Soil micromorphology of clayey hill slopes, central Italy

D. Magaldi · M. Giammatteo · P. Smart

Abstract Thirty-one undisturbed samples were collected from depths of 1.5 to 3.0 m on clayey hill slopes in the Pliocene and Allochthonous geological formations of Tuscany and Abruzzi in central Italy. Thin sections were made from each of the samples and the micromorphological aspects described semi-quantitatively using both microscopic and image analyses. The results were compared with the three, broad hill slope profiles – straight, convex and concave. The study showed that hill slope evolution by both creeping and surface and subsurface runoff has changed the conditions within the clay fabric and that linear voids due to tension and shear processes have formed in the soil. The data suggest that clayey hill slope form evolves from convex to concave via a linear shape.

Résumé Trente et un échantillons intacts de matériaux argileux ont été prélevés, en situation de versant, à des profondeurs comprises entre 1,5 et 3 mètres, dans les formations du Pliocène et de l'Allochtone de la Toscane et des Abruzzes. A partir de ces échantillons, des lames minces de sols ont été réalisées pour une étude semi-quantitative de la micro-morphologie, utilisant le microscope polarisant et l'analyseur d'image. Les résultats ont été rapportés aux principales formes de profil topographique de versants (rectiligne, convexe, concave). L'étude a démontré que l'évolution des versants argileux suivant des processus de reptation et du fait des écoulements superficiels et hypodermiques conduit à des modifications de la texture des sols argileux, avec formation de micro-vides allongés résultant des efforts de tension et de cisaillement affectant les sols. Les données obtenues suggèrent que les versants argileux évoluent d'une forme convexe vers une forme concave, en passant par la forme rectiligne.

Keywords Soil micromorphology · Image analysis · Clay slope evolution · Soil mechanics

Mots clés Analyses d'image · Evolution des versants argileux · Mécanique des sols

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Introduction

The shape of a hill slope is linked to diverse geomorphic processes which in turn are strongly influenced by factors such as climate and lithology (McFadden and Knuepfer 1990). The geomorphic mass and surface processes interact with both the rate of rock to soil weathering and the tectonic activity (Weyman and Weyman 1977). The research was carried out to assess the relationship between hill slopes formed on clay materials in Tuscany and Abuzzi and the micromorphological aspects of the area.

Mass movements may produce deformation evident in both the soil fabric and the microstructure (Lafeber 1972; Rog and Woclawek 1972; Curmi 1979; Harris and Ellis 1980; Van Vliet-Lanoe 1985; Bertran 1993), with fractures often creating planes of weakness which lead to shear failure. According to Bertran (1993), "the soil deformation produced by mass movement gives rise to specific microscopic features". As hill slopes on soil materials appear to be conditioned by the processes acting on them, it may be possible to evaluate the relationships between shape, surface and geomorphic processes and the microstructural characteristics of C horizons (or deeper subsurface levels). Soil slope profiles are commonly relatively straight or convex/concave (Ruhe 1975). Mixed or more complex profiles have not been taken into consideration in this study, in view of their rarity. Convex form are generally related to shallow mass processes, including soil creep and laminar flow of water (Rice 1988), whereas concave profiles are frequently attributed to colluvial deposition at the

foot of hill slopes. An equilibrium state between these could be invoked to explain a linear form. Some years ago, Rohdenburg (1989), starting from the concepts of authigenic slope (generated by internal slope processes) and basigenic slope (generated by footslope-acting processes), suggested that curved profiles could result from both mass and surface processes whereas linear slopes are temporary forms mainly conditioned by runoff.
The present research was carried out on slopes of 20 to 30° formed on marine clayey sediments mainly of Pleistocene age – the so-called "Blue Clays" and the Allochthonous Complex consisting mainly of clay, shell and marl of Eocene to Cretaceous age. These geological formations outcrop in Tuscany and the Abruzzi regions of central Italy. The study deals with the relationship between the slope shape and the micromorphological aspects of the upper 1.5 to 3.0 m of undisturbed soil. In 31 locations in the middle part of the hill slope, a sample of approximately 250 cm^3 was taken to be studied in the laboratory.

