

5. DATA REPORT: PHYSICAL AND MAGNETIC CHARACTERIZATION OF AA AND PAHOEHOE FLOWS: HOLE 990A¹

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ABSTRACT

The overall good core recovery in the basaltic sequence and the dense recording of physical and magnetic properties in Hole 990A are well suited to investigate the lava pile in detail, although no wireline measurements could be achieved during the entire Leg 163. The goal of the investigation is to show the different lava flow types with their physical and magnetic properties, based on reliable measurements of density and susceptibility with a sampling interval of 5 cm, and velocity and magnetic intensity with a sampling interval of 10 cm.

The top of the volcanic sequence at Site 990 is deeply weathered and oxidized, and all of the lava flow units have oxidized flow tops. In combination with the recovery of soil horizons, this shows that the eruption and emplacement of the lava flows occurred under subaerial conditions. This subaerial emplacement is also indicated by the physical properties with characteristic low density and velocity values at the flow tops, which is a function of the high degree of subaerial flow-top alteration. The lava pile was divided into aa, pahoehoe, and a transitional form as a result of optical core observations as well as by groundmass crystal texture measurements.

Highest density and velocity values are found in the aa flows; in particular the velocities of the pahoehoe flows are smaller than in the aa flows. In general, the pahoehoe flows show the highest magnetic intensities, whereas the magnetic intensities for the aa flows are 3.5 times smaller. The magnetic susceptibility shows an opposite trend.

INTRODUCTION

Ocean Drilling Program (ODP) Hole 990A on the Southeast Greenland margin (Fig.1) provides a unique chance to study the physical and magnetic properties of blocky aa and ropy pahoehoe lava flows. This superficial surface structure of lava flows has its origin in the volumetric flow rate, the eruption and cooling rate, and other parameters that are also reflected by distinct differences in the interior of the flows. Thus, the flow type tells us something about the physical volcanological process (Pinkerton and Sparks, 1976; Peterson and Tilling, 1980; Rowland and Walker, 1990; Hon et al., 1994; Ho and Cashman, 1997; Katz, 1997).

During Leg 163 at Hole 990A, we drilled into a suite of lava flows beneath a sedimentary cover (Fig.1). The first igneous unit was found in Section 163-990A-5R-1 at 212 meters below seafloor (mbsf). Altogether, 13 igneous units were recognized down to the bottom of the hole at 342.7 mbsf. The different lava flows could be clearly differentiated from each other by the presence of weathered or vesicular flow tops (Duncan, Larsen, Allan, et al., 1996; ODP Leg 163 Shipboard Scientific Party, 1996) (Fig. 2). The top of the volcanic sequence at Site 990 is deeply weathered and oxidized, and all of the lava flow units have oxidized flow tops. In combination with the recovery of soil horizons, this shows that the eruption and emplacement of the lava flows occurred under subaerial conditions. Subaerial emplacement is also indicated by the physical properties with characteristic low density and velocity values at the flow tops, which is a function of the high degree of subaerial flow-top alteration. In contrast to these subaerial lava flows, submarine lava flows (pillow lava) do not show these characteristic flow tops and bottoms.

Detailed descriptions of the variation of physical properties within subaerial basalt piles in different areas are given by Aubele et al. (1988), Planke (1994), Delius et al. (1995), Bucker et al. (1998), S. Planke et al. (unpubl. data). The latter two are dealing with Hole 990A data. All reveal characteristic low-density and low-velocity values in the flow tops. A comprehensive petrologic and structural summary of the volcanic succession in Hole 990A is given by Duncan, Larsen, Allan, et al. (1996). These lava flows can be subdivided into three types: aa, pahoehoe, and a transitional form.

This paper summarizes the physical and magnetic properties and the flow textures of aa, pahoehoe, and transitional form flows.

DATABASE

Because of bad weather conditions, no downhole measurements could be achieved during Leg 163. But the high recovery of basalt (70% overall core recovery) from Hole 990A enabled a dense sampling of physical properties measurements, including *P*-wave velocity, bulk density, natural gamma ray, magnetic susceptibility, and natural remanent magnetization. Gamma-ray attenuation porosity evaluator (GRAPE) density, natural gamma-ray, and magnetic susceptibility were measured with the shipboard multisensor track (MST) system on full-round cores with a sampling interval of 2 cm prior to sawing. As soon as possible after core retrieval, *P*-wave velocity was measured on seawater-saturated half-round cores with the Hamilton Frame velocimeter at an average sampling interval of 5 cm. Additionally, bulk density and velocity were measured on discrete samples (minicores with 1-in diameters and 1-in heights).

