Soil Formation, Diversity, and Behavior

Objectives

To gain a general understanding of:

- The 5 soil forming factors and 4 soil forming processes
- Soil diversity
- Soil behavior

Soil Formation

$$\text{Soil} = f(\text{PM, Cl, O, R, T})$$

<u>Factors</u>:

PM = parent material (rocks)

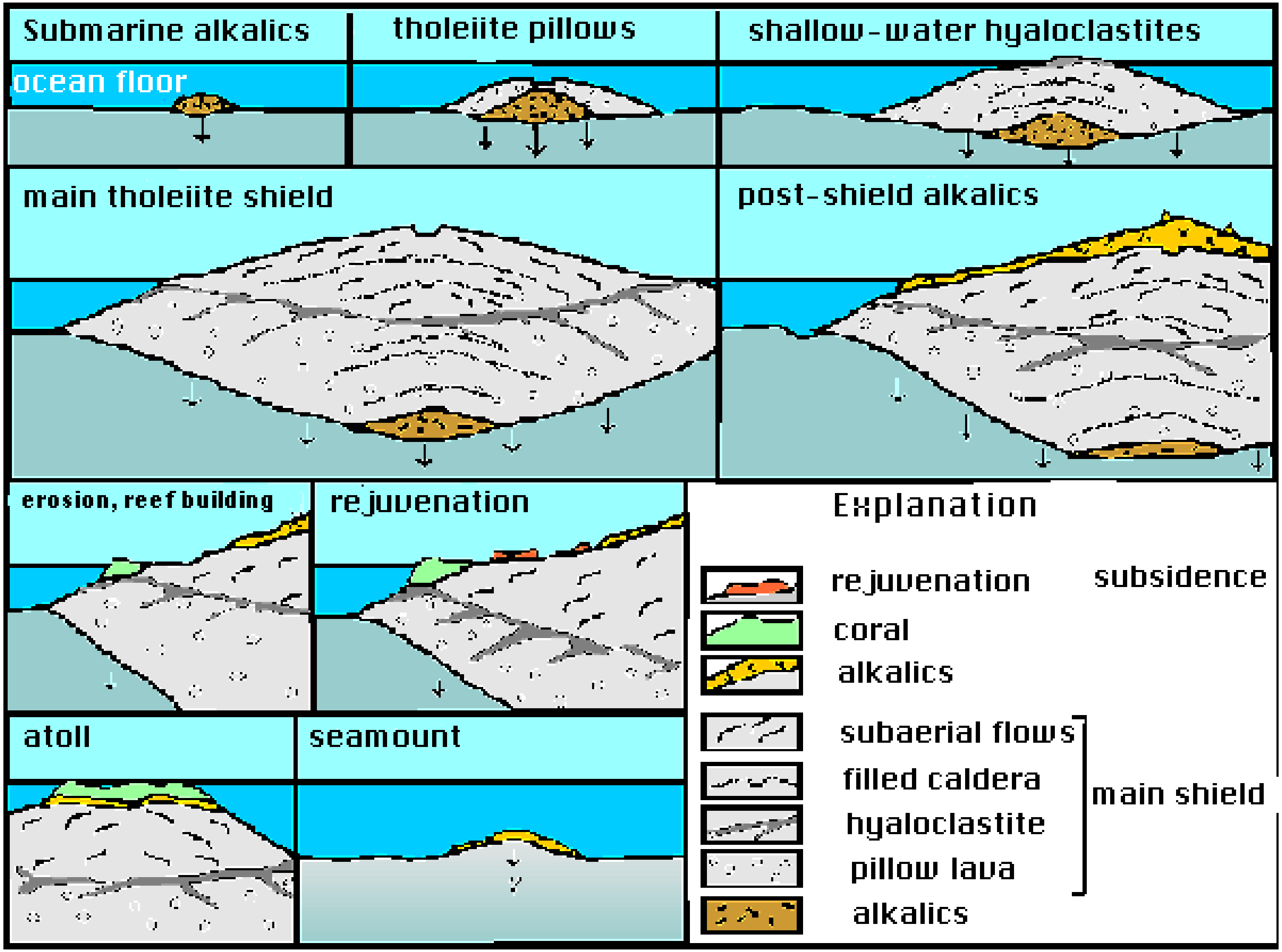
Cl = climate (precipitation and temperature)

O = organisms (plants and animals)

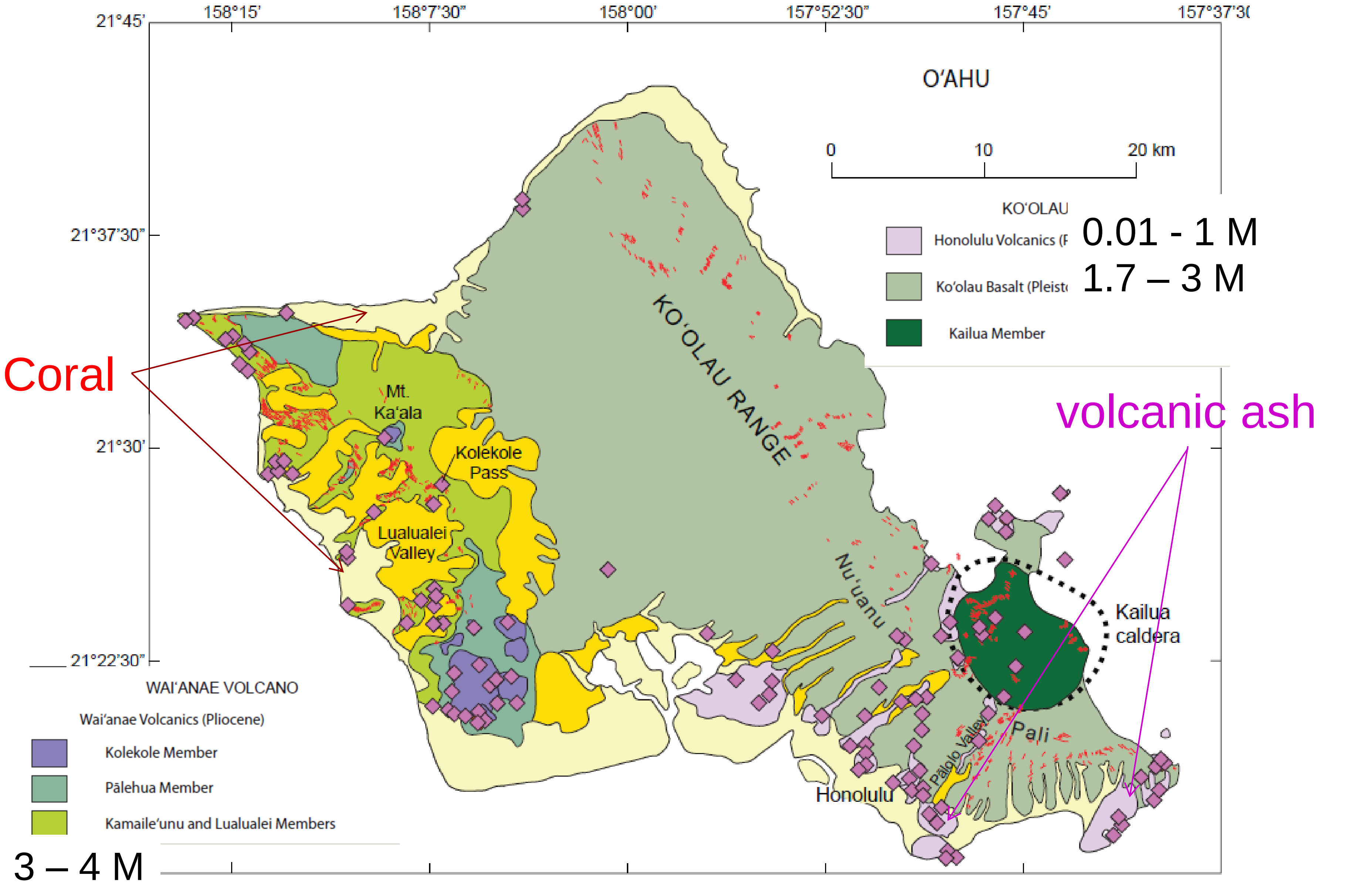
R = relief (topography, drainage)

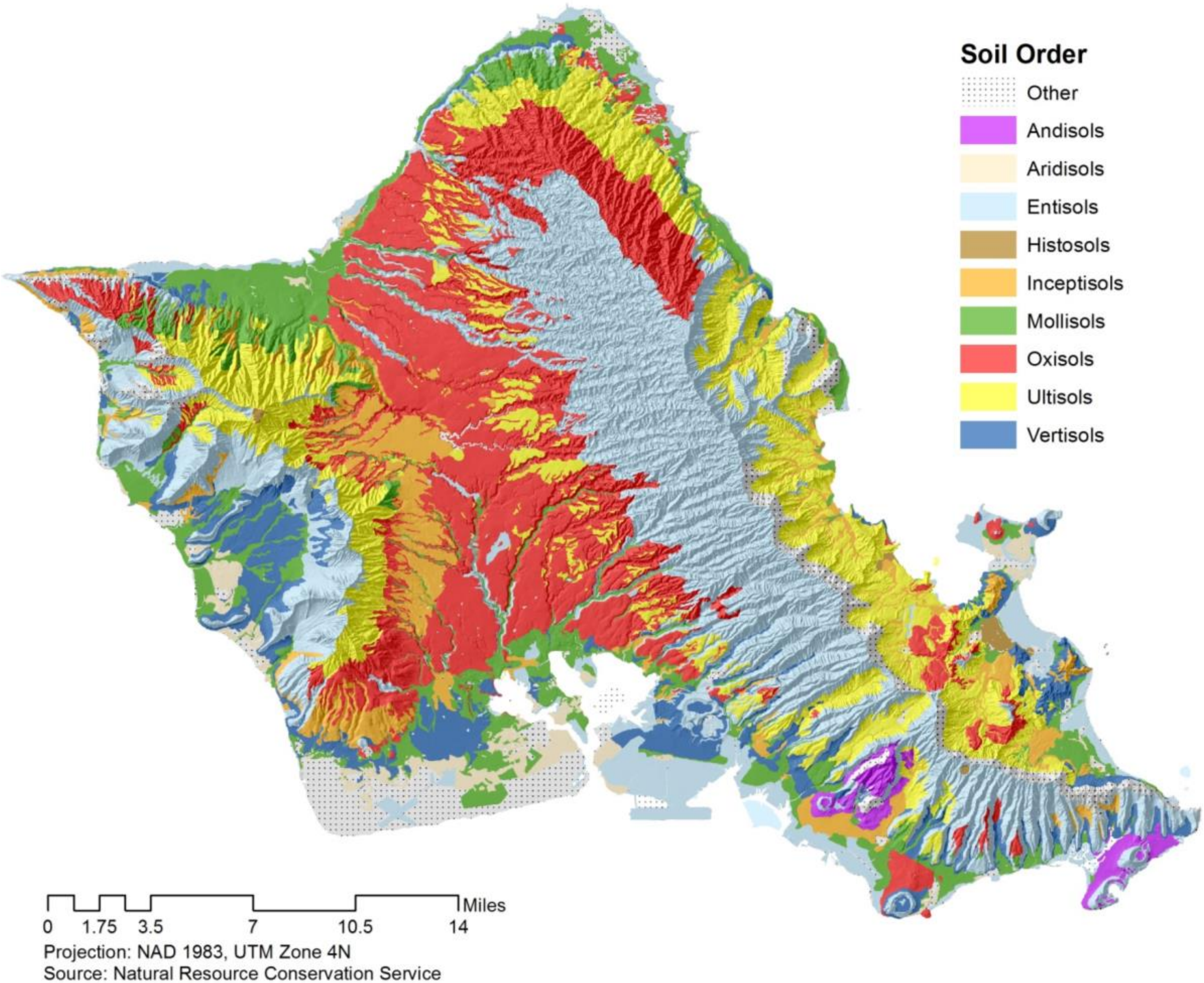
T = time

Stages of Volcanism



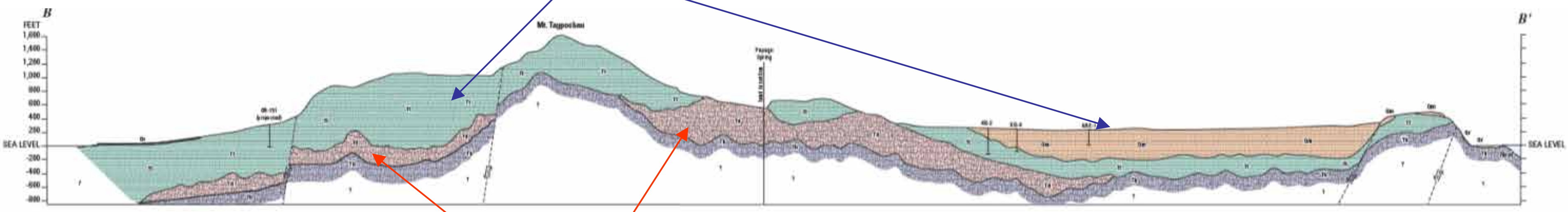
Volcanic Stages




Soil Order
Other
Andisols
Aridisols
Entisols
Histosols
Inceptisols
Mollisols
Oxisols
Ultisols
Vertisols
0 1.75 3.5 7 10.5 14 Miles
Projection: NAD 1983, UTM Zone 4N
Source: Natural Resource Conservation Service

