Variability of magnetic soil properties in Hawaii

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ABSTRACT

Magnetic soils can seriously hamper the performance of electromagnetic sensors for the detection of buried land mines and unexploded ordnance (UXO). Soils formed on basaltic substrates commonly have large concentrations of ferrimagnetic iron oxide minerals, which are the main cause of soil magnetic behavior. Previous work has shown that viscous remanent magnetism (VRM) in particular, which is caused by the presence of ferrimagnetic minerals of different sizes and shapes, poses a large problem for electromagnetic surveys. The causes of the variability in magnetic soil properties in general and VRM in particular are not well understood. In this paper we present the results of laboratory studies of soil magnetic properties on three Hawaiian Islands: O'ahu, Kaho'olawe, and Hawaii. The data show a strong negative correlation between mean annual precipitation and induced magnetization, and a positive correlation between mean annual precipitation and the frequency dependent magnetic behavior. Soil erosion, which reduces the thickness of the soil cover, also influences the magnetic properties.

Keywords: land mine detection, UXO detection, iron oxides, magnetic soils, soil development, Hawaii

1. INTRODUCTION

Electromagnetic (EM) and magnetic sensors are frequently used for detection of buried landmines and unexploded ordnance (UXO), but their performance degrades significantly at sites with magnetic soils and rocks. In environments with highly magnetic soil, magnetic and electromagnetic sensors often detect large anomalies that are of geologic, rather than metallic, origin[1]. Improved detection and discrimination performance can only be achieved when the natural variability of magnetic soil properties is known and when it is understood how magnetic soil material interacts with sensors. This information can be used to develop improved data processing algorithms.

The magnetic properties of soils result from the presence of iron oxides in different forms and quantities. Paramagnetic and antiferromagnetic iron oxides such as goethite and hematite may be abundant but play a minor role in determining the magnetic character of a soil. Ferrimagnetic minerals such as magnetite, maghaemite, and pyrrothite are the most magnetic of the iron oxides, and are of primary importance in their effects on geophysical sensors. Iron oxide minerals can be both pedogenic (i.e., a product of soil formation) and lithogenic (i.e., unweathered minerals from the parent material) in origin. There exist three magnetic effects that impact the magnetic and electromagnetic characteristics of the subsurface: (1) remanent magnetization, (2) induced magnetization, and (3) viscous remanent magnetization (VRM). Of these, induced magnetization and VRM cause major problems in processing electromagnetic data[2].

With increasing soil development and, thus, weathering the relative concentration of (magnetic iron oxide) minerals in the soil column changes[3]. It is expected that the dominant magnetic effect in a soil will change as well[4]. The degree of weathering of a soil is controlled primarily by time (soil age), precipitation, and temperature. However, currently the

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mineralogical and other weathering processes involved in changing the magnetic characteristics of a soil are poorly understood.

In Hawaii, soils are commonly highly magnetic, which causes problems with UXO clearance operations[4, 5]. The source of the iron oxide in soils is iron-bearing minerals in the earth crust or lithosphere. In Hawaii the basaltic rocks contain significant amounts of magnetite and other iron-containing minerals[6]. However, in soils developed on the relatively uniform parent material the induced magnetization varies significantly over relatively short distances and depends strongly on degree of soil development[4]. It is not known if this correlation between soil development and magnetic properties also exists for the viscous remanent magnetization. Because the parent material in Hawaii is relatively uniform it is possible to single out the effects of climate and soil age on the development of soil magnetic characteristics.

To meet the challenge of improving detection and identification of landmines and UXO in magnetic soils it is our objective to describe the variability in magnetic soil properties in the archipelago of Hawaii and to develop a conceptual model for the development of magnetic soils in tropical regions. In this paper we describe magnetic measurements from the islands of O’ahu, Kaho’olawe and Hawaii, all of which have the same parent material. We focus on the effect of climate gradients (mean annual rainfall), soil erosion, and the impact of soil age on the magnetic soil characteristics.

