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The Galápagos
A Natural Laboratory for the Earth Sciences

Karen S. Harpp
Eric Mittelstaedt
Noémi d’Ozouville
David W. Graham
Editors
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As the HMS Beagle sailed from Peru toward Galápagos in 1835, the young geologist and naturalist on board was looking forward to clambering around active volcanoes. As the boat sailed on to Tahiti after its five weeks in the archipelago, he thought about the whole volcanic landscape and some intriguing lava specimens that he’d found. But he also wondered about the strange natural life that he’d seen, with its extraordinary forms and diversity in such a small terrain so recently created out of the “unbroken ocean.” How might the living forms possibly be linked with the land forms in the play of air and ocean currents?

If only Darwin could have read these chapters and met their authors to talk with them about their discoveries and insights, and all the possibilities for further research that they point to! Darwin’s boldest speculation on geology in Galápagos focused on the formation of crystals in flowing magma and lava of different kinds. What the authors have now worked out and explained about the composition of the deep magma plume and its interactions with the ocean ridges around the spreading center would have excited him, for he was interested in the way that geological forces can transform whole land masses for their inhabitants. This volume shows vividly how the flux churns ceaselessly beneath the archipelago, driving all of its processes of change. It explains the long evolution of the great shield volcanoes, reveals the extraordinary pace of change on Fernandina, and explores the historical hydrogeography of Santa Cruz and San Cristobal to show the consequences for living communities through geological and now rapidly accelerating human time.

Each of these chapters is a rich fulfilment for that young man’s excited interest in the archipelago. For the sciences today, let Peter Grant speak.
A famous ecologist, G. Evelyn Hutchinson, once wrote a book entitled “The Ecological Theater and the Evolutionary Play” (Hutchinson 1965). The two metaphors are powerful in their simplicity. They forcefully convey the idea that biological evolution results from the interplay between organisms and their environment. If we want to truly appreciate the play, we need to understand the context—the scenery in the theater—and how it changes. Although much can be learned about evolutionary mechanisms from experiments conducted in the laboratory, for a full understanding of evolution we need to know how and why it occurs in the natural world. What better place to look for this than in the Galápagos?

In many ways, the archipelago is ideal for probing the geophysical, chemical and paleoclimatic reasons for a changing landscape because it is relatively young and volcanically active. The chapters in this volume reveal fascinating details of how the lithosphere, mantle plume, hotspot, and Galápagos Spreading Center have combined to produce a unique shifting kaleidoscope of islands. Seamounts are investigated to explore history out of sight, and lava-flow dating adds a more recent chronological perspective. The scenery in the theater has been repeatedly reconfigured, and the reasons are gradually being exposed.

And what of the play itself? The outline is well-known. Remote from the South American continent, the archipelago was colonized by finches, iguanas, tortoises, snails, beetles, fungi, lichens, angiosperm plants and a few other organisms. These ancestors, small in number, multiplied and diversified, so that instead of just one type of snail and one type of finch, there are now several, each having adapted to exploit different aspects of the environment. This is a textbook story of evolutionary diversification that took place rapidly, in the last few million years, and in the absence of humans. It is also a story of unusual animals being formed in isolation from their relatives; for example, iguanas that are otherwise terrestrial making a living in the sea.

For biologists, all of this variety provides a wonderful opportunity to examine how evolution occurs, gradually, in small steps; for example, how small variations on the theme of a tortoise carapace have resulted in shapes ranging from a dome to a saddle. Having worked out how evolutionary change has occurred, an investigator then seeks reasons for the change. A way to do this is to study the evolutionary process directly, as we have done with Darwin’s finches on the small island of Daphne Major (Grant and Grant 2014). This is not possible for most evolutionary questions because the time-scale is too large. Instead, one has to find an association between variation in a trait, such as the shape of a tortoise carapace, and variation in one or more environmental factors that can realistically be supposed to have caused the variation—evolutionary explanation, in other words, by inference.

At this point, the dynamic nature of the islands becomes very important. If there is one message in this volume for evolutionary biologists, it is that the size and disposition of the islands cannot be assumed to have remained unchanged while organisms evolved. Islands that are now separated were once joined, and before that they were separated. Reconstructions of the spatial and temporal configuration of islands are necessary for biologists to reconstruct evolutionary history. They are going to be increasingly important for those who follow in the footsteps of Charles Darwin in attempting to explain the unique Galápagos biota. For geologists, the challenge is to improve understanding of how the archipelago came to be the way it is: the sequence of major events and the mechanisms involved. This volume builds the platform from which future research will be launched.

REFERENCES


Much of the motivation for this monograph grew out of an international Chapman Conference, held in the Galápagos Islands in August, 2011, entitled “The Galápagos as a Laboratory for the Earth Sciences.” The meeting was organized to examine ocean island systems from an interdisciplinary perspective, from the deep mantle to the island surfaces and their biodiversity. Specifically, the primary objective was to integrate our knowledge of the geological, geochemical, and geophysical evolution of ocean island systems. The Galápagos Archipelago provided a unique and inspiring setting for the energetic discussions; many of the articles in this monograph emerged from those conversations. We thank the organizers of the Chapman Conference: Dennis Geist, Mark Richards, Karen Harpp, Gordon Grant, Cynthia Ebinger, Garrett Ito, Patricio Ramón, and Douglas Toomey. The conference was funded by generous contributions from the National Science Foundation, specifically the Division of Earth Sciences (Marine Geology and Geophysics, Petrology and Geochemistry, and Geophysics; EAR Award 1014620).

The editors thank the Charles Darwin Foundation, and especially the staff of the Charles Darwin Research Station, for their myriad of contributions to the conference and the work presented in this monograph. We would also like to express our thanks to Marco Bagnardi and Scott Baker for providing the satellite image for the front cover.

