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EVOLUTION OF THE COASTAL RELIEFS OF SOUTHERN PERU (*LOMAS*) AS SUGGESTED BY THE SOIL-LANDFORM RELATIONSHIPS: A CASE STUDY FROM MEJÌA SITE (DEPARTMENT OF AREQUIPA)

ABSTRACT: CALDERONI G., LAZZAROTTO L., RODOLFI G. & TERRIBILE F., *Evolution of the coastal reliefs of southern Peru (lomas) as suggested by the soil-landform relationships: a case study from Mejìa site (Department of Arequipa).* (IT ISSN 0391-9838, 2002).

The Peruvian coast along with a major portion of the Chilean coast constitute a continuous desert belt which extends in latitude for about 3500 km. In this area we have some of the minimum world based annual rainfall values, ranging from 5 mm in Northern Peru (Chiclayo) to 0.6 mm in Chile at Arica (Rauh, 1983). The mean temperatures are similar to the ones characterising other intertropical zones; at Callao they range from 16.9°C in September to 21.6°C in March, with minimal variations changing with latitude. Such climatic homogeneity depends both on (i) the specific morpho-structural situation characterised by a long chain of smooth hilly reliefs (*lomas*) parallel to the coast and on (ii) the presence of a cold oceanic stream (Humboldt stream) which moves northwards along the coast. This climatic homogeneity is abruptly suspended, approximately every 10 years, when there is an inversion in the oceanic circulation («*ENSO - El Niño Southern Oscillation*»). It therefore changes as soon as one moves from the coast towards the inner continent. From May through October the combined action of these factors produces a continuous dense layer of fog from 400 to 1000 m a.s.l. which is continuously supplied by the oceanic waters. As it has been observed that as the fog moves inland it spontaneously condensates into water at the troposphere-pedosphere interface, efforts have been focused on enhancing this process in order to utilize the fog as an effective water supply for the hyper-arid local environment. In particular, within the framework of an INCO/UE project coordinated by Università di Firenze (*Fog as a new water resource in Southern Peru and Northern Chile*) the main goal was to utilize the condensation water to restore the discontinuos forest cover («fog oases») which, according to Ellemberg (1959) in the past used to extend along the 400-1000 m a.s.l. hilly belt facing the ocean. For this purpose, in 1996, an experimental station was set up in a representative environment of Las Cuchillas, in the nearby of Mejìa (district of Arequipa).

Within the framework of this project, the authors objective was to characterise the soil-landscape relationships in a large area around the experimental station, the aim being to produce a soil-landscape model to be extrapolated in other comparable coastal Peruvian environments. In the preliminary stage, the use of Landsat and airborne images enabled the authors to divide the area into 5 soil-landform units which, moving in a direction perpendicular to the coast, outcrop in succession up to an altitude of 1000 m a.s.l. The soil survey carried out in the *lomas* unit, which included the experimental station, showed a very specific situation, never reported as yet. The field and analytical data, as well as the ^{14}C dating of the 2Abss horizon of the compound geosol (*Vertic Paleargid*), which is widespread in the area, allowed for the reconstruction of the following major stages in the environmental and geomorphologic evolution of this coastal portion of Peru:

I. first soil formation stage on the crystalline rocks, reflecting a period of tectonic stability. the occurrence of a dense plant cover is strongly suggested by a buried Btb horizon, rich in Fe, pointing to moist conditions;
II. first severe erosion stage due to either (i) new tectonic activity or (ii) long period of aridity producing a sharp morphology with V shaped valleys and boulder heaps on summits;
III. deposition of a thick ash layer, probably the onset of Holocene (Thouret & *alii*, 1999) by nearby volcanic activity;
IV. weathering of the above mentioned ash layer resulting in the formation of a geosol, the 2ABtss horizon of which has been dated between 4530 and 1870 years BP;
V. second erosive stage, implying both the truncation of the geosol and the formation of thick colluvial deposits on the valley bottom;
VI. emplacement of a thin whitish level of volcanic ash, continuously spread all over the area by the Huaynaputina volcano (attributed to the 1600 A.D. event, according to historical sources);
VII. soil formation processes on the above mentioned tephra, still in progress though at low rate because of the unfavourable climatic conditions;
VIII. third erosive stage (underway at present), especially active during the «ENSO events». In some instances the effects of the latter combined with deforestation and overgrazing in increasing soil erosion up to the point of exposing the crystalline bedrocks, causing mass movements and originating rills and gullies.

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The conclusion reached is that the present virtual lack of rainfall does not conflict with the observed advanced soil development in that the pedogenesis of the lower volcanic ash level could have occurred during a phase of humid climate. In turn, the former tree and bush cover probably disappeared because of the anthropogenic impact and its relics could have survived in the present arid conditions by uptaking enough water from the seasonal fog. In contrast with the common belief of an overall homogeneity of the soil cover along the S. Peruvian coast the results of the geomorphological and pedological investigations herein reported support a rather complex origin and differentiation.

KEY WORDS: Southern Peru, Arequipa, Coastal desert, *Lomas*, Soil-landform units.

RESUMEN: CALDERONI G., LAZZAROTTO L. RODOLFI G. & TERRIBILE F., *Evolución de los relieves costeros (lomas) del Perú Meridional, deducida por el análisis de las relaciones suelos-morfología en el área representativa de Mejía (Departamento de Arequipa).* (IT ISSN 0391-9838, 2002).

La totalidad costa peruana y gran parte de la chilena constituyen una faja desértica continua, que se extiende en latitud en unos 3500 km. Allí se registran valores mínimos de las precipitaciones anuales, quizás inferiores a cualquier otra zona de la Tierra: se pasa de 5 mm en el Perú Septentrional (Chiclayo) a 0,6 mm de Arica, en Chile (Rauh, 1983). También las temperaturas medias no son las que caracterizan otras áreas de la zona intertropical; a Callao éstas oscilan entre 16,9 °C en Septiembre y 21,6 °C en Marzo, con variaciones mínimas en el sentido de la latitud. Esta uniformidad climática es fruto sea de una situación particular morfológico-estructural, que se manifiesta en una larga cadena de relieves ondulados redondeados (*lomas*) con eje paralelo a la costa, sea de la presencia de una corriente oceánica fría (corriente de Humboldt) que la remonta; ésta se interrumpe, con ritmo más o menos de un decenio, con ocasión de una inversión de la circulación oceánica (acontecimientos «ENSO - El Niño Southern Oscillation») y se modifica en cuanto se pasa de la costa hacia dentro del continente. La acción concomitante de estos factores determina, además, la presencia estacional (de Mayo a Octubre) de una densa y continua capa de niebla, que queda incluida dentro de una faja altimétrica precisa (unos 400-1000 m s.l.m.) en continuo movimiento del Océano hacia el interior, al lado de las lomas costeras. El hecho de que este particular tipo de niebla, en continuo movimiento, se condense alrededor de cualquier obstáculo que se yergua en su camino, ha inducido desde hace tiempo a numerosas tentativas, dirigidas a utilizarla como recurso en este entorno hiperárido. También se está intentando, en el marco de un proyecto INCO/UE (*Fog as a new water resource in Southern Perú and Northern Chile*) coordinado por la Universidad de Florencia, de utilizar el agua de condensación para reconstruir el manto forestal que, como afirman algunos autores (Ellemberg 1959, en Rauh 1983), habría cubierto en el pasado, aunque no de manera continua (*fog oases*) las laderas colinares frente al Océano, limitado al susodicho intervalo de cuota. Con tal objetivo se preparó, en el 1996, el área experimental y representativa de Las Cuchillas, en los alrededores de Mejía (Departamento de Arequipa).

La intervención de los autores en este proyecto estaba dirigida a la caracterización de la relación suelo-paisaje en un adecuado entorno del área experimental, para poner a punto un modelo extrapolable a situaciones ambientales parecidas a lo largo de la costa peruano-chilena. Utilizando en la fase preliminar ya sean imágenes Landsat que fotografías aéreas, ha sido posible subdividir el área en cinco unidades morfo-edafológicas que se suceden, en dirección perpendicular a la costa, entre ésta y los 1000 m s.l.m. Un muestreo de los suelos dentro de la unidad «*lomas*», que comprende el área experimental, ha denotado una situación completamente particular, no señalada nunca en la literatura. Las observaciones de campo y los datos analíticos además de la datación ^{14}C del horizonte 2Abss de un *compound geosol (Vertic Paleargid)* extensamente presente en el área, han permitido reconstruir las fases sobresalientes de la evolución geomorfología y ambiental de esta porción de la costa peruana, que se pueden resumir así:

I. primera fase edafogenética, que interesa el zócalo cristalino, testimoniante de un período de éxtasis tectónica y presencia de una densa cobertura vegetal, compatible con la presencia de horizontes Btb enterrados con una activa dinámica del hierro (condiciones húmedas);
II. primera fase erosiva, muy importante, debida o a una reanudación de la actividad tectónica o al dilatarse los períodos de aridez, que genera una morfología accidentada, con valles a V y «acúmulo de bloques»;
III. deposición de un grueso nivel de cenizas, por parte de uno de los muchos volcanes que circundan el sitio en cuestión, probablemente al principio del holoceno (Thouret & *alii*, 1999);
IV. edagogenésis de esta ceniza, con formación del geosuolo antes citado, cuyo horizonte 2Abtss ha proporcionado una edad radiométrica comprendida entre 4530 y 1870 años BP.;
V. segunda fase erosiva, con truncamiento del geosuolo y formación de espesos depósitos coluviales en las vaguadas;
VI. deposición de la ceniza reciente por parte del volcán Haynaputina (1600 A.D., según las crónicas del tiempo), que cubre el paisaje con una alfombra blanquecina, continua, de modesto espesor;
VII. edafogénesis de la ceniza blanquecina, todavía en un estadio embrionario de desarrollo, dadas las particulares condiciones climáticas;
VIII. tercera fase erosiva (actual), particularmente activa con ocasión de los acontecimientos «ENSO», que ha alcanzado evidencias de elevada degradación, a veces hasta la exhumación del sustrato cristalino, con desarrollo de *rills*, *gullies* y movimientos de masa, también como resultado de la deforestación y del exceso de pastoreo.

Con este propósito se concluye que la contradicción entre la casi ausencia de precipitaciones y el estadio avanzado de desarrollo de los suelos es solo aparente, en cuánto que el proceso de edafogénesis de las cenizas inferiores puede comenzar durante una oscilación climática en sentido más «húmedo»; además, la cobertura arbórea vegetal, quizás destruida por la intervención antrópica, puede haber sobrevivido en las prohibitivas condiciones climáticas actuales explotando la capacidad de capturar volúmenes de agua no despreciables de las nieblas estacionales,. En otras palabras, el estudio geomorfológico y edafológico de las *lomas* de la costa peruana meridional ha revelado el elevado grado de complejidad del sistema suelo-entorno que, en un examen superficial, aparecia homogéneo.

TERMINOS CLAVE: Perú meridional, Arequipa, Desierto costero, *Lomas*, Unidades edafo-morfológicas.

