

Seafloor spreading theory and the odyssey of the green turtle

Archie Carr

University of Florida, Gainesville, Florida

Patrick J. Coleman

University of Western Australia, Perth, Western Australia

*Seafloor spreading theory seems to explain why the ancestors of a green turtle (*Chelonia mydas*) subpopulation which now travels 2,000 km from Brazil to breed at Ascension Island, were induced to swim oceanwards for increasing distances during the gradual separation of South America and Africa in the earliest Tertiary.*

A SUBPOPULATION of the green turtle (*Chelonia mydas*) lives on the coast of Brazil but breeds and nests 2,000 km away on Ascension Island in the central equatorial Atlantic¹⁻⁶. The feat of navigation involved in this odyssey has not been explained^{5,7}. A puzzle of equal stature, and of more fundamental importance, arises in trying to account for the initial stages in the evolution of the adaptation^{3,4}. Populations of the genus *Chelonia* have distinctive characteristics—enormous shoulder musculature together with its support, heavy fat deposits, and a peculiar jaw structure. The ecological regimen responsible for these characteristics is evidently the herbivorous feeding habit¹⁻⁸ and the need that this imposed for travel between a protected, shallow water pasture ground and the exposed shores on which suitable nesting beaches develop. Offshore and oceanic islands are likely to have good surf-built beaches and they almost always offer relative freedom from the nest-predators which plague mainland nesting beaches. In spite of these advantages, however, the Ascension colony has established the adaptations in the face of huge difficulties, inherent in the initial stages, which seem to make impossible demands on the process of natural selection. Seafloor spreading theory may bear directly upon this aspect, and it also offers clues to the navigation problem.

Turtles and central Atlantic opening

Marine turtles of *Chelonia* type inhabited the seas between 'North America' and northwestern Gondwanaland by the beginning of the late Cretaceous, about 100 million years (Myr) ago. Because of the cheloniid fossil record in this general area (refs 9-12 with the references provided there), we postulate that these ancient turtles included the ancestors of *Chelonia mydas*, even though its phylogeny cannot at present be reconstructed. (*Chelonia* has been found in Miocene sediments^{9,10}.) The northern coast of South America was a suitable habitat for these early turtles, providing a tropical to subtropical environment. There is fossil evidence that even then the herbivorous habit had evolved and that there was a separation of residence-pasture and breeding grounds¹². Mammalian egg-predators no doubt acted as a limiting factor in turtle ecology at this time, augmenting the advantage in island nesting.

The opening of the equatorial Atlantic¹³⁻¹⁶ (Fig. 1a and b), marking the final separation of South America and Africa at about 80 Myr ago, took place in steps: first, rift valley formation at about 110 Myr ago, or even earlier; second, sporadic but progressive ocean flooding with a strong west-to-east component by 90-80 Myr ago; and finally development of a ridge system which linked the spreading ridges of the North and South Atlantic and made of it a single ocean by 80 Myr ago.

Volcanic piles are a frequent feature of midoceanic ridges, and some may grow sufficiently to emerge as islands. As spreading

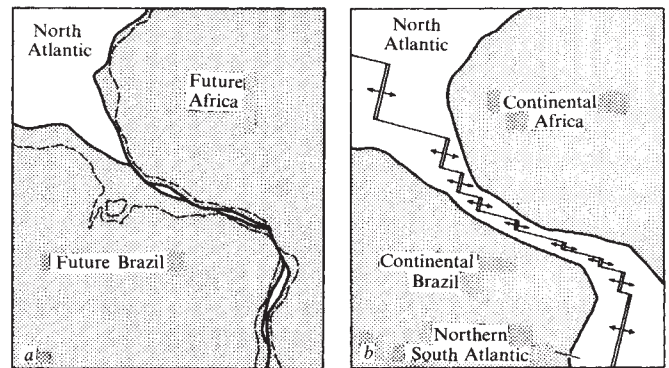


Fig. 1 a, Predrift reconstruction of equatorial 'South America' and 'West Africa', as parts of north-western Gondwanaland, based on the computer-tested bathymetric fit of Bullard *et al.* (ref 23). b, Reconstruction for the time of about 80 Myr ago. A 'Red Sea' connects the northern Atlantic with the younger southern Atlantic and its youthful spreading ridge. Spreading ridge detail is schematic.

continues, they become inactive and are carried outwards and downwards and become seamounts¹⁷, the deepest being furthest from the ridge axis. They are sporadically replaced by new volcanoes on the ridge so that for the continental observer the volcanoes march seawards through time (Fig. 2). The ancestral turtles could thus migrate outwards with the volcanic islands, without the demands on the process of natural selection becoming excessive.