We are also grateful to the American Geophysical Union and to Wiley for their editorial and management support. Telicia Collick (AGU), Colleen Matan (formerly AGU), Justin Jeffryes (Wiley), and Rituparna Bose (Wiley) helped make publication of the monograph a reality.

Most of all, we thank our thoughtful and talented authors and reviewers, without whom this monograph would not have been possible.
Discovered in 1535, the Galápagos Islands continue to be an intellectual inspiration, owing to their rugged volcanic terrain, their isolation, and their distinctive flora and fauna. As the highlight of young shipboard naturalist Charles Darwin’s voyage around the world on the HMS Beagle 175 years ago, the islands gained recognition through his publication, *On the Origin of Species by Means of Natural Selection*. In this work, Darwin illustrated the essential contributions played by the Galápagos Islands in his development of evolutionary theory. Since that time, scientific studies have shown the Galápagos to be a complex system in which climate, ocean currents, biology and geology profoundly affect one another. This monograph is an effort to synthesize interdisciplinary knowledge gained through decades of innovative, passion-driven research in this unique setting that reaches from the tops of volcanoes into the interior of the earth.

We have organized this work into sections on volcanism, surface process, and deep Earth processes. While the chapters are grounded in different disciplines and address a range of spatial and temporal scales, collectively they contribute to an integrated understanding of the Galápagos region, placing it in the context of other hotspots and volcanic island systems and illustrating how the archipelago truly serves as a natural laboratory for the earth sciences.

For at least twenty million years (and quite likely tens of millions of years longer), there has been nearly continuous volcanism in the Galápagos as a result of a mantle plume beneath the eastward-moving Nazca Plate. This volcanism created an approximately 3-km-thick platform, upon which sits a chain of islands and seamounts that provide important insight into mantle plumes and ocean island volcanism. The Galápagos and Hawai’i are among the most-cited expressions of hotspot volcanism, yet they differ significantly in their morphology, chemical composition and structural evolution [Poland, Chapter 2]. At length scales of hundreds of kilometers, some of the variations in island geochemistry may reflect a common source for plumes in the deep mantle, suggested by Harpp et al. [Chapter 3] to be the Pacific Large Low Shear Velocity Province.

Studies of individual islands also yield critical information about mantle dynamics and island volcanism. Kurz et al. [Chapter 4] combine surface exposure dating using cosmogenic $^3$He with geologic mapping to provide new estimates of volcanic eruption rates and the emergence age of Fernandina, the youngest Galápagos island. Until now, clearly delineating the chemical and physical progression of volcanoes in the Galápagos Islands has been problematic, but Geist et al. [Chapter 5] define a common progression in chemistry and eruptive style between islands. A very late stage of this volcanic evolution is revealed on Isla Floreana through newly identified diverse alkaline magmas that erupted over the past million years [Harpp et al., Chapter 6]. The chemical compositions of these magmas may in turn reveal fundamental characteristics about the mantle source supplying Galápagos volcanoes.

The location of the Galápagos on the equator, coupled with the conveyor belt of plume-generated islands, has far-reaching consequences for biodiversity, island hydrological systems, regional oceanography, and climate.
A multidisciplinary synthesis of more than forty years of first-hand observations with previous studies illustrates how plate tectonics and volcanism have played a vital role in Galápagos biodiversity, but it further reveals that anthropogenic influences are now becoming the dominant factor controlling introduction of species to the islands [Merlen, Chapter 7]. An examination of relative emergence ages of the islands in the context of models for the carrying capacity of native and endemic species as a function of island size further reveals the changing face of the Galápagos [Geist et al., Chapter 8].

Hydrologic systems, like island ecosystems, evolve as the islands age. A comparative study of the older San Cristobal and the younger Santa Cruz indicates that time since cessation of active volcanism, location within the archipelago, vegetation type, and degree of basalt weathering are the key factors controlling hydrologic systems [Violette et al., Chapter 9]. In a complementary approach, Jefferson et al. [Chapter 10] compile a global database of several factors thought to influence the hydrologic and topographic evolution of ocean islands, and suggest that the dissection of volcanic islands depends strongly on precipitation rate, beginning between 0.5 and 2 million years after island construction. The location and shape of the Galápagos Islands also have important implications for marine biodiversity and the distribution of oceanic currents. The Galápagos platform and islands act as an obstruction to the movement of ocean water, causing cold, bathymetry-driven upwelling and modification of the regional and ocean basin-scale dynamics and biogeochemistry [Karnauskas et al., Chapter 11]. The significance of submarine morphology is further revealed by analysis and modeling of two recent tsunami events in 2010 and 2011 that reveal strong, shelf-resonant modes linked to Galápagos bathymetry [Rentería and Lynett, Chapter 12].

Beyond the main archipelago, the Galápagos hotspot influences volcanism and tectonic processes across a region several hundred kilometers in radius. Several recent studies focus on the islands and numerous seamounts of the Northern Galápagos Volcanic Province (NGVP), the region between the Galápagos Archipelago and the Galápagos Spreading Center (GSC). Ito and Bianco [Chapter 13] present a state-of-the-art numerical model of sub-lithospheric plume flow in the Galápagos area that combines tectonic plate motions and observationally constrained ridge axis geometry. They find that regional geophysical and geochemical data are best fit by a model with a strongly temperature-dependent rheology in the underlying mantle, but without a significant increase in mantle viscosity, owing to dehydration during the early stages of melting. Analysis and modeling of shipboard gravity data for the NGVP seamounts and islands indicates that they are underlain by lithosphere of nearly uniform thickness, perhaps the result of heating by the nearby plume and significant magmatic underplating [Mittelstaedt et al., Chapter 14]. Detailed geologic sampling and chemical analyses of three NGVP islands reveals them to be distinct from the main archipelago volcanoes, and suggests that they originate by intra-plate deformation associated with anomalous stresses in the underlying lithosphere [Harpp et al., Chapter 15], a manifestation of interaction between the Galápagos plume and the adjacent spreading ridge. Geochemical and geochronological analyses of older seamounts in the eastern part of the NGVP reveal that this current pattern of discrete volcanoes situated between the GSC and the main archipelago also existed between three and six million years ago [Sinton et al., Chapter 16].

