The Galápagos as a Laboratory for the Earth Sciences

July, 2011

Field Trip Guide:

Part I. The Geology of the Galápagos
Part II. Sierra Negra Volcano
Part III. Santa Cruz Volcano

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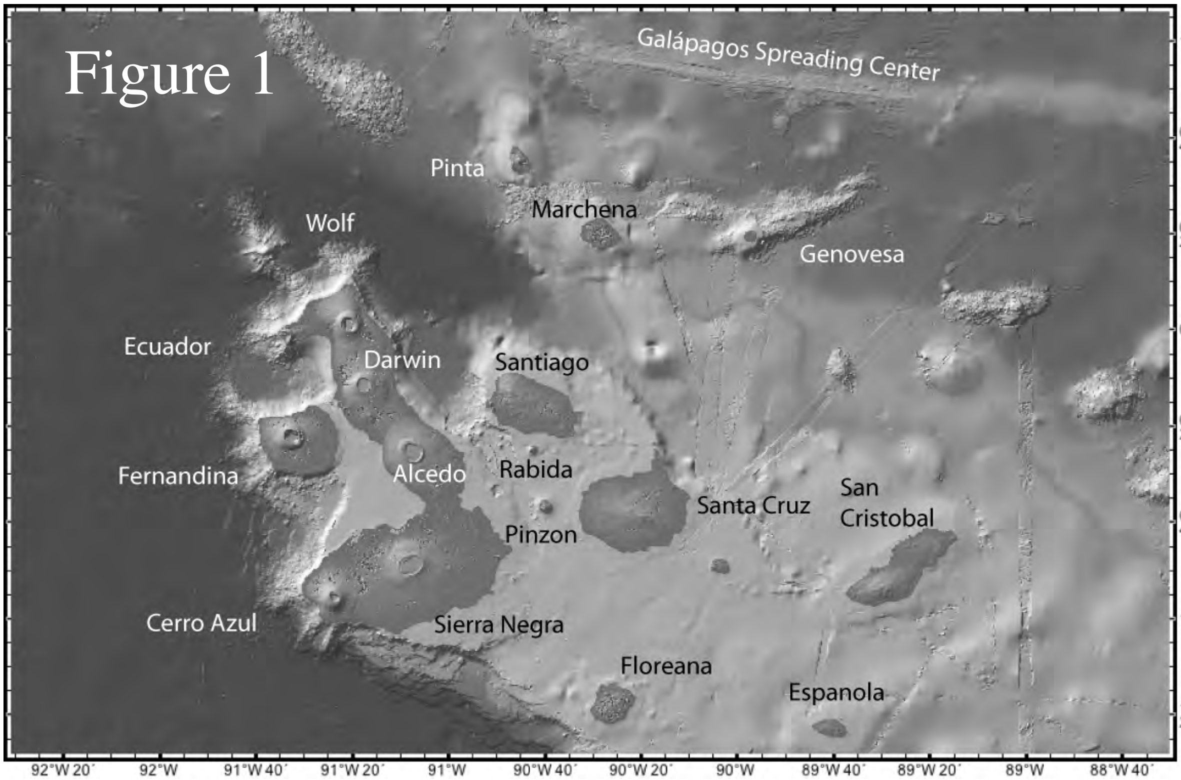
Figure 1
Galápagos Spreading Center
Pinta
Marchena
Genovesa
Wolf
Ecuador
Darwin
Santiago
Fernandina
Alcedo
Rabida
Santa Cruz
San Cristobal
Pinzon
Cerro Azul
Sierra Negra
Floreana
Espanola
1°N
0°N 40´
0°N 20´
0°
0°S 20´
0°S 40´
1°S
1°S 20´
92°W 20´
92°W
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91°W 20´
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89°W
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Figure 2

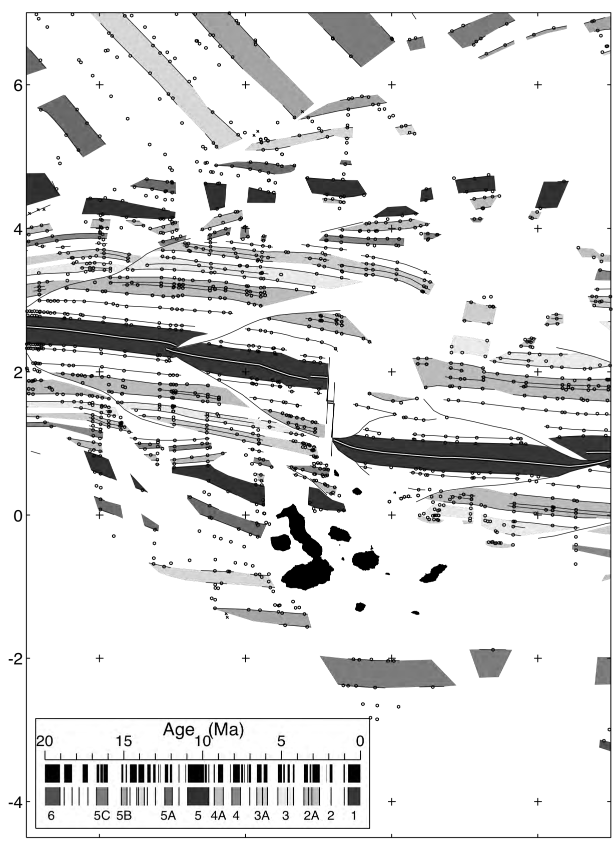

Age (Ma)
20
15
10
5
0
6
5C
5B
5A
5
4A
4
3A
3
2A
2
1
6
4
2
0
-2
-4
-94
-92
-90
-88

Figure 3

Figure 4

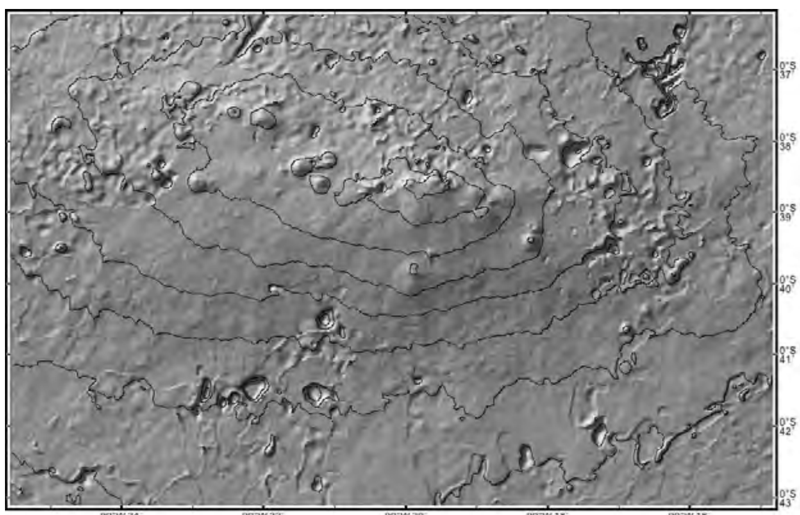
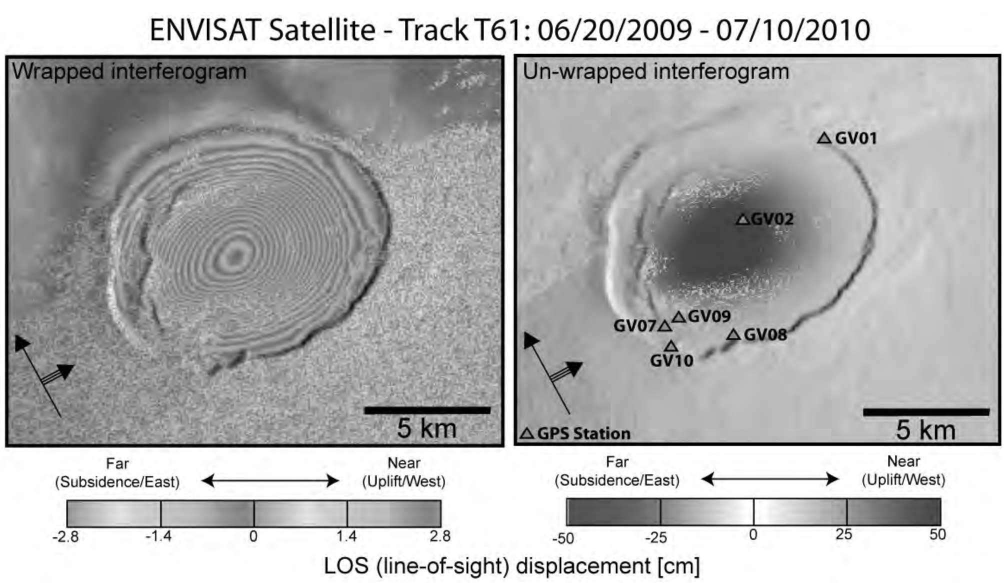


Figure 5



Captions for Color Figures (preceding pages):

1. Regional topography and bathymetry of the Galápagos.
2. Tectonic setting of the Galápagos and the Galápagos Spreading Center (from Wilson and Hey, 1995). Note that the azimuth of Nazca Plate motion is 91° in the hotspot reference frame, perpendicular to the motion of the Nazca Plate relative to the Cocos plate.
3. Aerial view of graben on the south side of Santa Cruz Island.
4. Detailed topography of Santa Cruz highlands. Note the abundant satellite cones and pit craters decorating the landscape.
5. InSAR imges of recent deformation of Sierra Negra's caldera floor, from University of Miami Geodesy Lab; Baker, S., Bagnardi, M., Amelung, F., unpublished 2011.