The magnetic intensities were measured every 10 cm with the shipboard cryogenic magnetometer. Prior to the measurement, an alternating field demagnetization at 30 mA was applied to remove secondary remanences, like drilling-induced magnetization (Y. Nakasa, pers. comm., 1996).

All measurements were checked by an intensive quality control, using the visual core descriptions (VCDs) (Duncan, Larsen, Allan, et al., 1996) for comparing and editing the data. During the MST measurements, data were taken at each predefined interval, whether there

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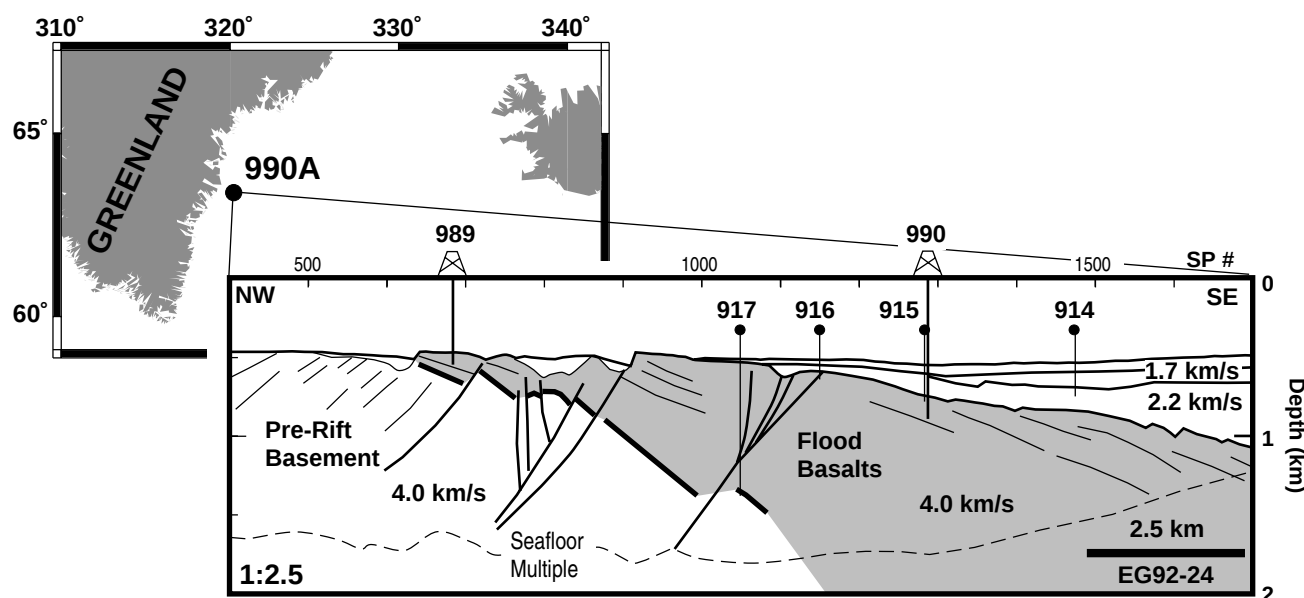


Figure 1. Location of Hole 990A at the Southeast Greenland margin. Drill Sites 914–917 from Leg 152 are also shown.

was full-round core or some core loss. This results in erroneous data at the measurement points where there was some core loss. By comparing the core measurements with the images from the core, it was possible to delete all those measurements where no full-round core was present. This quality control resulted in reliable physical properties values that do not show the minimum values produced by partial or total loss of core. Additionally, the shipboard GRAPE data had to be recalibrated using the results of the minicore density measurements. In contrast to the GRAPE density measurements, which are based on the attenuation of gamma rays traveling through the core, the minicore density measurements (buoyancy method) give absolute data. The Hamilton Frame Velocimeter measurements are in good agreement with the shipboard minicore measurements, whereas the swelling properties of smectite clays have permanently lowered the elastic properties of stored samples (S. Planke et al., unpubl. data). The results of the measurements after this quality control are shown in Figure 2 together with flow types and flow boundaries. The detailed structure of the volcanic pile is revealed by the very high sampling rate.

Flow textures were studied through both qualitative and quantitative methods. Qualitative core descriptions involved hand-specimen and thin-section inspection of core samples for both vesicularity and general groundmass characteristics. Selected samples from the different flow types were then chosen for quantitative analysis of both vesicle and crystal textures. Groundmass crystal textures measurements were based on backscattered electron (BSE) images collected using a JEOL 6300 SEM located at the University of Oregon. Optimal resolution was obtained with a 15-mm working distance, a 10-keV accelerating voltage, and a 5-nA beam current. Images of all samples were collected at a magnification sufficient to permit counting of 200 to 300 crystals per image. Because of the difficulties of working with holocrystalline samples, measurements were restricted to determination of crystal number density (the number of crystals per area).

