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DEVELOPMENT OF SOILS AND SITE QUALITIES ON BASIC VOLCANOCLASTICS WITH SPECIAL REFERENCE TO THE SEMIARID ENVIRONMENT OF LANZAROTE, CANARY ISLANDS, SPAIN

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ABSTRACT

Soils in six landscapes of different ages ranging from Miocene/Pliocene to the historic eruptions 260 years ago in Lanzarote (Canary Islands, Spain) have been mapped and analyzed. With additional information about the more humid parts of the islands, a soil-type stability diagram is shown which differentiates the humidity and the age of the landscape. The dynamic course of soil-forming processes since the late Pleistocene is demonstrated by quantitative figures on texture development, loss of bases, changes in the pore system, iron oxide formation, organic matter enrichment, carbonization, salt enrichment and clay movement. Within a range of about 40,000 years, soil development has resulted in a nearly complete replacement of the gravelly parent material by forming sand, silt and clay. A rapid increase in Fe-oxides and organic matter marks the early soil-development stages. A decrease in organic matter and clay illuviation, as well as the enrichment of carbonates, are prominent processes in the more advanced stages. A comparison of soil substances formed and the element budget is made between the Andosols from the highlands of Mexico (from andesitic ash, humid climate) and those from Lanzarote (from basaltic lapilli, semiarid climate). The development of site qualities is related to the development of individual site characteristics such as rooting depth, rootability, available water capacity, organic matter, and available P and K, depending upon time and slope position. All described site qualities show different dynamics in their courses of development, which is due to their different relations to soil forming processes.

Key words: Edaphology, Lanzarote, Canary Islands, Spain.

RESUMEN

Se realizó el cartografiado geológico y el análisis químico de los suelos de seis áreas de edad diferente, que varía desde el Mioceno/Plioceno hasta hace 260 años, edad de las erupciones históricas de Lanzarote, Islas Canarias, España. Con información adicional de las partes más húmedas de las islas, se elaboró un diagrama de estabilidad de tipos de suelo en el que se diferencia la humedad y la edad de las áreas. El curso dinámico de los procesos formadores de suelo desde el Pleistoceno tardío, se demuestra mediante cifras que cuantifican el desarrollo de la textura, pérdida de bases, cambios en el sistema de poros, formación de óxidos de hierro, enriquecimiento en materia orgánica, carbonización, enriquecimiento en sales y movimiento de arcillas. En un intervalo de 40,000 años, aproximadamente, el desarrollo de suelo ha resultado en un reemplazamiento casi completo del material parental, formando arena, limo y arcilla. Un incremento rápido en la cantidad de óxidos de hierro y de materia orgánica marca las etapas tempranas de desarrollo de suelo. Un decremento en la cantidad de materia orgánica y en la iluviación de arcilla, así como en el enriquecimiento en carbonatos, son procesos prominentes en las etapas más avanzadas. Se hace una comparación de las substancias del suelo formadas con la disponibilidad de elementos entre los Andosoles de las tierras altas de México (de ceniza andesítica y clima húmedo) con aquéllos de Lanzarote (de lapilli basáltico y clima semiárido). El desarrollo de las condiciones del lugar está relacionado con el desarrollo de las características individuales del lugar, tales como la profundidad de las raíces, actividad de las raíces, capacidad de agua disponible, materia orgánica, y P y K disponibles, dependiendo del tiempo y de la pendiente. Todas las condiciones del lugar descritas muestran dinámicas diferentes en sus cursos de desarrollo, lo que se debe a sus diferentes relaciones con los procesos formadores de suelo.

Palabras clave: Edafología, Lanzarote, Islas Canarias, España.

INTRODUCTION

Site qualities are in general very complex qualities which have to be qualified from observable and measurable site characteristics and to be evaluated for specific land uses (FAO, 1976). For the purpose of ecological land evaluation, the large number of characteristics should be summarized in statements about possible rooting depth, rootability and water-, air-, energy-, and nutrient budgets (Schlichting *et al.*, 1995). Further, statements about elasticity and stability of a site under a specific use are needed to establish a sustainable land use.

Since many site characteristics are the result of pedogenesis, the development of qualities is also closely related to the time-dependent development of soils. Usually, land evaluation accepts site characteristics only as time dependent for the surveyable period of a land use, which is relatively short in comparison to the formation of soils.

In general, the knowledge about volcanic soils has increased remarkably in the last decades, especially for the humid regions (*e. g.*, Theng [1980] and Gibbs [1980] for New Zealand; Fernández-Caldas and others [1982] for Canary Islands; Wada [1986] for Japan; Miehlich [1991] for Mexico). On the contrary, data about volcanic soils in arid and semiarid climates are still very scarce. This can be observed from the

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Andisol database (ICOMAND 9, 1987) which shows 260 Andisols of which only three are classified as Torrands and eight as Xerands. First examples of Andosols in a very dry environment have been shown in an international meeting in 1980 in Syria (ACSAD, 1980, Tour II).

Since most papers are very specialized *e. g.*, about soil classification, soil mineralogy, or chemical behavior of soil substances, it is the objective of this paper to connect knowledge about soil formation and the formation of site qualities on a long time scale.

MATERIAL AND METHODS

The climate of the island of Lanzarote (800 km^2, 29N) is characterized by an average annual precipitation of about 140 mm and an annual mean temperature of about 16 to 20°C. Air humidity is about 70% throughout the year. The prevailing moisture regimes according to Soil Taxonomy (USDA, 1992) are aridic tending to ustic at low elevations and xeric at higher elevations. The corresponding temperature regimes are hyperthermic and thermic. Due to its Atlantic position, the palaeoclimatic conditions are assumed to be relatively stable at least since the upper Pleistocene (Jahn, 1988).

