How Do We Study Killer Whales?

**by John Durban and
Volker Deecke**

Killer whales are the top predators in the world's oceans, abundant in some areas, and perhaps the most recognizable animal on the planet. It may therefore seem somewhat of a surprise that they are difficult to study. However, they are capable of rapid and long range movements, can be cryptic and hard to observe when they hunt and feed underwater, and are found at highest density in productive high-latitude areas, which can be hard to work in due to their remoteness and challenging weather conditions. Nonetheless, this challenge has inspired two generations of field biologists and naturalists to devote their lives and energy to learning about these most impressive of mammals. To do so, we have developed some innovative and state-of-the art research approaches, which we will describe here.
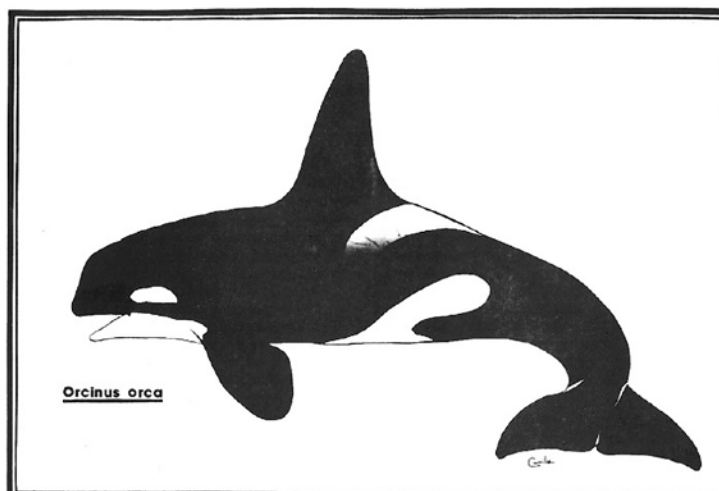
Citizen Science

Research on killer whales is not the sole purview of professional scientists. In more accessible areas, the public has long contributed to our understanding of killer whales by reporting sightings and collecting photographs. In the early 1970s, Mike Bigg and colleagues working with the Canadian Department of Fisheries and Oceans (DFO), and their US counterpart, Ken Balcomb, then working under contract from the National Marine Fisheries Service (NMFS), established public sighting networks as a first step in long-term studies of killer whales in the northeastern Pacific. Sighting networks continue to provide the basis for monitoring studies, even in remote areas like Antarctica, where cruise ship passengers regularly collect sightings and photographs.

Photo-identification

Although sighting data have been useful for identifying areas of regular use by killer whales, population studies have benefitted most from the discovery that individual whales could be readily distinguished from natural markings;

specifically, variability in the shape of the dorsal fin, pigmentation of the adjacent saddle patch, and naturally acquired nicks in the dorsal fin. Mike Bigg developed the tool of photo-identification in the early 1970s using these features to identify individual killer whales from photographs. At the same time, this approach was being developed in studies of humpback whales, right whales and bottlenose dolphins off the east coast of the US. These are not the earliest examples of using natural markings to document individual killer whales: hand-drawn illustrations by Clifford Carl documented individual variability in eye patch pigmentation within a group of killer whales stranded at Estevan Point on Vancouver Island in the 1940s. Ken Balcomb

Have you seen me? Poster distributed in the Pacific Northwest in 1976 requesting information from the public about killer whale sightings. Courtesy of Ken Balcomb, Center for Whale Research, WA.

and colleagues at the Center for Whale Research (CWR), WA., have now used eye patch distinctiveness to document the individual identify of killer whales netted during live-capture fisheries in British Columbia and Washington State in the early 1970s, by comparing archival images to a catalog of eye patch photographs from extant whales. Eyepatches are still the best way to identify very young killer whales before the saddle patch pigmentation develops and the animals acquire characteristic scars.

Fin and saddle patch photo-identification images, with long-term photographic re-sightings of an adult male "southern resident" killer whale (J1, top) and an adult female (J2, bottom) in 1976 (left) and again in 2010 (right), demonstrating the longevity of these distinctive natural markings. Courtesy of Ken Balcomb, Center for Whale Research, WA.