INTRODUCTION

The western coast of south American continent is characterized, along the stretch south of the Equator, by a climate showing characteristics of growing aridity as the latitude increases. This peculiarity, also present in the southern part of Ecuador, affects the whole Peruvian coast as well as most of the Chilean one. Rainfalls decrease progressively, reaching the absolute minimum value with respect to any other zone of the Earth: they range from 5 mm in Northern Peru (Chiclayo) to 0.6 mm in Arica (Rauh, 1983; Dillon & Rundel, 1989), a Chilean site located about one hundred km South of the study area. The extremely dissected relief is composed of a sort of hilly ridge (*Cadena Costanera*) the axis of which runs parallel to the coastline, at a distance of just 3-4 km. This ridge rarely exceeds 1000 m a.s.l., but it extends in length and originates a typical feature of the coastal landscape of Southern Peru, locally called *lomas*. Moving up towards the inner continent, the coastal relief changes abruptly, with subvertical scarps in some places, and wide uniform surfaces, sloping slightly towards the coast, the *pampas*. The latter are connected in turn with the pre-Andean footslope.

However, these morphological features of the coast, coupled with the presence of a particular oceanic circulation, allow the seasonal presence (from May to October) of a continuous dense fog layer within an altimetric belt ranging from 400 to 1000 m a.s.l. which, therefore, coincides with the *lomas* relief. Indeed this «advection fog», continuously moves inland pushed by a wind which, in the same season, blows from the Ocean (Oka & Ogawa, 1984). Because of this characteristic, whenever the fog meets an obstacle rising from the soil surface (such as the herbaceous or arboreal vegetation) it condenses and produces a quantity of water as much bigger as more extended is the specific surface exposed by the obstacle (Calamini & Salbitano, 1999).

The experiments carried out in hyper arid areas, such as the one examined in this study, aimed at obtaining water from the condensation of fog, for drinking and/or irrigation purposes, are not completely new (Schemenauer & Cereceda, 1992). In 1996 the problem was approached in a UE-financed project (INCO/CEE), coordinated first by the University of Padua, and then by the University of Florence, the title of which was: «*Fog as a new water resource in Southern Peru and Northern Chile*».

In the Mejìa zone (*Departamento de Arequipa*) the experimental area of Las Cuchillas was selected as being representative, and the objectives were the following:

- assess the quantity of water available from fog-capture, using the cheapest techniques and tools;
- test the possibility of establishing water reserves for distributing water during the fog-free season;
- attempt to reconstitute the forestry ecosystem, destroyed during the last decades by the growing anthropisation, by setting up experimental plots with both indigenous and exotic plants, irrigated by fog-collected waters.

The successful results obtained have pushed researchers on to extend this experience to other sites on the Peruvian coast, where the simultaneous presence of the following morpho-pedological conditions, as in the Las Cuchillas area, occurs:

- the presence of a hilly ridge parallel to the coast line, then normal to the direction of dominant winds, with the divide located entirely within the fog belt;
- the presence of some divide stretches coinciding with the heads of valleys open towards the coast;
- the absence of higher reliefs leeward to the coast, at least in the closest surroundings;
- the presence of soils able to sustain vegetation, even if degraded by overgrazing at present.

With this view in mind, the aim of this research was the accurate characterization of the landscape surrounding the Las Cuchillas experimental site, by subdiving it into the various morpho-pedological units which following each other in elevation from the Pacific coast up to *pampas* and pede-Andean reliefs. In other words, an attempt was made to establish a reference model for evaluating the suitability of other sites of the Peruvian coast for installing fog-capture devices which could assure an optimal water production.

Regarding the basic parameters to be taken into account when setting up any model aimed at identifying morpho-pedological units, the state of the knowledge concerning the whole Peruvian coast is rather scarce, as only studies and maps at a general reconnaissance level are available. We will refer to these later on.

MATERIALS AND METHODS

The study area (fig. 1) was analysed according to the methodology proposed by van Zuidam & van Zuidam Cancelado (1979). In particular, the preliminary recognition by

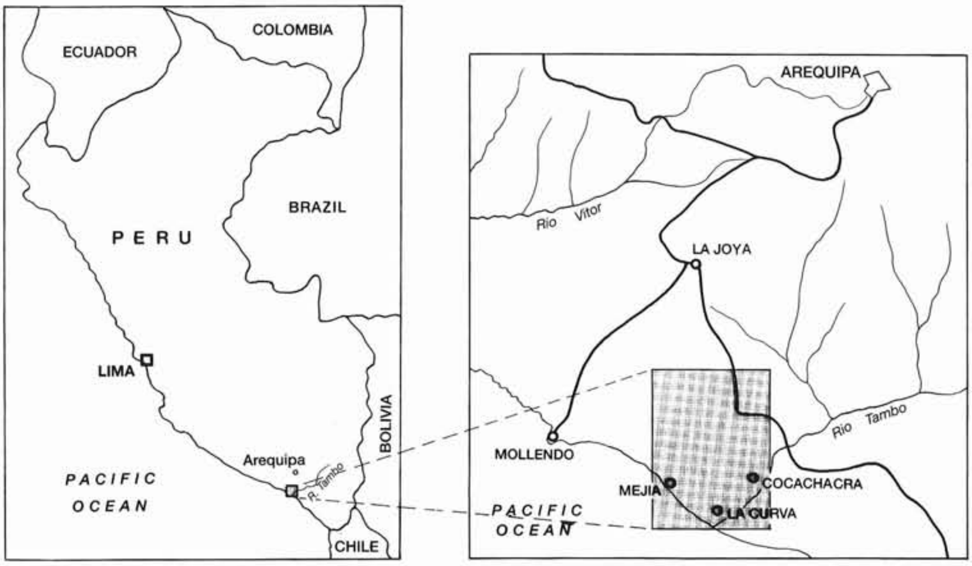


FIG. 1 - Location of the study area (Mejìa; Department of Arequipa, Southern Peru).

means of satellite imagery (Landsat TM) was refined on aerial photographs at the scale of ca. 1:60,000 in order to obtain an initial subdivision of the area into physiographic units and to select the best transects for on-ground controls. Once the overall framework had been obtained, it was decided to focus the investigation on the physiographic unit locally referred to as «*lomas*» as follows:

I. classification according to morpho-pedological units;
II. preliminary field campaign (1996) for ground thruthing and soil survey at a general reconnaissance scale;
III. physico-chemical and micromorphological analyses of the surveyed soils; ^{14}C dating of the two horizons richest in organic matter

Within the *lomas* unit 5 soil profiles were studied. They were described (Sanesi, 1977) and sampled following two methodologies: (i) sampling loose soil for chemical and physico-chemical analyses, (ii) undisturbed sampling using Kübiena boxes (5,0 x 10,0 x 3,5 cm) for micromorphological analyses. The Loose samples were air-dried and sieved (<2 mm).

The chemical and physico-chemical determinations, according to the MiRAAF (2000) methods, included the following measures: (i) pH, by the potenziometric method, on a soil-water (1:2,5) suspension; (ii) organic C and total N by gas-cromatography of the combustion products at 1000°C; (iii) soluble bases, by AAS, by leaching with a solution of ammonium acetate; (iv) acidity and soluble Al by leaching with KCl solution followed by titulation of distinct shares respectively by NaOH and HCl respectively; (v) cation exchange capacity (CEC) by summing up all the exchangeable cations; (vi) total acidity by leaching with a $BaCl_2$ solution followed by titulation with HCl. The assimilable P were analysed according to Olsen method. The surveyed soils were then classified according to Soil Taxonomy (USDA, 1998).

^{14}C dating were carried out on a sample pair (Rome –1064 and –1065) from the horizons higher in humic matter in the soil profiles Chihuanolo 1 and Las Cuchillas: further details on sampling sites, pedological and geomorphological implications are provided in Section 3.3.

Both soil samples underwent a special preliminary chemical treatment in order to remove the carbon-bearing compounds (both mineral and organic) which are suspected of producing unreliable ^{14}C readings because of their enhanced geochemical mobility.

The ^{14}C decay rate was measured with the liquid scintillation technique (LSC) by means of low background, multichannel β^- spectrometers. The benzene obtained with a home-made chemical apparatus, following a 4-step procedure was used as a counting medium.

Details on the synthesis of benzene, counting protocol have been reported elsewhere (Calderoni & Petrone, 1992). The statistical treatment of the counting data as well as their conversion into conventional radiocarbon ages (expressed in yr BP, 1950 being assumed as the present time) comply with the recommendations after Stuiver & Polach (1977) and Gupta & Polach (1985).

The dated humic matter was previously made rid of the fulvic acids fraction. In fact the latter are significantly mobile over the pH range of natural waters and therefore their age can therefore differ to an unpredictable extent from that of the host paleosol. By contrast, both humine and humic acids (the latter, in particular, following absorption onto the clay fraction of soils) behave differently in that besides of being better preserved through time because of their poor chemical reactivity as a rule are not mobilized by the circulating waters because of their insolubility at the ordinary pH's value. In this respect the results of previous accounts (Calderoni & Turi, 1998 and references therein) dealing with the significance and variations of the ^{14}C ages measured on distinct paleosol humic matter fractions provided sound evidence that the «apparent ^{14}C mean age» yielded by humine and absorbed humic acids are on one hand unaffected by the rejuvanization caused by allocthonous organic matter and on the other, are the ones best approaching the beginning of pedogenesis.

RESULTS

ENVIRONMENTAL FEATURES OF THE MEJÌA AREA

Location

The Las Cuchillas experimental site is located between 750 and 850 m a.s.l., at about 4 km from the Pacific coast and around 10 from the nearest village, the sea-side resort of Mejìa (figs. 1 and 2). From a physiographic point of view it lies entirely within the *lomas* landscape (fig. 3) between 350-400 (upper limit of the coastal terraced surfaces) and 900 m a.s.l. (lower limit of the pre-Andean *pampas*). Towards SE this area is limited by the terminal reach of the Rio Tambo, a perennial river, the catchment of which extends up to the offshoots of the *Cordillera Occidental*, the most developed ridge of the Andean mountain system.

The climate

The western slope of the Andes presents a wide range of climates, an in particular varied rainfall values, due to differences in both latitude and elevation. A common feature for the whole slope is the presence of a single rainy season, during the first four-five months of the year (Oka & Ogawa, 1984). However, the rainfall amount decreases considerably from North to South; for example, Arequipa (2440 m a.s.l., 16°30' S) has a short rainy season (from January to March) during which it falls the 98% of the 104 mm of the annual rainfalls. The environment is almost totally desertic; the only green spots are the plots cultivated thanks to the irrigation canals catching water from rivers, fed, in turn, bythe perennial glaciers located on the most elevated summits of the Andean Chain.

The so-called *costa*, i. e. the altimetric belt between sea level and about 1000 m a.s.l., presents an even greater aridity situation, but it has a particular characteristic: during the six months of the austral winter (from may to October, approximately) one can observe the formation, mainly in certain hours of the day, of a dense fog coming

FIG. 2 - The hilly landscape of the Mejìa *lomas*, as it appears from the Las Cuchillas ridge, just at the head of one of the deep steep valleys (*quebradas*) which characterize this typical morphology. Fog, even if not dense, hinders the view of the Pacific Ocean shoreline, less than 5 km away (*photo:* *G. Rodolfi*).

from the sea, which is called *garùa* in Peru and *camanchaca* in Chile. During the other six months the days are usually sunny. The meteorological stations located at sea level do not record appreciable variations in the air moisture content, because the fog layer forms between 400-500 and 900-1000 m a.s.l. Therefore, below this level the sky appears covered, but visibility is not reduced. As a matter of fact it would be more correct to speak about dense stratocumulous-type clouds, the origin of which is not yet completely clear, rather than about fog.