The island is built up by eruptive rocks which originated from six different eruptive phases, thus offering the opportunity to study soils in different landscapes of different ages (Figure 1). The age of the six basaltic series ranges from Miocene and Pliocene to the historic eruptions about 260 years ago. The geochemistry of the rocks is basic to ultrabasic with minor variations (Fuster *et al.,* 1968). The profiles analyzed were selected from the data collected after mapping of two areas in each of six different landscapes of Lanzarote. The maximum stage of soil development (indicated by stone content, texture, rubefication, carbonization) within every landscape was used as main criteria for selection. Age, parent material, soil unit, location and climatic parameters are presented in Table 1. For physical, chemical and mineralogical analyses, the methods of Schlichting and others (1995) were used. In the text, the abbreviations have the following meaning: sand, silt and clay based on C-free fine earth. CEC = Na-, NH_4-acetate cation exchange capacity. P_{ret} = P-retention (Blakemore and Daly, 1981; 100% = 5 mg P / g fine earth). Fe_d = dithionite-extractable Fe. X_o = oxalate-extractable Fe, Al, Si. AWC = available water capacity. Available (NH_4-Lactate soluble) P and K. Further information and specific data are given by Jahn (1988, 1995) and Zarei (1989).

RESULTS AND DISCUSSION

OCCURRENCE AND DISTRIBUTION OF SOILS

Depending upon the age of the landscape, a sequence of Regosols/Leptosols (depending upon content of gravels >2 mm) (landscape IV_B) – Andosols (landscape IV_A) – Calcisols/Luvisols (depending upon the stage of erosion) (landscape III) – heavily eroded sites with remnants of polygenetic

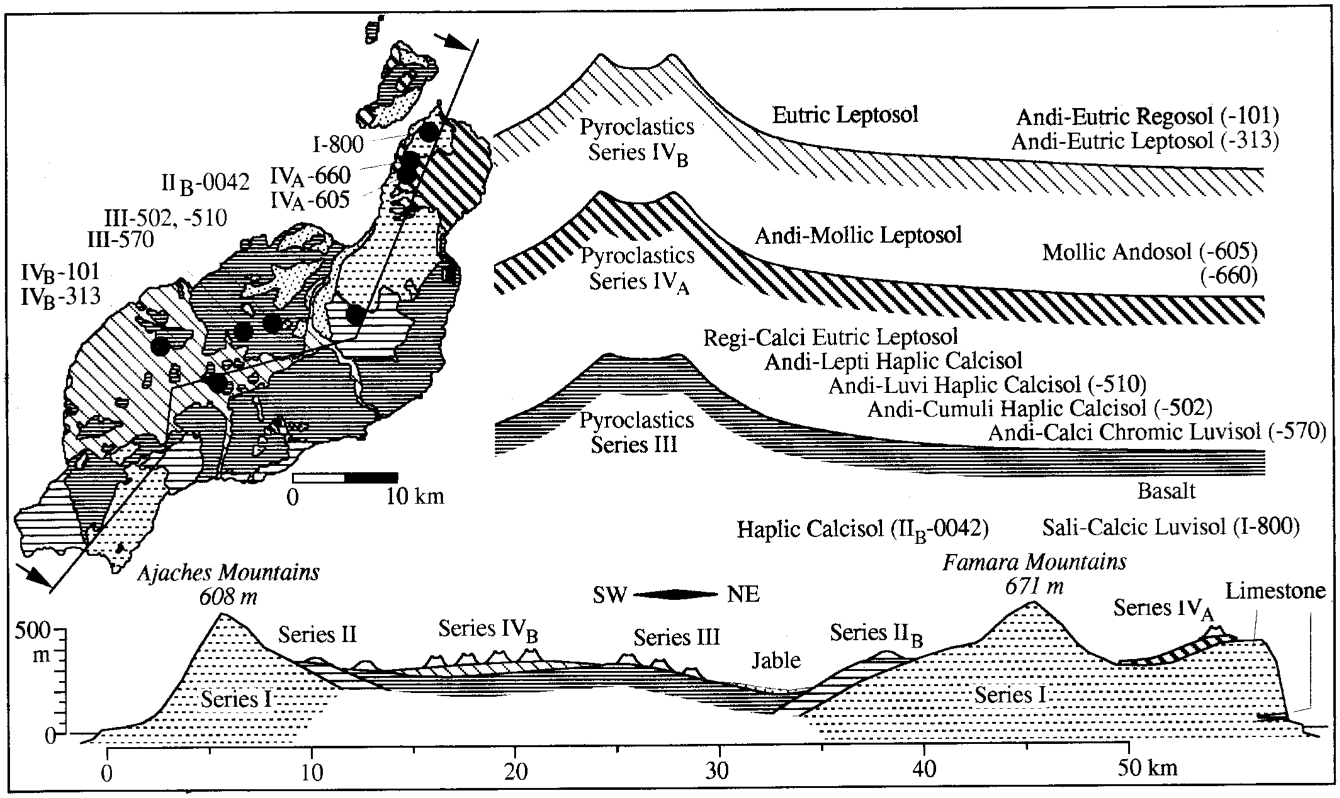

Figure 1. Geology of Lanzarote and toposequences of soils.

Table 1. Analyzed soils in relation to the geological formations of Lanzarote.

Geologic formation Age	Parent material	Soil type FAO-UNESCO (1994)	Number and location	Altitude [m a.s.l.]	Precipitation [mm]	Temp. [°C]
IV_B Recent ~260 years	Lapilli and cinders Ashy lapilli and cinders	Eutric Regosol Eutric Leptosol	IV_B-101 Montaña Negra IV_B-313 Caldera Blanca	130 180	150-200 100-150	18 18
IV_A Subrecent ~6,000 years	Lapilli and cinders Lapilli and cinders	Mollic Andosol Mollic Andosol	IV_A-605 Los Helechos IV_A-660 Monte Corona	440 420	150-200 150-200	16 16
III Upper Pleistocene ~40,000 years	Lapilli and cinders Colluvium Basalt	Luvic Calcisol Haplic Calcisol Chromic Luvisol	III-510 El Peñón III-502 El Peñón III-570 Erem. de los Dolores	250 230 270	100-150 100-150 100-150	17 17 17
II_B Upper Pleistocene	Basalt and colluvium	Haplic Calcisol	II_B-0042 Guanapay	325	100-150	17
I Pliocene	Basalt and colluvium	Calcic Luvisol	I-800 Malaya Chica	415	150-200	16

soils (landscape II_B, II_A, I), have been found. This has led to the assumption of a soil forming sequence of Regosols/Leptosols ⇒ Andosol ⇒ Cambisol ⇒ Luvisol ⇒ Calcisol ⇒ polygenetic soils. The Calcisols, Luvisols and the upper parts of polygenetic soils are partly classified as Solonchaks due to their high content of salts (depending on their position in the island).

