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How Mudrock and Soil Physical Properties Influence Badland Formation at Vallcebre (Pre-Pyrenees, NE Spain)

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Summary

Soils, regoliths and their parent materials were investigated in relation to the development of badlands in the Pre-Pyrenees, in NE Spain, on Late Cretaceous mudrocks under a mountain Mediterranean climate.

Whilst all the soils in the area which are developed on mudrocks show a good structure and support a dense plant cover, the bare parent materials slake very rapidly giving rise to badlands characterized by high erosion rates.

Several physical, chemical, mineralogical and micromorphological properties of soils, regoliths and related parent materials were analyzed in order to explain their different susceptibility to erosion and to determine which of all these properties are better related to such erosive behaviour.

Only micromorphological and porosity properties were able to explain the erosion susceptibility, whilst mineralogical, chemical and physico-chemical (specific surface area) properties were not.

Among the aggregate stability tests performed to estimate the relationships of soil components with the susceptibility to erosion, the Emerson test for macroaggregate evaluation, was particularly well suited. Although no good correlation was found between the Emerson test classes and organic matter content, we observed that the degree of slaking in organic-rich horizons, was always lower than in subsurface horizons and regoliths.

Consequently, as far as organic rich aggregates are present in the soil surface, the influence of water in producing slaking, swelling and then erosion, will be minimum. However, when regoliths and rocks are uncovered, the influence of water in these particular materials, through freeze-drying and swell-shrinking, will give rise to mudrock desintegration leading to accelerated erosion.

Resumen

Se caracterizan fisica, quimica, mineralógica y micromorfológicamente unas lutitas de finales del Cretácico, en el Prepirineo catalán, y los suelos desarrollados sobre ellas, en relación con el desarrollo de badlands.

Mientras todos los suelos de la zona desarrollados sobre lutitas presentan una buena estructura y soportan una buena cubierta vegetal que impide la erosión,

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las propias lutitas se disgregan y erosionan muy rápidamente dando origen a una morfología de badlands.

Sólo la micromorfología y la porosimetría de Hg son las metodologías analizadas que mejor explican los procesos conducentes a la erosión, mientras que los resultados de la mineralogía, la química y la superficie específica de los materiales presentan pocas relaciones con la susceptibilidad a la erosión de los materiales.

Entre las pruebas de estabilidad estructural llevadas a cabo para estimar las relaciones de los constituyentes del suelo respecto a la susceptibilidad a la erosión, el test de Emerson para evaluar la estabilidad al agua de los macroagregados, fue el método más idóneo. A pesar de que no se encontró una buena correlación entre las clases del test de Emerson y los contenidos de materia orgánica, se observa que el grado de dispersion en los horizontes superficiales, ricos en materia orgánica, es siempre inferior al de los horizontes sub-superficiales.

Asi pués, mientras hay agregados ricos en materia orgánica, la influencia del agua en disgregar, hinchar y en consecuencia erosionar es mínima. Sin embargo, cuando se decapan los horizontes orgánicos y queda el regolito o la lutita al descubierto, la influencia del agua en los proceos de hielo-deshielo y/o hinchamiento-desecación, da lugar a una disgregación de la lutita conducente a una erosión acelerada.

1 Introduction

Many soil and parent material properties have been studied on several occasions in an attempt to explain various aspects of badland development: pH, free iron, carbonates, cation exchange capacity and exchangeable bases, organic carbon, water soluble salts in saturation extracts, aggregate stability (evaluated through diverse tests), optical and S.E.M. micromorphology, mineralogy, consistency index, bulk density, permeability and infiltration rates, mechanical strength, aggregate and particle size distributions (Imeson et al. 1982, Imeson & Verstraten 1989, Gerits et al. 1987).

Other important parameters which should be taken into account in rock and regolith weathering studies are porosity and micro-porosity. These properties have been reviewed and studied by Taylor & Smith (1986) who consider that mudrock desintegration is promoted by a combination of shrinkage and swelling under climatic fluctuations. According to Terzaghy & Peck (1948), the larger pore spaces in a clay or mudrock are involved in mechanical responses such as capillarity, whereas smaller voids and pores are important in clay mineral (physico-chemical) swelling. Mechanical swelling occurs in response to elastic and time-dependent stress unloading which can be brought about by nature in tectonic uplift and erosion. On the other hand, physico-chemical swelling depends on the nature of clay minerals, some of which, like smectites, show the greatest expansion.

