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Recent studies have demonstrated the potentially serious impact of magnetic soils on the detection of buried objects such as land mines and unexploded ordnance (UXO) using magnetometers and electromagnetic inductions sensors, two methods that are routinely used in clearance operations. Magnetic soils can cause both equipment malfunctions and an increase in false alarms due to the presence of anomalies that have a geologic or pedogenic origin. To improve the discrimination performance of land mine and UXO detection sensors, there is a need for a better understanding of the natural variability in magnetic characteristics of soils. This research addressed this need by develop a conceptual model for the prediction of magnetic characteristics of soils developed on a wide range of geological parent materials, of different ages, and in diverse climatological environments. The research provides the Army with a new approach to the non-intrusive geophysical characterization of subsurface materials and their spatial distribution; the prediction of location, frequency, and scale of subsurface heterogeneity. The conceptual model that we have developed will allow for a better prediction of sensor capabilities in many iron-oxide containing field soils.

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FOREWORD

Recent studies have demonstrated the potentially serious impact of magnetic soils on the detection of buried objects such as land mines and unexploded ordnance (UXO) using magnetometers and electromagnetic inductions sensors, two methods that are routinely used in clearance operations. Magnetic soils can cause both equipment malfunctions and an increase in false alarms due to the presence of anomalies that have a geologic or pedogenic origin. To improve the discrimination performance of land mine and UXO detection sensors, there is a need for a better understanding of the natural variability in magnetic characteristics of soils. This research addressed this need by develop a conceptual model for the prediction of magnetic characteristics of soils developed on a wide range of geological parent materials, of different ages, and in diverse climatological environments.

The research provides the Army with a new approach to the non-intrusive geophysical characterization of subsurface materials and their spatial distribution; the prediction of location, frequency, and scale of subsurface heterogeneity. The research has led to an improved prediction of magnetic soil occurrences based on environmental characteristics such as soil age, climate, and parent material. Also, we anticipate that the research will improve imaging and detection of buried objects such as landmines and unexploded ordnance in magnetic soils through better background characterization and filtering techniques. The conceptual model that we have developed will allow for a better prediction of sensor capabilities in many iron-oxide containing field soils.

LIST OF ILLUSTRATIONS

Figure 1. Field soils are the product of parent material, climate, flora and fauna, topography, and time. Superimposed on these long-term factors are the effects of day-to-day weather conditions. As a result (tropical) field soils often exhibit extreme spatial and temporal variability that interferes with sensors for detection of land mines and UXO.

Figure 2. a) Cross plot of the average low-frequency mass-specific magnetic susceptibility (χ_{lf}) and the average frequency dependent magnetic susceptibility ($\chi_{fd}\%$) of 5 soils on Kohala Volcano and Mauna Kea Volcano on the Big Island of Hawaii. The error bars represent one standard deviation in the measurements. In addition, results for the measurements of 2 basalt samples from Kohala Volcano are given. The information in the legend stands for the volcano name, the number of the soil pit, and the mean annual precipitation in millimeters. b) Plot of $\chi_{fd}\%$ versus the iron content of the basalt sample and soils 1-3 on Kohala Volcano and soil 5 on Mauna Kea Volcano. c) Sampling locations.

Figure 3. Cross plot of low-frequency mass-specific magnetic susceptibility (χ_{lf}) and the frequency dependent magnetic susceptibility ($\chi_{fd}\%$) for 10 soils from Panama. The error bars represent one standard deviation in the measurements.

Figure 4. Cross plot showing average frequency dependent magnetic susceptibility and average low-frequency magnetic susceptibility for 9 soils in Ghana. All soils, except for those around Ejura and Tamale, are from the Bolgatanga area. The mean annual precipitation ranges from 1000 to around 1500mm/yr. This plot is based on data in Hendrickx et al. (2005).

Figure 5. Conceptual flow model describing how the magnetic susceptibility (χ_{lf}), the frequency dependence ($\chi_{\mathrm{fd}}\%$), and the iron mineralogy can be predicted using information on parent material, soil age, and mean annual rainfall (climate). Fire is an additional cause for soil magnetism. This diagram was

developed based on the data from Hawaii, Ghana, and Panama (Van Dam et al., 2005c). The inset shows the spread in data from Figures 2-4.