As mentioned in the introduction, the *lomas* landscape is a part of the more extensive Peruvian Coastal Desert which, in turn, constitutes the northward continuation of the Chilean Atacama Desert. Together, they form a continuous belt which extends for 3500 km from southern Ecuador (about 5°S) to central-northern Chile (about 30°S), along the coast of the Pacific Ocean. These conditions of extreme aridity are due to the existence of a particular climatic regime, dominated by a steady temperature inversion due, in turn, to the concurrence of two situations:

- the presence of the Humbolt (or Peruvian) Stream, a cold oceanic stream which forms in Antarctica and goes up the south-American coasts towards the Equator;
- the influence of a pronounced atmospheric subsidence associated with the stability of a subtropical anticyclone (Trewartha, 1981).

As a result, we have a general climatic homogeneity: within this long belt temperatures are generally lower than in any other site of the Earth located at the same latitude. For example, at Callao (12°S) the average temperature in March (summer) is 21.6°C, in September (winter) it is 17.5°C, whereas the absolute minimum is about 16.9°C. At Mollendo (17°C, more than 700 km South of Callao), near the study area, the average annual temperature is only 0.5°C lower (Rauh, 1983).

The hyper-aridity conditions of Southern Peru seem to be very ancient: a climate similar to the present-day one characterized these sites since Middle Miocene (Galli Olivier, 1967; Mortimer, 1973; Mortimer & Saric, 1975). The uplift of the Andean range played a primary role in determining the conditions of aridity still persisting: between Oligocene and Upper Eocene the *Cordillera* reached an elevation ranging from 2000 to 3000 m a.s.l., which was sufficient to create a barrier for the East-blowing trade-winds, which started to release their high content of humidity on the eastern (Amazonian) slopes. The costal belt was therefore exposed only to the West-blowing winds, also laden with humidity due to their run on the Pacific Ocean. At the same time the oceanic waters along the coast had a particular model of circulation, as a consequence of the increasing Antarctic ice cap: the above mentioned Humboldt cold stream. From that time on, within the contact belt between these two fronts, the periodic condensation of the ocean-coming humidity has originated the thick mantle of winter *garùa*, which lies between 400-500 and 900-1000 m a.s.l. (Troll, in Rauh, 1983). Above this elevation limit the fog dissolves, and the conditions of extreme aridity characterizing the pede-Andean *pampas* return, due to the fact that these boundless surfaces are not reached by summer rains either.

Another particular climatic phenomenon periodically affects the Peruvian coast: with a variable frequency, the subtropical anticyclone weakens and migrates southwards; the warm equatorial counter-current stream more or less

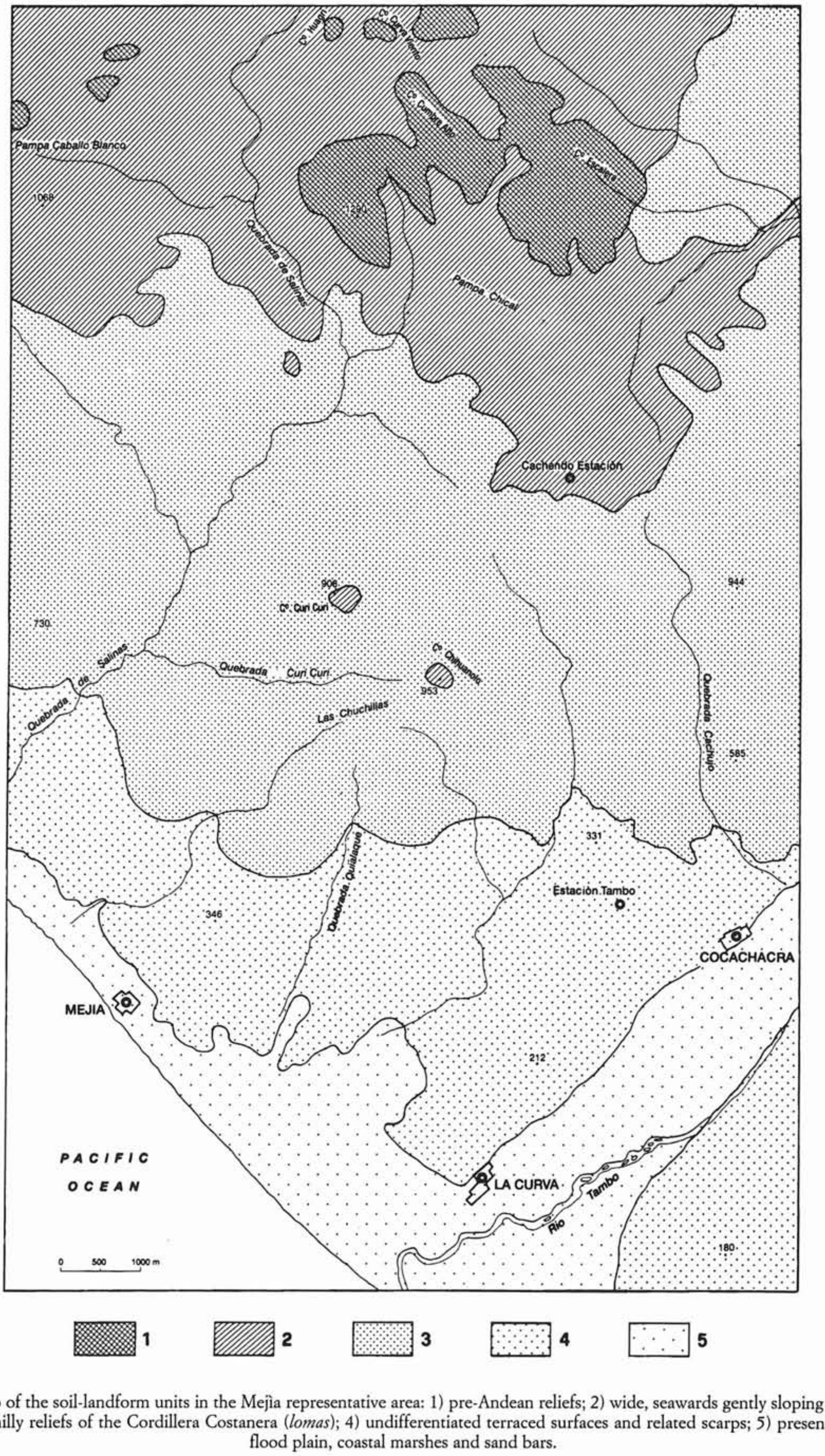


FIG. 3 - Sketch map of the soil-landform units in the Mejìa representative area: 1) pre-Andean reliefs; 2) wide, seawards gently sloping depositional surfaces (*pampas*); 3) hilly reliefs of the Cordillera Costanera (*lomas*); 4) undifferentiated terraced surfaces and related scarps; 5) present-day Rio Tambo flood plain, coastal marshes and sand bars.

gradually replaces the Humboldt stream, causing an anomalous temperature increase, with the immediate consequence of abundant and high intensity rainfalls (Pinna, 1977). This is the recurrent event known in literature as ENSO (*El Niño Southern Oscillation*) which usually occurs every 10-15 years, with variable intensity, around Christmas (*El Niño: the Holy Child*); rainfalls, limited to the coastal belt (no more than 10 km inland) originate flash floods along steep, usually dry, ravines (*quebradas*) and gullies (*càrcavas*) on the slopes. From another point of view, the sporadic, short periods (*tiempos de lomas*) when herbaceous vegetation can coat the hillslopes. The last two ENSO events occurred in 1982-83 (perhaps the strongest in the 20th century) and in 1997-98.

Geological features

In the Mejìa area the most ancient geological formations of the *Cadena Costanera*, and also of the whole Andean system, outcrop; they belong to the so-called *Complejo Basal de la Costa*, that is to the pre-Cambrian crystalline basement (Bellido & Narvaez, 1960). Two main units can be distinguished (fig. 4):

- *Metamorphic complex*. It outcrops over wide surfaces and constitutes the greater part of the Mejìa lomas, including the Las Cuchillas ridge. It is prevalently orthogneiss, derived from the metamorphism of a previous albitic granite (Bellido & Guevara, 1963); dark-grey stripes, containing quartz, feldspars and iron-magnesium minerals, as well as light-pinkish ones, with microcline and quartz, can be identified in it.
- *Acid intrusions*. Observed near the Mejìa beach, as little apophyses or stocks, they are composed of pink granite (Bellido & Guevara, 1963) with K feldspar, microcline, quartz, Ca-Na feldspar, biotite and horneblend.

Over the crystalline basement lies a thick (about 700 m) succession of sedimentary, effusive and pyroclastic formations, often in unconformity, the age of which lies between the Upper Triassic and the Pliocene (Garcia, 1968). However none of them outcrops, however, on the study area. The whole succession was affected by several cycles of tectonic activity, which caused some discordances and gaps. We have only mentioned this to state in advance that this activity, which also went on during the Quaternary, has not yet come to an end, as the seismicity of the area shows.

The continuity of the outcrops of the metamorphic complex is interrupted, here and there, by other localized intrusions, observed on the summit of both Cerro Chihuanolo and Cerro Curi-Curi. Their composition varies from place to place (Bellido & Guevara, 1963): granites, horneblenda granodiorites, quartz diorites, monzonites, riodacites, diabases. Some authors (as Bellido Bravo, 1982) think they are contemporary to the setting up of the huge Andean batholit; since they cross, metamorphosing them, all the formations of the above mentioned succession, comprised between the Upper Triassic (*Grupo Yamayo*) and the Middle Tertiary (*formaciòn Camanà*); their setting is believed to precede the latter period. These intrusions sharply differ, therefore, from the ones outcropping along the shoreline.

The Quaternary formations, lying discordantly on the previous ones, are essentially represented essentially both by marine and alluvial sediments of different age, sometimes on terraced residual surfaces (from 0 to about 350 m a.s.l.), and by at least two cycles of recent pyroclastic deposits. In the staircase-like arrangement, parallel to the coast line, one can observe at least three surfaces slightly sloping seawards, the continuity of which is broken not only by the course of the Rio Tambo, but also by the deep narrow *quebradas* coming down from the southern edge of the *pampas*. What we have therefore are some remnants, which probably cannot be correlated to each other, due to the fact that they have been affected by denudational processes for some time. The highest surface, which joins the *lomas* toe slope (350-400 m a.s.l.) is the one where the origin is most dubious, because there is no section available; it could be a remnant of an ancient abrasion platform, or of the effect of a Plio-quaternary phase of extensional tectonics, following a previous compressive one (Sébrier & alii, 1985), linked to the evolution of the Peruvian oceanic trench. As far as the two lower ones are concerned, the marine origin is confirmed by the fossils contained both internally and on the surface of the related deposits; often, however, they are covered by more or less thick alluvial or aeolian deposits.