Photo-identification has become the stock tool for research on killer whales, with individual recognition underpinning the majority of studies we conduct around the world. Using long-term photographic records of the same individuals (dating back as far as the late 1950s for "transient" killer whales in the northeastern Pacific), has proven this to be a robust method for individual-based monitoring over the long time periods required to study killer whales with life spans similar to humans. Thanks to diligent and skilled photo analysts like Graeme Ellis (DFO) and Dave Ellifrit (CWR), we now have long-term photo-id datasets that can be used to understand life histories and population dynamics, long-term changes in social structure, and movement patterns. In more remote regions, where it hasn't been possible to conduct full photographic population censuses, John Durban (NMFS) and colleagues have shown how repeated photo-identifications of the same whales have been used as "captures" and "recaptures" in mark-recapture models for estimating abundance and movements.

The ability to recognize individual whales at sea has captivated researchers and the public alike, providing a connection to the individuality of the whales. In his seminal 1987 book, *"Killer whales: A study of their identification, genealogy, and natural history in British Columbia and Washington State,"* Mike Bigg described the excitement during the early moments of a killer whale encounter when the individual identity of the whales was revealed. The advent of digital cameras and access to established photo-identification catalogs now provides this instant reward to a growing third generation of killer whale addicts, continuing to foster a sense of familiarity, interest and "ownership" in killer whale populations worldwide. This level of interest is of great help to researchers, as there are increasing numbers of public naturalists collecting identification photographs which can be used in scientific studies.

In addition to the identification of individual whales from photographs, images can also be useful for identifying killer whales to "type." For example, experienced observers in the northeastern Pacific can differentiate whales from "resident," "transient" and "offshore" killer whale lineages by appearance, and Bob Pitman and colleagues have used a collection of photographs from Antarctic and Southern Ocean waters to describe at least four different types of killer whales based on morphological differences, providing an early clue to genetic differentiation.

Photogrammetry

As top predators, there is considerable research interest in the prey requirements of killer whales, so that we can evaluate their predation impact on endangered marine species and detect threats to killer whales from prey shortages. This requires information on the size, growth and body condition of killer whales. John Durban and Kim Parsons, working with NMFS and CWR, developed a novel approach for obtaining morphometric measurements using two parallel laser-beam pointers to project a scale of known size that can be photographed on the whale's fin or body, and this is now being used to obtain measurements from several killer whale populations around the world. The advantage to this approach is that it can be implemented alongside photo-identification studies to monitor the long-term growth of identified individuals.

However, it has not been possible to measure total body length using the laser-metric approach because parts of the whale remain submerged, although length can be estimated if body proportions are known. Similarly, width measurements are unavailable, and these may be particularly useful for assessing changes in body condition. However, both these measurements can be directly estimated using aerial photogrammetry, where an aircraft is used to obtain high-quality images from directly above whales, and the altitude of the aircraft and focal length of the lens can be used to scale the image to a real size. Bob Pitman and colleagues first used this approach to measure body lengths of killer whales in Antarctica, and recently Holly Fearnbach, John Durban and CWR colleagues matched aerial photogrammetry images to a saddle-patch identification catalogue to obtain length and width measurements from known southern resident killer whales in WA and BC waters, so that size-at-age could be estimated to evaluate long-term growth trends.