Aa and pahoehoe flows are uniquely characterized by groundmass textures (Katz, 1997) that result from their very different flow transport and cooling histories (Ho and Cashman, 1997). The smaller average crystal size in the aa groundmass results from higher rates of

cooling ($>20^{\circ}\text{--}30^{\circ}\text{C/h}$) (Ho and Cashman, 1997), and thus higher rates of crystal nucleation ($\sim 1.0 \times 10^4/\text{cm}^3/\text{s}$) than in the better insulated, often slower moving pahoehoe flows. Groundmass textures thus provide a good diagnostic tool for identifying flow type when identification based on internal structure is ambiguous. Aa flows typically have 10 to 100 times the number of crystals in a given area as pahoehoe flows do, meaning that the average crystal size of pahoehoe flows is 3–10 times larger than that of aa.

A comprehensive petrological and structural summary of the volcanic succession is given by Duncan, Larsen, Allan, et al. (1996). The groundmass of all basaltic rocks consists of plagioclase (30%–50%), augite (20%–42%), magnetite (1%–4%), olivine (0%–4%), and mesostasis (0%–30%). All rocks from Hole 990A are moderately to completely altered by low-temperature secondary phases that replace primary minerals. The highly brecciated or vesicular flow tops especially show a high degree of alteration (see also Planke et al., Chap. 2, this volume). No significant differences in either primary mineralogy or phenocryst content were found between aa and pahoehoe flows (Duncan, Larsen, Allan, et al., 1996).

The lava flows cored at Site 990 range from aphyric to highly olivine or plagioclase-olivine-clinopyroxene phyric basalt. Most units are moderately phyric, although Units 6, 7, and 9 are aphyric olivine basalt. The flow thicknesses in general tend to increase upward, with units 1–3 reaching thicknesses of about 15 m. All recognized lava flows were subdivided into the aa, pahoehoe, and transitional categorizations described above (Duncan, Larsen, Allan, et al., 1996). Aa flows were identified by their thick brecciated flow tops (up to 0.5 m) and thin vesicular flow base (0.2–0.5 m). In contrast, pahoehoe flows showed thick upper vesicular zones and massive interiors, and they often had pipe vesicles at the base. Flows that showed some characteristics of both end-members were classified as transitional. Duncan, Larsen, Allan, et al. (1996) classified Units 1–3 and 13 as aa, 4–7 as transitional, and 8–12 as pahoehoe.

Measured physical and magnetic properties are shown in Figure 2 together with flow types, flow boundaries, and rock types determined on board ship (see Duncan, Larsen, Allan, et al., 1996). Because of the very high data density, a detailed structure of the volcanic pile can be seen.