2. SETTING

The islands of Hawaii form the youngest part of a chain of 107 individual volcanoes that stretch in a northwesterly to northern trend across the Pacific Ocean[7]. The chain began forming over 80 million years ago as the Pacific Plate moved across a stationary mantle plume. The development of the Hawaiian volcanoes can be subdivided in four stages, each with distinct geochemical characteristics: (1) the submarine alkalic preshield stage, (2) the subaerial shield stage characterized by tholeiitic basalts, (3) an alkalic postshield stage, and (4) a rejuvenation stage. The volume of shield-stage tholeiitic basalts comprises 95-98% of all eruptive products[8], but a relatively thin layer of alkalic basalts of the postshield and rejuvenation stages may cover the main shield. The average magnetite and ilmenite content of tholeiitic and alkali olivine basalts, characteristic for Hawaiian lava, lies between 37-46 and 24-50 g/kg, respectively[9].

Soils make up approximately 55% of the land area of the Hawaiian Islands and are dominated by Histosols and Oxisols[10]. Soil development and variation in soil characteristics can be attributed to a number of factors. Due to the presence of steep and high volcanoes the climatic conditions can vary significantly over short distances. The main factors determining soil variability are the age of the soil, changing climate, increased precipitation with elevation, temperature, and drainage conditions. The forms of iron and other minerals in a soil change with time. With increasing time, soil depth usually increases. In the oldest soils only the most stable iron oxides remain[11, 12].

We have selected a total of 11 soil pits on three islands and four distinct volcanoes of different ages (Fig. 1). The details of the particular soils are presented in Table 1. Further information on the geology and setting of each particular study area is given below.

Table 1. Details of soil pits. *P* stands for mean annual precipitation.

Island	Volcano	Pit ID	*P* (mm/yr)	#samples	Soil information	Substrate age (My)
O’ahu	Waianae	-	1450	40	Helemono-Wahiawa Association	3.7
Kaho’olawe	Kanapou	A	250-600	7	Kaneloa Series	>1.03
Kaho’olawe	Kanapou	B	250-600	15	Puu Moiwi Series	>1.03
Kaho’olawe	Kanapou	C	250-600	15	Puu Moiwi Series	>1.03
Kaho’olawe	Kanapou	D	250-600	12	Puu Moiwi Series	>1.03
Hawaii	Kohala	1	1300	7	Maile Series	0.43
Hawaii	Kohala	2	750	7	Waimea Series	0.43
Hawaii	Kohala	3	180	9	Kawaihae Series	0.43
Hawaii	Mauna Kea	4	230	11	Waikui Series	0.375
Hawaii	Mauna Kea	5	5485	7	Akaka Series	0.375
Hawaii	Mauna Kea	6	3275	7	Hilo Series	0.375

2.1. O'ahu

The age of the Waianae Volcano on the western side of the island is 3.7My and of Koolau Volcano on the eastern side of the island is 2.6My[8]. Our test site is an Oxisols developed in fan deposits of the Waianae Range at the Schofield Barracks Army Base (Fig. 1B). The mean annual rainfall is approximately 1450mm/yr. We opened one soil pit at the test area.

2.2. Kaho'olawe

Kaho'olawe is the smallest of the eight major islands in the state of Hawaii and lies approximately 7 miles southwest of Maui (Fig. 1A). Its age is considered to be >1.03My[8]. Due to its position on the leeward side of Haleakala Volcano on Maui and its limited elevation (maximum 450 meters) Kaho'olawe receives very little rainfall, which ranges from 250 to 600mm/yr[13]. Overgrazing by cattle that were first introduced in 1864 has caused large areas of the island to be stripped of vegetation. The bare surface and the strong trade winds from the east have led to severe soil erosion. From 1941 to 1993 the island was used for military training and target practice. At our test site in the Navy QA Grid (Fig. 1C) we described 3 soil pits of the Puu Moiwi Series and 1 soil pit of the Kaneloa Series (Table 1)[14].

2.3. Hawaii (Big Island)

Hawaii is the youngest of the islands in the Hawaiian archipelago and is made up of several individual volcanoes. Mauna Loa and Kilauea Volcanoes are active[8]. We have collected soil samples from 3 soil pits on Mauna Kea Volcano deposits (0.375My old) and from 3 soil pits on the oldest volcano on the island, Kohala Volcano (0.43My old) (Fig. 1D). Younger dates have been suggested because soils have formed in volcanic ash, rather than in basalt[15]. The mean annual rainfall for the sampled soils ranges from 180 to almost 5500mm/yr[4].