The present-day formations are essentially composed of the alluvial deposits of the Rio Tambo, as well as of lit-

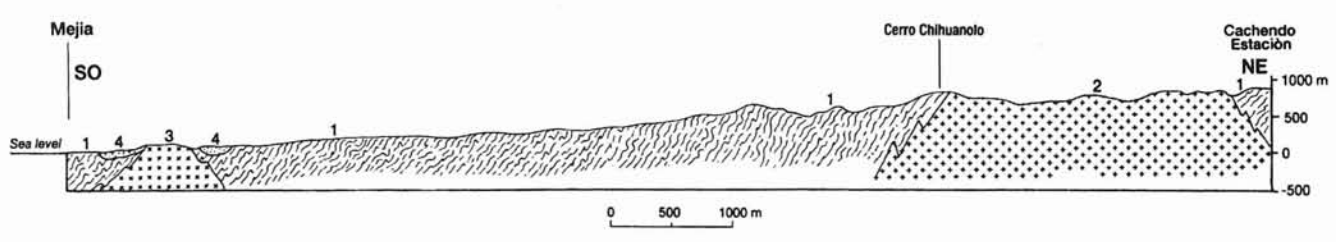


FIG. 4 - Schematic geological profile from the Mejìa shoreline to Cachendo Estaciòn, on the southern edge of *pampas* (957 a.s.l.): 1) pre-Cambrian metamorphic complex (ortogneiss); 2) pre-Tertiary undifferentiated intrusions; 3) acid pre-Cambrian intrusion (Mejìa pink granite); 4) colluvial and alluvial covers (Quaternary).

toral deposits, in the form of sandy bars enclosing extended swampy areas. Colluvial deposits have filled the bottom of many small valleys in the *lomas* landscape. In the bare areas wind can mobilize the finest particles, as the incoherent dusts and cinders from the eruption by the Huaynaputina volcano (in the Quechua idiom: «the boiling young man», also called «*Vesubio Andino*») in February 1600 AD, according to the chronicles of that time (Macedo Franco, 1996; Small & *alii*, 1997; Legros, 1998).

Vegetation

The Spanish word *lomas* refers literally to «backs». However, this term was introduced in the scientific literature by Louis Feullée (1710) to indicate the typical hilly reliefs of the Peruvian-Chilean coastal landscape (Calamini & Salbitano, 1999). In southern Peru it is not only used in this meaning, but it is also extended up to include the vegetation characterizing it. Along the *Cadena Costanera*, between Atico and Arequipa, Rauh (1983) distinguishes the following vegetation belts, which are distributed according to their elevation (fig. 5):

- 0 - 300 m: coastal *lomas* with *Neoraimondia*, spherical species of *Islaya* and creeping species of *Haageocereus*,
- 300 - 600 m: herbaceous and arboreous lomas,
- 600 - 1100 m: *Tillandsia* lomas,
- 1100 - 1400: rocky desert without vegetation,
- 1400 - 2000 m: Cactaceae desert with *Weberbauerocereus, Browningia candelaris*, and dwarf shrubs.

In the study area Cactaceae are found both above and below the fog belt, mainly on the North-East facing slopes, opposite the ocean. The arboreous lomas are composed by some species of Acaciae and Caesalpinaceae, which are to be found isolated, scattered or grouped in small communities. Some authors (Johnston, 1929; Ellemberg, 1959; Goodspeed, 1961) quoted in Rundel & *alii* (1991), have identified these formations with the terms *fertile belt*, *fog oases* and *meadows of the desert*, respectively.

THE MAIN PHYSIOGRAPHIC UNITS

In the Mejìa area five main physiographic units were identified. They succeed each other from the pre-Andean reliefs to thePacific coast, constituting a typical «catena». Besides being located at different elevations, they also differ in terms of particular microclimatic and pedomorphological conditions, as well as in the dominant morphogenetic processes. Each of them can be subdivided into sub-units, according to both slope morphology and type/density of the drainage pattern.

The pre-Andean reliefs (>1300 m a.s.l.)

The highest elevations of the area, about 1300 m a.s.l., are reached by NW-SE oriented ridges, parallel both to each other and to the shoreline, according to the main structural features (fig. 6). These ridges, formed by outcrops of the crystalline basement, are not continuous; rather they are stretches (Cerro Cumbre Alto, Cerro Escalera) or isolated summits (Cerro Huacra Cumbre, Cerro Curva Viento, Cerro Huagri) which stand for more than 300 m on the surrounding *pampa*.

The pampas *(1300-950 m a.s.l.)*

In Peru the term *pampas* refers to the wide, almost flat and even surfaces near the coast, but located at a certain elevation and characterized by extremely arid conditions (fig. 7). They stretch for many kilometres, forming the slightly sloping morphological connection between the volcanic cones of the Western Cordillera and the main erosional escarpement towards the coast. The related sediments are composed of pyroclastic material (mainly ashes and cinders), mixed with alluvio-colluvial deposits; these may have been deposited during the Plio-Pleistocene, probably coinciding with a climatic period which was more «humid» than the present-day one (Nimlos & Zamora, 1992). They seem to have buried a previous, more dissected, morphology, except for its highest stretches. Ac-

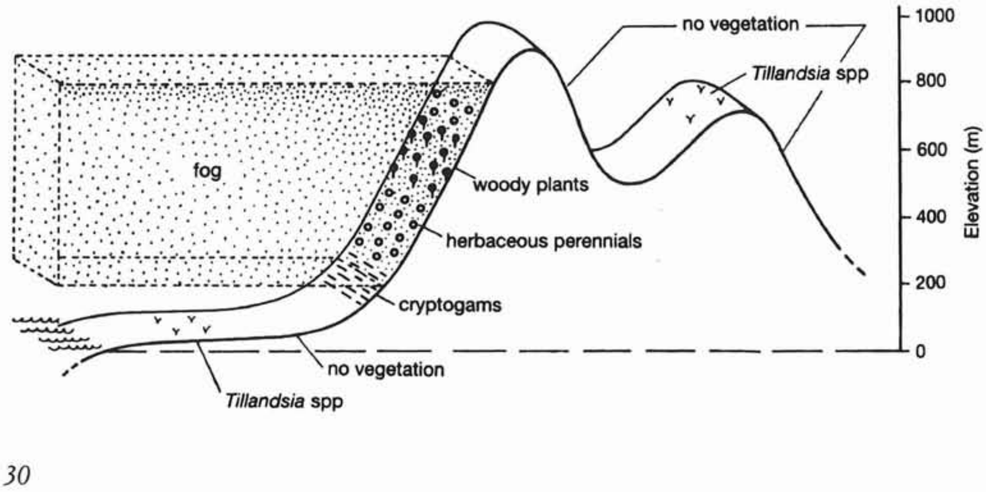
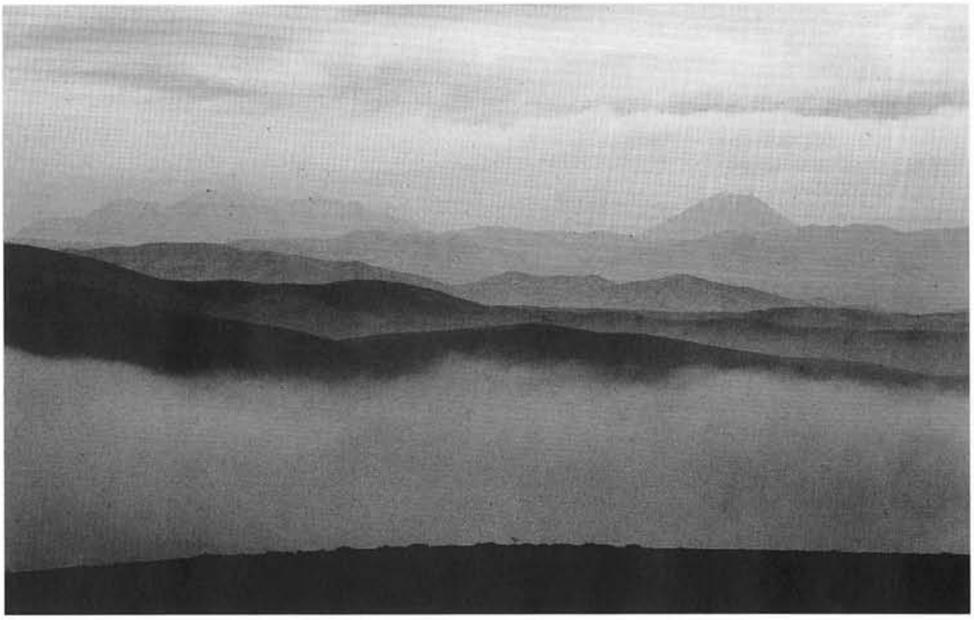


FIG. 5 - Diagrammatic sketch of vegetation zonation in the coastal reliefs of Southern Peru (redrawn from Dillon & Rundel, 1989).

FIG. 6 - Panoramic view of the pre-Andean reliefs, taken northwards from the summit of Cerro Chihuanolo (920 m a.s.l.). In the foreground the upper surface of the fog layer is evident. In the background, on the right, the upper part of the cone of El Misti volcano, which dominates the town of Arequipa (*photo: G.Rodolfi*).



cording to French literature, the *pampas* could therefore be defined as *glacis d'accumulation*. In the study area the continuity of their surface (Pampa Caballo Blanco, Pampa Chilcal), progressively declining seawards, is sharply interrupted, at about 950 m a.s.l., by the edge of the above mentioned escarpement. South of that, the summit of some reliefs located around 900 m a.s.l. (Cerro Chihuanolo, Cerro Curi Curi) even if located into the *lomas* unit, described later on, can be regarded as residual limbs of a *pampa*, which used to be more extensive, even though they are located in the lomas unit (described below).