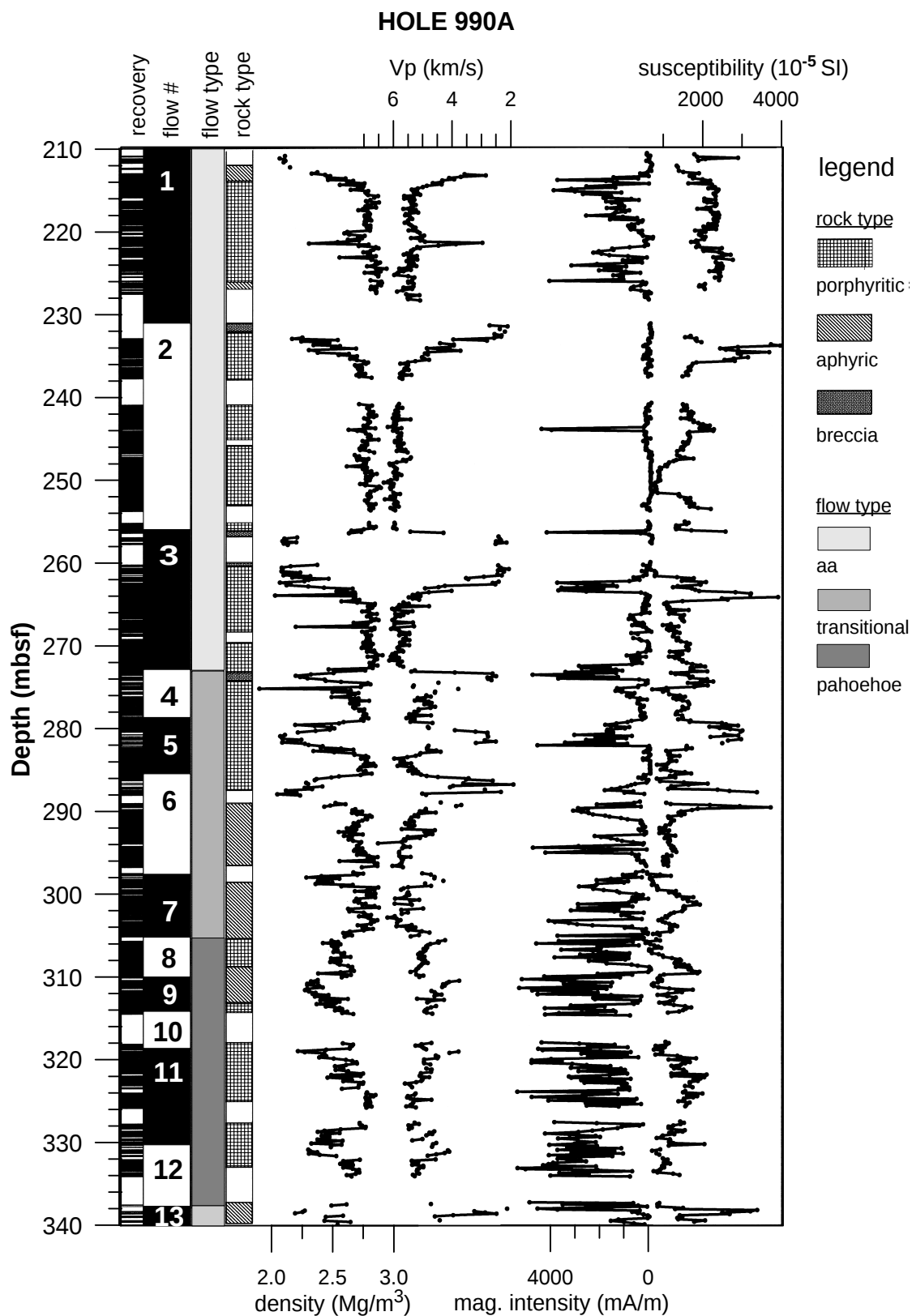


Figure 2. Downhole variation of the physical and magnetic properties in core from Hole 990A, together with core recovery, rock type, and flow type. Note the change in variation downhole. This is in relation to the upward change in flow type. Flow Units 1–3 and possibly 13 are relatively thick aa, 4–7 are transitional in nature, and 8–12 are thin pahoehoe flows (rock type and flow type from Duncan, Larsen, Allan, et al., 1996).

TEXTURAL CHARACTERISTICS OF AA AND PAHOEHOE LAVA FLOWS

Brief descriptions of the vesicularity of each flow unit from Site 990A are given in Table 1. Aa flows, both in the Hawaiian drill cores and in Hole 990A cores, are characterized by having very low vesicularity (<5%) in their interior parts, which leads to high overall flow densities. This feature was noted by early observers in Hawaii (e.g., Jaggar, 1920; Macdonald, 1953) and has been documented to result from both loss of volatiles from the flow surface during lava transport (Lipman et al., 1985) and from collapse and compaction of vesicles as the lava increases in both thickness and viscosity. Thus, typically, the only low-density portion of aa flows is the highly brecciated upper flow crust. These characteristics of the flows can be seen directly in both *P*-wave velocity and density profiles through the Hole 990A core sequence (Fig. 2).

Pahoehoe flows, in contrast, are highly vesicular. Thin pahoehoe flows are typically vesicular throughout their entire thickness, whereas inflated pahoehoe sheet flows in general have well-defined thin lower and thick upper vesicular zones separated by a massive flow interior (Cashman and Kauahikaua, 1997). The upper vesicular zone represents flow crust generated during active flow emplacement and can be used to estimate flow emplacement duration (Hon et al., 1994).

A brief qualitative summary of groundmass textures preserved in Hole 990A flow units is given in Table 1. Quantitative analysis and

SEM imaging have been performed for only selective flow units, results of which are included in Table 1, where appropriate.

PHYSICAL AND MAGNETIC PROPERTIES OF AA AND PAHOEHOE FLOWS

Discriminating between aa and pahoehoe lava flows is important in terms of understanding cooling and eruption rates and thus in deciphering the evolution and the history of the volcanic pile.

The physical and magnetic properties in Hole 990A, together with the flow type differentiation in aa, pahoehoe, and transitional form flows, are shown in Figure 2. In general, the massive and homogeneous flow interiors show the highest density and velocity values, whereas the flow tops and bottoms are characterized by extremely low values. Despite the large intra-flow variations in physical properties, an overall change with depth is also obvious. There is a general uphole decrease in susceptibility and a downhole increase in magnetic intensity, resulting in generally higher magnetic intensities for the pahoehoe flows and higher susceptibilities for the aa flows.

