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The movements of Great White Sharks (Carcharodon carcharias) *at Guadalupe Island*

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Great White Shark *Carcharodon carcharias* in front of First Canyon.
Photo: John Block

INTRODUCTION

The Great white shark (*Carcharodon carcharias*) is widely distributed, and located throughout temperate and sub-tropical regions in the northern and southern hemispheres. It is primary found close inshore to the surfline and even penetrates shallow bays, estuaries and the intertidal zone in continental coastal waters, but also frequents offshore continental and oceanic islands (especially those with pinniped colonies) and inshore and offshore fish banks. Relatively little is known of the abundance of this species, except that it is uncommon to rare compared to most other sharks where it lives. Pronounced periodicity in white shark abundance may occur in some areas, apparently correlated with temperature and to some extent with life stage, or by movements in response to prey concentrations or other stimuli (Compagno, 2001). In the waters off California and Mexico, white shark abundance varies seasonally and geographically, although over a large portion of the coast they are encountered year round (Klimley 1985, Long *et al*., 1996). White sharks also are known from the waters near the offshore Mexican islands of Cedros, San Benito and Guadalupe (McCosker and Lea, 1996). The latter is considered an important white shark aggregation site in the eastern Pacific and site fidelity has been indicated through repeated annual sightings of individuals. White sharks are present at the Island minimally between the months of July and January with August through December being the peak months (Domeiere and Nasby, 2007). Researchers have discovered that while away from the island, members of the species frequently travels to an area halfway between Baja California and Hawaii. The reasons for this behavior have not yet been identified but a mobile source of food like tuna could be a possible explanation (Domeiere, personal communication). Although the long scale movements (migrations) of the sharks from the island to other locations have been studied, the local movements remain unknown. The overall objective of this study is to describe the movements and behavior of the Great White Sharks in Guadalupe Island, Mexico.

STUDY AREA

Guadalupe is an oceanic island located approximately 260 km off the Pacific coast along the Baja California peninsula in northwestern Mexico. Guadalupe Island is about 36 km long on its north–south axis and 12 km wide on the east–west axis, with an approximate surface area of 250 km. The island is the peak of a seamount, which may have originated from several eruptive episodes, with the oldest exposed rocks being dated around 7 million years old (Moran 1996). The island is surrounded by depths of 3,600 m or more, it lacks a coastal platform, with the exception of the south end where there is a 4 km by 200 m depth platform between the island and the outer islets. The coast is composed of basaltic rocks, lava formations and cliffs (Pierson, 1987). The subtidal zone is composed of basaltic blocks, holes, crevices, caves, docks, basaltic columns, basaltic walls with vertical falls, grey-black sand and pebble bottoms (Stewart and Stewart, 1984). Guadalupe Island is in the south area of the California Current System (CCS) characterized for its upwelling. The conjunction of nutrient rich waters with the solar light generates an extraordinary productivity that explains the biological richness of this region. The Island is an important area of concentration of marine fauna, especially invertebrates, 126 species of fish, three species of pinnipeds and 18 species of cetaceans (Gallo-Reynoso and Figueroa-Carranza, 2005).

MATERIALS AND METHODS

Telemetry data for this paper was collected in October, November and December of 2006, and October and November of 2007. Sex and conspicuous characteristics of each individual were determined

Figure 1. Map showing important locations of Guadalupe Island

using underwater videos obtained when the shark was attracted to the boat (7 m fibber glass Mexican panga) with a piece of bait. Total lengths were estimated from repeated observations of the sharks next to the 7 m vessel. Temperature, swimming depth and movement data were obtained from five individuals (two females, approximately 4.9 and 5 m in length, and three males approximately 1.8, 3, and 4.5 m in length) using acoustic telemetry. Sharks were tagged by inserting a metallic dart into the dorsum (behind the first dorsal fin) with a tether attached to the depth and temperature sensing transmitter (V32 TP, Vemco Ltd.) using a pole spear. To determine if one of the females was feeding on seals, we used an internal transmitter (V32 T, Vemco Ltd.) with a temperature sensor in order to detect the rise in stomach temperature associated with swallowing warm-bodied mammals (Klimely *et al*., 2001). The attachment method consisted of inducing the shark to swallow a piece of bait with a transmitter hidden inside. Immediately upon tagging, sharks were monitored using a directional hydrophone and ultrasonic receiver (VR 100, Vemco Ltd.) designed for tracking of aquatic animals from a small boat. All data were gathered intermittently (when weather allowed and the shark could be located) over the two to three months period.

RESULTS

Data for the five tracked white sharks are given in Table 1. Initially we will describe the tracks of the five different sharks on an individual basis. After that, we will draw special attention to the differences in the behavior and movements among age classes.