Another important parameter which could be of great use in predicting soil and regolith behaviour with respect to erosion susceptibility is the specific surface area. This parameter tends to integrate the physical and mineralogical properties of a soil, taking into account for instance the amount and the kind of clay.

In Vallcebre, in NE Spain, the mudrocks from the Tremp formation are creating a badland topography dissected by gullies with erosion rates of about 9 mm/year (Clotet-Perarnau & Gallart 1986). According to these authors, the origin of such a degraded landscape is to be found in the nature of the parent material and in the strong climatic contrasts favouring the mudrock alteration.

Adjacent to and strongly in contrast with the bare regolith and mudrocks of the badland areas, completely vegetated soils with high, dense grasses developing on apparently well-structured soils, cover the rest of the landscape.

The aim of this study is twofold: in the first place it is proposed to explain through the analysis of several physical, chemical, mineralogical and micromorphological properties of soils, regoliths, and related parent materials (mudrocks), the susceptibility to erosion of covered soils and bare regoliths; in the second place it is to determine which of all these properties are better related to the susceptibility to erosion. The results may help in the understanding of badland evolution as this is becoming an important issue in the Mediterranean area because it is important to know the evolution of the large areas covered by such degraded landscapes.

2 Materials and methods

The mudrocks from the Tremp formation, of continental origin, in the Cretaceous-Palaeocene boundary, outcrop extensively in a broad band from a few hundred meters to a few kilometers in the Pre-Pyrenees. No data were available on the specific characteristics of these rocks except that they contain smectites. In Vallcebre, in the high Llobregat basin, in Catalunya (NE Spain), they are been intensively studied because a small watershed on these materials, formed by abandoned terraced fields, has been instrumented for a large research project on mediterranean desertification (Llorens & Gallart, this volume).

A few visible scars in the steepest portion of the well vegetated area clearly indicate the presence of mass movements which could trigger the development of new badlands. Moreover, small devegetated plots of a few square meters, presumable caused by human activities, may perhaps give rise to badland development too. Influence of vegetation and climatic extreme events on the badland development are discussed by Gallart & Clotet-Perarnau (1988).

The climate of the Vallcebre area is mountain Mediterranean: the annual precipitation varies between 800 and 1500 mm, showing a very irregular distribution during the year; the mean annual temperature is about 10°C, with a minimum of −10°C and a maximum of 30°C (Gallart & Clotet 1988).

Some of the aspects related to the surface hydrological behaviour of this land is reported by Llorens & Gallart (this volume).

A multi-approach characterization of 3 vegetated soil profiles (V-88, V-89 and V-91) and 5 bare regoliths (V-01, V-90, Reg.1-2, Reg.3-4 and Reg.5), was devised mostly based upon the properties which have proven to be indicative of erosion susceptibility (references previously quoted). This characterization includes the following:

- soil macromorphological description (FAO 1968).
- particle size distribution (through a "Sedigraph") without pretreatment for carbonate removal.
- pH in a 1/2.5 soil/water suspension.

- total and particle size calcium carbonate with a calcimeter.
- organic carbon by the classical Walkley and Black method.
- cation exchange capacity by using $BaCl_2$ for base saturation (Bascomb 1964); exchangeable cations extracted with NH_4OAc, determined by atomic absorption spectrophotometry.
- total and free iron through triacid attack and sequential extractions with dithionite-citrate-bicarbonate and oxalate respectively; pyrophosphate extractable iron (Bascomb 1968).
- mineralogy by X-ray diffraction: powder specimens for whole sample analysis and oriented aggregates for the clay fraction, with the classical tests of glycolation and heating.
- microporosity with a Carlo-Erba Hg intrusion porosimeter, model 2000 WS, allowing the characterization of pores ranging from 100μm to 0.0075μm.
- specific surface area through the water-vapour adsorption method (Orchiston 1953).
- micromorphological descriptions of thin sections (70×50 mm) from undisturbed, air dried, resin impregnated samples from every soil horizon and regolith (at 0–5 cm in all regolith and 5–10 cm in some of them). Bare regolith was sampled in two occasions, in summer and in winter to account for the differences observed in the field.