Not only are the absolute values of the physical and magnetic properties interesting, but also their variations and ranges. On average, the pahoehoe flows show the lowest variations in density and velocity and the highest variations in magnetic intensity (Figs. 2, 3). The variations in density and velocity for the aa flows are primarily caused by the brecciated and altered flow tops. The magnetic intensi-

Table 1. Summary of Hole 990A flow textural characteristics.

Unit	General structure	Crystallinity
1	Thickness: 19.2 m. The top 1.4 m is highly weathered; much of this unit is massive (<5% vesicles), with segregations and weak banding through most of the unit below 4.23 m. The lower vesicular zone is 20 cm thick.	
2	Thickness: 24.8 m. Flow top is highly oxidized breccia for >1.5 m. Some reincorporated crust and internal flow boundaries in the top 4 m. Flow is massive (<5% vesicles). Prominent banding appears at a depth of 6.48 m, continues downward through 20.5 m. Flow base is highly oxidized and finely vesicular.	Fine-grained (<200 μm) throughout, with larger (up to 300 μm) poikilitic oxide grains. Crystal number densities range from 800 (internal) – 1800 (flow top) / mm^2 .
3	Thickness: 17.5 m. Upper breccia zone is 4.4 m thick. Mesostasis banding appears at 6.25 m below the flow top and continues through most of the flow. The 25-cm flow base is finely vesicular.	
4	Thickness: 4.58 m. Flow top shows thin reddish breccia that grades downward into an irregular vesicular zone 14.2 m thick (up to 15% vesicles). Below this melt, segregations become more common and show banding. Finely vesicular lower boundary over 50 cm.	This sample is characterized by numerous plagioclase micropheocryst laths (~500 μm) in a finer grained matrix (<200 μm).
5	Thickness: 5.7 m. Flow top indistinct. The 0.83-m upper vesicular zone (up to 27% vesicles) is underlain by a 1.75-m-thick internal breccia zone. Below that lies another vesicular zone 0.87 m in thickness. The flow base is nicely preserved and shows the lower vesicular zone to be 50 cm in thickness.	
6	Thickness: 14.3 m. Brecciated flow top is 1.46 m thick and highly altered. Below this is a vesicular zone that also contains melt segregation blobs. Segregation bands are plentiful in the lower few meters of the flow. Flow base is vesicular over the lower 40 cm.	
7	Thickness: 6.1 m. Upper surface has a thin vesicular zone notable for the presence of numerous small vesicular blobs with a high number density of very small vesicles. Below this is an abrupt transition into a banded zone over 1.3 m. The lower vesicular zone is 50 cm in thickness.	
8	Thickness: 4.3 m. Flow top is reddish and fine grained. Upper vesicular zone is 2.65 m in thickness (<20% vesicles), although some vesicles are apparent throughout the flow. Irregular pipe vesicle structures rise to 45 cm above the flow base.	
9	Thickness: 4.1 m. Most of the flow is vesicular, with the upper vesicular zone persisting over 3.54 m.	
10	Thickness: 5.1 m. Most of this flow was missing, although the flow base was preserved as pipe vesicles over ~20 cm.	
11	Thickness: 11.06 m. This unit has a complex vesicle structure and appears to be a compound flow. The entire upper vesicular zone is 3.9 m thick (about 15%-20% vesicles). There are internal pipe vesicles and a quenched base, underlain by another flow top with irregular vesicles. The flow base as mapped has 10 cm of pipe vesicles.	Aphyric flow with a ground mass that varies from extremely fine-grained at the base (~1600 crystals/ mm^2) and coarser grained in the interior (~150 crystals/ mm^2).
12	Thickness: 7.4 m. The top is marked by reddish lava. Upper vesicular zone is 2 m thick, below which the flow is massive. There are pipe vesicles near the base of the unit.	
13	Thickness: unknown (base not recovered). Flow top is finely vesicular breccia, and the lowermost material recovered contains numerous mesostasis segregations.	

Note: Quantitative analysis results of groundmass textures are included where appropriate.