Geology of Tinian

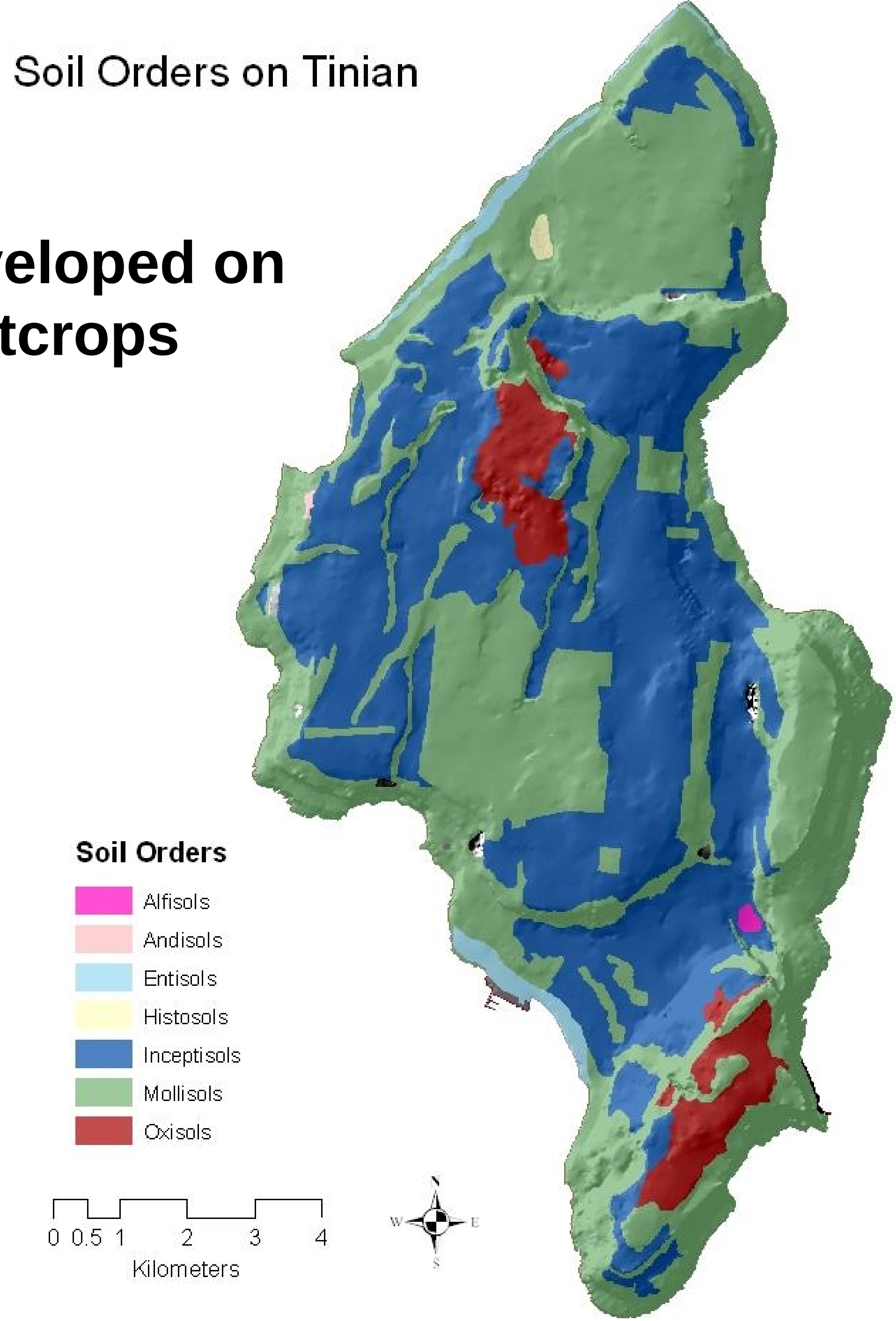
Limestone rock

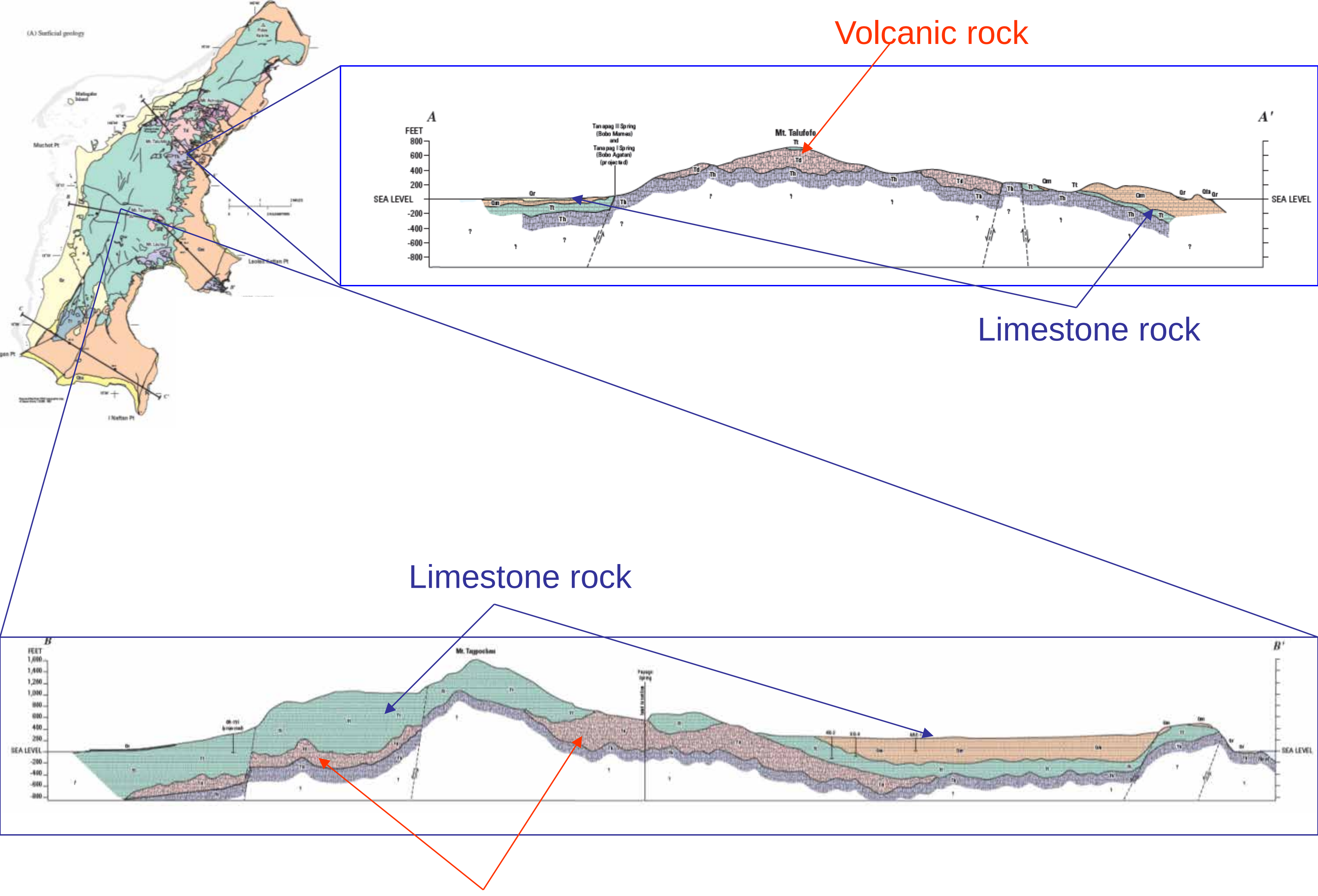


Volcanic rock

Source: R.L. Carruth (2003), USGS, Report 03-4178

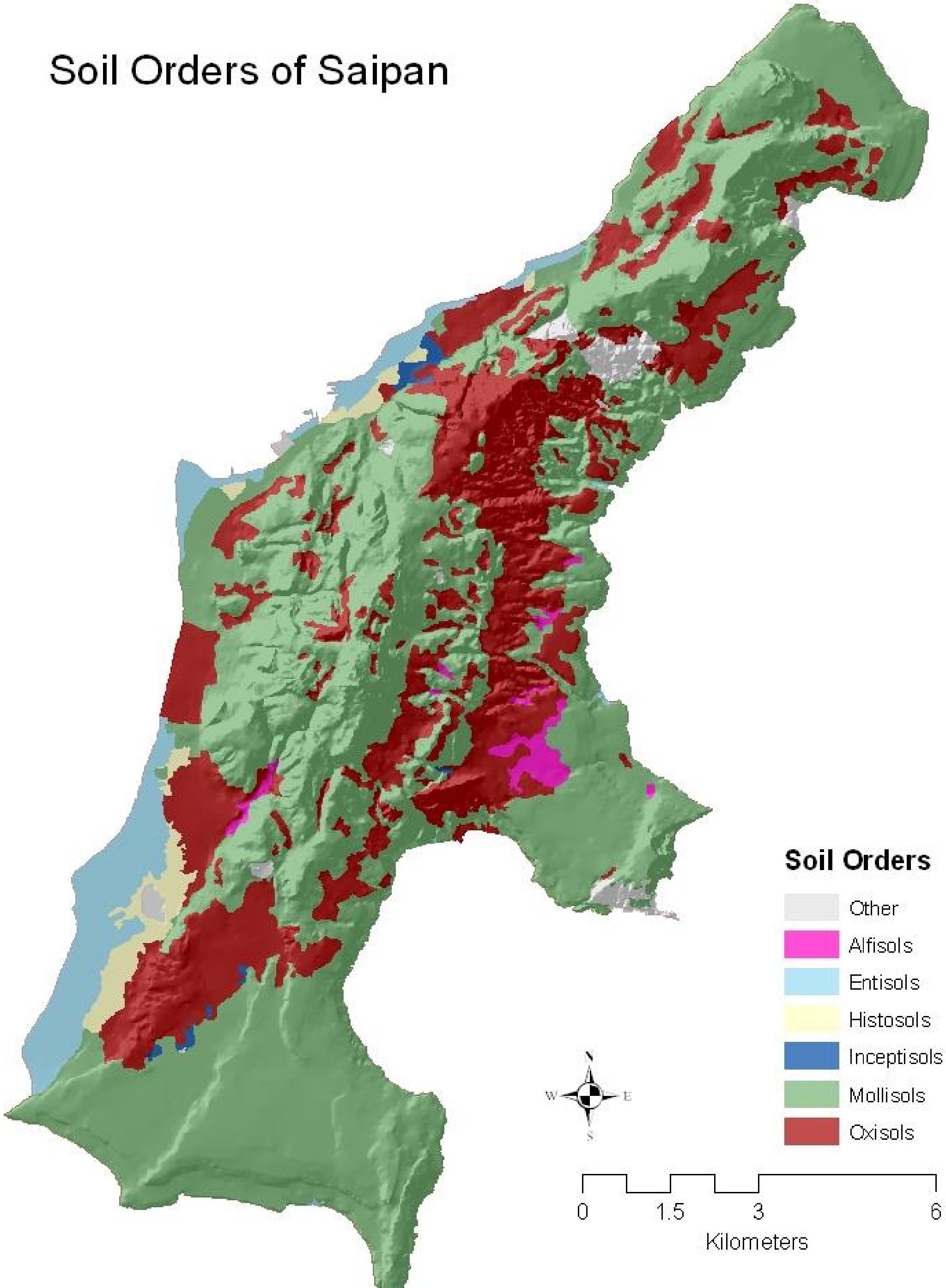
Oxisols developed on volcanic outcrops





Source: R.L. Carruth (2003), USGS, Report 03-4178

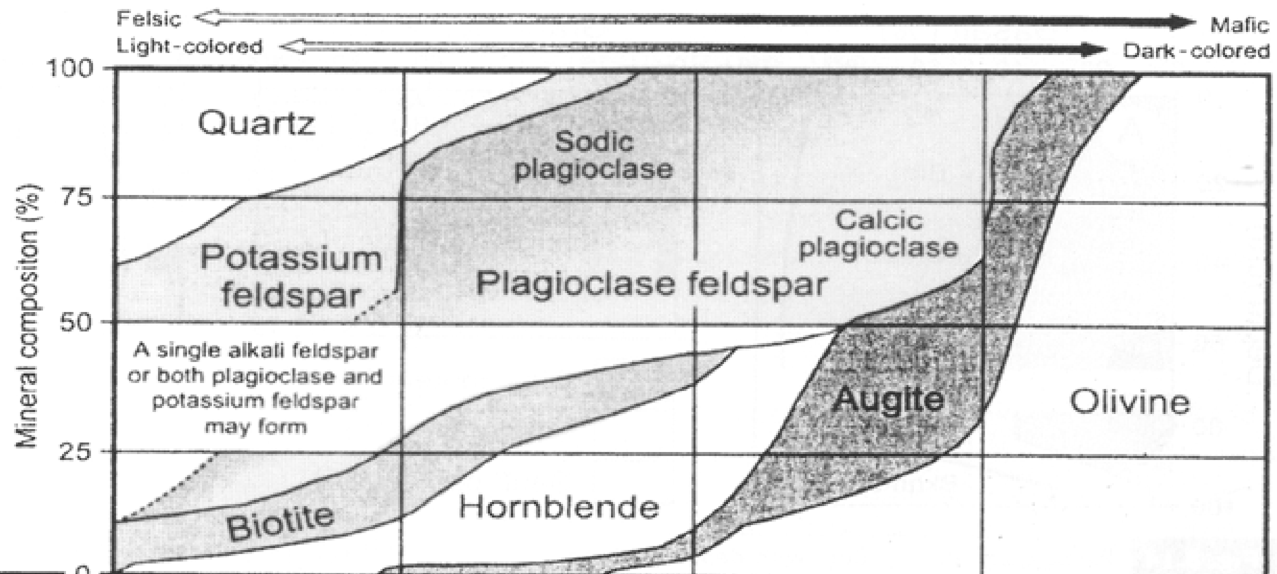
Soil Orders of Saipan



Map made by J. Deenik

Coarse ⟷ Fine

SiO_2-rich Fe/Mg-rich



Crystal size						
Very coarse (Pegmatic)		Pegmatic granite	Pegmatic diorite	Pegmatic gabbro	——	——
3 cm						
Coarse		Granite	Diorite	Gabbro	Peridotite	Dunite
0.1 mm						
Mixed sizes	Coarse matrix with some larger crystals — Porphyry	Porphyritic granite	Porphyritic diorite	Porphyritic gabbro	——	——
	Fine matrix with some larger crystals	Porphyritic rhyolite	Porphyritic andesite	Porphyritic basalt	——	——
0.1 mm						
Fine	No or very few larger crystals	Felsite if light in color Andesite if intermediate		Basalt	——	——
0						
Glassy		Obsidian (Pumice if frothy)		Trachyte	——	——

Source: Singer & Munns (1991)

Chemical composition of some common primary and secondary minerals.

