48hrs before the stranding (11.45 22 Jul 2011) was the NDG, with no RN vessels operating sonar. Although we cannot comment on other nation's movements or the whereabouts of any of their vessels at that time, we can confirm that no multi-national exercise activity was planned in the area during this time frame. **"**

Complete email transcripts with the Ministry of Defence are included in Appendix 1.

Section 21: Natural predators

There is little evidence in the literature to suggest that a pod of long-finned pilot whales could be affected by natural predators to the extent they would strand. There was no record of killer whale (*Orcinus orca*) sightings in the immediate area. The Seawatch Foundation collates sightings data for the UK and reported orca sightings around Orkney on the 11th, 13th, 19th and 20th July (per comm. Peter Evans, Seawatch). Whilst the potential influence of killer whales on this stranding event cannot be excluded, from the information available it is not considered a probable factor.

Section 22: Underwater detonations

The land to the west of the Kyle of Durness out to Cape Wrath includes a live bombing range used by the Ministry of Defence. It is both the largest live bombing range in Europe and the only one where live 1000-pound bombs may be deployed. Garvie Island is part of this range and is situated a couple of hundred metres offshore, approximately 4.5 km from the entrance to the Kyle of Durness. The island measures about 220x70 m and is primarily used for aerial bombardment practice. The mainland range has been operational since 1933 and Garvie island since 1939. In some cases the live bombs fail to detonate and the unexploded weapon falls to the seabed. This unexploded ordnance poses a potential hazard, so specialist divers from the Royal Navy Northern Diving Group (NDG) are deployed to locate these devices, fit them with plastic explosive and detonate them underwater. This clearance activity happens on a roughly annual basis. The NDG were running the 2011 clearance operations prior to and during the beginning of the MSE. A request was made to the Ministry of Defence (see Appendix 2) and the following information was provided:

22.1 Thursday 21st July 12:00h

- *2x4lb plastic explosive packs*
- *1x 540lb bomb detonated High order explosion*

22.2 Thursday 21st July 12:15h

- *2x4lb plastic explosive packs No High Order recorded*

22.3 Thursday 21st July 14:00-14:15h

- *2 x 4 lb Plastic Explosive Packs – 1x 540lb*
- *3x 1000lb bombs detonated*
- *High order explosions*

22.4 Friday 22nd July 11:20h

- MSE begins

22.5 Friday 22nd July 12:40h

- *2x 4lb plastic explosive*
- *1x 250lb High order bomb detonated*

22.6 Timeline for underwater detonation

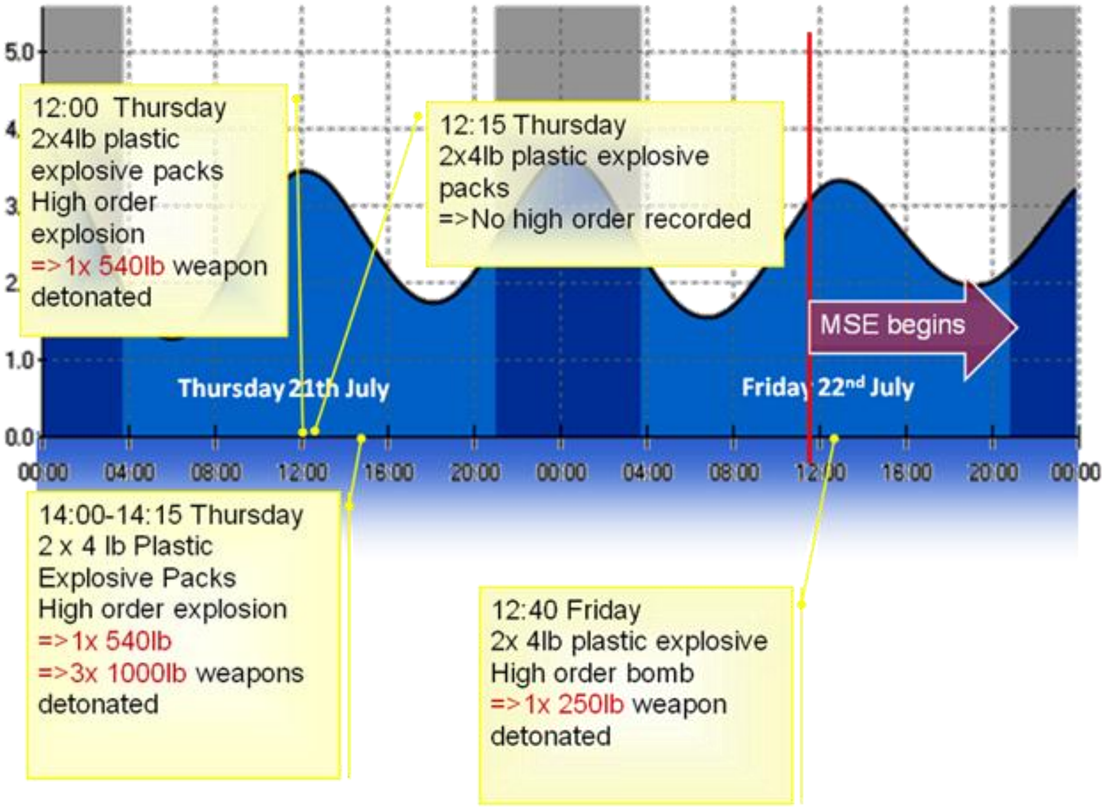


Figure 21: Timeline for underwater explosions at Garvie Island.