The environment is desert, and wind action is the dominant morphogenetic process. It affects the finest reddish alluvio-colluvial sediments, covered here and there by the light-grey pyroclastic materials from the eruption of the above mentioned Huaynaputina volcano in 1600 AD. Typ-

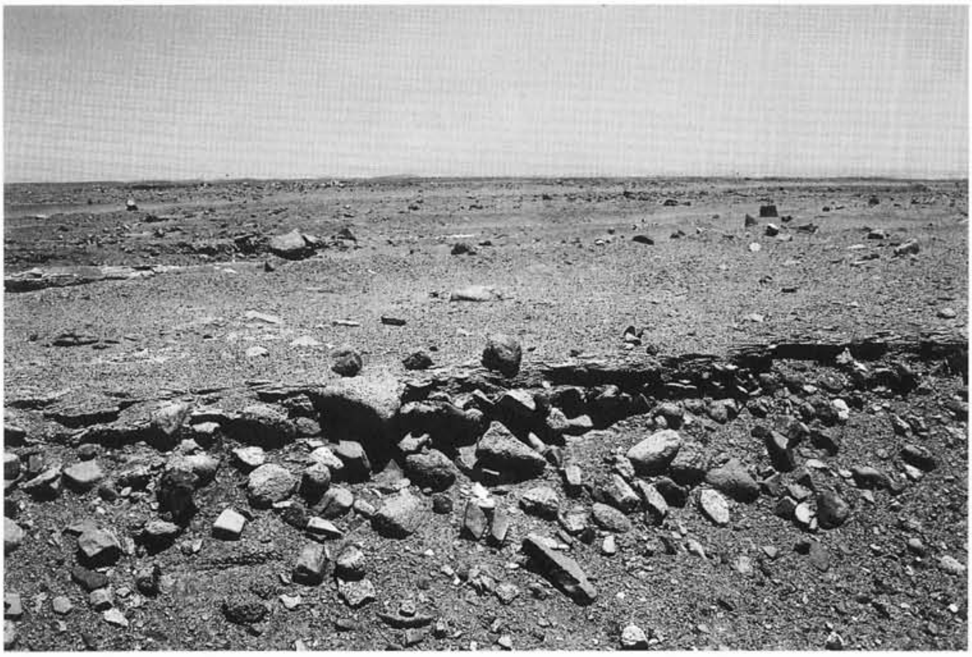


FIG. 7 - The *pampas* landscape, wide depositional surfaces slightly sloping towards the coast (*photo: G. Rodolfi*).

ical depositional landforms, similar to the *nebkhas* of the pre-Saharian expanses, can be observed on the leeward side of occasional obstacles, represented in most cases by an isolated bush or single plant.

The reliefs of the Cordillera Costanera *(950-350 m a.s.l.)*

The reliefs between the *pampas* and the coast are moulded on the crystalline rocks of the *Complejo Basal de la Costa*, too. The most evident morphological feature is the very high drainage pattern density: a myriad of small valleys, with steep slopes and deep V-shaped cross profiles, except in the highest reaches, merge into the main *quebradas* (Q. de Salinas, Q. Curi Curi, Q. Quialaque, Q. Cachuyo) which, in turn, flow into the Ocean. Strangely, their divides appear smoothed, with wide bending radii. The heads (*cabeceras*) of these hydrographic systems generally coincide with the escarpment limiting the pampas seawards, at an elevation of about 950 m a.s.l. However, some of the main *quebradas* (Q. de Salinas) can go up inwards for some kilometres, breaking the continuity of the *pampas* surface with deep gullies. From the aerophotointerpretation we could infer that this unit, which corresponds roughly to the *lomas*, does not show a uniform morphology: taking the drainage pattern density as the differentiating criterion, it can be subdivided into sub-units; i) dendritic high density, ii) parallel-dendritic medium density, iii) dendritic medium density). This characteristic can be related not only to the above mentioned lithological variability of the crystalline basement, but also to its fracture density and weathering degree. The bedrock formations only outcrop at the bottom of the main *quebradas* or, in the form of boulder heaps, on some divides.

However, the main feature of these *lomas*, which occupy an altimetric belt ranging from 950 to 400 m a.s.l., is the morphological contrast between their highest and lowest reaches: the convex cross-profiles of the divides, as well as the concave ones of the valley-heads, pass downwards to steep slopes and narrow deep valleys.

A slightly sloping surface, parallel to the shoreline, extends from about 400 to 350 m a.s.l., subdivided into residual limbs by the lower stretches of the main *quebradas*. It is in turn covered by the same mantle of pyroclastic deposits, and its origin is difficult to explain: since it represents the connection between the seaward front of the *lomas* and the lowest terraced surfaces, the hypothesis that it could have been an ancient marine abrasion platform, raised by tectonic movements, cannot be excluded.

The undifferentiated terraced surfaces (350-10 m a.s.l.)

The presence of various orders of terraced surfaces along the southern Peruvian coast, in a stretch located just north of the study area (San Juan-Marcona), has already been pointed out by Ortlieb & Macharé (1990). We would briefly like to mention the presence, below 350 m down to 10 m a.s.l., of at least two other orders of terraced surfaces, partially covered by colluvial and alluvial deposits, even coarse ones, or by aeolian sands (Bellido & Guevara, 1963); some remnants of Lamellibranchia have been found locally, testifying to the marine nature of those surfaces. As they have been dismembered into residual limbs and eroded on their edges, and also because of the lack of definite markers, it is difficult to establish any correlation among them. The most developed and continuous limb, extending from 270 to 150 m a.s.l. on the right side of the Rio Tambo, can be regarded as the remnant of an ancient fan-delta which. In turn, it covers fossiliferous, well stratified, sediments of undoubted marine origin; they outcrop as thick deposits either alongn the fluvial escarpment or along the ancient cliff limiting the above mentioned surface seawards.

The coastal plain and the beach of the Pacific Ocean (10-0 m a.s.l.)

The lowest terraced limbs are broken seawards, at an elevation of about 10 m a.s.l., by a rather sharp cliff, remodelled here and there by man's activity, which marks the passage to the coastal plain. The latter unit is constituted both by the terminal reach of the Rio Tambo flood plain and by some swampy, brackish, areas (*Lagunas de Mejìa*), extending behind the sandy bars which border the present day Pacific Ocean shoreline. Typical subsistence agriculture develops in the reaches free of hydromorphy.

THE *LOMAS* AND THEIR SOILS *(950÷350 m a.s.l.)*

As we mentioned above, in the Mejìa representative area there is a particular correspondence between the periodic fog belt (950-350 m a.s.l.) and the physiographic unit already defined as lomas. In order to characterize this unit, where the test site of the INCO/CEE project is located, better, a detailed geomorphological and pedological survey was carried out, the aim being to:

i) establish a correlation between relief elements (landforms) and soil types;

ii) clarify the genesis of this characteristic unit, key-factor for the reconstruction of the landscape evolution of this stretch of the *Cordillera Costanera*.

The sketch of fig. 2 represents the location of the studied profile inside the fog belt.

From a general view, the *lomas* landscape seems to be characterised by a lack of marked roughness and by the presence of two main morpho-pedological units: summits and slopes. The summits, both in form of isolated domes (Cerro Chihuanolo, Cerro Curi Curi) and ridges (Las Cuchillas) parallel to the shoreline, show smoothed convexities connected with wide saddles. At a closer view, this apparent homogeneity is interrupted here and there by heaps of rounded boulders which look like «ruins», especially on the summits (fig. 8). This is the typical appearance of the degradation of massive rocks, such as granodiorites or gneiss, which constitute the pre-Cambrian crystalline basement (*Complejo Basal de la Costa*). Other basement rocks outcrop as «spurs» on the steepest slopes. The fact that these rises appear «drowned» in an incoherent matrix, suggests the presence of a deep former surface, discordant with respect to the present-day one, buried under a mantle of pyroclastic deposits.

FIG. 8 - Blocks of crystalline rocks outcrop as «ruins» in correspondence with the *lomas* summits. The succession of some pyroclastic covers seems to have «drowned» a pre-existing, much more dissected, landscape. *Grindelia glutinosa*, in the foreground, is one of the herbaceous plants which grow inside the fog belt (*photo: G. Rodolfi*).

The *lomas* slopes, which occupy an elevation belt between 950 and 400 m a.s.l., are characterized by a complex morphology, with the convex profiles of the divides and the concave ones of the valley-heads, passing downwards to steep slopes and deep and narrow valleys. Here and there, as one can observe on the northern slopes of Cerro Chihuanolo, the highest reach of the 1st order (sensu Strahler) small valleys, immediately below the valley-heads, is effectively concave, with a wide bending radius; what we have are valley-bottoms filled by colluvial deposits, as one can observe going up the related incisions, even some metres deep in places, which have formed both along the main streams and on the slopes (fig. 9). These characteristic «gully»-type landforms, due to linear erosion by water, are periodically (every 10-15 years) reactivated, during the ENSO events, when the whole *costa* is subject to intense rainfalls; on this occasion their heads retreat upwards, sometimes reaching the divide areas. Preliminary observations have shown that the triggering and evolution of these gullies are also to be related to the activity of some digging animals.

The fact that the colluvial valley-bottoms are at present affected by linear, deeply carved and retreating landforms, induces to think that two different overland flow regimes could have occurred on the slopes in the recent past:

i) a laminar runoff, which could have transported and deposited the thick colluvial cover, partially filling the valley-bottoms;

ii) a channelled runoff, active up to now, which could have carved them causing the oucropping of the crystalline basement in places.

This succession of episodes could be related to some changes both in the rainfall regime and in land use. In this case the effects of a possible modification of the environmental conditions could only have occurred after 1660 AD, due to the fact that the greyish Huaynaputina ashes close the series of the valley-bottom colluvial deposits upwards.

Except for the lower terraces, the whole *lomas* area is characterized by the presence of a dark-brown superficial horizon, of variable thickness (thinner on the summits and thicker on depressions, rarely more than 1 m), fine-textured, prevalently clayey. In literature it is briefly described as «*...manto de arcillas grises o pardas......se trata......de depòsitos de origen eòlico y posiblemente en algo provienen de la destrucciòn in situ de las rocas subyacentes*» (Bellido & Guevara, 1963). On the contrary, what we have are fine, pedogenized, pyroclastic deposits, which can probably be referred to the emissions of the one of the several volcanoes close to the study area (Smoll & *alii*, 1997), for example the Misti, at a distance of less than 100 km, which have repeatedly erupted in a recent past (Thouret & *alii*, 1999). Another whitish horizon seems to lie discordantly on the latter; composed of the ashes of the Huaynaputina, its thickness varies (from few cm to some dm) according to the morphological position, too.

On the basis of both the documents available and several field checks, we tried to identify some representative sites in the two main morpho-pedological units: summits and slopes. They are arranged like a «catena» between the Cerro Chihuanolo and the plain located on the left side of the Quebrada Quialague, identified by the toponym «Suca»:

- Chihuanolo 1 (950 m a.s.l.) on the dome-like summit of the Cerro of the same name;

FIG. 9 - Gully erosion landforms, deeply carved on the thick colluvial deposits filling the bottom of the first order valleys. Their activity is closely linked to exceptional events (ENSO) with return times of about 15 years (*photo: G. Rodolfi*).

- Las Cuchillas (860 m a.s.l.) along a slightly sloping ridge, WSW-ENE oriented;
- Plot 1 (700 m a.s.l.), inside one of the experimental plots of the INCO/CEE project, on a slope of medium steepness;
- Plot 2 (650 m a.s.l.) inside the second plot, on a very steep slope.

On all these sites several soil profiles were described and sampled. Bearing in mind the aims of this research, hereafter we have only reported the data related to two soil types, which were considered as the most representative of the two main morpho-pedological units inside the *lomas* landscape:

- summit soils (Las Cuchillas);
- steep slopes soils (Plot 2).

FIG. 10 - Las Cuchillas («The Knives») ridge, selected as a representative area for the installation of fog «capture» devices (*atrapla-nieblas*) (*photo: G. Rodolfi*).

The summit soils

The representative soil of this unit is the *Las Cuchillas* profile (figs. 10 and 11), which is located in a small highland at 875 m a.s.l. The main morphological, micromorphological and chemical data of this soil are given in tables 1 and 2. The typical sequence of horizons is AC, 2ABtss, 2Bt and 2C, with a clear discontinuity at a depth of 15 cm between the loose AC sandy horizon and the underlying well structured clayey horizons.