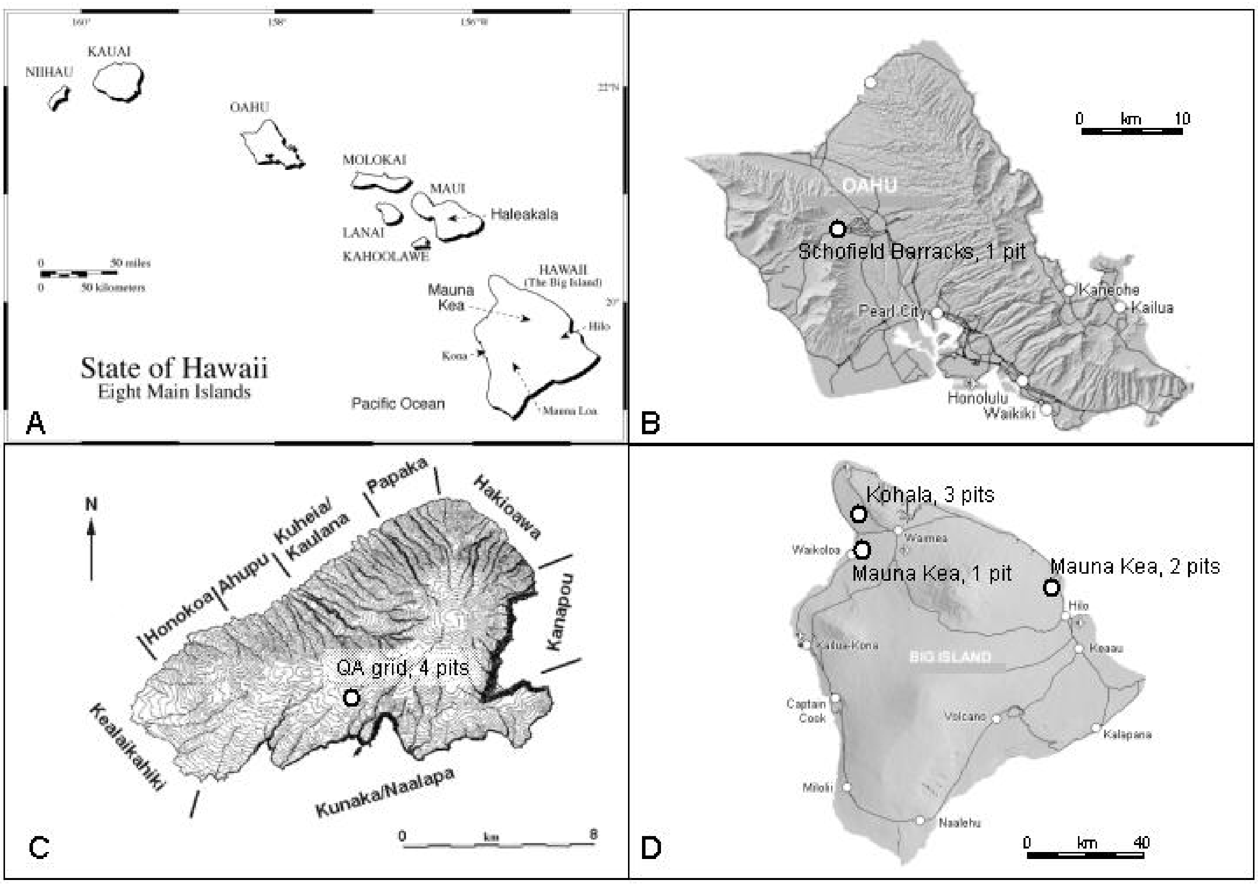

Fig. 1. Location of the eight main Hawaiian islands (A) and the field sites on O'ahu (B), Kaho'olawe (C), and Hawaii (D).

3. METHODS

After description of the horizon characteristics in the field, samples were collected for laboratory analyses of soil texture and mineralogy and frequency dependent magnetic properties. In the laboratory the samples were dried for a minimum of 48 hours at a low temperature (<50ºC), so as not to cause any chemical reactions. Next, $10cm^3$ pots were filled for measurement of the magnetic susceptibilities and their weight was measured on an A&D GR-120 balance with 0.1mg accuracy. The soil material was crushed (manually) to silt-sand grain sizes where necessary.