Three aggregate stability tests, taking into account different aspects of the structural condition of the materials, were also performed:

- Emerson or water coherence test (Emerson 1966), for macroaggregate evaluation, where class 1 represents the lowest coherence of fastest slaking behaviour and class 8 the highest coherence or no slaking at all.
- aggregate instability test (Henin et al. 1957), for macroaggregate evaluation.
- size distribution of <300μm microaggregates with laser light scattering (Pini & Guidi 1989), after dispersion in water during 1 min., for microaggregate evaluation.

3 Results and discussion

Description of representative soil profiles is reported in tab. 1.

The first striking result comes from the Emerson test, a measure of the slaking behaviour: most bare regoliths litterally disintegrate upon rapid wetting while aggregates from vegetated, organic-rich soils are considerably more resistant. This test confirms the previously stated field observations.

Micromorphological analyses reveal that deep regolith (5–10 cm) and parent materials are essentially formed by large lithic elements (>5 cm) separated from each other by narrowly open, accomodated and partially accomodated fissures. Lithic elements progressively decrease in size upwards; they are constituted by a very dense micritic mass with embedded sand and silt quartz grains, abundant, heterogeneous and irregular

Profile	Depth	Horiz.	Colour	Structure	Biol. Activ.	Boundary
V-88	2–10	Au2	75.YR 5/4	F. Sb. blck.	abund.	clear, smooth
	10–23	C	7.5YR 5/4	M. Sb. blck.	comm.	clear, smooth
	42–56	2C	10YR 6/6	C. gran.	few	sharp, smooth
V-89	2–12	Au2	10YR 5/6	F. Sb. blck.	abund.	clear, smooth
	12–21	Au2	10YR 5/6	M. Sb. blck.	many	clear, smooth
	22–30	C	10YR 5/6	F. gran.	common	clear, smooth
	49	2C	7.5YR 5/6	C. prism.	few	sharp, smooth
	>70	R	7.5YR 5/6	C. prism.	few	sharp, smooth
V-91	0–10	A	7,5YR 5/6	F. Sb. blck.	abund.	sharp, smooth
	10–20	Au2	7.5YR 5/6	M. Sb. blck.	abund.	sharp, smooth
V-01	surf.	R	2.5YR 6/4	C. gran.	few	sharp, smooth
	inf.	R	2.5YR 5/4	V.C. gran.	few	sharp, smooth
Reg. 1-2	surf.	R	5YR 6/3	V.C. gran.	rare	sharp, smooth
	inf.	R	5YR 5/3	massive	rare	sharp, smooth
Reg. 3-4	surf.	R	10YR 5/6	V.C. gran.	rare	sharp, smooth
	inf.	R	10YR 6/6	massive	rare	sharp, smooth
Reg. 5	surf.	R	2.5YR 5/4	V.C. gran.	rare	sharp, smooth
V-90		R	10YR 5/8	massive	none	sharp, smooth

Tab. 1: *Description of a representative soil profile.*

ferruginous impregnative nodules and some intercalations of birefringent clay (photo 1). Intercalations of clay are almost always interconnected by fissures.

Surface regolith (0–5 cm) show the same kind of lithic elements, of smaller size (<1 cm), separated by unaccommodated fissures. Bare regoliths sampled during winter show a lamellar microstructure in which horizontal fissures and cracks delineate planar lithic fragments.

Field observations have revealed that all bare regolith can form surface crusts, especially during the summer. The micromorphology of these crusts indicates that they are formed by three layers: a skin (about 0.1 mm thick) of alternate laminae of fine silt and clay; below, a layer between 0.5 and 1 mm thick, formed by the juxtaposition of sand size elements leaving a large amount of packing voids; and a very porous subjacent layer, 10 or more millimetres thick, with large vesicles among clusters of sand size elements with packing voids (photo 2). According to Chen et al. (1980), the upper layer constitutes a depositional crust, indicating the transport and deposition of fine particles by surface flow. The low thickness of this layer and the high porosity of subjacent layers suggests that this particular surface crusting by itself should not impede emergence as to explain the absence of vegetation. Rather, the increased porosity on the sub-surface layer and the apparent sparse and fragile bonds among regolith elements may favour the collapse of the whole surface layer due to either subsequent swelling and shrinking alternances or to external forces (rain, gravity).

