LAND AND SEA DISCOVERIES

In the 1950s and 1960s my father, André De Roy, nurtured a dream of finding a hidden freshwater oasis in the sunbaked hinterlands of our home island, Santa Cruz. While hunting goats (part of the pioneering life on Galápagos in those days), he spent many hours in this quest, scrambling down narrow basaltic fissures and crawling under thickets of thorny scrub. Gradually, he discovered an underworld of clear brackish water connected to the sea by tidal movements. Resting in one of these dim caverns after quenching his thirst one day, he noticed the faintest of movements among a filigree mat of floating plant roots. It turned out to be a tiny fish, virtually blind (vestigial eyes could be seen embedded in its transparent tissue) and almost devoid of any pigment, leading a secretive and extremely sedentary life in almost total darkness. It was eventually described as a new species in 1965: *Ogilbia galapagosensis*, the pink brotula (top), evolved in the underground aquifers described in this chapter. Ever inquisitive, André later noticed a similar shaped little fish slithering into the narrowest crevices of the lava reef just in front of the Charles Darwin Research Station, a 10-minute walk from the centre of Puerto Ayora, the largest settlement in Galápagos. This fish was bright red and sported pin-prick eyes. It was another new species, the orange brotula, named *Ogilbia deroyi* (above) in my father's honour the following year.
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that the aquifers form within the highly fissured basalts, and flow occurs at stratigraphical contacts between permeable and impermeable layers.

My conviction that the key to understanding Galápagos hydrogeology lay inside the island itself led to a helicopter-borne geophysical investigation carried out in collaboration with a Danish team of scientists. The method involves interpreting the response of subsurface strata to an induced electromagnetic field in order to detect layers of with different properties and thicknesses. The resistivity of each layer is dependent on the nature of the rock, water content, mineralization of water and clay content.

The resulting three-dimensional scan of the internal structure of both islands went far beyond all our expectations. For both islands, we saw a continuous and homogeneous deeply penetrating saltwater intrusion around the whole coastal fringe. Above the saltwater lies the freshwater lens which forms the basal aquifer. The thickness of the freshwater lens is greater on the windward mountainsides. I also gathered ground-based data on the basal aquifer of Santa Cruz from the open coastal fractures named 'grietas', and the recently drilled deep bore 5 km (3 miles) inland from the township of Puerto Ayora, both of which give direct access to this groundwater system. The water flow within this aquifer was thus characterized: water is present in the large, medium and small scale fractures of the un-weathered basalts. Possibly a perched aquifer also occurs on the southern mountainside of Santa Cruz, but with no outcrop to generate springs and rivers.

This new research lies at the crossroads between the geological sciences, which reveal the volcanic nature of the archipelago, and the biological sciences, which seek to understand the ecosystems and their living organisms. Water is a key factor by which the two are closely interrelated. Further work will be carried out to deepen our understanding of the subterranean water flow, especially the presence of perched aquifers, and to extend the study to the islands of Floreana and Isabela. The active volcanoes on Isabela will bring new information about the behaviour of water cycles in the proximity of magma chambers. Beyond the interest of earth scientists alone, this research opens new fields of investigation such as hydro-ecology, and can help provide viable solutions toward a more sustainable relationship between human development and the protection of unique ecosystems.

RIGHT AND FAR RIGHT: The same view from the rim of Cerro Azul on Isabela, taken a decade apart, reveals a bone-dry caldera 1973, but an extensive lake had appeared in the wake of a major El Niño in 1983. Today, only the cinder cone in the middle holds water.