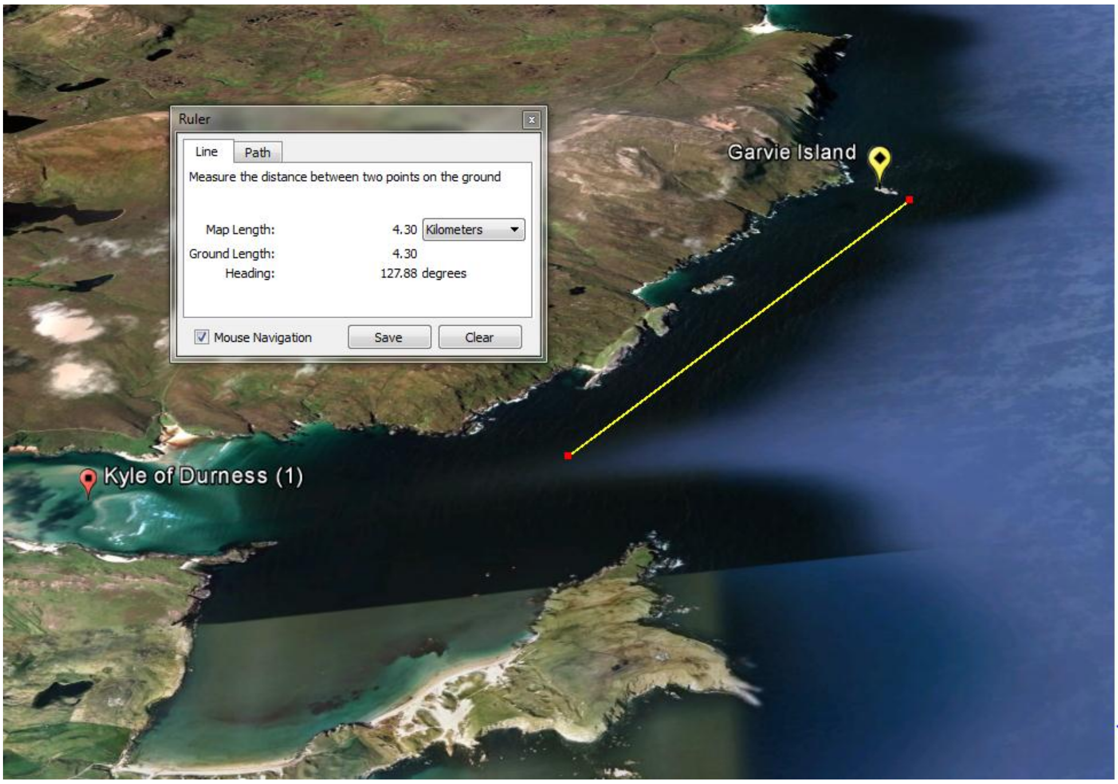
22.7 History of munitions disposal around Garvie

Table 4 shows the total munitions dropped on Garvie Island during 2011. The period May-July 2011 contained no high order explosions apart from the clearance work detailed above. It could be assumed therefore that the detonations prior to the MSE would be both novel and of sufficient magnitude to cause a behavioural and acoustic impact on any odontocetes in the vicinity.

Month	Weapons dropped on Garvie island
January 2011	Nil weapons dropped
February 2011	8 X Inert 1000lb Paveway II Bombs
March 2011	3 X 14kg Practice Bombs 5 X 1000lb High Explosive Bombs (1 of which was identified as unexploded ordnance)
April 2011	1 X 3kg Practice Bomb
May 2011	Nil weapons dropped
June 2011	Nil weapons dropped

July 2011	Nil weapons dropped. Range clearance conducted.
August 2011	Nil weapons dropped
September 2011	5 X 1000lb Inert Bombs
October 2011	10 X 1000lb He Bombs
November 2011	5 X 3kg Practice Bombs 4 X 14kg Practice Bombs
December 2011	8 X 14kg Practice Bombs

Table 4: Munitions dropped on Garvie Island during 2011 (data supplied by MOD)



Measure the distance between two points on the ground

Map Length: 4.30 Kilometers
Ground Length: 4.30
Heading: 127.88 degrees

☑ Mouse Navigation

Figure 22: Kyle of Durness and Garvie Island. Yellow line measures 4.3km (Image from Google Earth)

Section 23: Impact of underwater explosions on marine mammals

The precise sound profile and associated impact on marine life of the underwater explosions at Garvie Island will be influenced by the local bathymetry, hydrography and weapon detonation itself. As such the radiuses for each zones of impact are speculative. Human auditory studies suggest peak sound pulses exceeding 244 dB are likely to result in auditory damage. This threshold occurs at distances, in air, of 189, 407 and 877m from detonations of 1, 10 and 100kg of high explosive respectively[35,36]. Whilst it is not clear how this translates to the effect of underwater explosions on neighbouring cetaceans, the sequential detonation of three 1000 lb (454 kg) high explosives could plausibly have had a detrimental impact on any cetaceans within several kilometres [37,38]. Figure 23 below shows the possible effects of an underwater explosion on marine mammals depending on proximity to the source. The radius of each zone is heavily influenced by the type, frequency and duration of the propagating sound pulse, however in general the following zones will apply:

23.1 Blast trauma

If the magnitude and duration of the sound is sufficiently large to form a pressure wave, animals present within that zone may exhibit pathological lesions typical of blast trauma. None of the long-finned pilot whales examined showed indication of this type of trauma.