Light-colored minerals

Quartz	SiO_2
Orthoclase feldspar	$KAlSi_3O_8$
Anorthoclase feldspar	$(K,Na)AlSi_3O_8$
Plagioclase feldspar: Albite	$NaAlSi_3O_8$
Plagioclase feldspar: Anorthite	$CaAl_2Si_2O_8$
Nepheline	$NaAlSiO_4$
Calcite	$CaCO_3$
Gypsum	$CaSO_4 \cdot 2H_2O$
Kaolinite (clay)	$Al_2Si_2O_5(OH)_4$
Gibbsite	$Al(OH)_3$
Montmorillonite	$(Al,Mg)_8(Si_4O_{10})_3(OH)_{10} \cdot 12H_2O$

Dark-colored minerals

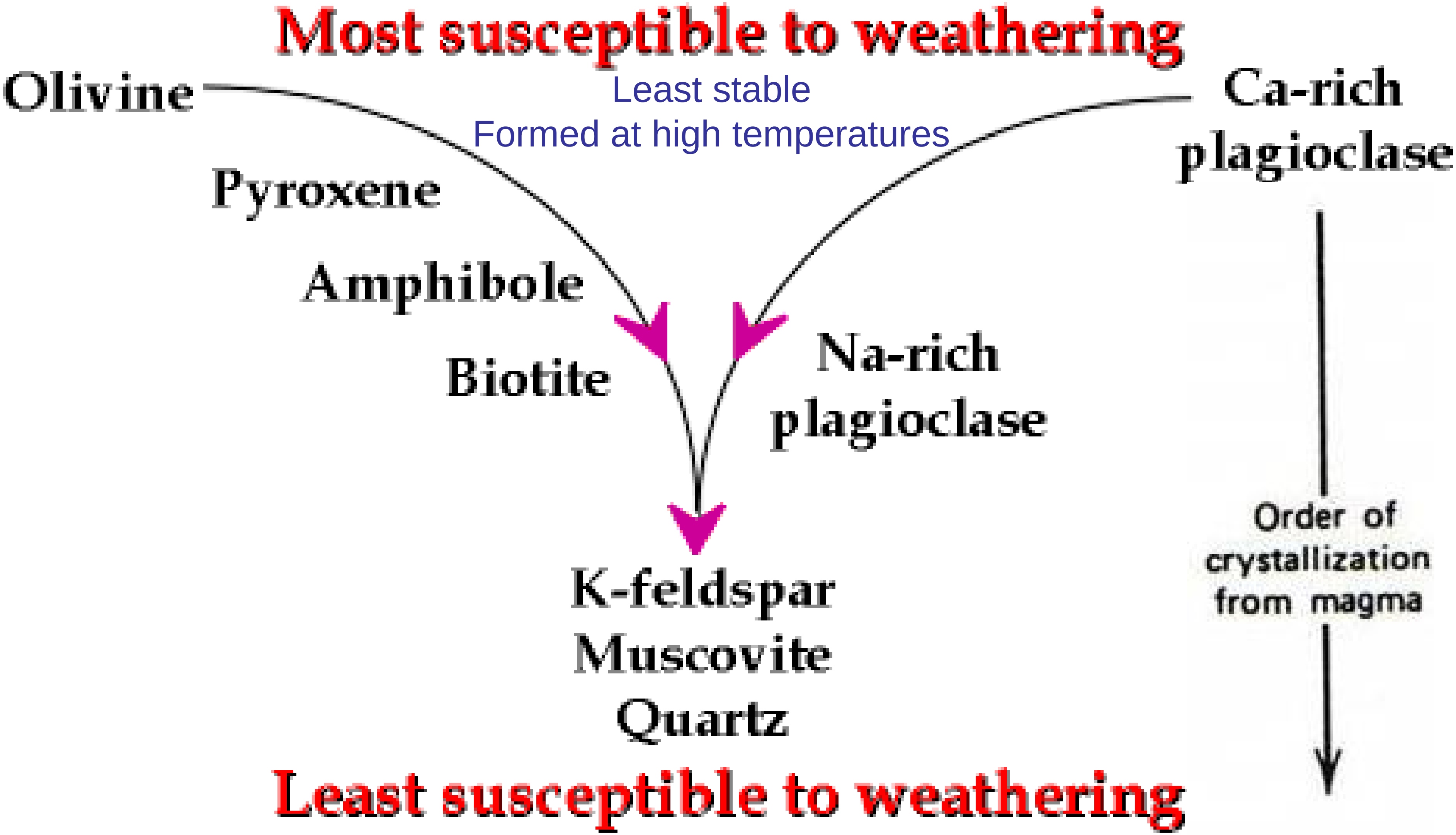
Biotite (black mica)	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
Olivine	$(Mg,Fe)_2SiO_4$
Pyroxene: Hypersthene	$(Mg,Fe)SiO_3$
Pyroxene: Pigeonite	$(Mg,Fe)SiO_3$
Pyroxene: Augite	$Ca(Mg,Fe)Si_2O_6 \cdot (Al,Fe)_2O_3$
Magnetite	Fe_3O_4
Hematite	Fe_2O_3
Ilmenite	$FeO \cdot TiO_2$
Melilite	$Ca(Mg,Fe)_2Si_2O_7$
Chlorite	$(Mg,Fe)_5(Al,Fe)_2Si_3O_{10}(OH)_8$
Limonite	$Fe_2O_3 \cdot nH_2O$

Source: Zumberge & Rotford (1983), p.21

Rocks to Soil

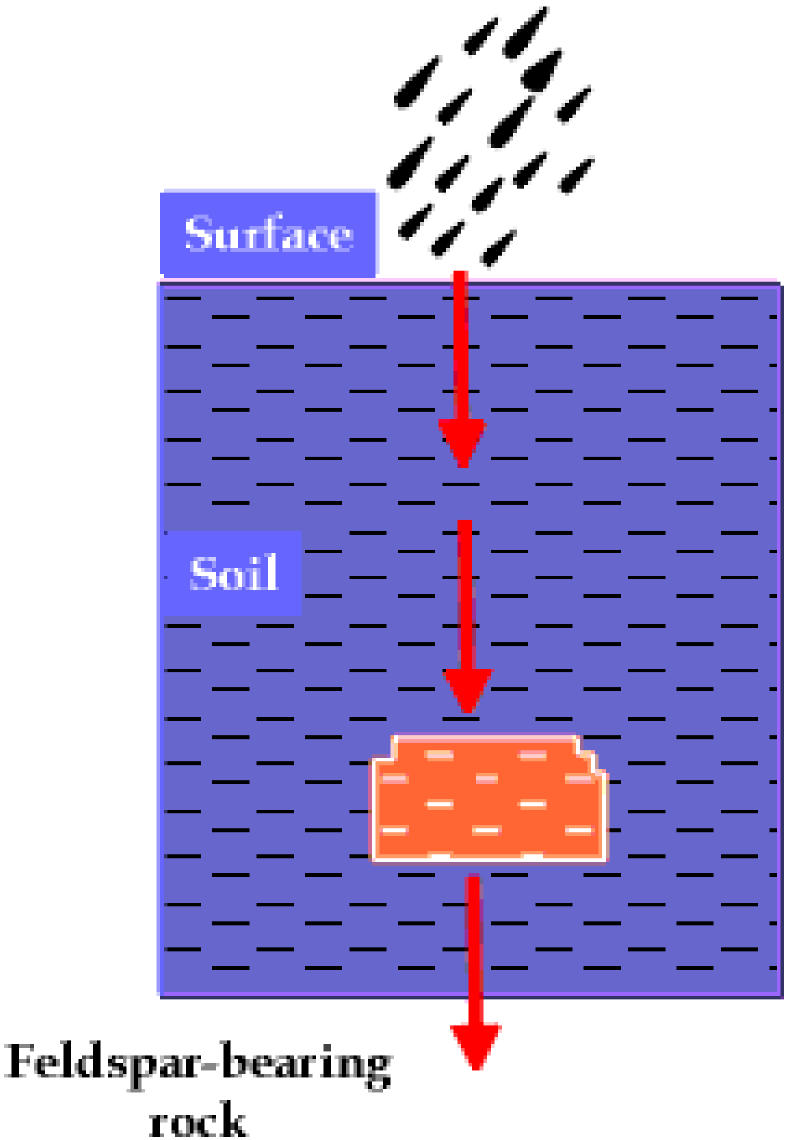
- Weathering
  - Physical: disintegration of parent material into smaller and smaller particles (no chemical change
  - Chemical: primary minerals in parent material subject to a variety of chemical reactions (hydration, hydrolysis, dissolution, acid reactions, complexation) forming secondary clay minerals (phyllosilicates, Al/Fe oxides)

Goldich Stability Series



Least stable
Formed at high temperatures

Most stable
Formed at low temperatures



Rain picks up CO_2 from the atmosphere

Water percolating through the soil picks up more CO_2 from the upper part of the soil profile becoming acidic

A feldspar crystal, loosened from the rock below, slowly alters to clay as it reacts with the acidic water

Water carries away soluble salts and SiO_2 to a stream

$$H_2O + CO_2 \text{ ------->> } H_2CO_3$$

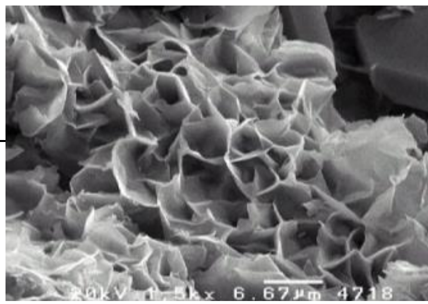
$$2KAlSi_3O_8 + 2H^+ + H_2O \text{ ------->> } Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$$

Feldspar *Kaolinite*

Clay Formation

Weathering Reactions of Pyroxenes

$Ca(Mg,Fe)Si_2O_6 + H_2O + H^+ =$ Ca-montmorillonite $+ H_4SiO_4 + Ca^{2+} + Fe(OH)_3$



$(½Ca,Na)(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4\ nH_2O$

Weathering Reactions of Orthoclase (K-Feldspar)

Step 1: $3\ KAlSi_3O_8 + 2\ H^+ + 12\ H2O \rightarrow KAl_3Si_3O_{10}(OH)_2 + 6\ H_4SiO_4 + 2\ K^+$

orthoclase — illite(~muscovite)

Step 2: $2\ KAl_3Si_3O_{10}(OH)_2 + 2\ H^+ + 3\ H_2O \rightarrow 3\ Al_2Si_2O_5(OH)_4 + 2\ K^+$

