The Pliocene Seamount Series of La Palma: A Field Trip along the Barranco de Las Angustias

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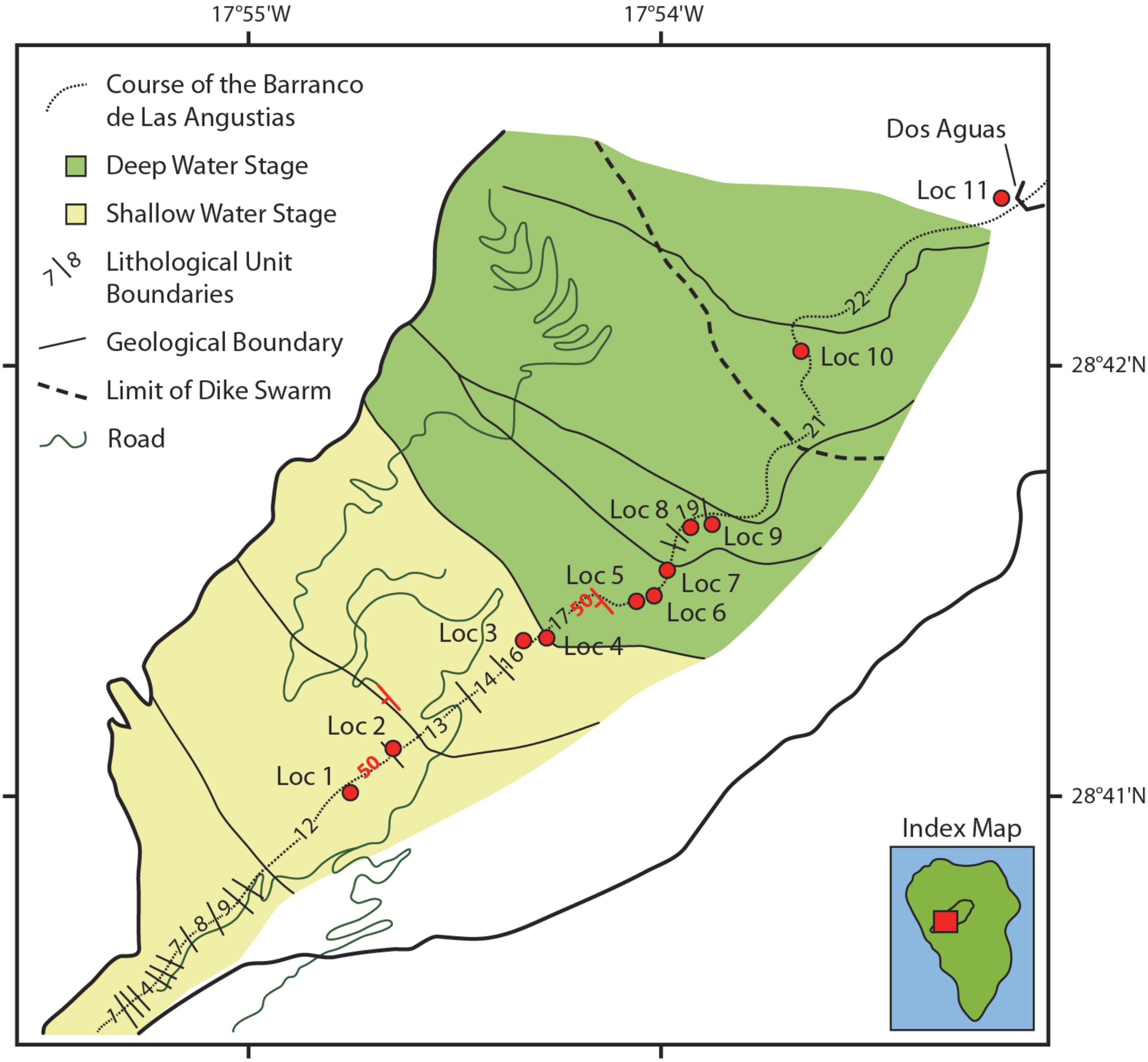

Figure 1. *Geological Map of the Seamount Series in the Basement Complex of the Island of La Palma. Excursion stops are indicated as Loc 1-11.*

Introduction

The Seamount Series of the Basement Complex on Island of La Palma, Canary Islands is exposed in the Barranco de Las Angustias ("Canyon of the Anguishes") and in the Caldera de Taburiente National Park. The Seamount Series is made up of 3.6 km of submarine extrusives and intrusives dipping 50° to the Southwest (Figure 1, 2; Staudigel and Schmincke, 1984; Staudigel and Clague, 2010). The Barranco de Las Angustias offers a well-exposed, continuous section through the seamount, descending to increasing depth and ending in a complex set of intrusive rocks that make up the rest of the Basement Complex in the Caldera de Taburiente. This section offers unparalleled exposure of diverse seamount lithologies, from pillow lavas to volcaniclastics and sheeted dikes and plutonics. The geochemistry of submarine extrusives includes a suite of alkali basalts ranging from very mafic Picrite/Ankaramite to rather silicic mugearites and trachytes. The section also provides a prograde metamorphic sequence that ranges from smectite/analcite at the top of the section and greenschist facies towards its base.

The field trip is set up as a one-day hike along the Barranco de Las Angustias from the parking area on the Southern side of the canyon to Dos Aguas and back. The net hiking time is approximately five hours and the complete field trip takes about nine hours. If necessary, the last stop may be cut out with a time savings of about 90 minutes. This field trip guide also includes a comprehensive description of the Barranco profile from Staudigel (1981) that augments the short description of the excursion locations and that may also be used for self-guided exploration through the entire section. It is definitely worth it to explore the upper sections of the profile on the SW end of the seamount exposure in the Barranco de Las Angustias (Figure 1). The latter is best done in two segments. For the SW part, drive your car on a little road southwest until you come very close to the river bed, and explore from there, following the profile description that is now a bit outdated but much can be seen, despite the new construction. The underlying Unit 12 is best explored by walking down-river from Location 1.

This field guide provides latitudes and longitudes for each location that should place the outcrop within a few meters on a well-referenced satellite Google map (satellite view). When relying on GPS alone, please consider that satellite coverage may not always be ideal, given the narrow gorges at some of these stops. This guide briefly describes the overall volcanological, petrological and metamorphic features of the seamount series followed by a short description for each of the excursion stops. A more comprehensive description of the exposed unit can be found in the overall section description.

Please also note that the gravel/sediment-fill of the canyon can vary by about 2 meters. The section description was made at a time of relatively high gravel load in the canyon, whereby the paleomagnetics drill holes are about at, or slightly above this high-mark. As a result the outcrops exposed deeper eroded portions of many outcrops that are fresher, but there also are more water-pools with sufficient depth that they provide obstacles to a canyon walk.

A note of caution about the weather and hiking terrain: Overall, the hike is not very strenuous or technical; there are very few steep inclines but no scary drop-offs. The main issues relate to the weather. During the summer months (July-September) it can be quite hot. Sun protection is essential (sunscreen, hat, sunglasses) and it is important to bring lots of water. You can resupply your water at the hydrothermal spring at Location 11, but not everybody likes the bubbly, iron-rich water. Also, you may not get to the spring if progress is too slow. Overall the hike is not challenging but trekking poles may be very handy, in particular for downhill walking and balancing on rocks when crossing the river. Water-proof hiking boots are advised, in particular for visits in the winter and spring months. Be aware of the danger of flash-floods. Half a dozen people were killed in a flood in November 2001, but only two bodies were recovered. Even though the chance is very low, be aware of flash-flood hazards and postpone your Barranco trip if there are dark rain clouds in the Caldera! Flash floods are extremely dangerous. Do NOT attempt to cross the river during such a flood. Seek higher ground and watch an amazing natural spectacle!

Structure

The Basement Complex of La Palma

The basement complex of La Palma is exposed in the Caldera de Taburiente and Barranco de Las Angustias area, typically weathering in gentler slopes than the overlying Coberta series and the debris avalanche deposits that can be prominently identified along the road entering the Barranco and in steep ridges in the Caldera (Anchochea et al., 1994; Carrecedo et al. 1999). The basement complex consists of two main units, the Seamount Series along the Barranco de Las Angustias and an intrusive complex insider the Caldera. Paleomagnetic evidence

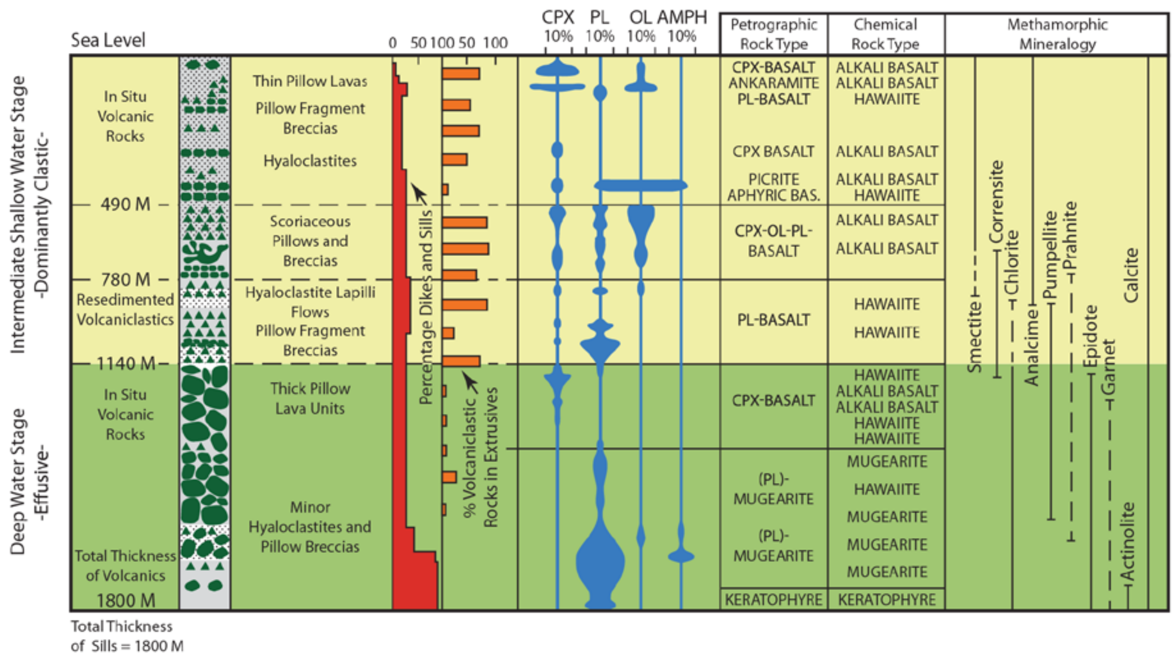

Figure 2. *Composite section through the Seamount Series in the Basement Complex of La Palma.*

suggests that some of the intrusives are clearly related to the (tilted) seamount series, while others likely belong to a younger, non-tilted intrusives (Gee et al., 1993). Hence, the intrusives in the Caldera de Taburiente reflect multiple phases of volcanic activity. The Basement Complex is separated from its younger overburden with an erosional unconformity.

The Seamount Series is between 2.8-3.0 Ma old on basis of foraminifera found in hyaloclastites interlayered with the pillow lavas of the Seamount Series (Table 1, Staudigel 1981). The oldest Coberta lavas were estimated to be about 1.7 Ma (Abdel Monem et al., 1972) and volcanism on this volcano lasted until about 0.4 Ma (Guillou et al., 2002). Most of the younger volcanics are found along the Cumbre Nueva on the Southern part of the island.

The basement complex consists of two major components; a plutonic core exposed in the central part of the Caldera de Taburiente, and the seamount series in the Barranco de Las Angustias. The Seamount Series consists of a layered sequence of pillow lavas and volcaniclastics that merges downwards into a sheeted dike swarm which, grades into the plutonic sequence in the Caldera de Taburiente. The layered pillow sequence dips 50° towards 230° (azimuth of dip vector). The Barranco de Las Angustias trends also roughly SW, and thus affords a section from the top of the seamount at the lower course of the creek (in the SW) to the bottom of the extrusive section near Dos Aguas (Staudigel 1981; Staudigel and Schmincke, 1984).

The extrusive Seamount Series may be divided in two major sections, the shallow water facies (Units 1-16) and the deep water facies (Units 17-22) (Figures 1, 2; Table 2). The shallow water facies is dominated by volcaniclastics that may have been deposited in situ or down-slope of the volcano. The deep water facies has about 20% volcaniclastics, which is similar to other seamounts such as the 150 m high abyssal hill at DSDP Site 417A (Staudigel 1981; Staudigel and Schmincke, 1984).