23.2 Acoustic impairment

The sensory apparatus of cetaceans has been shown to be vulnerable to damage by loud or prolonged noise. The hair cells in the ears of cetaceans transform pressure changes into nerve signals and if these are damaged the animal can be left functionally deaf [39]. Exposure to intense sound may produce an elevated hearing threshold, known as a threshold shift (TS). If the threshold returns to the pre‑exposure level after a period of time, the TS is termed a temporary threshold shift (TTS); if the threshold does not return to the pre‑exposure level, the TS is called a permanent threshold shift (PTS)[40]. Detection of TTS usually involves behavioural studies; PTS in contrast leads to changes in the auditory cell architecture which can in principle be detected at necropsy. This process requires histological fixation of the ears within hours of death as post-mortem autolysis can rapidly mask any underlying pathology. In this case, the facility was not available to extract and fix the ears within a time frame for meaningful analysis and therefore it was not possible to establish the hearing capacity for any of the animals involved in this stranding. It is plausible however that the magnitude and frequency of successive underwater detonations of 1000lb ordnance in the afternoon prior to the stranding event would have had a significant detrimental effect on the hearing and therefore navigational competence of any cetaceans in proximity. Given the precise nature of the sound profile and resultant acoustic trauma is a complex function of environmental and bathymetric factors, it is difficult to precisely establish the radius for these effects. Based on other studies [38,41] it is likely that this radius is greater than the maximum distance it was possible for observers on the NDG vessel to see from a rigid inflatable boat based observation platform less than 2 m above sea level. The only surveillance for cetaceans in the vicinity of Garvie Island prior to detonation of the underwater munitions was from this single platform by personnel not familiar with observing marine mammals. It would not have been possible therefore to effectively assess if animals were within the envelope where acoustic damage was likely.

23.3 Behavioural disturbance

Long-finned pilot whales are known to follow other members of the pod and appear to ‘spook’ relatively easily; a trait exploited for centuries by the Faeroese whale drives, where sound from small boats are used to drive the whales onto shore. There is no observable pathological legacy to a behavioural response and therefore the effect of the detonations on the long-finned pilot whales is largely conjecture. It is however plausible that the explosion on the Friday morning, once the animals were already in the Kyle, might have served to drive the animals further inland. Equally the reluctance of the pod to re-enter deeper water at the mouth of the Kyle despite being effectively herded for most of the Kyle length by the NDG divers, may be explained by a learned avoidance response to the earlier detonations or a post-stranding stress related response.

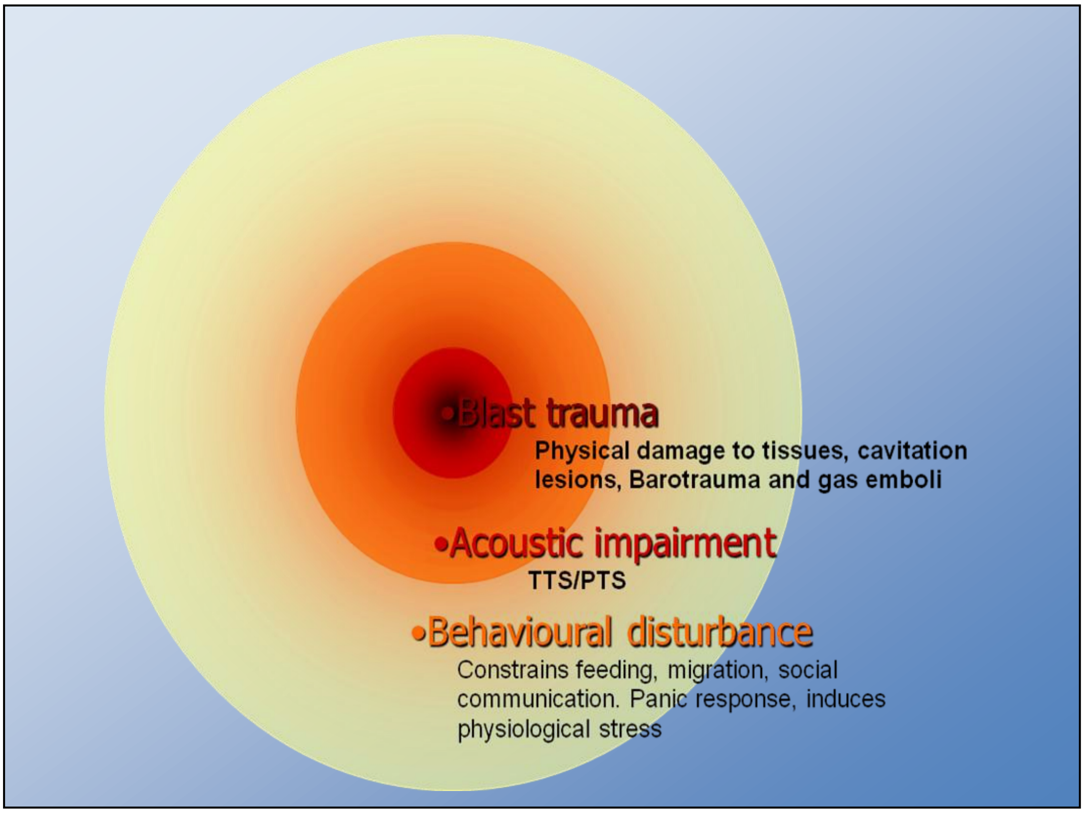


Figure 23: Schematic showing proposed zones of acoustic trauma or disturbance (adapted from Richardson 1999)