Paleoclimate and the Future

A Knife-edge Balance

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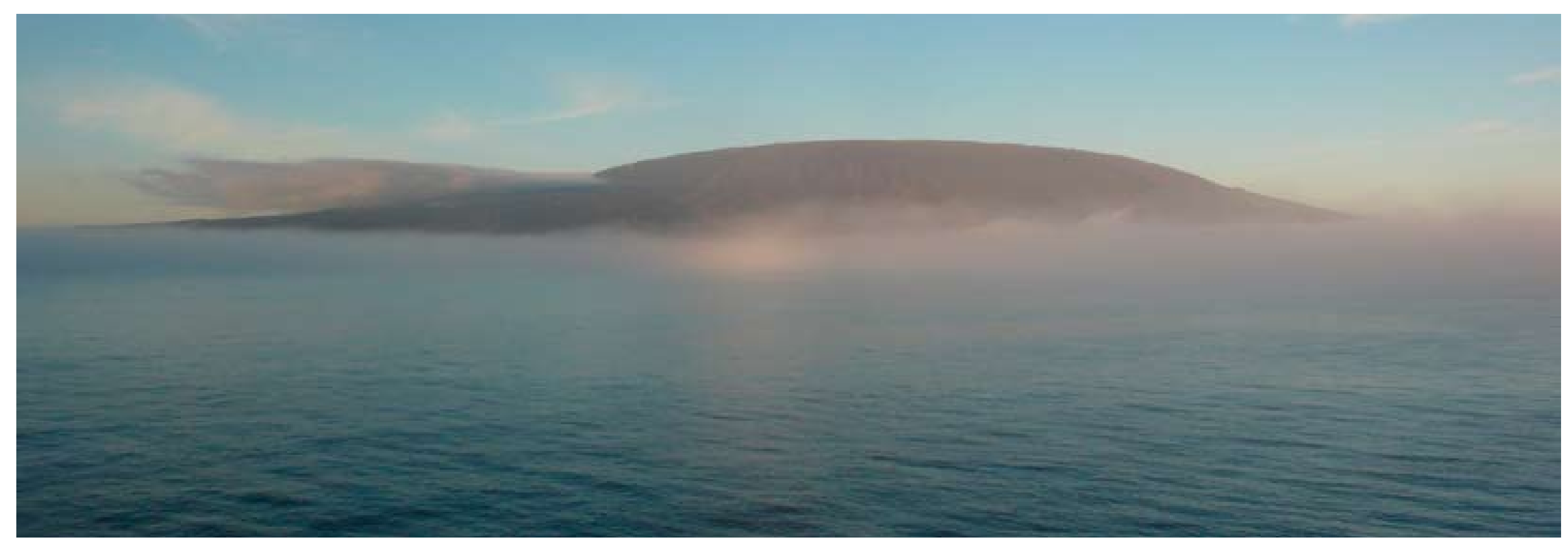
STRADDLING 0 DEGREES LATITUDE in the eastern Pacific Ocean, the Galápagos Islands are extremely sensitive to El Niño-Southern Oscillation (ENSO) events. Normally, the climate in this region is arid and remarkably cool compared to most tropical settings. A combination of local and remote oceanic and atmospheric processes account for the cold seawater that bathes the Galápagos Archipelago, causing this unusual situation in the eastern Pacific Ocean. Tradewinds that blow along the equator from east to west drive surface waters into the northern and southern hemispheres at right angles to the wind. These displaced waters are replaced by subsurface water that is upwelled, or 'pulled' up, from deeper and colder layers, contributing to the locally cool conditions. The Humboldt Current, with its origins in subpolar waters around Antarctica is kept cold by upwellings along the Peruvian coast, from where it flows northwest to Galápagos and combines with the cool and westward-flowing South Equatorial Current.

Yet another source of cold water originates from the opposite direction via the Equatorial Countercurrent (also known as the Cromwell Current), a deep stream moving west-to-east, contrary to the surface flow, and rising up where it encounters the undersea rampart of the Galápagos Platform.

Together, these cold waters are responsible for an inversion of air temperatures such that cold air near the ocean surface sits trapped beneath buoyant air warmed by the tropical sun, preventing the development of atmospheric convection cells that would otherwise bring abundant rainfall to tropical islands. A fog layer, locally called 'garúa' envelops the highlands of Galápagos, resulting from the condensation of moisture out of that warmer air where it comes into contact with the colder layer below. This situation prevails during the latter half of the year, usually lasting from June to December, in tandem with the southern (austral) winter.

During the southern summer, in mild years, the rain

BELOW: The strong presence of the cold upwelling Cromwell Current, or Equatorial Countercurrent, around the western part of the archipelago frequently brings thick sea fog lapping the arid shores of Fernandina Island.



