Reconnaissance study of Colola and Maruata, the nesting beaches of marine turtles along the Michoacan coast in southern Mexico

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Resumen

Las tortugas marinas de la especie *Chelonia agassizi* navegan anualmente cientos de kilómetros en mar abierto para llegar a sus áreas de reproducción y anidación. Se cree que esta tarea se realiza mediante el uso de información magnética terrestre y de aquella derivada de los atributos físicos de dichas áreas. Así, la geomorfología, topografía y geofísica de las playas natales pudieran facilitar a las tortugas el identificarlas. Este estudio describe estos elementos en las playas de Colola y Maruata, sitios de anidación de *C. agassizi* en México. Colola, en el oeste, es una playa elongada de 4.8 km de longitud y 150 m de ancho, limitada al norte por depósitos fluviales costeros. Maruata, en el este, es una playa curva de 2.3 km de longitud y 40 m de ancho bordeada por depósitos fluviales costeros al noreste y por pendientes coluviales de depósito volcano-sedimentarias en el sureste. Levantamientos topográficos y observaciones de campo realizados en Colola (otoño 1998/primavera 2000), documentaron que los perfiles de playa cambian durante y entre estaciones reproductivas. En Maruata las anomalías magnéticas tienen un rango de valores de 50 nT a nivel del mar a > 350 nT en el Cerro Vigía. El vector de campo geomagnético varia en inclinación e intensidad con la latitud a partir de la horizontal en Islas Galápagos hasta cerca de los 45° en el sur de México y de 30,000 nT a > 40,000 nT, respectivamente. Localmente la inclinación e intensidad en Colola y Maruata muestran valores de 44.87° y 40364 nT y 44.85° y 40353 nT, respectivamente. Estos parámetros pudiesen imponer limitaciones a la ecología sensorial de las tortugas.

Palabras clave: *Chelonia agassizi*, Geomorfología, magnetismo, perfiles topográficos, claves sensoriales, playas anidación, Sur de México.

Abstract

Marine turtles of the species *Chelonia agassizi* navigate hundreds of kilometers across the open sea between their reproductive and nesting areas every year. This task is thought to be carried out by utilizing information from the earth's magnetic field and other physical cues associated with natal beaches. Hence, geomorphology, topography and geomagnetic field anomalies might be important for marine turtle homing. This study describes such features in Colola and Maruata, the nesting beaches of *C. agassizi* in the southern Pacific Ocean margin of Mexico. Colola, on the west, is an elongated linear open beach of 4.8 km length and 150 m wide, limited at the north by coastal fluvial deposits. Maruata, on the east, is an arcute 2.3 km long and 40 m wide beach bordered by coastal fluvial deposits on the northwest and by colluvial slope volcano-sedimentary deposits on the southeast sector. Topographic surveys and magnetic field observations in Colola (Fall 1998/Spring 2000) documented that beach profiles change during a given and in between breeding seasons. In Maruata, magnetic anomalies range from ~50 nT at sea level to > 350 nT over the Vigía Mountain. Geomagnetic field vectors vary in inclination and intensity with latitude from the horizontal at Galapagos Islands to about 45 º in southern Mexico, and from 30,000 nT to over 40,000 nT, respectively. Locally, inclination and intensity at Colola and Maruata are 44.87º and 40,364 nT and 44.85º and 40,353 nT, respectively. These parameters may impose constraints to the turtles' sensory ecology.

Key words: *Chelonia agassizi*, Geomorphology, magnetism, topographic profiles, sensory cues, nesting beaches, Southern Mexico.

Introduction

The outstanding ability of marine turtles to precisely find their natal beaches and nesting sites after navigating vast distances across the open sea is still a conundrum to scientists in different fields. Although surely marine turtles use multisensory cues to achieve nest site selection and beach fidelity, the natural sources of sensory information that allow these behaviors to be displayed are yet a matter of controversy. In this context, visual, olfactory and magnetic stimuli are believed to provide short and long range clues for the turtles to define their migratory routes (Carr and Carr, 1972; Lohmann *et al*., 1999; Papi and Mencaci, 1999; Luschi *et al*., 2003, 2007; Gould, 2004; Nordmoe *et al*., 2004; Fuentes-Farías *et al*., 2008). In addition, humidity, sand grain size, sand compactness, vegetation, beach slope, temperature and magnetic blueprints are some of the beach features that might be used by turtles to identify nesting sites (Stancyk and Ross, 1978; Mortimer, 1982, 1990; Flores, 1992; Wood and Bjorndal, 2000; Kamel and Mrosovsky, 2004, 2005, 2006**;** Weishampel *et al*., 2006; Fuentes-Farías *et al*., 2008). Having this in mind, the study of the geomorphology, topography and physical attributes of the reproductive and nesting areas could help us in identifying the sources of natural information used by turtles to specify appropriate locations for displaying successful reproductive functions. In addition, studies like the present are also important for devising and planning knowledge-based conservation measures, strategies and programs.

It is under this assumption that we became interested in studying the nesting beaches of the sea black turtles *C. agassizi*. This species shows a relatively narrow range of geographical distribution being its main breeding sites a few beaches in Mexico and in the Galapagos Islands. In particular, in Mexico, Colola and Maruata beaches constitute the coastal reproductive sites of *C. agassizi* (Alvarado and Delgado, 2005; Fig. 1).