GWS-1. This male juvenile was initially tagged at 13:40 h on 10 October 2006 off First Canyon in the northeastern part of the island. It was found again on 10 November 2006 in the northern part of the bay. The shark swam north and south parallel to the coast during the entire track from Playa Norte to Palms Beach. The shark remained in the northern part of the bay during the day whereas at night it remained in the south (Fig.2 a). At the beginning of the track (12:52 hrs), the shark was near the surface (18 m); and from 13:18-15:58 hr, it began a series of diving oscillations between 37-80 m. At 15:59 hrs, the shark began another series of oscillations from near the surface to 45 m over a period of nine hours. After this, the shark made four vertical excursions between 59-68 m that continued until 6:14 hrs. After sunrise the shark made deeper dives reaching 90 m (Fig. 3a). GWS-1 showed a preference for shallow waters at night, spending 74% of the night between 10 and 30 m During the day 60 % of his diving oscillations were between 40 and 70 m (Figure 4a). The shark swam in water with temperatures between 10-22 °C with an average of 18.1 ° C appearing to favor warmer waters, spending 40 % between 20 and 21 ° C (Fig. 5 a).

GWS-2 was tagged with two transmitters (internal temperature-sensing, and external temperature-depth sensing) at 13:11 hrs on 23 November 2006 off First Canyon. On 5 December 2006, the shark was found between Punta Costilla and Shipwreck heading east. When it was 1.5 km away from the shore, it headed south reaching Nursery. It then switched direction to the north at 4 km to the east off Twin Canyons. Then it headed toward the coast at Palms Beach and maintained a northerly coarse parallel to the shore. It remained 2.5 km to the east between First Canyon and Playa Norte for some time and returned to the southeast. By 18:00 hrs, it moved again in front of Nursery. Afterwards she started to swim towards Palms Beach where she stayed for a while. By 05:00 hrs it was 1.6 km to the east of First Canyon and it remained for a considerable time away form shore (>1.5 km) between First Canyon and Twin Canyons. We stopped to follow the shark after 24 h at 1.6 km to the east of Twin Canyons. During the night GWS-2 traveled parallel to the shore for certain time but in the day she moved to wa-

Table 1. Sharks tracked in Guadalupe Island during 2006 and 2007.

Shark No.	Estimated Total Length (meters)	Gender	Transmitter	Tracking Date	Start Location	Track Duration (hours)
1	3	Male	External	10-11 Nov 06	First Canyon	22:23
2	4.5	Female	Ext. / Int.	5-6 Dic 06	Campo Norte	24:01
3	1.8	Male	External	7-8 Oct 07	Campo Norte	18:34
4	4.5	Male	External	3-4 Nov 07	Campo Norte	20:14
5	5	Female	External	10-11 Nov 07	Campo Norte	23:36

ters deeper than 365 m (Fig 2 b). When it was found, GWS-2 was over a depth of 186 m. By 10:35 hrs, it was at the surface for a brief period and it dived to a depth of 188 m. From 10:31- 15:33 GWS-2 began a series of diving oscillations between 138 m to 214 m. At 15:46 hrs, the shark started to go up and down remaining between 37 m and 100 m. At 01:37 GWS-2 began a series of diving oscillations form the surface to 200 m (Fig.3 b). GWS-2 showed a preference for deeper waters than GWS-1 at night, spending 71% between 70 and 90 m. During the day 55.8 % of his diving oscillations were between 160 and 220 m (Figure 4 b). This shark experienced a temperature range from 9 to 21 °C, appearing to favor cooler waters than GWS-1, spending 56% of the track in waters less than 12 °C (Figure 5 b). The data collected from the internal transmitter demonstrate that the internal temperature of the shark's stomach was maintained around 26 °C even when the shark dived more than 180 m with a water temperature of 9 °C. Although there was no feeding event recorded in the tracking data, two records of predation events were recorded on the island during our study. The first one was recorded on October 13th 2005 and the second one on October 4th 2007. In both cases the attack location

(N 29° 08.987' W 118°17.172' halfway between First canyon and Campo Norte) and the prey (juvenile northern elephant seal) were the same. In both occasions, the shark bit the pinnipeds from behind first. The seals were apparently disabled though still alive, they did not swim away. In less than two minutes, the shark attacked again, this time actually to consume the preys.

GWS-3. This 180 (TL) young of the year was tagged in front of First Canyon on 3 October 2007. The shark was found again in front of Twin Canyons on October 7th and the shark was tracked for 18 hours. During the track, the shark traveled continuously within a confined area of the northeast bay of the island from First Corner to Palms Beach (Fig. 2c). When it was found it was at 22 m and for the next hour he made regular dive oscillations between 32 m and 11

m. After that the shark remained between 30 and 70 m for three hours. By 19:58 h, the shark surfaced and after one hour it descended to 76 m. The shark remained between 5 and 40 m for 8 h with just two deep dives. Early in the morning the shark stayed between 40 and 80 m for 1:30 h and after another visit to the surface, the shark remained between 5-27 m for the rest of the tracking period (Figure 3 c). GWS-3 showed a similar distribution to GWS-1 of depth and temperature preferences. As GWS-1, GWS-3 spent more time in shallower waters at night, with a peak at 10–29.9m (Figure 4 c). During the day the peak was recorded at the same range. The shark preferred water temperatures between 13.8 y 21.2 ° C with the peak between the 20 and 21 ° C (Figure 5 c).