ABOVE: An atmospheric inversion layer caused by cold sea temperatures drapes a low cloud layer over the islands, breached only on their leeward, northern sides. Known locally as the garúa season, mist shrouds the highlands from June to December, yet no rain falls on the lowlands.
BELOW: Used by the locals to harvest salt, a briny pan near the Santa Cruz shoreline may harbour the records of prior climate in layered sediments, while dead barnacles on the surrounding rocks reflect high sea levels during recent El Niño conditions.

band known as the Intertropical Convergence Zone (ITCZ) that spans the tropical Pacific Ocean, moves south from its normal position well north of the equator. When it reaches its most southern seasonal migration, this convergence of southeasterly and northeasterly winds causes the inversion to collapse and convection to occur, bringing some heavy precipitation to Galápagos, usually in February–March.

What differentiates a true El Niño event, which generally occurs once every two to seven years, is when the ITCZ effectively remains stuck at its southern extent for an unusually long period, sometimes for many months on end. During particularly strong El Niño years, extensive depression of the subsurface cold ocean water causes sea surface temperatures to rise in the entire eastern equatorial Pacific Ocean (EEP) region, and the atmospheric inversion around Galápagos disappears completely, intensifying tropical convection cells further. During such periods, these usually arid Islands receive several times their normal rainfall, while global precipitation patterns are altered, with droughts in normally wet locations and torrential rains in desert environments, especially coastal South America south of the equator. At the same time, as the upwelling of cool, nutrient-rich water wanes, fish stocks plummet and marine birds and mammals perish, causing widespread ecologic and economic disruptions throughout the region.

ENSO and Galápagos

My interest in the Galápagos began when, in the summer of 2004, I set out to determine how the largest global climate anomaly on the interannual time scale, ENSO, behaved before the beginning of human perturbations to the world's climate systems, and consequently how it might change in the future. The Galápagos Islands are perfectly situated for this line of inquiry because they sit on the equator in the eastern tropical Pacific region most strongly impacted by El Niño. They have the added advantage of being home to many different types of fresh, brackish and hypersaline water bodies likely to contain the sediment layers we need to reconstruct rainfall patterns from the past.

The two other locations I first targeted for this work were Christmas and Washington Islands in the Northern Line Islands of the central equatorial Pacific, and Palau in the western tropical Pacific.

These three study sites span the entire tropical Pacific and are situated within regions that have a very strong rainfall response to El Niño. Like Galápagos, Christmas and Washington Islands become very wet during El Niño events, while Palau experiences drought.

A fundamental question in climate dynamics concerns the sign and magnitude of change in the ENSO system under different global climate conditions than those of today. Will El Niño cycles become more intense and/or frequent in response to global warming? Presently, we do not know. Predictions range from a significant strengthening of the phenomenon to no effect, or even weakening. Climate data that pre-date the latter part of the 20th century, a primary requirement in order to evaluate these possibilities, are scarce and, as a result, extrapolations from them are often contradictory.

Some climate-modelling studies indicate that El Niños will become more pronounced and/or more frequent in a warmer climate resulting from a buildup of anthropogenic greenhouse gases in the atmosphere. Different models, and the paleoclimate data that supports them, however, suggest exactly the opposite. That we are not able to confidently predict the sign of change in the ENSO system, never mind its magnitude, is worrisome. It suggests that there may be important physics in the climate system that we do not understand, or that our translation of such physics into mathematical models is flawed. The best hope of rectifying this situation is to generate detailed paleoclimate records in an attempt to validate these divergent climate hypotheses and models.

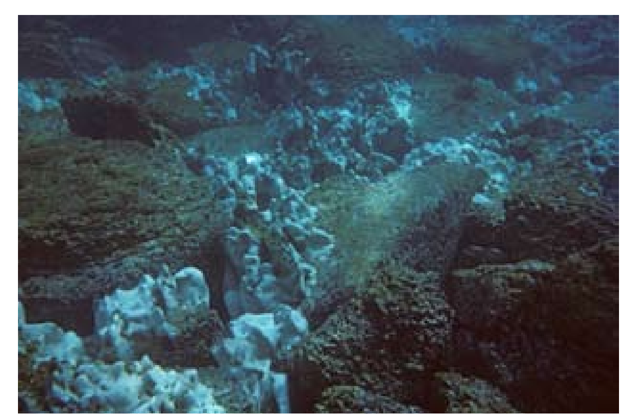
It is toward this end that I became involved in producing the longest, most detailed and most unambiguous reconstructions of ENSO variability

yet obtained from the EEP. In order to do that my colleagues and I are measuring the isotopes of hydrogen in the molecular remains of plankton in sediment cores that we collected in 2004 and 2008 from lakes, lagoons and bogs on six islands in the Galápagos Archipelago, deposits generally spanning the last 10,000 years.