Section 24: Discussion

There were three anomalies to account for in this investigation

1. *Why was a pelagic species close to shore?*
2. *Given the pod was inshore, what caused them to enter the shallow tidal Kyle?*
3. *Why were animals reluctant to leave the Kyle despite being herded by swimmers and small boats?*

24.1 Why were the long-finned pilot whales close to shore?

Local people involved in the rescue reported seeing a pod of cetaceans from the headland at Durness on Wednesday 20th July. These sightings were not corroborated however so it is not clear if they were the same animals, or even species, as involved in the subsequent MSE. Local fishermen reported that they occasionally see *G.melas* milling in Loch Eribolll and Figure 11 shows previous recorded sightings around the Pentland Firth. This could be due to a wide spectrum of reasons ranging from external factors such as predator or noise avoidance or internal reasons such as following a food source, transiting between feeding areas or seeking more sheltered waters due to slower or more debilitated members of the pod[10,42]. Alternatively, given the topography, the pod could simply have been taking the shortest route between feeding areas off the NE Atlantic shelf and this brought them close to land. Shipping traffic, seismic activity and climatic factors do not appear to have been unusual and information received from the Ministry of Defence stated there were no unusual naval activities in the region in the days before the stranding on the 22 July 2011. In conclusion, although, pilot whales are well known for dwelling mostly in shelf break habitat, it is equally well known that they also visit coastal waters fairly frequently; the exact reasons in this case are unknown and possible explanations are multiple. It is important to emphasise that, whilst proximity to land does not equate with an attempt to strand, once close to shore the pod would have been susceptible to specific hazards, stressors or stimuli which could have led to them entering the shallow Kyle and subsequently live stranding.

24.2 What caused them to enter the Kyle?

The possibility exists that the MSE occurred simply due to some intrinsic error of “navigation” within the social group. As can be seen from the topography of the area, the entrance to the Kyle of Durness is parallel with both the route into Loch Eriboll and the deep channel to the west of Cape Wrath leading into the Minch. If animals were coming from the north and heading down the Minch a small deviation in that route would lead into the Kyle.

Other external factors, such as the presence of other cetaceans, shipping and most forms of acoustic disturbance can be considered unlikely. In contrast, given the tempo-spatial correlation of the MSE with the munitions disposal of the NDG, the detonations have to be considered as an explanatory variable on the behaviour of any cetaceans in the area during the time of the explosions. Information received from the Ministry of Defence stating the average frequency and intensity of underwater explosions in the region (Table 4), indicate an extraordinarily high level of activity in the days leading up to the stranding. Given this, it is reasonable to assume that any animals in the vicinity of the explosions could have been affected. The propagation of underwater sound and the impact on animals is complex. However, based on previous studies [37,38,43] it would be reasonable to conclude the underwater detonations may have had a significant effect on the hearing, navigation and behaviour of any cetaceans in the proximity and these effects could persist for the period between the detonations on 21st July and the mass stranding the following day. It should be highlighted that there are only uncorroborated reports that cetaceans were seen in the area immediately before or during the detonations, however if this was the case then it plausible that animals were suffering a degree of acoustic threshold shift or disorientation which resulted in them entering the Kyle of Durness. Given the topography and tidal nature, this was a very unsafe location for that species and hence the large number of subsequent strandings.

24.3 Why were animals reluctant to leave?

It is not clear why the animals appeared to be reluctant to leave despite the best efforts of the rescue teams. It is possible this was a panic response amongst an already highly agitated and physiologically stressed population. The temporal and spatial proximity of acoustic disturbances generated by the underwater detonations at 12:40 on the Friday, would however provide a plausible reason for their observed reluctance to subsequently leave the region and return to the open sea as this would also be towards the direction of the original sound source. Long finned pilot whales are observed to be a highly social species and if aspects of this sociality involve a need to communicate with the whole group, then the lack of response from dead or acoustically impaired members of the group might inhibit departure.

Section 25: Summary of key points

- On 22nd July 2011 approximately 70 long-finned pilot whales entered the Kyle of Durness, a shallow tidal inlet bordering Cape Wrath, Northern Scotland (58°34'52"N 4°48'23"W) . As the tide receded at least 39 animals stranded, of which about 20 were subsequently refloated. Nineteen animals were known to have died during the MSE. Sixteen animals, comprising eight males and eight females were recovered for post-mortem examination.