The AC horizon is bright brownish grey, sandy silt (clay:14%), acid (pH:5.1) with low CEC (8.83 cmol/kg) and a high K saturated (12%) exchange complex; the matrix of this horizon (observed in optical microscopy) is glassy and it includes pumice grains. It is likely that the surface AC horizon developed from the products of the *Huaynaputina* 1600 AD eruption.

The 2ABtss, 2Bt and 2C horizons are much darker (dark reddish brown and yellowish brown) than the overlying horizon and have a strongly developed prismatic structure. These horizons, compared to the above horizon, have a higher clay content (clay content: 55-24-21%, respectively), they are subacid (pH: 6.6-6.6-6.5) and have a

TABLE 1 - Description of the *Las Cuchillas* profile
Abbreviations: «-» = absent; (M) = data obtained from micromorphological analyses

SITE DESCRIPTION
Land use: temporary pasture
Slope: 33%
Aspect: S - O
Elevation: 875 m a.s.l.
Geology: pyroclastic deposits of different age
Stoniness: absent
Rockiness: absent
Surface features: compaction

Geomorphology:
- *Dynamics:* under slow anthropic transformation
- *Landscape*: mountains
- *geomorphological agent*: overland flow
- *shape*: slope - saddle
- *position*: on the saddle
- *erosion*: absent; lack of water

Horizon	Depth (cm)	Lower boundary	Structure	Cracks.	Biological activity	Colour	Mottles	Coarse material (>2mm)	Coatings (M)		Concretions (M) %
									Type and frequency	colour	
AC	0 - 15	Sharp Undulated	Loose	—	medium	10YR 5,5/2	—	—	—		
2ABtss	15 - 40	Diffuse undulated	Coarse prismatic strongly developed	Large cracks	—	5YR 2,5/2	—	Small rock fragments	clay, abundant	yellow	4
2Bt	40 - 70	Diffuse	Angular blocky moderately developed	—	—	10YR 5/6	rare	—	clay, abundant	yellow	2
2C	>70		massive blocky	—	—	10YR 7/6	rare	—	clay, common	yellow	

TABLE 2 - Main chemical and physical data of the *Las Cuchillas* profile
Abbreviations: co. = coarse; (CO_3) = carbonates; Acid. = acidity; Exch. = exchangeable; «-» = absent

Horizon	Sand co.	Sand fine	Silt co.	Silt fine	Clay.	C org	N	P	(CO3) tot.	pH	pH	Ca^{+}	Mg^{++}	Na^{+}	K^{+}	Acid. exch.	Al^{3+}	CSC	Acid total	ECe
	%					%	%	ppm	%	H_2O	KCl	%						cmol$^{(+)}$/kg		mS cm^{-1}
AC	12.1	23.9	23.8	26.1	14.1	0.83	0.09	12	—	5.2	4.0	43.5	29.2	11.0	12.2	4.1	—	8.8	4.9	0.6
2ABtss	2.9	7.4	20.8	13.7	55.3	0.82	0.09	4	—	6.6	5.2	36.4	47.1	11.7	4.7	0.2	—	26.2	6.8	0.5
2Bt	0.4	7.5	28.2	39.5	24.3	0.14	0.02	3	—	6.6	4.9	31.7	47.6	16.0	4.4	0.2	—	21.9	6.0	0.5
2C	0.4	8.7	21.8	46.3	22.8	0.07	0.02	2	—	6.5	5.0	28.7	47.9	18.7	4.8	0.0	—	23.9	5.2	0.8

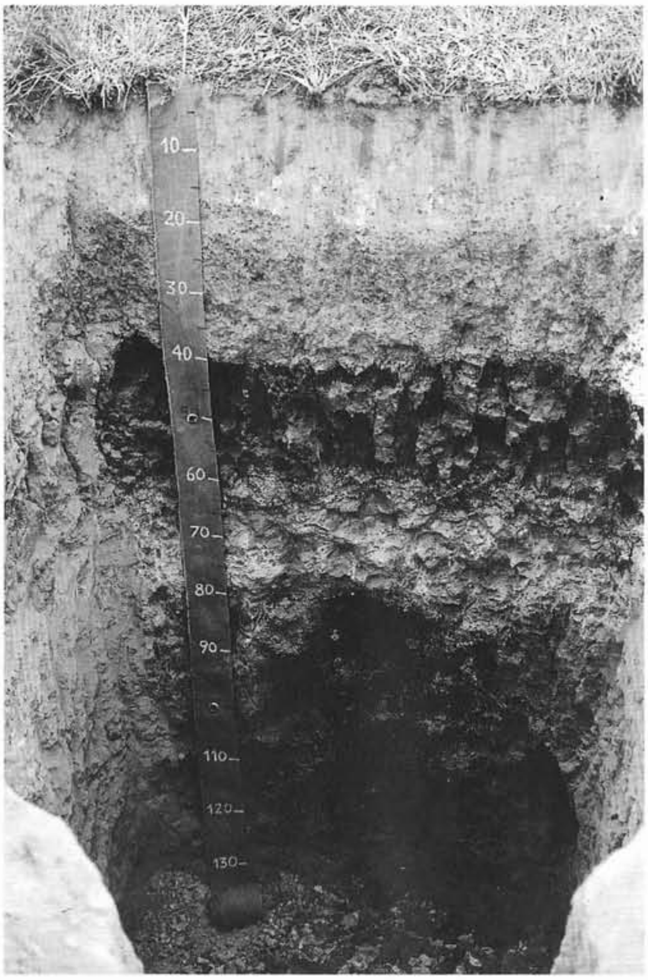


FIG. 11 - The profile of the «Las Cuchillas» soil. The succession of at least two episodes of pyroclastic deposition, is very evident.

much higher CEC (26.2-21.9-23.9 cmol/kg) with a high Mg content (about 47%) in the exchange complex. They also show, in thin sections, illuvial clay, vertic features and Fe concretions.

Overall the surface AC horizon shows weakly developed soil forming processes while the lower 2ABtss, 2Bt and 2C horizons have much more developed pedogenesis. The whole soil may be interpreted as a geosol (IUSS, 1994) and it can be classified as Vertic Haplargid.

The slope soils

This unit consists of soils having a depth ranging from 20 to 70 cm according to the slope gradient. The representative profile is Prova 1(named after the nearby experimental plot); in tables 3 and 4 the main morphological, micromorphological and chemical results are reported.

The representative profile is located at 680 m a.s.l. on a very steep slope (45%); it shows sharp discontinuities (fig. 12). A first discontinuity is observed at a depth of 70 cm between the first three horizons A, Bw1, Bw2 and the last two bottom horizons 2Bt1, 3Bt2. The main differences lie in the soil structure ranging from loose and weakly developed in the first 70 cm to well developed below 70 cm. The chemical data and in particular the K content in the exchange complex suggest another possible discontinuity at 20 cm, which might be referred to a colluvium rich in pyroclastic material.

The profile has a yellowish brown A horizon, which is silty sand (clay 17.2%) and acid (pH:4.9) and an exchange complex very rich in K (28%). The Bw1 and Bw2 horizons have, respectively, a sandy loam and loamy sand texture, respectively (clay: 7.4 and 5.0 %,); pH ranging from subacid to acid (6.0-6.6) and a K base saturation (from 4 to 1%) lower than the overlying A horizon.

The 2Bt1 and 3Bt2 horizons have a texture respectively clayey loam and sandy clayey loam texture (clay: 37.5-

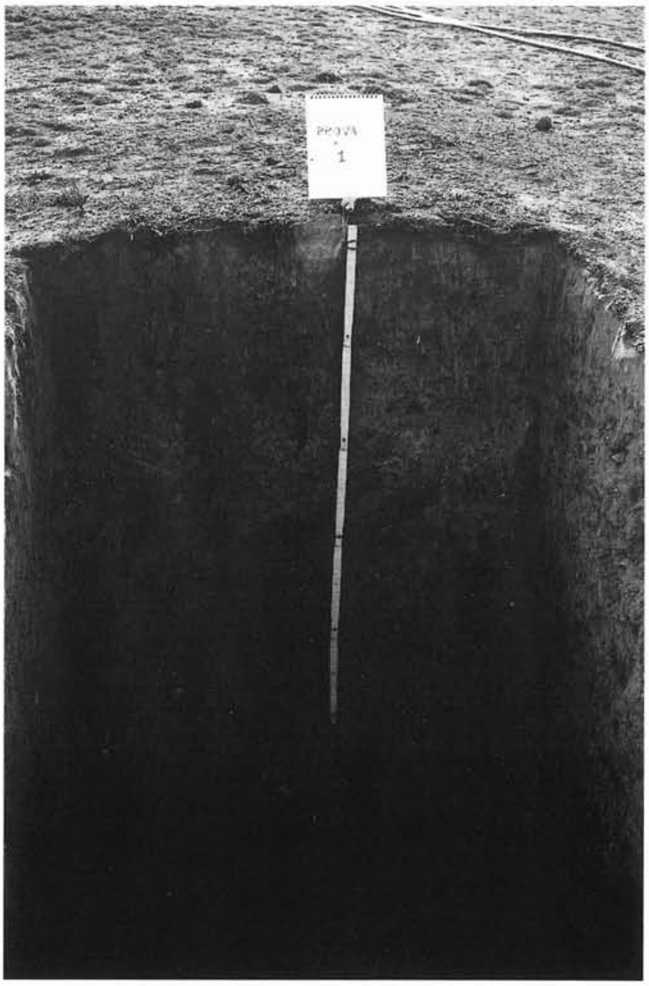


FIG. 12 - The profile of the «Plot 1» soil. Due to the steep slope, the pyroclastic cover is very thin; the crystalline rock of the pre-Cambrian basement outcrops at the base of the profile.