Vegetated soil surface horizons present granular structures which are composed

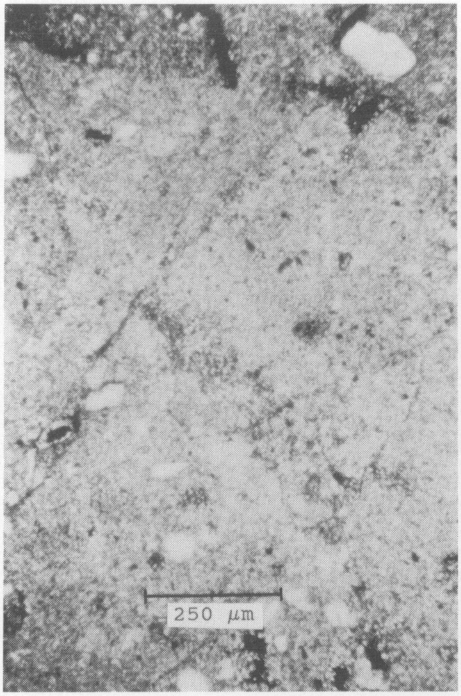

Photo 1: *Microphotograph of the parent material showing intercalated clays in a calcitic groundmass.*

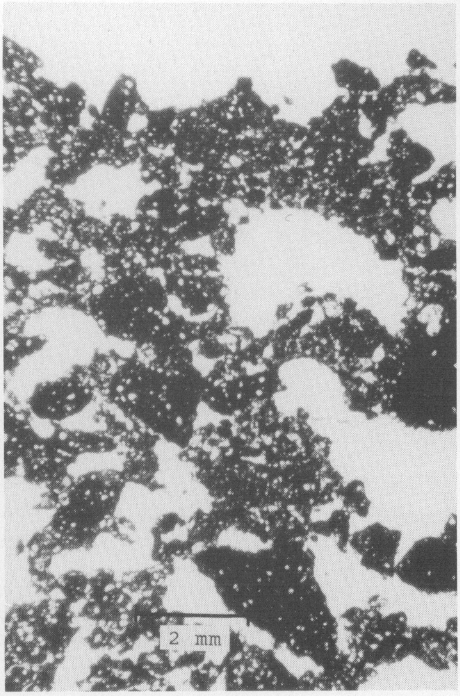

Photo 2: *Microphotograph of the surface crust forming on bare regoliths.*

either by organo-mineral aggregates, mainly of sand size, and by grains resulting from the fragmentation of the mudrock. Most of the latter grains are formed by a micritic mass sometimes with a strong ferruginous impregnation. Some of these grains have relatively angular shapes, suggesting an origin by in situ breakdown; others, quite rounded, may have been transported from upper topographic positions or been weathered by partial dissolution.

The mechanical analysis (tab. 2) indicates that most of the soils, regolith and parent materials are essentially silty, owing to the presence of abundant micrite and microesparite. The equivalent calcium carbonate content (tab. 2) of all materials is consequently high (up to 62%) and makes up the highest proportion of the silt fraction.

The main clay minerals (tab. 3) in both soils and regoliths are illite, kaolinite and smectite in relatively similar proportions, with a small amount of chlorite. There is a detectable increase in clay minerals with depth, especially smectite. The presence of this latter mineral ranges from 5% to 14% of the total.

Cation exchange capacity (tab. 2) ranges from a low 12.7 meq/100 g to a high 39.9 meq/100 g, following the trend of the clay content and its mineralogy. Calcium dominates the saturation complex, being magnesium, sodium