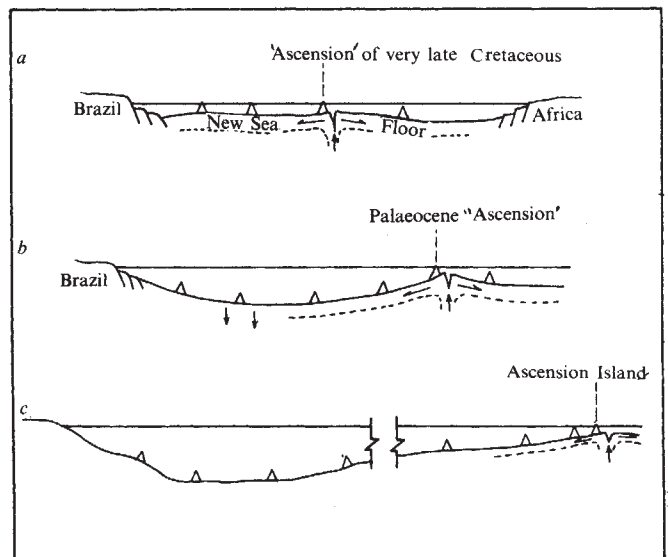


Fig. 2 The progressive appearance, then disappearance, of spreading ridge volcanoes as part of seafloor spreading mechanism. a, Approximately 70 Myr BP; b, approximately 60 Myr BP; c, approximately 1 Myr BP.

Turtle movement into the Brazil–West African channel

Before 100 Myr ago, turtle populations travelled between residence-pasture and breeding grounds along the shores of northern South America. By 90 Myr ago, a corridor had opened at the head of the gulf between Brazil and West Africa in line with the established longshore travel paths. By 80 Myr ago, the corridor was complete, much new coastline had been added, and there was a string of offshore islands. The exploitation of this oceanic channel by the turtles simply required repetitive extension of previous travel paths (Fig. 3). The bearings were WNW–ESE. This is close to a latitudinal course, and could be navigated relatively easily. Locating a particular beach on an island within this narrow sea or along its coasts would involve a longitudinal fix: local currents, rivers, even surfbeat, would offer individual signatures. It seems reasonable to assume that this pattern of travel, constant over a long period of time would become an established, heritable part of the turtle's behaviour.

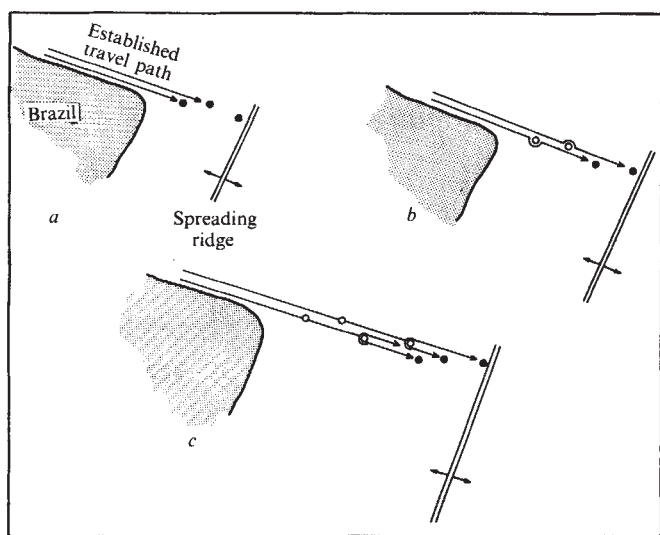


Fig. 3 As seafloor spreading proceeds, through stages *a*, *b* and *c*, new volcanic islands are generated near the ridge crest (double line). Older ones have moved out with the flanks of the ridge and gradually sink until they are submarine (open circle). As a former breeding ground becomes unusable, the turtle swims further on the same, or nearly the same, course.