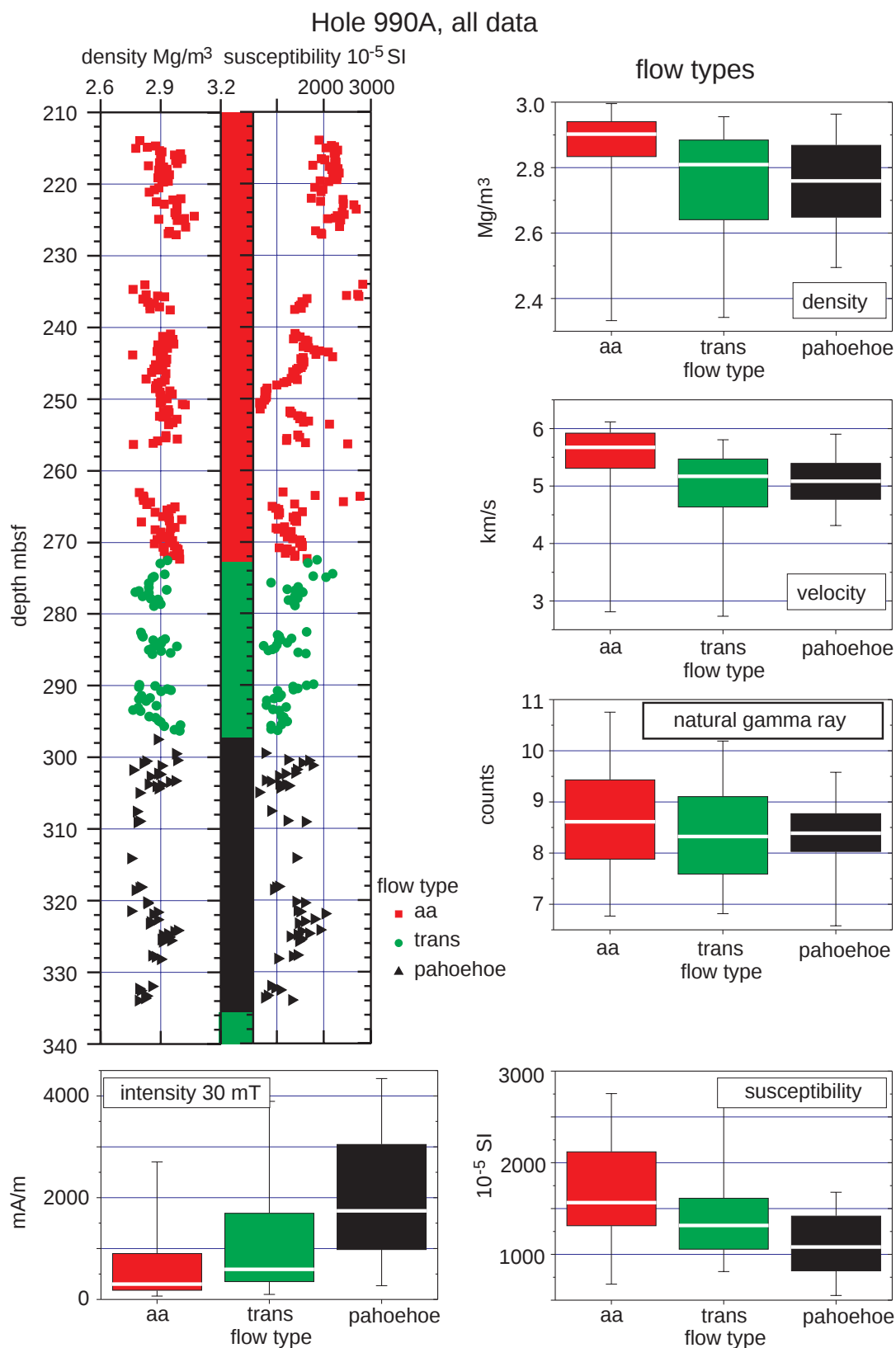


Figure 3. Box and whisker plots of the overall physical and magnetic properties of each flow type together with the downhole variation of density and magnetic susceptibility. The white lines inside the boxes represent the average values. The upper and lower boundaries of the boxes show the 25 and the 75 percentile, respectively. Thus, 50% of the data are inside the box. The whiskers (small horizontal lines at the ends of the vertical lines) are marking the 5 and the 95 percentile, respectively.

ty shows only some enhanced peaks, mainly in the top parts. The susceptibility is, in general, high for the aa flows, not only in the top or bottom parts, but also in the massive inner zones of the flows. Although the differences in magnetic properties behavior have several single or combined reasons (carrier of magnetization, concentration, grain size, grain shape, stress, and others), they might be potentially helpful in distinguishing flow types.

Both flow types show very low density and velocity values in their top parts as a result of the high vesicularity and scoriaceous or brecciated material, respectively, resulting in similar log or core measurement responses in the top part of the flows for both lava types. Although the different flow types are clearly visible in the flow tops (vesicular vs. brecciated zones), it is not possible to use the physical properties of the flow tops for lava type differentiation.

To demonstrate the impossibility of distinguishing between flow types by using the overall physical and magnetic properties, the average values are shown together with their statistical variation in Figure 3. The downhole plots on the left side show only values with densities $>2.7 \text{ Mg/m}^3$. This cut-off density value will serve as a discriminator as described later. The plots on the right side (considering all data) clearly show that all the average values are nearly identical in the 50% range.