Soil differentiation occurs firstly according to the age of the landscape, and secondly according to the position within the landscape (Figure 1). In the youngest only 260 years old Leptosols and Regosols (very rich in coarse volcanoclastics), the properties of the parent material are still dominant.

In the landscape which is about 6,000 years old, diagnostic A- and B-horizons with andic properties have developed from lapilli and cinders. This is the only area in Lanzarote where Andosols, according to the FAO-classification, occur. The formation of andic properties, diagnostic in IV_A-soils, may have been accelerated by the high relative humidity. Near or on the slopes of volcanoes, soils from coarser cinders are not as well developed as those from finer lapilli, so again Leptosols are found.

In landscape III (about 40,000 years old), lithogenic properties are more or less lost and pedogenic properties, such as loamy texture, lime enrichment, brownification and so on, are distinctively developed. Erosion and accumulation are important processes and sequences of Eutric Leptosols-Haplic Calcisols-Chromic Luvisols (with petrocalcic horizon)-colluvial Calcisols can be found. This landscape is widely used for agriculture. As a typical example, a soilscape in landscape III is shown in Figure 2. On the slope of the volcano El Peñón, Lepti-Haplic Calcisol occurs as a major soil type, associated with Leptosols on steeper areas and with Luvi-Haplic Calcisols on more flat areas. Downslope follows a sequence of Chromi-Haplic Calcisols, Luvi-Haplic Calcisols, Calci-Chromic Luvisols, Cumuli-Chromic Luvisols and Cumuli-Haplic Calcisols from soil colluvium in the plain. Typical for the land use is about 10 cm thick anthropogenic cover layer of lapilli to minimize unproductive evaporation. The soil sediments in the plain are widely used to build anthropogenic soils on eroded sites or on recent basaltstreams (IV_B).

In older landscapes (II_B, II_A, I), polygenetic soils with several sequences of fossil Luvisols, Vertisols and Nitisols, which are divided by petrocalcic horizons, do occur (Schüle *et al.*, 1989). These soils, which are mostly remnants on high plains and footslopes, are in the present time heavily affected by soil erosion (Figure 2). Rock outcrops and petrocalcic horizons, as well as Leptosols, Regosols and Calcisols resting on petrocalcic horizons, are dominant in the area.

Comparing the pattern of soils in the arid region with that in the more humid parts of the Canary Islands (*cf.* Fernández *et al.*, 1982; Departamento de Edafología, 1984), a soil type stability diagram can be drawn (Figure 3), which differentiates the humidity and the age of the landscape.

Under arid conditions, a very long stage for Regosols and only a short stage for Andosols occur. Clay movement and lime enrichment, as well as good conditions for nutrient availability, are diagnostic for older soils. In contrast, under humid conditions, the stage of Regosols is very short, while Andosols are stable for a long time. Later on, strongly weathered soils with ferralitic character are developed.

COURSE OF SOIL FORMING PROCESSES

Figure 4 shows schematically some important soil forming processes which occur in the soils of Lanzarote. The figure refers to the maximum stage of soil development of each landscape, namely Eutric Regosol for landscape IV_B, Mollic Andosol for landscape IV_A, and Chromic Luvisol for landscape III. The course of some important processes can also be observed from selected data of the most developed horizons (Table 2). Complete data sets are given in Jahn (1988, 1995).

Primary gravels of fine and medium sizes weather almost totally to finer fractions in about 40,000 years. This is also the case for sand in the most developed horizons. Fossil Vertisols of the older landscapes II and I show a texture development which reaches 80% clay content in fBt-horizons. An increase in clay content, which also means an increase in weathering intensity, is coupled with significant losses of Ca, Mg and Na. One m^3 of soil lost about half of the original amount of these elements within 40,000 years. The loss of sand is closely related to the loss of primary Ca (Figure 5), both being excellent markers of weathering intensity. Weathering produces at