Profile	Depth	pH	CO_3	C.E.C.	Exchangeable cations (meq·100 g $^{-1}$)				O.M.	Fe (%)		particle size (%)		
	(cm)		(%)	(meq·100 g^{-1})	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	(%)	total	free	sand	silt	clay
V-88	2–10	7.91	32.58	12.70	17.20	0.48	0.20	0.16	2.98	1.73	0.86	23.10	50.00	26.9
	10–23	8.14	32.58	15.10	16.40	0.54	0.20	0.11	1.90	1.65		22.90	45.10	32
	42–56	8.41	31.33	19.60	19.10	0.55	0.24	0.15	0.29	1.97	1.30	31.14	38.50	30.2
V-89	2–12	7.27	43.86	24.70	18.00	0.36	0.31	0.17	2.96	1.97	1.52	30.90	49.00	20
	12–21	7.39	36.34	28.20	17.80	0.28	0.36	0.16	1.38	2.98	1.83	20.30	54.20	25.5
	22–30	7.41	35.09	26.90	21.20	0.26	0.54	0.15	0.31	3.42	1.94	15.10	55.10	29.7
	49	7.84	36.34	31.00	24.60	0.40	0.40	0.21	3.29	3.29	1.77	12.30	56.20	31.6
	>70	7.85	35.09	30.70	30.20	0.44	0.61	0.17	0.05	2.88	1.59	18.30	54.30	26.9
V-91	0–10	7.42	22.56	30.10	28.40	0.56	0.49	0.21	1.23	2.88	2.07	5.10	40.80	54.4
	10–20	7.78	25.06	29.80	29.20	0.61	0.60	0.19	0.61	3.63	2.29	10.30	37.70	51.1
V-01	0–5	7.87	31.33	38.40	33.00	0.44	0.34	0.18	0.14	2.17	0.98	5.10	51.30	43.7
	5–10	7.91	36.34	39.90	30.00	0.50	0.40	0.24	0.78	2.22	1.12	5.70	58.40	35.8
Reg. 1-2	0–5	7.60	62.53		32.61	0.40	0.36	0.17	0.23	2.21	0.87	8.20	55.90	35.7
	5–10	7.70	44.66		33.20	0.32	0.27	0.16	0.22	3.58	1.00	6.60	56.50	36.9
Reg. 3-4	0–5	7.70	46.65		35.86	0.31	0.32	0.15	0.19	2.43	1.70	2.30	61.60	36.2
	5 10	7.70	37.22		36.23	0.35	0.26	0.15	0.22	2.77	1.56	6.30	57.20	36.5
Reg. 5	0–5	7.60	45.16		32.90	0.54	0.30	0.18	0.37	1.62	0.79	4.00	47.90	42.2
V-90		8.00	50.13	18.20	30.00	0.41	0.58	0.13	0.10	2.53		61.40	16.60	21.9

Tab. 2: *Chemical and particle size analysis.*

Profile	Depth (cm)	Sp. sf. (m^2/g)	Total mineralogy (%) Quartz	Feld.	Calc.	Kaol.	Illi.	Smec.	Chl.
V-88	2–10	161	23.5	1.0	52.9	9	5	5	2
	10–23	144	28.2	2.0	41.1	13	10	5	1
	42–56	113	27.9	1.6	39.3	9	11	10	1
V-89	2–12	103	27.5	1.0	46.0	8	10	7	0
	12–21	120	26.0	0.7	40.9	9	11	12	1
	22–30	115	23.6	2.2	36.2	10	13	12	3
	49	109	24.4	1.3	34.7	9	16	13	2
	>70	143	26.3	2.4	40.9	7	12	12	1
V-91	0–10	175	21.1	1.0	29.5	14	21	14	0
	10–20	140	20.5	1.4	28	17	21	11	1
V-01	0–5	313	20.4	0.4	44.7	8	19	7	1
	5–10	336	20.1	0.9	47.1	10	11	9	1
V-90		108	26.3	0.3	47.9	5	10	9	1

Tab. 3: *Mineralogical and specific surface analysis.*

and potassium always very low (<0.6 meq/100 g).

Total iron ranges from 1.62% to 3.63% while free iron values (extracted with dithionite-citrate-bicarbonate or d.c.b.), from 0.79% to 2.29%, represent about half of the total iron in the average samples (tab. 2). In the soils we observe a clear trend towards higher values in an upward sequence, which could indicate some chemical weathering. Oxalate and pyrophosphate extracted iron range from 0.15% to 0.35% and from 0.05% to 0.16% respectively, indicating that most of the free iron is in crystalline form, associated to mottling and impregnative nodules of the original mudrock.

Specific surface area (tab. 3) shows in almost all profiles an expected decrease with depth, initially assumed to account for the decrease in organic matter. However, there is no good correlation between the specific surface area and the organic matter. On the other hand, we have found a good expected correlation between specific surface area and clay ($r=0.81$, $p<0.01$) and a negative one with calcium carbonate equivalent ($r=-0.97$, $p<0.01$). The correlations between specific surface area and pores <0.3μm ($r=0.81$, $p<0.01$) and with microaggregates <20μm ($r=0.72$, $p<0.02$) corroborate the dependence of this parameter on the physical condition of the material.