Fig. 1.
Location of sampling zones in Tuscany (*1* Siena Province) and Abruzzi (*2* Pescara Province, *3* Chieti Province)

Methods and material

The study was carried out on two or three thin sections from each of the 31 samples taken from the C horizon and upper weathered bedrock. The soils are termed Calcaric and Eutric Regosols following FAO-UNESCO legend (1988) and the Carta dei Argillosi d'Italia or Clayey Soil Map of Italy by Calzolari and Magaldi (1993) at a scale of 1:500,000. Figure 1 shows the location where the samples were taken and Table 1 the number of samples and their soil texture. This area of Tuscany has been developed mainly for agriculture, with wheat on the flatter slopes and olive and grape cultivation on the steeper slopes. Wheat is the dominant crop in many areas of Abruzzi.
Large thin sections (70×55 mm) were made using air-dried, undisturbed samples in order to study the micromorphology, i.e. the description, interpretation and measurement of components, features and fabric in the soil and soil-like material using a petrography microscope (Bullock et al. 1985).

Table 1.
Location and texture of clayey samples collected in central Italy on the Pliocene Formation (Abruzzi and Tuscany) and the Allochthonous Formations (Tuscany)

Location	Number of collected samples	Texture
Province of Chieti (Abruzzi)	11	Silt loam and silty clay loam
Province of Pescara (Abruzzi)	6	Silty clay loam and silt loam
Province of Teramo (Abruzzi)	6	Silty clay loam and silt loam
Province of Siena (Tuscany)	8	Clay; clay loam and silty clay loam

Structure and fabric of groundmass

The following micromorphological aspects were described mainly according to the guidelines of Bullock et al. (1985) and Kemp (1985). In soil micromorphological research, structure deals with the size, shape and arrangement of primary particles and voids in both aggregated and non-aggregated material, as well as with the size, shape and arrangement of aggregates. A great variety of possible structures have been defined. The groundmass fabric is related to the fabric and microstructure of the soil. Of particular interest to the engineer, it involves the arrangement of the coarse and/or fine material forming the matrix of the sample, although the presence of any concentration features is not commonly included. The groundmass fabric may vary from undifferentiated to striated.
Each feature was placed in order of its diagenetic and/or pedogenetic evolution following previous work in various soils by Ferrari and Magaldi (1988). The distribution of the micromorphological features in the samples is shown in Tables 2, 3 and 4.

Anisotropy ratio

The anisotropy ratio (or birefringence ratio) discussed by Smart (1966) and Morgenstern and Tchalenko (1967) was later applied with modifications by Magaldi (1987) and Coultard and Bell (1993) to obtain a quantitative assessment of the degree of anisotropy of the orientation of clay domains in thin section. The ratio can be used to interpret the degree of preferred orientation in an aggregation of particles (Coultard and Bell 1993).
In this study, the analysis was based on the variation of light intensity over five fields of view (1 mm in diameter)

Table 2.
Synoptic analysis of the micromorphological characteristics of three slope profiles (see also Tables 3 and 4). *x* Average value±standard deviation, *n* Number of samples

	Convex slope	Straight slope	Concave slope
Microstructure	Few types, with massive one predominant; regular decrease in frequency of more evolved structures	Few types; vuggy is dominant; channel and crack types also occur	Many types but channel and crack types are not present; vuggy is dominant
Fabric of birefringence	All types occurring, the stipple form is dominant	The three more evolved types only are present (unistrial, stipple, mosaic)	Only four types occur; unistrial fabric is not present whereas crystalline and stipple are dominant
Ratio of anisotropy	x=0.21±0.08, n=14	x=0.25±0.06, n=7	x=0.19±0.09, n=10

per section, obtained by a full rotation of the section under crossed polarised light. Readings were taken every 20° of rotation by means of a microphotometric device. The degree of orientation was quantified by the ratio of the difference between the maximum minus the minimum values and the maximum value of the light intensity. The method may be used only for clayey and fine-textured soils. The ratio obtained ranged between 0 (fully randomly orientated clay domains) and 1 (one or two orthogonal orientations in each clayey domain). Coarse skeletal grains, which occurred only rarely, were not taken into account in order to avoid interference with general mass birefringence.