By 80 Myr ago the Brazil–West Africa sea channel had connected with the northern South Atlantic and its active spreading ridge (Fig. 1*b*). The ridge volcanoes which had formed earliest, were close to those which had arisen or were still arising at the eastern end of the sea channel. For these new ridge islands to become included in the range of breeding grounds it was necessary only that some turtles extend their travel path, that is, simply stay on course, assuming either that the turtle was distracted from its prime target; or that the target had become submerged and unusable. On return trips the turtles would be guided to the final landfall by chemical cues, by surfbeat or even by direct vision. A degree of elasticity in the establishment and recognition of breeding grounds is necessary, but not much more than seems consistent with that found in the modern green turtle¹⁸.

We envisage that by 70 Myr ago, the ancestors of the Ascension Island colony were making seaward breeding migrations of up to 300 km—a figure consistent with the spreading rate of 2 cm yr⁻¹ (refs 14, 19). This process continued (Fig. 3) assuming there was sporadic creation of volcanic islands; Ascension Island is the last and youngest of them (less than 7 Myr old^{19, 20}). What was probably the penultimate island is now a seamount 15 km away, which is submerged to a depth of 1,500 m (ref 21).

We cannot establish the existence of a narrow swathe of seamounts connecting north-east Brazil with Ascension Island,

because the detailed bathymetry is not well known. There is, however, a suggestion of a line of seamounts running south-eastwards from near Recife to about 30° W and then swinging east to Ascension (Fig. 4). This last limb is close to the trace of the Ascension Fracture Zone and its ridge¹⁹. The early Tertiary migration may have been controlled by volcanic islands that arose along the ridge.

Brazil to Ascension

We have argued that, since early in the Cainozoic era, the turtle has had an inherited tendency to swim a particular travel path, roughly WNW–ESE. This path can be followed by using the rising sun as a beacon to stay on latitude, an operation made simpler by the fact that the path is equatorial and the migration period is seasonal; turtles arrive at Ascension from February until May. Thus, for a December departure from the coast of northern Brazil the turtle heads directly into the rising sun (that is, ESE) and does the same every day. At night it rests below the equatorial current or even drifts eastwards with the counter-equatorial current⁵. The journey takes perhaps eight weeks. Because of the northerly drift of the sun at this time of the year, the general path followed from Brazil towards Ascension will describe a gentle arc, convex to the south, of the sort shown in Fig. 4. The required target is the intersection of the travel path with a plume of sensory clues arising from the island. Because of the equatorial current, which at this latitude has a southerly component, the stream line of solubles released from the island is favourably disposed to make the intersection and provide the turtle with a pathway to landfall; the stream line gives a longitudinal fix. The equatorial current also serves another important function, that of carrying the hatchlings, imprinted to Ascension, away from the ecologically unsuitable island⁵. The same requirements probably existed for the early Cainozoic populations, when the separation between Africa and South America was insufficient for development of an equatorial current. Reconstructions of late Cretaceous current systems²² allow us to postulate an equally favourable smaller current system which would perform the same functions during the early stages of the migration to the islands.

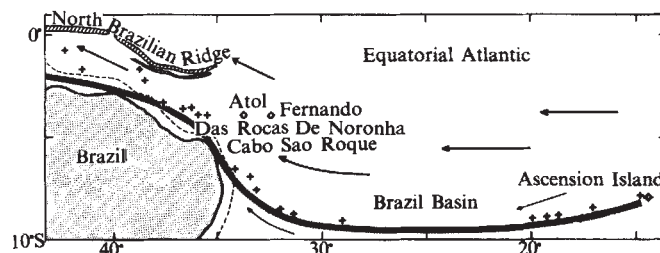


Fig. 4 The western equatorial Atlantic. The arrows indicate the generalised direction of the Equatorial Current (for the northern hemisphere summer). A possible line of seamounts (there are others) is indicated by the vertical crosses. Linking these is a hypothetical migration path (heavy pattern, still to be tested) taken by the Ascension turtles from Brazil to Ascension Island.