Knowledge of the size and body proportions of killer whales around the world can also help to refine our understanding of the taxonomic divisions within killer whales – together with genetic differences this information can be used to suggest different lineages, which may represent different species. Bob Pitman's aerial photogrammetry study showed that
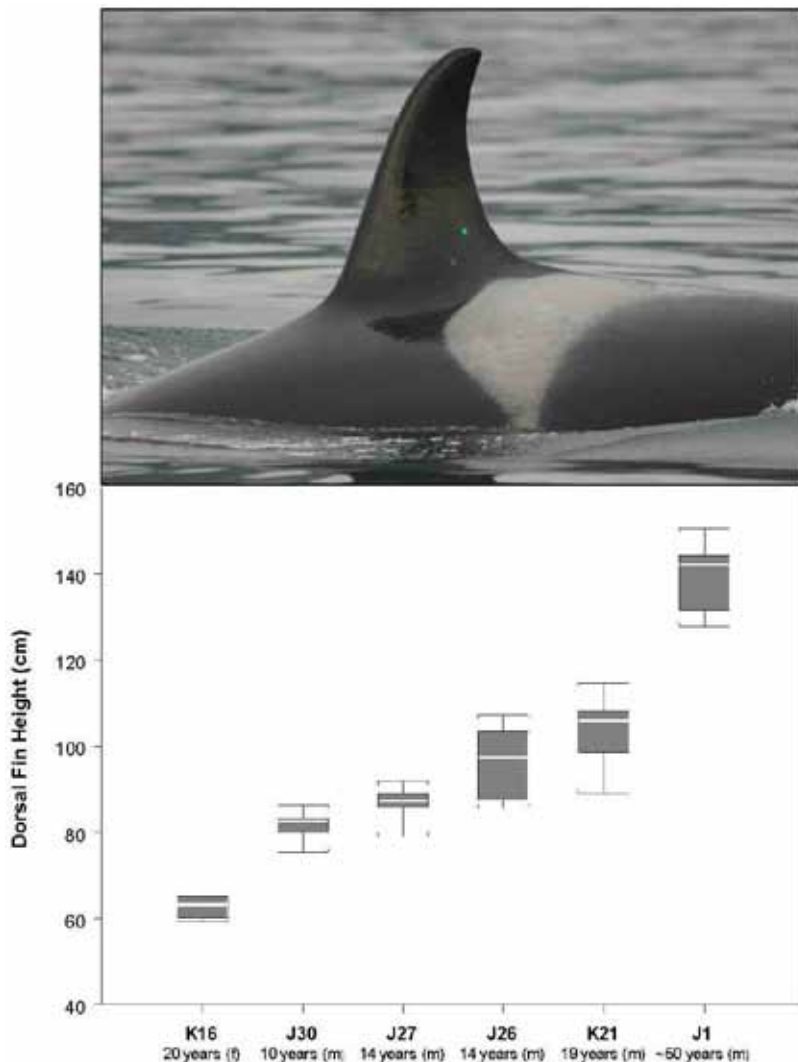
Two green laser-dots of 10cm separation projected onto the fin of an adult female killer whale to provide a scale of known size (top); repeated measurements of dorsal fin height using laser-metrics for 6 southern resident killer whales of varying age and sex (bottom). Adapted from Durban and Parsons, 2006. Marine Mammal Science 22:735-743 (Photo by John Durban, Center for Whale Research, WA).
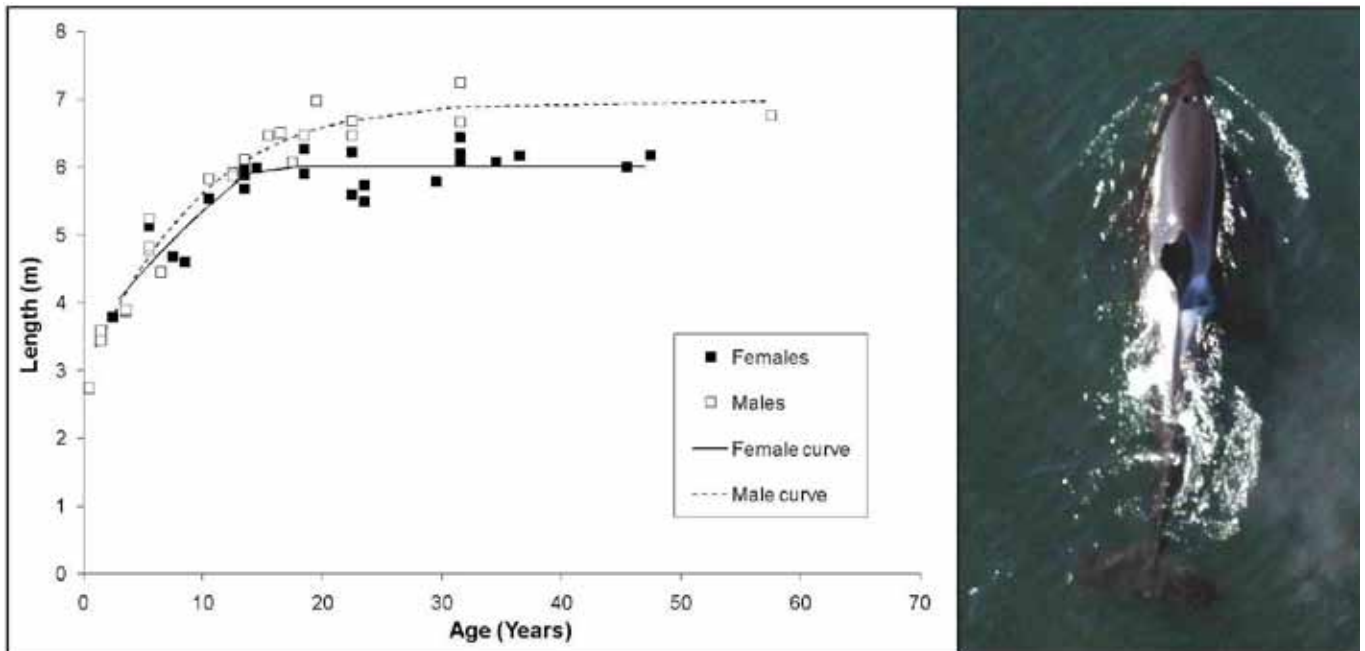
Total body length for southern resident killer whales of known age (left), estimated from aerial photogrammetric images of individually-identifiable whales taken from a helicopter at known altitude (right). Adapted from Fearnbach et al. 2011. Endangered Species Research 13: 173-180 (Photo by Holly Fearnbach, Center for Whale Research, WA).