Image analysis

Selected samples were examined by image analyser (KONTRON KS300) to obtain quantitative information on planar voids interpreted as shear or tension features. Only these voids were considered and most of the emphasis was placed on searching for possible signs of shearing and tension.
Considerable difficulty was experienced in classifying the voids. The criteria used were:

a. broad isometric voids with irregular edges: packing voids;
b. broad elongated to almost circular voids with smooth edges: channel and chambers formed by biological activity;
c. moderately broad voids with irregular edges and with constant width: tension cracks or shrinkage cracks;
d. long, narrow, straight voids: shear planes;
e. short narrow straight voids: shear planes, tension cracks or shrinkage cracks;
f. narrow irregular voids: tension cracks or shrinkage cracks.

The quantitative analysis was made on void types c to f. A set of eight photographs of vertical thin sections from the Pleistocene clayey formations of Tuscany were taken using a polarised microscope (see Fig. 2). Using this technique, voids appear black or dark grey. However, some particles had a grey colour and shape, similar to the voids. As a consequence, after careful examination of the thin sections, it was considered prudent to map the voids of interest by hand, using 220×100 mm prints, i.e. 4 times magnification (see Fig. 2). The final image analysis was carried out on these void maps to evaluate the azimuth angles of the types c–f voids.
The frequency of orientation data, ordered in 18 classes each 10° wide in the range 0 to 180° (Fig. 3), was analysed by common statistical descriptive methods in order to assess the degree of spread. This was evaluated by the Chi-squared test comparing sample frequency with a uniform distribution. The polar diagrams show a multimodal distribution with up to four modal values. For example, sample 107C appears to have four directions of preferred orientation (at approximately 45° to each other) whereas sample 6C has only one pronounced direction.

Table 3.
Structure types (% values). *Ab* Angular blocky, *sab* subangular blocks, *f* fissure, *c* crack. Pedogenetic and/or diagenetic evolution increase towards the right

	Massive	Spongy+vughy	Ab+sab+f+c
Convex	54	39	7
Straight	33	49	18
Concave	20	50	30

Discussion of results

The general results revealed different characteristics for each type of slope (Table 2). More detailed considerations can be derived by analysing the values for the microscopic features.
The results in Table 3 clearly show that convex slopes are a more primitive form than straight or concave slopes. The

Table 4.
Fabric types (% values). Pedogenetic and/or diagenetic evolution increase towards the right

	Undifferentiated	Crystallitic	Unistrial	Mosaic speckled	Stipple speckled
Convex	7	14	22	7	50
Straight			43	28	29
Concave	10	30		10	50

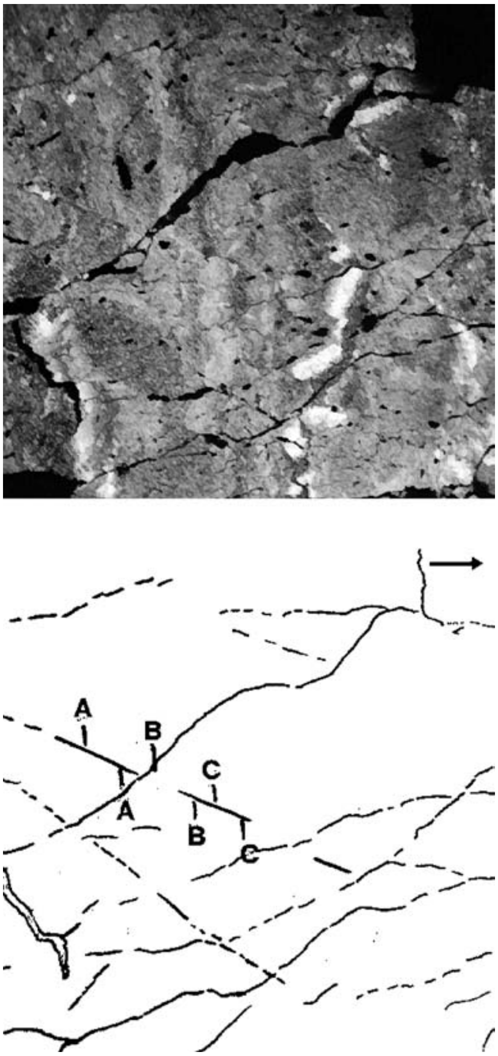

Fig. 2.
Photograph and map of the principal voids in sample CH3 (from Pliocene clay of the Chietei Province), 25° gradient, straight slope. *Arrow* marks the true vertical. Photograph width 4 mm. The *darkly shaded features* at the *top right* and *bottom left corners* are outside the sample. The map shows one, old closed shear plane with displacements of about 0.3 mm marked by *letters*. Almost parallel to this is another similar shear plane. Two sets of younger, partly open shear planes with little or no displacements are superimposed. There is a jagged tension crack near the *bottom left*. Other voids were caused by roots or fauna