GWS-4. This 140-cm TL male was tagged and released on 3 November 2007 in front of First Canyon. The shark was tracked just for twenty hours because it moved almost 3 km to the southwest of the island, and it was too rough to operate our skiff safely. From the tagging site, GWS-4 headed northeast, swimming close to the shore until it was at about 0.49 km to the east of Punta Norte, when the shark turned almost toward the southwest and returned to the tagging site. After that, it turned southeast close to the shore heading towards the outer islet. When it reached this point, it turned to the west 3.53 km where we lost contact with it at 10:08 a.m. (Fig. 2d). After his release at 13:46 h, GWS-4 immediately began a series of regular diving oscillations between the surface and 115 m. By 9:28 the shark did the deepest dive (311 m) recorded during the study and remained between 237 and 283 for the rest of the tracking (Fig. 3d). GWS-4 showed a similar preference for 10 - 50 m waters at night and day (Figure 4 d). During night and day most of his diving oscillations were between 40 and 49.9 m.

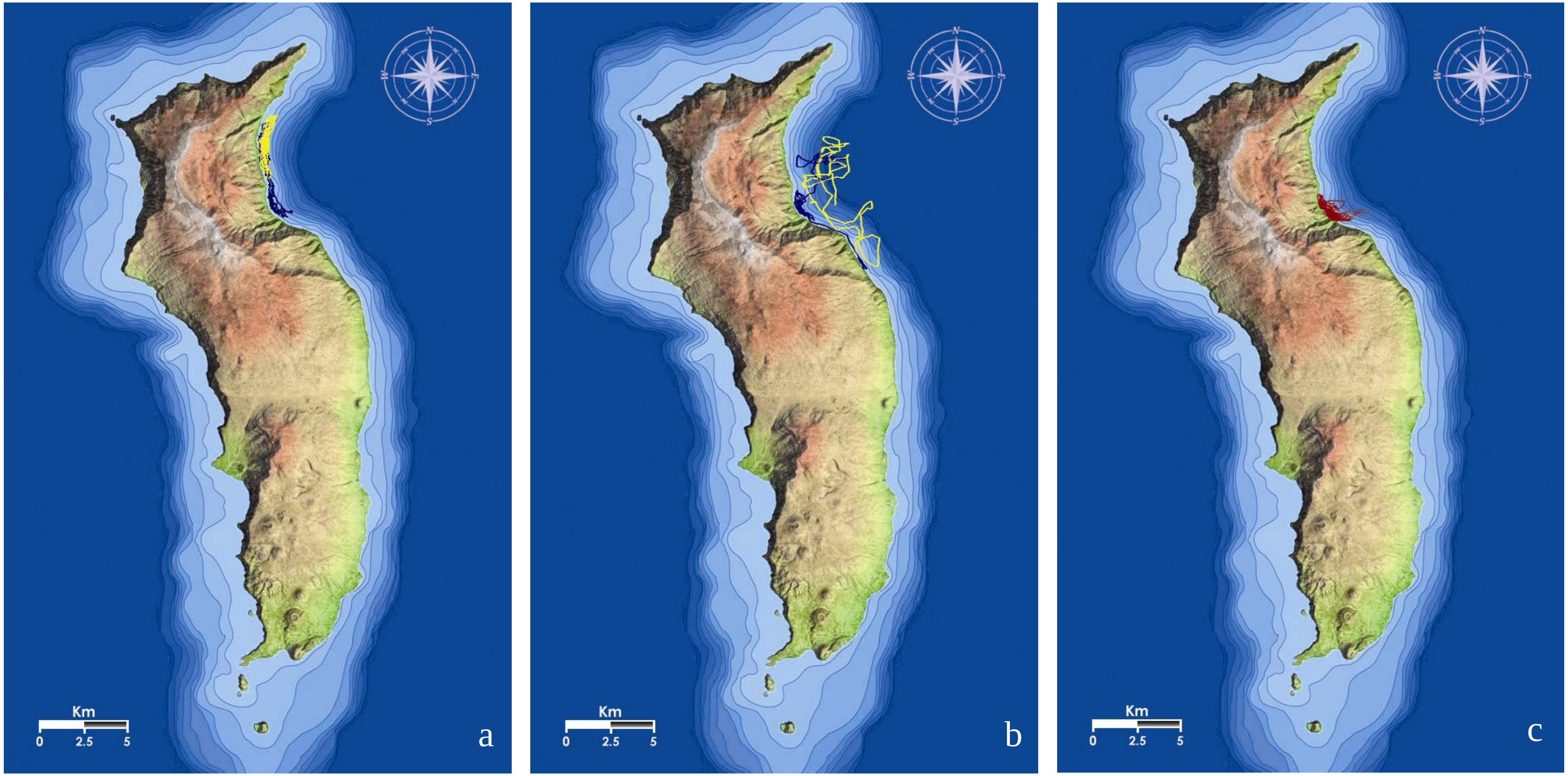

Figure 2. Tracks of three white sharks GWS-1(a), GWS-2 (b) and GWS-3 (c) at Guadalupe Island. Blue line represent night movements and yellow line day movements. In the last case the 24 hrs tracking is showed as red line.