illite — kaolinite

Weathering Sequence of Basalt Parent Rock

$$CaAl_2Si_2O_8 + 2H_2O + 4H^+ \longrightarrow Ca^{2+} + 2Al^{3+} + 2Si(OH)_4$$

Ca- plagioclase *Soluble silica*

Hydrolysis Reaction

$$Al^{3+} + Si(OH)_4 + 1/2H_2O \longrightarrow H^+ + 1/2Al_2Si_2O_5(OH)_4$$

Kaolinite

Synthesis Reaction

$$Al_2Si_2O_5(OH)_4 + 5H_2O \longrightarrow 2Si(OH)_4 + 2Al(OH)_3$$

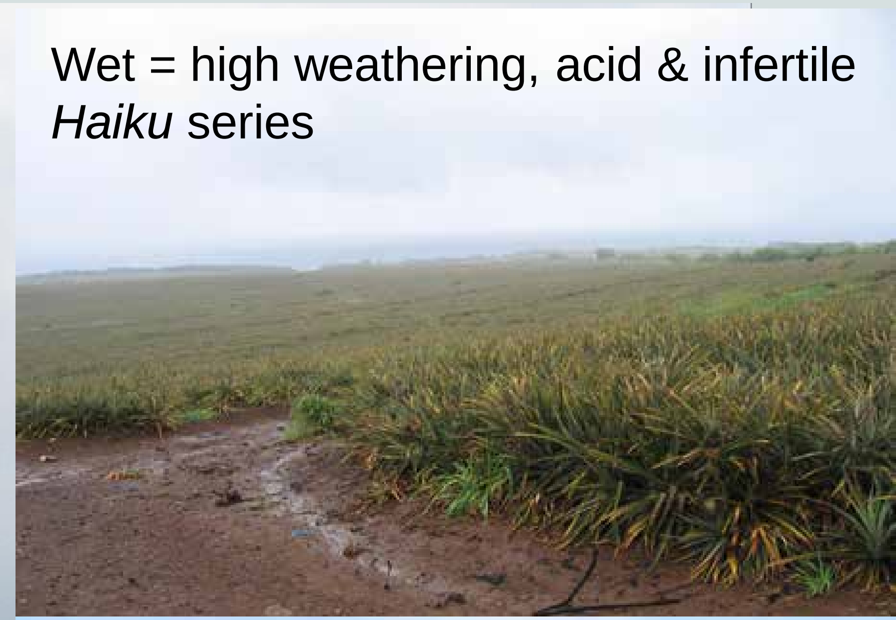
Kaolinite *Soluble silica* *Gibbsite*

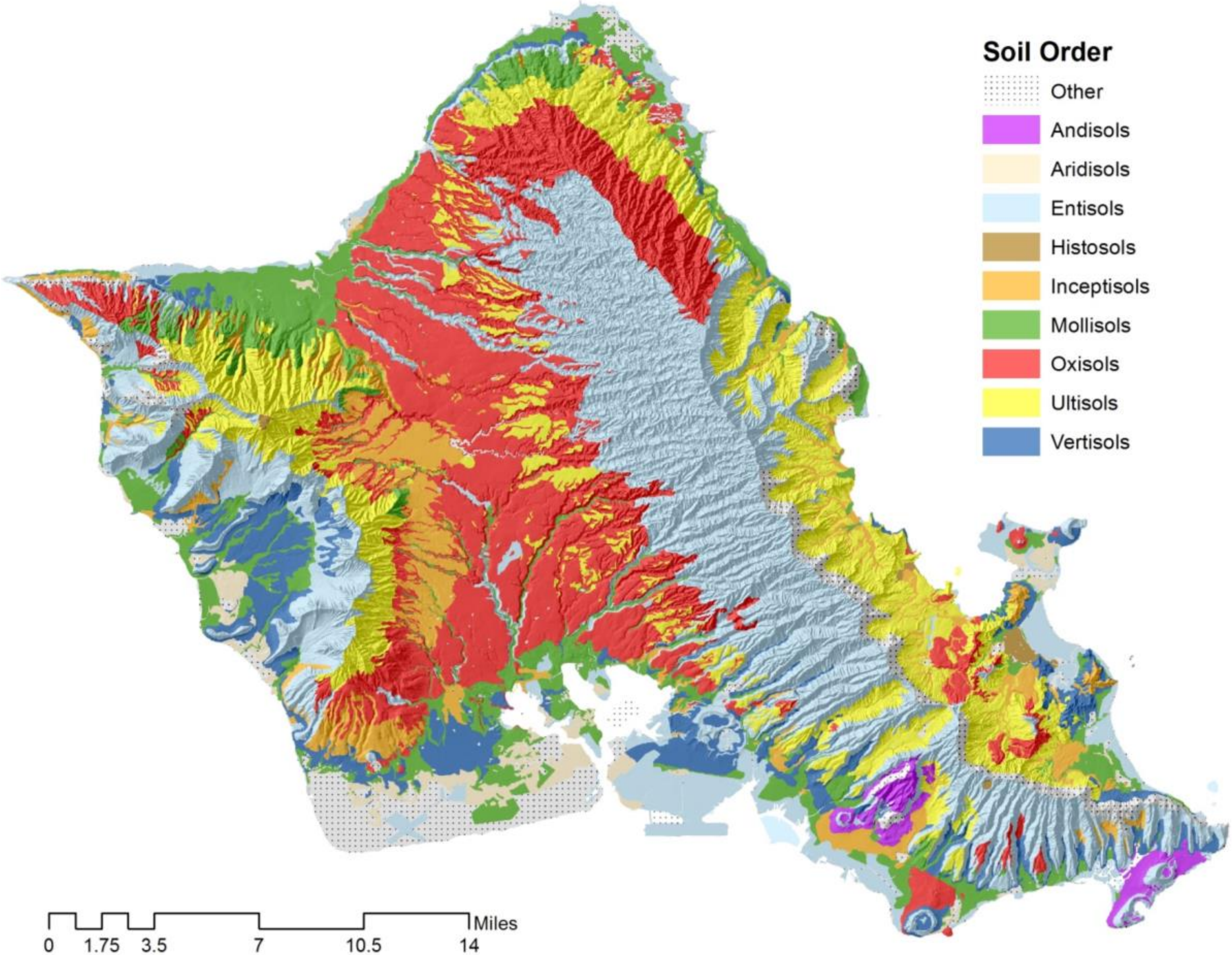
Desilication

RELATIVE DEGREE OF SOIL DEVELOPMENT	PROMINENT MINERALS IN SOIL CLAY FRACTION
1	Gypsum, sulfides, and soluble salts
2	Calcite, dolomite, and apatite
3	Olivine, amphiboles, and pyroxenes
4	Micas and chlorite
5	Feldspars
6	Quartz
7	Muscovite
8	Vermiculite and hydrous micas
9	Montmorillonites
10	Kaolinite and halloysite
11	Gibbsite and allophane
12	Goethite, limonite, and hematite
13	Titanium oxides, zircon, and corundum.

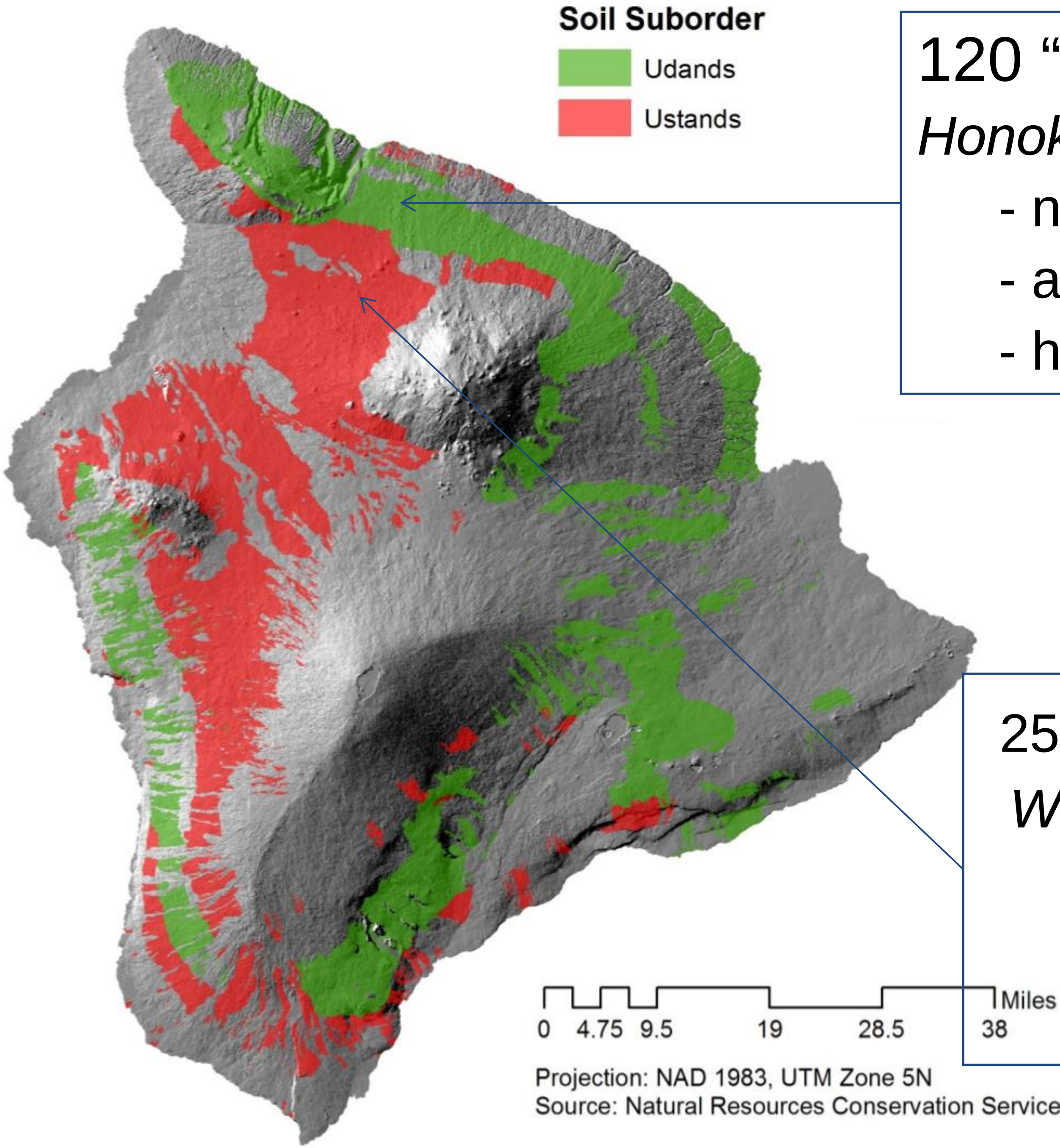
[a]Adapted from M. L. Jackson and G. D. Sherman. *Advances in Agronomy*.

Climate and Soil Diversity





Projection: NAD 1983, UTM Zone 4N
Source: Natural Resource Conservation Service



120 " Precipitation

Honokaa series

- nutrient depleted
- acid pH
- high organic matter

25 – 30" Precipitation

Waimea series

- nutrient rich
- neutral pH
- high organic matter

ELSEVIER

Chemical Geology 202 (2003) 195–223

CHEMICAL GEOLOGY
INCLUDING
ISOTOPE GEOSCIENCE

www.elsevier.com/locate/chemgeo

The impact of climate on the biogeochemical functioning of volcanic soils

Oliver A. Chadwick[a,*], Robert T. Gavenda[b], Eugene F. Kelly[c], Karen Ziegler[a], Carolyn G. Olson[d], W. Crawford Elliott[e], David M. Hendricks[f]

[a] *Department of Geography, University of California, Santa Barbara, CA 93106, USA*
[b] *USDA Natural Resources Conservation Service, Kealakekua, HI 96750, USA*
[c] *Department of Soil and Crop Sciences, Colorado State University, Ft. Collins, CO 80523, USA*
[d] *USDA Natural Resources Conservation Service, Soil Survey Division, Lincoln, NE 68508, USA*
[e] *Department of Geology, Georgia State University, Atlanta, GA 30303, USA*
[f] *Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85721, USA*

Received 2 November 2001; received in revised form 24 June 2002; accepted 6 September 2002

Abstract

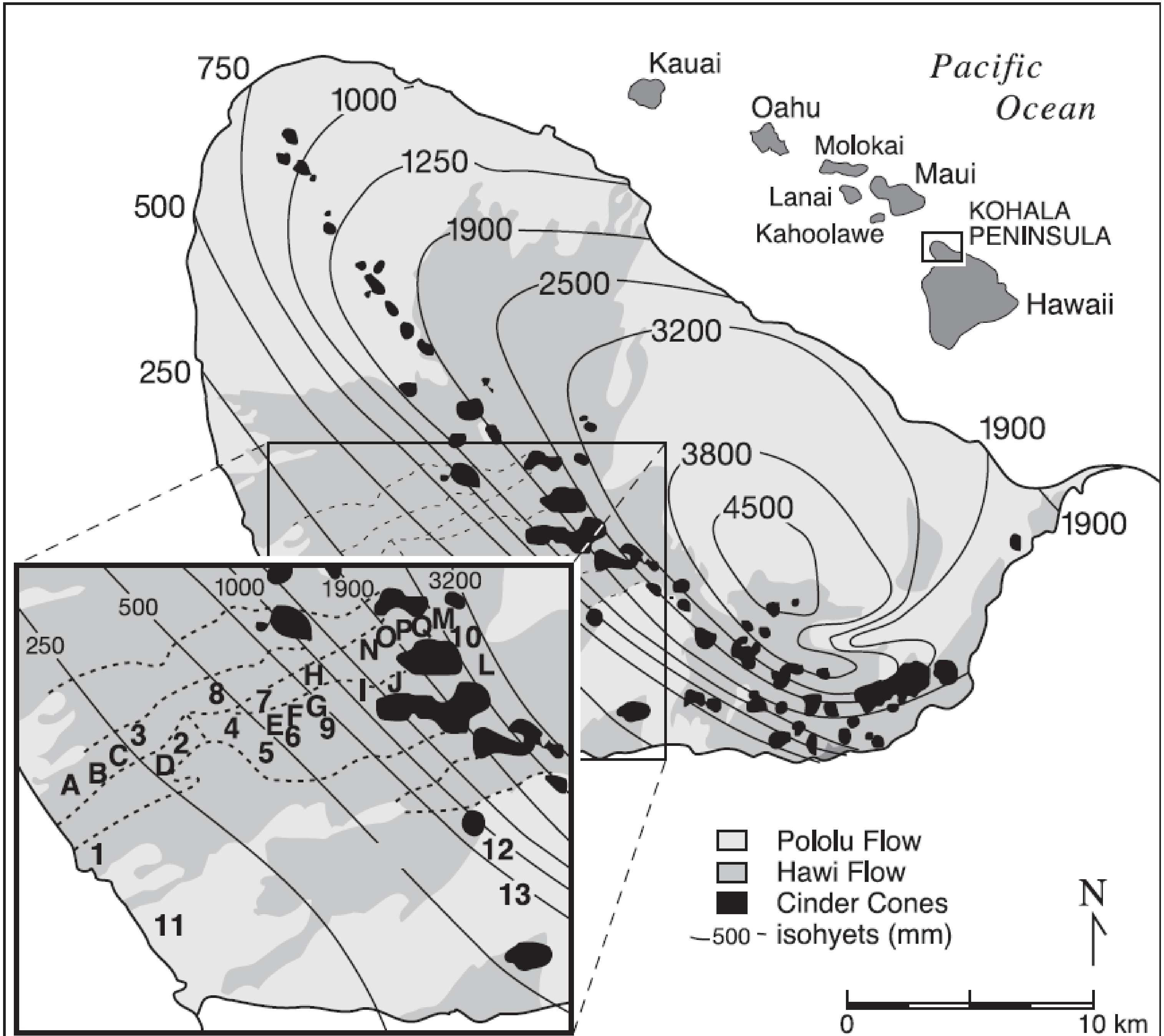
Rainfall and the amount of water available to leach ions from soil are among the most important features determining mineral weathering, secondary mineral synthesis and soil chemical properties. Along an arid to humid climosequence on Kohala Mountain, Hawaii, we sampled 16 soil profiles and found that weathering and soil properties change in a nonlinear fashion with increased rainfall. The lavas are influenced by a strong rain shadow with mean annual precipitation (MAP) averaging 160 mm near the coast and rising to >3000 mm near the summit. A temperature decline from 24 to 15 °C with increasing elevation is matched by lower potential evapotranspiration (ET). A water balance model (monthly precipitation minus monthly ET) defines three broad climate zones along the sampling transect: an arid zone with moisture deficit in every month, an intermediate zone with moisture deficit during low-rainfall summer months and moisture surplus during high-rainfall winter months, and a humid zone with moisture surplus during every month. The annualized water balance can be ratioed with the integrated porosity of the top meter of soil to provide a leaching index.

The index reaches 1 (total filling of the pore space on an annual basis) at about 1400 mm MAP. Index values >1 imply intense leaching conditions because of pore water replacement. In these 170 ka soils, leaching losses of soluble base cations and Si are nearly complete at index values >1, whereas only 60% of Al has been lost. At index values <1 leaching losses are progressively lower with the lowest rainfall sites having lost 10–20% of the original base cations and Si and none of the Al. At all sites, the secondary clay mineral assemblage is dominated by metastable noncrystalline weathering products; humid soil profiles contain very few crystalline minerals whereas the arid profiles contain halloysite, hematite, gibbsite and small amounts of carbonates. Soil surface exchange properties are influenced strongly by climatic conditions and show a dramatic threshold in base cation saturation, pH and effective cation exchange capacity (ECEC) at leaching index of 1 (1400 mm MAP). Soils with leaching index of <1 have high base cation saturation, near-neutral pH and high ECEC. At MAP >1400 mm, soil buffering capacity has been totally exhausted leading to low pH and low ECEC.