Introduction: Regional Setting of the Galápagos Islands

Tectonic Setting

The Galápagos Islands lie on the Nazca Plate just south of an active mid-ocean ridge, the Galápagos Spreading Center (GSC; Hey, 1977). The motion of the Nazca Plate in the hotspot reference frame is about 37 km/my at an azimuth of 91^o. Owing to relatively fast migration of the GSC to the northwest, the absolute motion of the Nazca plate is nearly parallel to the ridge, thus almost perpendicular to relative motion. Another important implication of the fast motion of the GSC relative to the Galápagos hotspot is that the ridge probably lay over the Galápagos hotspot sometime between 5 and 8 million years ago (Wilson and Hey, 1995).

The Galápagos Archipelago is almost certainly caused by a deeply rooted mantle plume. Geochemical studies first suggested this, on the basis of the primitive isotopic compositions of the lavas (Geist et al., 1988; White et al., 1993; Graham et al., 1993; Harpp and White, 2001). Since then, a steep-sided low-velocity seismic anomaly has been detected in the upper mantle between Fernandina and Isabela Islands (Toomey et al., 2001; Villagomez et al., 2009), and the bottom of the transition zone is deflected upward in this same region (Hooft et al., 2002).

The Galápagos hotspot has clearly affected the nearby GSC: along the axis of the ridge, its bathymetry shallows and there are pronounced gravity, isotopic, and geochemical anomalies (e.g., elevated $^{87}Sr/^{86}Sr$, La/Sm, K) when it nears the archipelago, peaking at about 91^{o}W (e.g., Ito and Lin, 1995; Verma et al., 1983). Likewise, the islands depart from the standard hotspot model in several ways. Most notably, the islands do not form a single line of age-progressive volcanoes, and the compositions of lavas are more like MORB than other hotspot lavas. These anomalies are almost certainly because of the proximity of the ridge.

Regional Geology

One of the most curious aspects of the Galápagos is that volcanism is relatively long-lived at any given volcano, with no recognizable hiatus. The western volcanoes are more historically active, and no rocks older than about 0.2 Ma have been found there, as the plate motions would indicate. In contrast, easternmost San Cristobal is largely surfaced with Holocene lavas despite that it is the furthest "downstream" in a plate tectonic sense. The youngest lavas at San Cristobal are not compositionally distinct from the older lavas, so it does not appear that the younger activity is the result of Hawaiian-style alkaline or post-erosional volcanism; a more straightforward interpretation is that volcanism is continual for over 2 million years. Also, both young and old volcanoes are strung out to the north and south, oblique to both plate motion and structures related to the GSC. Darwin (1844) noticed a distinct alignment of the Galápagos volcanoes (which are now referred to as the "Darwinian" trends) trending roughly N30W and N60E; although almost every researcher to work in the Galápagos has recognized these lineaments and proposed an explanation, none has been very convincing. Harpp and Geist (2002) and Mittelstaedt and Ito (2005) attributed the NW-trending Wolf-Darwin Lineament and the ENE trend near Genovesa Island to a combination of the stresses that develop around a ridge-transform intersection and strain-partitioning caused by transtension around the 91°W transform. Their models do not explain the lineaments of the central Galápagos Platform.

McBirney and William's (1969) pioneering geologic exploration of the Galápagos revealed that the archipelago is separated into several geologic subprovinces, on the basis of the ages of the volcanoes, their geomorphic forms, and the petrology of their lavas (McBirney and Williams, 1969)

The ***"old"*** subprovince comprises Española (Hall, 1983), Santa Fe (Geist et al., 1985), and Baltra Islands and Northeastern corner of Santa Cruz (Bow, 1979). These islands are the strongly-faulted remnants of ancient subaerial volcanoes that were active from about 3 to 1 Ma. The compositions of the lavas of these older volcanoes are not distinguishable from lavas of the surrounding, younger volcanoes. Curiously, these islands are aligned to about N30W, parallel to the regional alignment currently in the western Galápagos.

The ***central*** subprovince is made up of San Cristobal (Geist et al., 1986), Santa Cruz (Bow, 1979), and Santiago Islands (Swanson et al., 1974). The volcanoes have relatively shallow slopes, lack a caldera, and each has aligned systems of satellite vents. The lavas are dominated by primitive, high-MgO basalts that have rather extreme trace element variation; each of the islands has erupted an unusual suite of lavas depleted in incompatible elements (MORB-like tholeiites) as well as alkali-olivine basalts that are strongly enriched in incompatible elements. *Floreana* is unique and does not fit naturally in the other subdivisions (Bow and Geist, 1992; Harpp et al., unpublished). It has a subdued form, late parasitic cones, and a long-lived history, similar to the volcanoes of the central subprovince. Floreana's lavas are distinctly more alkaline than elsewhere in the archipelago, and many of them contain abundant mafic and ultramafic xenoliths (Lyons et al., 2006).

The ***western*** subprovince is made up of the historically active volcanoes of Isabela and Fernandina islands and Roca Redonda volcano. These are the classic Galápagos shields, with roughly symmetric forms, steep slopes, and large calderas. At one time, these volcanoes were thought to be made up of petrologically monotonous tholeiites. To some extent, this is true, but detailed exploration and study has revealed suites of lavas that are much more diverse. Cerro Azul has erupted picrites and tholeiitic and alkali-olivine basalts that are related to one another by high-pressure differentiation (Naumann and Geist, 1999). Fernandina (Allan and Simkin, 2000), Sierra Negra (Reynolds and Geist, 1995), and Wolf volcanoes (Geist et al., 2005) have erupted monotonous basalts with MgO = 5 to 7%. Roca Redonda has erupted picrites and alkali-olivine basalts (Standish et al., 1998). Volcan Ecuador likewise is somewhat alkaline but with a complex magmatic plumbing system (Geist et al., 2002). Alcedo has erupted a bimodal suite of basalts and rhyolites (Geist et al., 1995).

The ***northern*** subprovince is diverse petrologically: basically, the archipelago's entire range isotopic and trace element values is encompassed by the 5 islands, Wolf, Darwin (Harpp and Geist, 2002), Genovesa (Harpp et al., 2002; Harpp et al., 2003), Marchena (Vicenzi et al., 1990), and Pinta (Cullen et al., 1987). Likewise, each has a distinct form; Marchena and Genovesa have calderas, Wolf may have had one that has now mostly eroded, and the others do not.

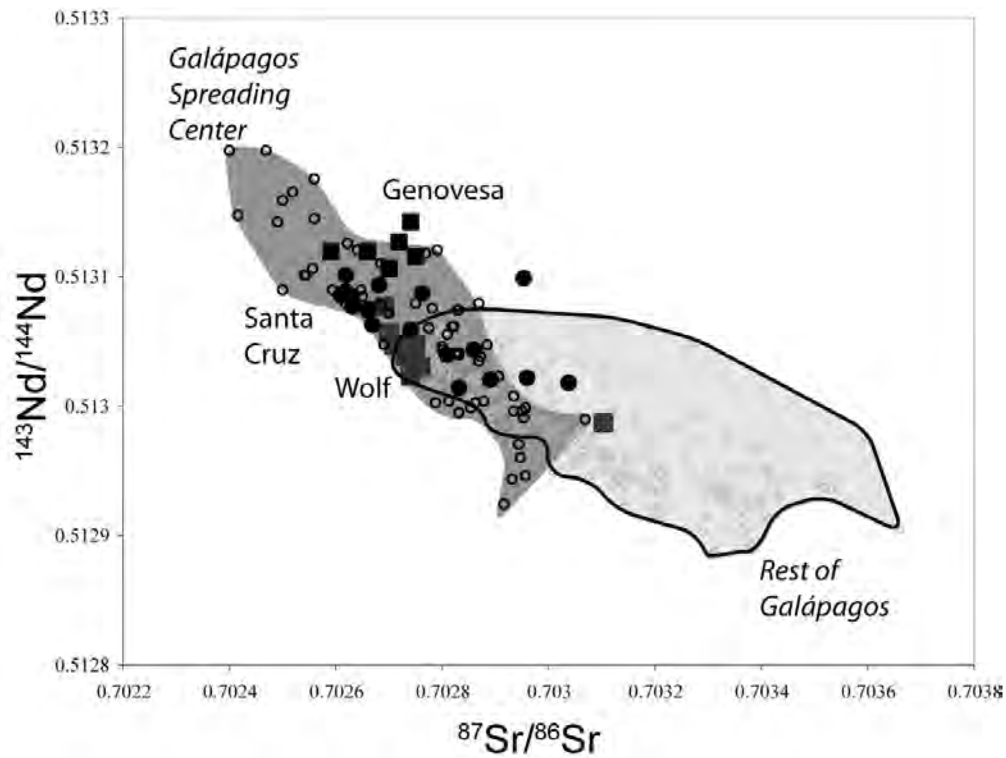
Regional Geochemistry

One of the most intriguing aspects of the Galápagos is that the volcanologic, petrologic, and geochemical features are spatially related. The most distinctive manifestation of this is the isotopic horseshoe, where the Sr, Nd, and Pb isotopes indicate the increasing influence of depleted mantle in the center of the archipelago, trailing off to the east (Geist et al., 1988; White et al., 1993; Harpp and White, 2001).