Table 1: Age diagnostic foraminifera found in the Seamount Series of La Palma
identifications independently by W.A. Berggren, J. Hueguera, P.R. Thompson

Unit 2:	Globorotalia Inflata	(0-3 Ma)
	Globoquadrina Altispira	(2.8-19 Ma)
Unit 5:	Globorotalia Puncticulata	(3-5 Ma)
Unit 6 (top):	Globorotalia Preinflata	(2.5-4 Ma)
	Globorotalia Crassaformis	(0-4 Ma)
	Globoquadrina Altispira	(2.8-19 Ma)
Unit 17 (top):	Globorotalia Crassaformis	(0-4 Ma)
	Globoquadrina Altispira	(2.8-19 Ma)

Pillows of various sizes are the dominant extrusive rock types in the seamount series, and with exception of a few very large pillows (>4 m) there are no massive flow units as they are quite commonly found in normal oceanic crust. Pillows generally have their typical (tubular) shapes and can be observed in cross section as well as in three-dimensional exposures (Figure 3). Individual pillow volcanoes display a characteristic size variation from large basal to small pillows at the top and distal flows

Volcaniclastics can be found in all sections of the Seamount Series including autochthonous or near-autochthonous volcaniclastics (Figures 4, 5) as well volcaniclastics that have been deposited distally from their source (Figure 6). Amongst the former are in situ pillow breccias (Unit 12, Loc 2, Figure 4; Unit 20, Loc 7, Figure 5) may be dominated by pillow fragments (Unit 16, Loc 3, Figure 6) or by fine grained hyaloclastite (Unit 20, Loc 8, Figure 7).

Figure 3. *Pillow lavas from Location 5. This allochtonous block shows the cross sections through pillows on the left side as they can be expected in a erosion surface on the Canyon walls. On the right side, weathering has exposed pillows in three-dimensional shapes, revealing their tubular character. This image is about 5 meters wide.*

Dikes (Figure 8) become increasingly abundant with stratigraphic depth into the seamount series and they take up about 50% of the volcano overall. The occurrence of dikes and other intrusives has been consistently under-estimated in the analysis of seamount (and volcano)-structure, yet they may be one of the major processes leading to over-steepened flanks and sector collapse. The nearly radial tilt of the seamount sequence is consistent with centered intrusion of sills and plutonics, raising the center more than the flanks. Three dike generations may be distinguished (Staudigel et al., 1986): (1) early feeders to the seamount lavas, (2) sills, and (3) feeders to the recent lavas.

Figure 4. *In Situ deposited pillow breccia near the base of Unit 12 at Location 2. Image is approximately 4 m wide.*

Figure 5. *In Situ pillow breccia at location 7 in Unit 20. Image is approximately 1m wide.*

Sills commonly show cpx and ol phenocryst enrichments in the lower parts suggesting gravity-driven settling prior to rotation. Furthermore, paleomagnetic evidence (Gee et al., 1994) suggests that the first two dike generations are rotated in conjunction with the extrusives while the near vertical and most recent dikes are not rotated.

Extrusive rock types span a wide range of alkali basaltic composition, including rare picrites/ankaramites near the top, hawaiites, mugearites and the basal trachytic rocks. The trachytes are now altered to keratophyre that occasionally still displays the characteristic groundmass texture and phenocryst alignment. Overall the most mafic rock types are in the upper section and the most silicic near the bottom, as can be seen by the variation of modal clinopyroxene down-section

Hydrothermal Overprint

The Barranco de Las Angustias section offers a continuous prograde metamorphic profile from alteration temperatures less than 10°C near the top to well over 200°C near the base. The metamorphic gradient was first described by Hernandez-Pacheco and Santin (1974), Staudigel (1981), and most recently by Schiffman and Staudigel (1994; 1996). Figure 2 includes a summary of mineralogical changes as they can be observed in the Barranco profile. In particular the transition of montmorillonitic clays to mixed layer (corrensite) and chlorite is very well expressed in this section (Schiffman and Staudigel, 1996).

Description of the Field Trip

Location 1 (28.68468°N, 17.91171°W): Unit 12 (top of sub-section 3; see Figure 9 for a detailed section through Unit 12). Walk due north from the parking lot, then west to an exposure to the NE end of a farm on the south-side of the river bed: Amoeboidal Pillows, in situ deposited pillow breccia. These rocks are characteristic for the in situ depositional facies of a seamount in shallow water conditions.

Location 2 (28.68604°N, 17.91038°W): Walk up-river to the most prominent pillow exposure on the northern side of the barranco-bed. The pillows represent the beginning of Unit 12 eruptive activity grading into a breccia (Figure 4). The base of Unit 12 is flat, nicely displaying the tilted bedding of the complex. Unit 12 overlies a sequence of mostly allochtonous breccias. Note the underlying hyaloclastite and the flat underside of the overlying pillows. Here is a good place to note the bedding of the complex!

Location 3 (28.68918°N, 17.90698°W): Walk a few hundred meters further north to Units 15/16. This is the first narrow spot of the Canyon with a bridge and pipes crossing, up stream from road crossing. Autochthonous pillow fragment breccias are exposed, overlain by some pillow lavas. The pillows define a nicely developed bedding plane at their base and they overly a series of breccias that are commonly inversely graded in individual layers, but overall fining upwards. These deposits probably represent turbiditic pillow fragment breccias, deposited on a nearly horizontal plane on the flanks of the seamount. Explore in the pillows and find a pillow with a secondary mineral filled, flat-bottom cavity that offers a paleo-horizontal that is parallel to the bedding of the nearby pillow breccias (Figure 10).

Figure 6. *Autochthonous pillow fragment breccias of Unit 16 at Location 3. The Image is approximately 10 m wide.*

Location 4 (28.68964°N, 17.90521°W): Walk just up-river until the first pillows indicate the boundary between Units 16/17. This boundary signifies the transition of the deep water facies to the shallow water facies of seamount extrusive activity. Fine grained hyaloclastite on the top of Unit 17 contains abundant foraminifera (Table 1). The abundance of epiclastic sediment components at this location may indicate an extended break in the deposition of volcanic material at this location. Note on your way to location 5 that the pillow diameters increase with stratigraphic depth.

Location 5 (28.691106°N, 17.90154°W): Allochtonous block of pillow lavas (about 4x4x4 m) The W-facing wall of this block shows extremely photogenic pillow lavas (Figure 3), some river-polished, some broken out to give a nice 2D and 3D view of pillow tubes right next to each other.

Location 6 (28.69205°N, 17.90048°W): Moving up-river, towards the beginning of the hiking path leading up on the northern slope. There are two very pretty allochtonous blocks of a tectonic breccia, in the river (2x1.5 m sticking out for a meter) about 20 m apart. This breccia (Figure 11) shows many puzzle shards cemented with carbonate (+silica?). This breccia is very instructive for studying breccia mechanisms that do not involve any post-fragmentation sedimentary transport and the cementing in a hydrothermal setting.

Location 7: (28.69303°N, 17.90041°W): Follow the path in the river bed, until it leaves the canyon bottom up on to the northern slope. Go past the place where the path goes upslope for < 20 m and you will find excellent exposure of a mono-lithological pillow fragment breccia on the north side of the creek just when it changes to a more northerly direction. Observe the transition from pillows to in situ pillow breccia (Figure 5) and finally into pillow fragment breccia.

Location 8 (28.69439°N, 17.89877°W): This location can be reached with a minor climb down from the hiking path. The spot to climb down is difficult to find if you are not familiar with the location of Unit 20, so you might want to go ahead to the next river crossing and then backtrack down river. If you do that you are passing Location 9 first and you might as well do this first and then move along to Location 8. From there, you might choose to climb back up to the hiking path. At Location 8 find a well bedded and cross-bedded fine grained hyaloclastites with occasional pillow fragments (Unit 20, Figure 7) on the north side of the creek. In this general region, also notice that many of the better-crystallized pillow interiors are replaced with epidote-rich metamorphic mineral assemblages. When you are done, it is an easy climb up to the hiking path that you came in on, back-track to the crossing and continue.

Figure 7. *Bedded fine-grained hyaloclastite of Unit 20 at Location 8. Width of photograph approximately 60 cm (with a 2.5 cm paleomagnetics hole in upper left).*

Location 9 (28.69391°N, 17.89802°W): Located about 100 m upstream from Location 8, and 50 m east of the path river crossing. This location on the South side of the creek displays a nodule dike with densely packed dunite nodules emplaced into the upper part of Unit 21 (Hernandez-Pacheco, 1975)

The path's crossing from north to south side of the Canyon is probably also a good lunch spot for this excursion. Upriver you find a narrow gorge with guaranteed shade and a water fall, but the crossing itself offers a bunch of rocks to sit on for lunch. Depending on your progress, you might have lunch before you go to Location 8 or after Location 9. After lunch there will be a walk of about half an hour to Location 10 without any stops, but there are many interesting features along the way. The abundance of dikes increases dramatically, and there are many interesting cross-cutting relationships between three generations of dikes.

Location 10 (28.70057°N, 17.89505°W): Observe sheeted dikes, their intrusive relationships and occasional screens of host rock. Well over 90% of the exposed rock is made of sheeted dikes (sills, with reference to the pillow complex bedding planes) and some minor near-vertical dikes that are radial to the center of the Caldera de Taburiente. Take a good half hour and have your participants find examples for the following:

Host Rock: there are a number of host-rock screens with mugearitic volcaniclastics with well-preserved pillow fragments, quenched margins, etc. Discuss volume relationships between dike and host rock considering the thin, tabular body of host rock just south of the path crossing.

Overall Geomorphology: At the path-crossing the canyon floor parallels the direction of the sheeted dikes, probably following and preferentially eroding an ankaramitic sill that shows almost granular weathering. More recent dikes also intruded preferentially into this dike, fragmenting its interior into several pockets all along the section.

Observe: Quenched dike margins, dike-in-dike intrusions, phenocryst accumulations within dike centers, asymmetric distribution of phenocrysts (largest number and sizes of cpx phenocrysts in the lower part of a dike. Most dikes are interpreted here as sills because their orientation is parallel to the overall bedding of the pillow lavas and hyaloclastites on top, and because phenocrysts settle to the lower part of these dikes.

If you go downriver, the canyon makes a sharp turn to the right (West), probably due to the preferred erosion of a series of young radial phonolitic dikes that are exposed on the S(E)-side of the Canyon. Note that these dikes cut through all other dikes.

When you are done with this stop, walk up-river to Location 11, following the hiking path on the South side of the canyon (canyon bottom is not recommended). During this hike, notice early on that the lava-screens in the sheeted dikes change to a white rock type, the keratophyres of Unit 22. Examine the texture of these screens that display mostly clastic rock types but also some flow-banded rock units. Pillow fragments were also found. There are many examples of cross-cutting relationships of dikes along the Canyon. However, before you move on, consider the time of day, the energy level of your group and note that this last stop will take you about 90 minutes round-trip. Going back will be an easy two hour hike to the cars from Location 10. If you decide that it is prudent to hike back, recommend your participants to go slow, take pictures and explore the geology they have seen so far in more detail. Encourage them to make a mental and photo collection of different structural rock types, they will not find anything like this diversity and level of exposure anywhere. Have them explore the dikes, the metamorphic progression and identify and measure bedding planes. Share your results at the end of the trip.

Figure 8. *Crosscutting dikes in Keratophyres of Unit 22. The image is approximately 2 m wide.*

Location 11 (28.70678°N, 17.88406°W): Walk all the way to the dam at Dos Aguas. It is probably best not to walk up on the hiking trail but rather follow the creek up, mostly on its northern side. Near Dos Aguas rocks are discolored into reddish tones by hydrothermal alteration. Note a CO_2 rich hydrothermal spring (Figure 12) within a small set of trees just north and down-river of the wall that guides the water into the upper aqueduct on the northern down-river part of the rock wall damming the river. The quite bubbly water is potable; you may fill your drinking bottles for the trip back.

If you have time to burn, you might want to go up-river towards the East and find the Cascada de Colores a dam that is stained with yellow/reddish hydrothermal deposits. It is one of the major destinations of travelers into the caldera.

The Seamount Series in a Profile in the Barranco de Las Angustias

The deeply eroded valley of the Barranco de Las Angustias displays a complete section through all major lithological units of the layered submarine complex. The following technical description was taken from field notes given in Appendix 1 of Staudigel (1981) and may be cited as such. This description gives a unit-by-unit summary of field observations, thin section data and some first order interpretations of the origin of textures and field relationships. Locations are given in Figure 1 and a review of geological data is given in Figure 2 and Table 2. Abbreviations are summarized at the end of this section. These unit descriptions may be used as a self guided tour through the whole section.