A density value of 2.7 Mg/m^3 is suggested as a discriminator between the altered and the unaltered flow sections based on the loss of ignition (LOI) values derived from X-ray fluorescence analysis (S. Planke et al., unpubl. data). The LOI is a parameter that is strongly controlled by alteration. All samples with a density $>2.7 \text{ Mg/m}^3$ have a LOI of $<0.5\%$, pointing to a very low alteration state. Only the parts of the core with densities $>2.7 \text{ Mg/m}^3$ were used for further investigations. This means that only the massive and homogeneous interior parts of the lavas are considered. The advantage of this filtering is to make the data comparable, because the massive parts of the flows are either not influenced or less influenced by alteration, and thus should reflect the intrinsic properties of each unit. The cut-off density value of 2.7 Mg/m^3 still provides sufficient data points from all flow units except for Unit 13 (see Figs. 2, 3).

Table 2 shows the average values and the standard deviations of the physical and magnetic properties of the flow types for densities higher than 2.7 Mg/m^3 . Discriminant values for the flow types are stippled, and it can be seen that aa flows are characterized by high velocity and density and a high susceptibility, whereas the pahoehoe flows are characterized by high magnetic intensities. But the average susceptibility difference ($1694\text{--}1260 \times 10^{-5} \text{ SI}$) is not as high as the average magnetic intensity difference ($387\text{--}1346 \times 10^{-3} \text{ A/m}$) (aa compared to pahoehoe). Note that the difference in average magnetic intensity between the flow types is about a factor of 3.5. The natural gamma-ray values are identical within one standard deviation (mean values of 8.1 to 8.6 counts).

The variation of physical and magnetic properties for the flow types is shown in Figure 4 in the same manner as in Figure 3, but here only samples with densities higher than 2.7 Mg/m^3 are considered for

the plots. The density and velocity values are clearly different, with the higher values for the aa flows (mean density of 2.91 Mg/m^3), and the lower values for the pahoehoe flows (mean density of 2.86 Mg/m^3). No big differences can be seen in the natural gamma-ray values. In contrast, the magnetic properties are well suited to distinguish between the flow types: pahoehoe flows show high magnetic intensities, whereas aa flows show generally higher susceptibilities. Although the whiskers in the plots (small horizontal bars describing the 95% level) at the right side of Figure 4 demonstrate that all flow types seem to have the same minimum values in magnetic properties, high maximum values are only recorded for pahoehoe or aa flows, respectively. There is only a little overlap in the boxes containing 50% of all samples. The same trend is reflected by the downhole core logs at the left side of Figure 4 for the density and susceptibility. Except for the natural gamma ray, all physical and magnetic properties show an intermediate behavior for the transitional flow type.

Table 3 is a summary of a suite of general diagnostic features for the various lava types. The combination of a low eruption rate and generally thin flow thicknesses makes it tempting to suggest a fast cooling rate for the pahoehoe flows, resulting in relatively small magnetic particles having a high magnetic intensity but a low susceptibility.

Until now, only the data from Hole 990A have been analyzed in detail with respect to changes in flow morphologies. Exploratory investigation of data from Holes 917A and 642E show similar clusters for the correlations between the physical properties and the flow types. Unfortunately, no magnetic data are available from Hole 642E, and only limited data exist from Hole 917A. For further investigations on subaerial volcanic rocks from large igneous provinces, it will be very important to get a complete as possible suite of downhole logs. The new downhole Geologic High-Resolution Magnetic Tool, with the measurement of induced and remanent magnetization, will be extremely useful for the interpretation of volcanic piles.

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Table 2. Average physical (arithmetical mean $\pm$ standard variation) and magnetic properties (geometrical mean $\div$ standard deviation) for the different flow types, Hole 990A.

Flow type:	Aa:	Transitional:	Pahoehoe:
Number of samples:	152	54	49
Density (Mg/m^3):	2.91 $\pm$ 0.06	2.87 $\pm$ 0.06	2.86 $\pm$ 0.07
Velocity (km/s):	5.69 $\pm$ 0.35	5.36 $\pm$ 0.36	5.35 $\pm$ 0.33
NGR (counts):	8.6 $\pm$ 1.1	8.1 $\pm$ 1.1	8.3 $\pm$ 1.0
Susceptibility (10^{-5} SI):	1694 $\pm$ 615	1269 $\pm$ 345	1260 $\pm$ 350
Magnetic intensity (10^{-3} A/m):	387 $\div$ 3.3	532 $\div$ 3.2	1346 $\div$ 2.6

Notes: All lava flow types have a density higher than 2.7 Mg/m^3 . Values in the shaded areas are characteristic for the flow types.

