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SOIL FORMATION ON HOLOCENE MORAINES IN THE CIRQUE DE TROUMOUSE, PYRENEES[1]

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SUMMARY.- Factors affecting rates and degree of soil formation on Holocene moraines are discussed with reference to moraine sequences in the Cirque de Troumouse, French Pyrenees. In particular, the role of time, slope position and post-depositional history are evaluated for three moraines ranging in age from c. 5000 to c. 1000 yr BP. Soil profile development, as determined by visual criteria, indicates differences in soil development between moraines of different age as well as between soils developed on the same moraine but occupying different slope positions. Particle size analysis and soil chemical analyses confirm that microtopography exerts a strong control on the extent and rate of soil formation, and must therefore be considered when sampling and describing soil chronosequences on glacial moraines.

RESUMEN.- Se discuten los factores que afectan a las tasas y al grado de formación del suelo en morrenas Holocenas, con referencia a la secuencia de morrenas en el Circo de Troumouse, Pirineo francés. En particular, se evalúa el papel del tiempo, la posición de la pendiente y la historia postdeposicional para tres morrenas ordenadas en edad desde c. 5000 a c. 1000 años BP. El desarrollo del perfil del suelo, determinado por criterios visuales, indica diferencias de desarrollo del suelo entre morrenas de diferente edad así como entre suelos desarrollados en la misma morrena, pero ocupando diferentes posiciones de la pendiente. Análisis granulométricos y químicos del suelo confirman que la microtopografía ejerce un fuerte control en la extensión y en la tasa de formación del suelo y, por tanto, debería ser tenida en cuenta en los muestreos y descripciones de las cronosecuencias del suelo en morrenas glaciares.

RESUMÉ.- On discute les facteurs qui affectent les taux et le degré de formation du sol en moraines Holocènes, avec référence à la séquence de moraines du Cirque de Troumouse, Pyrénées français. En particulier, on évalue le rôle du temps, la position de la pente et l'histoire postdépositionelle pour trois moraines ordonnées chronologiquement de c. 5000 à 1000 ans av. J.C.. Le développement du profil du sol, déterminé selon des critères visuels,

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signale des différences de développement du sol entre des moraines d'âge différent de même qu'entre des sols formés dans la même moraine,mais qui occupent différentes positions de la pente. Des analyses granulométriques et chimiques du sol confirment que la microtopographie exerce une forte influence sur l'étendue et les taux de formation du sol et par conséquent, elle devrait entrer en ligne de compte dans les échantillonnages et les descriptions des chronoséquences du sol en moraines glaciaires.

Key words: *Holocene, moraine, soil formation, catena.*

The time dependence of soil development is well documented. Following the pioneering work of JENNY (1941) many authors have described the general relationships that exist between the age of a landscape and the extent of soil profile evolution (BIRKELAND, BURKE & BENEDICT, 1989). Recently deglaciated landscapes provide many opportunities to study pedogenesis under "controlled" conditions. Relative age dating of moraines has allowed the construction of both quantitative and qualitative models of soil profile evolution over timescales ranging from tens to thousands of years (CHANDLER, 1942; CROCKER & MAJOR, 1955; VIERECK, 1966; BURKE & BIRKELAND, 1978; HARDEN & TAYLOR, 1983; MESSER, 1988 y 1989). To standardise sampling procedures and minimise variation between sites, most studies of soil formation on glacial moraines have described samples taken from crest or ridge top positions. By taking this approach the aim has been to eliminate the role of topography as a factor which might explain differences between soils developed on moraines of contrasting age. To take one recent example, MESSER (1988) examined regional rates of soil formation on eighteen glacier foreland on Southern Norway. This study related changes in several soil properties such as pH, organic matter and cation exchange capacity, observed from optimal sites, to age of the moraine which had been determined by lichenometry.

To consider the role of topography in the pedogenetic development in moraines adds another level of complexity to any resulting explanation but can yield important information concerning topography/time interactions (MCCARROLL & WARE, 1989). The objective of this paper is to describe the relationship between microtopography and soil development during the last 5000 years on Holocene moraines in the Cirque de Troumouse in the French Pyrenées. Preliminary studies of the influence of microtopography on soil profile form and chemistry carried out in North Norway have suggested that characteristic patterns of profile development and nutrient leaching can be distinguished for crest, mid and toe slope positions (PARKINSON & ROBERTS, 1985). The Cirque de Troumouse contains a complex suite of moraines and other geomorphological features of deglaciation during the Holocene, and has provided a suitable site for further investigation of the interaction between soil development and slope position on moraines of different ages. The ultimate objective has been to refine the use of soils as relative dating tool.