Antarctic type C killer whales from the Ross Sea are significantly smaller than killer whales measured elsewhere, further supporting genetic inference that "Ross Sea Killer whales" may be a distinct species. Aerial measurements, laser measurements and the size of stranded animals have been used to scale Uko Gorter's fantastic illustrations of the world's (currently recognized) killer whale ecotypes, which form the centerfold of this special issue.

Acoustic Research on Killer Whales

Much like we can identify individual killer whales from natural markings and can tell different populations and lineages of killer whales apart from the way they look, we can use sound to identify killer whale groups. Like other dolphins, killer whales produce three types of sounds. *Echolocation clicks* primarily function in orientation and prey detection: the animals emit these sounds and listen to the echoes reflect from objects which they use to obtain a three dimensional representation of their surroundings. *Whistles* are high frequency sounds that are probably used in communication over relatively short distances whereas *pulsed calls* are long-range communication signals that killer whales use to communicate over
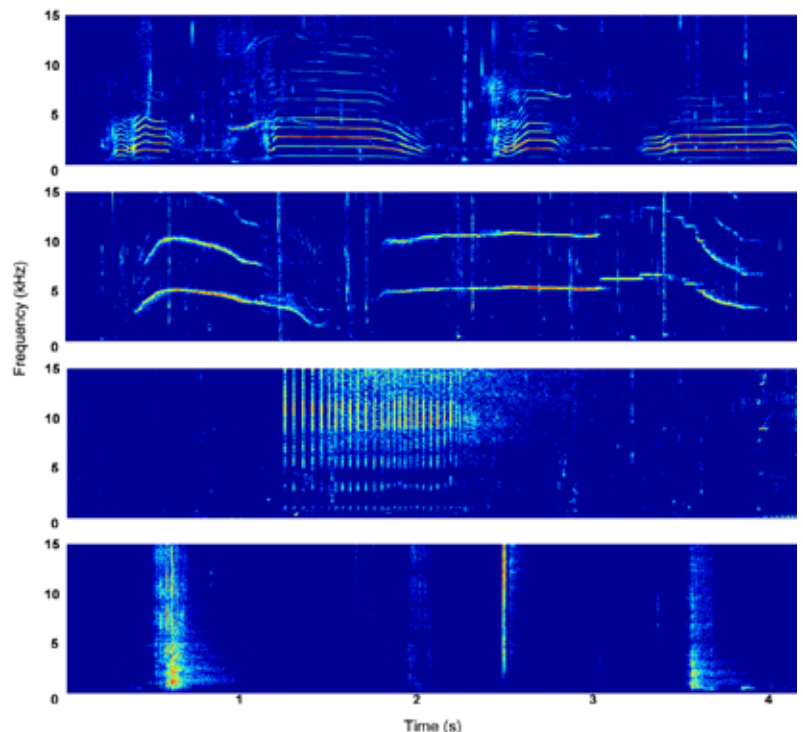
Spectrograms of (from the top down): pulsed calls, whistles, echolocation clicks and prey-handling sounds recorded from transient killer whales.

tens of miles. John Ford and Dean Fisher at the University of British Columbia first showed that killer whales have group-specific repertoires of stereotyped pulsed calls that we can use to tell different populations apart. Ford found that in some populations these dialects are so variable that we can use them to identify individual family groups. This means that we can track the movements of such groups with a minimum of field work, simply by deploying autonomous recording devices in strategic locations throughout their range. These devices are mounted on the sea floor, make a short recording at set intervals and can be deployed for up to a year. Once the devices are recovered and the data downloaded, the stereotyped call types in the recordings can tell us when certain killer whale groups passed in the vicinity of the recording device.