OBJECTIVES AND APPROACH

The goal of this project was to develop a conceptual model for the prediction of worldwide occurrence of magnetic soil properties, for which we used a combination of literature review, fieldwork, laboratory analyses and model development. The goal of the project can be subdivided in the following specific objectives:

1. Understand the distribution of magnetic soils around the world as a function of soil forming factors.

   To understand the role of the primary soil forming factors for the occurrence and distribution of magnetic soils we have reviewed the relevant literature. Also we used this review to select field sites that could be used to study the effect of specific soil forming factors on the magnetic properties of soils.

2. Measure the magnetic behavior of a wide range of soils from around the world.

   Members of the research team have conducted field surveys in several tropical and sub-tropical locations: Hawaii, Ghana, and Panama (Figure 1). By combining our efforts with other projects we have obtained samples from other interesting sites in Montana, California, and New Mexico. The fieldwork campaigns consisted of geomorphological and, if necessary, hydrological characterization of the sites, characterization of soil development and variability, and soil sampling. In some case we have measured magnetic soil properties in the field.

   Induced magnetization (IM) and viscous remanent magnetization (VRM) are the effects that impact the magnetic effects of soil on geophysical sensors. Soils with high IM (or magnetic susceptibility) are associated with the presence of ferrimagnetic minerals, and may affect both magnetometers and electromagnetic induction sensors. The VRM (or frequency dependent magnetic susceptibility) of soils provides a good measure for (1) the degree of soil development and (2) in combination with high IM, the performance of electromagnetic sensors. An improved understanding of induced magnetization and viscous remanent magnetization behavior of soils was accomplished by dual-frequency measurement of magnetic characteristics in the laboratory.

3. Analyze the mineralogical composition of magnetic soils.

   In the laboratory we have analyzed the mineralogical characteristics of key samples using a combination of chemical extractions, X-ray diffraction (XRD), X-ray fluorescence (XRF) spectroscopy, and thermogravimetry techniques.

4. Develop a conceptual model for the prediction of worldwide occurrence of magnetic soil properties.

   This objective was approached by combing field observations of geomorphological and drainage conditions with soil magnetic properties and other soils characteristics such as age, climate, and parent material.

MOST IMPORTANT RESULTS

- We have studied and sampled field soils with the goal of covering a large range of environmental conditions influencing development of tropical soils (climate, age, parent material). In Hawaii, where the basaltic parent material is similar everywhere, it is possible to analyze the effect of one soil the soil forming factors, identified by Jenny (1980), on the magnetic properties. By sampling soils of similar age along a transect with a strong gradient in mean annual precipitation we have shown that climate is strongly linked to the soil magnetic properties (Figure 2a). These data show the effect of progressive weathering (as induced by increasing mean annual precipitation) on the soil magnetic properties. Starting out from the parent material (basalt), initial soil development (Kohala 3) leads to an increase of both χ_{fd}% and χ_{lf}. Higher χ_{lf} values result from leaching of easy soluble soil minerals and thus, preferential accumulation of primary ferrimagnetic minerals in the B-horizons. With progressive soil development (mean annual rainfall increasing from 180 to 1300mm/yr), the relatively stable primary ferrimagnetic minerals transform to paramagnetic goethite and antiferromagnetic hematite, and consequently χ_{lf} decreases. Simultaneously, increased neoformation of ultrafine secondary ferrimagnetic minerals leads to a further increase in χ_{fd}%. With an increase in development stage (as indicated by χ_{fd}%), the amount of iron in the soil increases (Figure 2b).