The Pacific Mexican coast is characterized by steep rugged relief and relatively narrow coastal plains and beaches. They form distinct coastal landscapes that could be used by turtles as visual landmarks while approaching them from the open sea. Topographic relief along and across beach profiles may also provide clues for beach identification and nest selection (Motimer, 1982; Wood and Bjorndal, 2000). We thus studied relief and land forms in Colola and Maruata. Beach morphology and sedimentology were characterized by strong internal dynamics that led to seasonal and long-term changes. It was also investigated beach morphology and temporal modifications that may affect turtle homing and beach selection. Magnetic characteristics at regional and local scales were analyzed in the context of possible magnetoreception mechanisms. In this paper we present initial results aimed at characterizing the geomorphology, topographic and geomagnetic features of Colola and Maruata beaches.

Fig. 1. The marine black turtles *Chelonia agassizi* spend most of their lives in the eastern Pacific Ocean. The main nesting beaches are located in Colola and Maruata, southern Mexico and the Galapagos Islands.

Pacific Ocean coast

The Pacific coastal region of southern Mexico extends along an active tectonic margin characterized by an oblique subduction of the Rivera and Cocos plates (Fig. 1); this has been a major factor in shaping the morphology of the continental margin (Ramirez-Herrera and Urrutia-Fucugauchi, 1999; Ramirez-Herrera *et al.*, 1999). Southern Mexico shows characteristics of a truncated active margin, with granitic to granodioritic batholiths located close to the coast and the Middle America trench. The margin shows tectonic uplifts leading to significant erosion and exposure of the underlying intrusive basement.

The Michoacán coast lies between Colima-El Gordo grabens and the intersection with the margin projection of the Orozco Fracture Zone. The continental shelf changes laterally from less than 1 km to more than 2 km. The Pacific margin is characterized by high seismic activity and margin uplift (Ramirez-Herrera and Urrutia-Fucugauchi, 1999). The coastline is bordered landward by folded and fault-block mountains (up to 600 m high) that at some points extend to the coast. The intrusive bodies are part of granitic to granodioritic batholiths of early Tertiary age and were mainly emplaced in the volcano-sedimentary sequence of island-arc affinity developed during the Mesozoic. The island-arc sequences may have been accreted to southern Mexico during the late Mesozoic and early Tertiary (Urrutia-Fucugauchi, 1984, 1988; Urrutia-Fucugauchi and Valencio, 1986; Garduño-Monroy *et al.*, 1999).

The study area is located at the southern end of the Sierra Madre del Sur morphological province, within the narrow and elongated sub-province of coastal plains. Drainage shows a uniform to dense parallel dendritic patterns, with major rivers like Cachan and Coalcoman oriented normal or slightly oblique to the coast (Fig. 2).

Surveys of the geophysical field potential have been previously used to characterize the continental margin and to investigate on the crustal thickness and structure. Gravity and aeromagnetic anomalies are associated with the granitic batholiths (e.g., Rosas-Elguera *et al.*, 1996). Magnetic high-amplitude anomalies are present particularly over the sulfide and iron ore deposits, related with igneous intrusive bodies.

Nesting beaches and marine black turtles

The beaches of Colola and Maruata are located along the Michoacan coast at approximately 18º 18' 00" N, 103º 26' 45" W and 18º 15' 30" N, 102º 48' 49" W, respectively. Colola is an open beach of about 4.8 km long and 150 m wide; it is located northwardly and oriented NW-SE (Fig. 1). Maruata is a smaller beach that has 2.3 km long and some 40 m wide, located within the Maruata's bay (Fig. 2).

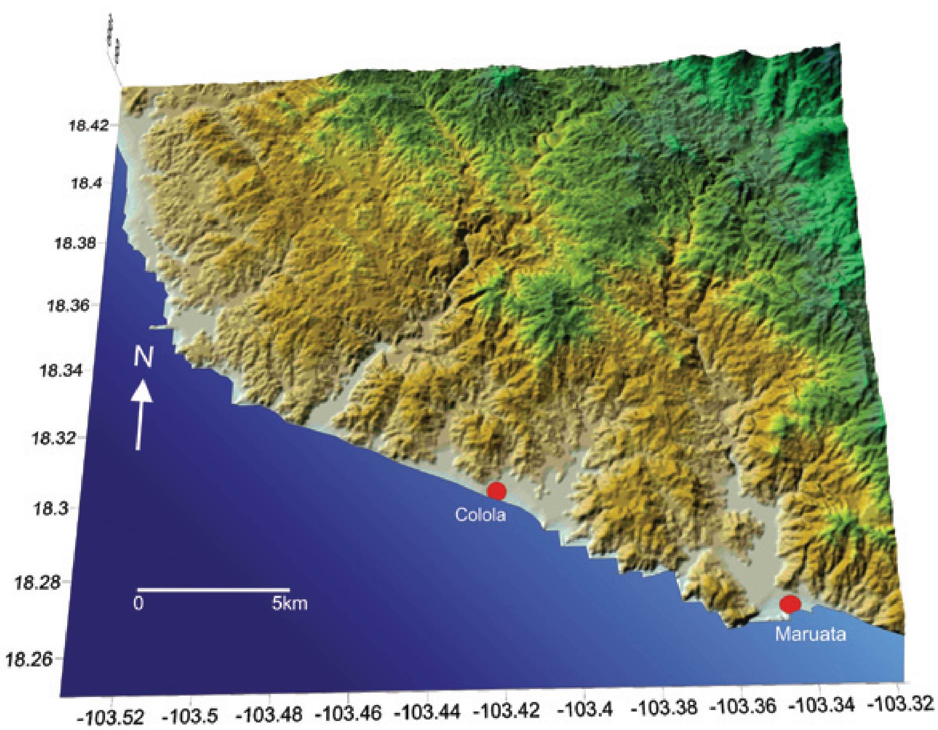

Fig. 2. Satellite Landsat thematic mapper (TM) image of the Colola and Maruata beach zones, Michoacan coast, southern Mexico.