Observations of Predation and Prey Sample Collection

Knowledge of the predatory role of killer whales clearly requires data on diet and prey preferences. The most direct source of data are observations of hunting and feeding behavior, which are easiest to make when killer whales capture big prey, such as large whales, or seals that can be observed to be taken from ice floes. However, even then these observations can be scarce and hunting/feeding behavior can be cryptic and hard to interpret. Observing kills requires long hours of effort, and careful observation protocols – for example, being far enough away to not disrupt hunting but close enough to confirm the prey species taken. Confirming kills requires robust standards for observational data, for example seeing the prey being broken up or consumed, generally involving the presence of birds and an oil sheen on the surface of the water, which is often associated with a fishy odor. Without these signs, it cannot be clear if a successful predation event occurred, or if the prey escaped. Such clear observations of predation can be rare to acquire – for example, it took more than ten years of observations before transient killer whales in the northeastern Pacific were confirmed to take marine mammal prey.

Rather than looking for signs of killer whale kills, a better strategy may be to listen for them. Work by Lance Barrett-Lennard and Volker Deecke has shown that killer whales hunting marine mammals typically keep quiet when searching for prey but produce calls, whistles and echolocation clicks after a successful kill. While many fishes have poor hearing abilities, all marine mammals have excellent underwater hearing and can probably detect killer whale sounds over significant distances. This means that mammal-eating killer whales need to rely on stealth to get close to their prey, but start calling, whistling and clicking once an attack has been successful. Researchers

can follow groups of killer whales while monitoring their vocal behavior with hydrophones and use such bouts of vocalizations as an indicator that a kill has occurred. Using this approach, Volker Deecke and colleagues have shown that groups of killer whales dismembering a marine mammal carcass also generate characteristic cracking and crunching sounds as bones are broken and blubber is stripped and these so-called Killing, Ramming and Crushing Sounds (KRaCS) are a clear indicator that an attack was successful. We can even use sound to study killer whale diets by asking potential prey species how they feel about certain killer whale groups: harbor seals in the Northeast Pacific for example respond very strongly to the calls of mammal-eating transient killer whales, but completely ignore the harmless fish-eating residents.

Once a kill has been confirmed through observation or listening, it has become standard to collect prey fragments, which can be used to identify the prey species. For example, John Ford, Graeme Ellis and colleagues have collected fish scales and tissue fragments from the vicinity of feeding eastern North Pacific resident killer whales for almost 40 years: scale analysis and aging techniques have been used to assess both the species and age of fish taken. Molecular genetic analysis has further been used to confirm species identity from both scales and tissue and in the case of Pacific salmon, can even tell which river the salmon spawn in. Marine mammal prey have also been identified using molecular genetic analyses of prey remains, notably in a study of transient killer whales feeding on submerged carcasses around Unimak Island, Alaska, where Lance Barrett-Lennard and colleagues used molecular genetic analyses of surfacing chunks of tissue to confirm that the carcasses belonged to gray whales. A similar method was used to confirm sharks, particularly sleeper sharks, as a key

Prey remains recovered from killer whale kills for genetic analysis to determine the prey species: Chinook salmon scales on the left; Steller sea lion remains on the right (Photo courtesy Lance Barrett-Lennard and Volker Deecke).

prey item of offshore killer whales in the northeastern Pacific, allowing quantification of the number of individuals taken during an eight-hour encounter.

Recently, the collection and analysis of killer whale feces has been developed as a further source of direct data on killer whale prey habits. NMFS scientist Brad Hanson and colleagues working in the San Juan Islands, WA, have demonstrated how fecal samples can be collected by patiently following behind the whales, with co-workers from Sam Wasser's laboratory at the University of Washington using a trained sniffer dog (a black Labrador retriever) to increase the number of samples collected.

Juvenile killer whale equipped with a digital recording tag. The tag is attached by four suction cups and records the whale's underwater movements as well as any sounds it makes or hears. Photo by Volker Deecke

Molecular genetic techniques can then be used to amplify the DNA of partially-digested prey species, as well as killer whale DNA from sloughed cells of the gut lining. The same fecal samples are currently being used to measure stress hormone levels of whales relative to periods of food limitation, and to conduct hormone assays to assess reproductive status.

Suction Cup and D-tags

A persistent problem when studying the behavior of killer whales and other cetaceans is that most of it happens underwater and out of our view. Listening to whales rather than looking at them is one approach to address this challenge, however, recent technological advances offer even more exciting insights into the underwater behavior of killer whales. Miniaturization of sensors and electronic components has led to the development of data loggers small enough that they can be attached to killer whales non-invasively with suction cups. Robin Baird, working with Simon Fraser University in Burnaby and Dalhousie University in Halifax, was the first to attach time-depth recorders to killer whales to investigate their diving behavior. That study documented significant differences in the diving behavior of males and females.