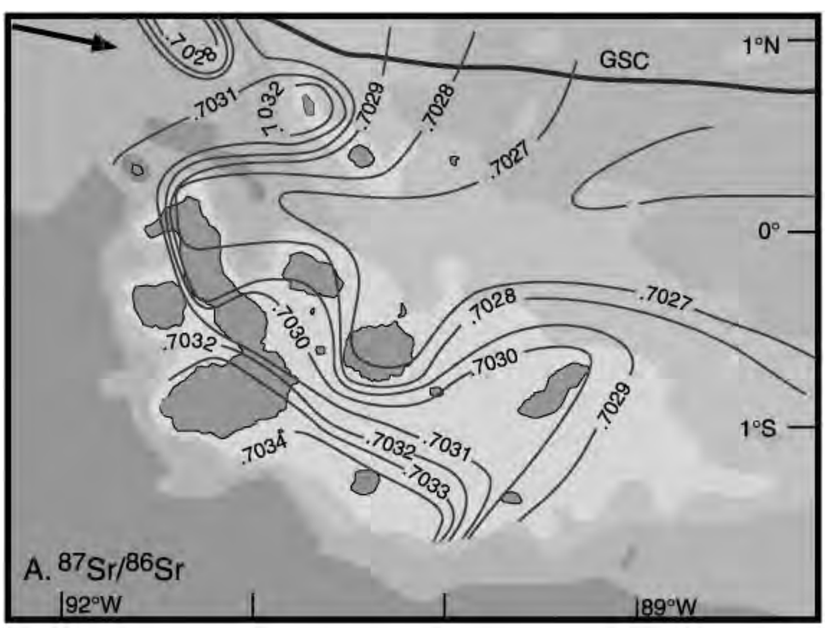
As with many other ocean island systems, isotope correlation diagrams have been interpreted as resulting from mixing between a relatively enriched plume and depleted mantle. The fine details of the correlations and inclusion of $^{3}He/^{4}He$ data indicate that the picture is much more complex, involving either more than two isotopic reservoirs, or segregation of the Sr, Nd, Pb, and He by melting and mixing processes (Graham et al., 1993; Kurz and Geist, 1999). Notably, Fernandina volcano has $^{3}He/^{4}He$ as high as 29 Ra.

The table below illustrates the regional volcanologic and petrologic relationships in the Galápagos. The volcanoes in each subprovince have similar elevations, caldera dimensions, and flank slopes. They also have similar ages. Lavas of the central sub-province tend to be primitive (e.g., high MgO concentration), but there are wide variations in the extent of differentiation. Likewise, these lavas have large ranges of incompatible element ratios, as exemplified by the standard deviation of K/Ti ratios. Lavas from the western volcanoes exhibit small differences in their incompatible element concentrations and some have limited ranges in [MgO]. Other western volcanoes have either more primitive lavas (Ecuador, Cerro Azul) or more evolved differentiates (Pinzon, Alcedo).

How much of this variation is attributable to the maturity of the volcano, and how much is due to other factors?



Sr and Nd isotopic data from the Galápagos. Note the broad overlap of Galápagos island lavas with the Galápagos Spreading Center field. There are at least 2 enriched endmembers defined by Floreana and Pinta islands.



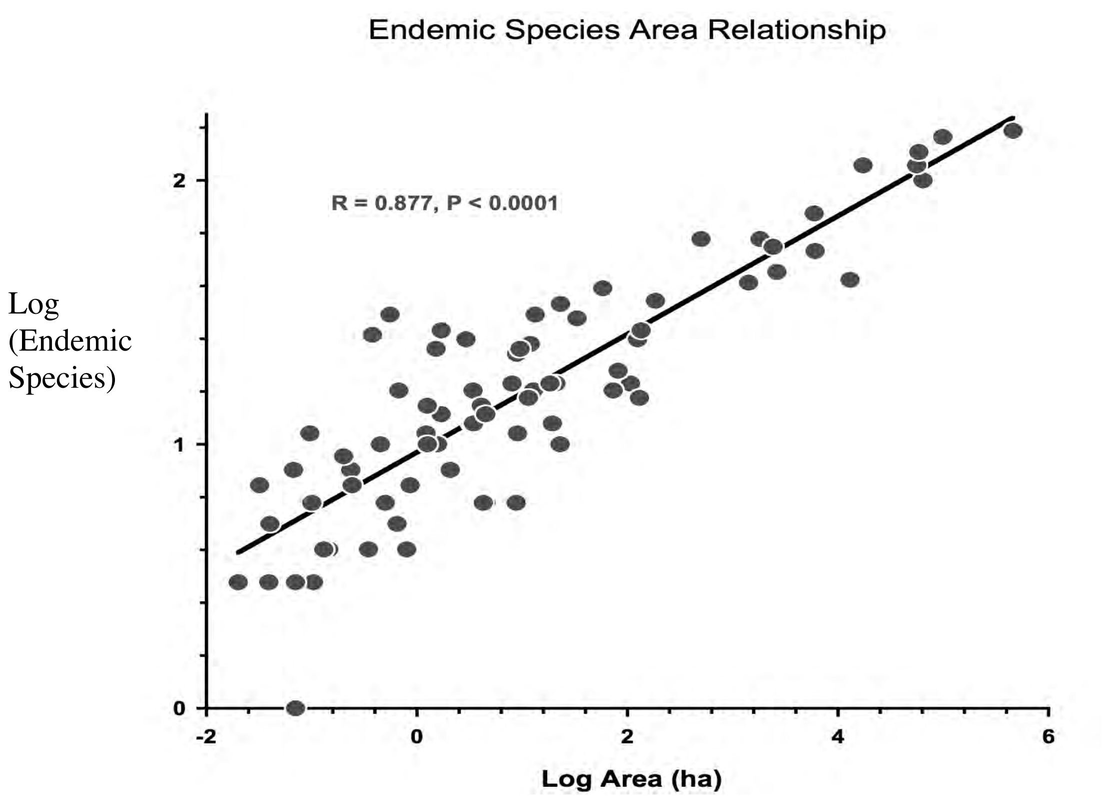
Isotopic and geochemical features of the Galápagos volcanoes have a clear spatial relationship. Lavas from the north-central part of the archipelago are depleted, whereas those from the west, north, and south are enriched. We refer to this as the "isotopic horseshoe", and it may be attributable to either plume-asthenosphere mixing or mixing with a lithospheric component.

Volcano	*Elevation (m)*	*Caldera Depth (m)*	*Age*	*MgO (wt.%)*	*100*K_2O/TiO_2 (Basalt)*
<u>Old Subprovince</u>					
Espanola	207	none	2.6 - 2.8 Ma		
Santa Fe	255	none	2.5 - 2.8 Ma	6.8± 0.7	34 ± 14
Baltra and N. Seymour	69	none	1.1 - 1.3 Ma		
<u>Central Subprovince</u>					
San Cristobal	714	none	0 - 2.3 Ma	9.1± 1.8	35± 12
Santa Cruz	859	none	0.05 - 0.59 Ma	7.7± 2.1	18 ± 8
Floreana	561	none	1.5 - 0.02 Ma	10.7± 2.0	62± 25
Santiago and Rabida	907	none	0 - 770,000	6.2± 3.4	19 ± 15
<u>Western Subprovince</u>					
Fernandina	1480	1100	0 - 6000	6.3± 0.4	14 ± 1
Cerro Azul	1620	480	0 - 82,000	7.5± 1.7	20 ± 3
Sierra Negra	1120	110	0 - 9000	5.5± 0.5	17± 2
Alcedo	1180	270	0 - 150,000	4.3± 2.2	17 ± 4
Darwin	1420	200			
Wolf	1720	660	0 - 173,000	6.0± 0.5	17 ± 1
Ecuador	730	640	0 - 130,000	6.6± 1.7	23± 2
Pinzon	457	150	0.7 - 1.2 Ma	4.1± 1.7	18 ± 4
Roca Redonda	50	none		12.8± 5.4	26 ± 2
<u>Northern Subprovince</u>					
Genovesa	74	65		7.4± 0.9	7 ± 2
Marchena	328	ca. 150	0 - 300,000	6.7± 0.3	15 ± 3
Pinta	629	none	0 - 700,000	6.3± 0.4	26 ± 4
Darwin I.	170	none			
Wolf I.	255	none			

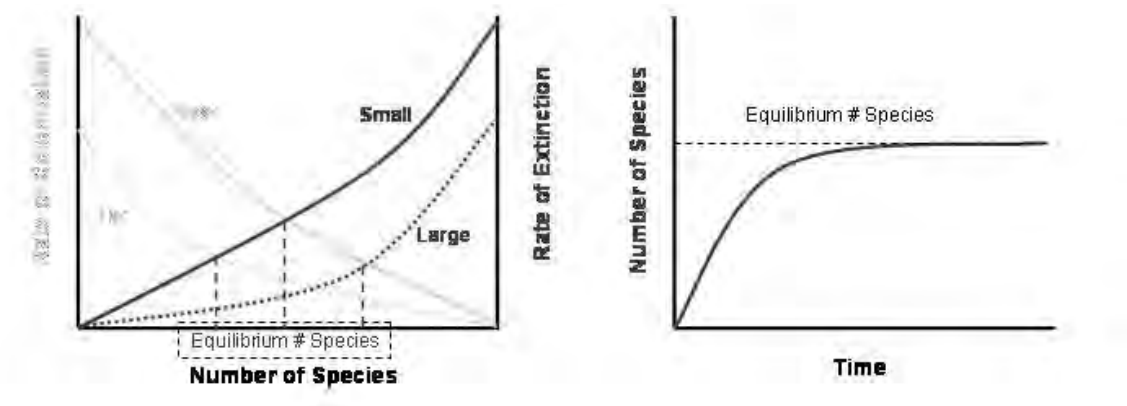
Geology-Biology Relationships

For good reason, the Galápagos Archipelago is best known for its endemic life. Although we lack a comprehensive understanding of the interaction between the geological and biological systems of the Galápagos, several interesting relationships have been well documented.