Colola and Maruata beaches constitute a part of the natural reserve legislated to provide protection to the populations of breeding marine turtle reaching them. The population of *C. agassizi* has been long studied by research groups from the Universidad Michoacana de San Nicolás de Hidalgo. These groups have paid particular attention on the population dynamics, functional sex ratio, number of live hatchlings and various nest features that may affect the reproductive success of the species (e.g., Zamora, 1990; Flores, 1992; Barrera, 1994; Hernández, 1995; Fuentes-Farias, 2001; Alvarado and Delgado, 2005). The breeding season in Colola and Maruata extends from August through March, peaking between the months of September and November.

Michoacan beaches have historically been characterized by the largest nesting population of *C. agassizi* in the east Pacific Ocean. These numbers, however, are plummeting in recent years because of illegal commercial over-exploitation. Indeed, the number of females nesting annually has declined from 25,000 in late 1960s to some 1,400 per year between 1982 to 2001. This trend in population numbers has been a matter of concern, particularly if the sexual maturity age and generation replacement is considered (Alvarado and Figueroa, 1989; Alvarado and Delgado, 2005). Genetic analyses reported by Chasin-Noria *et al.* (2004) however do not show evidence for population sub-structuring, bringing hope for conservation measures to be implemented without apparent loss of genetic diversity.

The black turtles in Colola and Maruata show sizes ranging from 0.6 to 1.1 m in length for females (mean 0.86 m) and from 0.71 to 0.85 m for males. The young hatchlings display sizes that go from 0.04 to 0.05 m (Alvarado and Delgado, 2005; Zamora, 1990). Sexual maturity varies from some 17 to 50 years, and probably is reached at some 24 years (Alvarado and Delgado, 2005).

Colola and Maruata beaches

The geomorphological characterization was made by analyzing Landsat thematic mapper satellite images (bands 4 and 7), 1:25,000 aerial photographs, 1:50,000 INEGI topographic maps and topographic surveys (of the beach areas), and by making field observations. The regional base digital terrain model (DTM) map was constructed from digitization of the 1:50,000 INEGI maps (Fig. 3). Major orographic elevations are located to the southeast behind the Maruata bay, with the Vigía Mountain corresponding to the highest elevation (Fig. 4). A terrain slope model was also constructed from the DTM. This model displays the major characteristics and differences between the Colola and Maruata beaches, showing the areas of influence of the drainage basins of the Maruata and Colola rivers and the rugged topographic barrier and promontory of Piedras Blancas placed between Colola and Maruata (Fig. 5). Analyses of the terrain slope map in terms of slope parameters show that Colola lies within a flat plain extending northwardly into the river drainage areas, with a region of extensive sediment accumulation and relatively pronounced beach inclination in comparison with Maruata, the latter having an area with a narrow sediment accumulation and moderate beach inclination. In addition, Colola beach is characterized by stronger slope values (categories 4 and 5) that are associated with coarser sand grain sizes. The geomorphological map for Colola and Maruata is illustrated in Fig. 6, which depicts some of the major differences between the beaches. Colola, on the west, appears as an elongated linear open ocean beach extending for about 4.8 km and limited by coastal fluvial deposits. Maruata, on the other hand, is a smaller arcute beach displaying 2.24 km of length, bordered by coastal fluvial deposits on the northwest and by colluvial slope volcano-sedimentary deposits on the southeast.

In our study, beach micro-relief was investigated during the turtle's breeding season at yearly intervals. This permitted to establishing beach dynamics and assessing seasonal changes induced by meteorological and ocean coastal processes. As mentioned before, the breeding season extends from August through March, a period that corresponds to the major hurricane and tropical storm activity in the Pacific. Our topographic surveys in Colola were conducted in October 1998 and April 2000; beach profile was then determined along five selected transects (350 m). Results are summarized in Figs. 7 and 8. The topographic profiles obtained for the two epochs show distinct features. Profiles measured during the Fall of 1998 (Fig. 7) showed gradual elevation changes in the west and the occurrence of depressions to the east forming shallow coastal lagoons, extending to the vegetation line at the higher beach elevations. The western-most profile 1 (Fig. 7) showed elevation changes from 0 to 5 m combined with an abrupt slope in the first 20 m. In contrast, for the Spring of 2000, profile 1 was characterized by an elevation difference up to 11m and a steeper slope. The western and central sectors show higher elevations in Spring 2000 as compared with the softer slopes observed during the Fall of 1998. The eastern sector was characterized by less significant seasonal changes. Colola is characterized by along-beach changes marked by beach width variations and lateral changes of the topographic landscape (Fig. 4), and by strong dynamical seasonal changes, implying that during a given breeding season and in between breeding seasons, beach characteristics shift significantly.