Interaction of the Galápagos mantle plume with the GSC results in long-wavelength geophysical and geochemical anomalies along the spreading ridge. Canales et al. [Chapter 17] provide evidence that melt supply along the spreading ridge axis is influenced by the plume. Their data from a wide-angle seismic refraction experiment at three locations along the western GSC indicate increasing crustal melt fractions and melt connectivity at decreasing plume-rise distances. In contrast to previous studies that suggest a strong influence of the Galápagos plume on basalt chemistry along the GSC, Graham et al. [Chapter 18] find only typical mid-ocean ridge basalt 3He/4He ratios in axial GSC lavas, and conclude that He-rich material in the core of the upwelling plume beneath the islands is sheared away from the GSC by eastward motion of the overlying Nazca plate.

The scope of this AGU Monograph is distinctive both in content and form, and we would like to recognize the diversity of authors who have worked diligently to present their research in a manner both accessible and interesting to the broad community of earth scientists who study ocean island systems, volcanology, the mantle, surface processes, and biological processes. We only mention first authors here, owing to space constraints, but acknowledge the important contributions of all coauthors as well.

Willington Rentería is an Ecuadorian researcher, currently working at the National Oceanographic Institute of Ecuador (INOCAR) and Ecuadorian Tsunami Warning Center, who completed his graduate work at Texas A&M University and presents the first published work on tsunamis in Galápagos. Godfrey Merlen is an independent researcher, long-time Galápagos resident, and scientific advisor to the Galapagos National Park and Biosecurity Agency, renowned in the islands for his conservation efforts and his skills as a naturalist. Dennis Geist (University of Idaho) has been studying Galápagos volcanoes since his dissertation on San Cristobal Island under the supervision of Alexander Mc Birney (University of
In the 1980s, and is currently president of the Charles Darwin Foundation. Karen Harpp (Colgate University) has investigated the interaction between the Galápagos plume and the spreading center, leading a recent oceanic cruise to the Northern Galápagos Volcanic Province. Mark Kurz (Woods Hole Oceanographic Institution, WHOI) and Christopher Sinton (Ithaca College) use complementary geochronological methods to provide ages of both subaerial and submarine lavas throughout the Galápagos. Sophie Violette (Ecole Normale Supérieure and CNRS) and Noémi d’Ozouville (formerly Université Pierre et Marie Curie, UPMC-Sorbonne Universités, now Charles Darwin Foundation) led the first effort to study hydrological processes on the Galápagos Islands, which now involves Ecuadorian doctoral students and several local Galápagos institutions. Michael Poland (U.S. Geological Survey) is a scientist at the Hawaiian Volcano Observatory, giving him an important lens through which to view the Galápagos from the perspective of the most intensively studied archipelago on earth.

Kris Karnauskas (WHOI) models oceanographic current interactions and their effect on climate, whereas Garrett Ito (University of Hawai‘i) has developed numerical models of mantle plumes that investigate how they influence geochemical characteristics of ocean island systems. Anne Jefferson (Kent State University) applies her expertise in Cascade arc volcanoes to provide insight into hydrologic processes and landscape evolution on shield volcanoes and volcanic ocean islands. Juan Pablo Canales (WHOI) uses innovative seismic data analysis methods to investigate the structure of magmatic plumbing systems at mid-ocean spreading ridges. Finally, David Graham (Oregon State University) examines the distribution of noble gases in submarine lavas as a window into the behavior of mantle plumes.

Our hope as the editorial team is that the diversity of studies represented in this Monograph illustrates the importance of long-term, integrated, multidisciplinary work for achieving a thorough understanding of ocean island systems. This truly interdisciplinary volume demonstrates the intricate connectivity of geology and biology in the Galápagos, and underscores the need for continued research and dedicated conservation efforts in this unique and inspirational speck of land in the middle of the Pacific Ocean.
2
Contrasting Volcanism in Hawai’i and the Galápagos

Michael P. Poland1

ABSTRACT

The archipelagos of Hawai‘i and the Galápagos originated at mantle hotspots, yet the volcanoes that make up the island chains differ in most respects. Some of the most important differences include the dynamics of magma supply, characteristics of magma storage and transport, morphology, and compositional and structural evolution. Of particular significance in the Galápagos is the lack of well-developed rift zones, which may be related to higher rates of pre-eruptive inflation compared to Hawai‘i, and the absence of widespread flank instability—a common feature of Hawai‘i’s volcanoes. The close proximity of the Galápagos to a mid-ocean-ridge system may account for many of the differences between Hawaiian and Galápagos volcanoes. The Galápagos archipelago is built on young, thin oceanic crust, which might allow for contemporaneous growth of numerous volcanoes, and its volcanoes are fed by a mix of plume and asthenospheric melt sources. Hawaiian volcanoes, in contrast, grew in the middle of the Pacific Plate on older, thicker crust, where localized changes in mantle and lithosphere structure and composition did not exert dominant control over volcano evolution.