Table 2: Summary of Lithological Units along the Barranco de Las Angstias

Unit #	Thickness	% dikes	corr. thick.	total thick.	tot/corr thick.	litho-logy	petro-graphy	elevation a.m.s.l
1	13	0	13	13	13	c	cpx,ol	143
2	50	5	50	63	63	l	cpx,ol	144
3	23	10	20	86	83	c	siderom	147-148
4	13	45	7	99	90	l	cpx,ol	156-158
5	5	5	5	104	95	l	cpx,ol	158
6	53	5	50	157	145	l	pl,cpx	158-162
7	122	0	122	279	267	gap		162-169
8	90	5	85	369	352	l	aph	169-173
9	50	0	50	419	402	gap		173-175
10	22	0	22	441	424	l/c	ol,cpx	175-176
11	85	20	68	526	492	l	aph	176-181
12	360	20	288	886	780	c	cpx,ol	181-210
13	250	30	175	1136	955	c	pl,aph	210-220
14	80	20	64	1216	1019	l	pl	220-230
15	28	5	28	1244	1047	l/c	p1, cpx	230-232
16	110	20	88	1354	1135	c	cpx	232-238
17	480	25	360	1834	1495	l	cpx, aph	238-275
18	30	10	25	1864	1520	c	pl	275-277
19	120	60	48	1984	1568	l	aph	277-287
20	6	5	6	1 990	1574	c	pl	287-288
21	530	45-95	163	2520	1737	l/c	pl (amph)	288-375
22		95				c/l	keratoph	375-

*The **thickness** of a unit is given in meters for the location at the Barranco bottom; **% dikes** is the relative amount of dikes was estimated in the field by visual integration of 10m intervals for the whole unit and averaging the individual data; **corr. thick**. is the thickness of any unit without dikes (this thickness reflects the actual erupted thickness of a given unit if all dikes were introduced parallel to the bedding. Particularly for the upper portion, this correction procedure tends to over-correct, since only a fraction of the dikes are actually sills, most dikes are vertical or oblique to the bedding); **total thick.** is the sum of all unit thicknesses from top = stratigraphic depth; **tot. corr. thick.** is the stratigraphic depth corrected for dikes; **lith. rock type** is the lithological rock type: c-clastic, 1-lava flow (pillows, sheet flow); **petrography** is the petrological rock type based on phenocryst assemblage of a given unit (see notes below); **elevation a.m.sl.** indicates the location and the extent of a given unit in the Barranco de Las Angustias in meters above mean sea level. These elevations have been determined from the 1:5000 topographic map issued by the Cabildo Insular of the province of Tenerife in Santa Cruz de Tenerife.*

Unit 1

Type:	heterolithological clastic unit (fine grained hyaloclastite, broken pillow clasts, examples of some complete pillows
Location:	143 m above s.l.
Thickness:	13 m
Samples:	267
Subunits:	none
Alteration:	texture of HC completely altered and voids filled with anal, smec, thomp
Petrography:	cpx (ol) basalt with soph grdm.

Unit 1 is a very poorly sorted heterolithological clastic unit consisting mainly of broken pillow clasts and some isolated pillows with a fine grained hyaloclastite matrix (< medium lapilli ~75%). The lower contact to Unit 2 dips about 50/228, 44/228 (individual measurements). The isolated pillows or lava sacks have oval to round cross sections of 20x70 cm and are embedded in fine grained hyaloclastite. Other block sized clasts are angular pillow or lava-sack fragments. Coarse and medium lapilli sized rock fragments are usually rounded. The finer grained matrix is generally very altered. Its texture is partially preserved between the isolated pillows (sample 344) and completely destroyed by mechanical/tectonic perturbation in the other portions of Unit 1 (45, 265, 340, 341). However, zeolite vesicle fillings are preserved in this unit.

Unit 2

Type:	pillow basalt, topped by a wedge shaped clastic subunit
Location:	144 (top of unit)-147 m above s.l. (base)
Thickness:	50 m
Samples:	9, 101, 268, 402, 418
Subunits:	**(A)** top: clastic wedge with bedded hyaloclastite, opening South **(B)** main pillowed unit comprising 95% of entire unit
Alteration:	highly altered, fine grained groundmass completely replaced by anal, smec
Petrography:	cpx phyric basalt with soph/int grdm

Subunit (A) Top: A wedge shaped clastic unit, conformably overlying the pillowed section forms the top of Unit 2. The subunit consists of 60% fine grained matrix (fine lapilli and ash) and it shows crude bedding which dips about (44/265; 55/260), roughly conformable or slightly oblique to the top contact (50/228; 44/228). The clasts are lapilli and block sized isolated pillows or pillow fragments (up to 20-30 cm).

Subunit (B) Main Pillowed Unit: Pillow cross sections are round-oval near the top and become flattened toward the base. The average size of pillows varies from 20-30 cm at the top to 100 cm wide flat pillows at the base of Unit 2. Pillow interstices are filled with bedded fine grained, relatively dense hyaloclastite (e.g. 418) comprising 10-25% of volume at the top, and 5-10% at the base, of Unit 2. Large amounts of inter pillow hyaloclastite are found between pillows. Pillow diameters vary from 20-30 cm at the top to up to 100 cm wide flat pillows at the base of Unit 2. Pillow interstices are filled with mostly bedded fine grained hyaloclastite comprising up 10-25% at the top and 5-10% at the base of Unit 2. Large amounts of inter pillow hyaloclastite allows pillows to have completely round to oval cross sections, whereas pillows associated with less abundant hyaloclastite are flatter with round tops and bases molded around the underlying rock.

The margins of the pillows consists of an outer, 8 mm thick massive zone of green altered glass, a 2 mm thick variolitic transition zone and an inner, 10 mm wide reddish brown quench zone. The inner portion of the pillows is made from greenish-gray fine grained basalt. Vesicles about 1-2 mm in diameter occur beneath the quenched rind comprising up to about 10-20% of a 5-15 cm thick zone. Vesicles > 1-2 mm are generally enriched in the center of pillows. The large flat pillows in the lower portion of Unit 2 show enrichment of cpx phenocrysts up to ~20% in the lower 2/3 of a pillow while vesicles are concentrated in the top 1/3 of the pillow. Other pillows are concentrically zoned, usually with phenocryst rich interiors but phenocryst poor interiors were also observed. Radial cracks, usually filled with secondary phases (chiefly calcites and zeolites), are well developed in outer, dense zones and in phenocryst poor portions of pillows.

Basalts from the upper portion of Unit 2 (LP 9) have 4% cpx, 2% olivine phenocrysts with a subophitic-intersertal texture. The abundance of cpx is variable and was observed as high as 15% at the base of the unit.

Occasional picritic pillows occur in the upper portion of the unit. A sinuous aphyric dike 80 cm wide cuts through the top of Unit 2.

Unit 2 is thoroughly altered. The fine grained groundmass is typically altered to analcite and smectite; thomsonite/natrolite, calcite and chabasite also occur.

Inter pillow-hyaloclastites are generally bedded or laminated, the bedding of fine grained material often being convex upwards. These hyaloclastites are composed of medium to coarse ash and are fossiliferous (Globorotalia Inflata (0-3.0 Ma); Globoquadrina Altispira (2.8-19 Ma) and well sorted).

Top and base of Unit 2 are discordant. However, because Units 1 and 3 show strong evidence for tectonic emplacement and Unit 2 shows consistent bedding and consistent stable NRM (Natural Remanent Magnetization) directions with the rest of the layered complex, it is interpreted that this unit was deposited continuously with the rest of the layered complex.

<u>Unit 3</u>

Type:	bedded, fine grained hyaloclastite
Location:	147-148 m above sea level S-side of valley
Thickness:	23 m
Samples:	10,419 and 420
Subunits:	none
Alteration:	very altered; anal, smec
Petrography:	Sideromelane shards, ~90 ash fraction

Unit 3 is a well bedded, fine grained, vesicular (<fine lapilli) hyaloclastite. It is well sorted, consisting mainly of coarse-medium ash sized glass particles which are angular and usually very vesicular (60-80% vesicles 0.2-0.05 mm in diameter). Most layers are about 20-40 cm thick and graded. Unit 3 shows several unconformities (e.g. 20/170; 28/140; 35/195) and individual blocks of fine grained hyaloclastite are rotated relative to each other. This results in very variable directions of bedding planes: 78/305; 85/088; 77/100; 70/105; 76/255; 65/165; 55/176; 72/264; 32/205 (measured along the outcrop from W to E).

<u>Unit 4</u>

Type:	pillow basalt associated with breccias at the base and a massive dike at top of unit
Location:	156-158 m BAB
Thickness:	13 m
Samples:	30, 102 I-II
Subunits:	**(A)** basal flow units
	(B) normal pillows
Alteration:	anal, smec, cc, n/t
Petrography:	cpx (ol) basalt with soph grdm.

The base of Unit 4 is formed by two massive flow units, with basal and top breccias of ~2 m total thickness. This basal subunit conformably overlies the bedded top of Unit 5 (55/235; 55/232; 58/245). These flow units vary in thickness from 25-75 cm, are at least 4m long and have a blunt thick front end. They show irregular surfaces with two types of protrusions: wavy protrusions with amplitudes of several cm and wavelengths of about 10 cm, and mushroom shaped intrusions of 5-15 cm height and 5-10 cm width at the top. These flow units have concentric variation in vesicle content and size: the outermost, quenched margin is dense and has only minor amounts of small vesicles; towards the center 2-3 cm wide zones, enriched in vesicles (about 20%) alternate with 0.5-2 cm thick, vesicle poor zones. The vesicle size varies from about l mm in the outer zones to 2-3 mm towards the center of these flow units.

The two flows at the base are associated with a breccia which covers the approximately 100x150 cm wide irregularly shaped pockets between mega pillows. The breccia is made up mainly (~60%) of probably interconnected irregular, sometimes broken, block sized lava bodies with thickness of 3-20 cm. These lava bodies can sometimes be traced into regular pillow tubes above this 2 m thick basal unit. The space between the irregular and broken pillows is mainly filled with dense, glassy, fine/medium lapilli sized angular fragments. Finer grained material (< lapilli) is nearly missing, spaces between fragments are void or filled with zeolites. These flow units have concentric variation in vesicle content and size: The outermost quenched margin is dense and has only minor amounts of small vesicles and then 2-3 cm wide zones enriched in vesicles (~20%) alternate with 0.5-2 cm thick, vesicle poor zones. The vesicle size varies from about l mm in the outer zones to 2-3 mm towards the center of these flow units. Small lava bodies in the brecciated zones are relatively dense, the bigger ones frequently having a central zone with more abundant vesicles.

The basal zone grades into normal closely packed pillows towards the top. These pillows vary in diameter from 20-60 cm and develop vesicle rich zones underneath the quenched margins. The often dense pillow interiors show radial cracks, mainly in the outer dense portions. Parallel to the concentric variation in vesicle content, and slight variations in cpx phenocryst content also occur.

The basalts of Unit 4 have subophitic-intersertal texture with about 5% cpx, 3% ol and pl-microphenocrysts. The samples studied in thin section are very vesicular and closely resemble basalts from Unit 2.

Within the exposed area, Unit 4 is deposited on a flat, originally horizontal plane, formed by the wedge shaped Unit 5. However, the (not exposed) N-extension of the base of Unit 4 cannot continue as exposed since the underlying Unit 6 can continuously be traced up to higher stratigraphic levels than this extension. Unit 6 is interpreted to represent a hill and Units 4 and 5 were deposited on the south facing slope.

Unit 5

Type:	clastic unit with fine grained hyaloclastite matrix, isolated lava sacks and pillow fragments
Location:	158 m BAB
Thickness:	wedge shaped, approx. 5 m on N side of Barranco and > 10 m on S side
Samples:	32, 231
Subunits:	**(A)** lower half on N slope
	(B) upper half on N slope correlated with lower half on S slope
	(C) upper half on S slope
Alteration:	altered, cc, anal, smec
Petrography:	cpx, ol, soph, basalt (ANK)

A 25 cm wide potential feeder dike to Unit 5 is exposed in Unit 6: It winds through the pillow interstices and ends in Unit 5. However, there are differences in cpx/ol phenocryst ratios between the dike and Unit 5; the dike is made up from picrite (~40% ol) with very little cpx, whereas Unit 5 is made up mainly from ankaramitic basalt with abundant ol phenocrysts.