The magnetic susceptibility was measured at two frequencies (0.46/4.6kHz) using a Bartington MS2B sensor. All measurements were conducted at the "1.0" sensitivity setting. Each sample was measured three times (except for the samples from O'ahu, which were measured one time) with an air reading before and after each series for correction of drift. The mass-specific susceptibility (χ) was calculated from the volume-specific susceptibility (κ) using $\chi = 10\kappa / m$, where m is the sample mass in grams[16]. The (percent) difference between readings at the two frequencies can be used to estimate the viscous remanent magnetization of the samples. The frequency dependent susceptibility was calculated using $\chi_{lf}\% = ((\chi_{lf} - \chi_{hf}) / \chi_{lf}) \times 100$, where χ_{lf} is the mass-specific susceptibility measured at a frequency of 0.46kHz and χ_{hf} is the mass-specific susceptibility measured at 4.6kHz[16].

4. RESULTS

The measured values of mass-specific magnetic susceptibility at all three islands range, with a few exceptions, from 5 to $25 \cdot 10^{-6}$ m^3/kg. These values agree quite well with data from comparable parent materials, published in the literature[17, 18]. The measurements from the soil pit in O'ahu show a fairly constant pattern with values around $10 \cdot 10^{-6}$ m^3/kg (Fig. 2A). A sudden change to values around $15 \cdot 10^{-6}$ m^3/kg at a depth of 60cm is associated with a color change indicative of a change in mineralogy. $\chi_{lf}\%$ is constant for the entire sampled profile and varies around 3%.

The measurements of Kaho'olawe samples indicate a high average mass-specific magnetic susceptibility for soils B, C, and D and lower values for soil A (Fig. 2B). The large difference is remarkable because all four samples are located in a small area (30×150m)[14]. Soil A is constant for the entire profile, while the measurements for the other soils show a characteristic pattern with the highest values occurring between approximately 10 and 80cm depth. In the top 10cm, as well as below 80cm, the values decrease. The values in soil A are similar to those at 1 meter depth in the other soils. The severe erosion that characterizes the soils on this island can explain the differences. In soil A most of the original soil profile has been eroded and as a result the weathered basaltic bedrock (saprolite) is now relatively close to the surface (around 20cm). In the saprolite both mass-specific magnetic susceptibility and frequency dependent susceptibility are low. In the other soils, a far more complete soil profile is present. The soils are characterized by the relative enrichment of superparamagnetic ferrimagnetic minerals in the B horizon, which causes the frequency dependent behavior[16]. The superparamagnetic ferrimagnetic minerals can be both magnetite and maghaemite[14]. At depths below 80cm the soil characteristics change. The color changes from reddish to yellowish (the same color as in the entire profile of soil A), which indicates a transition to saprolite material. Saprolite has been found at depth in all these profiles.

The soils from the Big Island were located on two different volcanoes. The soil pits on Kohala Volcano lie on a well described transect along a clear climate gradient[15]. In these soils there is a strong correlation between mean annual precipitation and the magnetic characteristics (Table 1, Fig. 3A). Soil 3 with the lowest rainfall exhibits an irregular pattern that can be explained by the proximity of the bedrock. Close to the bedrock the mass-specific as well as the frequency dependent susceptibility is low (compare with soil A in Fig. 2A). In the B horizon (20 to 40cm depth) relative enrichment (due to leaching and/or alteration of other minerals) with unweathered primary magnetite causes the large values up to $70 \cdot 10^{-6}$ m^3/kg. In the overlying A horizon, the organic matter causes a reduction in χ. The soils from Mauna Kea Volcano are located at two different sides of the island (Fig. 1D). Pit 4 is located in a soil formed in sand-sized colluvium of volcanic origin and is characterized by low rainfall amounts. The age of the deposit is unknown. Soils 5 and 6 are located on the eastern side of the island and are characterized by high rainfall amounts. The measurements for these soils show low values (3 to $8 \cdot 10^{-6}$ m^3/kg) for the mass-specific susceptibility and relatively high values (6 to 8%) for the frequency dependent magnetic susceptibility.