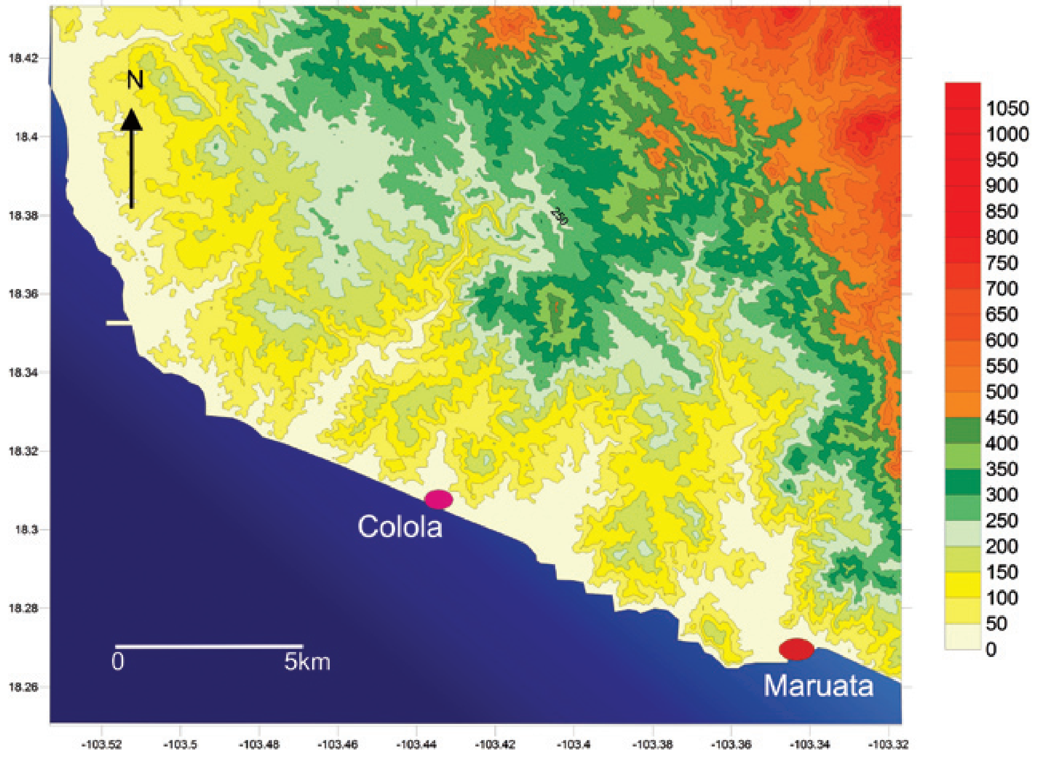

Fig. 3. Digital terrain model (DTM) for the Colola and Maruata beach zones in the Michoacan coast of southern Mexico.

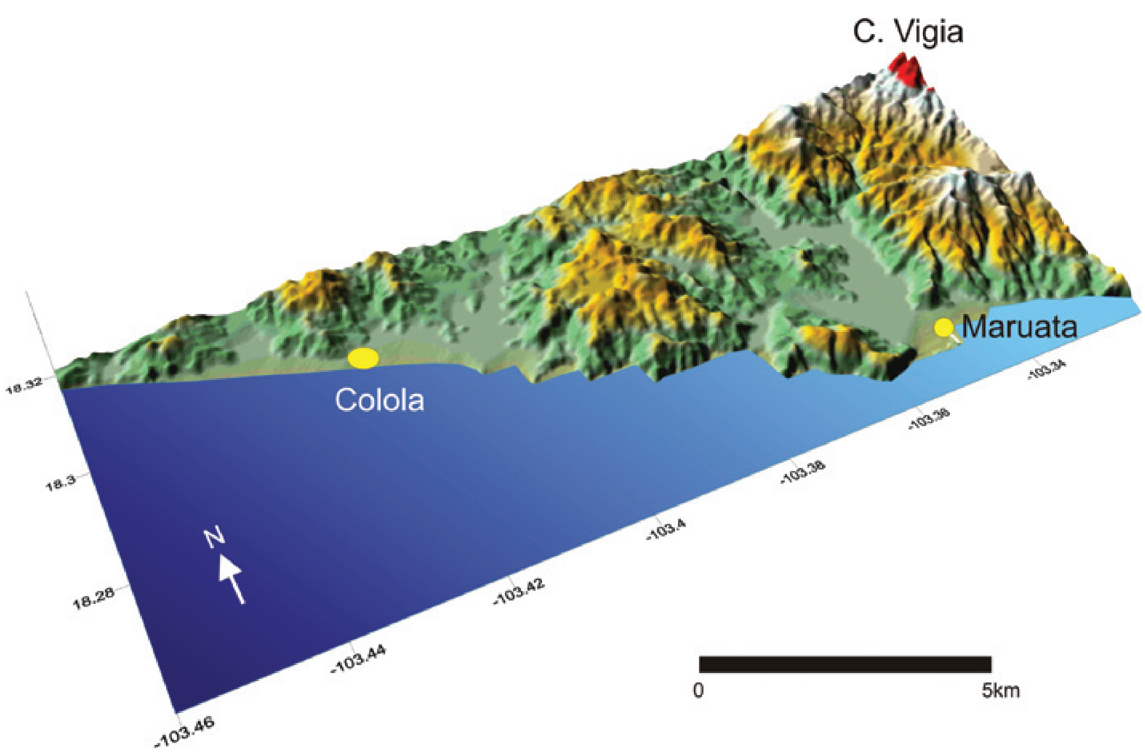

Fig. 4. Orthographic three-dimensional digital model for the Colola and Maruata beach zones. The highest elevation corresponds to the Vigía Mountain to the north of the Maruata beach. Note that the topographic elevations increase from west to east along the Colola open-sea beach to the Maruata bay closed beach.