- Soils formed on parent materials low in iron-bearing materials usually have a lower absolute magnetic susceptibility (χ_{lf}) as well as a lower pedogenic enhancement (which may be approximated by χ_{fd}%) of the magnetic character, as was shown for soils in Northern California and in Brazil (Da Costa et al., 1999; Singer and Fine, 1989). We observed similar soil magnetic behavior in data from Panama. Magnetic data from multiple soil pits in two first-order drainages basins in the Rio Chagres watershed show distinct differences related to the parent material. The Rio Chagrecito soils (open diamond in Figure 4), which are formed in volcanic parent material, have values for χ_{lf} that are comparable to those in Hawaii. The low values of χfd% may be attributed to the abundance of mass movements on the steep slopes of the drainage basins, preventing soil stabilization and the development of pedogenic superfine magnetic minerals. The Upper Piedras soils, which have developed on granites, are characterized by low values for χ_{lf}. The other soils that were studied in Panama are located near the Technological University of Panama (UTP) and near the town of Achiote, and have been formed in volcanic parent material and sandstone, respectively.
- The magnetic signature of a soil is not necessarily correlated with that of the substrate. Magnetic data from soils in Ghana developed on sandstone and granites (both with few primary magnetic minerals) show that the low-frequency mass-specific magnetic susceptibility correlates positively with the frequency dependent magnetic susceptibility (Figure 4). This indicates that the magnetic susceptibility is predominantly the effect of magnetic soil enhancement with superparamagnetic ferrimagnetic grains. No clear correlation between mean annual precipitation and magnetic properties has been found. However, the data suggest that χ_{lf} and χ_{fd}% are lowest for young soils, and for soils that are poorly drained.
- We have measured the frequency dependent magnetic properties for hundreds of soil samples in the laboratory. Our work strongly indicates that the magnetic properties and types of minerals responsible for soil magnetism can be predicted using the same five variables (parent material, age, climate, topography/drainage, and fauna) that describe the stage of development of a soil (Jenny, 1980). Because information on these soil-forming factors can, for many locations worldwide, be found in geological, soil and climate databases, a better understanding of the link between the five variables and soil magnetism will allow for the prediction of EM and magnetic sensor performance without having been in the field.
- The final part of the project was to combine field observations of geomorphological and drainage conditions with soil magnetic properties and other soils characteristics such as age, climate, and parent material to develop a conceptual model for the prediction of soil magnetic properties. We have developed an initial, conceptual model to predict soil magnetic properties (Figure 5). This model, which is based on the measurements of soils from various locations in Ghana, Panama, and Hawaii, allows for the prediction of soil magnetic properties based on information on soil age, climate, and parent material. The model provides information on magnetic susceptibility, which is an important variable to predict performance of magnetometers, and frequency dependence, which is an important variable to understand soil development and to predict performance of electromagnetic inductions sensors. The model can be applied over a broad range of tropical and subtropical soils and is simple to use. However, some of the definitions in the model are currently poorly constrained.

- This research has formed the basis for a new full-length proposal that aims at improving the conceptual model. By improving the phenomenological understanding of soil and iron weathering in a wide range of environments and by expanding our worldwide dataset of soil magnetic properties hope to develop a quantitative predictive model for soil magnetism.

In this research we have discussed the major weathering and soil forming processes that play a role in the magnetic enhancement of soils in the tropics. Transformation to and neoformation of (superparamagnetic) ferrimagnetic grains occurs in most soils providing enough time and the correct environmental conditions. It seems apparent from our data, as well as information from the literature that there are clear correlations between soil magnetic properties and parent material, precipitation, and soil age. Low values for χ_{fd}% are generally associated with poorly developed or young soils, while with increasing weathering and soil formation the frequency dependent magnetic susceptibility increases. We attribute the observed inverse relation between χ_{lf} and mean annual precipitation for soils developed on basaltic substrates to an increase in transformation rates of primary ferrimagnetic minerals to other, less magnetic minerals. The positive correlation relation between χ_{fd}% and mean annual precipitation (observed for soils developed on all types of parent materials) can be attributed to increased neoformation of superparamagnetic ferrimagnetic grains with higher rates of soil formation.

PUBLICATIONS

Papers published in peer-reviewed journals

Van Dam, R.L., Borchers, B., and Hendrickx, J.M.H. 2005. Strength of landmine signatures under different soil conditions: implications for sensor fusion. International Journal of Systems Science, 36(9), 573-588.

Papers published in non-peer-reviewed journals or in conference proceedings

Hendrickx, J.M.H., Harrison, J.B.J., Van Dam, R.L., Borchers, B., Norman, D.I., Dedzoe, C.D., Antwi, B.O., Asiamah, R.D., Rodgers, C., Vlek, P. and Friesen, J. 2005. Magnetic Soil Properties in Ghana. In: Detection and Remediation Technologies for Mines and Minelike Targets X (Eds R.S. Harmon, J.T. Broach and J. Holloway, J.H.), 5794, pp. 165-176. SPIE, Bellingham, WA.

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Manuscripts submitted, but not published

Van Dam, R.L., Harrison, J.B.J., *Rittel, C.M., Hendrickx, J.M.H., and Borchers, B. Submitted. Magnetic Soil Properties at Two Arid to Semi-arid Sites in the Western United States. The International Society for Optical Engineering, SPIE, 2006.

Van Dam, R.L., Hendrickx, J.M.H., and Harrison, J.B.J. Submitted. Magnetic Susceptibility to Characterize Soil Development on Basaltic Substrate, Hawaii. World Congress of Soil Science 2006.