Subunits (A) and (B) have a bimodal grain size distribution and contain 50-75% clasts of 10-40 cm diameter in a well-sorted sideromelane-ash matrix (~70% medium ash). Matrix and clasts are comagmatic based on identical phenocryst assemblage. **Subunit (A)** consists of 30-50% fine grained matrix; clasts are mostly angular pillow segments (10-40 cm) with about 1/3 representing complete pillows with nearly round cross sections. **Subunit (B)** is topped with a well bedded (55/235; 55/232; 55/245) fine grained layer, but has only 20-30% fine grained matrix in its major portion. **Subunit (C)** is poorly sorted and the average grain size is finer than in **Subunits (A) and (B)**. Ankaramitic pillows usually are smaller than in the less phyric **Subunits (A) and (B)**. The most characteristic difference is that the matrix contains abundant rock fragments of holocrystalline basalt.

Unit 5 is composed of subophitic ankaramitic alkali basalt with ~15% cpx phenocrysts (< 3 mm) and 10% ol phenocrysts (< 2 mm). Foraminifera in the hyaloclastite include Globorotalia Puncticulata (3-5 Ma).

Unit 6

Type:	pillow basalt with minor amounts of fine grained hyaloclastite
Location:	158-162 m BAB
Samples:	12, 31, 34-36, 102 III-IX , 103, 423-425.
Subunits:	none
Alteration:	smec, analc, n/t, chab, op
Petrography:	pl, cpx basalt with soph/int grdm

Fine grained inter pillow hyaloclastites occur throughout Unit 6 with decreasing abundance from the top (5-10%) to the base (< 5%); three types of occurrence were distinguished in Unit 6: **(A)** inter pillow hyaloclastite (in normal pillows) occurring throughout the unit. Foraminifera (with age ranges) Globorotalia Preinflata (2.5-4 Ma), Globorotalia Crassaformis (0-4 Ma); Globoquadrina Altispira (2.8-19 Ma); **(B)** inter pillow hyaloclastite in partially brecciated coherent pillows on the N-slope of the Barranco; and **(C)** hyaloclastite fracture fill in the middle section of Unit 6.

(A) The inter pillow hyaloclastite in the upper portion of Unit 6 is well sorted (medium/coarse ash), slightly layered and consists mainly of sideromelane ash. The top of the unit is formed by fine grained hyaloclastite with the uppermost portion containing frequent nannofossils. The hyaloclastite contains frequently tabular glass shards of ~2-20 mm size and fine grained hyaloclastites and glass shards showing the same phenocryst assemblage as the host rock. The bimodal distribution of inter pillow hyaloclastite indicates dual sites of origin for big glass shards and the fine grained hyaloclastite: the layered and well sorted character of the latter indicates a distant source of origin from the same eruption (same phenocryst assemblage) and transport by currents to the present site of deposition, whereas size of big glass shards and parallel alignment to the pillow rind indicates an in situ origin.

(B) Inter pillow hyaloclastite, situated between partially broken, but coherent pillows were studied as a possible source region for fine grained hyaloclastites. The hyaloclastite is very similar in appearance to inter pillow hyaloclastite in normal pillow lavas: the upper portion of this 5 m thick and 15 m wide hyaloclastite-rich zone contains up to 15% fine grained hyaloclastite, the abundance decreases towards the base to 10%. The stratigraphically lower hyaloclastite is coarser grained (coarse ash vs. medium ash higher up in the sequence). Fine-grained hyaloclastite in this portion is bedded; well-sorted clasts smaller or larger than ash are generally missing.

(C) The hyaloclastite filled fracture is constantly about 25 cm wide and at least 15 m deep, with an average dip of 30/124, roughly 60° to the horizontal plane through the layered complex (Figure 1). This fracture opened mostly along pillow margins, rarely cutting through pillows. The fracture was first filled with hyaloclastite and then intruded by a dike causing a perlitic texture in the hyaloclastite at the contact. Within this fracture, three different hyaloclastite deposits can be distinguished: Bottom facies, hyaloclastite fill, and the late fill. The bottom facies consists mainly of fine grained hyaloclastites with frequent large basaltic fragments deposited during or soon after opening of the fracture. The major portion of this fracture consists of well sorted medium ash sized hyaloclastite resembling inter-pillow hyaloclastite. In the upper portion of this fracture, the hyaloclastite becomes poorly sorted, heterolithological, and contains nannofossils. This indicates a slow deposition rate of hyaloclastite either at a late stage of the eruption or after the eruption. Next to this fracture and in the neighboring pillows pockets are filled with hematite.

The inter pillow matrix in the lower portion of Unit 6 consists of a very poorly sorted breccia of sideromelane or basalt lapilli generated by shattering of pillow margins. The finer grained fraction (ash) is absent, either because it was not formed by this brecciation mechanism or it was transported away from the currents always accompanying submarine eruptions.

The pillows of Unit 6 display a variety of shapes and sizes. Three types are distinguished: some foreset bedded pillows mainly in the upper section, normal pillows occurring throughout Unit 6, and some large, irregular feeder pillows in the lower portion of Unit 6. The average size of pillows increases from the base of this unit.

Foreset bedded pillows consist of a thin feeder tubes about 25 cm in diameter, which form a steep slope and feeds a larger pillow 40-80 cm) with a blunt end when the slope becomes shallower. Some flow directions of such pillows were measured: 31/110 E; 34/127 SE; 23/088 E and 42/130 SE, indicating a paleo slope of ~30° S.

“Normal pillows” represent closely packed lava tubes varying in size from 20-40 cm at the top to 80-100 cm at the base of Unit 6. The base of individual pillows is molded around the underlying rocks, the tops are usually concave upward. At the base of Unit 6, some ponded, feeder -pillows cover outcrop areas of >3x5 m, and are usually flat-topped and often covered with layered, fine-grained hyaloclastite. They form irregular bodies with lava toes 20-40 cm thick and up to 100 cm long, forming the sides of the main body. These lava toes and pillows have identical cross sections and therefore the lava toes may represent the origin of such tubular lavas. The lava toes at the sides of such feeder pillows interfinger with neighboring pillows, lava toes from neighboring feeder pillows, or lie directly on top of each other. The flat tops, often covered with bedded hyaloclastite indicate that these-lava bodies were ponded.

The 8-12 mm thick pillow margins of Unit 6 develop green altered glassy margins which grade into a variolitic transition zone and into better-crystallized pillow interiors. Pillows can be “massive" with an even distribution of vesicles and phenocrysts, or show a variable, concentric distribution. Concentric variation of vesicle content is particularly frequent in big feeder pillows. The vesicle content of layers can vary in a symmetric or asymmetric fashion: either thinner, dense, vesicle-poor layers (1-2 cm thick) alternate with thicker (2-5 cm) vesicle-rich layers symmetrically or the vesicle poor zone has a sharper outer transition and a continuous transition to the inner vesicle-rich zone which display quench features. The vesicle size generally increases towards the center of the pillow, from about 0.1-1 mm near the rim to 2-3 mm in the center. The pillows frequently show pipe vesicles of 2-3 cm diameter and 1-2 cm length (first observed in this outcrop by Vuagnat, 1961). These pipe vesicles may be replaced by sheet vesicles, parallel to the direction of flow in the steep feeder pipes of the foreset bedded pillows. In some big pillows, transitions between pipe vesicles and central cavities were observed. However, pipe vesicles are missing in the large feeder pillows.

Radial cracks in pillows are best developed in lava tubes with round cross sections and in the dense (outer) portions of the pillows. They become very irregular and poorly developed in better-crystallized and vesicular (inner) zones. Some big, massive pillows and dikes show nearly columnar radial jointing (also described by Vuagnat, 1961). Early formed radial cracks often show quench zones. Later cracks do not develop quench zones and often form extensions of these earlier cracks, or cross cutting with them. Open cracks in pillows are filled with secondary phases or hyaloclastite.

Unit 7

Type:	breccia, poorly exposed
Location:	162-169 m above sea level
Thickness:	90 m
Samples:	none
Subunits:	none
Alteration:	altered to zeol, smec
Petrography:	cpx basalt?

Unit 7 is very poorly exposed. There are only patchy and very badly altered outcrops along the sides of the Barranco, which are covered with gravel to varying extents depending on the amount of erosion and sedimentation by the Angustias River during past winter storms. Unit 7 consists of a mainly cpx phyric pillow breccia with some dikes. Dikes are completely fractured and disaggregated, but still in place. The whole unit is altered to an extent not allowing a clear distinction whether or not a given outcrop is in place or emplaced by landslide or tectonic movement.

Unit 8

Type:	pillows, brecciated on top and base
Location:	169 m above s.l.
Thickness:	90 m
Samples:	37, 38, 103
Subunits:	none
Alteration:	Altered to zeol, cc, analc
Petrography:	Aph hawaiite with pl micro-phenocrysts and 1-2% euh cpx

Unit 8 forms a prominent cliff on the south slope of the Barranco, about 200 m E of the seismic station 'Taburiente'. Because of poor outcrops and intense alteration, bottom and top are poorly defined. Unit 8 may just represent a pillowed layer between clastic Units 9 and 7. Paleomagnetic data suggest that this unit is not rotated with respect to the other portions of this layered complex (Bleil, Gee, pers. comm.)

Unit 8 is mainly brecciated at the top, where pillows and breccias form layers of ~1-2 m. They become more frequent downwards and form a 90 m thick solid layer of with only minor amounts of clastic rocks. The top breccia is very poorly sorted and consists of 60% angular lapilli, 30% blocks and 10% fine grained matrix. Abundant zeolites are formed in the high volume of voids between and within fragments. Pillows show regular shapes and vary from 20x30 cm to 60x80 cm in size. The inter pillow matrix is formed by poorly sorted, coarse clasts, mostly spalled off pillow margins. Some dikes occur in the lower portion of this unit.

Unit 9

Type: pillow fragment breccia, poorly exposed
Location: 170-175 m above s.l.
Thickness: 50 m
Samples: none
Subunits: none
Alteration: altered to smec/zeol.
Petrography: heterolithological/ cpx basalt

Outcrops of Unit 9 are extremely poor, altered and discontinuous. It is mainly made up of cpx-phyric pillow breccia. Pillows are observed in some outcrops others consist mainly of fine-grained, poorly-sorted heterolithological breccia with abundant holocrystalline fragments.

Unit 10

Type: Pillows with fine grained, inter pillow hyaloclastite and layered hyaloclastite at top
Location: 175-176 m above s.l.
Thickness: 22 m
Samples: 39-42, 84-87, 104, 149, 404, 427-431, 432.
Subunits: **(A)** Top hyaloclastite (2 m)
(B) Ultramafic Pillows (20 m)
Alteration: ol partially replaced by chrys, ant, analc and smec
Petrography: Picrite, < 32% euh. ol, <5% euhedr. cpx

Subunit (A): The top hyaloclastite is a wedge shaped unit, thinning out northward. It is exposed for ~10 m along strike and has a maximum thickness of ~3 m. The very top is poorly sorted containing abundant rock fragments of mainly lapilli-sized picritic basalt. The remainder is well sorted, bedded (~54/225), and occasionally crossbedded. The grain size varies from medium ash to coarse ash, with up to 10% fine lapilli (20% the uppermost portion). The hyaloclastite has the same phenocryst assemblage, but is generally less phyric than the pillows.

Subunit (B): The pillowed portions contain about 5% fine grained hyaloclastite matrix which is identical to the overlying hyaloclastite. It is mostly well bedded, the bedding being generally parallel to the bedding of the layered complex (e.g. 40/240). Because of the abundance of fine-grained, inter pillow matrix, pillows tend to have round or tubular cross sections, even though the shape of pillows is sometimes difficult to recognize because of the intense serpentinization of the ol-phenocrysts. Pillow sizes vary from 20x30 cm to 30x40 cm at the top of the unit and from 30x40 cm to 50x80 cm at the base. Even though there are some smaller pillows at the base of Unit 10, the average pillow size clearly increases towards the base. The glassy margins are 3-4 mm thick and are altered to dense, green smectite. These glassy rims contain significantly less and smaller phenocrysts than the interior of the pillows. This outer glassy band shows a sharp transition to a 15 mm wide layer of closely packed olivine phenocrysts which become less densely packed towards the interior of the pillow. This glassy band seems to melt together at pillow contacts. Individual pillows can be recognized most easily in the partially serpentinized masses by following the glassy bands. The inner portions usually do not show variation in grain size or vesicle content. Unit 10 is cut by a dike of varying thickness with abundant dunite nodules. This dike has an irregular orientation (88/245, 82/214, 90/250, 90/260, 73/250) and it is the most altered of t-he nodule-bearing dikes in the basal complex (this dike was previously described by Hernandez-Pacheco, 1975).