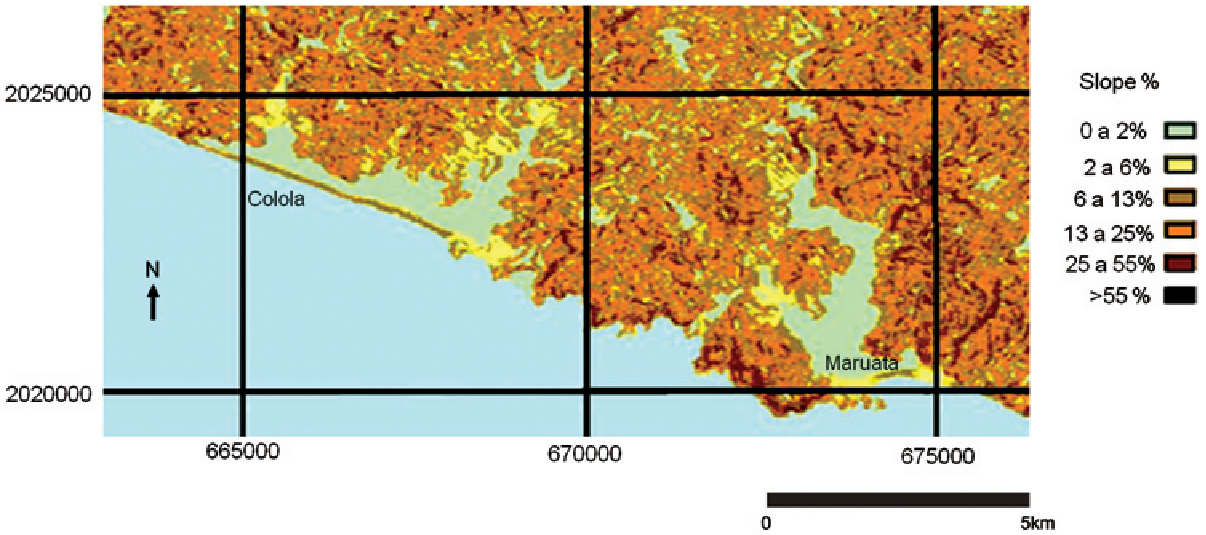

Fig. 5. Slope model for the Colola and Maruata beach zones in the Michoacan coast of southern Mexico.

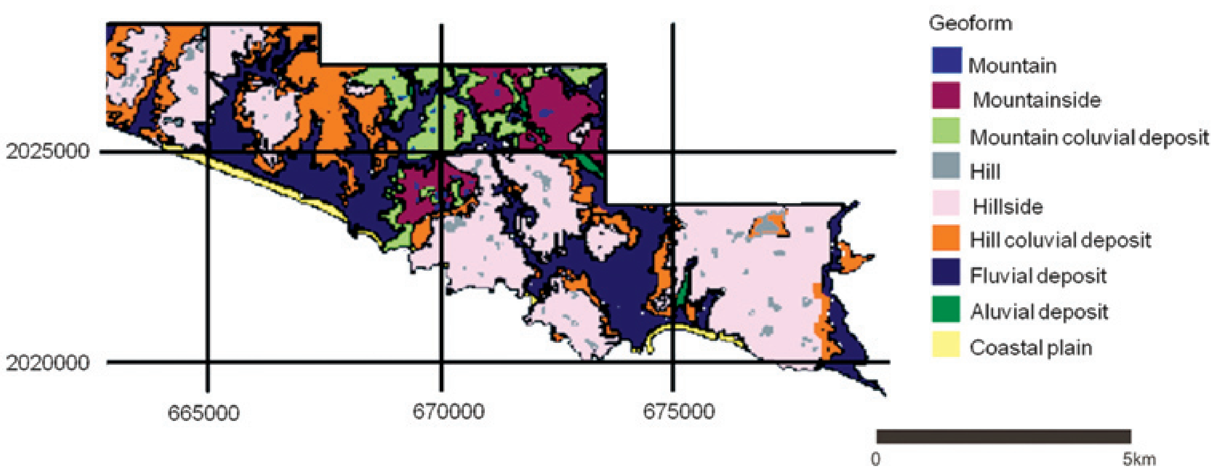

Fig. 6. Geomorphological map for the Michoacan coast in the Colola and Maruata beach zones.

Regional magnetic anomalies constitute a common feature among granitic batholiths in the continental margin. In some cases, such anomalies run across the coastline, indicating that intrusive rocks extend into the continental slope. As a part of this study, we evaluated the presence of regional magnetic anomalies over Colola and Maruata and their vicinity (Fig. 9; Servicio Geológico Mexicano, Scale 1:250 000, code number: Lázaro Cardenas E-13-6-9, 1994). The total field of magnetic anomalies was measured with a proton magnetometer flying at 350 meters of altitude. The region is characterized by low amplitude, long wavelength anomalies (200 nT) superimposed on intrusive rocks. Strong magnetic anomalies are about 350 nT. Such values are associated with the highest elevation (600 meters above sea level) in the area known as the Vigía Mountain, a geological form shaped by granitic intrusions of. The magnetic gradient runs from ~50 nT at the coastline to ≥ 350nT at the peak of the Vigía Mountain, shifting in 50nT every 1 kilometer. Finally, on the beaches' surface, it was detected low amplitude long wavelength anomalies, indicating absence of buried intrusive bodies.