1. Pedogenesis on Holocene moraines

The precise manner of the interaction, and the weighting attributable to individual pedogenic factors will vary from soil to soil, therefore studies of rates of pedogenesis are applicable only to very specific environments. The role of topography as a factor controlling the rate of soil formation is often difficult to evaluate, and so it is best kept constant in comparative studies.

Slope position is a particularly important contributor to the process of soil formation in recently deglaciated environments. A two dimensional representation of the distal and proximal slopes of a typical end moraine is given in Figure 1. Soil profiles observed at crest, mid and toe slope positions differ from each other as a result of a combination of processes whose relative contribution will vary from site to site. Traditional studies of the relations between soils on hillslopes focus on the role of soil water as a medium for the transport of ions from higher to lower parts of the slope. Over a long time soils at the base of the slope will tend to become deeper, more organic and nutrient rich while those at the top will become more acid, nutrient poor and may exhibit signs of incipient podsolisation (PARKINSON & ROBERTS, 1985).

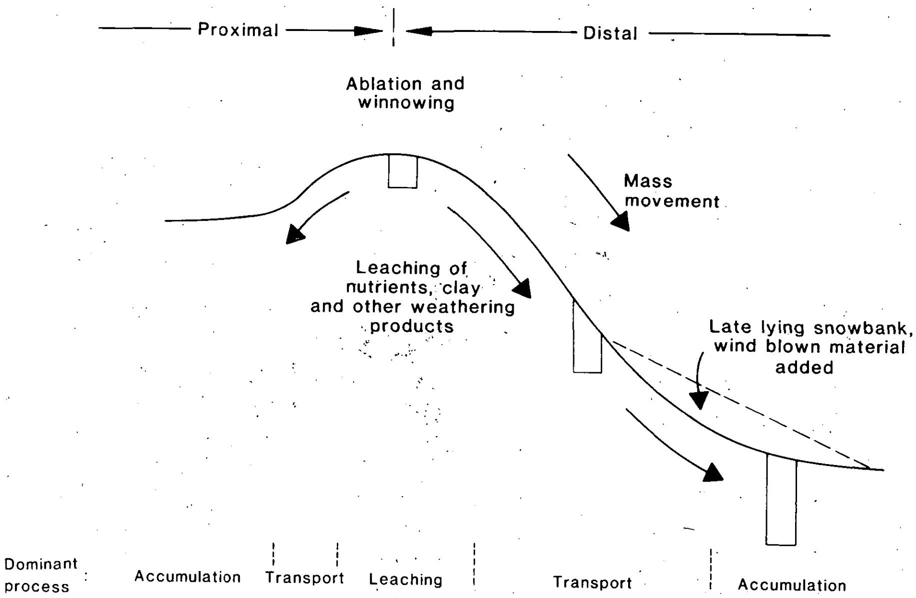

Figure 1. Microtopography and soil formation at crest, mid and toe slope positions on terminal moraines. *(Microtopografía y formación de suelo en la cresta, parte media y parte baja de la ladera en morrenas terminales).*

In proglacial environments rates of soil formation are often slow, but complex. The low annual temperatures inhibit the development of a stable vegetation community. Typically, mean annual temperatures near the snout of a mid-latitude glacier can fluctuate around 0-5ºC, which in consequence restricts significant biological activity to only a few summer months. The relative role of aerial deposition, leaching and transport of weathering products depends upon slope position (Fig. 1). Soils which form at crest positions experience a more severe climatic regime, due to exposure and lack of protection from late-lying snow banks. In consequence, these soils may be more leached, less well vegetated and shallower than those which develop at toe slope positions. In order to evaluate the relative contribution of age and slope position on soil formation on moraines, data for selected soil parameters from contrasting microtopographical sites from the Cirque de Troumouse are presented and discussed.