Technical reports submitted to ARO

None

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REPORT OF INVENTIONS

None

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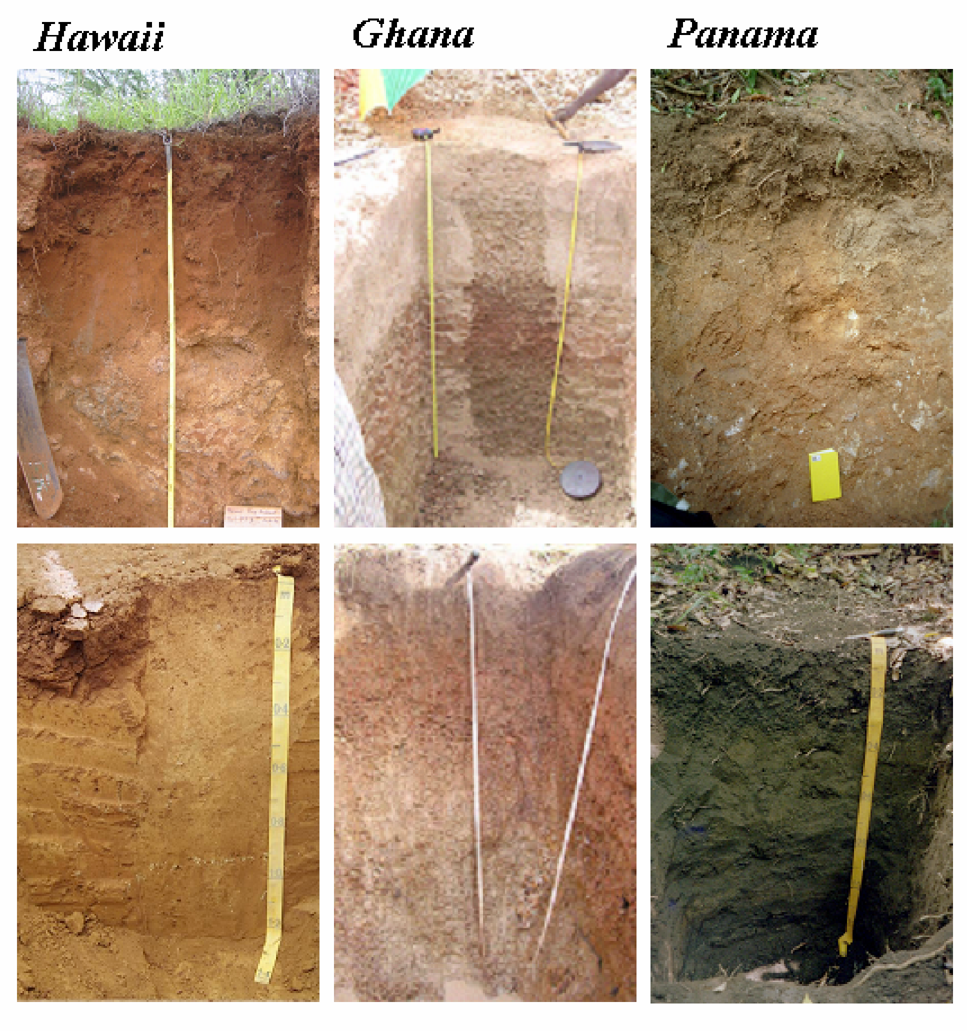
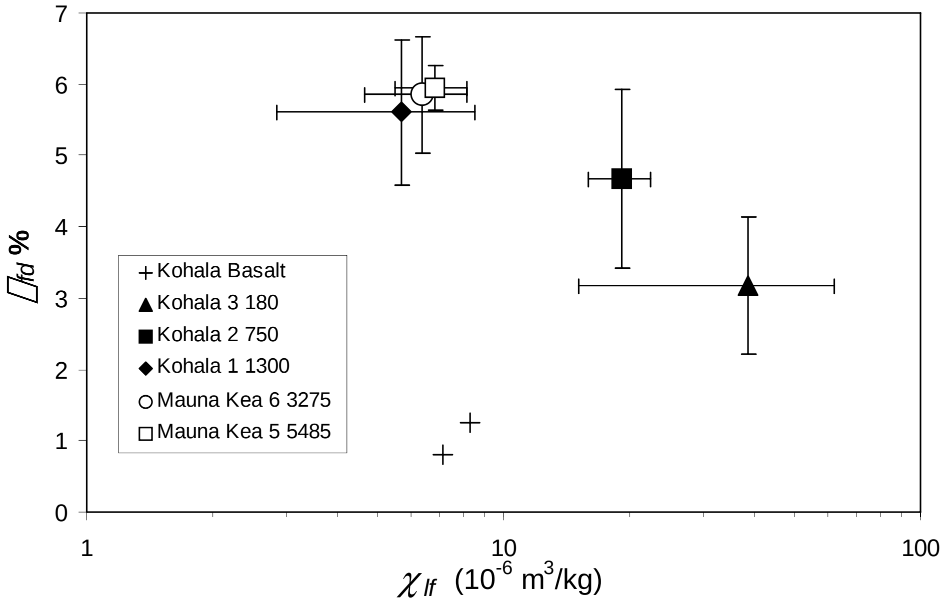
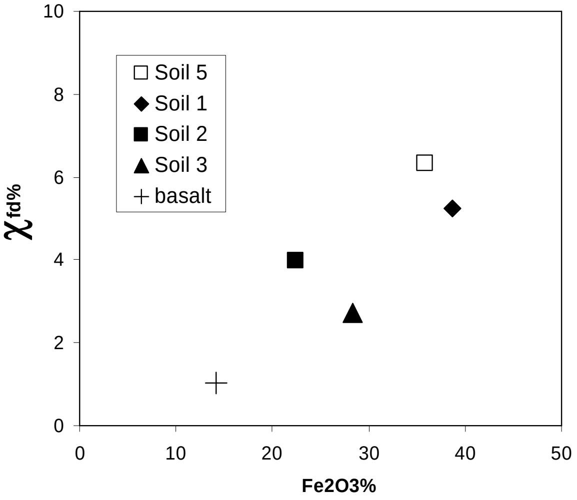
APPENDICES