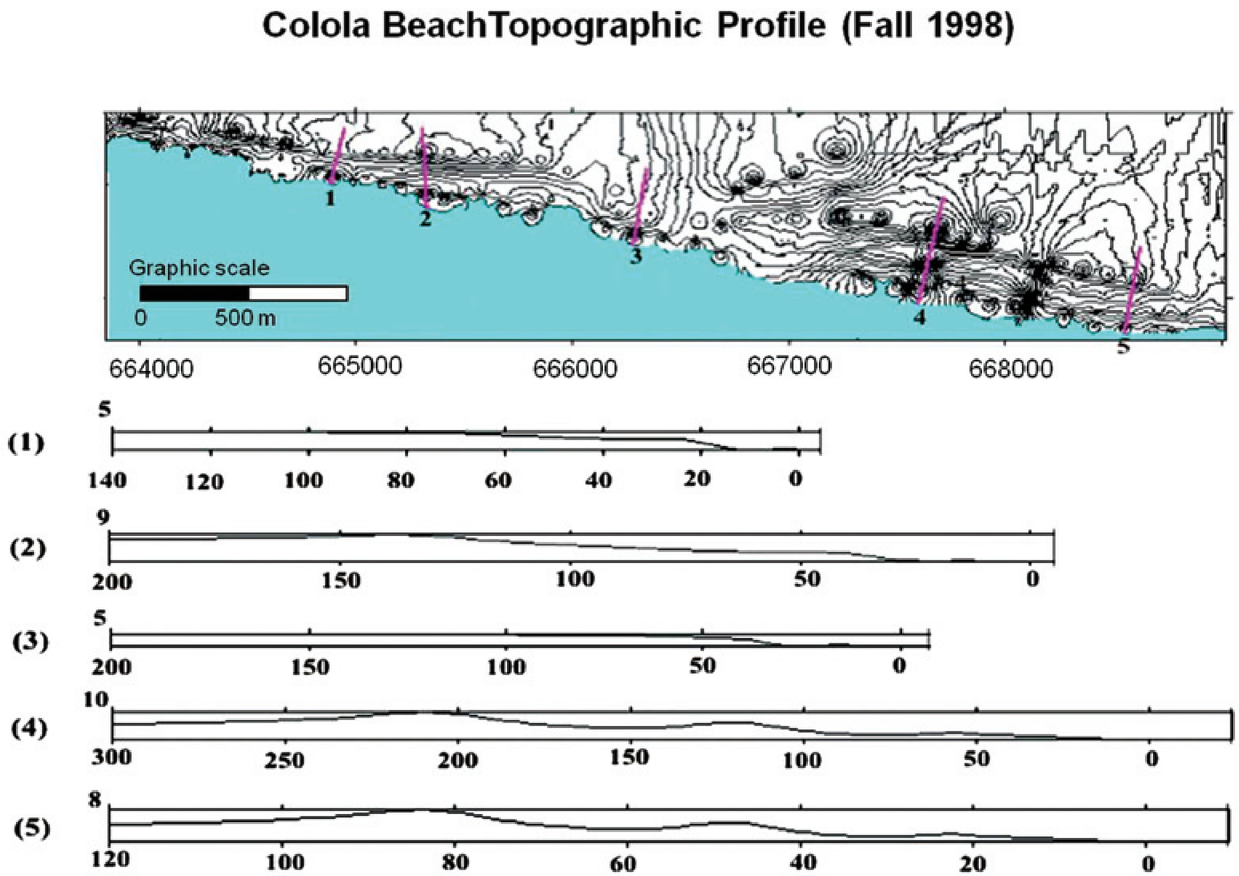

Fig. 7. Topographic map of Colola beach with profiles of topographic survey for Fall 1998.

The geomagnetic field is characterized by the dipolar geocentric axial component that originates in the outer core. At the earth's surface, the inclination and magnitude of the geomagnetic field vector vary from the horizontal at the magnetic equator to the vertical at the magnetic poles. In the area studied, the geomagnetic inclination varies significantly with latitude from the horizontal near the Galapagos Islands to about 45 degrees downward in southern Mexico. The intensity, on the other hand, ranged from 30,000 nT to over 40,000 nT. The global and regional geomagnetic field at the earth surface has been measured by a global network of geomagnetic observatories and temporary stations, and recently with geophysical satellites. The reference geomagnetic field is estimated from spherical harmonic analyses and summarized in the reference international field models (IGRF). The geomagnetic field data for Mexico has been analyzed from geomagnetic models and measurements at the Teoloyucan geomagnetic observatory and secular variation stations of the national network (e.g., Urrutia-Fucugauchi and Campos-Enriquez, 1991; Campos *et al.*, 1991). The geomagnetic field vector shows a time variation, with changes of a few arc minutes per year in declination and inclination. The intensity has been decreasing in the past centuries at rates that vary in specific location. In Colola and Maruata, the secular variation decrements at about 75 nT per year. The geomagnetic secular variation implies that, over long periods, the geomagnetic field parameters shift, reason by which animals using these parameters as migratory cues must to take these changes into account.

Discussion

Marine turtles precisely find their natal beaches and nesting sites after navigating long distances across the open sea. Visual, olfactory and magnetic stimuli are believed to provide short and long range cues for the turtles to define their migratory routs (Carr, 1988; Lohmann *et al.*, 1999; Papi and Mencaci, 1999; Luschi *et al.*, 2003, 2007; Gould, 2004; Fuentes-Farias *et al.*, 2008), whereas humidity, sand