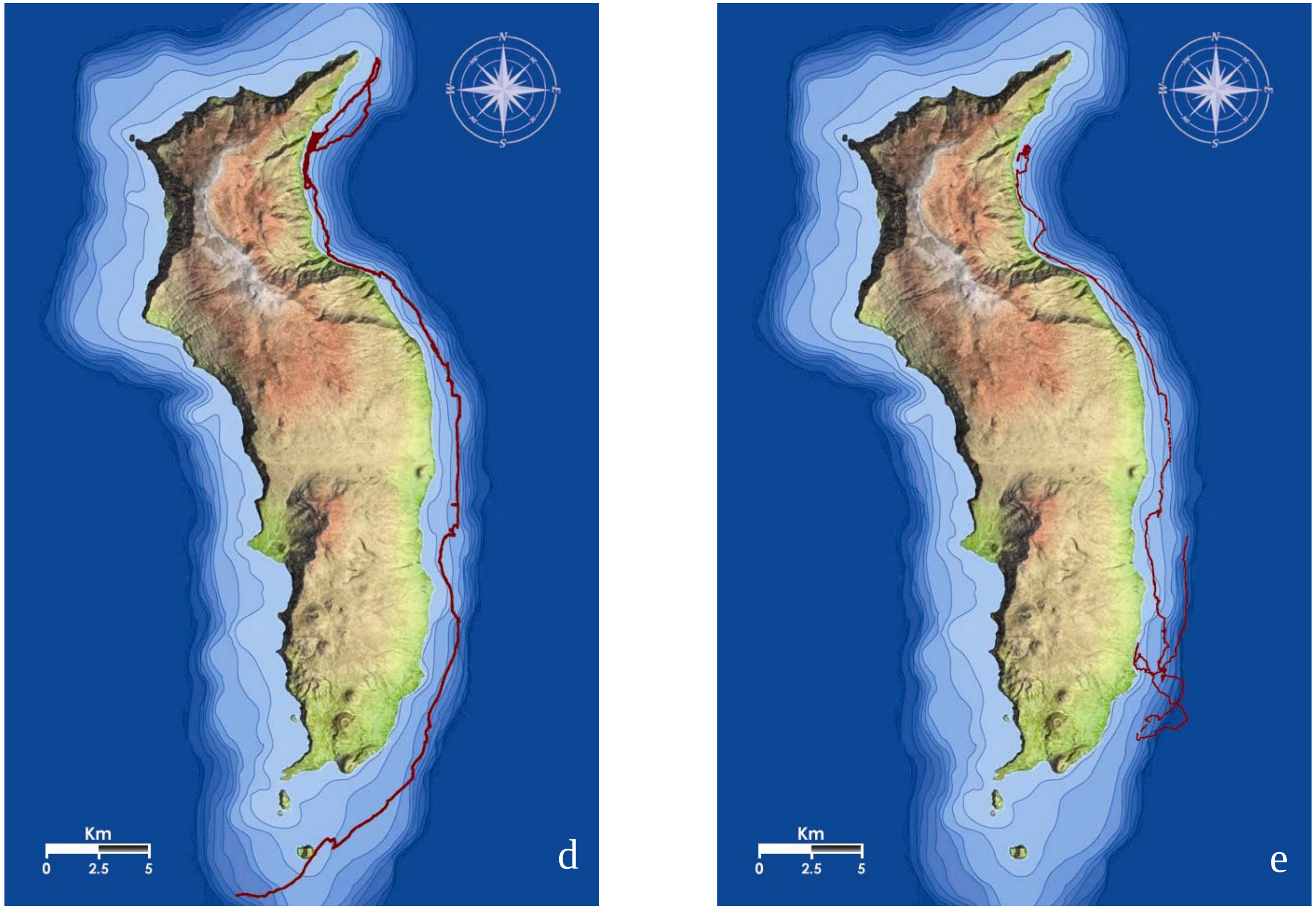

Figure 2. Tracks of two white sharks GWS-3(d), GWS-4 (e). The 24 hrs tracking is showed as red line.