Unit 10 can be followed for about 1 km on the N slope of the Barranco de Las Angustias. This correlation is in the direction 48/230 confirming that this unit was emplaced on an originally horizontal plane.

Unit 11

Type: pillows with minor amounts of fine grained inter pillow hyaloclastite; frequent dikes at the base
Location: 176-181 m above s.l.
Thickness: 85 m
Samples: 44, 82, 105-107, 234, 403, 433-435, 438-440
Subunits: none

Alteration: anal, cc, smec in vesicles and veins.
Petrography: aph, <1% cpx, some pl microphen. soph/int grdm

Unit 11 is an aphyric to slightly cpx-phyric pillow unit with minor amounts of fine-grained pillow matrix; it is conformably overlain by the ultramafic pillows of Unit 10. The base is formed by some massive flows with a top and basal breccia. These flows are overlying the very smooth planar surface of Unit 12. In its middle section, Unit 11 is cut by a 3-4 m wide breccia filled fissure. The pillows form two opposing cliffs near the seismic station Taburiente, which is built within this pillow unit. Upslope correlation of Unit 11 is difficult because of poor outcrops.

The 5-10% fine-grained inter-pillow matrix, in the top 10 m of this unit, is crudely bedded and well sorted. It often has some fine laminar bands of very fine grained material (mainly dust fraction material). Some pillow interstices are only half-filled. During pillow emplacement the bedding of the soft sediment was bent up indicating, that pillows sink in this soft hyaloclastite matrix. The pillow margin in contact with this hyaloclastite stays coherent in the sand sized matrix, but it spalls off and forms cm size protrusions in the upper finer grained portion. The uppermost portion of the inter pillow space without hyaloclastite, is filled with very poorly sorted fine lapilli which spalled off the pillow margins during emplacement of the pillows. This fraction of the inter pillow material lacks fine grained matrix; voids are filled with secondary phases.

Pillow shapes and sizes vary systematically with depth in Unit 11: at the top, thin pillow tubes of ~20-40 cm diameter are frequent, while some 100 cm pillows are present, with depth, the pillow size increases to 40-50 cm (the smallest pillows at the bottom of this unit are ~35 cm). In the lower half of the unit, pillows become much larger and irregular (most are about 100 cm diameter with some as large as ~500x200 cm). Pillows with diameters <50 cm are rare or absent. The pillows are normal in the upper portion and become bulky and sometimes irregular in shape at the bottom. Some Pillows on the South slope show well developed Elephant-Hide surface structures similar to pillows on Hawaii and the ocean floor (Moore, 1965). The base of Unit 11, exposed east of the seismic station, is formed by massive flows, with variable thickness (50-120 cm) and brecciated tops and bottoms. Flows can be traced approximately 20 m along strike. The surface of this flow does not have a well-defined glassy margin but rather the top portion is relatively smooth and the base looks scoriaceous and is very irregular. The flow has a uniform massive appearance with some banding and some vesicle-rich zones. In the thin zones of the flow the vesicles coalesce to very irregular 1-2 mm thick, 10cm long cavities, parallel to the direction of flow. The vesicles and cavities are usually empty but some are filled with secondary minerals. The breccia forms a 20-50 cm thick layer at the top and base of this massive flow and is very poorly sorted with fine grained matrix <10%. It consists of some large clasts, possibly interconnected and some individual broken clasts. Similar to the massive flow, the interconnected or broken clasts do not have a well defined, dense, glassy margin and look scoriaceous.

West of the seismic station, within the South cliff, there is a 6 m wide breccia zone. The breccia zone is oriented ~50/100 (±10°/±5°) and 86° to the bedding of the complex (c.f. Figure 28). This oblique breccia zone can be correlated with a breccia on the other side of the Barranco at the south cliff, and reaches at least 15 m deep into Unit 10 and is at least 40 m long. This breccia zone is concordantly overlain by pillows. The pillows at the margin of this breccia zone are often partially brecciated but still form coherent pillows. The dominant direction of fractures in pillows is 40/075, roughly parallel to the strike of the big fracture. The breccia is monolithologic and it consists of angular clasts, mainly of lapilli and block size (1:1), with fine grained material (< lapilli) <10%. In the center of this breccia zone there is a large flow with brecciated rims and columnar-jointed interiors. This breccia zone therefore is a fissure, which opened during eruption of Unit 11. It was filled with breccia and a lateral flow and then covered with pillows of Unit 11.

Numerous intrusions, into pillows, inter-pillow spaces, and emptied pillow interiors, are exposed along the course of the Barranco in the lower 2/3 of Unit 11. In the upper portion, 30% of these intrusions follow along the pillow margins and intrude into hollow pillows. In the lower 1/3 they chiefly cut discordantly through pillows. Orientations of these dikes are very irregular, but they are in the same range as the fissure: 58/170, 80/135, 50/100. Some of these dikes were traced into pillows. Pockets of massive hematite (compare analysis LP 44-1) were found along dike margins in some pillows and pillow interstices.

All basalts (feeder dikes and pillows) in Unit 11 (feeder dikes and pillows) are made up of aphyric pillow basalts with slightly cpx phyric varieties (<1% subh cpx) occurring near the top. The groundmass is subophitic-intersertal. Vesicles and veins are filled with cc, smec, n/th, op; interstitial microcrystalline groundmass is replaced by smec, cc, n/t.

Unit 12

Type:	Amoeboidal Pillow tuff breccia and Pillow-rind breccia
Location:	181-210 m above s.l.
Thickness:	360 m
Samples:	83, 108-113(D,TS), 151-160,235, 358,362365, 409, 410, 436-437, 442-444, 495-508
Subunits:	Sections 1-6
Alteration:	glass, olivine completely altered, some fresh(?) glass in sections 5 and 6.
Petrography:	Cpx-ol (pl) basalt (often ankaramitic)

Unit 12 consists of monolithological amoeboid pillow(-tuff) breccias and pillow-rind breccias; it is crudely bedded and can be subdivided in 5-15 m thick cycles. These cycles are reflected in sections of lava flow units or clastic units. Lava flow units occur in many different types ranging from closely packed pillow lavas to sheet flows of irregular amoeboid lavas, or clastic layers with frequent individual lava sacks or pillows. Clastic units are generally crudely bedded and poorly sorted. These breccias show significant variability with respect to the grain size distribution and to the character of clasts >medium lapilli in size. In the following description flow units and breccia units are described independently.

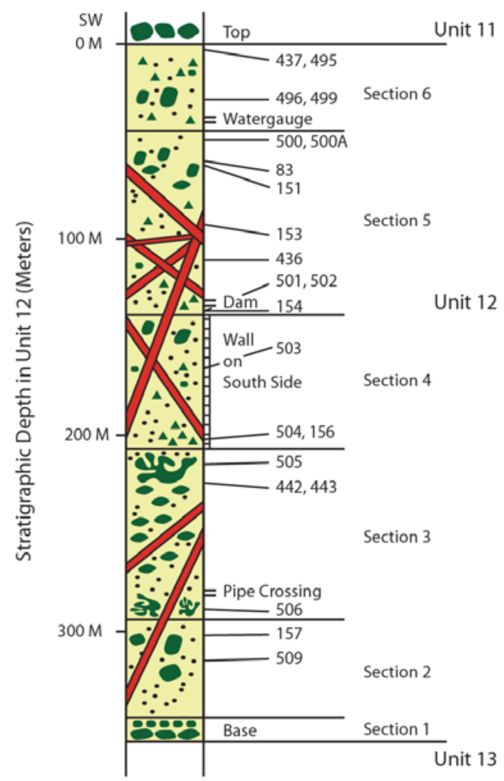

Figure 9. *Unit 12 in the La Palma Seamount Series.*

I. Lava Flow Units

(A) *Closely packed tubular lava with minor protrusions*

The base of Unit 12 (Section 1) is formed by normal pillow lava which forms a lenticular layer of 5-15 m thickness which extend for several hundred of meters along strike. It has a flat, originally horizontal base (50/220), overlying the fine grained hyaloclastite from the top of Unit 13. Pillows in this unit are tube-shaped with average tube diameters of ~35 cm, varying from approximately 25x35 to 60x120 cm. Pillows usually have nearly round cross sections with their bases molded around the underlying rock. Fine grained matrix is absent; pillow interstices are filled with secondary materials and spalled off, dense glass shards of up to 3x20 mm. The pillows have relatively dense glassy margins: partially spalled off, dark green altered glass (5-10 mm) grades into a yellow transition zone (5 mm) and a reddish-brown variolitic zone (8 mm). Within this zone, intense vesiculation is observed, the highest vesicle contents being about 10 cm from the margin. The biggest vesicles can be found in the center o£ these pillows (3-25 mm in diameter). Large pipe vesicles with cross sections of up to 5 mm and up to 7 cm length were observed to extend from the bottom to the center of individual pillows, sometimes with distances of less than 2 cm between individual pipes. These pipe vesicles often represent melt-filled segregation vesicles (Smith 1967).

(B) *Loosely packed tubular lava with abundant protrusions*

Those lavas which occur in Sections 2 and 3 are made up from 35-80 cm tubes with frequent protrusions. Protrusions have very variable shapes: They range from irregular surfaces with wavy protrusions of ~10 cm amplitude and 10-20 cm wavelengths to toes of 10-40 cm length with a blunt, 5-10 cm wide end and frequently thinner necks. Protrusions can also have mushroom shapes, with stems up to 20 cm and heads of 10-20 cm width, or lie flat on the pillow surface (e.g. 20 cm width and no more than 5 cm height). These lavas display glassy margins similar to normal pillows. Vesicles are usually enriched in the center of such pillows or in big protrusions. These pillows are richer in quenched material than normal tubular lavas. The matrix between the pillows is commonly very poorly sorted, the biggest clasts (bombs) possibly representing sections through interconnected or broken off protrusions. Coarse lapilli and most of the medium lapilli represent broken off fragments of those protrusions or spalled off glassy margins. The finer grained material (<20%) consists mainly of fine vesicular lapilli, with only minor ash. Lavas with protrusions occur mainly in the top portion of section 2 and base of Unit 3.

(C) *"Amoeboidal Lavas"*

Protrusions can become very delicate and comprise a significantly higher total volume than the central body. Those lavas were called amoeboid lavas previously (Dimroth et al., 1978). Such amoeboid lavas have a body consisting mainly of irregular wavy arms of 4-10 cm diameter and up to 150 cm length. Cross sections of individual amoeboid lava bodies cover 30x60 to 80x200 cm. The arms of such amoeboid lavas are either irregularly oriented, pointing upward or are aligned parallel to the bedding. Sometimes the arms are interconnected with arms of neighboring amoeboidal lavas forming irregular lava sheets of 200-300 cm thickness and large lateral extent. The amoeboid lavas occur in a stratigraphic position similar to the tubular lavas with protrusions. They form distinct beds and they occur to higher stratigraphic levels (top of Section 3). Amoeboid lavas mainly consist of very fine grained-glassy basalt, which is usually less vesicular than the lavas with protrusions. However, the poorly sorted matrix between the amoeboid lavas is very vesicular (40-70%). The matrix is finer grained than the matrix of the lavas with protrusions. However, the matrix between both types does not contain significant amounts of material < fine lapilli. Voids are usually filled with analcite or smectite.

These lava flow units **(A)** through **(C)** occur only in Sections 1-3; higher up in this sections these are replaced by layers enriched in large isolated primary volcanic fragments (such as pillows or lava sacks).

This distinct variation in style of lava flow units indicates different depositional mechanisms. While the bottom layer of closely packed pillows was deposited in a quiet, effusive style, the upper, more irregular lavas suggest a different type of flow. These lavas must have been emplaced as subaqueous flows, since they are always concordant to neighboring layers. A shallow or deep intrusion or flow under an insulating blanket would probably yield in occasional discordant intrusions or perturbations of the neighboring units which were not observed. These often very fragile flows must have been deposited by magmatic processes and cannot be emplaced or redeposited by sedimentary processes, since they would break very easily. However, the flow units higher up in Unit 12 are replaced by clastic units enriched in primary volcanic clasts higher up in Unit 12, which can be deposited by sedimentary processes. This was shown for one lava sack in the upper portion of Section 5 which showed NRM directions different from the rest of the complex (Bleil, pers. comm.).

II. Breccia Units

Fragments < coarse lapilli are uniform throughout this unit, but there are distinct differences between types of bomb/block sized clasts which makes distinction between these two groups possible.