TABLE 3 - Description of the Plot 1 profile
Abbreviations: «-» = absent; (M) = data obtained from micromorphological analyses

SITE DESCRIPTION
Land use: temporary pasture
Slope: 45% with frequent steep slope change (up to 60%)
Aspect: S - E
Elevation: 680 m a.s.l.
*Geology:*ash layer over colluvium deposits over weathered rock
Stoniness: rare
Rockiness: absent

Surface features: undulating slope once affected by mass movement; cattle tracks due to overgrazing *Vegetation*: rare shrubs, few grass
Geomorphology:
Dynamics: ancient landslide body, now stable
landscape: hilly reliefs
geomorphic agent: overland flow, mass movements
shape: slope
position: upper portion of the landslide
erosion: present day: absent; active only in case of rainfall events

Horizon	Depth (cm)	Lower boundary	Structure	Cracks.	Biological activity	Colour	Mottles	Coarse material (>2mm)	Coatings (M)		Concretions (M) %
									Type and frequency	colour	
A	0-20	undulated clear	loose	—	common	10YR 5/4	—	—	—		
Bw1	15-50	undulated clear	fine crumb moderately developed	—	rare	10YR 5/6	—	—	clay, rare	yellow	1
Bw2	50-70	irregular clear	loose	—	—	10YR 6/4	—	—	—		
2Bt1	70-100	diffuse	medium prismatic well developed	—	—	5YR 4/3	abundant (10YR 3,5/6)	—	clay, abundant	Reddish brown	5
3Bt2	>100		massive and fine blocky weakly developed	—	—	2,5 YR 3/6	rare	small rock fragments; common	clay, rare	Reddish brown	

TABLE 4 - Main chemical and physical data of the Plot 1 profile
Abbreviazioni: co. = coarse; (CO$_3$) = carbonates; Acid. = acidity; Exch. = exchangeable; «-» = absent

Horizon	Sand co.	Sand fine	Silt co.	Silt fine	Clay.	C org	N	P	(CO3) tot.	pH	pH	Ca$^+$	Mg^{++}	Na$^+$	K$^+$	Acid. exch.	Al^{3+}	CSC	Acid total	ECe
			%			%	%	ppm	%	H$_2$O	KCl			%				cmol$^{(+)}$/kg		mS cm^{-1}
A	21.0	20.4	17.7	23.7	17.2	1.35	0.16	11	—	4.9	3.8	43.4	13.9	3.1	27.7	9.9	5.9	7.1	6.79	0.3
Bw1	41.0	20.6	14.1	16.9	7.4	0.35	0.05	5	—	6.0	4.6	70.5	21.1	3.7	3.7	1.0	—	9.7	1.52	0.3
Bw2	57.0	19.9	9.1	9.0	5.0	0.13	0.02	3	—	6.6	4.3	64.0	30.9	3.5	1.0	0.6	—	8.0	1.55	0.2
2Bt1	25.8	11.9	15.0	9.7	37.5	0.21	0.01	2	—	7.3	5.5	32.5	53.9	4.7	8.3	0.7	—	14.2	3.43	0.3
3Bt2	39.0	16.2	10.8	7.5	26.4	0.24	0.04	2	—	7.4	5.7	31.3	57.1	4.8	5.9	0.9	—	11.2	2.14	0.2

26.4%), a neutral pH (7.3-7.4) and Mg representing more than 50% (54-57%) of the exchange complex. The analysis of the thin sections shows the presence of reddish clay coatings, Fe-Mn concretions and segregations along with common quarzite grains. The occurrences of these grains, along with the colour of the clayey matrix (very different from the overlying horizons), demonstrate the different nature of the parent material between the surface and the deeper horizons. These deep horizons can then be interpreted as having developed over crystalline rocks rather than pyroclastic materials.

To sum up, the A, Bw1, Bw2 horizons (surface soil) developed from pyroclastic materials, produced by the Huaynaputina volcano in 1600 AD, and show a weak pedogenesis. The lower 2Bt1 and 3Bt2 horizons have a much more developed pedogenesis (moving from Bw2 to

2Bt1 there is a clay increase of 32,5 %) and they can be interpreted as part of a paleosol that developed over crystalline rocks. This soil can be classified as *Vitrandic Haplargid.*

RADIOCARBON DATING

Table 5 shows both the conventional and the calibrated ^{14}C ages, along with some general features of the dated pedostratigraphic horizon 2Abtss sampled in the Chihuanolo1 e Las Cuchillas profiles which originated in two quite distinct geomorphologic contexts.

Both the ^{14}C readings and the $\delta^{13}C$ data were only measured on the humic matter fractions referred to as «humine» and «humic acids strongly adsorbed by the mineral matrix». These were selected for their geochemical behaviour and because they had previously been checked for reliability.

It should be noted that the ca. 2100 yr difference between the two conventional ^{14}C ages yielded by the samples Chihuanolo1 (*Rome-1064:* 4010±90 yr BP) and Las Cuchillas (*Rome-1065:* 1910±50 yr BP) is very significant and it does reflect the far more advanced maturity of the former profile with respect to the latter. This finding is consistent with the $\delta^{13}C$ values obtained from the humic matter from the two profiles. The data in table 5 show that the Chihuanolo 1 sample (–22.8 per mill) is higher in ^{13}C than the Las Cuchillas sample (–26.5 per mill). This probably shows that the former profile was affected by the first diagenesis for longer and the biogeochemical processes were therefore effective in the selective removing of ^{12}C from the functional groups of the humic matter.

Because of the secular variations in the tropospheric $^{14}CO_2$ level the conventional ^{14}C ages can differ to a significant extent from the calendar ages. However, on the basis of the listed calibrated ages, the beginning of the pedognetic process at Chihuanolo 1 and Las Cuchillas can be referred to the 4585-4350 (90% probability) and 1920-1820 (95% probability) calendar BP time spans, respectively.

DISCUSSION

The data obtained from the above mentioned morphopedological units allow us to reconstruct some steps in the morphological evolution of the *lomas* landscape. Three different soils groups have been identified:

I. soils on the most recent pyroclastic deposits composed of the superficial horizons of the two morphopedological units;
II. clayey and vertic geosols, on the ancient pyroclastic deposits (buried horizons of the Las Cuchillas profile);
III. clayey paleosols on crystalline bedrock (buried horizons of the Plot 1 profile).

The present-day soils on the recent pyroclastic deposits

These are the soils resulting from the present-day soil forming processes, compatible with the current climatic regime. They develop on the pyroclastic cover material, produced by the eruption of the Huaynaputina volcano in 1600 A.D., which covers the study area as a whole. In the description of the single profiles they are identified as A or AC horizons. They are very recent soils which underwent light pedogenetic processes, due mainly to both climate aridity and the lack of vegetation cover. The parent material appears loose and structureless. From a physicochemical point of view the most evident data, common to the superficial horizons, are: (i) the low clay content (texture from sandy-silty to silty-sandy), (ii) the pH from peracid to acid, (iii) K^+ content and acidity, sometimes provided by Al^{+++}, relatively high in the exchange complex.

The clayey and vertic geosols on the ancient (buried) pyroclastic deposits

This group includes all the AB, B and C horizons described in the Las Cuchillas profiles. The common physico-chemical characteristics are: (i) the high clay content, with texture from clayey to clayey sandy and loamy; (ii) the pH values from subacid to neutral; (iii) the high content of Mg^{++} and Na^+ in the exchange complex. These horizons probably come from buried soils, formed in cli-

TABLE 5 - Radiometric age relative to the same pedostratigraphic horizon in two different morphological setting
*: values determined by gas-volumetric approach on extracted samples utilised for dating;
**: calibrated interval (±1σ) obtained using Stuiver & Reimer database (1993, 1999)

Profile	Elevation (m a.s.l.)	Morphology	Horizon and depth	C_{org} (%)*	$\delta^{13}C$ *1000*	Age *(yr BP)*	Calibrated age *(yr BP)***
CHIHUANOLO 1	970	Summit of dome-like reliefs	2ABss 9-13 cm *(Rome-1064)*	1.50	–22.8	4010 ± 90	4770-4410 4585-4350 (ca 90%)
LAS CUCHILLAS	875	Divide area, saddle-like	2ABtss 15-40 cm *(Rome-1065)*	2.97	–26.5	1910 ± 50	1920-1820 1920-1820 (ca 95%)

matic conditions different from the present-day ones, which produced either a high degree of structure, or the vertic characters in the Las Cuchillas profiles, or clay cutans and fillings. The very dark colour and the presence of a glassy matrix confirm the volcanic origin of these soils, although, from a taxonomic point of view, they cannot be classified as Andosols.

The clayey paleosols on crystalline bedrock

The paleosols formed on crystalline bedrock were observed in the Plot 1 profile. They are the 2Bt1 and 3Bt2 horizons, and they show, at same time, similaraties and differences with respect to the geosols on pyroclastic deposits.

The similarities are to be found in the structure, even in this case it is strongly developed, in the clay content of the fine fraction, as well as in the presence of some pedogenetic figures such as clay illuviations and Fe-Mn concretions. These common features are explained by the fact that both soils can be formed in the same climatic conditions, characterized by abundant rainfalls, different however from the present-day ones.

The discrepancies are: (i) pH (subalkaline), (ii) the cations of the exchange complex, all of them present in very different contents,(iii) the reddish colour contrasting with the brown of the soils on pyroclastic deposits, (iv) presence of quartz grains, (v) reddish colour of clay cutans. It is therefore likely that the paleosols on crystalline bedrock are older and not contemporary to the geosols on pyroclastic deposits. The discrepancies are mainly due to the different nature of parent material, referable to crystalline rocks (granodiorites), as by the presence of a quartz-rich sandy fraction demonstrates.

We must not omit the fact that this paleosol can also be found at the base of the other profiles, at depths greater than those reached by digging; in fact, in the Plot 1 profile, this soil is preserved at such a steep slope gradient (45%) that it has prevented the formation, or caused the erosion, of the soil on the pyroclastic deposits.

The radiocarbon dating results of the humic matter from the pedostratigraphic horizon 2Abtss sampled in two distinct locations bracket the 4010-1910 yr BP time-span. According to Scharpenseel (1972) and Holder & Griffith (1983), in the vertisol horizons (thus, akin to the ones discussed herein) the humic matter fractions, which are more reliable for ^{14}C dating of present and fossil soils can be immobilized through interactions with the clay minerals. In favourable conditions, because of their long residence time such humic matter fractions can almost be referred to as a «passive organic carbon reservoir» because of their long residence time and in this respect they provide the best record of the pedogenesis.

The above leads us to the following inferences:

1) the radiocarbon age yielded by the older Abss pedostratigraphic horizon (e.g., Las Cuchillas site, 4010±90 yr BP), represents a valuable *ante quem* setting for the emplacement of the parent material, made up by the ancient tephra deposit,
2) the ^{14}C reading for the younger Abss pedostratigraphic horizon at the Chihuanolo 1 site points out that the phase of enhanced pedogenetic evolution did occur prior to 1910 ±50 yr BP),
3) the between-age difference can be accounted for by the pattern of the landscape evolution, reasonably different according to the overall environmental conditions. In particular, the main features of the Abss horizon at Las Cuchillas (thickness, preservation, topography, among-horizon boundaries, % of skeleton are consistent with a better humic matter preservation than at Chihuanolo 1.

THE ANTHROPIC INFLUENCE

In the paragraph 3.1.4 it was emphasized that in the *lomas* the present day vegetation is grouped according to the elevation ranges and also that little tree plant communities such as *Acaciae* and *Caesalpinacee* do indeed exist.

On the basis of this sporadic occurrence of tree plants, Ellemberg (1959, in Rauh, 1983) proposed that in Central and South Coastal Peru, the area having an elevation range between 300 and 600 m a.s.l. was, until few centuries ago, occupied by broadleaves forest. He proposed that the disappearance of this forest (a part from a few relics) was to be related mainly to the anthropic influence such as deforestation and overgrazing. In order to sustain this hypothesis, it was stated that the maximum vegetation development (nowadays mostly grasses) of the *lomas* occurs in the wintertime; this is also the season of the fogs and it coincides with the arid season in the *Cordillera*. In such periods the *indios* of the *Cordillera* used to bring their livestock thus producing a kind of transhumance.

This practice has been carried on to the present-day, with the major difference that the animals are brought by lorries. This only happens on the rare occasions of the «ENSO» events (*tiempo de lomas*), when continuous vegetation covers the slopes. Even if this environmental condition is rare (every 10-15 years), overgrazing occurs and it induces soil degradation processes which reduce the potential productivity of the land (fig. 13).