Owing to the higher vapor pressure of water (H_2O) relative to deuterated water (DHO) — that is, water that has one deuterium atom, which is just a hydrogen atom with a neutron in its nucleus, and therefore a mass of two rather than one, and one hydrogen atom as opposed to two hydrogen atoms — evaporation enriches lakes and oceans in deuterium (D), while precipitation enriches them in hydrogen (H). During El Niño events, when torrential rains occur in the EEP, we expect the D/H ratio of lakes to decrease. Conversely, during La Niña episodes (when opposite conditions to El Niño prevail), the rain-starved lowlands of the Galápagos become tinder-dry and the normally rain-soaked volcanic peaks are moistened only by fog-drip from the enveloping stratus clouds. Thus, with a single source (rain) and sink (evaporation), the D/H ratio of water in closed lake systems are sensitive to the balance between precipitation and evaporation. During El Niño events their level tends to rise and the D/H ratio decreases. Conversely, during periods of weak ENSO activity the levels fall and the D/H ratio of the water increases.

Since changes in the hydrogen isotopic ratio of water must accompany the hydrologic changes, we are reconstructing water D/H variations in lakes and lagoons by measuring D/H values of lipid molecular fossils from plants and algae whose sole source of hydrogen is the lake water in which they live. Our studies with cultures of seven species of phytoplankton, and likewise in the field, have shown that the D/H ratio in algal lipids tracks the D/H ratio of the water in which they live with near perfection. These variables are recorded in the remains of such organisms deposited long ago in undisturbed lake

ABOVE: Roiling thunderstorms over Santa Cruz are a daily event during an El Niño year, when nutrient-poor seas tend to be exceptionally clear.
BELOW LEFT AND RIGHT: Contrasting undersea conditions show barren rocks and bleached coral heads during prolonged El Niño conditions (left), compared to lush seaweed beds and abundant invertebrate life when nutrient-rich upwellings are profuse.



UNIQUE FLAMINGO ENCLAVE IN THE PACIFIC

The Caribbean flamingo, *Phoenicopterus ruber* (above), closely related to the old world greater flamingo, is the only member of this ancient bird family with a foothold in the Pacific Ocean. Living in hyper-saline pools tucked behind beaches along the lava shorelines, small flocks feed on minute crustaceans, drawing their intense colour — the brightest of any flamingo — from the pigments of microscopic red algae that represent the base of this remarkable salt-loving food chain. Though permanent residents, they lead a precarious existence and rarely breed. Flamingo habitat is very susceptible to slight sea-level changes and heavy rains, particularly during El Niño events, which may flood nesting areas or allow fish to enter the lagoons from the sea, decimating their food supplies. Periodic archipelago-wide censuses show the Galápagos population hovers below 500 individuals.
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sediment layers. The Galápagos Islands present an ideal opportunity to record these variations through time, with lakes serving as fixed sampling stations of the eastern Pacific marine temperature variations.

The story in the sediment

In September 2004 we cored the sediments of El Junco Lake on San Cristóbal Island. This lake occupies a maar (explosion crater) in the cone forming the island's 750 m (2460 ft) summit, and became the focus of our primary investigation. It is enveloped for most of the year by the stratus clouds characteristic of the EEP climate. The lake is endorheic (a closed basin) and fed only by rain falling directly onto its surface and on the narrow annulus of the crater rim (see also chapter: d'Ozouville).