This navigatory scheme is simpler than that of Koch *et al.* (ref 7). In particular, it calls for a smaller plume from Ascension, in keeping with the size and nature of the island, and allows for recognition of Ascension emanations, as a new element, against the African background or 'noise' with which the equatorial current is loaded (the Congo contribution alone is massive). If the sun, in combination with chemoreceptive detection of the Ascension plume, is used as a navigational beacon, there would seem to be a corollary which can be examined: turtles from northern parts of the resident grounds would depart first and those from southern parts (south of Recife) would depart later. This is a necessary consequence of the northerly swing of the sun during the visitation period.

Inheritance of behaviour

We suggest that the process of racial learning is of the repetitive, stepping-stone type, which requires no radical change in behaviour at any point. The hypothesis puts the migration to Ascension Island in an evolutionary framework by allowing selective and adaptive processes to operate over a great period of time. Indeed, the period of time may be too long to be acceptable to some. If we are right it means that an extant species has inherited a vital behaviour pattern from ancestors that lived 40 Myr ago and more. In purely taxonomic terms these ancestral species were different, and perhaps very different, from *Chelonia mydas*. In the face of this somewhat unpalatable notion, we take comfort in the realisation that species are more than flesh and bones, especially bones. For the Ascension Island colony, we accept the seaward migration drive as an inherited feature that predates other morphological features conventionally used in systematics to define taxa at species and genus levels. We also accept the far reaching implications which lie behind this statement and its preamble, but we do not have space to discuss them here.

This article is the result, and therefore an acknowledgment, of the scholarly opportunities given to one of us (P.J.C.) during a year as Visiting Professor at the Hawaii Institute of Geophysics, University of Hawaii, where the Director, George Woollard, gave special help. A.C. received support from the National Science Foundation.

Received October 26, 1973; revised January 22, 1974.

¹ Carr, A., and Hirth, H., *Am. Mus. Novit.*, 2091 (1962).

² Carr, A., *Scient. Am.*, 212 (1965).

- ³ Carr, A., in *Animal Orientation and Navigation* (edit. by Storm, R. M.), 35 (Proceedings of 27th Annual Biological Colloquium, Oregon State University Press, Corvallis, 1967).
- ⁴ Carr, A., *So excellent a fish* (Natural History Press, Doubleday, New York, 1967).
- ⁵ Carr, A., in *Animal Orientation and Navigation* (edit. by Galler, S. R. et al.), 469 (National Aeronautics and Space Administration, SP-262, Washington DC, 1972).
- ⁶ Da Costa, R. S., *Bol. Estud. Pesca (Braz.)*, 9, 21 (1969).
- ⁷ Koch, A. L., Carr, A., and Ehrenfeld, D. W., *J. theor. Biol.*, 22, 163 (1969).
- ⁸ Ferreira, M. M., *Arg. Estud. Biol. mar., Univ. Fed. Ceará*, 8, 85 (1968).
- ⁹ Bergounioux, F. M., in *Traité de Paléontologie* (edit. by Piveteau, J.), 5, 487 (Masson, Paris, 1955).
- ¹⁰ Hay, O. P., *Carnegie Inst., Washington, Spec. Publ.* 75 (1908).
- ¹¹ Zangerl, R., *Fieldiana: Geol. Mem.*, 3, 279 (1960).
- ¹² Zangerl, R., and Sloan, R. E., *Fieldiana: Geol.*, 14 (2), 7 (1960).
- ¹³ Dietz, R. S., and Holden, J. C., *J. geophys. Res.*, 75, 4939 (1970).
- ¹⁴ Larson, R. L., and Pitman, W. C., *Bull. geol. Soc. Am.*, 83, 3645 (1972).
- ¹⁵ Le Pichon, X., and Hayes, E. D., *J. geophys. Res.*, 76, 6283 (1971).
- ¹⁶ Maack, R., *Kontinentaldrift und Geologie des Sudatlantischen Ozeans* (Walter de Gruyter, Berlin, 1969).
- ¹⁷ Menard, H. W., *J. geophys. Res.*, 74, 4827 (1969).
- ¹⁸ Carr, A., and Carr, M. H., *Ecology*, 53, 425 (1972).
- ¹⁹ van Andel, Tj. H., Rea, D. K., von Herzen, R. P., and Hoskins, H., *Bull. geol. Soc. Am.*, 84, 1527 (1973).
- ²⁰ Bell, J. D., Atkins, F. B., Baker, P. E., and Smith, D. G. W., *Eos (Trans. Am. geophys. Un.)*, 53, 168 (1972).
- ²¹ Daly, R. A., *Proc. Am. Acad. Arts Sci.*, 60 (1925).
- ²² Gordon, W. A., *J. Geol.*, 81, 269 (1973).
- ²³ Bullard, E., Everett, J. E., and Gilbert-Smith, A., *Phil. Trans. R. Soc.*, A 1088, 41 (1965).