2. Geomorphological evolution of the Cirque de Troumouse

The Cirque de Troumouse has a north-easterly aspect with a steep, limestone headwall (RITTER, 1988) and a wide, gently sloping cirque floor. The base of the cirque comprises a series of intermediate, intrusive, igneous rocks. Outcrops of shale interbeddeb with sandstone help to differentiate the western slopes of the basin. The Glacier de la Munia, c. 2720 m is constrained in extent by a series of bedrock ledges on the back wall. Beneath Pène Blanque (Fig. 2) is a small glacier (c. 2350 m) downwasted between steep moraine walls. The Holocene moraine sequence in the cirque is partially buried by two rockfall deposits. The outermost rockfall deposits, predominantly of shale, is in an advanced state of weathering and is referred to as the debris cones in Fig. 2. This debris must have been derived predominantly from the south-western slopes of the headwall. Further blocks, often in excess of 3 m^3, and predominantly limestone in character, are more clearly derived from the main headwall between Pène Blanque and Pic de la Munia. The blocks rest on and between the outermost moraine ridges and relate to deglaciation following subsequent Holocene advances. Both episodes of rockfall post-date the formation of moraines on the cirque floor.

During the Holocene the glaciers within the cirque coalesced to produce a large lobe of ice which extended into the Valley of Héas (1400 m). As climate improved the main ice lobe separated to form a rock glacier and moraine sequence. Dating of these moraines has been made possible through examination of a small bog near the lip of the cirque which has provided evidence of two Holocene ice advances (GELLATLY, GROVE & SWITZER, 1992). The cirque floor terminates abruptly in a pronounced rock step towards the northern edge of the basin. At the edge of the cirque, the Lacs des Aires (2089 m) occupy a bedrock depression which drains directly over the rock lip. The lakes are dissected by the outermost moraine, a discontinous line of boulders which rise up and over a small bedrock prominence on the eastern side of

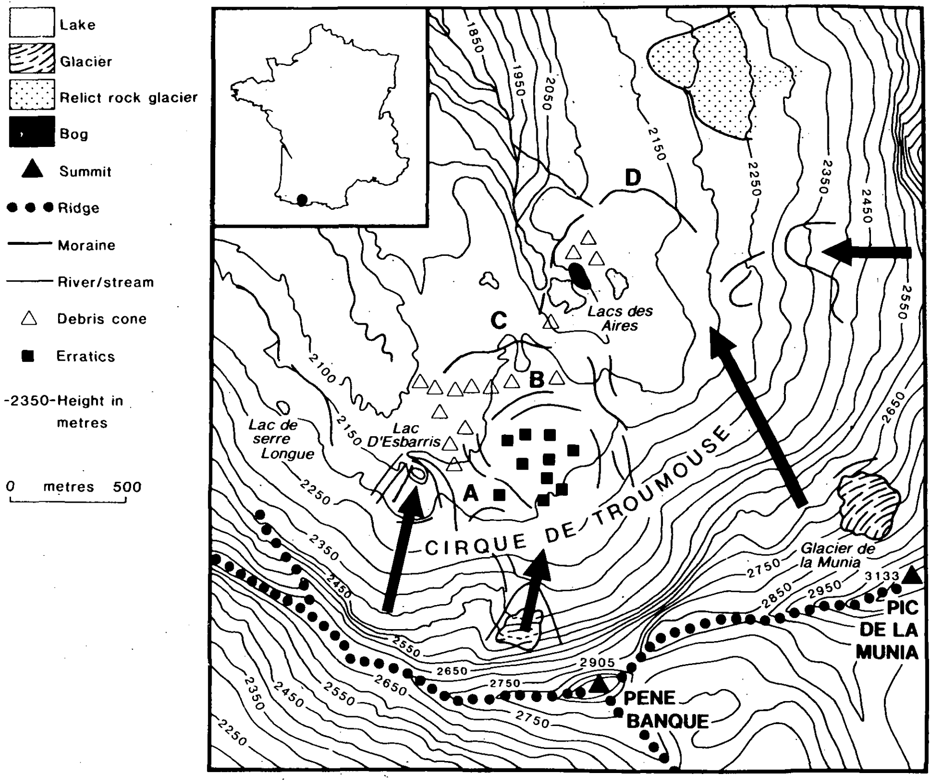

Figure 2. Distribution of principal moraines, showing ice flow directions within the Cirque de Troumouse. (Inset: location map). *(Distribución de las morrenas principales, con indicación de las direcciones de flujo del hielo en el Circo de Troumouse).*

the lake bed. Here a small bog, 2-3 m above the cirque floor and lying directly within the outher moraine limit, permits detailed reconstruction of Holocene fluctuations within the cirque. A core derived from the bog, revealed a dense, fibrous layer up to 1.7 m thick of undecomposed vegetative material resting upon a sequence of silts and layered glacial clays. Towards the base of the core (c. 2.5 m) two layer of glacially derived silts separated by an organic layer have been dated. The lower silt unit is truncated and the organic horizon which rests directly above has provided a radiocarbon age of 5190 + 90 BP (Q2722). The same organic unit grades into the upper silt layer where a date of 4955 + 90 (Q2723) was obtained. There is clear evidence of two phases of glacial activity, one concluding before 5190 + 90 and a second commencing close to 4955 + 90. Elsewhere in the cirque a series of undated moraines indicated the fluctuation of the glaciers within the basin throughout the Holocene. It can be assumed that the outer moraine (D) dates from before 5190 + 90 and that the adjacent moraine (C) was probably deposited before