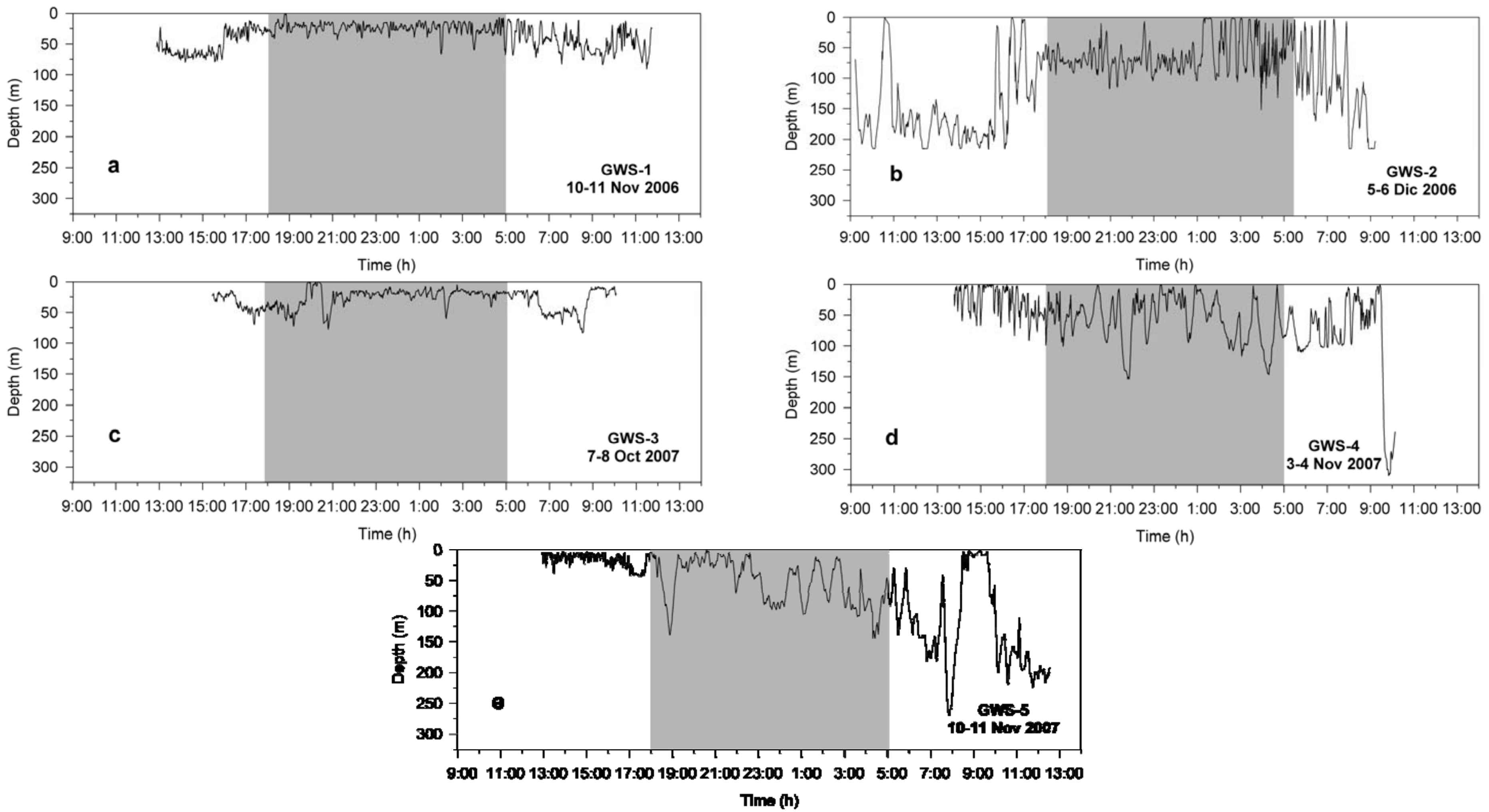

Figure 3. Swimming behavior of the five white sharks . a – GWS- 1, b – GWS-2, c – GWS-3, d – GWS-4, e – GWS-5. Nighttime indicated by stippling.