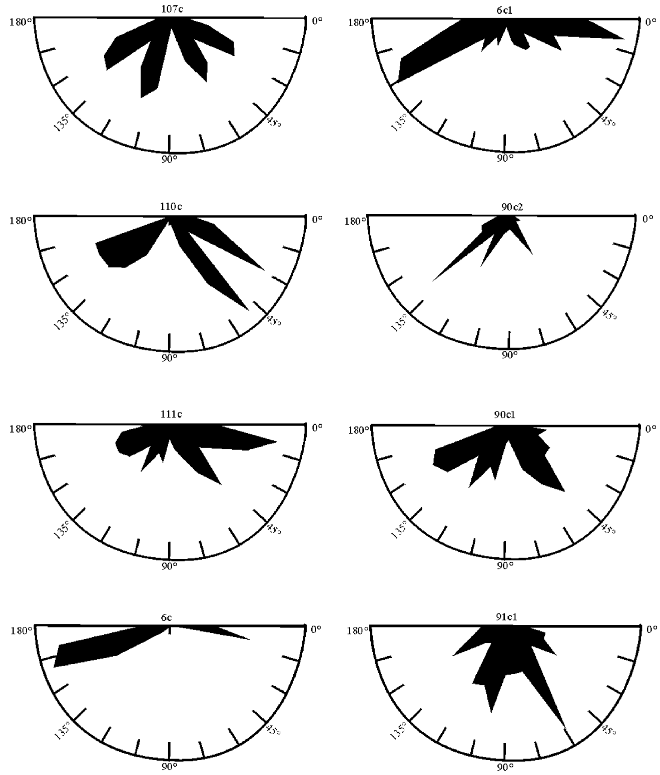

Fig. 3.
Polar diagrams for orientation in vertical plane of c–f types of voids (see text)

concave slopes are more evolved whereas the straight linear slopes represent an intermediate stage of slope evolution. It would appear that there is an evolutionary trend from convex to straight where the massive structure becomes pierced with holes and hence spongy or vuggy. The slope then changes from straight to concave where the material breaks up and becomes divided by fissures and microfissures formed between soil peds, resulting in angular to subangular blocks. The results in Table 4 support this hypothesis.
Amalgamating the mosaic speckled and stipple speckled fabrics, which are quite similar, produces approximately equal totals. It would appear, therefore, that there was no essential difference in the frequency of speckled fabric between the three types of slope profile. The strong occurrence of unistrial fabric in straight slopes could be explained by considering that the straight slopes are beginning to develop microshears.
The anisotropy ratio (Table 2) is low and similar for all types of slope. Nevertheless, the higher value of mean anisotropy ratio for the straight slopes seems to agree with the high proportion of unistrial fabric observed for these slopes. This is also supported by the degree of anisotropy seen in the speckled and crystalline fabrics in thin section.
A possible theoretical explanation for the patterns obtained from the polar diagrams is given below.

1. Clayey slopes are commonly subjected to soil creep which is likely to act as a shear process parallel to the slope (A–A′ in Fig. 4a) and a tension process approximately perpendicular to it (B–B′ in Fig. 4a). This was initially suggested by Culling (1963), even if some recent research does not support this simple model (Clarke et al. 1999).
2. Clay shrinkage and swelling is generally assumed to take place in most clayey materials. According to Dudal (1967), Magaldi (1974), Ahmad (1983), Blokhuis et al. (1990) and Whitlow (1990), the preferred orientation of clay domains in relation to the slope angle could be identified by two intersecting preferred orientations at about 45° to each other (CC′ and DD′ in Fig. 4b). These orientations should also indicate where soil would be prone to cracking.