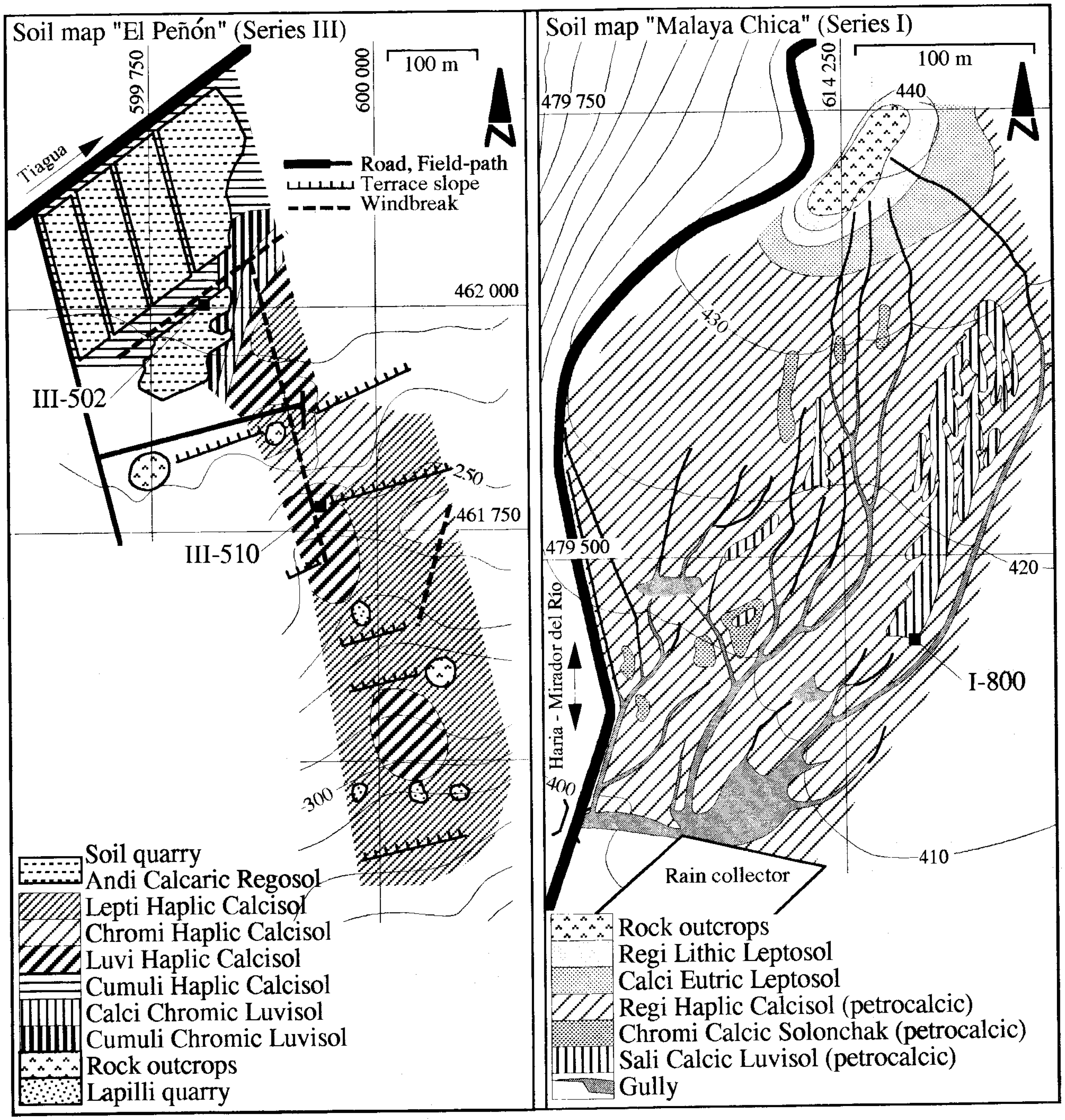

Figure 2. Soil maps of landscapes III (left) and I (right).

first more silt than clay, until the weathering stage of the Andosols IV$_B$. In later weathering stages, the silt content decreases and only clay is formed. Over the whole period and based on an entire profile, it can be observed a more or less constant clay formation of about 6 g/m^2·year. This rate increases to an average of about 200 kg clay per m^2 in the Luvisols of landscape III. The content of silt and clay of older weathering stages has only a loose relation with the loss of mobile primary elements, due to silty aeolian additions (Saharan dust), which differ in amount from soil to soil and from horizon to horizon. Using quartz content as a calculation basis, aeolian addition amounts 4% of the fine earth of IV$_B$-soils, around 20% in IV$_A$-soils and higher than 20% in older soils. Older soils developed on basalt streams (which have in the beginning of soil formation a very rough surface) may contain more than 50% of aeolian material in the fine earth, as for example III-570. In these soils, a large part of the silty material is already altered to clay (Jahn, 1995).

Changes in texture cause changes in pore size distribution, in which the amount of coarse pores decreases while fine and medium pores increase. Between the stages of Regosol and Andosol, the increase in fine pores is steeper than in medium

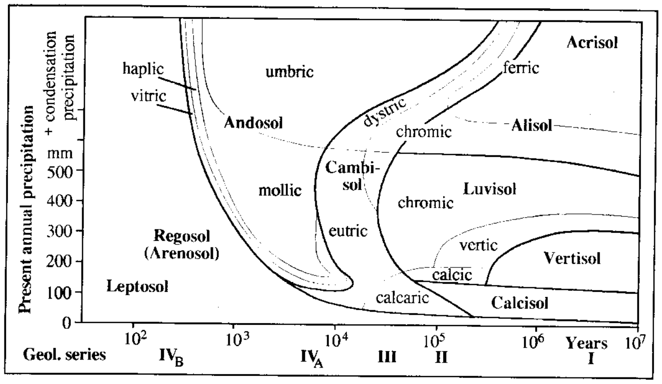

Figure 3. Occurrence of soils (Canary Islands) in relation to moisture and age of parent material.

pores. A reverse development can be observed in the stage between Andosols and Luvisols.

A large increase in iron oxide formation is bound to the development of Andosols with a relatively high activity level all the time. The Andosols have up to 8 kg Fe-oxides/m^2. This amount is only slightly greater in the older soils, but is characterized by qualitative changes of the oxides (increase of crystallization). Aeolian additions, which are low in Fe-content, attenuate the oxide content in older soils.

The accumulation of organic matter is at its maximum during the Andosol stage (more than 10 kg/m^2), where amorphous material occurs and enforces the storage of humic substances.

A very prominent process is the accumulation of calcium being released by rock weathering and added (as calcite) by aeolian material (almost dissolved and reprecipitated) and accumulated as secondary carbonates (Jahn and Stahr, 1994). The increase in carbonates is controlled by the water budget, which changes with the development of texture and pore size distribution. This causes lime enrichment to occur closer to the surface and also diminishes leaching in older soils.

Likewise, with increase in water capacity (under the given climatic conditions, indicates decreasing leaching rates), the accumulation of aeolian sea-salts increases. From the uptake of potassium, a minimum annual deposition of 0.3 l/m^2 is calculated.

Clay illuviation is lowest in the Andosol- and carbonated Luvisol stage and must be highest in the stage in between. In this stage, an annual clay movement of slightly more than 1 g/m^2 is estimated, which is about one fifth of the newly formed clay.

All soils have neutral to slightly alkaline pH values, suggesting that acidification does not occur. The cation exchange capacity increases in the early stages of soil formation much more than the clay content (Figure 6). This increase is linked to the formation of amorphous weathering products (short range order minerals), as well as to the storage of humic substances in the Andosols. Later, the exchange capacity of clay decreases from several 1,000 meq/kg clay in the Andosols to about 500 meq/kg clay in the Luvisols and Calcisols. A relatively high P-retention with an average of 70% is coupled to the Andosols. The Leptosols/Arenosols have distinctly lower CEC values. In contrast to the insignificant lower CEC of Luvisols/Calcisols, fBt-horizons have significantly lower values.