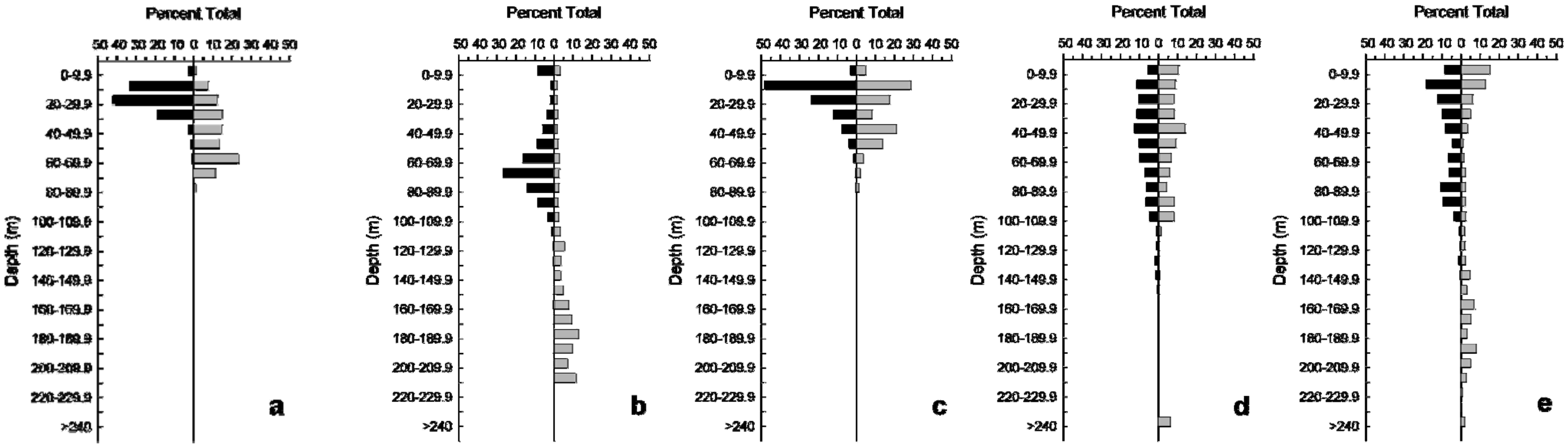

Figure 4. Percentages of the total number of depths recorded for the great white sharks : a – GWS-1, b – GWS-2, c – GWS-3, d – GWS-4, e – GWS-5. Solid bars to left of the ordinate denote the nighttime swimming depths and stippled bars to right of ordinate indicate daytime depths.

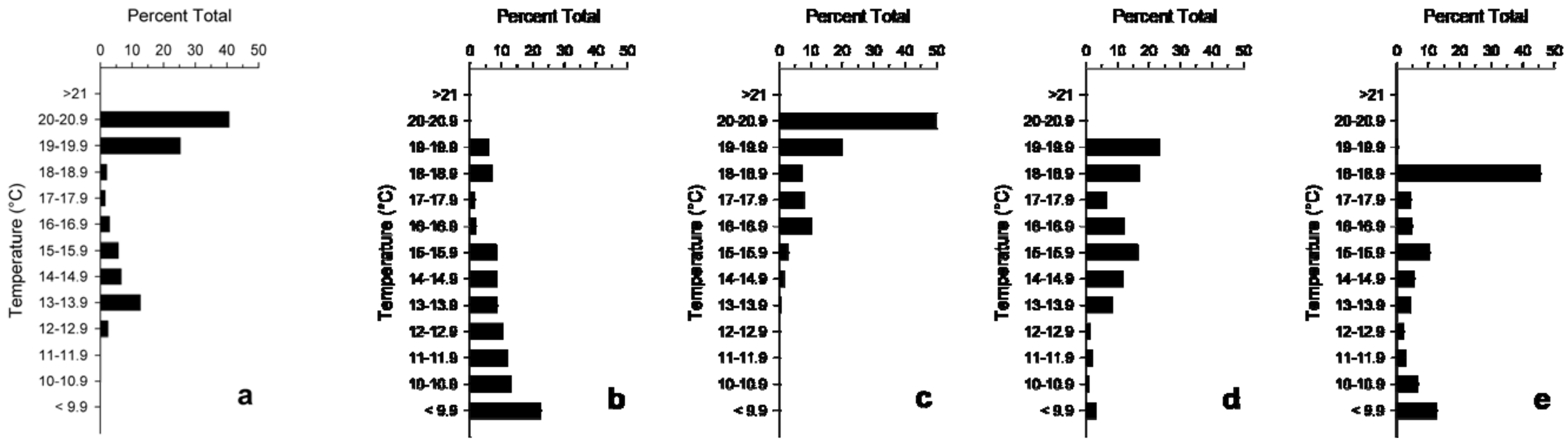

Figure 5. Percentages of total number of measurements of different temperatures recorded at five great white sharks : a – GWS-1, b – GWS-2, c – GWS-3, d – GWS-4, e – GWS-5.

The shark experienced a temperature range of 7.8 to 20.5 °C with an average of 16.4 °C spending most of the time in 19-19.9 ° C (Fig. 5 d).

GWS-5. The female was tagged in front of Campo Norte on 10 November 2007. She traveled continuously near the east coast of the Bay parallel to coast heading south throughout almost the entire 24-hr track. When it reached Pillar Point it started to move 3.34 km to the east of Fjord. After this point the shark moved to the shore and started to head north until contact was lost at 1.98 km to the east of Roca Gaviota (Fig. 2e). After her release at 12:58 hrs, the shark slowly ascended to 15 m and began a series of diving oscillations between 0 and 50 m for the next five hours. At 18:25 hrs, the shark descended to 138 m, then ascended again to the surface, and made dive oscillations between 0 and 50 m until 21:51 h. By 22:00 h the shark started to dive between 11 and 174 m until 7:43 h. After this the shark dived to the maximum depth of that tracking period of 265.9 and went to the surface again. After this, she started a series of diving oscillations between 111 and 224 during the rest of the tracking (Fig. 3e). During the night the shark remained in waters above 110 m spending most of the time between 10 and 40 m (39 %). In the day the shark moved trough the water column between surface and deeper than 240 m remaining most of the time in waters less than 50 m (Fig. 4 e). This shark experienced a broad temperature range from 9.2 to 19.4 °C staying most of the time between 18-18.9 °C (45.4 %) with a second peak from 9-9.9 °C (6.6 %) (Fig. 5 e).