Hg-intrusion porosimetry (fig. 1) reveals a foreseen increase in total porosity from the parent material towards the soil surface. It is interesting to observe an increase in large pore upwards in the profile. Moreover, small pores disappear progressively upwards indicating that the smallest pores, originally as simple packing voids, open up when the mudrock progressively creates cracks and fissures upon freezing. This assumption is corroborated by micromorphology. There is also a good relationship between microporosity and the slaking behaviour: the larger the amount of small pores, the higher the slaking behaviour of the material. Pores <0.3μm, when dry, can exert a strong capillary suction. Indeed, differential pressures in the entrapped air in

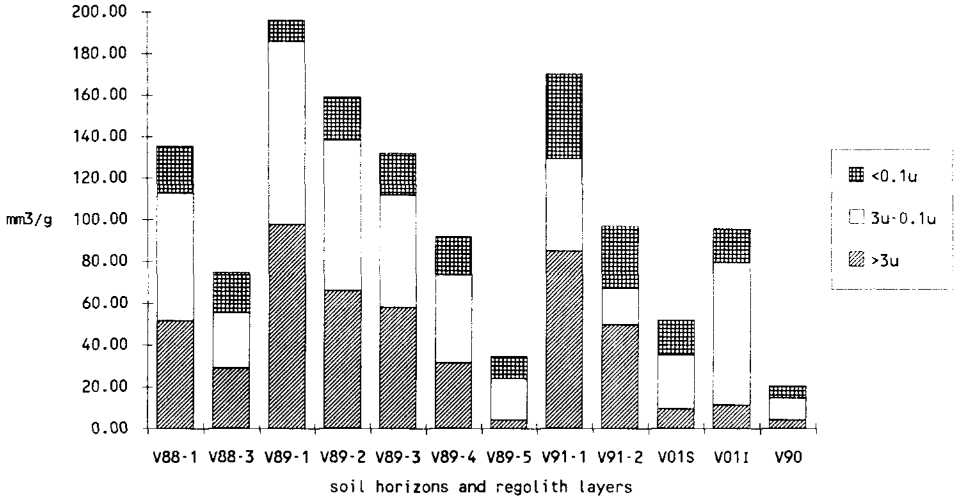

Fig. 1: *Hg-intrusion porosimetry.*

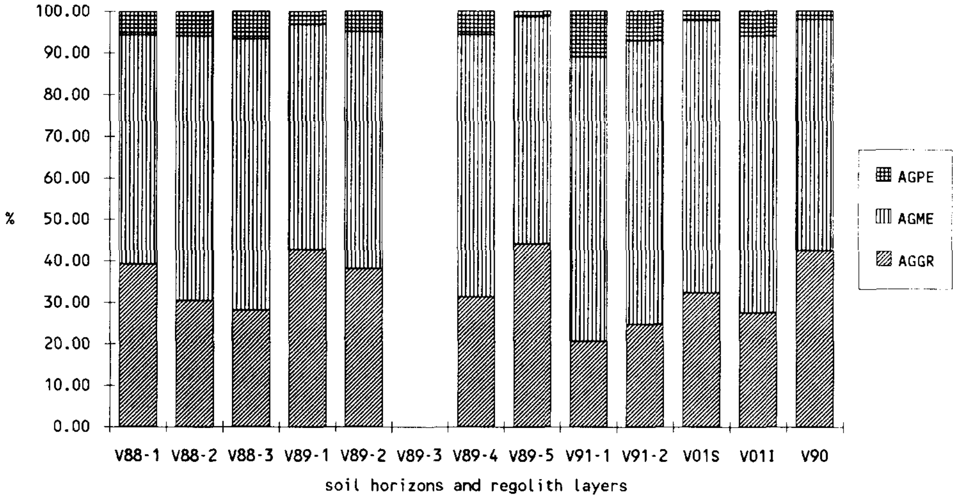

Fig. 2: *Water-resistant microaggregate size distribution.*
AGPE are aggregates <2.4μm
AGME are aggregates 2.4–19μm
AGGR are aggregates 19–53μm

different pores are known to be responsible for the breakdown of aggregates or clods.

Microaggregate size distributions (fig. 2) show a slight decrease in microaggregates ($>19\mu$m) with depth, as well as an increase in fine silt size microaggregates. Comparing this results with those from particle size analysis (tab. 2) it is possible to infer the relative resistance of aggregates $>19\mu$m.