Quantitative as well as qualitative changes characterize the clay fraction which increases continuously up to ~250 kg clay/m^2 in soils of series III. In the Andosols, secondary formation of allophanes, hydroxides and oxides occurs. The older Luvisols/Calcisols are clearly dominated by smectitic new formations which are partly transformed to illite. The aeolian addition results in the occurrence of illite and kaolinite in all soils (Jahn *et al.*, 1987; Jahn, 1995).

COMPARISON WITH SOIL DEVELOPMENT IN A MORE HUMID CLIMATE

The data presented here can be compared, *e. g.*, with data of Miehlich (1991) for Andosols from Mexico, because of a

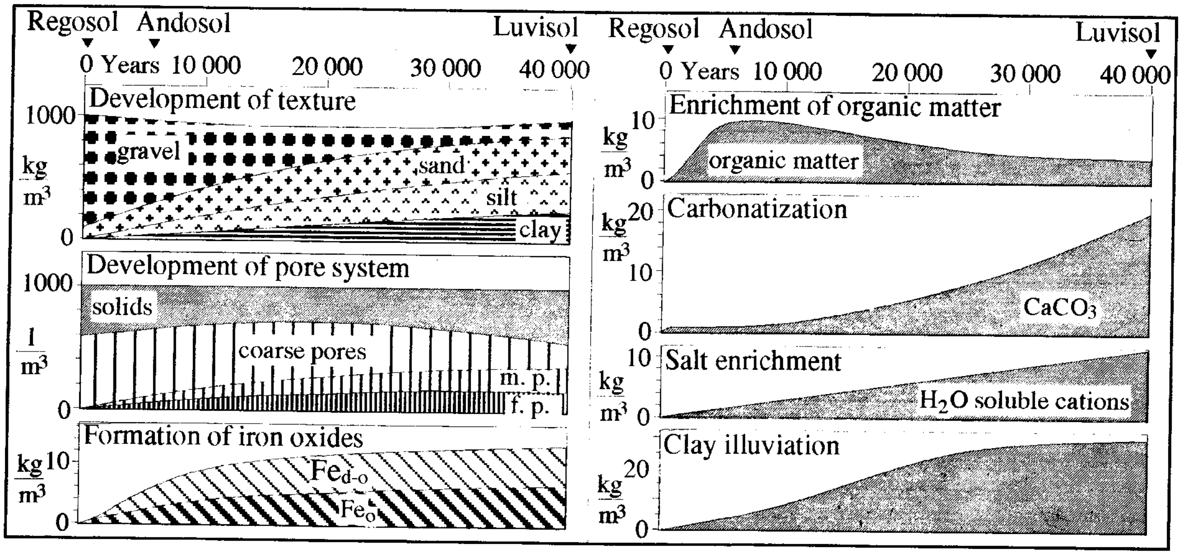

Figure 4. Course of soil forming processes with time in the weathering of 1m^3 basaltic pyroclastics.

Table 2. Selected data of the most developed horizons of soils from the landscapes IV$_B$, IV$_A$, III, II$_B$ and I.

Number	Hor	Depth [cm]	Gravel [%]	Sand [%]	Silt [%]	Clay [%]	pH KCl	CEC [meq/kg]	P_{ret} [%]	Fe_d [%]	$Fe_{o/d}$	Al_o [%]	Si_o [%]
IVB-101-5	Bw	8.2-8.5	n.d.	77	17	6	7.5	143	18	0.47	0.85	0.21	0.24
IVB-313-4	Bwk	3.2-5.0	1	77	16	7	7.8	87	52	0.37	1.02	0.15	0.21
IVA-605-5	Ah	47-64	58	46	41	13	6.9	838	65	3.43	0.39	1.48	0.81
IVA-660-2	Ah	16-34	51	34	49	17	7.5	506	43	2.56	0.22	0.50	0.28
III-510-5	Btk	39-58	2	4	30	66	7.8	385	61	1.11	0.24	0.13	0.11
III-502-12	Bt2	200-215	0	2	38	60	7.7	n.d.	n.d.	1.32	0.11	0.10	0.08
III-570-6	Bt	60-80	80	1	32	67	7.2	409	34	1.44	0.09	0.12	0.07
IIB-0042	fBt	250-300	0	2	22	76	7.1	425	15	0.89	0.10	0.09	0.06
I-800-13	fBt	325-365	0	1	17	82	7.6	377	12	1.09	0.06	0.09	0.06

more or less similar structure of data. Differences in the soil forming factors are primarily in terms of climate (see Table 3), and to a lesser extent in the parent rock and time (age of soils). Another general difference between the two areas is given by the continuous addition of Saharan dust to the soils in Lanzarote. This effect can be recalculated from the data given by Jahn (1995). The initial rock mass is calculated based on Al in rock and soil, assuming that Al is a stable element (on whole soil basis) in the semiarid climate of Lanzarote. The comparison uses an initial rock mass of about 1 m^3.

Primarily due to climatic differences, there is a big dissimilarity in the formation of secondary minerals (clay) and in leaching of elements. Secondary minerals are six times higher in Mexico's example than the autochthonous clay in Lanzarote. This is attributed to the much more intensive desilication (11 times) and only slight losses of bases (1.7 times). The latter is controlled by the different nature of the parent material (relative higher losses of Ca and Mg from basaltic material, relative higher losses of Na and K from andesitic material). Desaturation of bases results in pH$_{KCl}$ of 5.4 in Mexico, whereas in Lanzarote the pH is still at or above 7, which is clearly above the "normal range" of pH-values considered to be between 5 and 6 for Andosols (Quantin, 1972). Surprisingly, the turnover of Fe (Fe$_d$, Fe$_{d/t}$) by forming Fe-oxides is in both cases more or less the same, although in the Mexican Andosols it has lower crystallinity. The Si/Al ratio (1.2) of the secondary minerals of the Mexican Andosols is closely related to the Si/Al ratio in the autochthonous clay of Lanzarote's Andosols. The much higher amount of short range order clay can be seen from the Al$_o$ data, which is seven times higher in Mexico. Due to higher plant productivity and also higher amounts of short range order minerals (forcing stable organo-mineral complexes), the storage of organic matter is five times higher in Mexico than in Lanzarote. $CaCO_3$ is only formed in the lower horizons of Andosols in Lanzarote. Since the aeolian input of $CaCO_3$ must have been much higher than the actual amount found, an additional leaching of Ca from aeolian material is expected to have occurred (Jahn and Stahr, 1994).