2.1. INTRODUCTION

The first decade of the twenty-first century saw a revolution in understanding of Galápagos volcanism. Before the year 2000, the majority of scientific investigations on Galápagos volcanoes were devoted to petrologic and geologic research (e.g., Banfield, 1956; Mc Birney and Williams, 1969; Simkin and Howard, 1970; Nordlie, 1973; Simkin, 1984; Chadwick and Howard, 1991; Geist et al., 1994). In particular, studies of magma supply, storage, and transport were largely restricted to petrologic [e.g., Reynolds et al., 1995; Geist et al., 1998], structural [e.g., Cullen et al., 1987; Munro and Rowland, 1996], and modeling [e.g., Chadwick and Dieterich, 1995] analyses, owing to an almost complete lack of geophysical monitoring data. The application of satellite-based interferometric synthetic aperture radar (InSAR) to the Galápagos in the late 1990s began a new era in understanding how Galápagos volcanoes worked by revealing some of their dynamic processes for the first time.

InSAR is a space-based geodetic technique in which radar images of the same area on the ground from about the same point in space are acquired at different times and combined to map surface displacements over the time spanned by the images [Massonnet and Feigl, 1998]. The most significant implication of this technique is that high-spatial-resolution deformation measurements can be collected from remote areas without ground-based equipment. Jónsson et al. [1999] was the first to apply InSAR to the Galápagos, modeling ground motion associated with an eruption on the southwest flank of Fernandina in 1995. Amelung et al. [2000] subsequently reviewed deformation of the western part of the archipelago using InSAR data that spanned from 1992 to 1999. Their results demonstrated that nearly every volcano on Isabela and Fernandina islands experienced inflation during that period, some at rates of several tens of centimeters per year (Figure 2.1). Additional constraints on geophysical activity at the Galápagos have

1U.S. Geological Survey—Hawaiian Volcano Observatory
subsequently included campaign and continuous GPS [Geist et al., 2006a; Chadwick et al., 2006], microgravity surveys [Geist et al., 2006a; Vigouroux et al., 2008], and seismic deployments [Tepp et al., 2014].

In contrast to the Galápagos, geophysical monitoring in Hawaiʻi began with the establishment of the Hawaiian Volcano Observatory on the rim of Kilauea Caldera in 1912, enabling detailed examination of magma supply, storage, and eruption [Apple, 1987; Kauahikaua and Poland, 2012]. Such studies were critical to the development of models for hotspots [Wilson, 1963] and mantle plumes [Morgan, 1971]. Frequent and accessible eruptions at Kilauea also facilitated the first calculation of contemporary magma supply to a volcano [Swanson, 1972]. Models of dike emplacement have been developed and tested in Hawaiʻi [e.g., Pollard et al., 1983], and the geometry of magma storage at Kilauea and Mauna Loa is increasingly well-constrained by ever-improving monitoring data and sophisticated analyses [e.g., Cervelli and Miklius, 2003; Amelung et al., 2007; Baker and Amelung, 2012; Poland et al., in press].

The long history of research in Hawaiʻi has led to those volcanoes being used as idealized examples of oceanic shields. Hawaiian volcanoes, however, are a poor analog for those in the Galápagos. Although both systems are dominated by basaltic compositions that have an ultimate origin within the mantle, numerous differences are readily apparent. For example, Hawaiian volcanism is currently occurring in the middle of a tectonic plate, but the Galápagos hotspot is interacting with a nearby mid-ocean ridge [Sleep, 1990; Feighner and Richards, 1994]. Active Galápagos volcanoes also have very different morphologies than their Hawaiian counterparts and deform at higher rates, and nine Galápagos volcanoes have erupted since 1800, compared to four in Hawaiʻi. This chapter explores the similarities and differences between volcanoes of Hawaiʻi and the Galápagos, from magma supply from the mantle to ultimate eruption at the surface. Insights into Galápagos volcanism are based upon a solid foundation established by geologic and petrologic research [e.g., McBirney and Williams, 1969; Simkin, 1984] and pay special attention to current magmatic configurations inferred from modern geophysical data, especially deformation. While Hawaiʻi remains one of the best natural laboratories for basaltic volcanism in the world, some processes associated with the growth and evolution of ocean island volcanoes may be better studied in the Galápagos.

2.2. MAGMA SUPPLY

The Hawaiian hotspot has the highest buoyancy flux—a measure of the amount of material ascending within the mantle plume—of any hotspot in the world [Davies, 1988; Sleep, 1990]. The modeled buoyancy flux of the Galápagos plume is several times lower than that of Hawaiʻi, implying a slightly cooler plume [Sleep, 1990; Ito et al., 1997; Canales et al., 2002; Hooft et al., 2003]. Nevertheless, the actual volume rate of volcanism produced by the two hotspots over the last several million years is comparable, in the range of 0.1−0.2 km³/yr (Figure 2.2) [Canales et al., 2002; Van Ark and Lin, 2004]. The similarity in magma supply despite the difference in buoyancy flux may be attributed to the older and thicker lithosphere beneath Hawaiʻi as compared to that beneath the Galápagos [Canales et al., 2002; Gibson and Geist, 2010], which may restrict the amount of melt that reaches the surface. In Hawaiʻi, the supply of magma that reaches the volcanoes is well-constrained, thanks to the decades-long record of historical eruptions and geophysical monitoring. Using recent deformation data, the magma supply characteristics of Galápagos volcanoes can also be explored.