Even though the oldest rocks exposed on the islands are only 3 Ma, this does not mean that is the time limit for evolution (c.f., Hickman and Lipps, 1985). For many years, the youthfulness of the archipelago was paradoxical, as molecular biology studies showed that, for example, marine and land iguanas diverged from a common ancestor about 10 million years ago. As is well known by most geologists, ocean islands sink as they are carried away from a hotspot, mostly owing to thermal contraction of the lithosphere. This was proven for the Galápagos, when sunken islands as old as 10 Ma and 14 Ma were discovered downstream (in terms of plate motion) on the Cocos and Nazca plates (Christie et al., 1992; Werner et al., 1999). Thus, we conclude that multiple sets of paleo-Galápagos islands existed, and that the unusual life forms have colonized each subsequent set as evolutionary stepping-stones.



Dozens of studies have shown that island biodiversity is exponentially related to island area, which is true for the Galápagos as well. The paradigm is that island biodiversity reaches a steady state, where colonization rate equals the extinction rate, and the latter is mostly due to island area.

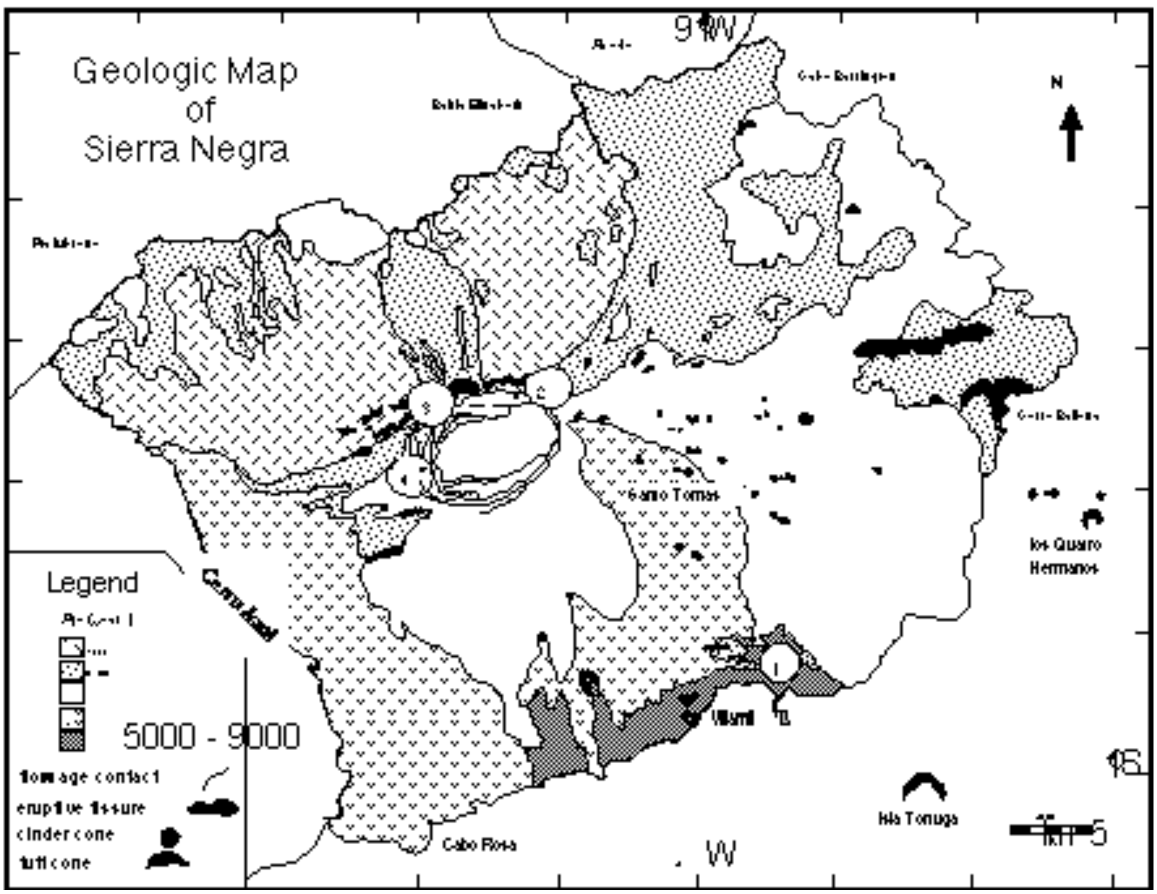


The details of the relationship in the Galápagos exhibit some anomalies, some of which are geologically related. For example, one of the biggest negative anomalies is Baltra (which we will visit). As opposed to most of the other islands, which are volcanic landforms, Baltra is a fault block. Thus, its emergence could be much younger than the ca. 1.3 Ma crystallization age of its lavas. Also, because of its fault-block origin, it is flat-lying, creating a single inland climatic zone; volcanic islands of equal area generally are higher, providing more ecological zones. Other islands that deviate in the negative sense from the correlation are very young, hence have not have had time for colonization. A good example is the lack of lava lizards (*Tropidurus)* on Genovesa Island; even though Genovesa is far from the focus of the hotspot at Fernandina, the island is very young (~300,000 yrs; Harpp et al. 2002).

A more direct linkage between geological and biological evolution exists on Alcedo Volcano, on Isabela Island. Mitochondrial DNA indicates that all of the modern tortoises on that volcano descend from a single female ("Eve") that was alive about 100,000 years ago (Beheregaray et al., 2003). This time almost exactly coincides with a Plinian eruption on that volcano (Geist et al., 1995). Thus, we have hypothesized that the explosive eruption nearly extinguished that race of tortoises, leaving only a small subset as ancestors to the modern day population.

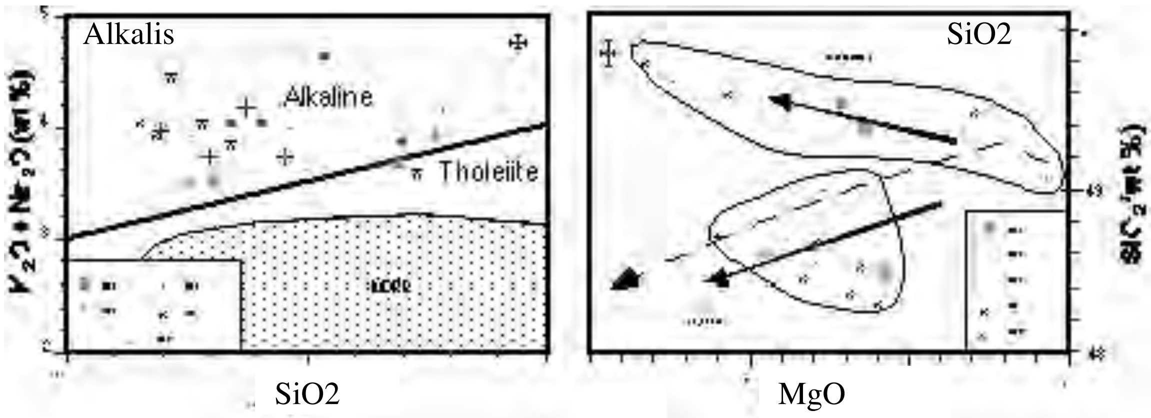
Part II. Sierra Negra Volcano

Owing to a permanent human population in Puerta Villamil and the highlands, Sierra Negra is the most accessible volcano in the western Galápagos. Sierra Negra volcano is 60 km long and 40 km wide and rises 1100 m above sea level. It is by far the most voluminous of the western Galápagos shields and exhibits many unusual morphologic features including an extensive lower flank apron, a large complex caldera, and a volcano-wide system of ENE-trending radial and circumferential fissures (Reynolds et al., 1995). The recent geologic history of Sierra Negra is characterized by voluminous eruptions of a'a' from a complex of radial and circumferential fissures on the northern caldera rim. These define an ENE rift system that extends from the lower flanks and deflects around the large summit caldera.