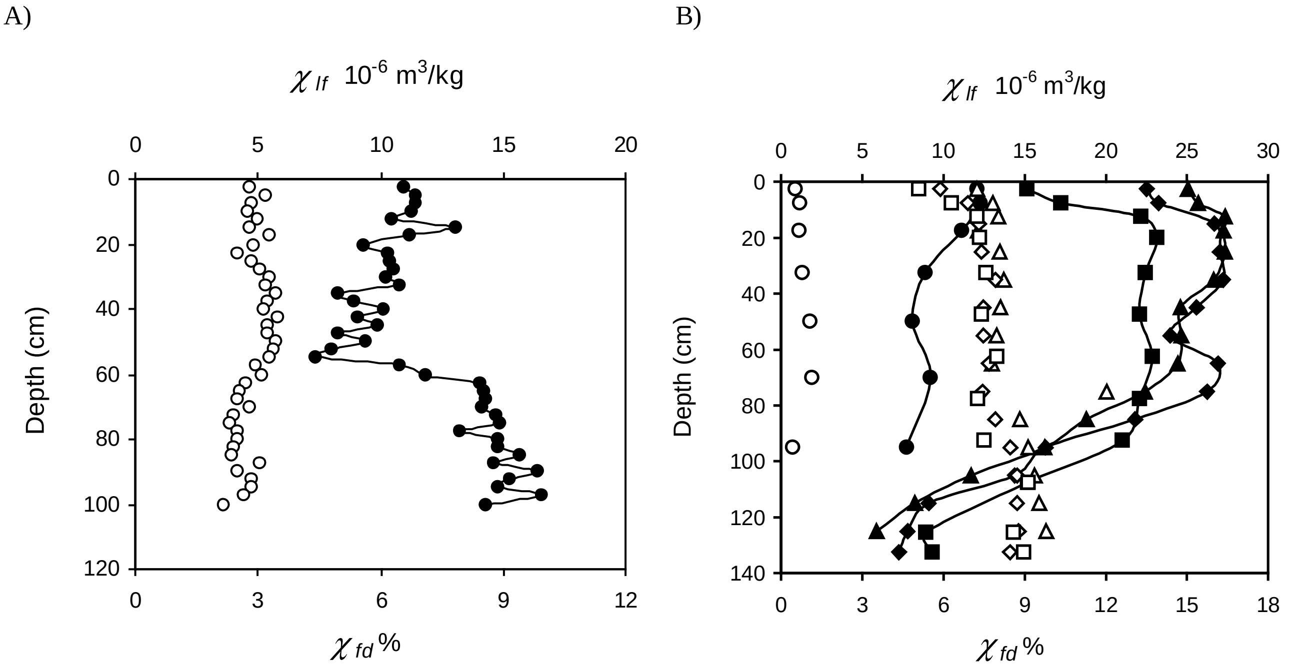

Fig. 2. A) Graph showing magnetic susceptibility variations with depth for 1 soil pit on O'ahu. B) Graph showing magnetic susceptibility variations with depth for 4 soil pits on Kaho'olawe (Circles, soil pit A; Triangles, soil pit B; Diamonds, soil pit C; Squares, soil pit D). In both graphs, the solid symbols represent low-frequency mass-specific susceptibility values (upper axis) while open symbols stand for percent frequency dependent mass-specific suscpetibility values (lower axis).