A sophisticated D-tag developed by Mark Johnson and Peter Tyack at Woods Hole Oceanographic Institution not only records continuous time and depth, but also carries a compass and acceleration sensors to record the three-dimensional movements of tagged killer whales at very high resolutions (enough to resolve individual fluke beats). In addition, the tag has two built-in hydrophones and can record high-quality underwater sound for up to 24 hours allowing us to detect any sound the tagged individual produces or hears. For the very first time this tag therefore enables us to correlate vocal behavior and underwater movements of killer whales providing exciting insights into how these animals use sound to coordinate movements and how they respond to sound stimuli in their environment. Volker Deecke, Patrick Miller and colleagues have used such digital
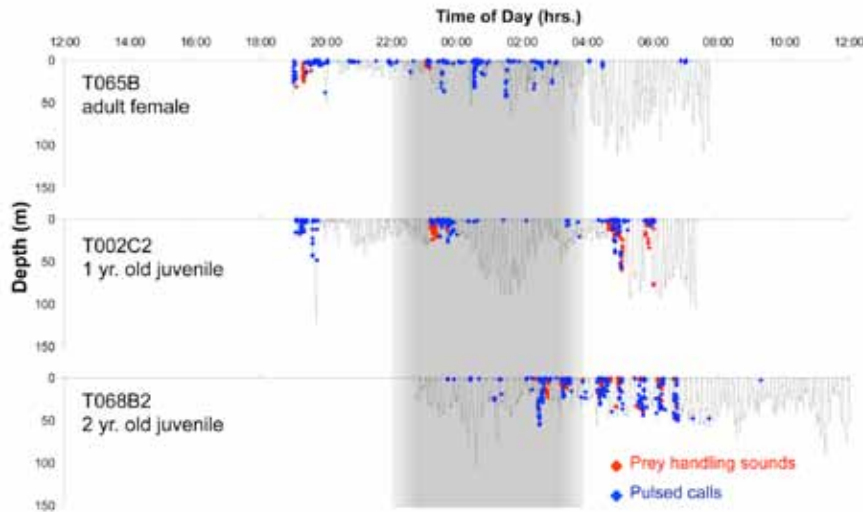
Dive profiles of three transient killer whales outfitted with digital recording tags in Southeast Alaska. Gray shading indicates the hours of darkness. Red diamonds designate characteristic crunching sounds indicative of a marine mammal kill, blue diamonds designate bouts of vocal behavior. Courtesy of Volker Deecke

recording tags to study the night-time behavior of transient killer whales in Southeast Alaska. The tags allowed them to document successful attacks even in complete darkness by listening for bouts of vocal behavior and characteristic crunching sounds generated during prey handling. This showed that transients are also able to find and capture marine mammals at night without needing vision to locate their prey.

Biopsy Sampling

In the 1990s, Lance Barrett-Lennard from the University of British Columbia and


A small 9g biopsy dart (orange tail) is fired by a pneumatic rifle and bounces off the saddle of a transient killer whale in Alaska, with a small inch-long cutting tip collecting a 0.5g plug of skin and blubber for a suite of laboratory analyses. Photo by Dave Ellifrit, NOAA Alaska Fisheries Science Center, NMFS Permit No. 782-1719

colleagues at DFO developed a remote biopsy system using a lightweight dart to collect a skin and blubber sample from free-swimming killer whales. At the time, no one could have imagined the range of studies that would be possible using this small tissue sample, about the size of a pencil eraser. Now, hundreds of biopsy samples have been collected from killer whales throughout the world, enabling a whole suite of laboratory-based analyses to assess dietary preferences, contaminant loads, approximate age, patterns of relatedness, population structure and species identity.

Dietary preferences can be inferred through chemical analyses of fatty acid composition of the blubber portion of the biopsy sample, as well as stable isotope ratios in the skin plug. Notably this has been used by Peggy Krahn, David Herman (NMFS) and colleagues, who were able to use these chemical signals to document the persistent prey specializations of residents (fish) and transients (marine mammals) over a wide area of the North Pacific, and to infer that the diet of transients was comprised of a variety of marine mammal prey, not solely or primarily endangered Steller sea lions. These qualitative inferences are a useful supplement to direct observations of predation and prey sample collection, which have been limited in remote waters.