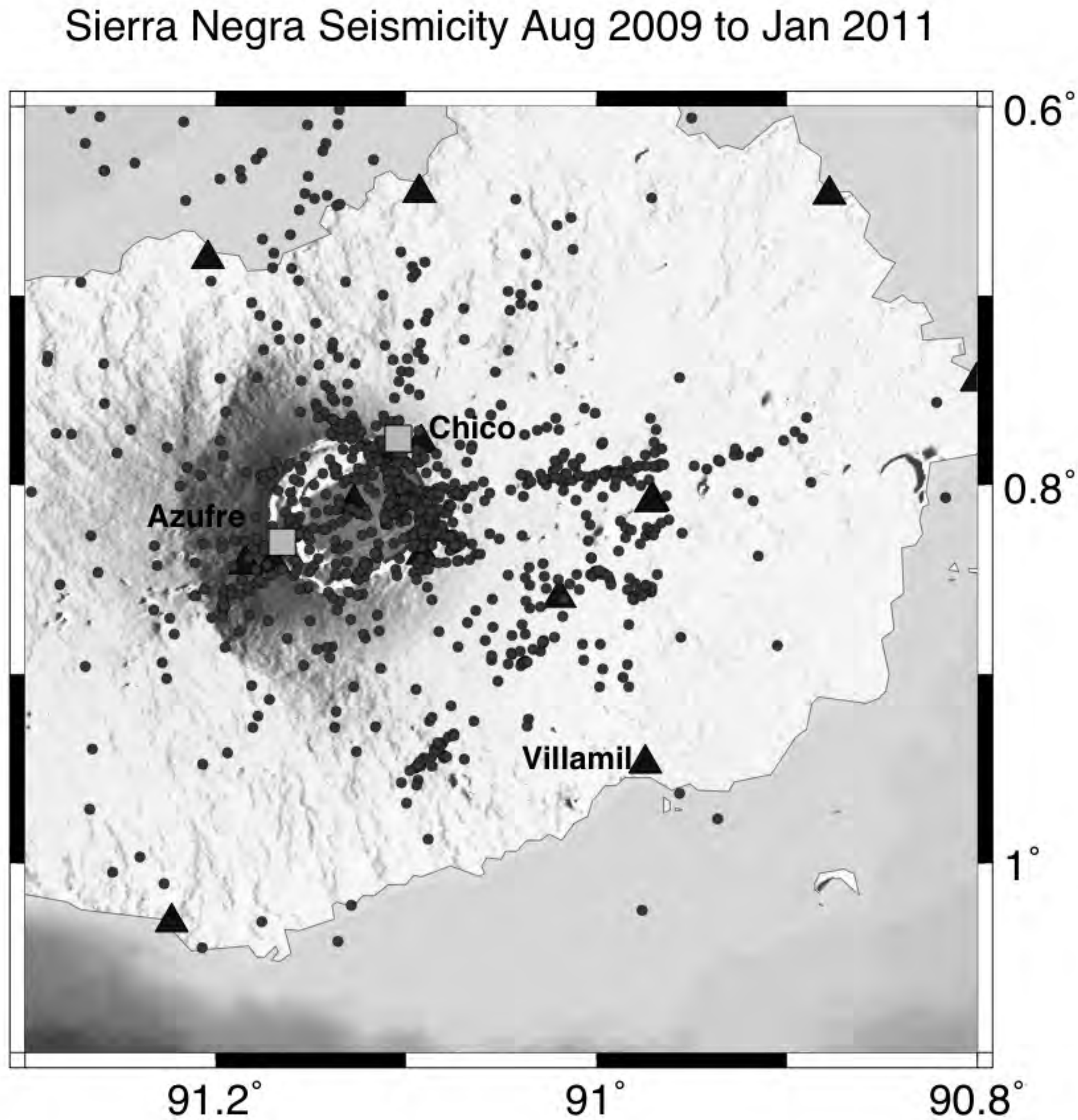
Dated lava flows on Sierra Negra range from 400 to 6900 years old. Reynolds et al. (1995) mapped the distribution of 5 age units based on extent of weathering and geochronological data.

In comparison to other western Galápagos volcanoes, Sierra Negra's somewhat subdued profile is principally due to its large discharge rate and voluminous eruptions, which cause most lava to accumulate on the lower flanks, resulting in the development of a large coastal apron.

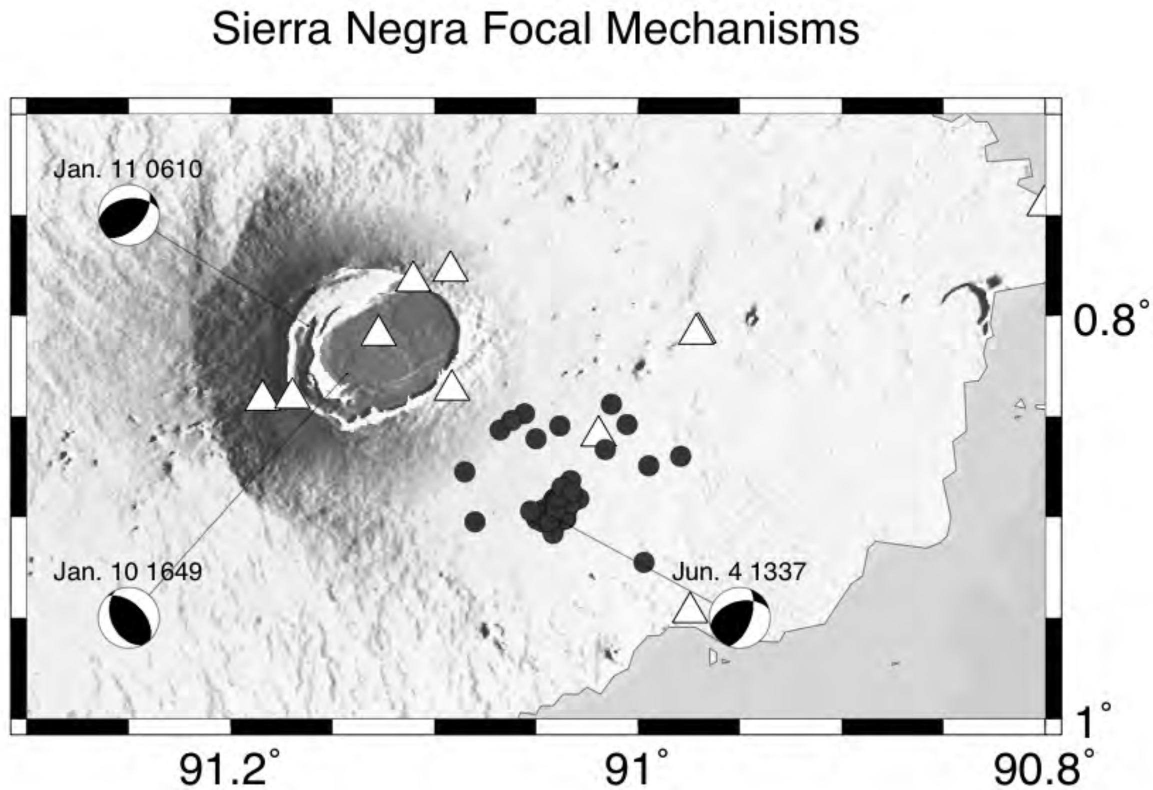


Sierra Negra has erupted Fe-rich, hypersthene-normative tholeiitic basalt of limited compositional range (Reynolds and Geist, 1995). The major and trace element data indicate a comagmatic relationship by fractional crystallization of the observed phenocryst phases. Sierra Negra lavas have the most radiogenic lead and strontium isotopic ratios in the western Galápagos, indicating that the magmas have a relatively large contribution of plume material and have been only minimally contaminated by entrainment of MORB-producing mantle. Magmatic $^{3}He/^{4}He$ isotopic ratios from Sierra Negra are approximately 15 times the atmospheric ratio. High Sm/Yb ratios, light rare earth element (LREE) enrichment, and a steep REE slope are consistent with an origin by moderate extents (5-15 %) of partial melting of a garnet-lherzolite source with REE characteristics that are between chondritic and depleted mantle sources.

Dr. Cynthia Ebinger installed a dense broadband seismic network on Sierra Negra in 2009, and the instruments have just been recovered. She and her student Dustin Cote have provided their preliminary data. Although seismic activity is concentrated around the caldera margins, there is surprising activity on the flanks, especially in a linear zone extending east of the caldera.



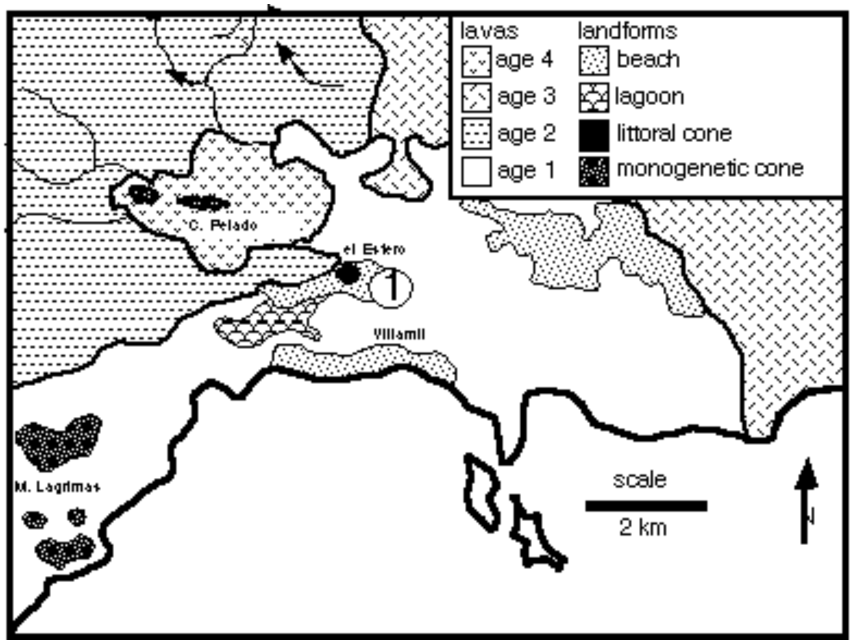
Sierra Negra Seismicity Aug. 2009 to Jan. 2011: Seismicity recorded by the 16-station Sierra Negra Integrated Geophysical Network (SIGNET). Triangles are station locations, squares indicate points of interest, dots are epicentral locations. Volcano-tectonic seismicity levels between 7/09 – 1/11 are high (2-3 earthquakes/day). Over 1900 earthquakes (1.5 < ML < 3) have been located, with the majority concentrated along the Sierra Negra caldera fault system and at the 2005 eruption site. Narrow zones of shallow seismicity (<2 km subsurface) mark E-W striking chains of cones on the east and west flanks of Sierra Negra, implying aqueous or magmatic fluid movement along fissure systems beneath the chains. Reverse and normal faults are illuminated on the SE flank by a linear swarm striking tangential to the caldera rim.