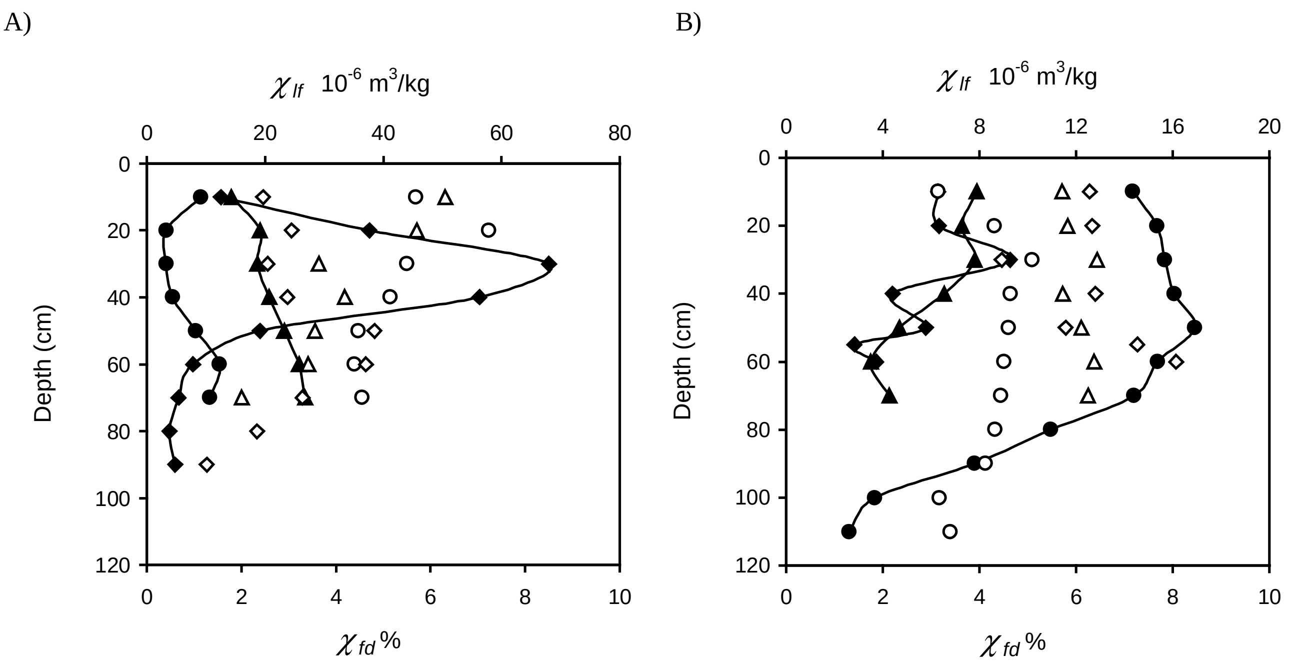

Fig. 3. Graphs showing magnetic susceptibility variations with depth for 6 soil pits on the Big Island of Hawaii. A) Kohala Volcano (Circles, soil pit 1; Triangles, soil pit 2; Diamonds, soil pit 3). The mean annual precipitation decreases from around 1300mm for soil pit 1 to around 180mm for soil pit 3. B) Mauna Kea Volcano (Circles, soil pit 4; Triangles, soil pit 5; Diamonds, soil pit 6). Solid symbols represent low-frequency mass-specific susceptibility values (upper axis). Open symbols stand for percent frequency dependency values (lower axis).

5. DISCUSSION AND CONCLUSIONS

Using the data from the three islands we have attempted to correlate the magnetic properties with the soil age. This has proved extremely difficult, probably because of the effects of climate, vegetation, erosion, and possibly other factors interfering with the signal. Based on two soils from O'ahu and the Big Island (soil 1) with comparable rainfall rates it appears that an increase in age results in an increase in induced magnetization (χ) and a decrease in frequency dependent behavior. To improve our understanding of the relation between soil age on soil magnetic properties we plan to study a well described chronosequence in Hawaii[11].

Earlier it has been reported that there is a clear inverse correlation between rainfall rate and induced magnetization[4]. Figure 4 shows the correlation relation between mean annual precipitation and mass-specific and percent frequency dependent magnetic susceptibility. The rainfall amount on the Kohala and Mauna Kea Volcanoes on the Big Island shows strong inverse correlation with mass-specific magnetic susceptibility (solid symbols, Fig. 4A). This correlation is especially strong for the data points with a mean annual rainfall below 1500mm. Above around 1500mm mean annual rainfall the correlation is weak. Although an exponential curve fits the data quite well (see Fig. 4A) the individual parts of the curve above and below around 1500mm/yr can also be described by a linear trend line. The data for all 11 soils analyzed show a similar decrease in χ with increasing rainfall (Fig. 4B).