The Henin aggregate instability test (tab. 4) shows that all soils have aggregates with very low Is (instability) values, indicating good stability in water. Aggregats $>200\mu$m stable in water range from one third to two thirds of total <2 mm aggregates. A quite acceptable correlation was obtained between the stable aggregates $>200\mu$m and the clay/free iron ratio ($r=0.5$, $p=0.05$); but a poor correlation was observed between the former and the specific surface area (r Spearman $= 0.5$, $p=0.17$) and no correlation was found with any other property.

On the other hand, the Emerson test (tab. 4) which measures the slaking behaviour, shows a quite higher degree of slaking in regolith than in surface, organic-rich horizons. A good correlation has been observed between the Emerson test and the sand fraction (r Spearman $= 0.58$, $p<0.04$), indicating that the degree of resistance is directly related to the sand content. The Emerson test and the silt fraction content correlate inversely (r Spearman $= -0.53$, $p=0.06$), the slaking behaviour being directly proportional to the total silt fraction.

It must be pointed out that the highest correlation value was obtained between the C.E.C. and the Emerson test (r Spearman $= -0.80$, $p=0.001$). This result would suggest that the slaking behaviour of the Vallcebre soils and regolith is associated to chemical properties, as C.E.C. integrates chemical parameters.

The poor correlation between the Emerson test and the stable aggregates $>200\mu$m in the Henin test (r Spearman $= 0.45$, $p=0.16$), along with the respective correlations found between both aggregate stability tests and all other parameters, suggests that the water coherence test is better suited to explain the erosive behaviour of Vallcebre mudrocks and soils than the Henin test in any of its three sub-tests (aggregates immersed in water, alcohol and benzene). The degree of slaking in surface, organic-rich horizons is always lower than in C horizons and regolith, regardless that neither direct correlation was found between the W.C.T. and the organic matter content nor with the specific surface area.

Beside the above results, very poor or no correlation at all was observed between the following variables:

- C.E.C. and both the clay fraction and the whole clay minerals.
- the smectite content does not correlate well either with the slaking behaviour or with the structural stability tests. This fact, along with the good correlations between some pore classes and the slaking behaviour suggest that microporosity is the first factor for such slaking, while the mineralogical characteristics are in this case of lesser importance.
- organic matter content and large stable aggregates; regardless this lack of correlation, the fact that organic horizons resist water erosion much better than C horizons or regolith indicates the positive role of organic matter in macroaggregate

Profile	Depth	W.C. test	Henin water stability test					
			aggregate >200μm			aggregate <20μm		
			H20	alcoh.	benz.	H20	alcoh.	benz.
V-88	2–10	5	51.18	74.13	62.04	0.60	0.68	0.81
	10–23	4						
	42–56	2	48.13	67.13	70.04	0.53	0.74	0.76
V-89	2–12	3	42.79	61.18	28.37	0.65	0.53	0.80
	12–21	3	41.89	52.22	28.79	0.79	0.74	0.83
	22–30	1	49.8	61.83	31.25	0.62	0.58	0.95
	49	2	38.3	73.81	25.34	0.65	0.54	1.15
	>70	2	37.83	72.21	25.12	0.66	0.79	0.98
V-91	0–10	3	66.91	81.38	29.57	0.60	0.60	1.71
	10–20	2	64.06	80.09	13.12	0.58	0.60	1.46
V-01	0–5	1	36.68	37.75	36.10	0.86	0.69	0.85
	5–10	1	32.67	38.17	35.09	0.79	0.71	0.85
Reg. 1-2	0–5		88.40	89.32	69.27	0.21	0.20	0.47
	5–10		74.84	77.92	63.72	0.39	0.41	0.37
Reg. 3-4	0–5		90.71	89.90	69.85	0.77	0.68	0.92
	5–10		63.50	67.39	44.58	0.58	0.63	0.81
Reg. 5	0–5		74.92	78.80	63.52	0.38	0.28	0.39
V-90		8						

Tab. 4: *Aggregate stability analysis.*

stability. Consequently organic matter and free iron, as states previously, are the two factors maintaining the structural health in Vallcebre soils. Anyhow, some correlation exists between o.m. and large pores >30μm ($r=0.65$, $p<0.05$), suggesting the favourable effect of o.m. in promoting larger aggregates with large interpedal pores.

As a consequence of all the above results, we can state that the influence of smectite clay in the mudrock and in the soil is completely different: in the mudrock, non-ferruginous clay (from the patches observed microscopically) can swell easily thus causing the breakdown of the material, which has no other aggregating cementing agent than the clay itself and the calcite. In soils, Ca saturated smectites in amounts ranging from 5% to 13%, along with free iron and organic matter, does not seem to represent a factor of instability of aggregates. The particle size of the calcite, mostly silt, is obviously important in maintaining a calcium saturation high enough to prevent clay dispersion.