Preliminary focal mechanism solutions for earthquakes from Sierra Negra. Note epicentral uncertainty is ~1 km. To the southeast, a swarm of ~20 earthquakes in June 2010 occurred on a steeply dipping reverse fault system as shown by the focal mechanism. Within the caldera, the sinuous ridge indicates compressional mechanisms consistent with previous work done in studies of trapdoor faulting in the caldera (e.g. Chadwick et al. 2006, Jónsson 2009).

Day 1: Villamil

The area surrounding the village of Villamil on the southern flank of Sierra Negra includes some of the oldest lavas on the volcano as well as evidence of recent uplift and examples of coastal phreatomagmatic activity. Numerous monogenetic cones dot the landscape. Large-scale surface features such as tumuli and pressure ridges are well preserved in the lavas, but delicate surface textures are long since eroded. The orientation of pressure ridges and flow surface cooling joints indicate that the flows originated from eruptive centers on the upper east flank near the village of Santo Tomás.



A littoral cone, now partly excavated, is located about a kilometer inland. It is constructed of 10-15 cm- hick beds of normally graded scoria, intercalated with coral and shell fragments. The uppermost surface is partly overlain by spatter and unconsolidated beach sediments. The ^{14}C age of shell fragments obtained from the littoral cone provides an age of 3195 ± 100 yr. Other nearby deposits provide evidence for long term coastal uplift. A small, 5 m thick, age 4 (see map above) plagioclase-phyric a'a' flow erupted from a fissure centered at Cerro Pelado northwest of Villamil. In addition, an isolated lagoon and two raised beach deposits 1-2 km north of Villamil lie at 5-14 m elevation are interpreted to represent former shoreline deposits, suggesting that the area has been uplifted since the eruption of age 2 lavas. The long term rate of uplift of this part of the coast ranges from 1 to 17 mm/yr and is based upon the relative position of the beach deposits between two dated lava flows.

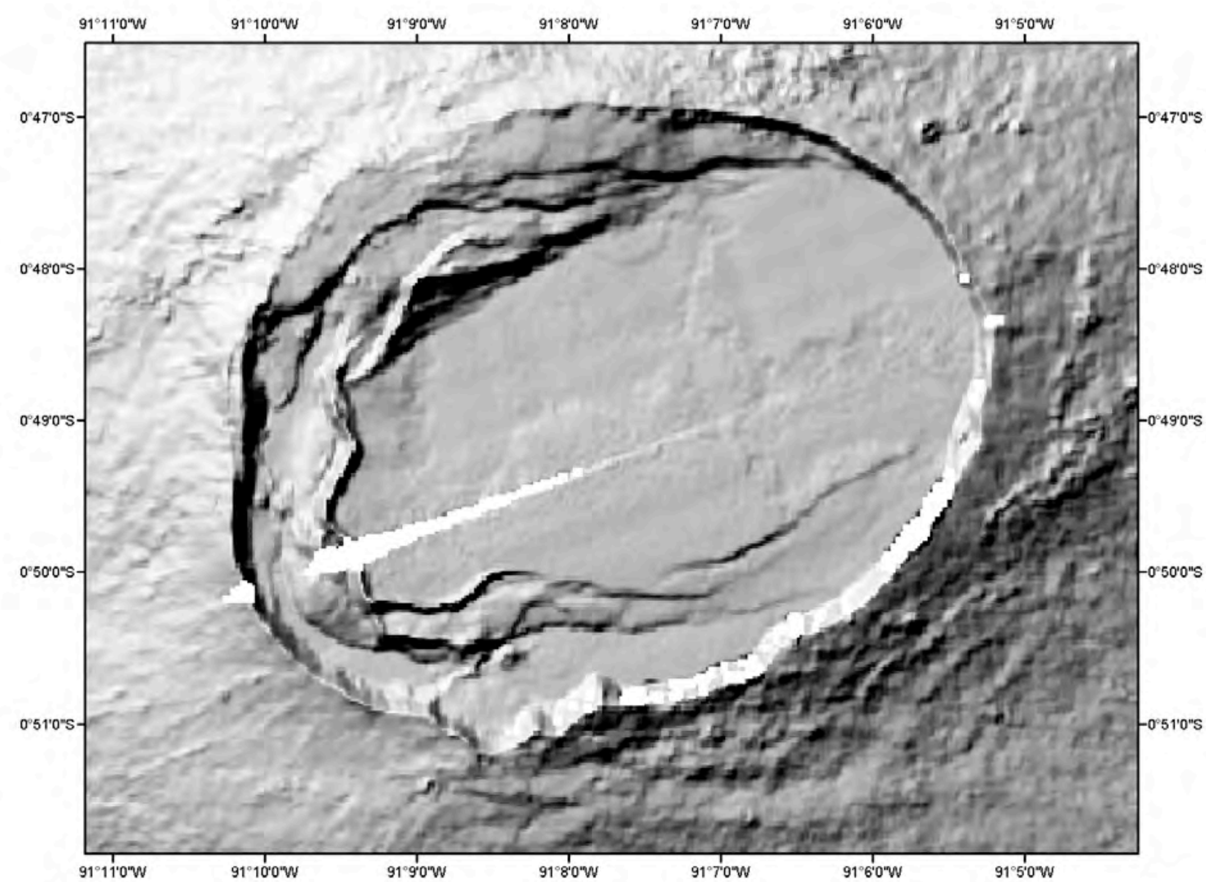
Day 1: Western Caldera Rim

This stop provides a view into the summit caldera. The summit of Sierra Negra is entirely occupied by a shallow, elliptical (7 x 10 km) caldera. Near-vertical ring faults circumscribe the summit on three sides and expose 100 to 140 m of lava flows. The north rim is outlined by an arc of recent eruptive fissures. Sub-parallel sets of caldera growth faults cut the western and southern caldera walls and are not associated with eruptive activity. Sierra Negra's caldera differs substantially from those of Fernandina, Wolf, and Cerro Azul, which have deep (480-1100 m), smaller diameter (4-6 km) calderas and wide rims.

The central caldera floor is covered by age 3 a'a' that dips gently to the east. The north section of the caldera is controlled by an east-trending sequence of normal faults resulting in a series of small horst and graben blocks that gradually step down from the north caldera wall to the central caldera floor. Displacement along the individual faults ranges from 3 - 10 m. The west caldera floor contains a set of much larger down-dropped blocks, the sum of which forms a N-S trending moat. The moat is punctuated by cinder cones and sulfur fumaroles and separates the caldera walls from a high sinuous ridge. Several small outward-curving benches are positioned in front of the west-facing scarp of the sinuous ridge.

The most remarkable structural component of Sierra Negra's caldera is the sinuous ridge. It consists of a 14 km-long complex set of overlapping, tilted blocks of caldera floor, the whole of which forms a curving C-shaped ridge that is open to the east. The entire structure is formed of outward curving faults. Fault scarps dip steeply (60-90^{o}), whereas the ridge flow tops initially dip inward at 20-600, then bend sharply to merge with the gently dipping (1-3 ^{o}) central caldera floor. Vertical displacement along the ridge varies from 1 m in the east part of the caldera to over 100 m in the west. In places, the sinuous ridge is higher than the caldera rim. None of the other Galápagos calderas exhibit such an unusual and complex caldera floor morphology.

Several large (M > 4) earthquakes have been measured geodetically and seismically along the sinuous fault, particularly on the southern side. In April 2005, we recorded 86 cm of motion, but no surface break was observed. A fresh ~1 m scarp surface was mapped after the 2005 eruption, which we attribute to a precursory earthquake.



The sinuous ridge is caused by an expanding sill located about 1.9 km beneath the caldera floor. The sill has aerial dimensions slightly smaller than the caldera, about the same area as that enclosed by the sinuous ridge.

The prominent fumarole system is called Volcan Azufre and was studied by Goff et al. (2000). In 1995, the temperature was measured to be 210°C. The residence time of water is < 40 years.

Day 2: Volcan Chico

Volcan Chico is part of the 1979 circumferential fissure. During the two month-long 1979 eruption, two areas of the circumferential fissure system 3 km apart were simultaneously active. Both areas are surmounted by a line of spatter ramparts and cinder cones that are oriented diagonally across the upper flank and curve around the summit caldera as part of the larger circumferential eruptive zone.