A) B)

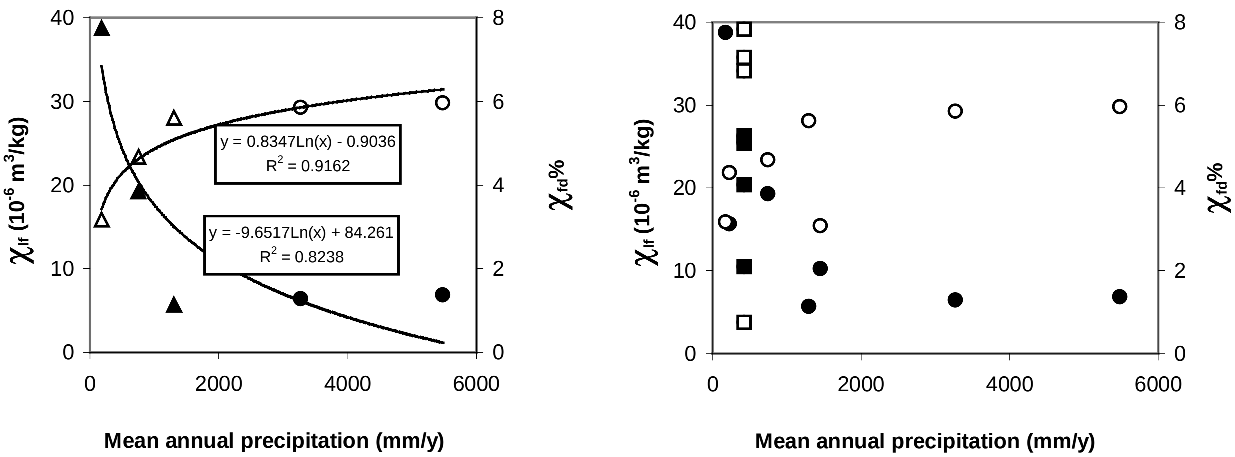

Fig. 4. Graphs showing the relation between mean annual precipitation and mass-specific and percent frequency dependent magnetic susceptibility, respectively. Solid symbols represent low-frequency mass-specific susceptibility values (left axis) while open symbols stand for percent frequency dependency values (right axis). A) 5 soils on the Big Island (Triangles, Kohala Volcano; Circles, Mauna Kea Volcano). B) data from all 11 soil pits from three islands (Table 1); squares represent data from Kaho'olawe Island. Values have been averaged over the top 50cm of the soil profile.

The data from Kohala and Mauna Kea Volcanoes on the Big Island show that the mean annual precipitation is positively correlated with the frequency dependent magnetic susceptibility (open symbols, Fig. 4A). Similarly as for the mass-specific magnetic susceptibility this correlation is especially strong for the data points with a mean annual rainfall below 1500mm, which corresponds with data presented in literature[19]. An increase in precipitation leads to an increase in weathering, which in turn causes a larger amount of superparamagnetic iron oxides to be formed. In contrast to temperate soils where the relative enrichment of secondary superparamagnetic ferrimagnetic minerals mainly occurs in the A horizon[20], in Hawaii we see this occur especially in the B horizon. The values from all 11 soils on the three islands of Hawaii show a similar trend, but here the soils from Kaho'olawe form distinct outliers (open squares in Fig. 4B). The low outlier is easily explained as this represents soil A, which was severely eroded. For the high outliers no explanation is available at this point.

We postulate that the observed correlations and patterns are the result of the gradual transformation of primary magnetic minerals (mostly magnetite) into secondary superparamagnetic minerals (maghaemite and magnetite). The parent material contains large amounts of magnetite and other iron oxides. During the initial stages of soil formation, leaching and transformation of more soluble minerals lead to relative enrichment of primary magnetite in the B horizon. Magnetic measurements on these samples will show high mass-specific magnetic susceptibility values and low viscous remanent magnetization values. With increasing soil formation, more primary iron-containing minerals will weather, and secondary minerals will form in the soil profile. A combination of neoformation of non-magnetic iron oxides such as hematite and goethite (explaining the yellow or red color of older soils) and neoformation of superparamagnetic magnetite and maghaemite grains explains the mutual decrease in χ and increase of the frequency dependent behavior. We are attempting to characterize the types and amount of iron oxides in the different soil horizons using a variety of chemical extraction techniques, X-Ray diffraction, X-Ray fluorescence, and thermogravimetry.

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