(A) *Bomb-sized fragments in primary breccias*

Lava-Sacks are 30-150 cm in diameter. They commonly form spherical to ovoid bodies with internal structures identical to pillows. Some lava sacks have loosely attached, concentrically-arranged multiple quenched margins. Some Lava sacks have up to five concentric layers of glassy margins, each separated from the other by some dark green altered hyaloclastite in an extremely vesicular zone underneath the corresponding glassy margin. Lava sacks with coherent, concentric glassy margins are extremely rare. Usually they have only one glassy margin and the separated margins can be found in the adjacent matrix, completely disconnected from the pillow. Such spalled off complete pillow rinds are an extremely important fragment type in the upper portion of this unit and the abundance of one-side quenched pillow rinds in these breccias stresses the importance of this primary volcanic brecciation mechanism. Lava sacks form up to 40% of 2-4 m thick layers in Sections 4-6. The matrix of such lava sack-rich zones is similar to the other brecciated units, and consists of very poorly sorted breccias.

Amoeboid lava bodies, disconnected from a lava flow occur either as complete, irregular bodies of 20-150 m diameter or as broken clasts. They occur in sections 2-6 in individual 50-250 cm thick layers. With a poorly sorted clastic matrix. They usually have irregular nearly equidimensional shapes with stubby, short protrusions; amoeboids with unbroken, long, delicate protrusions are rare and are restricted to distinct layers, commonly with a fine grained clastic matrix. The breccia overlying the basal closely packed pillow lavas (Section 1) consists almost entirely (60-80%) of broken amoeboidal clasts or ~3-15 cm size. Usually however, the breccias contain less than 40% such clasts and the remainder of the breccia consists of a poorly sorted matrix.

Breccias with amoeboid lavas in the upper part of Unit 12 often contain ribbon or spindle bombs, 5-10 cm thick and up to 40 cm long. They resemble subaerial spindle bombs; they are very vesicular (> 50%), often oxidized to a reddish color, and typically have ellipsoidal shapes-drawn out edges (sometimes pointing up) and a thickening belly. Ribbon bombs occur only in the upper portion of Unit 12 and are most frequent in Section 5. The occurrence of those oxidized spindle bombs may indicate development of a subaquatic/subaerial eruption column at a shallow eruption depth of this seamount.

(B) *Block sized pillow fragments in clastic breccias*

Clastic fragments represent segments of pillows or lava sacks, characterized by curved glassy margins or vesicle rich zones. Their gray color is obvious, making them very easily recognizable in the greenish brown alteration colors of the remainder of this unit. Only two minor occurrences of breccias dominated by such clastic fragments were found at the top and the base of Section 4. They form lenticular/wedge shaped layers consisting of ~40% clastic blocks and coarse lapilli and of ~60% poorly sorted fine grained matrix.

(C) *Lapilli sized fragments*

Coarse lapilli sized fragments (most of the medium lapilli fragments) are usually of the same type of clasts as the bomb sized fragments characteristic of the particular unit. The rest of the medium lapilli and the fine lapilli are made up of green altered glass fragments with very abundant fine vesicles (40-70%). Finer grained material (dust and ash) usually comprises about 10% of the bulk rock, higher in the section it becomes more abundant (~20% at the top of Unit 12, the top most layer consists almost entirely of ash and dust fragments).

Grain size distribution: Individual layers are always very poorly sorted, i.e. they contain clasts of all grain sizes from blocks and bombs to ash. However the shifts in the relative proportions of grain sizes make an individual unit appear fine grained or coarse grained. The visually most obvious shifts are in the sizes and proportion of bombs/blocks and in the relative proportions of medium to coarse lapilli: a typical coarse grained layer contains up to 30% coarse bombs or blocks (up to ~50 cm size) and the matrix is dominated by coarse lapilli comprising 30-50% of the breccia; the remainder of such a unit is made up mainly of medium lapilli and finer-grained material. A fine grained layer would contain ~20% of relatively small bombs or blocks (~20 cm) and the matrix would contain 30-50% lapilli (10-20% coarse, 20-30% medium lapilli and 20% fine lapilli and ash). Finer grained layers are usually thinner than coarse-grained layers (30-120 cm vs. 50-200 cm). Coarse layers are sometimes reversely graded with a grain supported top which is often covered by a 1-2 cm wide band of fine grained material on their top. This fine grained band follows the often irregular surface of those coarse grained layers with approximately constant thickness.

There is a variation in clastic rock types which parallels the variation in flow unit type. The average grain size of clasts decreases towards the top of Unit 12 and therefore, finer grained, glassier material becoming more abundant. This indicates that the proportion of explosive material increases towards the top (in a pyroclastic succession this does not necessarily imply that the explosive phase was later, it can happen that the lower strata are deposited from a lower portion of a collapsing or stationary eruption column). Spindle bombs in the upper portion also indicate deposition of more explosive material in the top possibly, from a subaqueous/subaerial eruption column. The broken pillow breccias in the middle section of Unit 12 indicate clastic depositional/brecciation mechanism in this section.

The top and base of Unit 12 in the profile along the Barranco de Las Angustias show originally horizontal orientations, parallel to the general bedding of this complex (top: 45/225, 45/238, 45/228; base: 55/ 232, 58/239, 45/222, 58/235, 54/235, 50/232). The correlation of this unit is generally very difficult, since this type of mainly fine grained pillow breccia is very easily eroded and outcrops of the intensely altered upper slopes of the Barranco de Las Angustias are biased towards the more alteration resistant pillows and dikes. However, the rock type correlates quite well, confirming the basically horizontal tabular shape of this unit. This seems to indicate, that this unit was deposited on a plateau on the La Palma seamount and that its eruption did not result in a hill.

Unit 12 is made up completely from cpx/ol basalt with occasional plagioclase microlites. It contains up to 15% cpx phenocrysts (euhedral, <5 mm) and up to 10% ol phenocrysts (euhedral-subhedral, <4 mm). The groundmass is mostly tachylitic-intersertal and contains up to 10% plagioclase microlites. Glass is mostly altered to brown or green smectite; some fresh glass (?) may be preserved in Section 5. Olivine is altered, but it is partially preserved in ol-rich pillows in Section 5. The closely packed pillow lavas at the base of Unit 12 (LP 113) are composed of aphyric basalt with intersertal groundmass and abundant segregation vesicles.

Unit 13

Type: allochtonous lapilli breccias and pillow fragment breccias
Location: 210-220 m above s.l.
Thickness: 250 m
Samples: 88, 89, 446-449, 509--511
Subunits: none
Alteration: very altered, chl, ab, zeol, sph
Petrography: pl phyric and aphyric basalt clasts in aphyric tachylite breccia.

Unit 13 is layered and conformably overlies Unit 14 exposed in a cliff (10 m above and South of the Barranco bed), in the Barranco outcrops however, Unit 14 forms a hill and in this region clasts of Unit 13 and lavas of Unit 14 are mixed. This indicates that Unit 13 and Unit 14 were deposited in rapid succession.

The lowermost 10 m of this unit on the South cliff are made from a coarse grained, layered pillow breccia. Its lower 2m consists of 50% blocks (< 20 cm), within 10 m this increases to about 70% grain supported blocks up to 40 cm in size. Most of these, often slightly rounded blocks, can be recognized as pillow fragments (rare curved glassy margins and curved vesicle-rich zones). The fine-grained matrix between those clasts is poor]y sorted (~60%, coarse and medium lapilli, ~40% fine lapilli and ash).

Towards the top of Unit 13 the proportion of fine layers increases (thicknesses vary from 50-200 cm), which are generally poorly sorted and the grain sizes vary significantly. A typical fine grained layer may contain 5% blocks <20 cm, 10% coarse lapilli, 35% medium lapilli, and 50% finer grained material. Coarse grained layers are thinner (30-80 cm), very heterogeneous in composition and grain size, and often reversely graded. Such a coarse grained layer may consist of ~30% blocks (increasing to 70% at the top of some reversely graded units) up to ~30 cm in size, and 70% finer material mostly consisting of coarse lapilli, the medium/fine lapilli and ash matrix comprises less than 30% of the matrix. Towards the top of Unit 13 the average grain size decreases; coarse grained layers are replaced by individual blocks, usually occurring in 'layers' (< 5% in a given layer). The top of Unit 13 is made up from a relatively well bedded fine grained lapilli stone and fine-grained hyaloclastite, forming a largely horizontal top (for orientations see Unit 12). Blocks, coarse lapilli and significant portions of the medium lapilli fraction are made up from of pillow fragments. They are usually angular, but the edges are often rounded. They consist mostly of pl phyric basalt, but aphyric and slightly cpx phyric types are observed too. Finer-grained particles are usually angular and consist of very fine-grained basalt or sideromelane. Vesicle contents are usually high (< 40-80%).

Occurrences of often rounded, heterolithological clastic fragments indicates a clastic component involved in the formation of this breccia. Poor bedding, sorting and reverse grading shows that these breccias were probably deposited in a turbulent flow such as a landslide or a debris flow. This deposit is therefore considered to be a seamount flank or apron deposit rather than a deposit on top of a seamount. The flat top of this unit indicates that the breccia left a smooth topography behind, rather than creating steep slopes, and thus was formed near the bottom of a slope.

The main type of clasts are aphyric basalt with subophitic/intersertal groundmass texture, pl microlites and ~30% ves <l mm (LP 446), and pl/cpx phyric basalt. The latter is characterized by up to 5% euh; pl glomerocrysts (<3 mm) with typically rounded sector zoned Ti augites (<3 mm) in an intersertal groundmass. Vesicles are generally filled with smec, cc, and zeol (LP 447,449). The finer grained matrix of this hyaloclastite consists mainly of aphyric tachylite and glass shards mostly replaced by analc (LP 448).

Unit 14

Type: pillow lavas with some big flows
Location: 220-230 m above s.l.
Thickness: 80 m
Samples: 114
Subunits: none
Alteration: chl, cc, smec, Zeol
Petrography: pl basalt

The top of Unit 14 is complex, whereby 10 m above the Barranco (on the South face) it is formed by pillow basalt and in the Barranco bottom it forms a complex zone of intermingling of pillows from Unit 14 with clasts of the overlying breccia Unit 13.

The lower half of this unit consists of "normal" tubular pillow basalts with 30-80 cm, round/oval cross sections and some irregular, large pillows up to 150x150 cm. The pillows are usually massive, with poorly developed radial cracks and showing a slight increase in size and volume of vesicles towards the center. Inter pillow spaces are void or filled with zeolites or spalled off pillow margins (~0.5-2 cm size particles). Some pillows show partially spalled off, complete, multiply-quenched margins.

The upper half of Unit 14 can be subdivided in two parts: a lower, irregularly pillowed unit and an upper transition zone between Units 13 and 14. Both zones are cut by abundant dikes. The irregularly pillowed section consists of mega-pillows up to 300-400 cm diameter with abundant protrusions. Some of these pillow; originate from several individual pillows (tubular with protrusions) which were welded. Other big pillows include clasts from the overlying breccia. In those cases, quench zones are developed against the clasts. The upper transition zone extends stratigraphically higher than expected from the horizontal course of the 13/14 boundary on the South cliff 10m above the Barranco bottom. The slope of this hill is this hill is ~30°. This section consists of ~30% primary magmatic clasts (completely surrounded by glassy margins) from Unit 14, and ~50% angular, 5-20 cm big fragments of Unit 13. The matrix consists to 25% of lapilli and 5% ash.

Unit 14 is made up of plagioclase glomerophyric basalt with ~15% euhedral plagioclase phenocrysts <1.5 mm. Its groundmass has an intersertal/subophitic textures and it contains ~5% <2 mm big vesicles. These are filled with smectite, carbonate, chlorite, zeolites and sphene, the fine grained groundmass is mainly replaced by smectite.

<u>Unit 15</u>

Type:	wedge shaped pillow basalt with fine grained, clastic top (lapilli breccias)
Location:	230-232 m above s.l.
Thickness:	28 m
Samples:	115, 162, 163, 535-542
Subunits:	**(A)** basal pillows
	(B) top hyaloclastite
Alteration:	chl, cc, smec, sph
Petrography:	cpx, pl basalt

Unit 15 has a pillowed base of ~15 m overlying the flat top of the pillow breccia of Unit 16 (48/222) and grades into a hyaloclastite layer with a laminated horizontal top. The pillows of Unit 15 thin out on the North slope, while they can be traced to higher elevations on the south slope. The horizontal base is exposed for more than 300 m on the both slopes. Unit 15 is made up from nearly aphyric basalt.