A surprising, but powerful, discovery was that it is possible to estimate the age of killer whales from their blubber fatty acid compositions. This discovery was made by David Herman and colleagues during investigations of diet, and was validated by examining the estimates for animals of known age from long-term photo-identification studies. Relatively precise estimates (within three years of the known age) were possible for males and females of both residents and transients, demonstrating the general utility of this approach. This technique therefore allows aging and age structure analysis
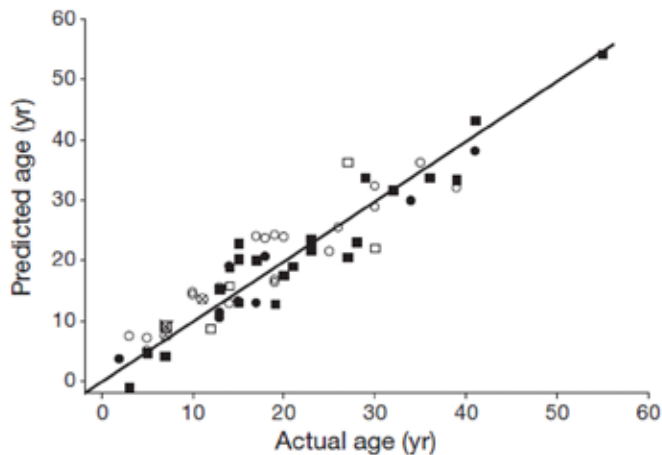
Plot showing the significant relationship between the actual ages of 59 known-age resident and transient killer whales and the ages predicted from their outer blubber fatty acid compositions. Adapted from Herman et al. 2008, Marine Ecology Progress Series 372:289-302

in populations for which long-term demographic monitoring has not been possible, and has been used to compare the age composition of transient and resident populations in the Gulf of Alaska and Aleutian Islands.

Persistent organic pollutants (POPs) are acquired when killer whales eat contaminated prey, and accumulate in their blubber layers throughout their lives. Peter Ross and colleagues at DFO first measured high concentrations of POPs (e.g. PCBs) in blubber biopsy samples of killer whales, highlighting potential health risks if and when these blubber fat stores are metabolized and when fat is passed from lactating females to their young. Peggy Krahn, Gina Ylitalo and colleagues at NMFS have also shown how POP "signatures" can be traced to pollution sources and therefore used to infer feeding in specific regions. For example, they have identified a "California signature" to infer repeated feeding in California Current waters by part of the endangered southern resident killer whale population that is more regularly encountered off Washington and British Colombia during the summer months.

Molecular genetic analysis of killer whale DNA was the first use of skin biopsies, but is also an approach that continues to develop and provide fascinating insights. Lance Barrett-Lennard used genetics to assess patterns of relatedness within and between killer whale populations in the northeastern Pacific, including examining the mating systems of killer whales by identifying parentage. This work on population structure is now being extended by Kim Parsons and colleagues working more widely in the North Pacific, and is also being conducted in the North Atlantic by Andy Foote and co-workers. Genetics can also be used to infer the evolutionary relationships of different killer whale populations, and recent sequencing of the full

mitochondrial genome has provided sufficient detail to perform an examination of worldwide relationships among killer whales, suggesting the possible existence of multiple species. Intriguingly, the same sequences can be used to examine parts of the genome that are under selection – for example, Andy Foote and colleagues have recently shown that the two types of killer whales regularly encountered in icy Antarctic waters (types B and C) are under selection for altered cellular metabolism, perhaps an adaptation to living in the extreme cold. We expect further investigation will provide some key insights into the evolution of killer whales, offering clues to their success in occupying the varied habitats of all the world's oceans.

Satellite Telemetry

Understanding the ecological impact of killer whale predation, the factors determining their distribution and the relationship between killer whale types requires data on their movements. Although it is possible to infer the movements of some populations from intensive and long-term photo-identification efforts, this is generally not the case, particularly in remote environments, challenging winter seasons, or new study areas. In these situations, satellite transmitter tags have emerged as a practical tool for directly monitoring movements beyond the time frames possible in costly field surveys. Recent advances in satellite tag electronics have allowed tags to be developed that are small enough to be deployed externally on the dorsal fin using crossbows or pneumatic rifles, without the need for physical capture and restraint. Specifically, Russ Andrews from the Alaska SeaLife Center and University of Alaska