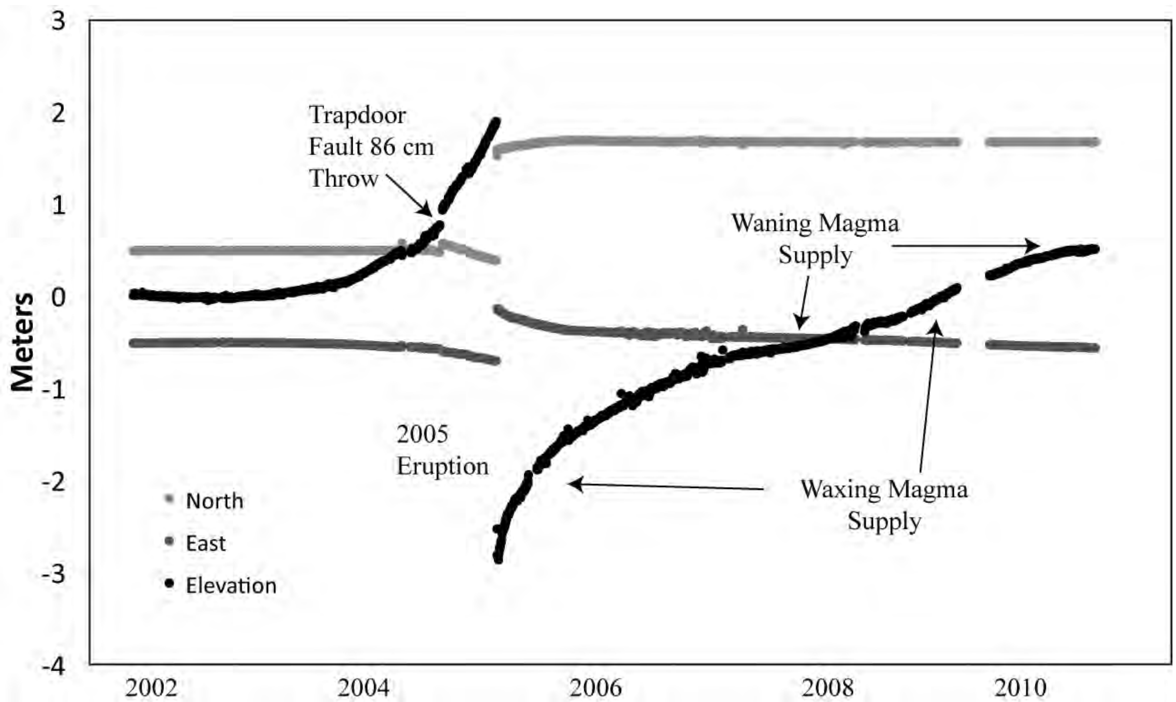
The 2005 Eruption

After 26 years of repose, Sierra Negra began a major eruption at about 17:30 (local) on October 22, 2005. The initial explosion sent a plume 13 km high. Early in the eruption, a 1.5 km-long curtain of fire obliquely cut the northern caldera wall, sending lava down the north flank and into the caldera. During the second day of the eruption, the outboard segment of the fissure began to wane, so the only lava on the flank was clastigenic, and from this point on, most lava filled the eastern caldera floor. The eruption continued until October 30. A rough estimate of the eruptive volume is 150 million cubic meters DRE.

By far most of the lava flowed over the northern caldera bench and pooled as a giant a'a' flow in the eastern part of the caldera floor. This had been the low point of the caldera floor, due to a broad syncline. Pahoehoe lobes broke out of the pooled a'a' as the flow spread later in the eruption.

Sierra Negra's caldera floor had shown a remarkably transient history of uplift since 1992, probably reflecting the filling of a sill at about 2000 m depth (Amelung et al., 2000; Geist et al., 2005). During the 1990s, the caldera floor bowed up over 2 meters, which was punctuated by a trapdoor faulting event along the southern fault system in early 1998. This was followed by deflation from 2001-2002. Inflation began again in 2003 and accelerated to over 2 m/y in 2005. On April 16, 2005, another trapdoor event (83 cm of thrust motion; M 4.8) occurred, with a nearly identical epicenter as the 1998 event.

During the 8 days of the eruption, the caldera floor subsided elastically 2 m, and the caldera contracted by about 6 m. Since the eruption, the caldera has begun inflating again at 4.4 m/y (as of Dec. 10, 2005).



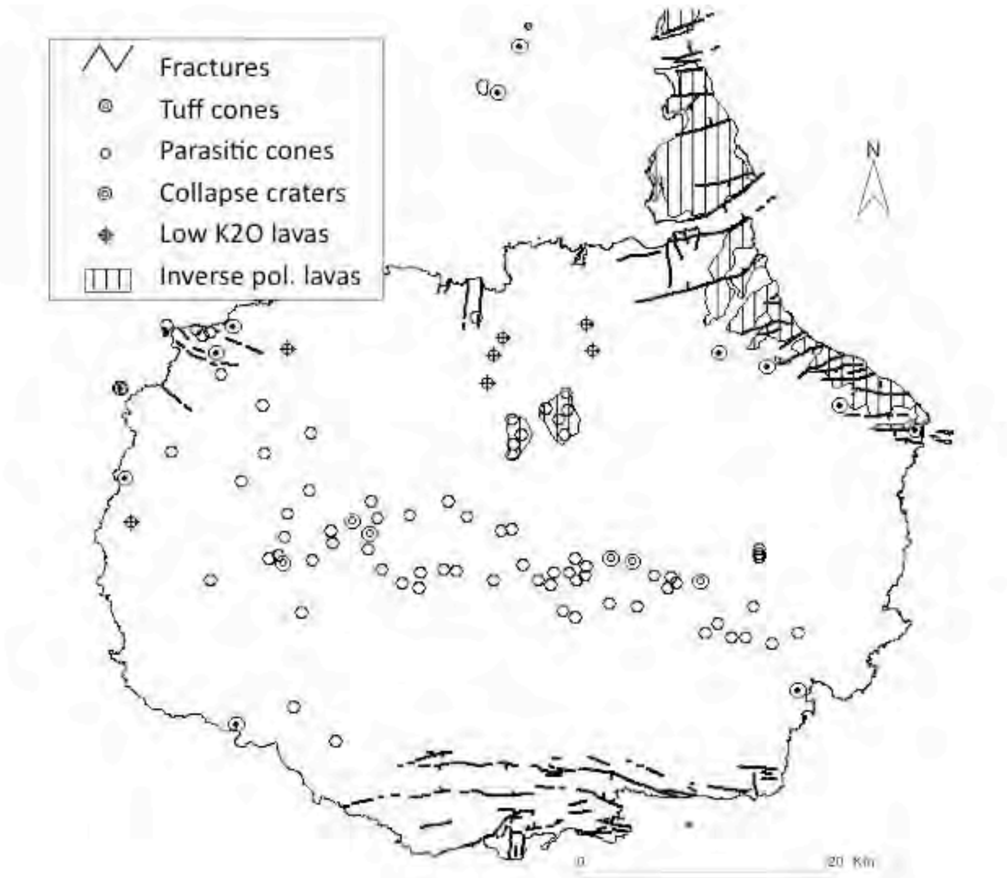
Deformation history of the center of the Sierra Negra caldera, measured by GPS. After several years of cm-scale deformation, the caldera floor bulged ~2 m before the 2005 eruption. The bulging was largely elastic but was punctuated by a reverse faulting event in April 2005 (Chadwick et al., 2006). During the eruption, the caldera subsided elastically by 5 m and began to inflate the day after the end of the eruption.

Part III. Santa Cruz Island

Santa Cruz is the second largest of the Galápagos Islands. The airport on Baltra Island is the main arrival point to the Galápagos, a road across the island from north to south takes people to the main town of Puerto Ayora, largest in the islands and the site of the Charles Darwin Research Station.

The drive from the Canal de Ithabaca (north coast Santa Cruz) to Puerto Ayora crosses from the leeward side of the island, where you can observe the different vegetation zones, from the arid coastal zone, to the dry forest, the transition zone and finally the humid highlands and the scalesia forest. Once you pass the scalesia forest, you come onto the windward side of the island and the agricultural zone, where introduced plants replace most of the original humid ecological zone. The side of the road preserves a few places where water runoff from the very heavy rains earlier this year eroded into pre-existing ravines. Once you pass the village of Bellavista, you head down toward Puerto Ayora and the arid zone again.

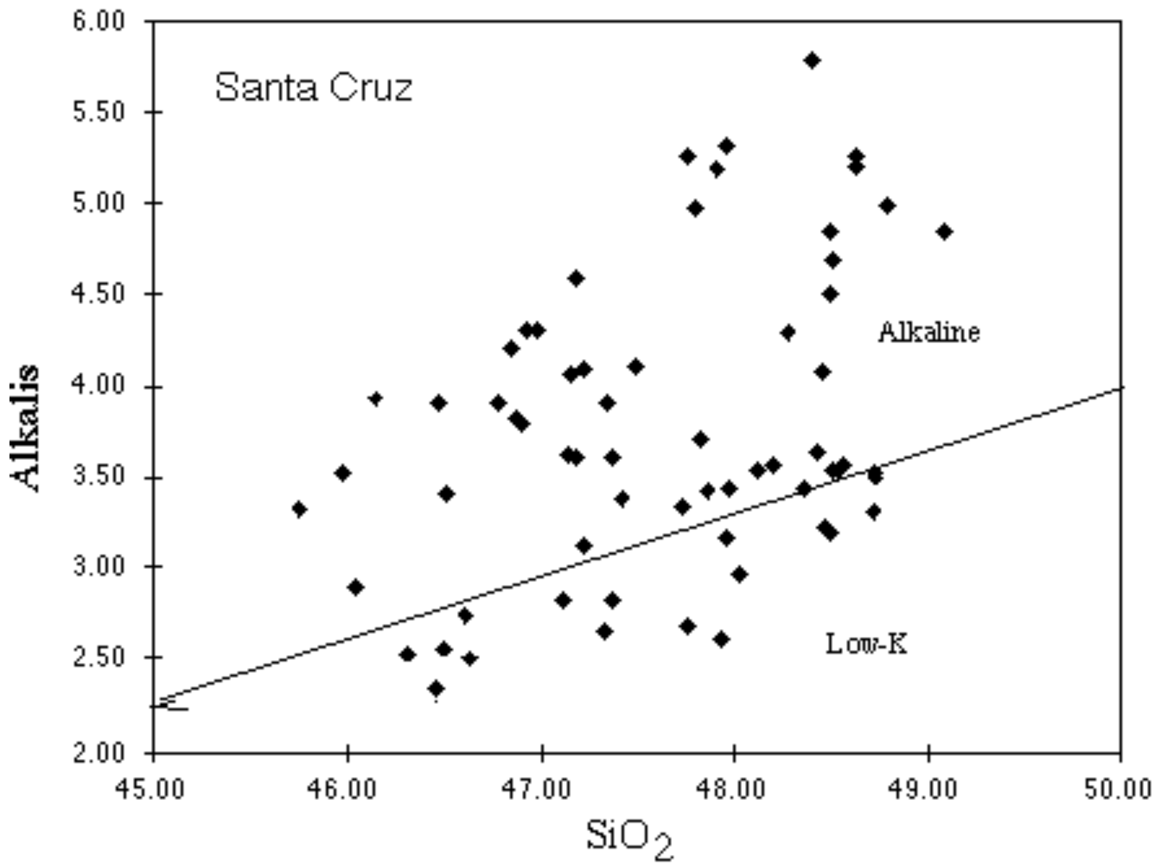
The bedrock of the island comprises two geologic parts: the northeastern end is termed the "Platform Series" and the main shield the "Shield Series" (Bow, 1979). The Platform Series is distinctly older and is made up of submarine flows and limestones overlain by subaerial pahoehoe and a'a. It is strongly faulted and is separated from Baltra and N. Seymour islets by two large grabens (which you can see from the airplane; and you cross the Baltra graben while you come the channel from the airport). Precise K-Ar ages of the Platform Series cluster around 1.3 Ma, although imprecise ages are as great as 3.8±1.8 Ma.