![Figure 2.1 Deformation observed on Fernandina and Isabela Islands by InSAR from 1992 to 1998. Volcanoes on both islands, with the exception of Ecuador, show deformation of at least several centimeters, and two of the volcanoes erupted during the time spanned by the image—Fernandina in 1995 and Cerro Azul in 1998. Figure is adapted from Amelung et al. [2000] (reproduced with permission from Macmillan Publishers Ltd: Nature, doi:10.1038/35039604, copyright 2000).](image-url)
2.2.1. Competition for magma supply and interactions between volcanoes

Magma supply to Hawaiian volcanoes, particularly Kīlauea, has been the subject of numerous studies. Swanson [1972] estimated magma supply from the effusion rates of three long-term eruptions at Kīlauea between 1952 and 1971. The eruptions were associated with minimal summit deformation, implying that nearly all of the magma supplied to the volcano was erupted—approximately 0.1 km$^3$/yr. Other authors subsequently combined erupted volumes and modeled magma storage over periods since 1950 to infer similar supply rates to Kīlauea’s shallow magmatic system [e.g., Dzurisin et al., 1984; Dvorak and Dzurisin, 1993; Poland et al., 2012]. In contrast, magma supply to Mauna Loa during the same period appears to have been lower (compared to pre-1950 supply), as implied by infrequent eruptive activity, suggesting that Kīlauea and Mauna Loa compete for magma from the hotspot [Moore, 1970; Klein, 1982]. There is also evidence that the supply varies over shorter intervals. For example, supply from the mantle hotspot more than doubled during the mid-2000s and affected both volcanoes, resulting in a period of inflation at Mauna Loa, increased effusion rates and inflation at Kīlauea, and changes in eruptive activity at Kīlauea’s summit and east rift zone [Poland et al., 2012; Gonnermann et al., 2012].

If Kīlauea and Mauna Loa (and the two other historically active Hawaiian volcanoes of Hualalai and Lo‘ihi) are competing for magma from the Hawaiian hotspot, a similar process may be occurring between the nine historically active volcanoes of the western Galápagos: Fernandina, Cerro Azul, Sierra Negra, Alcedo, Darwin, Wolf, Santiago, Marchena, and Pinta (although the latter two volcanoes, located east of the largest islands, are comparatively small in volume; see http://www.volcano.si.edu for descriptions of activity at individual volcanoes). Indeed, the islands of Fernandina, Santiago, and Isabela occupy a region roughly the same size as the Island of Hawai‘i (Figure 2.3), and compositional variations among lavas erupted from the western part of the archipelago suggest a systematic variation in the rate of supply to the volcanoes [Naumann et al., 2002].

Figure 2.2 Time-averaged igneous volume flux for the Hawaiian Emperor chain (thin black line, from Van Ark and Lin [2004]) and Galápagos archipelago (thick grey field, from Ito et al. [1997]).

Figure 2.3 Shaded relief images of the islands of Hawai‘i (left) and the western Galápagos (right) shown at the same scale. Volcanoes are indicated, with the dates of the most recent historic eruption, if any, in parentheses. Closer volcano spacing, smaller volcano size, and larger calderas are evident in the Galápagos.
The short record (since the 1990s) of deformation in the Galápagos supports variable magma supply to the volcanoes. For example, Sierra Negra inflated during 1992–2000, deflated during 2000–2003, rapidly inflated from 2003 until its 2005 eruption, deflated during the eruption, and experienced rapid post-eruptive inflation that decayed to no deformation by late 2011 [Amelung et al., 2000; Chadwick et al., 2006; Baker, 2012] (Figure 2.4). This highly variable deformation before the 2005 eruption, which occurred without any known secondary magma storage located away from the main subcaldera reservoir, suggests that the rate of supply to the volcano from the hotspot source was unsteady and possibly discontinuous. Rapid post-eruptive inflation may have been initially driven by a pressure imbalance between a partially evacuated shallow reservoir and a deeper magma source, as has been proposed at Kilauea [Dvorak and Okamura, 1987; Dvorak and Dzurisin, 1993]. Rapid pre-eruptive inflation, however, argues for an increase in magma supply to the volcano [e.g., Poland et al., 2012]. In contrast, the neighboring Cerro Azul, which erupted in 1998 and 2008, inflated by more than 10 cm during 2000–2003, but rates waned after 2003 [Baker, 2012]. Perhaps much of the magma supply to Sierra Negra was diverted to Cerro Azul around 2000, when Sierra Negra’s inflation rate diminished, but was then directed back to Sierra Negra in 2003, leading up to its 2005 eruption. Fluctuations in magma supply may have also occurred at Fernandina, as indicated by a transition from sustained, low-rate eruptive activity that produced pāhoehoe flows in the past (indicative of high magma supply rates by analogy with Kilauea) to infrequent, short-lived, higher-effusion-rate ‘āʻā eruptions at present (implying a lower supply), although a lack of age-dating precludes assignment of specific activity durations [Rowland, 1996].

The mechanism for such deep-seated variation in magma supply between adjacent volcanoes over time scales of years to decades (or longer) is unclear. A connection between Kilauea and Mauna Loa has long been a source of speculation [Stearns and Macdonald, 1946], but isotopic differences in erupted lavas argue for independent mantle source regions for the two volcanoes [e.g., Frey and Rhodes, 1993]. Correlations between deformation at Kilauea and Mauna Loa in the 2000s [Miklius and Cervelli, 2003] have been used as evidence that pressure changes can be transmitted through a porous melt zone in the asthenosphere, providing a connection between the volcanoes while retaining independent mantle source areas [Gomberg et al., 2012]. Galápagos volcanoes are also compositionally and isotopically distinct [McBirney and Williams, 1969; White et al., 1993], arguing against a direct, shallow connection between shields. Nevertheless, deformation data indicate that volcanoes in the western part of the archipelago interact, as demonstrated by complimentary deformation between Cerro Azul and Sierra Negra (described above) and the cessation of inflation at Wolf and Alcedo when Fernandina erupted in 2009 [Baker, 2012]. A pressure linkage at depth, akin to that modeled for Hawai‘i, is a possible explanation for correlations in deformation observed at Galápagos volcanoes, but stress interactions are more consistent with the nearly instantaneous nature of the changes in deformation style [Baker, 2012]. Regardless, petrologic data indicate that a physical pathway may occasionally exist between volcanoes.
in Hawai‘i, as well as between Galápagos shields. Lava flows with Mauna Loa-like compositions have erupted from Kilauea during the past 2,000 years, possibly due to lateral intrusion of Mauna Loa magma into Kilauea’s plumbing system [Rhodes et al., 1989]. Likewise, compositionally distinct magmas have been observed to erupt from the “wrong” volcano in the Galápagos, perhaps as a result of lateral intrusion, incomplete mantle mixing, or advanced mantle melting [Geist et al., 1999].