DISCUSSION

Size at maturity for males is about 350 to 410 cm, with adolescence roughly between 250 and 400+ cm. Females mature somewhere between 400 and 500 cm. Size at birth is assumed as being between 109 and about 165 cm (Compagno, 2001). According to this data the sharks we tagged correspond to one young of the year, (GWS-3), one juvenile (GWS-1) and one adult (GWS-4) in the case of males and two adults in the case of females (GWS-2 and 5). The young of the year is the first record of a shark of this species that small in Guadalupe Island. The smallest total length recorded before (from 1999 to 2005) was 2.5 m (Domeiere and Nasby, 2007). The behavior of the young of the year (YOY) and the juvenile (GWS-3 and GWS-1 respectively) were similar. Both of them patrolled very close to the coast during night and day without going out from the northeast bay. Although GWS-1 was most of the day time in the north part of the bay, it remained during the night in the same area of the YOY's movements (Figs. 2a and 2c). Although the presence of these juveniles on this specific area from First Corner to Palms Beach could suggest that it is a protected area, the oceanic topography (submarine canyons) and the presence of adults on the same area during the night (Fig .2 b) disagree with this hypothesis. When the juveniles were on this area during the night, they showed patterns (shallow excursions) that could be related to feeding (Fig. 3a, 3c). There are different potential preys for juvenile white sharks that perform nocturnal migrations to the surface in Guadalupe Island. There are three species of squid (*Onychoteuthis banksi, O. borealjaponica and Dosidicus gigas)*, two mackerels (*Scomber japonicus,* and *Auxis thazard*), sardines (*Sardinops carulea*), flying fish (*Cypselurus californicus*) and anchovies (Gallo-Reynoso, 1994). Both juveniles were in upper waters than adults staying above the 50 m depth most of the time and even closer to the surface at night (3 a, 3c). Also their temperature preferences showed a narrower range than adults staying most of the time between 19-21 °C waters. Small sharks could loose more heat because of their larger surface area to volume ratio compared with bigger sharks. The YOY was able to spend some time between 13-16°C during vertical excursions although it represents less than 6 % of the time. Deward *et al*., (2005) reported that a YOY in California Bight was able to spend up to 80 min in waters at 9°C although most of the time (89 %) the shark remained between 16-22 °C. They suggested that the explanation could be that thermal inertia and absolute heat production will be less for smaller great white sharks. The incidental take of young sharks in different parts of the world, has provided the opportunity to examine stomach contents and it is apparent that, when compared to adult white sharks, the juveniles have a substantially different diet. Several authors have suggested a size-related ontogenic shift in prey type, with small young white sharks feeding on invertebrates, fishes and elasmobranchs and large adults preying more frequently on pinniped and cetaceans (Tricas & McCosker 1984, Casey & Pratt 1985, Klimley 1985). Deward *et al*., (2004) suggested that given the considerable shift in diet and the differences in geographic location, inferences about juveniles based on adult behavior are questionable. Current understanding of great white shark juvenile's biology in Mexico is based only on the incidental take of juveniles in the west coast of Baja California (Sosa, personal communication). The information presented here is the first record of the behavior of juvenile great white sharks in Mexico. According to Klimley (1985) Adult females give birth to pups during late summer and early fall south of Point Conception in the west coast of California and the pups remain inshore at that time. Deward et al., (2004) found that juvenile white sharks have a strong affinity for coastal regions. Despite this affinity for coastal regions after being born, the presence of this young of the year suggest that maybe Guadalupe Island could be a nursery ground for this species in Mexico.