4955 + 90. The nested series of younger moraines (B) mantled by more recent rockfall deposits, show a high degree of soil development which is described further. It is estimated from snowline altitudes that the inner moraines (A) around the Lac D'Esbarris (2200 m) were deposited around 1500-1000 yr BP. Present day snowline in the cirque is > 2800 m, whilst around 5000 yr BP snowlines are likely to have been depressed by 400 m (BARRERE & PAQUEREAU 1960). An analysis of soil development across the suite of moraine ridges assists in determining the rate and pattern of soil development and highlights the effect of microtopography on soil formation within the last five thousand years.

3. Effect of time and microtopography on soil development

3.1. *Sample collection and analysis*

Soil samples were collected from profiles developed at crest, mid and toe slope positions on three moraines in the Cirque de Troumouse, labelled A, B, and C in Fig. 2. The distal slope of moraines A and C and the proximal slope of moraine B were sampled. Sampling of the distal slope of moraine B was not feasible due to excessive disturbance of this slope by recent rockfall material. Sampling was impeded on moraine D due to the presence of boulders. The moraines on the western side of the cirque are dominated by shale making comparison with the other sites inappropriate. Air-dry soil samples were analyzed for the following properties: particle size analysis by wet sieving (> 63 mm fraction) and photo-scanning sedimentograph (< 63 mm), organic carbon by wet oxidation (TINSLEY 1950), pH with a 1:2.5 soil: water extraction ratio, cation exchange capacity and exchangeable cations by atomic absorption spectrophotometry.

3.2. *Soil and vegetation description*

The soils formed on moraines within the Cirque de Troumouse can be classified in simple terms as Brown soils (ELLIS, 1979), with varying degrees of incipient podzolisation. Unlike soils described from similar mountain environments in (ELLIS, 1979; PARKINSON & ROBERTS, 1985; MCCARROL & WARE, 1989), these soils are not so extensively podsolised, primarily as a consequence of the wider abundance of base-rich materials in the moraines. All profiles showed some degree of bleaching of sand sized quartz grains in the Ah horizon, but development of an eluvial Ea was inhibited. These profiles can be tentatively classed either as Inceptisols or, in the case of those with more pronounced bleaching and B horizon iron enrichment, Spodosols, with cryic or mesic temperature regimes (SOIL SURVEY STAFF, 1975).

A prominent feature of all moraine derived soils is degree of variability between profile pits, due to the poor sorting of the parent material. Many studies of pedogenesis in similar geomorphological situations have for this reason confined sampling to the surface horizons. When samples are taken from deeper horizons within such soils, it is accepted that there will be some bias towards locations where it is physically possible to collect samples.

The vegetation thoughout the cirque is dominated by coarse grasses (*Deschampsia* and *Nardus* spp.) with smaller proportions of other perennials (*Vaccinium, Calluna, Rhododendron* spp.). Although there were variations between sites, there was no consistent relation between slope position and vegetation pattern. All the soils can be classed as well drained, so in consequence it is not surprising that no consistent pattern of vegetation was observed. *Vaccinium, Calluna* and *Rhododendron* are all examples of species which are known to accelerate the process of podsolisation (ELLIS, 1983), the soils in the Cirque de Troumouse are no exception in this respect.

3.3. *Particle size distribution and silt: clay ratios*

Weathering results in the comminution of particles within the soil/parent material environment. As time proceeds, the breakdown of rock fragments leads to the predominance of smaller particle sizes, but his simple trend is often made more complex by additions and losses to a developing horizon, either from upslope or higher within the soil itself (the process of clay translocation, for example) or from external sources, such as wind blown silt. The results is that coarse but variable textured parent materials can be modified during pedogenesis. It is often therefore difficult to identify trends in size distribution that can be related to soil forming factors such as time or slope position.