2.2.2. Archipelago-scale magma supply

The approximate magma supply from the Galápagos hotspot over millions of years is known from the isostatic crustal thickness of the archipelago, as shown in Figure 2.2[60,676]. Supply to individual volcanoes over thousands of years can be estimated by dividing volcano volume by age, although low erosion rates mean that age constraints on most Galápagos volcanoes are lacking [Reynolds et al., 1995; Naumann and Geist, 2000]. On time scales of interest to humans, contemporary magma supply to individual volcanoes can be estimated by long-term effusion rates and deformation data. Historical Galápagos eruptions have been of shorter duration compared to, for instance, some Kilauea eruptions, so using effusion rates to infer supply is not feasible. Instead, supply must be estimated from the amount of magma stored over time—a calculation that is now possible using deformation data from InSAR and GPS.

Current rates of magma storage in the Galápagos are best constrained at Fernandina and Sierra Negra, where deformation and eruptions have been most thoroughly studied. The modeled volume increase in two storage reservoirs beneath Fernandina from 2003–2005, before its eruption, was 0.0029 km³/yr, and, in the year following the eruption, was 0.0037 km³/yr [Chadwick et al., 2011], representing minimum magma supply rates. The minimum eruption rate over the last 1,000 years at Fernandina is remarkably similar: 0.005 km³/yr, determined from cosmogenic helium age constraints on surface lava flows [Kurz et al., 2005]. In reality, the magma supply to Fernandina may be several times higher than modeled magma storage rates, because the deformation models used do not account for magma compressibility [e.g., Johnson et al., 2000; Rivalta and Segall, 2008]. Even so, the supply rate to Fernandina appears to be lower, by at least an order of magnitude, than the 0.1 km³/yr supplied to Kilauea prior to 2003 [Poland et al., 2012].

Sierra Negra is the largest volcano in the Galápagos by volume and appears to have the highest contemporary supply rate, based on evidence from geology [Reynolds et al., 1995; Naumann and Geist, 2000], petrology [Naumann et al., 2002], and deformation [Amelung et al., 2000; Chadwick et al., 2006] (Figure 2.4). Sierra Negra’s historical eruptions also tend to be the largest by volume in the archipelago, reaching 0.9 km³ in 1979 [Reynolds et al., 1995] and 0.15 km³ in 2005 [Geist et al., 2008]. Models of inflation in the two years before the 2005 eruption indicate magma accumulation rates of 0.017–0.064 km³/yr [Chadwick et al., 2006], similar to the volcano’s historical eruption rate of 0.012 km³/yr [Reynolds et al., 1995]. When accounting for un-modeled magma compressibility, the magma supply rate for Sierra Negra may begin to approach that of Kilauea.

Rates of present-day magma supply to other volcanoes of the western Galápagos are not well-constrained, but they are probably much less than those of Fernandina and Sierra Negra, based on their lower rates of inflation and infrequent eruptions. Fernandina and Sierra Negra deformation modeling and InSAR observations at other Galápagos volcanoes suggest that the cumulative storage rate for all western Galápagos volcanoes is roughly equivalent to the 0.1 km³/yr pre-2003 magma supply rate to Kilauea. (In the early 2000s, the cumulative modeled magma storage rate at Fernandina and Sierra Negra was 0.02–0.07 km³/yr, and magma storage at most other western Galápagos volcanoes indicated by InSAR [Amelung et al., 2000; Baker, 2012] could increase this rate by, perhaps, an additional 0.01 km³/yr). This is roughly consistent with the similar crustal volume fluxes (a measure of crustal volume beyond normal oceanic crust thickness over time) for the two hotspots [Ito et al., 1997; Van Ark and Lin, 2004].

The magma supply to Galápagos volcanoes currently favors Fernandina, Cerro Azul, and Sierra Negra, all of which have erupted and experienced high rates of inflation since 1990, but the supply appears to vary widely between volcanoes over both short and long time periods. For example, the long-term eruption rate at Cerro Azul, based on its subaerial volume and exposure of an 80 ka lava flow near the base of the caldera, is approximately 0.0005 km³/yr—the lowest in the archipelago [Naumann and Geist, 2000; Naumann et al., 2002]—yet the volcano erupted in 1998 and 2008. InSAR data since 1992 indicate multiple episodes of rapid inflation at Cerro Azul [Amelung et al., 2000; Baker, 2012], implying high rates of current magma supply. In contrast, Alcedo is in a waning phase of activity. Alcedo’s eruption rate has decreased by an order of magnitude in the last 100 k.y. [Geist et al., 1994], suggesting a long-term decrease in supply to that volcano. Recent inflation at Alcedo, however, indicates that short-term surges in supply still occur [Baker, 2012].

In addition to the overall magma supply rate, there are several similarities in how magma is fed to volcanoes in Hawai‘i and the Galápagos. The highest rates of contemporary magma supply are not at the leading edge of the hotspots, defined by Fernandina in the Galápagos and Lō‘ihi in Hawai‘i [Geist et al., 2006b] but, instead occur a few tens of kilometers back along the hotspot track, at
Sierra Negra and Kilauea. Additionally, because several volcanoes are competing for magma, supply can switch between volcanoes on time scales of years to decades. A noteworthy difference between the systems is the greater number of volcanoes competing for supply in the Galápagos and the roughly simultaneous—rather than sequential, as with Hawai‘i—formation of the western Galápagos volcanoes. Both of these characteristics, in addition to volcano spacing and alignment, are evidence that lithospheric structure exerts a control on Galápagos volcanism [Naumann and Geist, 2000; Naumann et al., 2002]. Whether or not the Galápagos hotspot experiences short-term (i.e., years-long) surges of magma, as recently demonstrated for the Hawaiian hotspot from 2003–2007 [Poland et al., 2012], is unknown.