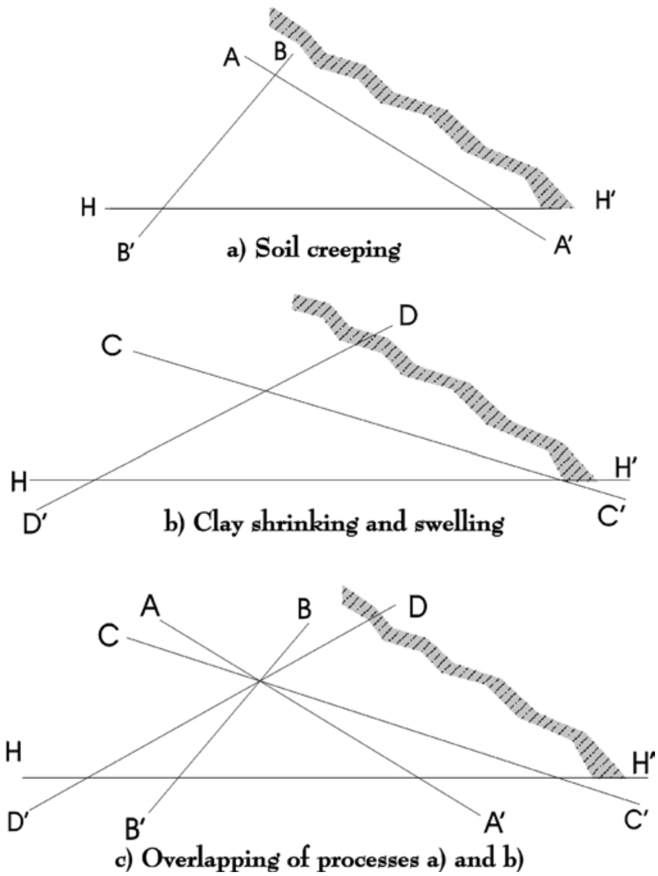

Fig. 4a–c.
A theoretical hypothesis regarding the more frequent fractures (linear voids) occurring in clay hillslope material (vertical section). **a** Fractures (AA′ and BB′) generated by soil creeping in a slope whose profile is parallel to the AA′ direction. **b** Fractures (CC′ and DD′) generated by clay shrinkage and swelling under normal stress. **c** Fracture directions obtained by overlapping of the previous diagrams

3. The overlapping of the directions resulting from both processes (1 and 2 above) is the pattern of discontinuities seen in Fig. 4c, with four preferred orientations.
4. The difference between the patterns could derive from different intensities of the processes and from other "casual" events.
5. The fracture orientation values as assessed by the Chi-square test appear to have an unproven relationship to the anisotropy ratio.

Excluding external causes, the forms found on clay slopes are mainly dependent on meteoric surface water, subsurface runoff, infiltration, and possibly deeper flow. The velocity of water flow within the hill mass is according to the nature of the underlying bedrock and the depth at which the water movement takes place. Soil creep is believed to be mainly responsible for determining the convex slope form, in association with water flow which significantly decreases with depth within a soil profile (Weyman and Weyman 1977). With concave slopes, turbulent flow commonly occurs (Rice 1988) and, consequently, a relationship is developed between the slope form and the microfeatures which can be observed in fresh or slightly weathered material. Starting from this hypothesis, the following trend is suggested:

convex slope → straight slope → concave slope

The convex slopes are relatively stable, although they are being gradually reduced, evolving to straight slopes by undifferentiated surface or subsurface sliding. Subsequently, these develop into concave slopes where surface runoff results in strong as well as deeper infiltration. Some field examples from Tuscany (Calzolari et al. 1989; Calzolari and Ungaro 1998) show the frequent occurrence of convex slopes within the more differentiated soils (Xerochrept or Ustochrept after the USDA Soil Classification). On the other hand, poorly evolved soils (Xerochrent or Ustochrent) occur on slopes with straight or concave profiles.

Conclusions

The possibility of using a micromorphological methodology for assessing the trend of subsurface movement of clay slopes and perhaps for testing general models of slope development under mass wasting processes has been considered. It is suggested it could be used in best management/soil conservation practice. It is concluded, therefore, that a worthwhile study could be undertaken to develop automatic description of soil microfeatures in order to achieve greater precision and reduce the time required for each of the individual measurements.

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