DEVELOPMENT OF SITE QUALITIES

Focusing soils as a stand for higher plants, the possible rooting depth and rootability define the soil space for

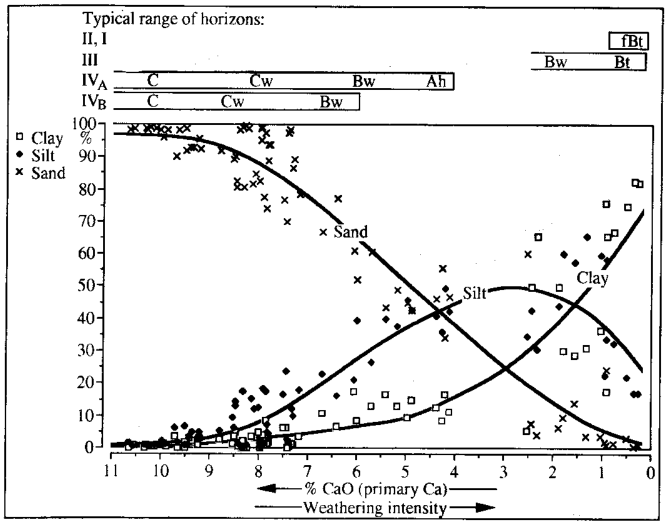

Figure 5. Relation between grain fractions and loss of primary Ca due to weathering.

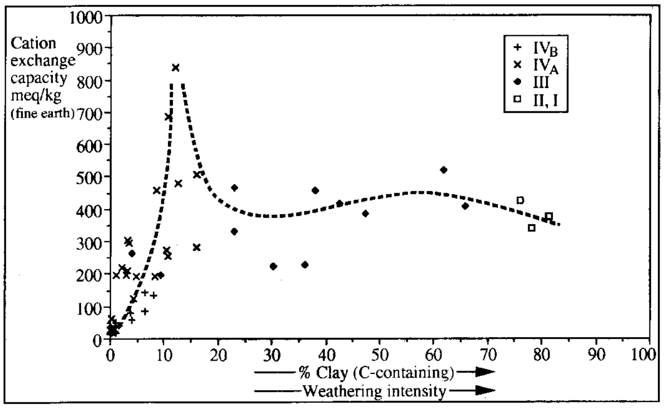

Figure 6. Relation between cation exchange capacity and weathering intensity.

Table 3. Comparison of formed soil substances and element budget between Andosols of the highlands of Mexico (after Miehlich, 1991) and from Lanzarote.

	Mexico Andosols from andesitic ash (3CD) (9,500 years, 800-1,400 mm P, 5-11°C)			**Lanzarote** Andosols (Ø of -605 and -660) from basaltic lapilli (IV$_A$) (~6,000 years, 150, 200 mm P, ~16°C)				
	Amount			Autochthonous and aeolian amount			Aeolian import	
		[kg/m^2]	[% amm]		[kg/m^2]	[% amm]		[kg/m^2]
Actual mineral mass		516			980			75
Initial rock mass		774	150		963	98		—
Secondary minerals		123	24					
Clay		~sec. minerals			34	3.5		13.5
Corg		29	5.7		5.4	0.55		—
CaCO$_3$		0	—		2.5	0.25		(14)
Alo		16.2	3.2		2.4	0.25		n.d.
Fed		6.1	1.2		6.3	0.64		~1.0
Fe$_{o/d}$	0.81			0.43			n.d.	
Fe$_{d/t}$	0.25			0.25			~0.4	

Element	In secondary minerals		Leaching from iem**		In clay Autochtonous		Aeolian	Leaching from iem**		Aeolian import
	[kg/m^2]	[iem**]	[kg/m^2]	[% iem**]	[kg/m^2]	[% iem**]	[kg/m^3]	[kg/m^2]	[% iem**]	[kg/m^2]
Si	19.6	9	90.7	39	2.7	1.3	3.4	8.2	4	18.3
Al	16.2	23	12.0	17	2.3	3.4	1.4	-	-	4.6
Ca	1.1	5	10.3	37	0.1	0.1	0.04	9.9	15	5.6
Mg	0	-	4.5	28	0.4	0.6	0.11	9.9	16	2.1
K	0	-	7.8	63	0.12	1.6	0.4	0.4	6	0.9
Na	0	-	14.4	58	0.0	0.0	0.0	3.0	14	0.8
Ti	0	-	0.17	5	0.4	2.8	0.14	0.7?	4?	0.5
P	0.4	55	0	0	0.14	4.7	0.01	-0.13	4	0.0
Fe	5.2	18	4.2	14	3.2	4.0	1.1	3.1?	4?	2.5
Mn	0.2	31	0.04	7	0.05	4.1	0.01	0.1	9	0.03

*amm: actual mineral mass, **iem: initial element mass

which other soil characteristics, such as available water capacity and nutrient quantities, have to be evaluated. Root penetrability, a result of many characteristics (*e. g.*, stone content, strength of peds, bulk density, penetration resistance), is generally bad in the stony IV$_B$-soils. It is partly limited by stones in the IV$_A$-soils, by depth in III-soils with petrocalcic horizons and slightly limited by strong ped formation in fossil soils. The soil depth in very weakly developed IV$_B$-soils is normally limited by the underlying rock. For IV$_A$-soils, large differences occur which depend on slope position. The depth of soil formation decreases from 3 to 4 dm on hilltops to around 2 dm along slopes and increases to about 7 dm in depressions. Soil depth here generally depends on weathering intensity which is higher in depressions due to more moist conditions. In older soils, soil depth is mostly a result of soil erosion and deposition. Along the slope in Figure 3 (left), soil depths which range from a bare rock surface to more than 5 m can be observed in soils derived from pyroclastics. Moreover, rooting depth is generally limited by very hard petrocalcic horizons. Soils derived from massive basalt in landscape III occur usually in more or less level landscapes, with a depth of more than one meter, but high stone content limits their rooting space.