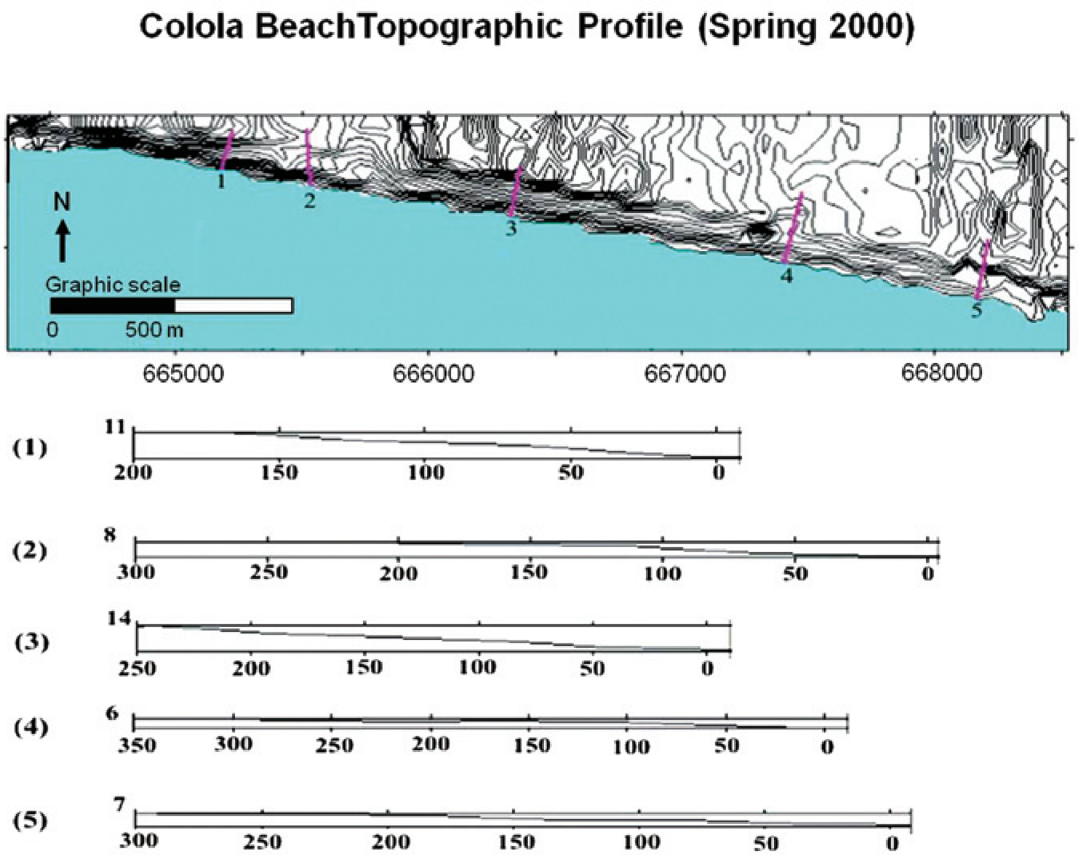

Fig. 8. Topographic map of Colola beach with profiles of topographic survey for Spring 2000.

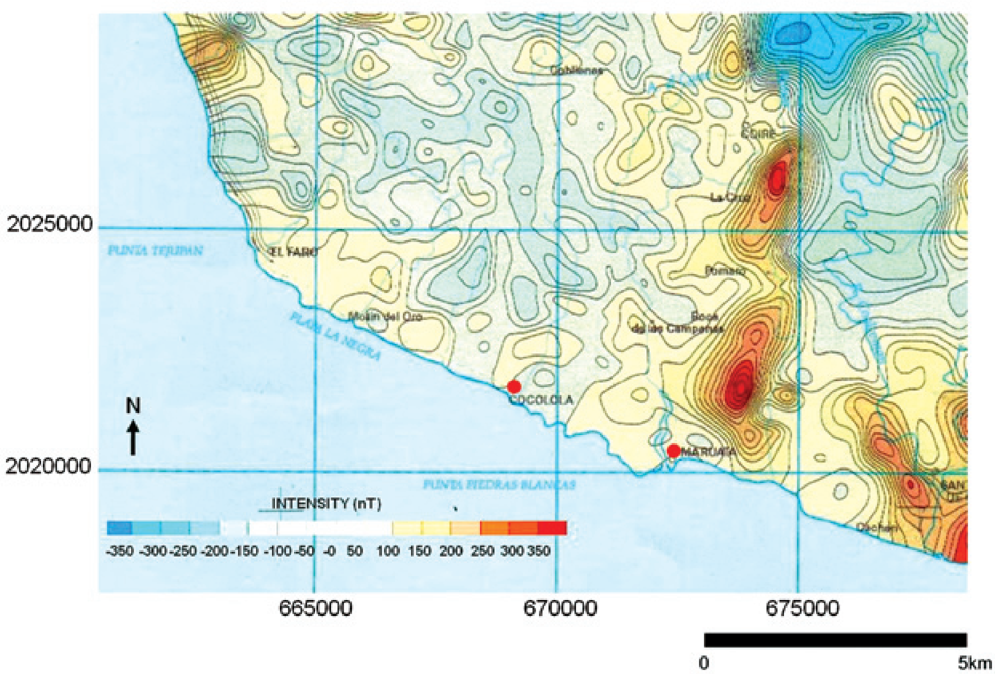

Fig. 9. Aeromagnetic anomaly map for the Michoacan coast at scale 1:250,000. Location of the Colola and Maruata beaches is indicated by the red dots. Note the occurrence of large positive elongated anomalies over the Vigía Mountain and low amplitude smooth anomalies over the coastal areas, including the Maruata and Colola beaches.

grain size, sand compactness, vegetation, temperature and local magnetic properties might be used to identify nesting sites (Stancyk and Ross, 1978; Mortimer, 1982, 1990; Flores, 1992; Wood and Bjorndal, 2000; Kamel and Mrosovsky, 2004, 2005, 2006; Weishampel *et al*., 2006; Fuentes-Farias, 2001; Fuentes-Farias *et al*., 2008). The study of the geomorphology, topography and physical attributes of the reproductive and nesting areas could then help us in identifying the sources of natural information used by turtles to specify appropriate locations to have successful reproductive functions.

In the context of investigating the sensory ecology of magnetic-based orientation mechanisms for open sea navigation, homing and nesting site selection, the marine black turtle stands as an attractive animal model given their long range migratory behavior across large areas of the eastern tropical Pacific Ocean (Seminoff *et al*., 2002), and the fidelity displayed by this species to their natal beaches (Alvarado and Figueroa, 1992).

The southern Pacific Ocean margin is characterized by a steep rugged relief and relatively narrow coastal plains and beaches that present characteristic coastal landscapes that could provide potential visual landmarks for turtles approaching the coast. Hence, the topographic relief and along and across beach profiles likely provide characteristic clues for beach selection, identification and characterization. In our study, beach morphology and sedimentology are subjected to strong internal dynamics that surely leads to marked seasonal and long-term changes, implying that beach geo-morphology of the *C. agassizi* nesting beaches shift during the life-span of turtles. Beach dynamics should then be accounted for creating models and studying factors that may affect homing and nest site selection.