Geologic map of Santa Cruz Island, from Bow, 1979.

The Shield Series erupted from a series of vents oriented WNW. The shield is entirely normally polarized, and K-Ar ages range from imprecise dates as old as 590±270 ka to more precise ages as young as 24±11 ka. Several prominent fault scarps oriented ENE cut Shield Series lavas in the town of Puerto Ayora; there is no obvious tectonic reason for these impressive faults.

The Shield Series lavas are compositionally indistinguishable from the bimodal alkali-olivine/low-K tholeiite series of Santiago and San Cristobal. As on those islands, the two series are isotopically indistinguishable, thus are thought to result from different extents of partial melting. Also, picrites and high-Mg basalts are the most abundant lavas. Some of the alkaline magmas are as evolved as hawaiite. Santa Cruz is in the center of the isotopic horseshoe and, with the exception of Genovesa, has erupted the most depleted magmas in the archipelago (White et al., 1993).



Compositional variation of Santa Cruz lavas.

Los Gemelos (The Twins)

Los Gemelos are a pair of pit craters in the scalesia forest near the summit of the island but slightly off to the west, just on the border between the leeward and the windward sides. They are uneruptive collapse features, which likely originated above a large dike emplaced during the latest stage of volcanism on Santa Cruz.

As you can see on the geology map from Bow, and also nowadays with a tour on Google Earth (!), there are a dozen of such collapse craters around the summit of the island, most of which are aligned with the NW-SE trending cones and located on the north side of the volcano.

The vertical faces of the collapse craters expose excellent outcrops of the succession of thick lava flows of the shield series. Other features can be observed on the walls such as small lava tubes, dikes and sills. The succession of lavas lacks thick paleosols. This might be due to the continuous nature of the volcanic activity or the very slow soil formation processes on the island. Modern soil depths vary from 5 cm to 50 cm and occasionally 1 m on the windward side of the island.

Adjacent to the eastern Gemelo, there is a very narrow and deep crater. This crater has been explored by speleologists and invertebrate specialists (Bacallardo and Armas, 1992).

The scalesia forest is a great place to look for a rare variety of the Darwin Finches, the woodpecker finch, and also large billed and small billed tree finches, vegetarian finch, warbler finch, ground finches, vermillion flycatcher, the Galápagos dove, and the short-eared owl.

This area is also a good place to observe the problems that the islands are facing with invasive species. The *Rubus niveus*, Indian raspberry, is a highly invasive plant that is greatly affecting the scalesia zone and is being controlled heavily by the Galápagos National Park.

Red Mine (La Mina Roja)

The development of the town of Puerto Ayora has required a large amount of building material. Originally, beach sand was being used to build houses, with the limitation that the salt-water content affects the viability of the cement and oxidizes rebar. Subsequently, scoria cones have been quarried. Most of the water used for the construction is brackish water from the basal aquifer.

La Mina Roja is the most actively exploited and largest of the quarries. It is located in a very special biological transition zone on the northern leeward side of the island. Almost the entire scoria cone has now been dug out. Note the abundant, large plagioclase phenocrysts, which you will also see in much of the road gravel in Puerto Ayora.

There are some very interesting localized features related to the scoria cone. Faults can be observed in the walls of the excavations. Harder to process volcanic necks are contoured by the machinery and remain in the middle of the quarry. Soil profiles can be seen on the outer edges of the cone, along with erosion and weathering features. It appears that a lava flow of about 50 cm capped a part of the scoria cone.

Another interesting feature of the scoria cones is the way that they were either deposited asymmetrically because of prevailing winds, and/or that they have weathered asymmetrically.

Royal Palm Lava Tube

Santa Cruz has the largest number of preserved lava tubes in the Galápagos (Balázs, 1972, Gallardo G., and Toulkeridis T. 2008). This is probably due to a perfect combination of slope and eruptive rates in the latest phase of volcanism. The tunnels on Santa Cruz extend from the coastal area to the summit of the island.

Each tube has a unique geometry. Some are very long, some are perfectly circular, some have collapsed roofs. All are fascinating for the detailed patterns on the walls and the animal life that makes use of them. A core being drilled to locate a seismometer on a farm on the eastern side of the island intersected a lava tube at 100 m depth. No lava tube is filled with water, but during heavy rain, water can move through the roofs of the tunnels almost immediately, reflecting the high permeability of the fractured lava.

The lava tunnel of the Royal Palm hotel is an example of a complex lava tunnel, with various levels, large cavities, and small passages.

El Chato

The Galápagos Islands are named after the giant tortoises, called “Galapago” by the early Spaniards who visited the islands, because their carapaces reminded them of their horse saddles. In the humid zone of the Santa Cruz highlands, there are a number of exceptional places to see giant Galápagos tortoises in their native habitat. We will drive down the western side of the island through a village called Santa Rosa, nearby where there is a small freshwater spring (the only one known on the island) at the base of one of the scoria cones.

The 10-minute walk to El Chato, a shallow pond where the tortoises like to roam, is just on the lower border between the agricultural zone and the Galápagos National Park. In addition to tortoises, you will be able to see native vegetation. This is also a good place to note the extreme differences in weathering rate between the humid southern flank of the volcano and arid northern flank.

Media Luna

In the event of fair weather, we will complete a 10-km roundtrip hike to Media Luna to see one of the most photogenic satellite craters in the islands and hydrologic features, including the upper watersheds and the Miconia shrub forest. The hike traverses the boundary between the agricultural zone and the Galápagos National Park. This area is covered by an inversion fog layer from June to December, called the “garúa” season. This is a very important place for an endemic marine bird called the Galápagos Petrel that nests in burrows along the ravines and the slopes of cones.

Soils are very thin in the area, and a lot of fractures make surface runoff quickly disappear into the underground. At the base of the summit craters, there are sphagnum bogs that have been cored to sample pollen.

La Camiseta or Other “Grieta”

The basal aquifer of Santa Cruz is accessed through open fractures (“grietas”) in the coastal area for most of the municipal water supply. Most of these fractures are faults from an east-west set of horsts and grabens; the largest graben forms Academy Bay, and the cliffs bordering the harbor and town are scarps. Depending on the site, the water table is found at a depth of 5 to 25 m, very close to sea level.

There are currently 3 grietas being used by the Municipality and a number of other grietas being used privately. The water from the basal aquifer is brackish, and the water level is influenced by the tides.

The newest site that the Municipality operates is the La Camiseta grieta. It is located 2 km west of the town, in the Galápagos National Park area. It was necessary to get special permission from the Ministry of Environment and the Galápagos National Park to allow this site to be exploited. The advantage of this site is that it is located sufficiently far away from the town so that the basal aquifer is not contaminated with fecal coliform, as is the basal aquifer in the vicinity of the town. Individual houses, hotels, businesses, and institutions all have septic tanks without drainage fields, owing to the absence of soil and the high population density.

This location is also a great example of the arid-zone forest. Along the route, we will pass an area were intermittent ponds form during extremely rainy years.

Analyses of Santa Cruz Lavas Observed on Field Trip:

	E-1	Sc-46	Sc-106	SC-155	SC-64
	Darwin Station	Cliff behind Station	Ithabaca Channel Platform Series	Highland cone	Low-K Tholeiite
SiO_2	46.14	46.04	48.73	48.12	46.31
TiO_2	2.01	1.32	1.73	2.30	1.01
Al_2O_3	16.10	15.47	15.12	17.29	16.33
MgO	10.43	11.37	9.72	6.37	11.91
Fe_2O_3	2.26	5.28	4.48	3.52	2.18
FeO	9.07	6.45	6.60	8.12	8.19
MnO	0.19	11.37	0.18	0.18	0.18
CaO	9.19	9.86	9.86	10.14	11.24
Na_2O	3.64	2.65	3.10	3.22	2.53
K_2O	0.28	0.23	0.39	0.31	0.05
P_2O_5	0.24	0.19	0.23	0.43	0.12

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