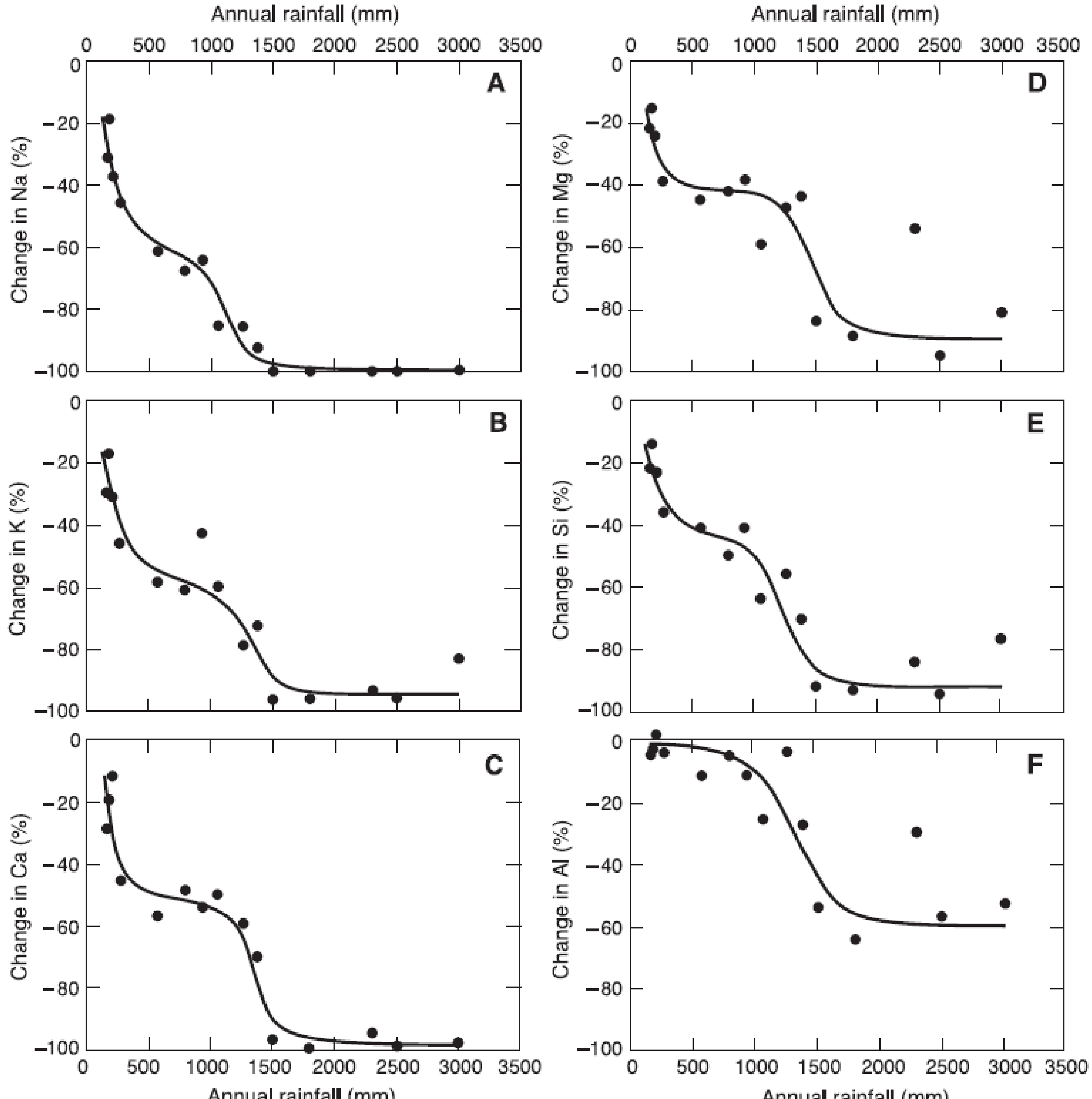
The nonlinear decline in ECEC is irreversible under natural conditions; base cation depleted soils will remain so even if the climate shifts to drier conditions. In contrast, a climate shift to wetter conditions can drastically modify surface chemical

* Corresponding author. Tel.: +1-805-893-4223; fax: +1-805-893-8686.
E-mail address: oac@geog.ucsb.edu (O.A. Chadwick).

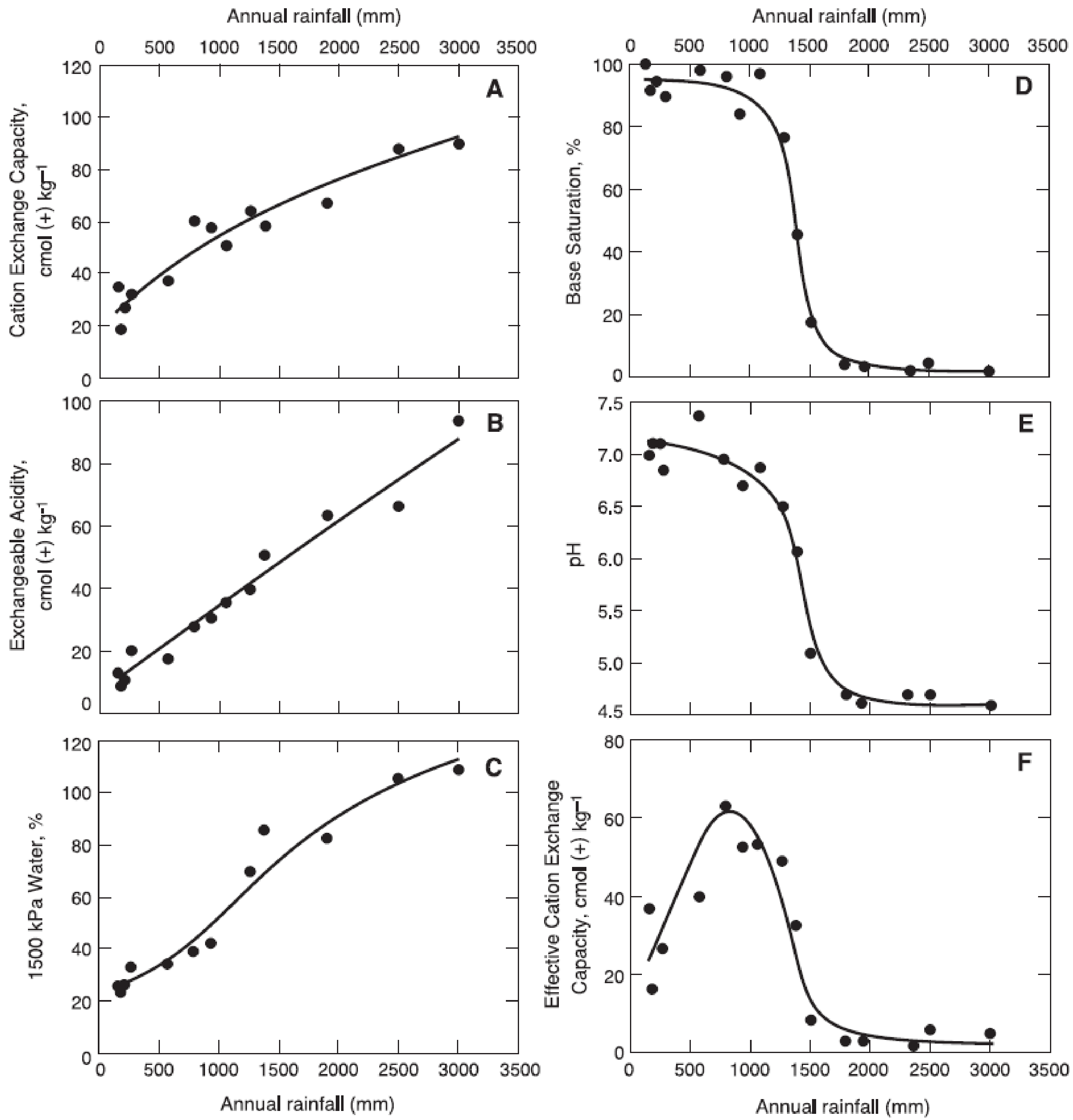
0009-2541/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/j.chemgeo.2002.09.001



Pacific Ocean
Kauai
Oahu
Molokai
Maui
Lanai
Kahoolawe
KOHALA PENINSULA
Hawaii
750
1000
1250
500
1900
2500
3200
250
3800
4500
1900
1900
250
500
1000
1900
3200
N O P Q M 10
L
H
I J
8 7
G
E F
4
6 9
3
2
C
B
D
5
A
1
12
13
11
Pololu Flow
Hawi Flow
Cinder Cones
500 isohyets (mm)
N
0
10 km