In the case of adults, the behavior differs a lot from that of juveniles. GWS-2 remained 24 hours in the northeast bay of the island staying close to the coast during the night and away from shore during the day up to 3.3 km to the east (Fig. 2 b). The female made a number of deep dives during the daylight hours and remained most of the time at depths greater than 170 m probably searching for prey. Demersal fish that could be potential preys for the white sharks in Guadalupe Island includes flounders, rock fish, grey smoothhound shark, swell shark and the horn shark (Gallo-Reynoso *et al*., 2005). This behavior could be restricted to day light since Gruber and Cohen (1985) found by retinal histological analysis evidence for diurnal vision in this species. Early in the morning of December 6th the female started a series of diving oscillations from 180 m to the surface. It is interesting that during this movements to the surface, some of them where related with the location of northern elephant seal colonies. According to Le Boeuf and Crocker (1996) the diving pattern of the northern elephant seal is, in part an adaptation for avoiding encounters with predators like the Great White Sharks by swimming faster in waters over the shelf than off it, surfacing for shorter intervals, and long duration dives in the range of 200-600 m. Maybe this diving pattern performed by the GWS's could be related to the search of seals on the bottom and in specific areas at the surface such as seal colonies. Unfortunately internal temperature of the stomach did not showed a predation event although the elevation of stomach temperature above ambient temperature recorded for this female (17 °C) was broader than the maximum reported (14.3◦C) from adult white sharks by (Goldman, 1997). Although Domeiere and Nasby (2007) mentioned that they have never witnessed a shark feeding on a pinniped in Guadalupe Island during their study, we witnessed two predation events on juveniles of the northern elephant seal. In both cases, the shark bit the seals from behind. Despite phocids (seals) propel themselves using their lower body and hind flippers, after this initial attack a seal would be less likely to escape (Ainley et al., 1985). It is interesting that although the number of attacks was low, the prey were juveniles of the northern elephant seal. In the Farallons Islands, Ainley *et al.* (1981) concluded that elephant seals were more vulnerable than sea lions, and that regardless of species, subadult animals were more vulnerable than adults perhaps as a function of experience; many are probably naive about sharks or about maintaining vigilance for danger in general. On the other hand, the smaller (young) pinnipeds may be of a size more manageable by sharks, and thus size of prey relative to size of predator may in some way factor into the sharks' seeming preference for small animals. Although great white sharks are considered an expedient species to use as subject to study sharks predation, due to the relative ease with which can be observed attacking and feeding on pinnipeds at certain sites (Compagno, 2001), Guadalupe Island does not seem to be the case. According to Compagno (2001), large white sharks are not restricted to pinniped prey (even in areas with pinniped colonies and abundant seals), but also catch large teleost fishes, sharks and rays, birds, dolphins and marine reptiles, and are presumably capable of subsisting on such other small to large prey, in areas where seals are uncommon or absent (Mediterranean Sea, Spencer Gulf in South Australia, Brazil).

GWS-4 and GWS-5 showed a completely different behavior on the horizontal movements than the juveniles and GWS-2. GWS-4 did a long distance movement (5 km) to the north and returned again to the bay to start a continuous movement of 43.04 km to the south of the island. GWS-4 showed a similar preference for 10 - 50 m waters at night and day probably because it was moving constantly in a specific direction. It is interesting that during the night, the shark performed deeper dives of around 100 to 150 m. It is possible that the sharks might have been following patterns in the magnetization of the seafloor, which is to some extent linked to bottom topography (Klimley *et al*., 2002) in order to orient their movement during the night. At the end of the track the shark descended to the deepest record for all the sharks (311 m) and although it spent most of the time at 19 °C-19.9 °C waters, GWS-4 experienced the lowest temperature recorded for all the sharks (7.8) during this last dive. Probably the shark was descending to where magnetic gradients are steeper, more perceptible, and useful to guide migratory movements (Klimley et al., 2002). According to Domeiere and Nasby (2007), males were found to arrive at the island as early as July. Possibly GWS-4 was starting his migration to the west. GWS-5 did a long distance movement form the Bay very similar to that of GWS-4 although when it reached Pillar Point it started to move southeast and after this point the shark moved to the shore and started to head north again. Two days after that her presence was recorded on the northeast bay. Differently from GWS-4, GWS-5 did deeper dives during the day after it went to the east of Pillar Point and remained at depths from 11 to 224 remaining almost 7 % of the time in 9-9.9 °C waters probably searching for demersal preys on the bottom like GWS-2. Goldman and Anderson (1999) found larger individuals swam within particular areas around the Farallon islands whereas smaller individuals did not restrict their movements in the same manner. They hypothesize that despite the high frequency of predation on northern elephant seals in the fall the majority of the shark's movements are probably related to their search for these prey. In Guadalupe Island the small individuals restrict their movements to specific areas whereas adults did not. Probably the movements of the sharks in Guadalupe is not related to the search of northern elephant seals during this months. Pinnipeds may be especially important prey for white sharks where they occur together, especially at seal colonies where pinnipeds are highly vulnerable (Compagno, 2001). According to the local fishermen the greatest incidence of attacks on seals in Guadalupe Island occurs during January and February although our sampling ended in December and Domeier and Nasby (2007) only did three trips during January without finding any records of predation events. Further research on the behavior of the great white sharks during these months will elucidate if the presence of the sharks is related with the presence of the pinnipeds or other prey in Guadalupe Island. The information obtained during this research provides new insights into the movements and behaviors of white sharks in Mexican waters. Previous information about this species was based on dead organisms giving a little insight into the biology of living sharks. Our goal is to continue this research in order to provide scientific information germane to the management and conservation of this shark species at Guadalupe Island and throughout the waters of Mexico.

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