- One adult male, SW2011/303.5 had a large, purulent abscess in the left scapulo-humoral joint. The pathology appeared severe enough to compromise use of the joint. *Brucella ceti* was isolated from shoulder and testes although there was no indication of systemic illness. The animal was in normal body condition, suggesting it was able to successfully forage.
- All other biological indicators suggest the pod was healthy, in good body condition and was not suffering from any significant infectious, metabolic or toxic burden.
- There was no evidence of barotrauma consistent with the direct physical effects from underwater explosions. Due to the rapid autolysis of hair cells, the impact of acoustic trauma and hearing derangement could not be reliably assessed by histopathology.
- Long-finned pilot whales are highly social and known to follow conspecific ‘pilot’ leaders, therefore the presence of disease or derangement in one individual may influence the actions of the whole pod.
- Once the pod was within the Kyle of Durness, navigational error would definitely be a contributing factor to live stranding, as the topography and large tidal range would leave them poorly able to navigate in the rapidly changing, flat and shallow habitat.
- Munitions disposal operations conducted in the vicinity of the Kyle of Durness the day before and during the MSE was the only external event with the potential to cause the MSE.
- The magnitude, frequency and proximity of the multiple detonations in the day prior to the stranding, and the single high order detonation shortly after the beginning of the mass standing were plausible sources of significant disturbance to any neighbouring marine mammals.
- Furthermore, the area of acoustic disturbance from underwater explosions of the magnitude seen prior to this MSE would almost certainly have been larger than the area observable from the rib-based observation platform. Consequently the mitigation practices employed by the Northern Diving Group were insufficient to adequately assess if cetaceans were in the vicinity.

- It is therefore probable that the presence of a potentially compromised animal, navigational error in a topographically complex region and the serial detonation of underwater ordnance were the most influential factors in this mass stranding event.

Table 5 summarises the findings and highlights factors most plausible at having a contributory role in the MSE.

Potential causal factors	Proximity to coast	Entered tidal kyle	Reluctance to leave	Evidence
X No likely influence			? Possible influence	Y Likely influence
Boat strike	x	x	x	No evidence of external injury
Bycatch or entanglement	x	x	x	No evidence of external injury
Acute physical injury	x	x	x	No external trauma apart from that consistent with live stranding and no evidence of physical damage due to barotrauma
Biotoxins from algal blooms	x	x	x	None of the long-finned pilot whale tissue samples were to be above 5ng/g, the minimum limit of detection indicating there were no biotoxin burden affecting these animals
Toxic PCB burden	x	x	x	Total burden was low compared to findings in other cetaceans species PCB induced effects considered very unlikely
Toxic heavy metal burden	x	x	x	Strong correlation between Hg and Se but overall low burden of contaminants
Morbillivirus	x	x	x	No clinical evidence, negative by PCR
Gas/ fat embolism	x	x	x	No evidence on histopathology
Storms or climatic influence	x	x	x	Weather unremarkable prior to and during stranding
Abnormal tides	x	x	x	Decreasing tidal range
Seismic activity or airguns	x	x	x	No seismic survey activity recorded in region
Mid-frequency/sidescan sonar	x	x	x	No Royal Navy activity reported within 50NM at time of stranding
Echosounder	x	x	x	No Royal Navy activity reported within 50NM at time of stranding, no unusual shipping activity in the area.
Fishing activity	x	x	x	No abnormal fishing activity noted around time of MSE
Disturbance by commercial shipping	x	x	x	Busy area for shipping traffic but no unusual activity recorded from Automatic Identification System (AIS) logs
Earthquakes	?	x	x	3.5 magnitude recorded 6 days previously but too far away with land barrier between so not considered likely
Inshore foraging	?	x	x	Possible reason for inshore proximity. No evidence of recent feeding in examined animals. Cephalopod food source reported to be in close inshore waters.
Predator attack/presence	?	?	x	Orca sightings around Orkney 60NM distant, no offshore sightings reported
Infectious disease	?	?	?	One animal with septic shoulder joint, *Brucella ceti* isolated from abscess and testes. Lesion severe but animal not thin. 'Sick leader' hypothesis could have caused group to enter kyle.
Detonation of underwater explosives	x	Y	Y	Three high order (1000lb) bombs detonated within 24 hours of the stranding. One detonation (250lb) on morning of MSE after long-finned pilot whales sighted in Kyle
Navigational error	x	Y	Y	Kyle of Durness could have been confused with neighbouring deep waters of Loch Eribolll or the Minch. Shallow sand and sinusoidal topography of Kyle make an effective 'whale trap' for animals entering on a high tide

Table 5: Summary of findings in the 2011 Durness mass stranding event

Section 26: Conclusion and future recommendations

Following an extensive investigation into a range of factors, munitions disposal operations conducted around Garvie Island the day before and during the MSE, was the only external event with the potential to cause the MSE.

This coincidence in time and space is not in itself sufficient evidence for excluding a simple navigational error of the group, and the effect of a shoulder infection in one of the necropsied cases is ambiguous. Nonetheless, the identified underwater explosions deserve further attention and development of more robust mitigation and monitoring strategies to assess the hazard this activity presents to marine life.

The Royal Navy were keen to highlight that munitions disposal operation at Garvie island had been occurring for several decades without incident and there is no record of other MSEs in this location from the UK stranding records. It has been suggested that historical operations at Garvie Island, and other similar munitions disposal sites around the UK, are investigated to explore any possible coincidence so far between these operations and cetacean stranding events. Such an analysis would reveal if the Kyle of Durness MSE was an isolated event or if unexplained MSEs could be reinterpreted in the light of a better knowledge of munitions disposal operations.