Hawaii
Ghana
Panama

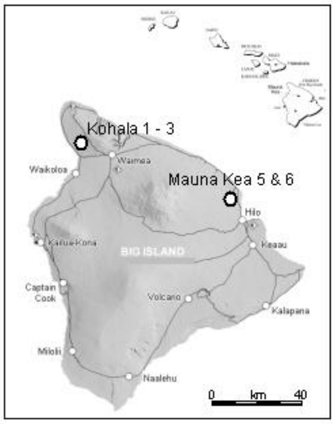
a)


7
6
5
4
3
2
1
0
χ_{fd} %
1
10
100
χ_{lf} (10^{-6} m^3/kg)
+ Kohala Basalt
▲ Kohala 3 180
■ Kohala 2 750
◆ Kohala 1 1300
○ Mauna Kea 6 3275
□ Mauna Kea 5 5485

b)


10
8
6
4
2
0
$\chi_{fd\%}$
0
10
20
30
40
50
Fe2O3%
□ Soil 5
◆ Soil 1
■ Soil 2
▲ Soil 3
+ basalt

c)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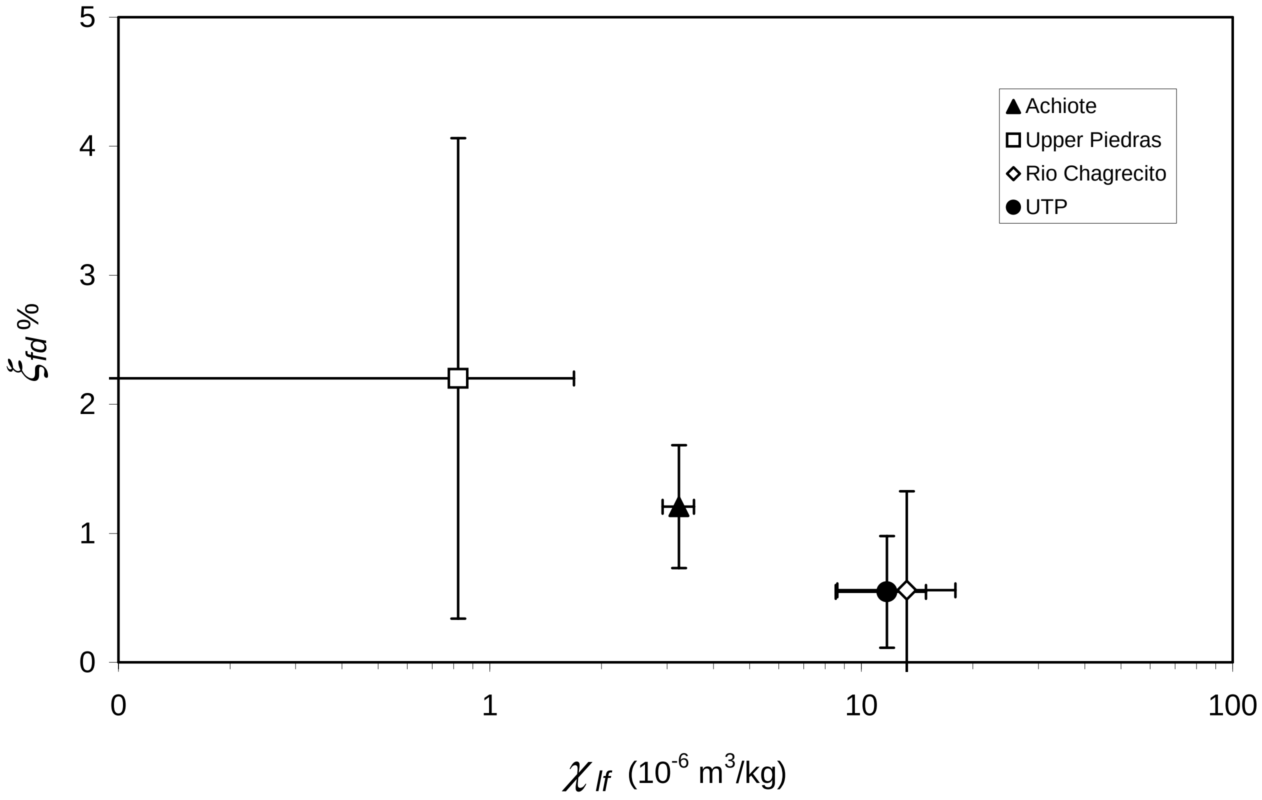
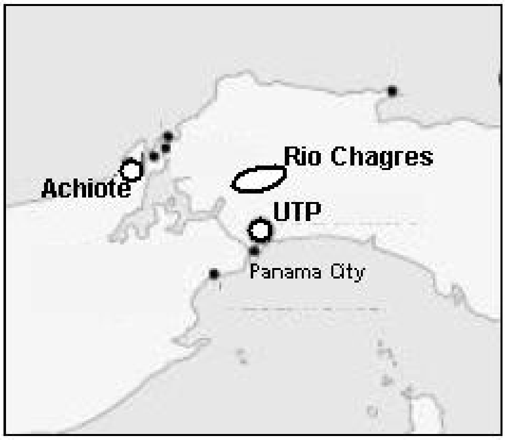
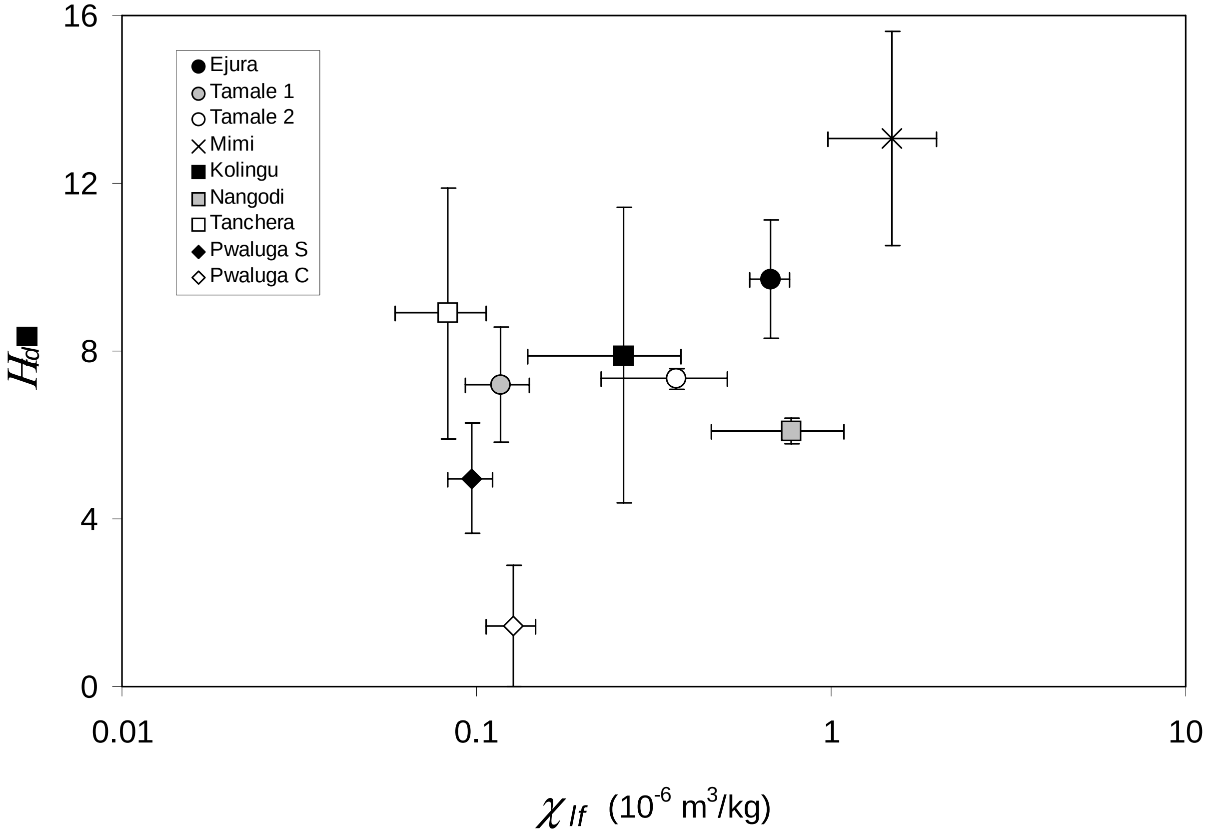
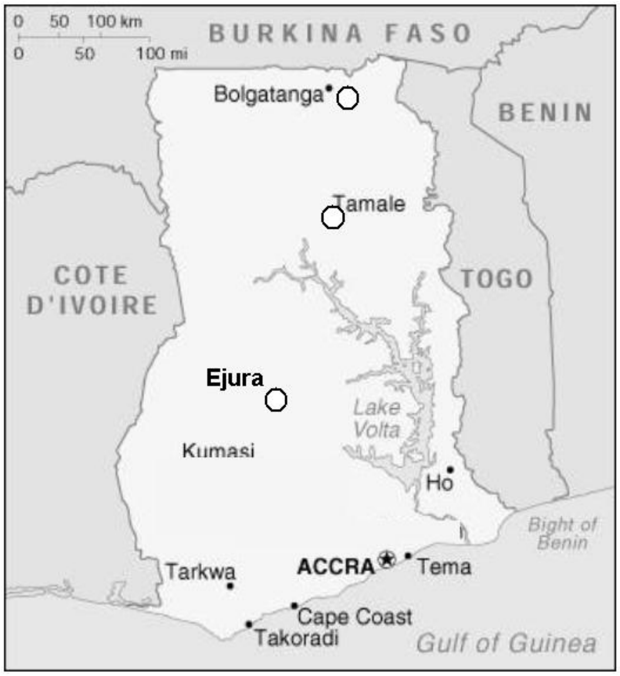
Waimea
Waikoloa
Mauna Kea 5 & 6
Hilo
Keaau
Kailua-Kona
BIG ISLAND
Captain Cook
Volcano
Kalapana
Milolii
Naalehu
0
km
40