### 2.3. Magma Storage

Deformation data are critical to assessing the characteristics of present-day magma storage beneath active volcanoes. For example, repeated leveling from 1967–1968 demonstrated that the center of inflation at Kilauea migrated over time, suggesting a complex magmatic system beneath the summit of the volcano [Fiske and Kinoshita, 1969]. Increased spatial resolution of surface displacements from InSAR has helped to better define the geometry and depth of magma storage areas at Kilauea [Baker and Amelung, 2012; Poland et al., in press]. Before the application of deformation measurements to Galápagos volcanoes, magma reservoir characteristics were inferred from geologic studies. Caldera morphology suggests large volumes of magma storage in centralized chambers with limited or no storage beneath volcano flanks [Muro and Rowland, 1996; Naumann et al., 2002]. Modeling the pattern of circumferential and radial eruptive fissures that typifies most western Galápagos volcanoes argues for sub-caldera diapir-shaped reservoirs [Chadwick and Dieterich, 1995]. InSAR and GPS have enabled much more detailed modeling of magma storage characteristics, including the depth, geometry, and number of magma reservoirs beneath individual volcanoes [e.g., Amelung et al., 2000; Jónsson et al., 2005; Chadwick et al., 2006; Geist et al., 2006a; Yun et al., 2006; Jónsson, 2009; Chadwick et al., 2011; Baker, 2012; Bagnardi and Amelung, 2012]. Deformation at all of the western Galápagos can be approximated by spheroidal or sill-like sources within about 5 km of the surface, although the geometry of magma storage differs from volcano to volcano [Amelung et al., 2000; Baker, 2012].

#### 2.3.1. Characteristics of magma storage

General patterns of magma storage in Hawai‘i and the Galápagos can be discerned from caldera shapes and sizes. The area of a caldera is thought to reflect the extent of subsurface magma reservoirs, and Galápagos calderas are generally larger than those in Hawai‘i [e.g., Naumann et al., 2002] (Figure 2.3). For example, the largest caldera in Hawai‘i, at Mauna Loa, has dimensions of 3 × 5 km [Lockwood and Lipman, 1987], while the smallest caldera in the western Galápagos, at Cerro Azul, measures 2 × 4 km and the largest, at Sierra Negra, is 7 × 9 km [Naumann et al., 2002]. Magma storage may therefore be more important to the evolution of volcanoes in the Galápagos and involve greater volumes than in Hawai‘i. In addition, caldera morphology can hint at the nature of subsurface storage. Calderas that are nested and have scalloped outlines indicate piecemeal collapse from different centers. The only such caldera in the Galápagos is at Cerro Azul and suggests magma storage in small, ephemeral chambers that may not mix and homogenize, which is consistent with the eruption of primitive lavas at that volcano (but nowhere else in the western part of the archipelago) [Naumann et al., 2002].

Present-day magma reservoirs are best investigated by geophysical data, particularly deformation measurements. Co-eruption deformation is especially useful for mapping magma reservoir location and geometry. Due to the lack of deformation measurements during eruptions, magma storage at Darwin, Wolf, and Alcedo is least-understood in the Galápagos, compared to that of Sierra Negra, Cerro Azul, and Fernandina. InSAR data indicating inflation of Darwin and Wolf have been modeled by point sources of volume change at depths of 3 and 2 km, respectively [Amelung et al., 2000], although data are sparse and probably cannot constrain more complex geometries. Petrologic data from Wolf are indicative of magma storage at 2 km depth [Geist et al., 2005], consistent with deformation modeling. Subsidence at Alcedo during 1997–2001 can be modeled with a source depth similar to that of Darwin and Wolf—about 2.2 km—but is decidedly asymmetric and best fit by a subhorizontal ellipsoidal source, elongated NW-SE, that may represent a cooling and crystallizing magma body [Hooper et al., 2007]. Magma storage at Cerro Azul is deeper than at other Galápagos volcanoes, with spherical source models indicating depths of 5–6 km [Amelung et al., 2000; Baker, 2012].

Abundant deformation data and eruptive activity are essential for refining models of magma storage. For example, initial models of Fernandina deformation suggested magma storage in a spherical reservoir at a depth of 3 km [Amelung et al., 2000]. Campaign GPS data from 2000–2002, however, indicated a source depth of only 1 km [Geist et al., 2006a]. InSAR- and GPS-derived deformation measurements taken before, during, and after eruptions in 2005 and 2009 revealed an even more complex system. Models of those data require two connected reservoirs, at depths of approximately 1 and 5 km [Chadwick et al., 2011; Bagnardi and Amelung, 2012; Bagnardi et al., 2013].
Deformation at Sierra Negra is the best-monitored and best-studied of any volcano in the Galápagos. Deformation patterns (Figure 2.5) suggest a magma storage geometry that is simple when compared to that of Fernandina. Models of pre-, co-, and post-eruptive deformation all argue for a sill-like structure at approximately 2 km depth [Amelung et al., 2000; Jónsson et al., 2005; Chadwick et al., 2006; Geist et al., 2006a; Yun et al., 2006; Geist et al., 2008; Jónsson, 2009]. Yun et al. [2006] noted that deformation models are insensitive to the sides and bottom of the magma reservoir if the depth, compared to the radius, is small (2 km and 6 km, respectively, for Sierra Negra), so sill- and diapir-shaped geometries fit the data equally well.