The soils in the Cirque de Troumouse are derived from mixed limestone and schistose parent materials, which have broken down to given soil particle size distributions that are dominated by the sand (0.06-2.0 mm) and silt (0.002-0.06 mm) size fractions. Detailed size analyses were carried out for all samples that were subject to chemical analysis; however only selected examples are presented here to illustrate the general character of the soil materials. In Fig. 3 typical variations in size distribution for a moraine slope sequence are shown. Histograms of percentage gravel, sand, silt and clay are plotted for three slope positions and three horizons. At the crest of the slope the surface soil sample is very coarse; gravel sized particles (> 2.0 mm) comprise 28 % of the sample by weight. Lower in the profile, the sand and then the silt fraction have assumed dominance. Lower down the slope a similar trend is observed, but even in the surface horizon of the toe slope soil gravel is a subsidiary mineral component, although silt is dominant at the surface as well as at depth.

Progressive weathering results in the mean particle size becoming smaller in older soil profiles. One method of assesing this tendency for soils formed on moraines of contrasting age is to examine the silt: clay ratio. Lower ratios indicate higher relative clay percentage and all, other thing being equal,

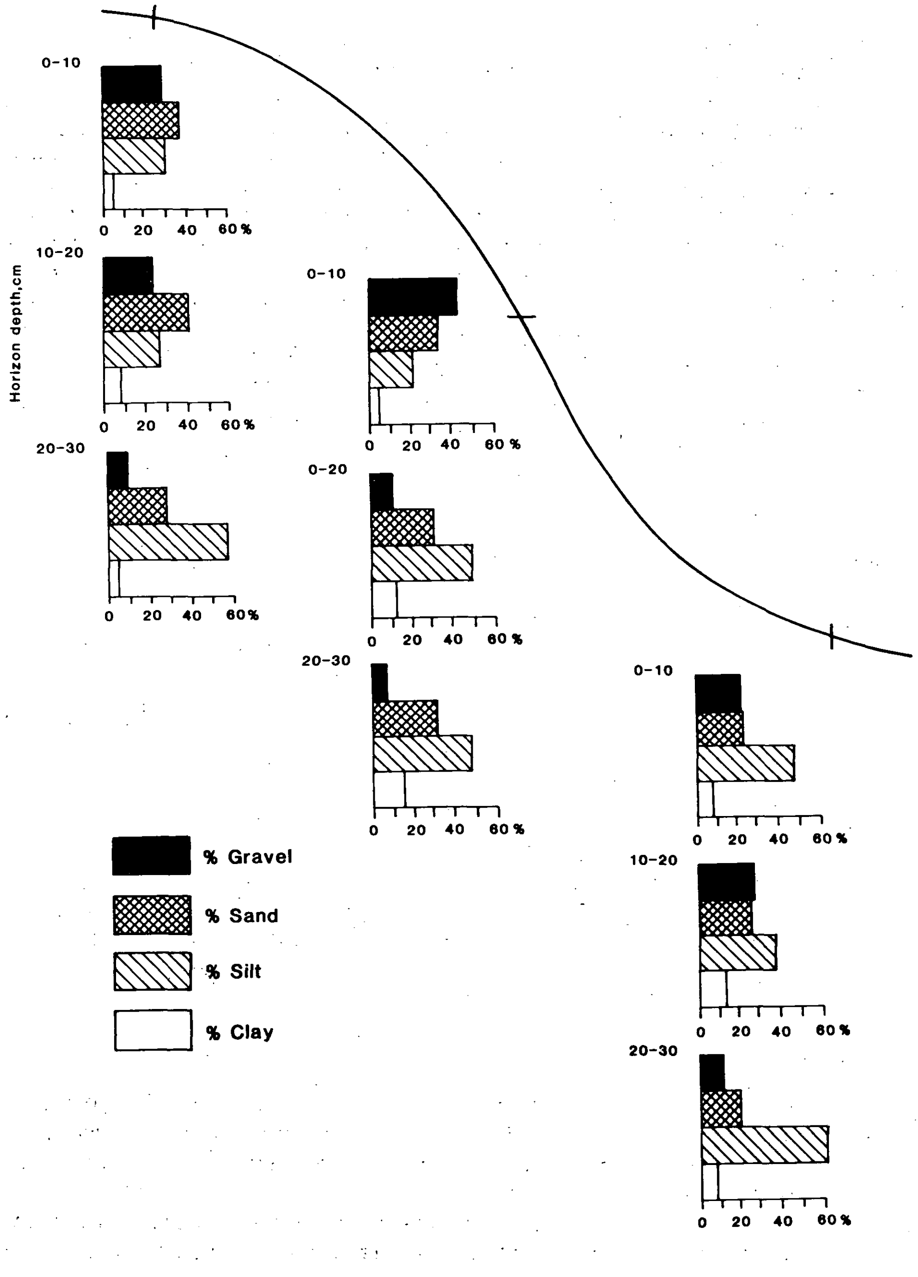

Figure 3. Variations in particle size distribution and sample depth, moraine C. *(Variaciones en la distribución de tamaño de las partículas, morrena C).*