Communication lines with the Ministry of Defence and DECC have been strengthened, and requests for activity logs of operations capable of generating underwater noise now form a core part of UK mass stranding investigation protocols.

Whilst it is important not to attribute definitive causation to tempo-spatial correlation in a single mass stranding event, many acoustic or behavioural triggers do not leave diagnostic lesions which can be detected after the event, and therefore ‘proof’ of either causation or exclusion is difficult. In terms of assessing pathological effects of sound exposure on hearing capacity, techniques have been developed to examine the ultrastructure of the ear and the hair cells responsible for sound transduction. However, due to the rapid autolysis of hair cells, ears have to be extracted and fixed within a few hours of death. Outwith this time window the pathology associated with acoustic trauma becomes indistinguishable from that of autolysis. In this case the logistics of organising necropsies meant the facility to extract and fix the ears was not available and the opportunity to collect information on the impact of acoustic trauma and hearing derangement was missed.

Following the events of the 2011 MSE, investigations into the 2012 mass stranding event in Pittenweem, Fife, prioritised the removal of ears from cases. The outcome of this investigation are detailed in a separate report but as a result of this and subsequent strandings events a protocol has been developed to provide the necessary training and logistical support to improve the success rate of inner ear analysis.

Section 27: Suggested mitigation

This specifically concerns mitigation strategies for the detonation of underwater munitions. Overall, an improvement of the Marine Mammal Observation (MMO) protocol when undertaking activities at Garvie Island is advised. Combining observations from platforms at sea with information from land based observation platforms would enhance the information on the occurrence of cetaceans within the envelope where acoustic damage is likely.

Following a liaison meeting in on 16th July 2012 with members of the NDG the following mitigation practices were discussed with a view to assessing their feasibility for deployment in this and subsequent years.

- Consider deployment of acoustic monitoring equipment in the waters around Garvie Island to properly characterise the extent and magnitude of the detonation blast profile. Systems for real time monitoring are available and this is probably more effective in the long term and more reliable in poor weather.
- Consider deployment of passive acoustic monitoring equipment as a tool to assess the presence of ecolocating odontocetes in the critical area.
- Train and use marine mammal observers to be stationed on appropriate vantage points to scan for cetaceans along a section of coastline either side of Garvie Island. Develop systems for relaying this information to the NDG.
- Improve communication systems between members of the disposal team and shore based observers.
- Wherever possible, use a type of charge to deactivate the device which burns out rather than explodes the target device. This was suggested by members of the NDG as a technique routinely used in some parts of the world. It has a good success rate, but no significant extra cost in terms of time, resources or diver safety. Given the potential damage to marine life from the ‘high order’ explosions of conventional disposal techniques, it is questionable why this method has not been used routinely in the past.
- Avoid serially detonations in a small time window.

It is not clear if any of these measures were taken during subsequent munitions disposal operations however no cetacean strandings were reported from the vicinity of the Kyle of Durness during or after the period of disposal operations in 2012. No unexploded munitions were observed prior to the 2013 range clearance or found during survey. There were therefore no unexploded ordnance detonations off Garvie Island in 2013.

The costs and benefits of mitigation and monitoring have to be assessed and a reasonable balance approach taken, however the particular characteristics of the disposal operations around Garvie Island suggest improved mitigation strategies are necessary, feasible and potentially effective. The ‘whale trap’ topography of the Kyle of Durness combined with the populations of cetaceans known or assumed to use neighbouring waters, and the short, predictable, but potentially significant window during which underwater detonations are conducted, do not preclude a similar event occurring again in future. For that reason consideration of the mitigation suggestions listed above are strongly advised.

Section 28: Acknowledgements

Logistical, technical and scientific input to this investigation was supplied by a large number of individuals, groups and organisations. Their collective time, knowledge and expertise were essential for this work to be undertaken and the authors would like to extend their thanks to all involved in this investigation. Particular thanks are due to all the individuals from Durness and the RN Northern Diving Group who assisted with the stranding refloat and carcase identification and recovery. Extensive photographs were provided by BDMLR and SSPCA, whose staff and volunteers were also instrumental to the successful refloat of so many animals. Thanks to Rod Jones from the Fleet Maritime Environmental Policy centre for collating MoD activity logs and providing valuable feedback on the report. Comments on the draft text were supplied by Harriet Auty, Kate Brooks, Mark Tasker and Alicia Coupe.

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Appendix 1: Email transcripts

date: 9 August 2011 09:11

subject: Royal Navy Northern Diving Group Assistance

This is a reply on behalf of the Royal Navy.

I can confirm that the Royal Navy has been conducting Cape Wrath range clearance for over 30 years without incident. The current team (NDG) had been on task since Tuesday 19th July, and ceased on Thursday 4th August. The range clearance occurs annually, and in more recent years has taken place in July/August each year.

An NDG team member ashore was informed by a local hotelier of the stranding at 1120hrs on Friday 22nd July. He arrived at the Kyle where he made contact with MCA officials, and other locals, who requested NDG's assistance. The whales were already stranding having, according to local eye witnesses, followed a school of salmon into the Kyle. At 13:15hrs he was eventually able to contact the diving team at sea who immediately ceased operations and made their way to the Kyle approx. 6km away. The only underwater detonation that day was at 1250hrs. Prior to that, the last small explosion was at 1417hrs Thurs 21st July. 13:30-13:45hrs the team arrived by boat and were able to assist in shepherding the majority of the pod back out to sea, as well as assisting with the stranded mammals.