The available water capacity (AWC) is related to texture, bulk density and kind of peds. Highest AWC of about 20% by volume can be found in the Andosols. In older soils, AWC ranges between 10 and 20%, and is lowest (%) in the very sandy IV$_B$-soils. For soils of series IV$_B$, only very low AWC can be found, regardless of slope position. The variability of these Regosols is more dependent on the primary constitution, which is the variability in particle size dependent to the distance to the emission point. Because of the rapidly increasing silt content towards the soils of IV$_A$, the available water is relatively high. However, because of the shallow soil depth and stone contents, the profile contents of available water range from low to moderate. The variation is moderate and varies with slope position (Figure 7). The soils of series III are more influenced by slope position. For soils in landscape IV$_A$ and III, soil depths of 3 to 4 dm are usually enough to store the precipitation of about 150 mm in the wintertime.

The air capacity, given through coarse pores, is best in younger soils. In the course of soil development, limited coarse pores, with a volume less than 10% (by volume), occur only in Bt-horizons of landscape III and older. Because of the negative water budget, reducing conditions are only expected to occur under irrigation.

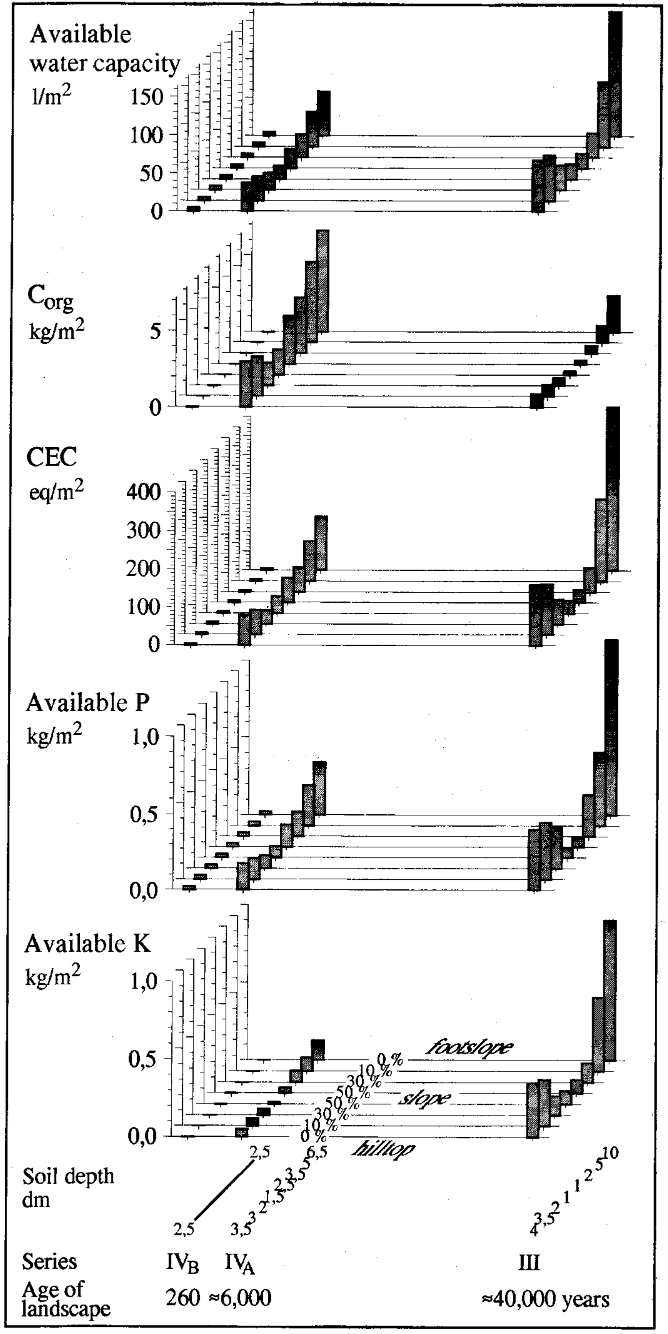

Figure 7. Time dependent development of available water capacity, organic matter, CEC, available P and K in different slope positions.

To summarize the nutrient status of the soils, Figure 7 presents the profile contents of C_{org}, CEC, and available P and K. CEC is rated as medium and high in the soils of landscapes IV_A and III. Available K increases continuously from the youngest to the oldest soils. With the exception of the Regosols, the quantities of these soil parameters are high and very high. In addition to the K released from the parent material and aeolian dust, a continuous supplement from wind blown sea spray occurs, causing therefore no K-deficiency in high illitic soils.

The course of development of available P is comparable to the development of AWC and CEC with a large increase towards the Andosols. In all soils, high levels of available P were found. Big differences exist in relation to the total contents of P. In the Regosols, only about 20-30% of P_t is available; in the Andosols, about 50-60%; and in older soils, nearly 100%. P-retention seems not to be a big problem in the dry Andosols. A maximum of only 68% P-retention was measured in the lower part of IV_A-605. All other soils have distinct lower values.

In contrast to AWC, available P and K, the storage of organic matter (time dependent) and N, are very different with a distinct decrease from the Andosols to older soils. Only during the andic stage in IV_A do stable organo-mineral complexes occur. Therefore, the maximum for carbon and nitrogen storage can be found in this stage of soil development.

Considering the time-dependent changes in texture, the changing contents of organic matter and development of peds, it is possible to construct the soil erodibility in the course of time. For the development of the erodibility of topsoils, only uncertain information is available, because of man-made changes in texture through the use of lapilli layers to control evaporation. In general, the development of erodibility in topsoils must be slower than in subsoils, because of slower weathering intensity at the top. The recent topsoils in landscape III have a moderate to moderately high erodibility (according to the K-factor of Wischmeyer and Smith, 1978). Based on a whole profile, a maximum site instability between the stage IV_A and III can be assumed, which is confirmed by the field observations. Lapilli layers on the topsoil, from recent volcanic eruptions or artificial ones, are however a good protection against soil erosion.