The pillows are typical, closely packed tubular lava flows with round/oval cross sections varying from 30-120 cm in diameter. Pillows develop regular quenched margins with relatively dense inner portions, with poorly developed cracks. Pillows often develop radial pipe vesicles; in some pillows flat based central cavities were observed, with their bases approximately parallel to the bedding. Near the base of Unit 15, some 250x500 cm, flat-topped ponded feeder pillows occur. They have many sidearms interfingering with neighboring normal pillows, and are similar to some ponded lava flows in the lower portion of Unit 6. On top of the big feeder pillows and in some central cavities of individual pillows some partially spalled-off quenched pillow rinds form a brecciated top layer. Otherwise there is no inter-pillow breccia.

The clastic unit on top of the pillow lavas has several facies. The lowermost layer is developed only on the South side of the Barranco and occurs in a finer-grained variety between the uppermost pillows on the North slope. It consists of a monolithological pillow breccia with 60% angular pillow fragments, < 25 cm, in a matrix of mainly medium lapilli. Towards the top fine grained and coarse grained layers alternate, with the grain sizes decreasing towards the top. The top is made up from 8 m of well layered hyaloclastite (52/224, mainly medium ash sized particles), which is sometimes interlaminated with some fine ash/dust layers.

Figure 10. *Pillow with central, flat-bottomed cavity giving an indication of paleo-horizontal (Unit 16, Location 3).*

The pillow basalt is made up from cpx, pl phyric basalt (~2% cpx, <0.1 mm, euh; ~1%pl <0.1 mm, euh, altered) with ~5% vesicles (<2 mm). The subophitic-intersertal groundmass is altered to cc, smec, and sphene. vesicles are filled with smec, chl, ab, zeol and pump.

Unit 16

Type:	multi-lithological pillow breccia
Location:	232-238 m above s.l.
Thickness:	110 m
Samples:	164-168, 237, 405-408, 452-462, ~94, 543, 546-552
Subunits:	none
Alteration:	Vesicles filled with cc, chl, ab, smec, zeol, pump. Grdm repl. by smec, ep, chl,
Petrography:	mostly cpx phyric basalt (also aphyric clasts)

Unit 16 is a heterolithological pillow breccia sandwiched between two pillowed units. Its top is planar and dips consistently with the remaining complex (48/222, 48/220).

The lowermost 5m of this unit grades from a fine grained base (40 cm e.g. LP 405,406) through a lapilli dominated layer (40 cm e.g. LP 408) and to an extremely coarse-grained breccia. It is made up of well-sorted, fine grained layered hyaloclastites (mainly ash sized with ~25% fine/middle lapilli) overlying the pillows of Unit 17. The next layer (~40 cm) includes about 50% angular blocks, mainly pillow fragments <25 cm with a matrix of lapilli-sized clasts. A 4 m thick layer with ~50% large blocks (up to 50-60 cm) was deposited next. These blocks are very angular and consist mainly of aphyric basalt and, to a lesser extent, cpx-phyric basalt (pyroxene occurs often as black smectite pseudomorphs with cpx morphology and cleavage, but some fresh cpx preserved as well). The matrix is made up from very vesicular coarse basaltic lapilli while the smaller fraction makes up less than 20% and consists mainly of vesicular, green glass.

The remainder of Unit 16 consists of 50-70% block sized pillow fragments of different petrographic rock types (mainly of cpx phyr basalt, similar to that which underlies Unit 17, but also some nearly aphyric or slightly pl phyr basalts) and of a fine grained pl basalt matrix. Most of this matrix material is made from coarse lapilli, finer grained material usually being less than 5%. Relative proportions of grain size fractions vary on the scale of several meters, coarse grained layers are frequently reversely graded at the top. Towards the top, some very well-sorted coarse-grained layers occur: they consist of 70-80% blocks (<20 cm), which are nearly isometric and often have slightly rounded edges. Therefore, the character of this breccia becomes more mature towards the top; sorting becomes better, layering more pronounced, clasts become more isometric and more rounded.

The breccia consists of clasts (> medium lapilli) of various lithologies and of a fine grained matrix consisting of pl/cpx basalt. The matrix material includes ~5% subh pl phenocrysts (< 0.5 mm) and ~2% subh cpx pl phenocrysts (<0.5mm). The matrix is otherwise composed completely of sideromelane with 5-10%, 2 mm vesicles. Secondary phases are ab, smec and cc. Clasts are mainly of cpx basalt of a similar type as Unit 17 basalts. This type has 5-10% euh-subh, often sector zoned Ti augites of l mm in an oph/soph/int groundmass with opaques. These basalts have 5-15% vesicles of 1-3 mm diameter filled with smec, chl, cc, pump and ab. The fine grained groundmass is altered primarily to smec. Other clasts include ~1% of anh pl phenocrysts (<l mm) and <5% Ti-augites. Others are nearly aphyric with 1-2% of cpx microlites. The alteration assemblage is the same in all rock types.

<u>Unit 17</u>

Type:	pillow basalt with some massive flows and some breccias
Location:	238-275 m above s.l.
Thickness:	480 m (dike volume subtracted: 360 m)
Samples:	65-67, 116-121, 169-172, 216, 286-291, 399, 40Q, 457-459, 544, 545
Subunits:	**(A)** upper portion from top to some massive flows at ~245m above s.l.
	(B) lower portion from breccia at ~247m above s.l. to base
Alteration:	pl replaced by ab, in groundmass and ve
Petrography:	Cpx basalt at top, aphyric mugearite in lower portion

Units 17-22 are distinctly different from Units 1-16, which represent the mainly clastic upper portion of the La Palma seamount. Units 17-22 consist mainly of lava flow units and are probably structurally similar to abyssal hills which originate at mid ocean ridges (e.g. DSDP site 417A) or near-ridge seamounts. Two Subunits may be distinguished: the upper portion, reaching from the top of Unit 17 to some massive flows in the middle section at ~445 m above s.l. and the lower portion, possibly brecciated on the top, forming the lower half of this unit. Both subunits consist predominantly of closely packed tubular pillow lavas with minor amounts (<5%) of fine grained hyaloclastite in the upper portions. Pillow lavas at the top of the upper portion are tubular with diameters varying from 20-40 cm; farther down, some extremely flat, sheet like pillows were found, and at the bottom several massive flows of 150-800 cm thickness and at least 4-12 m lateral width were observed. The lower section is also made from tubular pillow lavas with tube diameters varying from 30-80 cm. A partially drained pillow in the lower portion of Unit 17 developed a very well defined planar lava surface of 40/225. Near the base of Unit 17 some amoeboidal pillows developed. While the pillows generally develop cooling textures similar to most other pillows in the layered complex, the massive flows at the bottom of the upper section show a very distinct textural variation. The top glassy margin changes more rapidly into a coarser-grained texture than in the case of normal pillows. This texture becomes continuously coarser grained reaching a maximum grain size about one third from the bottom. The transition of the very coarse grained doleritic interior texture, to the quenched bottom facies occurs within approximately 10 cm from the base, indicating an asymmetric cooling of these units. Most massive flows are more vesicular in the top portion, while some segregation pipe vesicles (~3 mm diameter) or vesicle trains occur at the bottom. This textural variation is very similar to textures found in massive flows in various DSDP basement holes (e.g. a 37 m thick flow in Site 418A, see also Kirkpatrick & Hodges 1978).

At the border between the two subunits, a dunite nodule bearing dike is exposed in the Barranco bed (this location is also mentioned in Hernandez-Pacheco, 1975). This nodule dike increases to extreme thicknesses (>5 m) on the north slope, about 50 m up from the Barranco bottom, and it may be correlated with another nodule dike in the next side valley, north of this location.

Petrography and texture change drastically within and between the upper and the lower portion. The upper portion (LP 118) consists of basalt with 2-5% euh/subh, often sector zoned Ti-augites. The groundmass changes from mainly intersertal/tachylitic at the top 100m to intersertal/subhedral further down in the upper portion. The massive flows at the bottom of this subunit have a doleritic texture with anhedral Ti-augites minor amounts of opaques and apatite, and very few vesicles. The secondary minerals in the upper portion of this subunit are: cc, smec, sph, chl and zeol in vesicles and veins and smec, op and sph in the groundmass. The massive flows contain ep, ab, chl, pump, preh, cc and op.

The lower portion of Unit 17 lacks cpx phenocrysts and even the groundmass contains very little cpx. These basalts are pl phyric (1-2%; 1-3 mm, euhedral) mugearite with increasing abundance of pl phenocrysts towards the base. The groundmass is intersertal subophitic, mainly consisting of plagioclase, various amounts of tachylite and occasional apatite needles. The secondary phases are distinctly different and better crystallized than in the upper portion of Unit 17: ep, chl, pump, cc, and minor zeol, sph in vesicles, the groundmass contains ep, op, sph.

Diagnostic foraminifera from the upper portion of Unit 16 are Globorotalia Crassaformis (0-4 Ma) and Globoquadrina Altispira (2.8-19 Ma).

Unit 18

Type:	monolithological pillow breccia
Location:	275-277 m above s.l.
Thickness:	30 m
Samples:	64, 173-176, 2~2
Subunits:	none
Alteration:	ep, cc, ab, chl, zeol in vugs and varioles, fs replaced by ab
Petrography:	pl basalt

In Unit 18 pillow lavas grade upward into a monolithological pillow breccia. The basal portion of this unit is made from tubular, closely packed pillow lavas with round-oval cross sections of 30-55 cm diameter. The pillows develop normally quenched margins with rare amoeboidal protrusions. These pillows are concordantly overlain by a grain-supported coarse grained breccia (~80% bombs/blocks <50 cm; 10% coarse lapilli; 10% < coarse lapilli). The coarsest fraction consists mainly of 40-50 cm complete lava sacks, irregular pillows, and small amounts of fragmented pillows. Above this, in a 2 m thick layer on top of this zone primary magmatic clasts (pillows, lava sacks) decrease significantly in abundance, and the fine fraction (<coarse lapilli) increases to ~30%. This trend of decreasing grain size continues until another coarse grained layer appears (with ~60% blocks, 20% coarse lapilli, 20% <coarse lapilli). This layer contains mainly broken clasts of pillows and very dense, almost glassy lapilli. Above this, the block sized fraction decreases to about 10%, consisting mainly of isometric clasts of amoeboid pillows and about 20% long shaped irregular pillows with protrusions. The lapilli fraction increases to about 50-70% consisting mainly of medium lapilli. The matrix between lapilli sized fragments is mostly filled with secondary minerals, the ash fraction comprises less than 5-10% of the bulk rock, and the dust fraction is absent. Some carbonate ooze was found on top of this breccia unit.

The monolithological character of this unit and the gradual change from pillows to pillow breccias indicates that the unit was formed in situ, and represents a primary volcanic pillow breccia. The rocks become increasingly glassy and finer grained toward the top of Unit 18 indicating that the intensity of quenching and shattering increases towards the top. The matrix of this breccia is very poorly sorted and the fine grained portion is very small, and the fraction finer than medium ash is missing. This means that the process of brecciation either yielded mainly coarse grained material, or the fine grained material was transported away by currents.

Near Unit 18, in the Barranco sediments, a several meter large boulder with partially brecciated pillows was observed. It is made up from the same petrographic rock type as Unit 18 and consists mainly of closely packed pillow lava. Many of these pillows show ruptured margins with nearly vertical mini faults with offsets of several centimeters. These offsets can be traced into the pillow interior for 5-15 cm and they heal in the interior of the pillow which was still in a plastic state when the mini-faults were formed. Therefore, a mechanical stress was imposed on pillows while they still had molten interiors. This mechanical stress can be generated when a rapidly built submarine hill becomes instable, during volcanic eruptions. This mechanism would possibly initiate a brecciation process yielding a pillow breccia like Unit 18.

Unit 18 consists solely of slightly pl phyric mugearitic basalt with ~1% euhedral/subhedral phenocrysts up to l mm length. This basalt is very vesicular (10-30% vesicles of <2 mm diameter) and its groundmass texture is intersertal-tachylitic. Veins, vugs and vesicles are filled with ep, cc, chl, ab, op, and minor amounts of sphene.

Unit 19

Type:	closely packed pillow lavas
Location:	277-287 m above s.l.
Thickness:	120 m (dike volume subtracted 48 m)
Samples:	63, 122-124, 177
Subunits:	none
Alteration	ep, chl, cc, ab, pyrite, in vesicles, replacing fs and groundmass.
Petrography:	mainly aphyric mugearitic basalt with occasional pl phenocrysts.