5
4
3
2
1
0
ξ_{fd} %
0
1
10
100
χ_{lf} (10^{-6} m^3/kg)
▲ Achiote
□ Upper Piedras
◇ Rio Chagrecito
● UTP


Rio Chagres
Achiote
UTP
Panama City



● Ejura
● Tamale 1
○ Tamale 2
× Mimi
■ Kolingu
■ Nangodi
□ Tanchera
◆ Pwaluga S
◇ Pwaluga C
16
12
8
4
0
H_d
0.01
0.1
1
10
χ_{lf} (10^{-6} m^3/kg)



0 50 100 km
0 50 100 mi
BURKINA FASO
BENIN
TOGO
COTE D'IVOIRE
Bolgatanga
Tamale
Ejura
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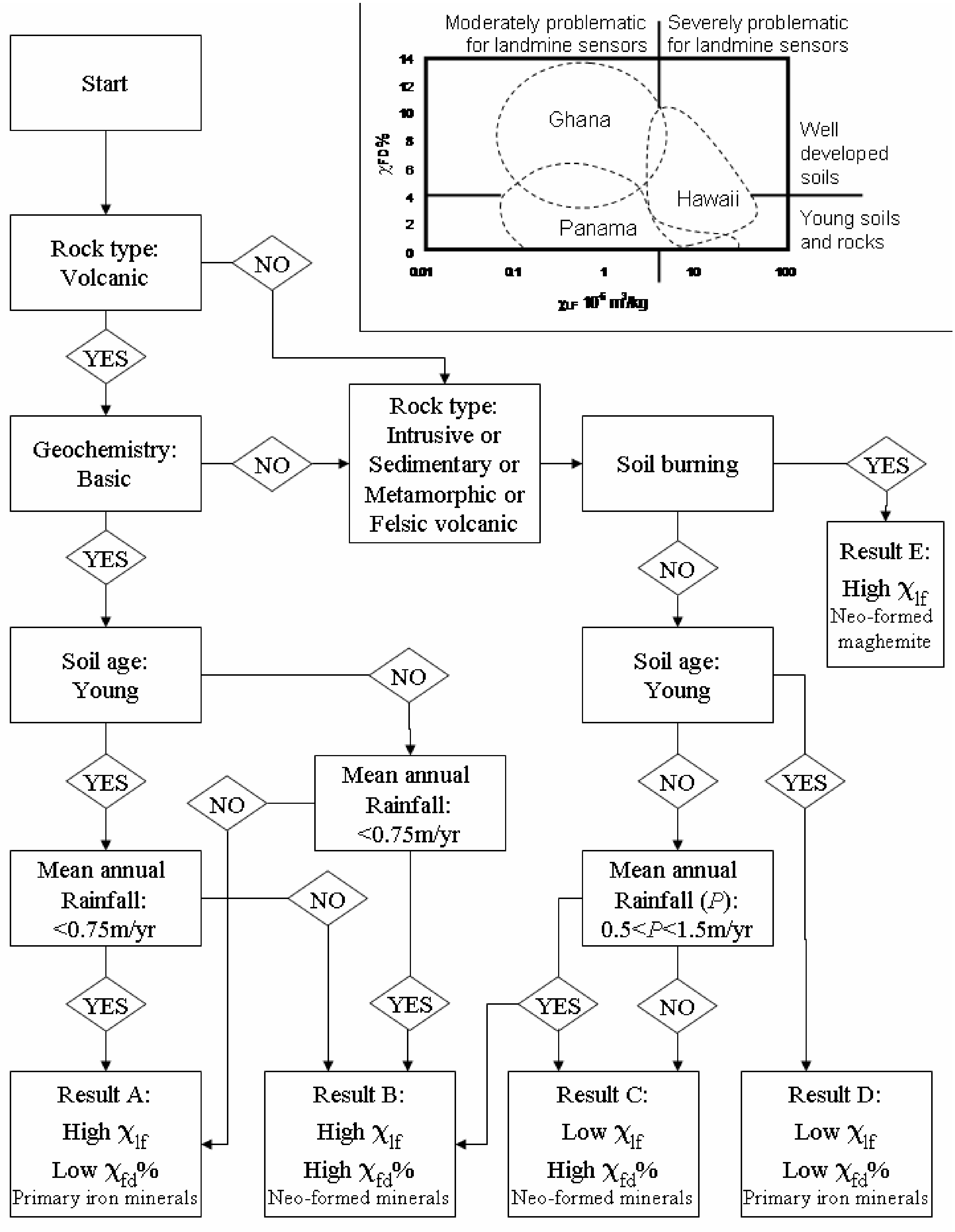
Kumasi
Ho
Bight of Benin
Tarkwa
ACCRA
Tema
Cape Coast
Takoradi
Gulf of Guinea



Moderately problematic for landmine sensors
Severely problematic for landmine sensors
χFD%
14
12
10
8
6
4
2
0
0.01
0.1
1
10
100
χLF 10⁻⁶ m³/kg
Ghana
Hawaii
Panama
Well developed soils
Young soils and rocks
Start
Rock type: Volcanic
NO
YES
Geochemistry: Basic
NO
Rock type: Intrusive or Sedimentary or Metamorphic or Felsic volcanic
Soil burning
YES
Result E: High χlf Neo-formed maghemite
YES
NO
Soil age: Young
NO
Soil age: Young
YES
NO
Mean annual Rainfall: <0.75m/yr
NO
YES
Mean annual Rainfall: <0.75m/yr
NO
Mean annual Rainfall (P): 0.5<P<1.5m/yr
YES
YES
YES
NO
Result A: High χlf Low χfd% Primary iron minerals
Result B: High χlf High χfd% Neo-formed minerals
Result C: Low χlf High χfd% Neo-formed minerals
Result D: Low χlf Low χfd% Primary iron minerals