Following no further sightings of the whales since Saturday 23rd July, and ensuring the usual Environmental Management Standard Operating Procedures were followed, range clearance recommenced on Thurs 28th July. There is a narrow window of opportunity to complete this work during summer months before resources are redeployed and weather deteriorates.

We can also confirm that the only Royal Naval unit within 50 nm (circa 90 km) of the incident and up to 48hrs before the stranding (1145 22 Jul 2011) was the NDG, with no RN vessels operating sonar. Although we cannot comment on other nation's movements or the whereabouts of any of their vessels at that time, we can confirm that no multi-national exercise activity was planned in the area during this time frame.

The full listing of the detonations by NDG is as follows;

Tue 19th July 11 - Nil detonations – weather precluded EOD operations. Diving training conducted in Loch Eriboll only.

Wed 20th July 11 - Nil detonations – diving search operations Cape Wrath range.

Thu 21st July 11 - 1200 – 2 x 4 lb Plastic Explosive Packs – 1 x 540 lb HE Bomb detonated with High Order recorded.

1215 – 2 x 4 lb Plastic Explosive Packs – No High Order recorded.

1415 – 2 x 4 lb Plastic Explosive Packs – No High Order recorded.

1417 – 2 x 4 lb Plastic Explosive Packs – No High Order recorded.

Fri 22nd July 11 - 1250 – 2 x 4 lb Plastic Explosive Packs – 1 x 250 lb HE Bomb detonated with High Order recorded.

From Sat 23rd July to Weds 27th July there were no detonations carried out by NDG.

The range is closed for the summer so there will be no other military activity being conducted using explosives during this period, and we can also confirm that there were no live firings or bombings during this timeframe.

Regards

Policy Secretariat, Navy Command HQ,

date: 22 March 2012 17:05

Long-finned pilot whale stranding, Kyle of Durness, 22/07/2011

Thanks for your email. I am sorry for the delay in coming back to you but I wanted to make absolutely sure that we had triple-checked the information to ensure that it is accurate.

As regards, the activity on Friday 22nd July, I can confirm that there was only the one RN diving activity on that day. The last diver arrived on the surface at 1239 with the explosion shortly afterwards, as previously advised.

Our detailed analysis has, however, revealed that there was a larger explosion on the Thursday afternoon than previously advised. In particular, I understand there was a high order explosion with 1 x 540 lb and 3 x 1000 lb bombs shortly after 1422 on that day.

I apologise for this omission in the previous information provided; but, as I have indicated, we believe the information provided in respect of events on Friday 22nd July is correct.

Appendix 2: Cetacean ear extraction and fixation protocol

Protocol reproduced with kind permission of Michel Andre, Laboratori d'Aplicacions Bioacústiques, Barcelona, Spain (michel.andre@upc.edu, www.lab.upc.es) a standard ear extraction and fixation protocol can be downloaded at:

www.lab.upc.edu/papers/Ear_extraction_and_fixation_protocol_LAB.pdf

Introduction

There is an increasing concern about the impacts of anthropogenic underwater noise on cetacean populations. For this reason, the analysis of the ears and especially the presence of possible lesions in the organ of Corti represents a fundamental effort to assess the implication of acoustic trauma in stranding events, otherwise not detectable by routine histopathology techniques.

The difficulty relies in obtaining fresh material rapidly fixed by proper solutions and in accessing the cochlea by decalcifying methods without affecting the inner ear soft structures.

The Laboratory of Applied Bioacoustics (LAB) has developed a fast decalcification protocol for use with most of the common odontocete species (see Figure 24) that allows a fast diagnosis of acoustic trauma.

Figure 24: Periotic bone decalcification results from a harbour porpoise (Phocoena phocoena) after an exposition of 26 hours with the rapid decalcifier RDO®. While other decalcifiers need around three months for a similar complex size, RDO® allows obtaining very fast results.

TYMPANIC-PERIOTIC COMPLEX

The tympanic and periotic bones house the middle and inner ear, respectively. These structures are partially fused forming the tympanic-periotic complex (Figure 25). The tympanic-periotic complex is surrounded by aerial sinuses called peribullar sinuses and suspended in the peribullar cavity through ligaments that hold it fixed and acoustically isolated it from the rest of the bones of the skull, except the sperm whales and some beaked whales who present the tympanic-periotic complex partially fused to the temporal bone.