In order to give a rough estimate of the occurrence of this anthropic activity, we shall report the data (possibly underestimated) given by the landlord of the *Las Cuchillas* site. During the «*tiempo de lomas*» the pasture lasts until the end of March. Of the 13,200 ha of the land, only 3,000 ha are left available for pasture, probably following a rotation scheme. The landlord receives a kind of rent fee (*yervaje*) from the shepherds for the whole season. In most rainy seasons, the estimated number of sheep and goats is about 14,000 on 3,000 ha (about 4.7 animal/ha); the number of cattle is about 2,100 on 3,000 ha (about 0.7 animal/ha). Considering that the slopes are already deeply degraded such an animal load is very high; this is made worse if we consider that this practice affects the same area for a long time.

This destructive action has been repeated on several occasions, as observed by one of the authors, also during

FIG. 13 - A feature common to the entire *lomas* landscape: cattle-tracks due to overgrazing, which originate irreversible soil degradation (*photo: G. Rodolfi*).

the ENSO event of 1997-98. A further problem which makes this situation worse I another practice of the shepherds and farmers who, despite the prohibition, cut the plants for food and heating.

Near the *Las Cuchillas* site, along the valley of *Quebrada Quialague*, at an elevation of 400 m a.s.l., we found the only green spot consisting of a cultivation which occupies a residual edge of a terraced surface. The cultivation consists of vegetables for subsistence (two old *campesinos* live there), 2 rows of centuries-old olive trees (*Olea europea L.*) still productive and surely introduced by Spanish settlers. There is also a water spring, located at the bottom of the Quebrada, which produces a very limited amount of water (just enough for subsistence) and is transported through a channel partly infilled by soil material. The typology of this channel, along with its large dimension, seem to suggest that, in the not too distant past, the flow of this spring was much greater and/or, there may have been more springs. This must be considered together with the residual man made agricultural terraces that are still recognisable on other nearby slopes.

THE QUATERNARY CLIMATIC OSCILLATIONS AND THE ROLE OF FOG

The above reported considerations point out more evidently the contrast between the present-day climatic situation and a supposed higher fertility of this environment in the past, strictly linked to a larger availability of water.

In the paragraph 3.1.2 we mentioned the fact that a climate similar to the present-day one already existed since middle Miocene (Galli Oliver, 1967; Mortimer, 1973; Mortimer & Saric, 1975). Altough there are proofs of short periods with higher rainfalls during both Pliocene and Quaternary (Alpers & Brimhall, 1988) in correspondence of glacial phases. Moreover, according to Craig (1985, in Rundel & *alii*, 1991), also during Holocene some pluvial episodes, with some influence on the biological componemt of the environment, could have occurred. It would be confirmed by the characteristics found within the soils of the Las Cuchillas site which, showing an advanced process of clay illuviation, delineate punctual past pedoclimatic conditions, in determining which water played a fundamental role.

On this subject it is not to forget that, due to its particular dynamics, the *garùa* condenses on the surface of any obstacle it meets on its way (in particular: herbaceous plants, shrubs and trees) and transfers into the soil some volumes of water other than negligible (Walter, 1973, in Rauh, 1983). Some artificial capture systems, located in favourable morphological conditions for the assessment of the process (Oka, 1986; Schemenauer & Cereceda, 1992, 1994; Cereceda & *alii*, 1997) as well as for attempting to re-establish the vegetation cover on the *lomas* (Calamini & *alii*, 1998) were settled in some different sites of the Peruvian-Chilean desert. The most significative experience, which allowed the researchers to face and assess the phenomenon in its reality, has been that one carried out and described by Calamini & Salbitano (1998 and 1999), in the framework of the above mentioned INCO/CEE project: in the close neighborhood of the Las Cuchillas site some adult trees, belonging to relic populations of *Caesalpinea spinosa*, were equipped for catching and measuring all the water provided by fog condensation. From the results summarized in table 6 one can infer a significative correlation between the troughfall values and some characteristics of the single trees, as the canopy volume, the total height and the elevation a.s.l. Averaging the data reported in table 6, it results that an adult tree of *Caesalpinea spinosa* was able to transfer into the soil, during 40 days inside the most «foggy» period, more than 1,3 m^3 of water.

Therefore, we could advance the hypothesis that the lower tephra of Las Cuchillas and surroundings has undergone a relatively rapid pedogenesis, during one of the Quaternary (or maybe even Holocene) climatic oscillations, as the radiometric data seem to prove. The development of *Vertic Paleargids* could have allowed the settlement of a «fog oasis» with a relatively dense herbaceous and tree cover. During the following aridity periods, the water needed for the subsistence of the plants could have been provided by the fog caught by themselves, at least till to the beginning of the uncontrelled anthropisation.

CONCLUSIONS

The observations which have been made on the landscape morphological features and on the main soil types of the *lomas* area, enable us to attempt an environmental reconstruction of the various phases which have produced this typical landscape of coastal Peru. It must be emphasized that this reconstruction does not take into account the neotectonic activities which have affected the landscape of *Meja* as indicated by the presence, at different elevation, of relics of terraces (Ortlieb & Macharé, 1990).

A succession of the possible evolution phases follows:

1) *First pedogenetical phase.* The crystalline Precambrian bedrock and the granite intrusions underwent strong weathering processes. Relic evidence of this pedogenesis consisted in the buried and deeply weathered Bt horizons in the Plot 1 profile. This soil testifies to a period of high water availability, of tectonic stability and of dense vegetation cover. The chemical weathering processes, particularly active along the cracks of the basement, detached spheroid unweathered rock blocks (corestone, boules, cfr. Twidale, 1982) in the regolite mass.
2) *First erosive phase.* The soils which developed from the crystalline rocks were subjected to severe water erosion, possibly related to a decrease in the density of the vegetation land cover induced by extensive periods of aridity and/or the beginning of new tectonic activity. The selective removal of the fine fraction of the regolite produced an uneven slope morphology, especially in the ridge morphological units. The shaped large spheroid blocks produced a «ruin-like» landscape; these blocks of various dimension could then be distributed along the slope because of successive rock downfall or because of the action of overland flow. The valleys (also the small ones) tended to assume a deep V morphology and relics of soils were preserved in specific morphological settings (against slope position, concavities along the slope, any natural pocket).
3) *Deposition of the ancient ash layer.* After one or more eruptive events of the nearby volcanoes, a cover of pyroclastic material (especially ash) was deposited, thus levelling the previous morphology. The depth of this cover ranges from few decimetres on the ridges and steeper slopes to one or more meters in the depression morphologies (a further colluvium contribution must also be considered). There is not enough information to associate this volcanic cover with a specific eruptive centre. On the basis of tephrostratigraphy Thouret & *alii* (1999) recently identified four possible eruptive phases of the Misti Volcano (about 100 km from the study site) occurring from the last part of a Glacial stage at about 14690 yr B.P. to more recently between the last part of the Glacial stage and the Holocene.
4) *Pedogenesis of the ancient ash layer.* The general climatic postglacial amelioration and/or the abundant water produced by the condensation of fog, favoured the rapid pedogenesis of the ash layer with the formation

TABLE 6 - Main morphological features and cumulated values of troughfall and stemflow in adult *Caesalpinea spinosa* trees (97.6.29 - 97.8.8 field survey) (from Calamini & Salbitano, 1999)

Plant identif. nr.	Elevation *(m a.s.l.)*	Diameter Brest Height *(cm)*	Total height *(m)*	Canopy projection *(m^2)*	Canopy volume *(m^3)*	Branch volume *(m^3)*	Leaf area *(m^2)*	Troughfall *(litres)*	Stemflow *(litres)*
2	610	25	6.6	38.2	85	0.39	25	1614	18
4	570	19	4.7	29.6	40	0.27	11	900	23.7
6	470	18	5.4	45.4	48	0.32	6	1061	17
7	460	22	4.0	31.5	30	0.16	3	997	29.3
8	460	8	2.5	4.0	3	0.01	2	124	4.6
10	700	40	8.0	62.5	234	0.99	11	3010	40
12	745	40	6.5	55.2	111	0.56	24	1397	25
13	670	30	7.5	52.9	142	0.33	10	1643	19.8
14	640	40	6.3	58.3	105	0.85	18	1538	23

of a geosol (*Vertic Haplargid*) such as the one of *Las Cuchillas*. Two samples of this soil (and more specifically the horizon 2ABtss) have produced a radiometric age ranging between 4530 and 1870 yr B:P:

5) *Second eruptive phase*. Renewal of the erosion processes, in particular of the sheet-interrill type that truncated the soils developed on the ancient ash layer and partially infilled the valley floor with a deep colluvium deposit. These processes produced a much more open landscape with a concave lateral profile.
6) *Deposition of the recent ash layer*. The eruption of the Huaynaputina volcano in 1600 AD produced a pyroclastic deposit of a very distinct whitish ash which covered the landscape with a continuous layer.
7) *Pedogenesis on the recent ash layer*. This pedogenesis is still at the initial stage, because of the extreme climatic conditions and also because of the increasing anthropic influence over the landscape.
8) *Third erosive phase*. Deforestation, and successive overgrazing, induce two major consequences: (i) the lack of any water, produced by fog condensation, in the soil; (ii) the development, on the less protected slopes, of large gully erosion features (rills, gullies); this was facilitated by the activities of gallery producing animals. The presence of livestock-produced animal tracks, as a consequence of occasional overgrazing, play an important role in the mass movement initiation processes. The colluvium valley floors are deeply excavated by gullies; this process can lead to the outcropping of the crystalline basement, which, being more resistant, can be considered the basal level for all erosion processes. This erosion produces the progressive withdrawal of the valley headings, reaching, in some cases, the watershed divisions.

On the basis of the information obtained it is possible to draw some conclusions.

- The Quaternary cover of the *Lomas* of Mejia is not of eluvial genesis, as affirmed by local geologists, but it can be related to at least two different pyroclastic deposits (mainly ash layers).
- The contradiction between the lack of rainfall and the stage in soil development is only apparent, because the water needed for the activation of the soil forming processes and for sustaining the vegetation cover could be produced by a more humid climatic oscillation.
- This vegetation cover could have survived the subsequent aridity periods because of the presence of water produced by fog condensation (fog oasis).
- The present-day condition of lack of tree vegetation seems to be due to anthropic factors (deforestation).
- Overgrazing practices occurring during the rare «ENSO» rainfall event induced the erosional processes.
- Anthropic activity is confirmed as being the major cause of the breakdown of the very precarious and delicate ecosystem functioning mechanisms.
- The attempt to refores the *lomas* utilizing fog water harvesting must take sociological and economical issues into account.

The relevance of these preliminary results, obtained from the combination of both geomorphologic and pedological studies, has enabled us (i) to formulate some hypotheses on the environmental evolution of the *lomas* and (ii) the recognize the high degree of complexity of the soil system. The study area, apparently quite homogeneous, hides very diverse soil types with different chemical and physical properties; some of these soils depict a soil environment with a great potential in terms of chemical and physical fertility.

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