a longer weathering history. In Fig. 4 this pattern is incompletely demonstrated, with silt: clay ratios for soils in comparable slope positions showing declining ratios with increase in moraine age. In addition there is a slope position effect, with ratios decreasing towards the base of each slope profile. Comparisons between soils formed on moraines in similar landscape positions may be valid indicators of temporal effects. In this case the declining silt: clay ratio with increasing age indicates the proposed age sequence for these soils. However, there are two complicating factors. Firstly, the difference between crest, mid and toe slope positions may be due to some of the processes described in Section 2, namely post-depositional modification by wind, with winnowing occurring at the exposed crest position and deposition at toe slope positions (GELLATLY, 1986). Secondly, the ratios observed within profiles do not show regular decreases with depth which would be consistent with an age-related process Only detailed mineralogical analysis will reveal whether these changes are due to additions of wind blown material following moraine deposition, or in situ weathering and soil translocation.

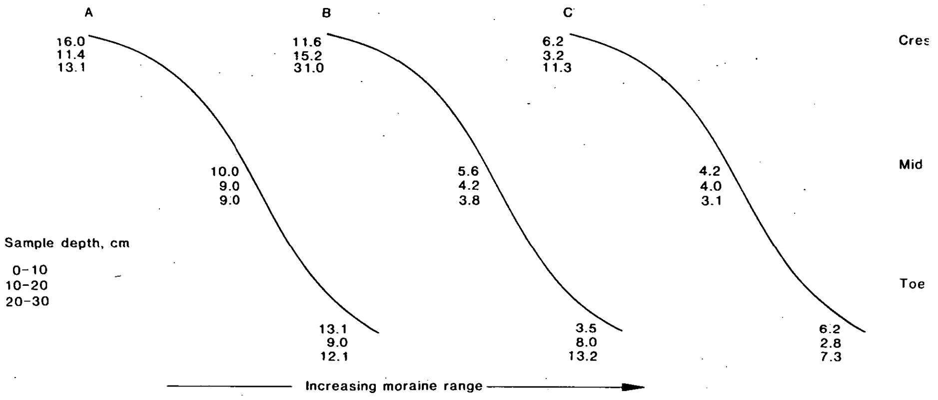

Figure 4. Silt: caly ratios for crest, mid and toe slope positions, moraines A, B and C. *(Ratios limo: arcilla en la cresta, parte media y parte baja de la ladera, morrenas A, B y C).*

3.4. *Soil chemical properties*

Many chronosequence studies have demonstrated close relationships between time and the evolution of soil chemical properties. The majority of these studies have been carried out on young sequences, often less than 1000 years old. The three moraines under study here are dated at between 1000 and 5000 yrs. B.P. In consequence several characteristic soil properties are well advanced, as indicated by profile morphology. Results presented here are confined to three soil chemical properties: organic carbon, pH and exchangeable cations.

3.4.1. Organic carbon

The accumulation of organic matter at the surface of a weathered material under a developing vegetation cover is initially rapid, even in mountain environments (e.g. MESSER 1988). After several hundred years the rate of change becomes very much smaller and will eventually tend to zero. The organic carbon contents of the soils on moraines A, B and C show little consistent variation with age (Fig. 5), but do illustrate a slope position effect. Topsoil organic carbon contents tend to be higher at ridge crest positions, where shallower soils have a higher proportion of the organic carbon in the surface horizon. Toe slope soils are invariably deeper, resulting in more extensive rooting and hence elevated organic carbon contents in the lower horizons sampled.