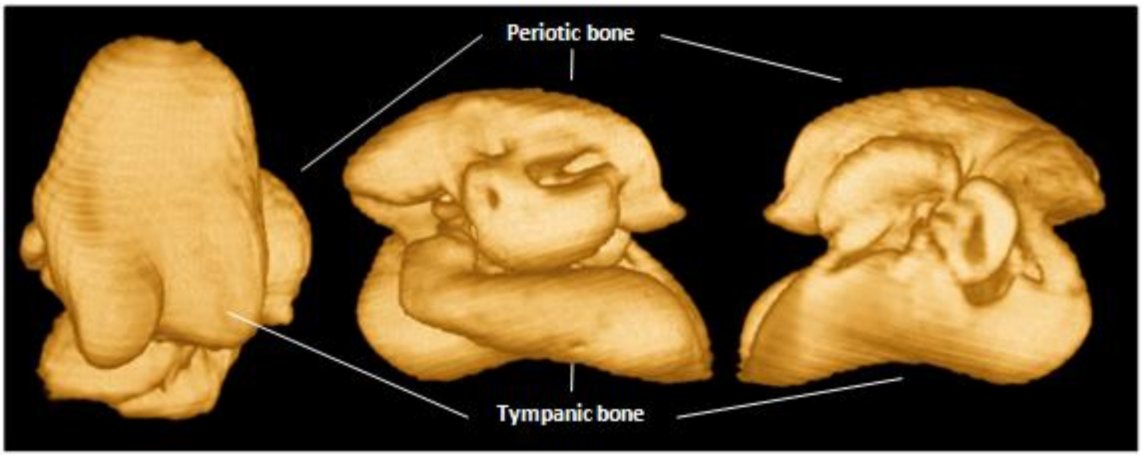

Figure 25: Computerized tomography images 3D reconstruction from the tympanic-periotic complex of a bottlenose dolphin Tursiops truncatus in ventral, medial and lateral vision from left to right, respectively

Extraction

1.- With small specimens, it is recommended to remove the head of the animal for an easier manipulation.

2.- Taking into account the localization of the tympanic-periotic complex), the easiest way to access the ears is to carefully remove the lower jaw.

4.- Situating the head in a ventral position and removing the soft tissues and ligaments (Figure 5) allows to proceed to the tympanic-periotic complex extraction.

5.- Incise **gently around** the tympanic-periotic complex with a small knife (a scalpel can be used for the final stage of the extraction) to cut the ligaments that maintain the ears in the parotic sinus

Fixation

6a.- At that stage, the ear could be fixed simply placing it in a fixative solution: glutaraldehyde 2.5% with phosphate buffer 0.1M (these solutions will be provided). The ears can also be injected with a mixture of paraformaldehyde 0.5% with glutaraldehyde 1% with phosphate buffer 0.1M or alternatively be injected with formaldehyde 10%.

However, for a better result we recommend to follow the protocol described in point 6b.

6b.- If already experienced with the injection protocol, you may want to:

1) separate the periotic from the tympanic bone (Figure 26);

2) cut the stapedial ligament and remove the stapes. If it does not come off easily, it helps passing a scalpel through the junction;

3) make a **little and very superficial** hole to the oval and round window membranes;

4) using a soft catheter from the same diameter as the windows size, **progressively and very slowly (with very little pressure)** introduce the fixative solution (glutaraldehyde 2.5% with phosphate buffer 0.1M) (Figure 26)) through the oval window and the round window until the solution percolates the entire structure.

The ears can also be injected with a mixture of paraformaldehyde 0.5% with glutaraldehyde 1% with phosphate buffer 0,1M or alternatively be injected with formaldehyde 10%.

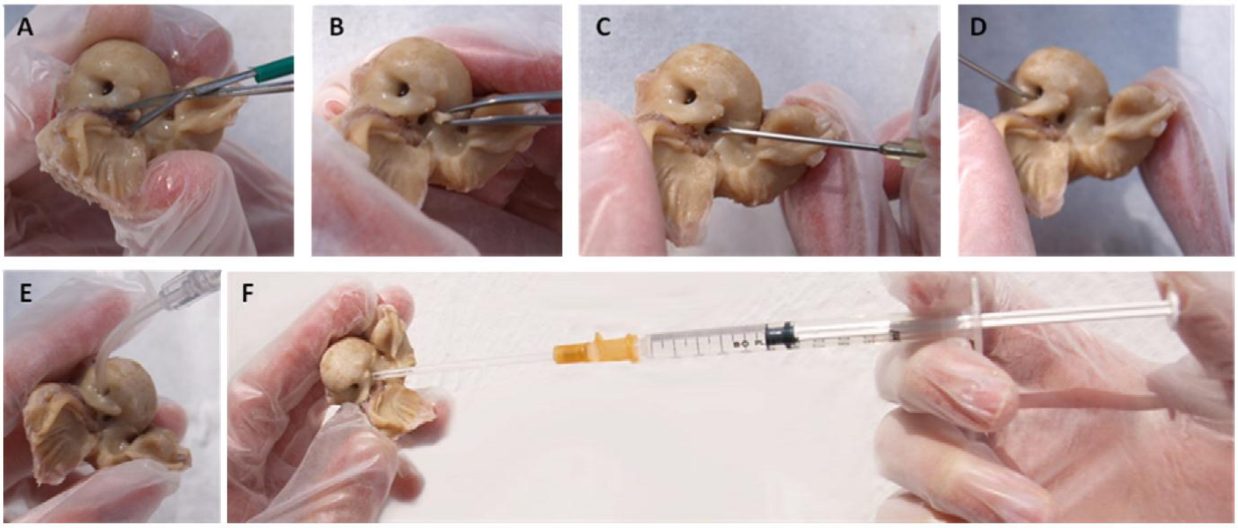

Figure 26: Tursiops truncatus periotic bone used to illustrate all the injection process: A) cut of the stapedial ligament, B) stapes extraction, C and D) realization of a little and very superficial hole to the oval and round window membranes respectively, E and F) very slow and progressive perfusion (with very little pressure) of the fixative through the oval window and the round window until solution has percolated the entire structure.