LETTERS TO NATURE

PHYSICAL SCIENCES

Uranium in HR8911

IN recent years there has been growing interest in analysing stellar spectra in order to observe *r*-process elements (which are synthesised by neutron capture on fast time scales). Cool Ap stars seem to be the most likely objects to display lines of such elements^{1,2}. We report here preliminary results concerning some anomalies in the spectrum, which were obtained during analysis of the Cr-Eu-Sr peculiar star HR8911 (κ Piscium) and which show evidence for the presence of *r*-process elements in this object.

Four Mount Palomar spectrograms of HR8911 were measured, one of which was at 4.5 Å mm⁻¹ dispersion, and the spectral lines identified from tracings obtained with a Hilger microphotometer. As only about 2/3 of the spectral lines belonged to common elements of A-type stars, we further examined the unidentified lines in the plate at higher dispersions to search for *r*-process elements. We compared the stellar wavelengths and intensities with those listed by Zeidel *et al.*³. It is important to stress that the following results concern a single spectrogram, whereas HR8911 is a spectrum-variable star and cursory inspection of the other plates shows considerable spectral variations. For example, in another plate lines of Fe I 43, usually strong in spectra of A-type stars, are much fainter than in the measured spectrogram.

Of the heavy elements synthesised in *r*-processes⁴ the presence of osmium and uranium has been confirmed in our analysis. All unblended Os I lines with intensity greater than 50 in the intensity scale of Meggers *et al.*⁵ have been found in

the spectrum, together with many blended, and fainter lines, such as those observed in the spectrum of 73 Draconis⁶. Unblended Os II lines have not been observed. Almost all unblended lines of U II with intensity greater than 40 have been found in our spectrogram and the presence of many other blended lines is suspected. In addition, we remark that the two strongest U II lines ($\lambda = 3,859.58$ Å and $\lambda = 3,854.66$ Å) are unblended and clearly visible in the spectrogram.

Furthermore, there is some evidence for the presence of both neutral and singly ionised platinum in the atmosphere of this star, because the four strongest unblended lines of Pt I and some blended lines of Pt II were observed in the tracings. In addition, the strong Pt II ultraviolet line at $\lambda = 3,551.37$ Å is clearly visible in the other plates (10 Å/mm⁻¹ dispersion).

Among the other *r*-process heavy elements, we found no lines of gold, mercury, lead and bismuth. There are, however, some lines coincidental with Ir I lines, the strongest at $\lambda = 3,800.12$ Å. This is unblended and clearly visible in the spectrogram.

In conclusion, it seems that HR8911 shows evidence for *r*-process elements, so it must be added to those Ap stars in which such elements have already been detected. Thus the complex problem of the origin of Ap stars requires a theory which accounts for the presence of these elements in many objects. The hypothesis of a supernova explosion of a nearby star⁷ is an acceptable theory because the nucleosynthesis of the *r*-process elements requires a very high neutron density, such as that found in the interior of a highly evolved star. We notice further that in this case magnetic accretion⁸, could have an important role.