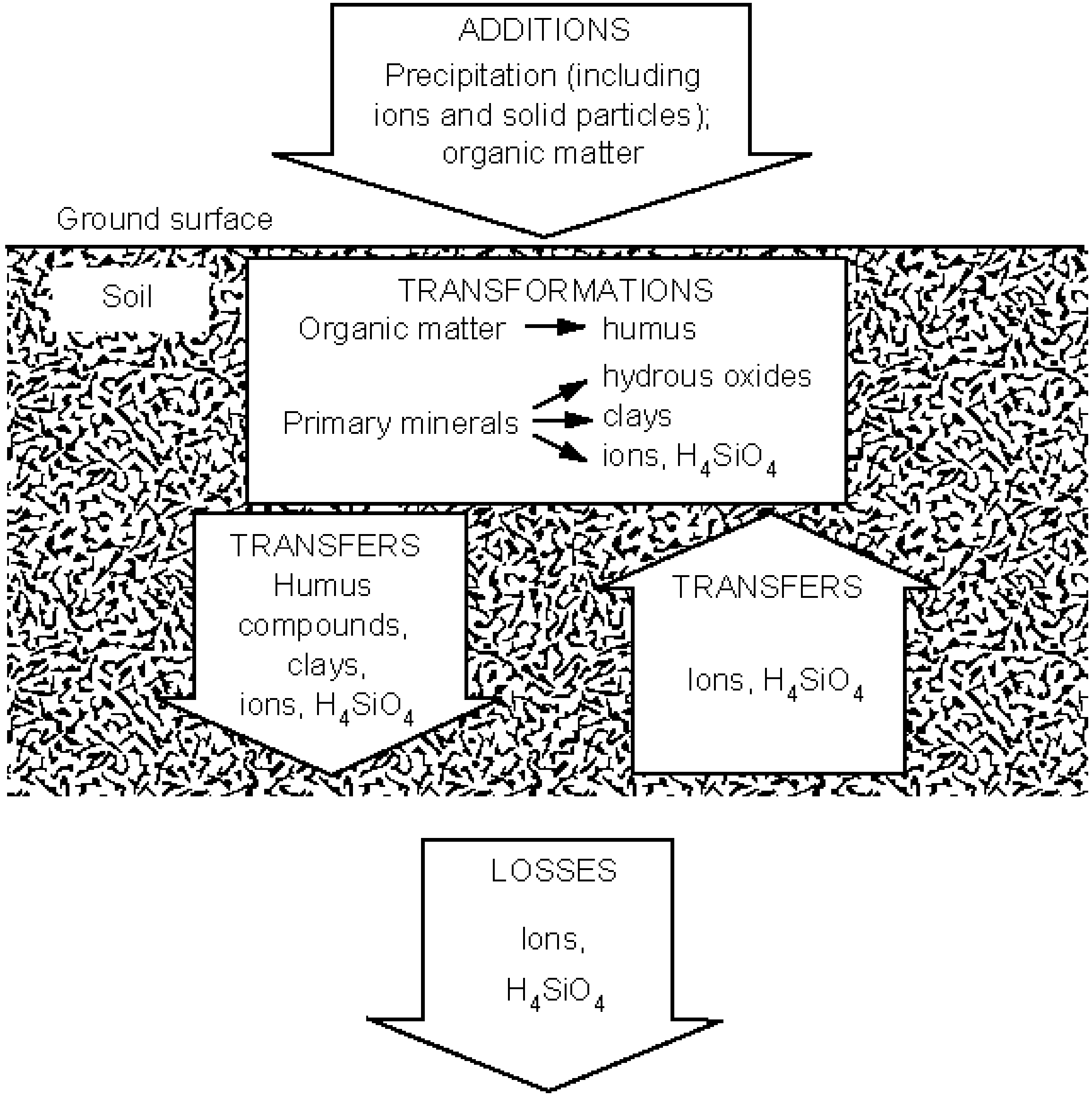


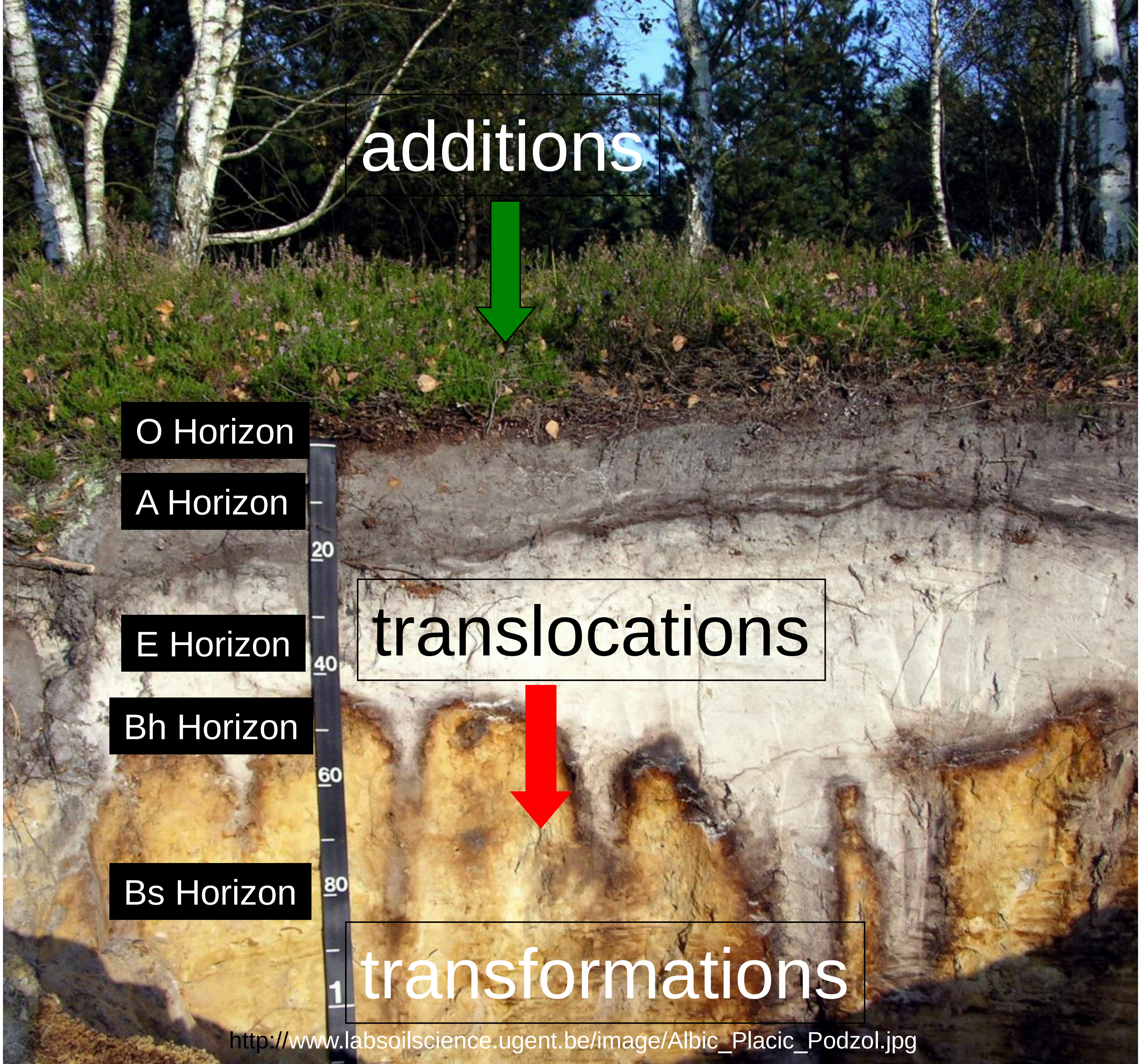
Annual rainfall (mm)
0
500
1000
1500
2000
2500
3000
3500
A
B
C
D
E
F
Change in Na (%)
Change in K (%)
Change in Ca (%)
Change in Mg (%)
Change in Si (%)
Change in Al (%)
0
−20
−40
−60
−80
−100



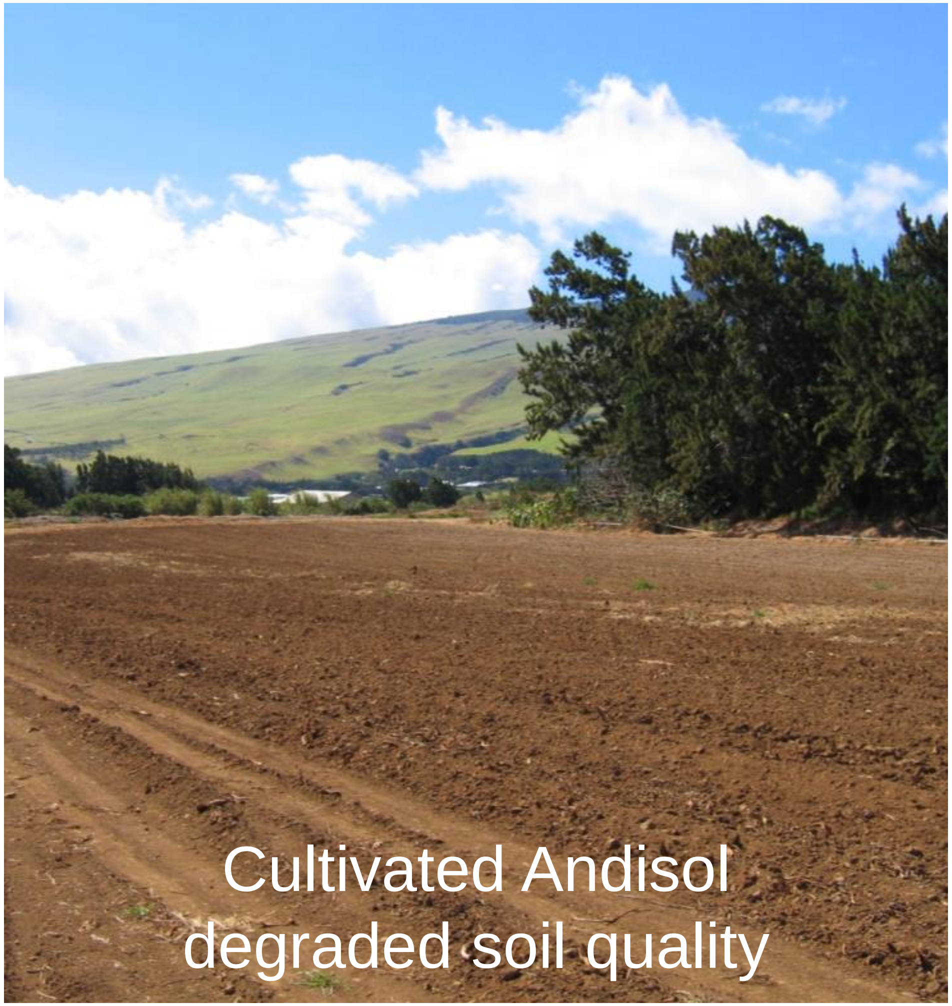
Annual rainfall (mm)
Cation Exchange Capacity, cmol (+) kg⁻¹
A
Exchangeable Acidity, cmol (+) kg⁻¹
B
1500 kPa Water, %
C
Base Saturation, %
D
pH
E
Effective Cation Exchange Capacity, cmol (+) kg⁻¹
F

Soil Forming Processes



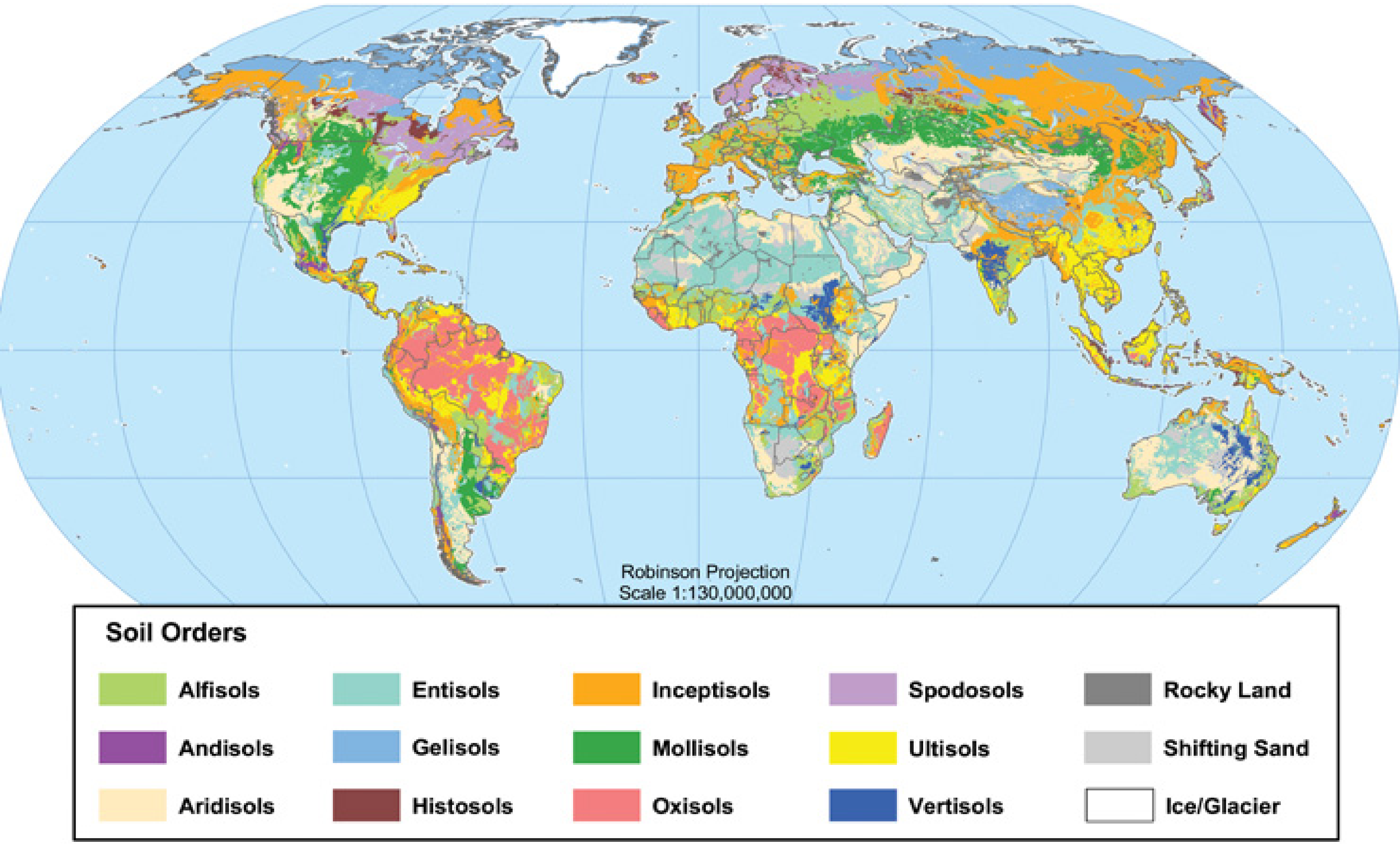

additions
O Horizon
A Horizon
20
E Horizon
40
translocations
Bh Horizon
60
Bs Horizon
80
transformations
http://www.labsoilscience.ugent.be/image/Albic_Placic_Podzol.jpg