After flying to San Cristóbal, our team set up in Hotel Mar Azul, where we were able to use the restaurant area to spread out our equipment and sediment cores. The first day was spent hauling our gear over the crater rim to the lake edge. Fortunately, there is a road that meanders most of the way up the volcano, so we only had to carry our equipment uphill for half a kilometre or so. Though aware that El Junco Lake was cool and enveloped by clouds most of the time, one still has 'tropical' in mind when being less than 100 km (60 miles) from the equator. Not so. Except for a few sunny hours, we ended up working in many layers of clothing and in full raingear for the two to three weeks we conducted our sediment coring.

Samples were extracted our samples from El Junco using a piston corer operated from a raft constructed from two rubber dinghies and a plywood platform. The upper 3 m (10 ft) of sediment was soft mud and easy to penetrate. Below that came a 9-m (30 ft) thick layer of very stiff red clay deposit that was extremely difficult to bore into. After twice losing a core barrel at around 4 m (13 ft) below the lake floor, we managed to fine-tune our method, but it was slow-going, usually hammering the core head into the substrate centimetre by centimetre, then extracting the full core barrels again centimetre by centimetre with a giant corkscrew-like apparatus. On several days we recovered just one or two metre-long (3 ft) sections. Several times we abandoned the coring platform to let its buoyancy do the work pulling out buried core barrels for us. After three weeks, however, we obtained close to 40 m (130 ft) of sediment from seven different sites in the lake, with the deepest hole reaching about 12 m (40 ft) and quite possibly the last warm (interglacial) period 120,000 years ago. After this, we were able to enjoy the beauty and unique flora and fauna of the Galápagos Islands for a couple of days, before returning to the laboratory to start the real work.

Our measurements of hydrogen isotope ratios in molecular fossils from green algae in the El Junco Lake sediment, though still ongoing, have produced some surprising results. First, we discovered that there was just one other period during the last 5000 years that was as persistently dry — presumably the result of strong and/or frequent La Niña events — as the late 19th and early 20th centuries, and this happened in the 10th century A.D., during a period known as the 'Medieval Warm Period'. Second, the wettest episode of the entire last 5000 years of Galápagos climate — presumably the result of strong and/or frequent El Niño events — was from 1200 to 1800 A.D., a period known as the 'Little Ice Age'. If we extrapolate these findings into the future, when tailpipe and smokestack emissions will likely double the amount of carbon dioxide and other greenhouse gases in the atmosphere, warming the global climate dramatically, we would predict that the Galápagos Islands will become even dryer than they are today. If this scenario is correct, such a shift toward aridity would likely have severe consequences for plant and animal species that are already at or near their tolerance level for water deprivation.

Our findings are at odds with other studies on the frequency and intensity of El Niño events during the last millennium, which mostly suggest strong and/or frequent El Niño prevalence during the Medieval Warm Period and weak and/or infrequent events during the Little Ice Age. As additional data from other locations are generated, and computer-based simulations of the climate are performed, we will be able to confirm whether our interpretation of the data from El Junco is correct. Unfortunately, most current computer simulations of the climate system are not even able to reproduce the ENSO cycle accurately, and they incorrectly place an ITCZ in both hemispheres. In addition, there are very few sediment or coral archives in regions most sensitive to El Niño with the length and temporal resolution required to address this question in detail. So the controversy over El Niño predictions will not be solved in the immediate future without recourse to deciphering the detailed scripts we have begun to uncover in these lakes. Extrapolating from the unusually strong El Niño events of the last 30–40 years into the future is probably too simplistic, given the relatively short period of time that this covers. It may be that such recent, multi-decadal periods of strong ENSO occurred every few centuries and thus may be independent of the buildup of greenhouse gases that began 150 years ago. Thought-provoking as these initial findings may be, we will unfortunately need a lot of additional data before we can draw definitive conclusions.

RIGHT: With its impermeable clay floor allowing sediments to accumulate over millennia, the author's main study site in misty El Junco lake on San Cristóbal is revealing startling insights into past climate patterns.

ABOVE LEFT AND RIGHT: After five months of heavy rains during the 1997–98 El Niño, the normally arid *Opuntia* cactus forest on Santa Cruz was smothered in fast-growing vines (left), in sharp contrast to normal coastal conditions in a dry year, such as the land iguana habitat on Santa Fe (right).
BELOW: During prolonged La Niña conditions, when rains may fail for several consecutive years, land iguanas starve to death while their marine counterparts thrive.