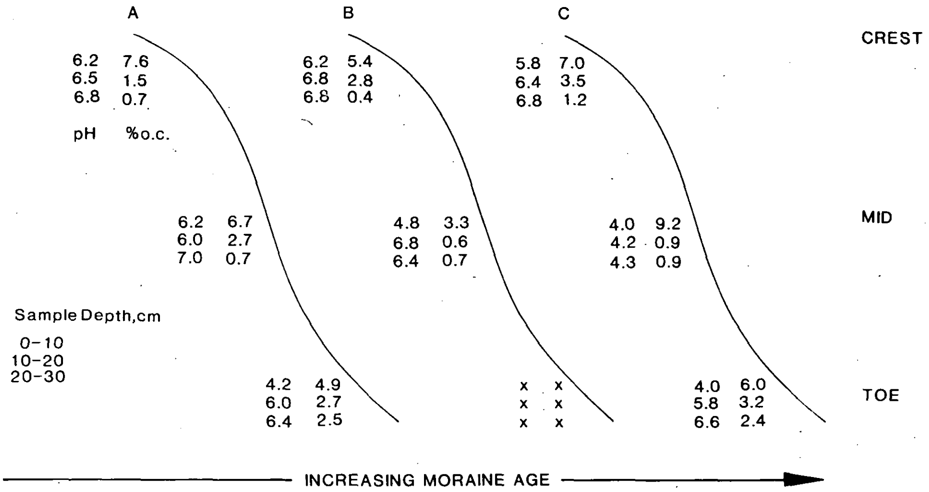

Figure 5. pH and organic carbon for crest, mid and toe slope positions, moraines A, B. and C (x = missing values). *(pH y carbono orgánico en la cresta, parte media y parte baja de la ladera, morrenas A, B y C. x = valores perdidos)*

3.4.2. pH

Soil pH on all three moraines reflects the dominance of the base rich parent material, with the exception of the toe slope sites where pH values fall below the 6-7 range measured elsewhere on the moraines, which may be linked to the higher organic carbon contents which give a potential for generation of organic acids on decomposition (Fig. 5). The high initial pH of the freshly weathered limestone and schistose material has restricted the development of podsolisation in these soils, such that marked horizon bleaching that occurs in similar situations in other artic/alpine soils does not occur to the same extent in the Cirque de Troumouse.

3.4.3. Exchangeable cation composition

Exchangeable cation composition for these soils is given in Table 1. As is usual for soils in humid regions, calcium is the dominant cation on the exchange complex of these soils, with potassium, magnesium and sodium being subsidiary. With the exception of the surface soils at crest sites, most samples have concentrations less tant 1 meq/100 g soil, on an air-dry basis.

TABLE I

Exchangeable cation concentrations for soil samples from moraines A, B and C (x = missing values). *(Concentraciones de cationes intercambiables en muestras de suelo de las morrenas A, B y C (X = valores perdidos)*

MORAINE A	Depth,cm	Kmeq/100g	Mgmeq/100g	Nameq/100g	Cameq/100g
Crest	0-10	0.238	1.111	0.484	15.495
	10-20	0.043	0.221	0.213	10.827
	20-30	0.035	0.115	0.119	14.017
Mid	0-10	0.154	0.544	0.177	2.874
	10-20	0.043	0.054	0.139	0.405
	20-30	0.025	0.029	0.117	0.536
Toe	0-10	0.088	0.134	0.114	0.276
	10-20	0.029	0.047	0.102	0.620
	20-30	0.028	0.026	0.100	0.154
MORAINE B					
Crest	0-10	0.129	0.770	0.123	13.326
	10-20	0.028	0.258	0.113	16.998
	20-30	0.013	0.158	0.090	19.040
Mid	0-10	0.035	0.091	0.106	0.964
	10-20	0.027	0.039	0.121	0.770
	20-30	0.032	0.042	0.103	0.927
Toe	0-10	x	x	x	x
	10-20	x	x	x	x
	20-30	0.026	0.126	0.105	0.410
MORAINE C					
Crest	0-10	0.145	1.339	0.136	7.111
	10-20	0.048	0.315	0.102	1.604
	20-30	0.032	0.080	0.132	0.755
Mid	0-10	0.243	0.604	0.155	1.919
	10-20	0.056	0.118	0.146	0.561
	20-30	0.037	0.062	0.089	0.352
Toe	0-10	0.123	0.292	0.153	0.851
	10-20	0.033	0.105	0.113	0.270
	20-30	0.021	0.031	0.105	0.168

At the crest sites, where the influence of the parent material is likely to be most strongly felt and soils are shallowest, concentrations exceed that level, particularly in the case of calcium. All cations shôwn preferential accumulation in the topsoil, due to selective ion uptake by roots and subsquent return to the surface of the soil in leaf litter. The extent of nutrient stratification in soils is related to vegetation type and climatic conditions (OVINGTON, 1958). Potassium and magnesium both show pronounced stratification, much more so than sodium, which is less closely involved in uptake processes as it is not an essential macronutrient. There are few obvious differences between the younger and older moraines. The most noticeable difference is the reduction in calcium concentrations in the crest soils as moraine age increases (Table 1).