Galápagos volcanoes appear to have a variety of magma plumbing geometries, from simple (Darwin and Wolf, although this view may be biased by low deformation rates and no recent eruptive activity) to comparatively complex (Fernandina’s two-tiered reservoir system). Based on analogy with Hawaiian volcanoes, this diversity...
of storage geometries should not be a surprise. Summit magma storage at Kilauea includes at least two [Cervelli and Miklius, 2003] and, perhaps, three or four [Poland et al., 2012; Baker and Amelung, 2012; Poland et al., in press] reservoirs of varying sizes, or even a “plexus” of dikes and sills [Fiske and Kinoshita, 1969], with the main storage area at approximately 3 km beneath the south part of the caldera and the shallowest reservoir at an approximate depth of 1 km near the caldera center. Mauna Loa’s magma plumbing system has at least two components, modeled as a spherical source approximately 4 km beneath the southeast margin of the caldera and a dike-like tabular body that runs the length of the caldera with a top at the same depth (the bottom depth is difficult to resolve) [Amelung et al., 2007; Poland et al., in press]. The consistency of primary storage at 3–5 km depth in both Hawai‘i and the Galápagos may represent a neutral buoyancy level for mafic magma within basaltic shields [Ryan, 1987]. The reason for the existence of secondary magma storage zones at approximately 1–2 km beneath the caldera floors of Kilauea and Fernandina is less clear, but could reflect low-density, gas-rich magma that might be expected to exist at higher levels within frequently active basaltic volcanoes.

### 2.3.2. Magma storage beneath volcanic flanks

The major difference in magma storage between Hawai’ian and Galápagos volcanoes is the general absence of well-developed subaerial rift zones in the Galápagos, and instead the presence of a characteristic pattern of circumferential eruptive fissures close to the summit and radial fissures on the flanks [McBirney and Williams, 1969; Nordlie, 1973; Simkin, 1984; Chadwick and Howard, 1991]. The exception is Ecuador volcano, which hosts a well-developed subaerial rift zone that may have formed in response to sector collapse [Geist et al., 2002]. Submarine rift zones are present on Fernandina, Wolf, Cerro Azul, and Ecuador [Geist et al., 2006b]. Well-defined subaerial rift zones are not common, however, and are clearly not as important for magma storage and transport as in Hawai‘i; with the exception of Ecuador volcano, only a few diffuse rift zones with subtle topographic ridges are present, for example, on Wolf volcano [Chadwick and Howard, 1991; Geist et al., 2005]. The general lack of rift zones in the Galápagos is attributed to contemporaneous growth of the volcanoes—gravitational stress from preexisting volcanoes is thought to influence Hawaiian rift-zone formation—and a lack of thick ocean-floor sediments (due to the young age of the sea floor) that might promote rift-zone spreading [Nakamura, 1980; Simkin, 1984; Dieterich, 1988; Chadwick and Dieterich, 1995].

The absence of subaerial rift zones in the Galápagos is probably one of the causes of the higher rates of deformation observed there. At Kilauea, summit inflation rarely exceeds several tens of centimeters before an eruption occurs [e.g., Fiske and Kinoshita, 1969; Poland et al., 2012]. In contrast, Sierra Negra inflated by approximately 5 m between 1992 and 2005, with an inflation rate that reached about 1 cm/day immediately prior to its 2005 eruption (Figures 2.4, 2.5) [Chadwick et al., 2006; Geist et al., 2008]. One reason for the small deformation in Hawai‘i, compared to the Galápagos, is that magma is stored not only beneath Kilauea’s summit, but also within its rift zones at both shallow (2–3 km) [e.g., Poland et al., 2012, in press] and, possibly, deep (3–10 km) [Delaney et al., 1990; Cayol et al., 2000] levels. Some of the magma pressure at Kilauea can therefore be directed from the summit reservoir into the rift zones, preventing large-magnitude summit deformation. The lack of rift zones at Galápagos volcanoes means that magma pressure within subcaldera reservoirs is transmitted primarily to deform the surface. More frequent intrusions and eruptions in Hawai‘i, and particularly at Kilauea in recent decades, may also prevent large inflation magnitudes because the volume of magma stored at Hawaiian volcanoes is less than the volume stored at Galápagos volcanoes.

Despite the scarcity of subaerial rift zones, magma does intrude beneath the flanks of Galápagos volcanoes during radial fissure eruptions, probably fed by shallow (0–3 km) intrusions propagating away from subcaldera magma reservoirs [Jönsson et al., 1999; Bagnardi et al., 2013]. Flank intrusions apparently also occur at deeper (>3 km) levels in the form of sills. Circumstantial evidence for such intrusions includes uplift at Punta Espinosa, on the northeast flank of Fernandina, and Urvina Bay, on the west side of Isabela Island at the intersection between Darwin and Alcedo volcanoes. Uplift at Punta Espinosa in 1927 occurred so quickly that an anchored fishing boat was grounded and stranded [Cullen et al., 1987] (Figure 2.6A), and uplift of tens of centimeters was associated with earthquakes in the mid-1970s [Simkin, 1984]. In 1954, uplift of Urvina Bay raised the sea floor as much as 5 m above sea level and extended the shoreline more than 1 km (Figure 2.6B) in less than an hour, stranding and killing many forms of marine life [Couffer, 1954; McBirney et al., 1985; Cullen et al., 1987]. These uplifts were presumably driven by the intrusion of sills [McBirney et al., 1985; Geist et al., 1994], but no geophysical evidence exists to test this hypothesis. In 2006 and 2007, InSAR detected the intrusion of sills beneath Fernandina’s southern flank at a depth of approximately 4.5 km—about the same level as the deeper subcaldera magma reservoir [Bagnardi and Amelung, 2012]. Although far smaller in magnitude than the 1927 and 1954 uplifts, the 2006 and 2007 sills confirm that intrusion of magma beneath the flanks of Galápagos volcanoes can occur below the level of the radial dikes.