For agricultural purposes, the site qualities derived from these characteristics are very unfavorable conditions in the Regosols IV_B, independently of slope position. In the Andosols of landscape IV_A, many moderate conditions occur. The low available water capacity is the main limiting factor. In case of irrigation, a very precise working system has to be introduced, to save water in these very quickly draining soils. On slopes and hilltops, the soils of landscape III have low available water capacities. Furthermore, they have a higher erodibility and there is a danger of salinization.

CONCLUSIONS

Soil formation acts very dynamically on pyroclastics, even in a semiarid environment, where a chronosequence of Leptosol/Arenosol ⇒ Andosol ⇒ Cambisol ⇒ Luvisol ⇒ Calcisol ⇒ polygenetic soils can be found in landscapes from Recent until Pliocene age.

The most important soil forming processes are brownification, clay formation, clay illuviation, ped formation, element export from the topsoil and calcification.

Andic soil development in the semiarid climate (~200 mm P) of Lanzarote is possible, but typical andic soil properties occur only in a very limited space of time during soil formation.

The soil formation from the autochthonous parent material is modified by aeolian additions of Saharan dust.

In comparison with Andosols from a more humid climate (Mexico), the Lanzarote Andosols show much less clay formation (six times), desilication (11 times), formation of short range order minerals (seven times), storage of organic carbon (five times), only slightly less loss of bases (1.7 times), equal formation of Fe-oxides and equal Si/Al ratio of autochtonous formed clay.

With soil formation, site qualities also change dynamically with time. The development of different site characteristics has different time dependent functions.

The site quality for agricultural use results from different single characteristics in very unfavorable conditions for the Regosols IV$_B$, favorable conditions for the Andosols IV$_A$ and deeper soils of landscape III.

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BIBLIOGRAPHICAL REFERENCES

ACSAD, 1980, Soil classification workshop: Damascus, The Arab Center for the studies of arid zones and dry lands, Tour II, Guide.

Blakemore, Searle, and Daly, B.K., 1981, Methods for chemical analysis of soils: New Zealand Soil Bureau Scientific Report 10 A.

Departamento de Edafología, 1984, Suelos volcánicos: Tenerife, Spain, Universidad de La Laguna, Congreso Internacional de Suelos Volcánicos, Tenerife, Spain, Guía de Campo, 282 p.

FAO, 1976, A framework for land evolution: Rome, Food and Agriculture Organization of the United Nations, Soils, Bulletin, v. 32, 72 p.

FAO-UNESCO, 1994, Soil map of the world—Revised legend with corrections: Rome, Food and Agriculture Organization of the United Nations, United Nations Educational, Scientific and Cultural Organization, International Soil Reference and Information Centre, World Soil Resources Report 60, Reprinted as Technical Paper 20, 140 p.

Fernández-Caldas, E.; Tejedor-Salguero, M.L.; and Quantin, P., 1982, Suelos de regiones volcánicas, Tenerife, Islas Canarias: Santa Cruz de Tenerife, Spain, Colección Viera y Clavijo, t. 4, 250 p.

Fuster, J.M.; Santin-Fernández, S.; and Sagredo, J., 1968, Geología y volcanología de las Islas Canarias, Lanzarote: Madrid, Spain, Instituto "Lucas Mallada", C.S.I.C., 177 p.

Gibbs, H.S., 1980, Soils—an introduction: Wellington, New Zealand, 115 p.

ICOMAND, and Leamy, M.L., 1987, Circular letter No. 9: New Zealand Soil Bureau, Department of Scientific and Industrial Research, circular letter, no. 9, 57 p.

Jahn, Reinhold, 1988, Böden Lanzarotes—Vorkommen, genese und eigenschaften von böden aus vulkaniten im semiariden klima Lanzarotes (Kanarische Inseln): Stuttgart, Hohenheimer Arbeiten, Ulmer, 257 p.

———1995, Ausmaß äolischer Einträge in circumsaharischen Böden und ihre Auswirkungen auf Bodenentwicklung und Standortseigenschaften. Habilitationsschrift, Hohenheimer Bodenkundliche 23, 213 p.

Jahn, Reinhold, and Stahr, Karl, 1994, Formation of petrocalcic horizons in soils from basic pyroclastics under the semiarid climate of Lanzarote, Spain: Mexico, Transactions of the XVth Congress of ISSS, Acapulco, Mexico, Transactions, v. 6a, p. 474-480.

Jahn, Reinhold; Zarei, M.; and Stahr, Karl, 1987, Formation of clay minerals in soils developed from basic volcanic rocks under semiarid conditions in Lanzarote, Spain: Catena (Giessen), v. 14, no. 4, p. 359-368.

Miehlich, Guenter, 1991, Chronosequences of volcanic ash soils: Hamburger Bodenkundliche Arbeiten, v. 15, 207 p.

Quantin, Paul, 1972, Les andosols—Revue bibliographique des connaissances actuelles: France, Editions de l'Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), série Pédologie, v. 10, p. 273-301.

Schlichting, E.; Blume, H.P.; and Stahr, Karl, 1995, Bodenkundliches Praktikum: Blackwell, 2nd ed., 295 p.

Schüle, J.; Stahr, Karl; Zarei, M.; and Jahn, Reinhold, 1989, Basaltverwitterung und Bodenentwicklung seit dem mittleren Tertiär auf Lanzarote, Kanarische Inseln (Profil Malaya Chica): Zeitschrift für Pflanzenernährung und Bodenkunde, v. 152, p. 105-113.

Theng, B.K.G., 1980, Soils with variable charge: New Zealand Society of Soil Science, Palmerston North, New Zealand, 448 p.

USDA, 1992, Keys to soil taxonomy: Pocahontas, Pr., Blacksburg, Virg., U.S. Department of Agriculture, Technical monograph, v. 19, 541 p., 5th ed.

Wada, Kojo, ed., 1986, Ando soils in Japan: Japan, Kyushu University Press, Tukuoka-shi, 276 p.

Wischmeier, W.H., and Smith, D.D., 1978, Predicting rainfall erosion losses—a guide to conservation planning: U.S. Department of Agriculture, Agriculture Handbook, v. 537, 58 p.

Zarei, M., 1989, Verwitterung und mineralneubildung in böden aus vulkaniten auf Lanzarote (Kanarische Inseln): Berlin, Verlag B. Schulz, 255 p.

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