Human Activities



http://replantingtherainforests.org/site/images/stories/tp1.jpg

Global Soil Regions

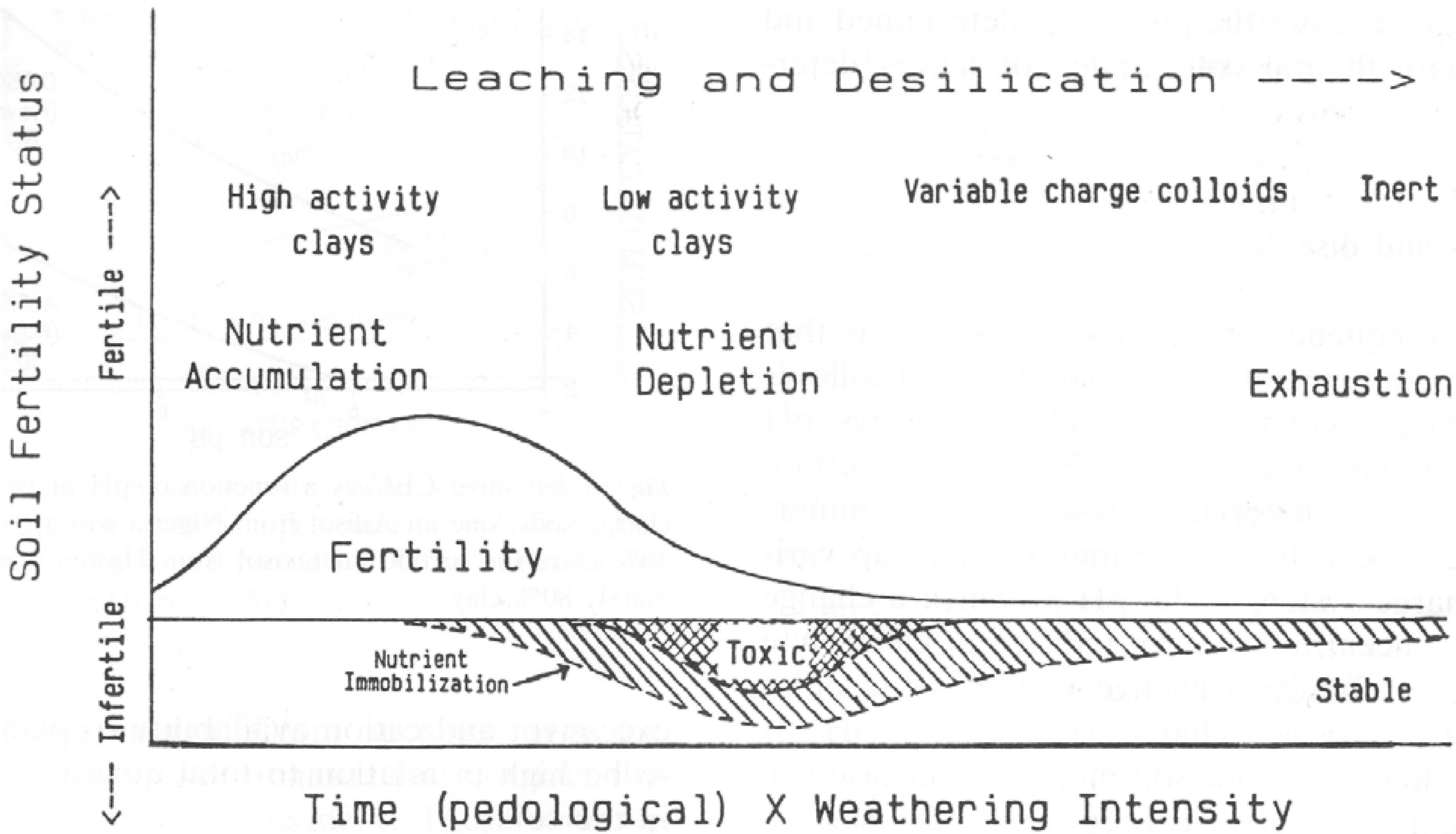


USDA NRCS
US Department of Agriculture
Natural Resources
Conservation Service

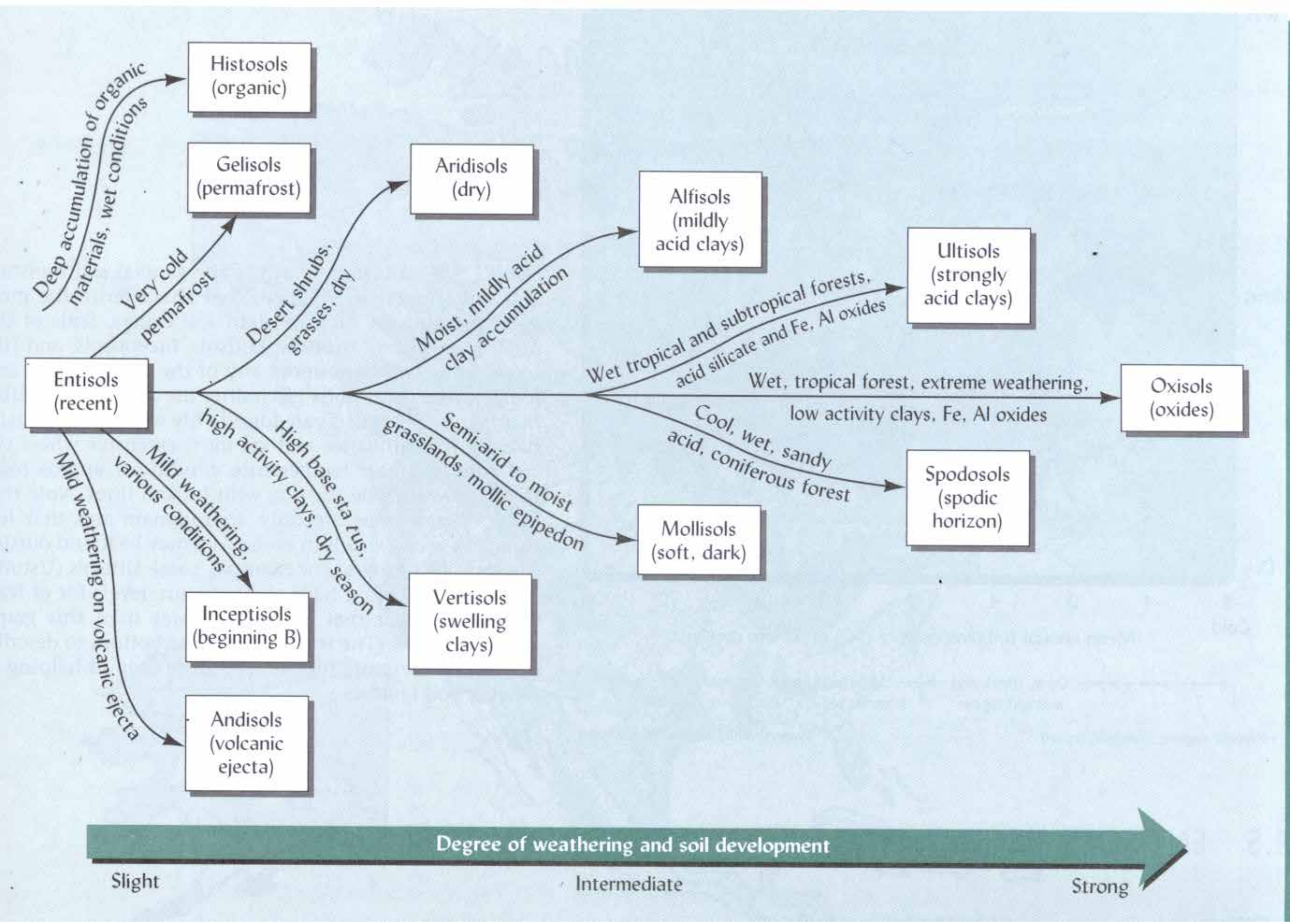
Soil Survey Division
World Soil Resources
soils.usda.gov/use/worldsoils

November 2005

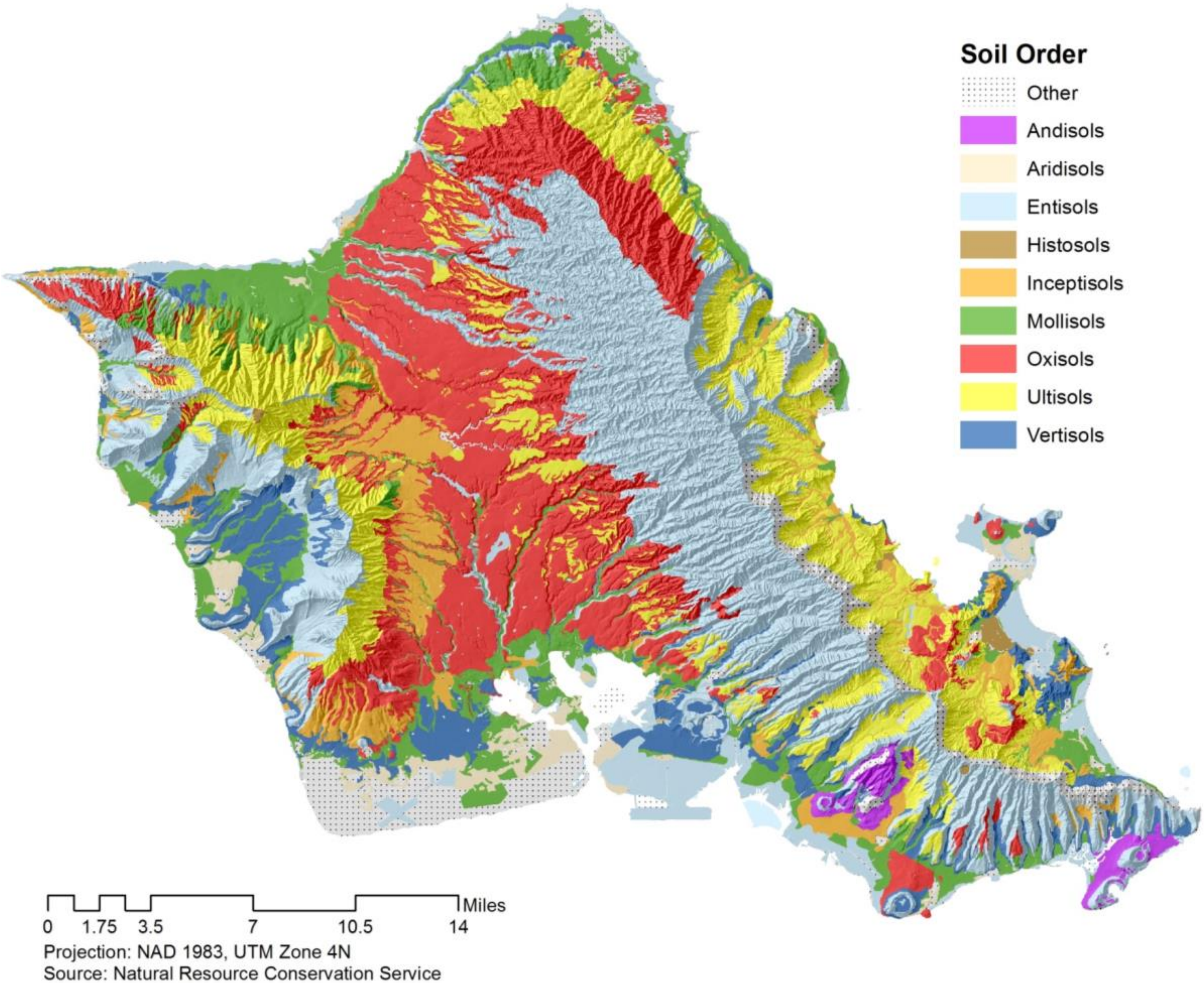
Weathering Intensity and Soil Fertility



Fox et al. (1991)



Brady & Weil (2004)


Soil Order
Other
Andisols
Aridisols
Entisols
Histosols
Inceptisols
Mollisols
Oxisols
Ultisols
Vertisols
0
1.75
3.5
7
10.5
14
Miles
Projection: NAD 1983, UTM Zone 4N
Source: Natural Resource Conservation Service

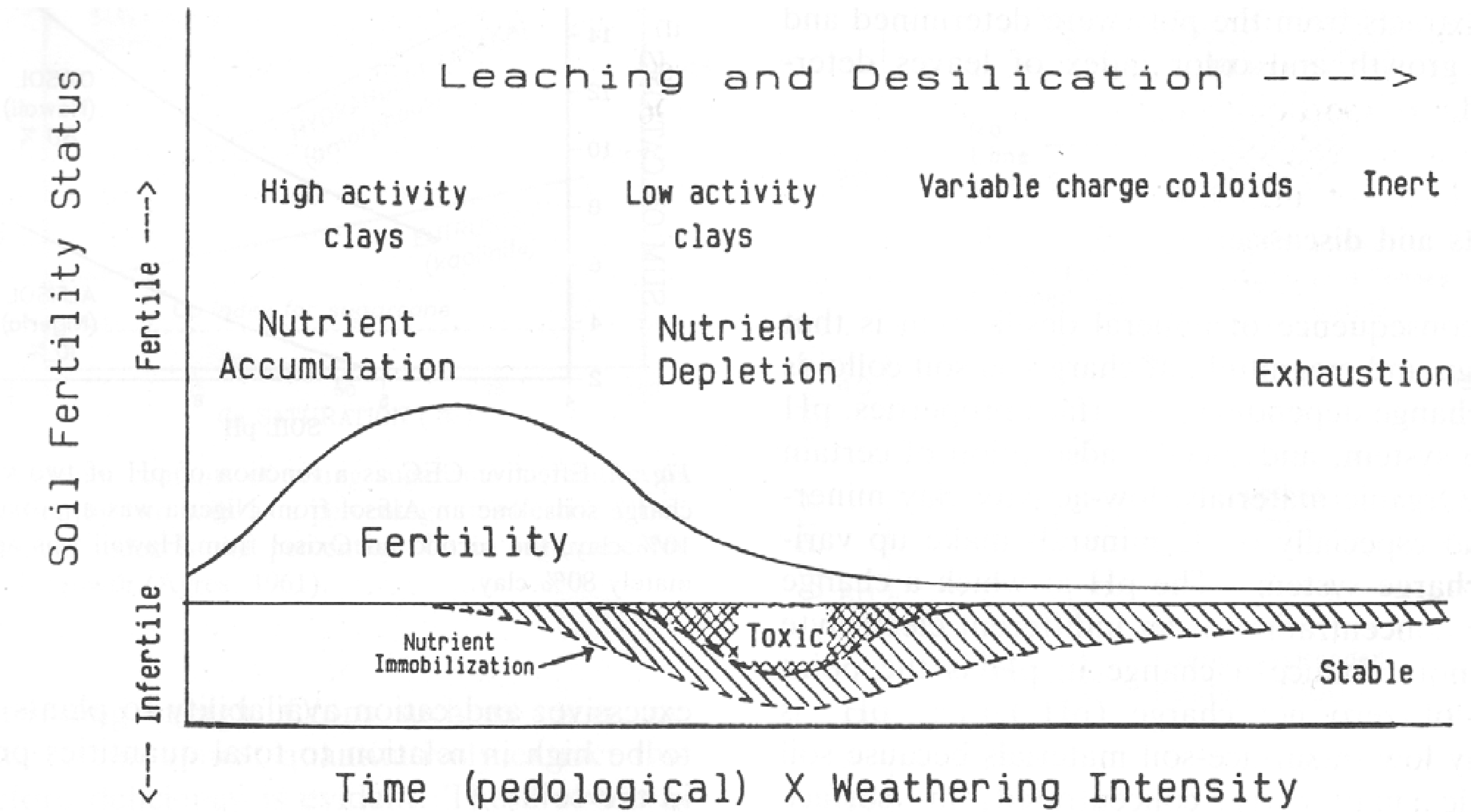
Lualualei soil series

Fine, smectitic,
Isohyperthermic,
Typic, Gypsitorrerts

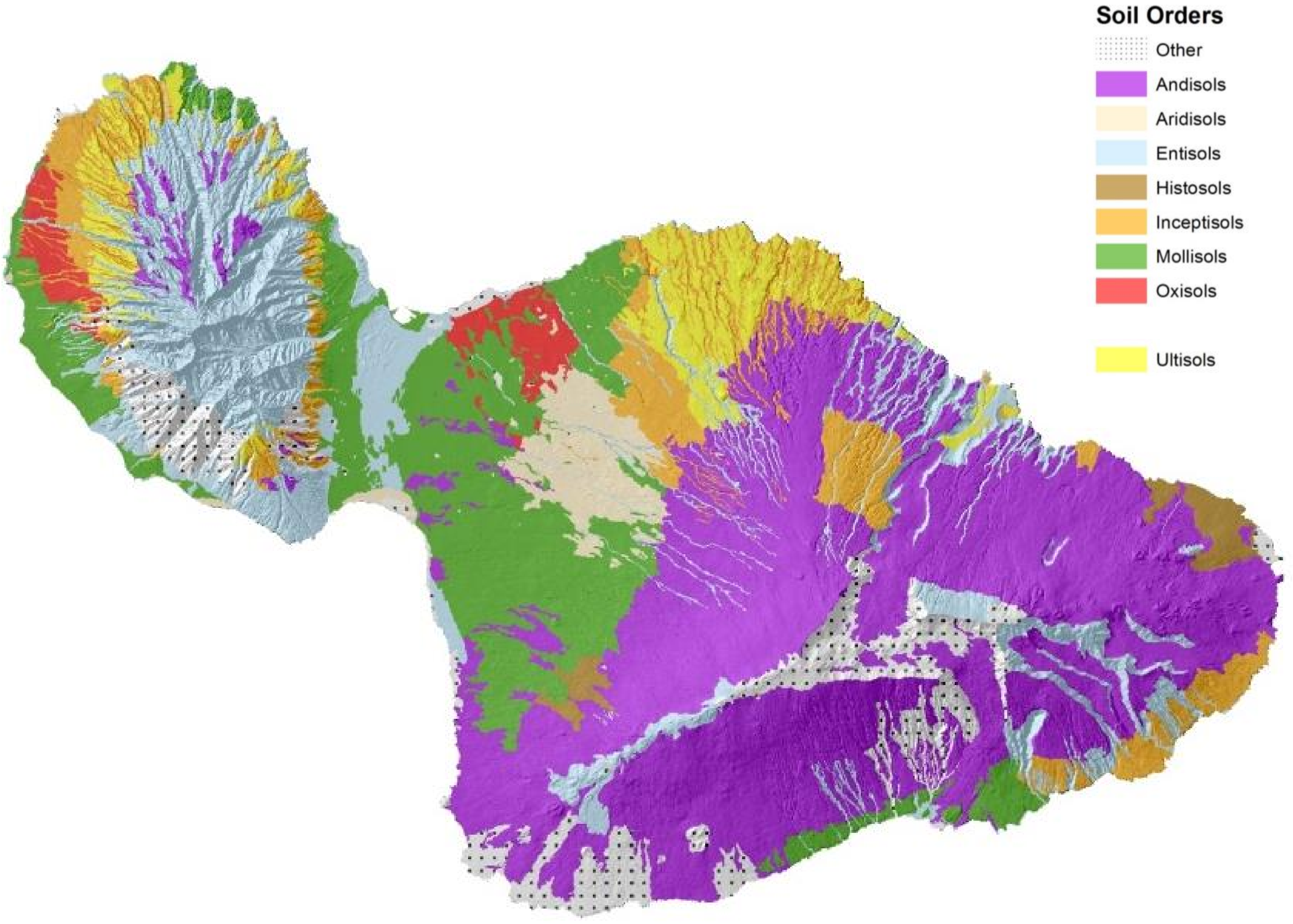
- slightly alkaline pH
- high CEC
- rich in plant nutrients
- shrink swell clays

webmineral.com/specimens/photos/Smectite.jpg

Weathering Intensity and Soil Fertility



Fox et al. (1991)