In addition to being influenced by parent material, exchangeable cation composition can be affected by other factors, such as slope position, vegetation type and rainfall solute inputs into the soil. It is difficult to separate out the relative contributions of these factors to the resulting concentrations measured in soil samples. However, slope position is the dominant factor, as it may lead to local variations in precipitation receipt, persistence of snowbanks and vegetation distribution. Ultimately the soil solute chemistry will be closely related to slope position, even when considering landforms on a microtopographical scale (PARKINSON & ROBERTS 1985). Assuming that the parent material had a constant composition over each site (not a valid assumption if significant post-depositional additions have occurred), then variations in the ratios of different cations must be the result of subsequent soil processes; in particular the preferential movement of more mobile cations downslope. Relative ion replaceability, or the ease of removal from specific charge sites, varies with charge and ionic radius. BOHN *et al* (1979) orders the exchangeable cations Na>K>Mg>Ca, with calcium being leas mobile. Using this ranking, it would be expected that calcium would accumulate relative to other cations at the top of a catena, and that therefore the ratio of calcium to other cations would be widest at this position.

In Fig. 6 calcium: magnesium and calcium: potassium ratios are plotted. There is a clear slope position trend and a less clear age trend. For each moraine the ratios are widest at the slope crest and narrowest at the toe slope position, confirming the relative ion replaceability ranking given by BOHN *et al* (1979), and agreeing with the results of PARKINSON & ROBERTS (1985). Comparison between moraines can only be tentative, but the general trend is of declining ratios with time, suggesting that the "imbalance" in relative cation concentrations is bein modified by the soil/vegetation system, resulting in a greater nett loss of calcium than of the other basic cations.

4. Conclusions

Soil/slope relationships are well established for mature soil sequence in accessible environments. In mountain areas harsh climate and sampling

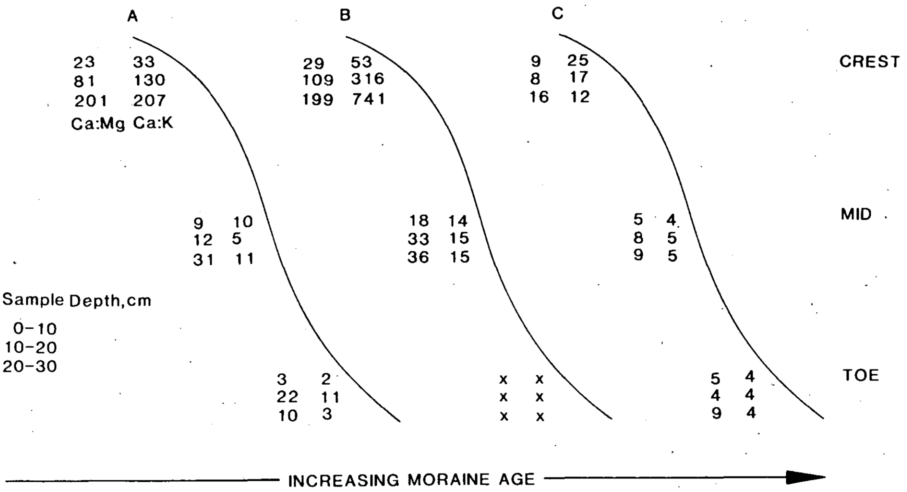

Figure 6. Exchangeable calcium: magnesium and calcium: potassium ratios for crest mid and toe slope positions, moraines A, B and C (x = missing values). *(Ratios calcio intercambiable: magnesio y calcio: potasio en la cresta, parte media y parte baja de la ladera, morrenas A, B y C. x = valores perdidos).*

difficulties often restrict investigations of soil properties, to the extent that spatial patterns are not fully investigated. Inadequate temporal frameworks may restrict the applications and interpretation of soil chronosequence studies as a means of determining patterns of geomorphological change. In recent years more attention has been given to the investigation of the variability of soil physical and chemical characteristics in deglaciated areas.

In this paper microtopography induced chemical differentiation of solute characteristics is shown to be an important process in these relatively immature soils that have formed in the Cirque de Troumouse since deglaciation. Silt: clay and exchangeable cation ratios display a strong slope position dependence, suggesting liknkage. It is therefore essential that soil sampling and description in these environments takes into account slope position, which will influence estimates of rates and extent of soil development.

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