Colola on the west appears as an elongated linear open ocean beach extending for about 4.8 km and some 150 m wide, limited to the north by coastal fluvial deposits (Fig. 6). Maruata, on the other hand, is an arcute smaller 2.3 km long and 40 m wide beach bordered by coastal fluvial deposits on the northwest and by colluvial slope volcano-sedimentary deposits on the southeast (Fig. 6). Visual sighting of landmark topographic elevations or characteristic coast landscapes as observed from open sea has been proposed as an orientation aid for turtles approaching to the coast (Avens and Lohmann, 2003). In general, young turtles approaching the sea for their first time move down slope along the beach and, if visual clues are used, the coastal landscape may be imprinted in their memories during the initial navigation away from natal beaches (Salmon *et al*., 1992). In the case of the Colola and Maruata beaches, the coastal landscape is characterized by mountain elevations of the intrusive bodies, with spatial differences within and between beaches (Fig. 4). Higher orographic elevations forming the beach landscape that might be observed from farther away while approaching the coast are present in Maruata, with the Vigía Mountain on the northeast (Fig. 4).

Colola is characterized by along beach changes marked by beach width variations and topographic 'landscape' lateral changes (Fig. 4). Topographic surveys and field observations at different epochs (Fig. 7 and 8) also documented strong dynamical seasonal changes, implying that during a given breeding season and in between breeding seasons, beach characteristics shift. The turtle nests are preferentially located in the middle zone of the beach profile (Fuentes-Farias *et al*., 2008). In Colola beach, nesting zones lie at around 100 m from the beach tide front (Fig. 7 and 8). Nests are not uniformly distributed along the beaches; in Colola beach there are two preferred zones corresponding to the western sector (around 800 m long) and the central sector (around 350 m long). In Maruata, turtle nests are preferentially located at the South terminal end (Alvarado and Figueroa, 1989; Fuentes-Farias, 2001). The number of female turtles breeding during each season is larger in Colola than in Maruata (Alvarado and Delgado, 1985-2000), which may correlate with the size and magnetic properties of the beaches.

The Pacific coast is characterized by low amplitude long wavelength aeromagnetic anomalies, with superimposed positive anomalies of > 200 nT over intrusive bodies. In some cases, the magnetic anomalies extend over the continental slope reflecting the presence of the large granitic batholiths in the margin. The magnetic anomalies observed over the Colola and Maruata beaches are of intermediate size in terms of the amplitude and the wavelength as compared to other anomalies along the margin. The aeromagnetic anomaly is greater just north from the Maruata bay, and in Colola, the anomalies are of low-amplitude and long wavelength. In Maruata, magnetic anomalies show stronger changes from 50 nT at sea level to ≥ 350 nT over Vigía Mt. The beach area is characterized by low amplitude long wavelength anomalies, indicating absence of intrusive bodies extending to the beach zone.

Conclusions

In this study we concentrate on characteristics of nesting beaches, possible factors involved in beach selection and factors involved in homing and orientation. Interest also arose from potential use of magnetic compass sensing in open sea orientation and geomagnetic characteristics within the beaches related to acquisition mechanisms in hatchling turtles.

Turtles show strong behavior for natal homing and nest site fidelity, which makes study of beach characteristics important. *C. agassizi* turtles show narrow ranges of breeding sites, restricted to specific beaches in Michoacan coast. It has been proposed that steep rugged relief and relatively narrow coastal plains and beaches provide characteristic coastal landscapes that may be used by turtles as landmarks while approaching the coast from open sea. Topographic relief and along and across beach profiles may provide characteristic clues for beach identification. In Colola and Maruata this may be the case because there is a unique topographic feature (i.e., Vigía Mountain) that could constitute a landmark for orientation and identification.

Colola is an elongated linear open ocean beach limited by coastal fluvial deposits and Maruata is an arcute smaller beach bordered by coastal fluvial deposits and colluvial slope volcano-sedimentary deposits. Colola shows along-beach changes marked by width variations and topographic 'landscape' lateral changes. Beach morphology and sedimentology are normally characterized by internal dynamics, which reflects in marked seasonal and long-term changes. Topographic surveys and field observations at different epochs document seasonal changes, implying that during given and in between breeding seasons, beach profiles change. This implies that beach characteristics evolve during the life-span of turtles and beach dynamics should be accounted for in models and study of factors controlling homing and nest selection.

Beach areas show low amplitude long wavelength anomalies that may not play a major role in homing. Geomagnetic inclination at Colola is 44.87^{o} with an intensity of 40,364 nT and at Maruata inclination is 44.85^{o} and intensity is 40,353 nT. Local changes in the beaches are in the order of 0.02 degrees in inclination and 10 nT. This imposes constraints in proposed magnetoreception mechanisms.

The Michoacan Pacific coast is characterized by low amplitude long wavelength aeromagnetic anomalies, with superimposed positive anomalies of > 200 nT over intrusive bodies (e.g., Vigía Mountain anomaly > 350 nT). Magnetic anomalies may become important over short distance ranges, nesting site selection, fidelity and beach sand physical and mineralogical properties. If these factors are important for magnetoreception fixation in hatchling turtles, the narrow ranges in magnetic parameters observed in the beaches suggest that care should be exercised if hatchling turtles are removed from nests to other locations. This may affect their perception mechanisms and may be important in conservation programs.

In the central-eastern Pacific Ocean, geomagnetic vectors show inclination changes of 45 degrees and intensity changes over 10,000 nT. Geomagnetic field regional spatial changes may play a significant role in navigation and homing, where changes are sufficiently high in magnitude and inclination to be detected and used for long-distance open ocean navigation, within detection capabilities of marine organisms and potential use for orientation.

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