A small 40g satellite LIMPET tag attached to the dorsal fin of an adult male transient killer whale in Alaska. The red arrow indicates the tag location. Photo by John Durban, NOAA Alaska Fisheries Science Center, NMFS Permit No.782-1719
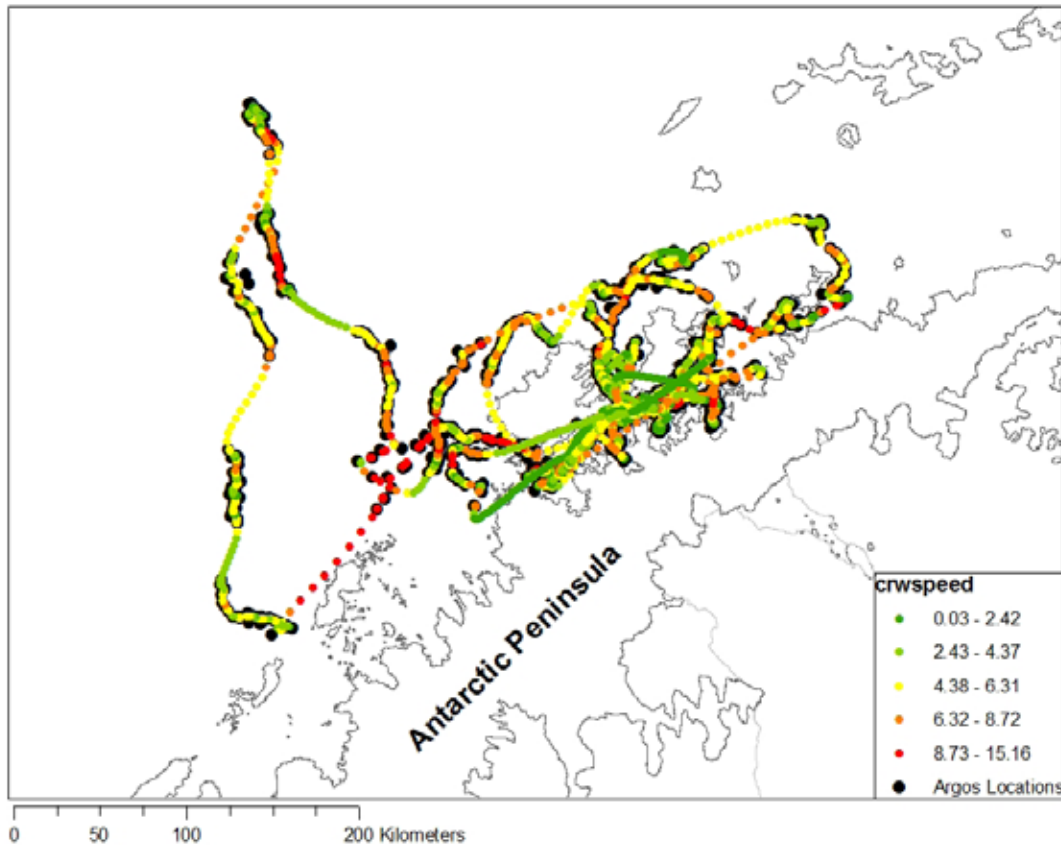
Movement track of a type A killer whale on the western side of the Antarctic Peninsula over a 44-day deployment of a satellite LIMPET tag. Closed black circles show locations calculated by satellite receptions of tag transmissions, and a movement model has been used to estimate displacement speeds (in km/hr) along the track. Courtesy of John Durban, NOAA Southwest Fisheries Science Center.

in Fairbanks has developed a Low Impact Minimally Percutaneous External Transmitter (LIMPET) tag, which attaches to the outside of the dorsal fin using two titanium barbs. More than 50 of these small, 40g tags (smaller than a standard box of matches) have now been deployed on killer whales, primarily in remote study areas in Alaska and Antarctica, with tag longevity of more than 100 days and tracked individual movements of more than 9000 km (5,600 miles).

Regular transmissions from these tags can be used to provide information on fine-scale movements and habitat use. Furthermore, these transmissions can be received by satellites and processed in near real-time, which can be used to guide field teams to find whales for more frequent observations. For example, Bob Pitman and John Durban were able to use satellite tag locations to re-find focal groups of type B killer whales in the Antarctic pack-ice almost daily over multiple weeks to greatly increase the number of feeding observations possible in this challenging environment. With continued advances in electronic miniaturization and battery technologies, we expect future versions of LIMPET tags to be even smaller, and also to incorporate additional sensors to study diving behavior and relatively fine-scale changes in movement, further providing a window for remotely viewing the behavior of killer whales.

An Ongoing Legacy

We are indebted to the pioneers of killer whale research – Mike Bigg, Graeme Ellis, Ken Balcomb and John Ford. We have learned from them, been inspired by their work and commitment, and we try to follow their example. We now have a growing toolbox of research methods which we can use to unveil the fascinating lives of killer whales around the world. We hope this special edition will similarly inspire a new generation of killer whale researchers to join in this challenge.

Whalewatcher

Killer Whale:

The Top, Top Predator

Special Guest Editor
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American Cetacean Society