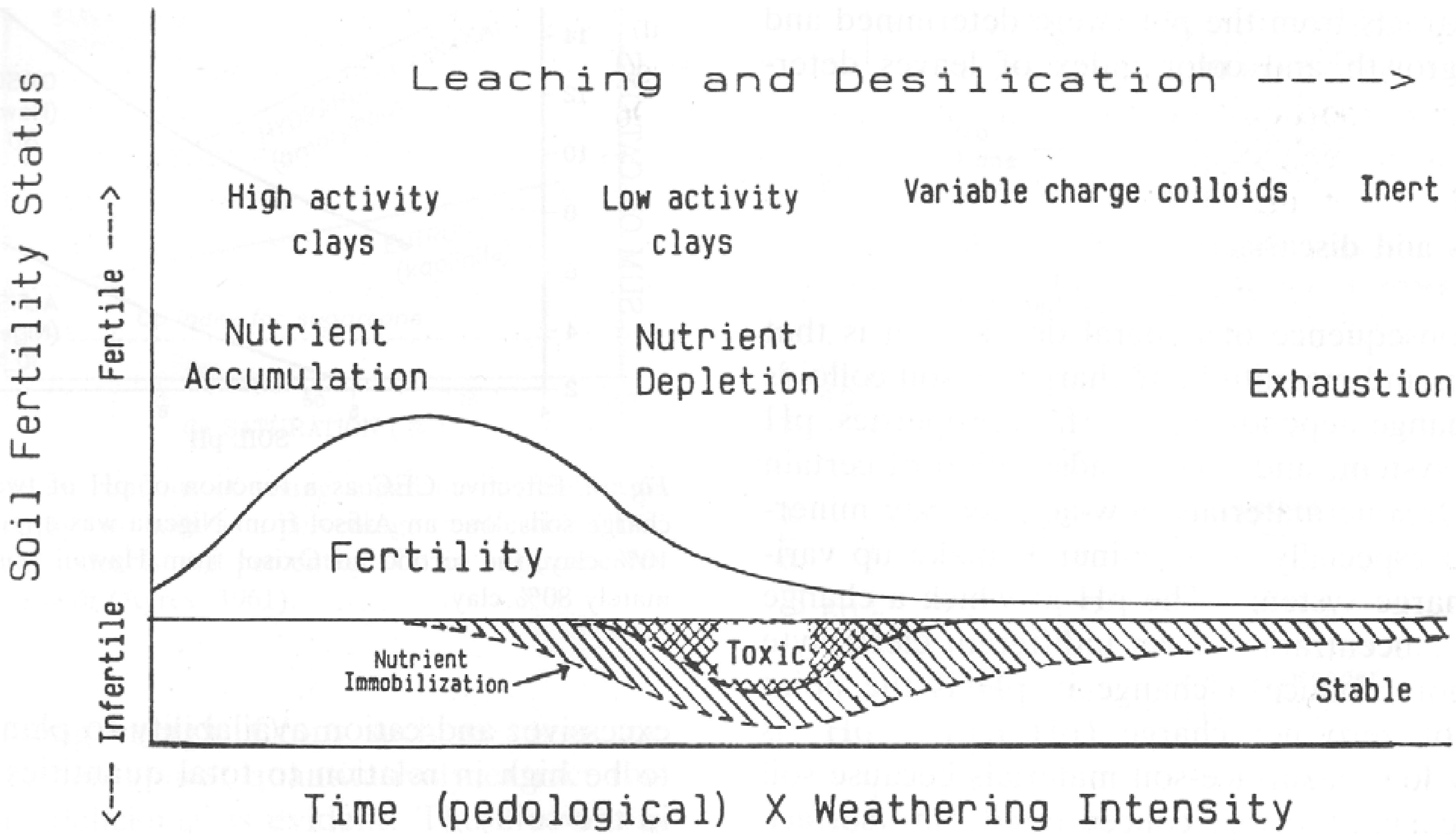

Soil Orders
Other
Andisols
Aridisols
Entisols
Histosols
Inceptisols
Mollisols
Oxisols
Ultisols

Haiku soil series

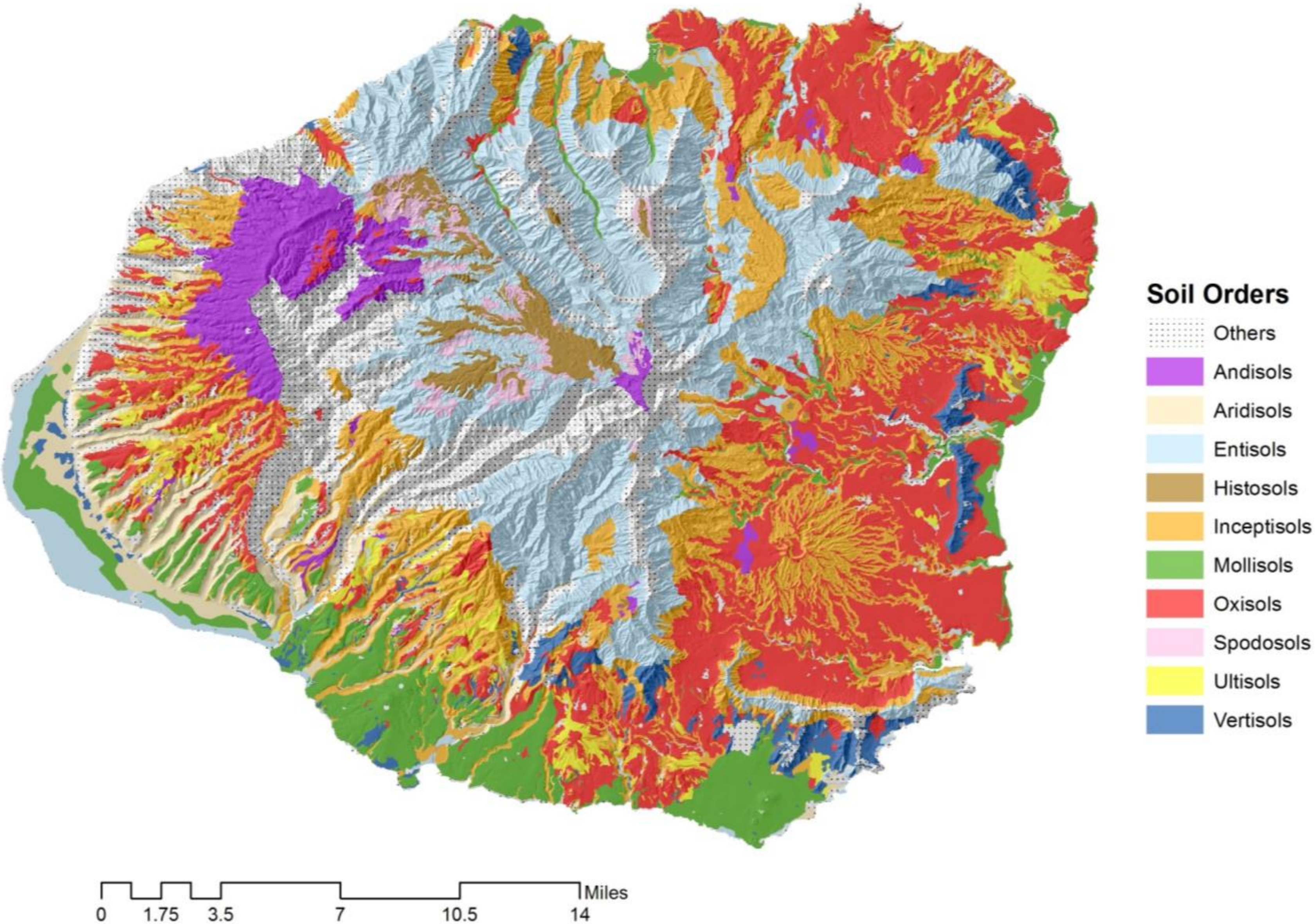
Fine, ferritic,
Isohyperthermic,
Ustic, Palehumults

- acid pH, Al toxicity
- low CEC
- rich in organic matter
- low in plant nutrients

Weathering Intensity and Soil Fertility



Fox et al. (1991)



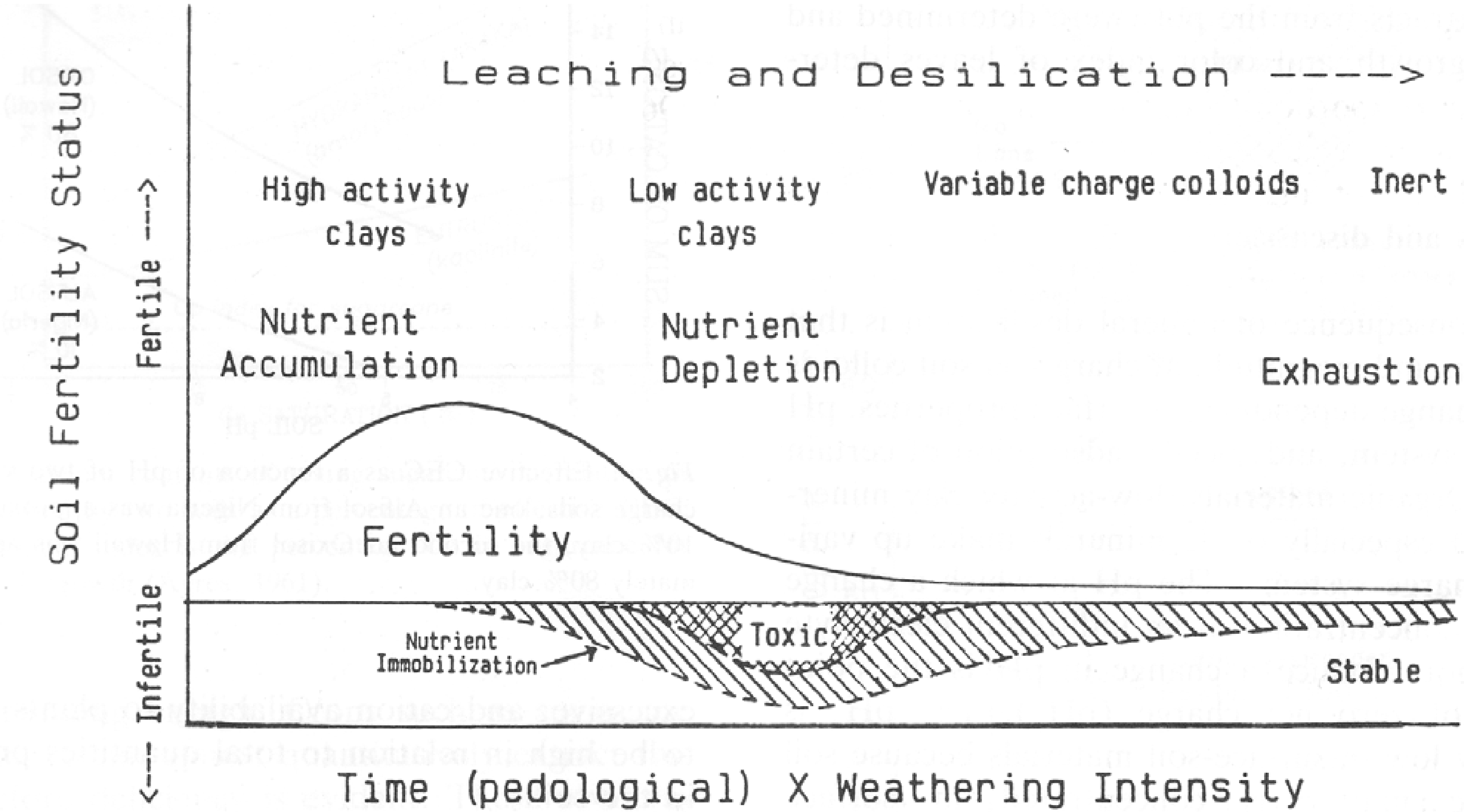
Projection: NAD 1983, UTM Zone 4N
Source: Natural Resources Conservation Service

Kapaa soil series

Very fine, sequic, iso-Hyperthermic, anionic, acrudox

- acid pH
- very low CEC
- low nutrient reserves

Weathering Intensity and Soil Fertility



Fox et al. (1991)