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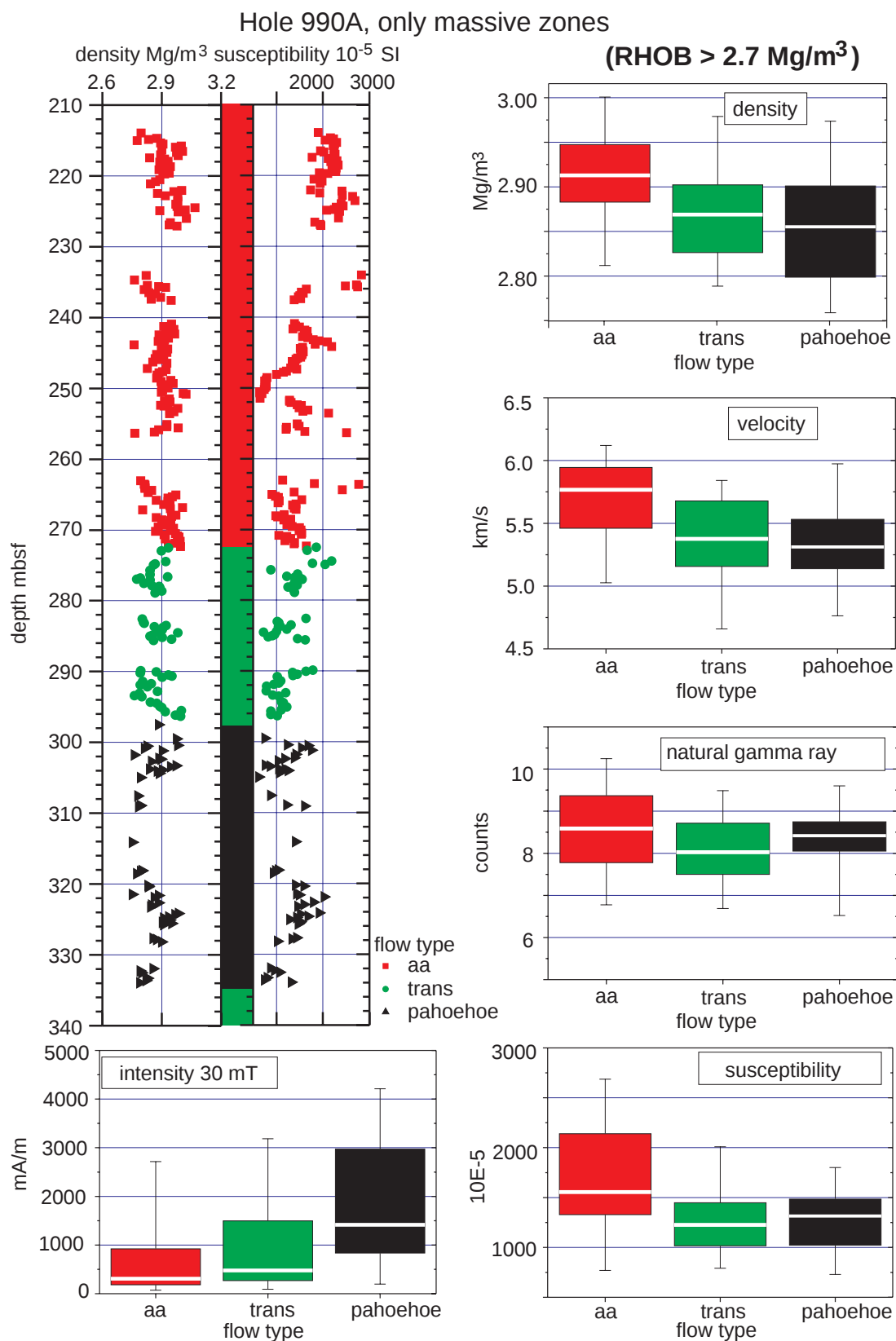


Figure 4. Box and whisker plots of the physical and magnetic properties of each flow type together with the downhole variation of density and magnetic susceptibility for only the massive interiors of the flows with a density higher than 2.7 Mg/m^3 . The white lines inside the boxes represent the average values. The upper and lower boundaries of the boxes show the 25 and the 75 percentile, respectively. Thus, 50% of the data are inside the box. The whiskers (small horizontal lines at the ends of the vertical lines) are marking the 5 and the 95 percentile, respectively.

Table 3. General qualitative description of diagnostic features for the flow types aa and pahoehoe.

Diagnostic features	Aa	Pahoehoe
Density	High	Low
Velocity	High	Low
Susceptibility	High	Low
Magnetic intensity	Low	High
Crystal grain size	Fine	Medium coarse
Vent location	Distal	Proximal
Eruption rate	High	Low
Thickness	Thick	Thin
Viscosity	High	Less

Note: Table in part taken from Walker, 1971; Sahagian et al., 1989; Rowland and Walker, 1990; Hon et al., 1994.