Figure 11. *Tectonic breccia exposed as an allochtonous block in Barranco de Las Angustias (Location 6). Note that major units remain in place while being quite fragmented.*

Unit 19 is made up from closely packed lava tubes. Its top is identical with the basal pillows of Unit 18; the base is defined by some massive flows overlying a fine grained hyaloclastite.

The pillow tubes of Unit 19 are round-oval shaped with round tops, the bases molded around the underlying rocks, and the average tube diameter varying between 25 and 45 cm. At the bottom of Unit 19 there are some bigger flows with thicknesses up to several meters. Inter pillow hyaloclastite is less than 2%. The pillows show frequent concentric zonation of vesicle size and content. Vesicle-rich zones grade from outer portions with abundant vesicles to inner zones with fewer and smaller vesicles.

Unit 19 is made up from mugearitic basalt with variable pl phenocryst content. It is nearly aphyric at the top, contains ~5% euhedral pl phenocrysts (up to 2 mm) in the middle portion, and at the base of Unit 19 pl contents decrease to about 2% (<0.7 mm). The basalt has a subophitic groundmass consisting of pl, op and microcrystalline matrix with 5-10% vesicles up to 2 mm in size. Vesicles and veins are filled with ep, chl, ab, cc, pump and op, the groundmass is replaced by cc, ep and op.

Unit 20

Type:	fine grained hyaloclastite
Location:	287-288 m above s.l.
Thickness:	6 m
Samples:	57, 62, 411-414
Subunits:	none
Alteration:	ab, chl, ep, cc, zeol, sphene
Petrography:	sideromelane with some pl phenocrysts (ol psm)

Unit 20 is a lenticular shaped, well bedded (48/245, 48/245, 50/244) clastic unit. It reaches its maximum thickness (6 m) in the Barranco bottom. On the South side of the Barranco it is ~4 m thick and on the North slope it grades into a pillow breccia. This unit can be traced at least for 30 m along strike and it grades from fine grained to coarser grained varieties from south to north and from top to base.

Unit 20 is layered; individual layers are variable in thickness and in grain size, which ranges from very coarse (mainly coarse lapilli) to coarse layers (medium-fine lapilli) and fine layers (ash). Very coarse layers often form lenticular bodies, 40 cm to 1 m thick and several meters wide. They are usually reversely graded and their to consists of >50% grain supported coarse lapilli and blocks. The blocks mostly represent aphyric mugearitic pillow segments, coarse lapilli consist of crystalline basalt fragments or sideromelane, all finer material is made from basaltic glass. Very coarse layers are sometimes overlain by a band of l cm very fine material (< coarse ash). Coarse layers usually have constant thickness between 1-10 cm. They contain ~30% medium sized lapilli (rock fragments and dense, glassy basalt)~40% fine lapilli and 30 % ash (all glassy/ dense basalt). Fine grained layers have the same thickness as the coarse layers but they are made up of > 90% coarse ash.

The grain size in Unit 20 seems to generally decrease from the base to the top; the bottom half frequently contains some complete, irregular pillows. The base of Unit 20 overlies conformably Unit 21. Different types of layers do not alternate in a systematic fashion; they are generally well bedded, sometimes cross bedded. The finer grained layers are generally well sorted mostly with vesicular medium ash. The pillow basalt Unit 21 includes in its upper portion several lenses of similar hyaloclastite deposits (less than 1 m thickness).

Unit 21

Type:	pillow basalt, associated with occasional breccias or hyaloclastites
Location:	288-365 m
Thickness:	530 m; corr. 163 m
Samples:	29, 47-56, 125-138, 178-187, 196, 293-296, 464, 465, 466, 487, 488-493
Subunits:	**(A)** Top mugearite pillows
	(B) Recreation Canyon Pillows
	(C) Bottom Pillows
	(D) Basal Breccia
Alteration:	ep, chl, cc, grt, sph, ab, pyrite
Petrography:	mugearitic pl, amph (ol/psm) basalt

Unit 21 consists of mugearitic pillow basalts with occasional pillow breccias or hyaloclastites. It is frequently cut by dikes, the relative abundance of dikes to wall rock increases stratigraphically downwards from ~40 vol% (Section 1) to 50-80 vol% (Section 2), 80-90 vol% (Section 3) and 80-95 vol% (Section 4). Therefore, particularly in Subunits 4 and 5, basalts occur only as screens of ~2x4 m, and it becomes very difficult to judge field relationships. For this reason descriptions are less detailed and several different lithological rock types were included in this unit.

Subunit (A): The top mugearite extends from the top of Unit 21 at 288 m BAB to the crossing of the mule path leading to Dos Aguas. It consists of mugearitic pillow basalts with up to 10% fine grained inter pillow hyaloclastite at the top. The hyaloclastite forms lenticular beds of ~3x2 m between big pillows and is similar to the hyaloclastite of Unit 20. Pillows are tubular (30-60 cm diameter) or bulky (40-100 cm diameter). Pillows are formed from two distinct petrographic rock types: highly plagioclase phyric mugearites mainly on the north slope and less pl-phyric types on the south side of the Barranco. The less phyric types dominate in the barranco bed, the phyric type occurs only occasionally. The centers of pillows contain up to 40% vesicles and vugs; round vesicles are filled with epidote, big vugs are filled with big crystals of calcite and epidote. The groundmass of some pillow interiors is replaced by a fine grained mixture of epidote and calcite. In the upper portion of this section a 80 cm wide dunite nodule bearing dike is exposed: It consists of 20 cm wide, nodule free rims and the center portion contains about 50% rounded, nodules with 5-10 cm diameter (Hernandez-Pacheco 1975).

Subunit (B): The Recreation Canyon Series is composed of pillows with tube cross sections varying from 40x80 cm to bulky pillows of 100x200 cm. It does not have any significant amounts of fine grained hyaloclastite. The petrographic rock type changes within this subunit from the E end of the narrow canyon where the sparsely phyric mugearite is replaced by a highly pl-phyric type. Some big pillows also contain up to 5-10% amphibole phenocrysts.

Subunit (C): This subunit mainly consists of bulky pillows of highly pl phyric mugearite with occasional occurrence of round amphibole phenocrysts (same as in Subunit B). The top (i.e. the section west of the aqueduct) consists of a complex clastic unit. At its top the breccia is oxidized and the clasts of this "breccia" are incorporated in a mugearite matrix rock which shows quench contacts against these clasts. Further east from this (stratigraphically below), this breccia has a clastic matrix which is highly recrystallized. The breccia consists of 0-30% pillow segments, 0-50% amoeboidal pillows and 30-60% fine grained matrix (< coarse lapilli).

Subunit (D): The Basal Breccia is exposed only in a few big screens at the base of Unit 21. The biggest screen is approximately 4x4 m wide and consists of a basal fine grained layer and a top coarse grained layer. The bedding is parallel to the strike of the layered complex (~46/230). The coarse layer consists to 25% angular mainly mugearite and less keratophyre clasts (<40 cm). One clast of cpx basalt was found in this breccia. This is the only occurrence of cpx basalt deeper than Unit 17. The remainder of this breccia is made from 15% coarse mugearite lapilli, 30% medium lapilli and ~30% fine grained recrystallized matrix. The fine grained basal layer contains only a few blocks, ~20% coarse lapilli, 50% medium lapilli and 30% fine grained matrix. Big clasts have ~40% vesicles.

Unit 21 consists of plagioclase phyric mugearite with 2-10 % euhedral plagioclase phenocrysts <4 mm. The fine grained groundmass material consists mainly of plagioclase microlites, opaques, and fine grained matrix with 10-40% vesicles <4 mm. The fine grained groundmass material is replaced by chlorite, epidote, or albite, vesicles are filled with epidote, carbonate, chlorite, sphene, albite, chlorite, pumpellyite and garnet. Neighboring vesicles often have similar assemblages of secondary phases (often mono-mineralic). Sometimes whole pillow interiors are completely replaced by epidote, while the textures remain preserved.

The mapped boundary between the very pl-phyric and the less pl-phyric portions of Unit 21 is highly oblique to the course which would be expected from the generally very consistent bedding. The highly phyric portion represents a hill which is exposed to the north of the barranco and the less phyric mugearite forms a wedge shaped apron on the south slope of this hill.

Figure 12. *CO_2-rich mineral spring near Dos Aguas (Location 11). The spring has about a diameter of 5 cm and the surrounding area is characterized by iron oxide or iron hydroxide deposits that encase leaves from overhanging trees.*

Unit 22

Type:	keratophyre breccia
Location:	365 m above s.l. and in the lower course of the Barranco de Taburiente
Thickness:	no estimate possible
Samples:	15-25, 140, 141, 188-195, 197-199, 203, 222, 223
Subunits:	none
Alteration:	ab, ep, chl, grd completely albitized
Petrography:	trachytic fine grained matrix; with few fs (sanidine) phenocr. compl. repl.

Unit 22 is a keratophyre breccia and occurs as screens within the dike swarm which usually makes up >90 vol %. Individual screens rarely exceed a size of 2x2 m and are either completely made up from massive keratophyre or as breccia. Breccias dominate in the Bco de Las Angustias, massive screens frequently occur in the outcrops along the lower Barranco de Taburiente. The flow banding of the massive portions often resembles pillow like structures, but it never is possible to distinguish flow units. The brecciated portions dominate, they are often bedded (usually parallel to the general bedding). The fragments are usually angular, from block size to lapilli, which are the most frequent size. The clasts occasionally resemble pillow segments. The fine grained matrix is completely recrystallized and fragments < medium lapilli usually cannot be distinguished. The keratophyres are completely recrystallized and consist to ~95% of albite, the remainder is mostly epidote, but hydrogarnet, chlorite and amphibole occur as well. The ground mass often has a trachytic texture and some portions have big phenocrysts which may have originally been sanidines.

Notes, Abbreviations and Conventions Used

Measurements of Bedding Planes and Lineaments: Bedding measurements are given using the angle of dip (first two digits) and the direction of dip (last two digits). More than one data pair indicate several individual measurements of the same bedding plane unless otherwise noted. Lineaments are noted as a vector, giving orientation and direction (e.g. 30/110 S)

Grain sizes: Following Fisher and Schmincke (1984): blocks/bombs > 63 mm; lapilli 2 mm-63 mm (coarse 20-63 mm, medium 6.3-20 mm, fine 2-6.3 mm), ash: .063 mm-2 mm (coarse 0.63-2 mm, medium 0.02-.63, fine 0.63 - .02 mm), dust < 0.063 mm. The relative amounts of blocks, bombs, coarse and medium sized lapilli are usually visually integrated at a given outcrop. Relative amounts of ash fractions or dust are always estimated from thin section observation.

Rock Types: AB alkali basalt bas basalt, **D** dike **H** hetero- lithologic **HC** hyaloclastite **P** pillow, **Ker** Keratophyre, **M** monolithologic **MF** massive flow **Pbr** Pillow breccia **PM** pillow margin; **Petrography: ab** albite, **amph,** amphibole, **anal** analcite, **ant** antigorite, **ap** apatite **aph**, aphyric, **cc** carbonate **chab** chabasite **chl** chlorite **chrys** chrysotile **c px**clinopyroxene **ep** epidote **grt** garnet **ms** muscovite **natr** natrolite **n/t** natrolite/thomps. **ms** muscovite **natr** natrolite **ne** nepheline **n/t** natrolite/thomp. **ol**olivine **op** opaques **pl**plagioklase **pump** pumpellyite **preh** prehnite **PY** pyrite **san** sanidine **ser** sericite serpentine **smec** smectite **sph** sphene **tc** talcum **thom** thompsonite **zeol**zeolite **zir** zirkon, Parentheses indicate abundance < 1 vol% **Texture: allog** allotriomorph/gran **ang** angular **anh** anhedral **aph** aphyric **con** conchoidal **cr** compl. replaced**d** diameter/l **eu** euhedral **f** form **gran hypg** hypidiomo **int** intersertal **isom** isometric**matr** matrix **mic** microlite **oph** ophitic **pang** panidiom/gran **pil** pilotaxit **phyr** phyric **pr** partially replaced **subh** subhedral **soph** subophitic **s z** sector zoned tabular **tach** tachylitic **To** Ti-augite **tra** trachytic **v** in vesicles **vve** in vesicles and veins **ve** in veins **Locations: Bco** Barranco **BAB** Barranco de Las Angustias **BAA** Bco Almendro Amargo **BH** Bco Huanaguo **BL** Bco de Los Limones **BT** Bco Taburiente **200m** elevation in Bco outcrops **[2]** Unit 2 **RC** road cut **Various: sec** secondary phases **TS** Thin Section **NRM** Natural Remanent Magnetization **PM** Paleomagnetics Sample

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