4 Conclusions

It is usually said that cementing agents (calcium carbonate, iron oxides) result in the stabilisation of particles in the range 250–2000μm and prevent slaking; also that calcareous soils are generally well aggregated and do not slake readily. Whereas Vallcebre soils, regolith and parent materials present a very high aggregate stability index according to the

Henin test, they do slake quite readily in water, as shown by the Emerson test. Accordingly, most of the analyzed physical and chemical properties have not been very useful to explain by themselves the behaviour of Vallcebre lutites. Nevertheless, this study has shown the primary importance of the initial microporosity in the behaviour of these materials as well as the influence of freeze-thaw effects. It has also revealed the importance of smectite clay and its special occurrence in patches surrounded by a micritic groundmass as a secondary factor of slaking.

Consequently, soil and regolith micromorphological and microporosity parameters seem to be of paramount relevance in understanding the slaking behaviour to account for the erosive behaviour of Vallcebre materials.

It must be pointed out that structural instability indexes from surface horizons alone are not sufficient to attract attention on the erosion danger; subsurface horizons, regolith and parent materials structural indices must be also taken into account. In this particular study where we have dealt with calcareous mudrocks, the Emerson test has been the best suited aggregate stability test to account for the susceptibility to erosion.

It would have been desirable to found more reliable relationships between stability tests and some simple parameters (like specific surface area, for instance) to enable a better prediction of soil susceptibility to erosion. However this has not been possible in this instance.

Porosity analyses have corroborated the field observations by Clotet-Perarnau & Gallart (1988). As they suggested, frost-defrost action plays an important role in softening the mudrock: "during winter, frost action is able to soften the mudrock and a weathered cover a few centimeters deep appears at springtime. Snow melting or weak spring rains produce saturation of this weathered mantle and some flow scars and chutes are visible on slopes, while flowing materials accumulate in the main rills or on footslopes. Wind and sunshine desiccation produce small mud fragments which collapse and form small talus deposits on most of the footslopes. In summer, convective downpours sometimes accompanied by hail, produce rapid erosion of most of the weathered mantle, and its deposition in the main channels".

It is believed that the first stage of rock disintegration is caused by the jointing which is largely due to the stress unloading when rocks become exposed at the earth surface (Carroll 1970). In Vallcebre mudrocks, frost action accelerates the development of a fissure network, as seen through thin sections. Once these fissures are created, in the initial stages of pore enlargement, water either from thawing or from rains, along with the presence of expansible clays, plays an important role in mudrock breakdown. The possibility of water reaching the initial pores is related to their sizes and degree of connectivity. Once the waters have reached the finest pores and got in touch with the patches where smectite clays are present, as shown by micromorphology, they chause the swelling of the clay thus favouring the rapid slaking of the mudrock.

Besides the importance of microporosity and clay minerals, which have been considered as the cause of slaking, swelling and erosion, it is essential to point out the effects of water on these materials. In well aggregated soils, water does not show an erosive action. First of all, violent slaking is almost non-existent because surface, organic-rich aggregates do show well interconnected and enlarged fissures. Secondly, organic matter, either in the form of mucilaginous materials or as humus exerts a positive action against slaking. Nevertheless, when water reaches the regolith, its slaking and swelling action promotes the disintegration of the material.

Consequently, as far as a soil cover protects the mudrock from raindrops (water) or from freezing (ice), no erosion problems will be present. When mass movements, upon water saturation of a thick layer, or human activities eliminate the organic horizon and uncover the mudrock, very rapid slaking takes place, giving rise to gullies which are the first stages in badland development.

It is suggested that Vallcebre mudrocks might have always undergone erosion process. But man, through traditional terracing and water channelling (surface drainage) and specially through their maintenance, impeding that ditches became gullies, was able to master the best managing practices for such land.

Abandonment of fields is progressively deteriorating the terraces and drainage pathways, giving rise to the creation of devegetated plots and the risk of triggering badland formation. On the other hand, where relatively organic and deep soil is maintained, vegetation becomes denser and forest expands. Consequently, the future of this relatively fragile land lays in adequate soil maintenance and avoiding field abandonment.

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