THE METHODOLOGY OF PHOTO INTERPRETATION OF MASS MOVEMENTS WITH SPECIAL REFERENCE TO THE SPANISH PYRENEES, TREMP, NORTHERN SPAIN*

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ABSTRACT. — This paper is concerned with an evaluation of the use of geotechnical methods for examining and predicting the development of unstable areas by means of aerial photographs carried out in the Tremp Basin, Northern Spain. The aerial photographic identification criteria of a mass movement is a landform deformation. The aerial view of this geometrical media gives invaluable information when examined under the stereoscope. It enables reduction of time and effort spent in the field and gives an insight into certain problems unapproachable within the time available from afield study. Through the recognition and delineation of airphoto pattern areas (geotechnical units), it has been possible to select the typical unstable areas for detailed investigations. The severe problems in the area occurred, mainly along the boundary of two susceptible formations between Paleocene Red Marls (Tremp Formation) and intensely jointed compact Eocene limestones, resulting in the spectacular case of instabilities. The Quaternary deposits, where they cover the Paleccene Red Marls, have also been encountered in the hazardous slope failures.

INTRODUCTION

The area under investigation is located within the province of Lerida (Northern Spain) about one hundred kilometers north of the provincial capital (Fig. I). The River Pallaresa is the main river in the arearrunning down to the south through the Pyrenees. The River Conques and River Rucos are the main tributaries draining the basin into the Pallaresa. The Tremp Basin which occupies the main part of the study area is in the southern slopes of the Pyrenean mountains and has a surface area of about 200 sq. km. Erosional processes, including mass movements, affect most of the rock formations and rejuvenate the morphology of the area. The recent geodynamical factors show important developments to be studied within the framework of any engineering project in order to ensure alignate soil conservation and protection of the construction works and structure. The aerial photographic studies, backed with the geotechnical methods, greatly assist in recording the geodynamical processes and to predict their future development.

GEOLOGICAL SETTING

There is an east-west trend of all geological formations resulting from the Pyrenean orogeneses. The oldest rock formation in the area is the Middle Cretaceous cyrstalline limestones having relatively high relief because of its high resistance to erosion. The Upper Cretaceous soft marls and marly sandstones conformably overly the Middle Cretaceous. The extensive Paleocene Red Marls (Tremp Formation) cover most of the area. These marls are highly plastic

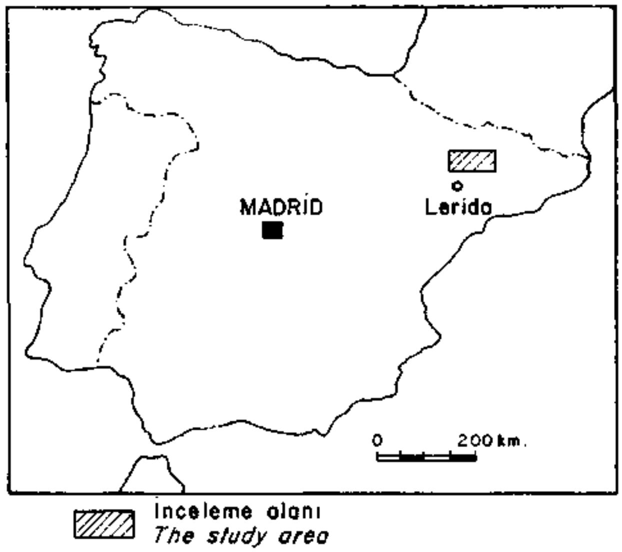


Fig. 1 - The location map of the study area.

and have a low resistance to erosion. For this reason, they are always found in the lower parts or on the slopes. The whole Eocene stratigraphy is represented in the area. They are well-stratified and densely jointed, compact limestones which are also interbedded with dark gray plastic marls. The boundary between Paleocene and Eocene is sharp and distinctive. During the Quaternary period different climatic regimes resulted in the formation of different landforms and in the deposition of materials.

AIRPHOTO INTERPRETATION METHODS

Aerial photographs have been very useful in establishing the paleomorphological development which led to the acquisition of a complete picture of the landforms of the area. This is because they allow the interpreter to have a general view of several landforms simultaneously and consequently to make comparisons and establish a morphogenetic relationship between them (Avcı, 1977).

Twenty-four black and white panchromatic aerial photographs were used at a scale of 1:30,000 in the laboratories to carry out the preliminary survey. The detailed study was concentrated on an area covered by twelve photographs. The other photographs were used only for establishing the general morphogenetic relationship of specific landforms with their surrounding areas.

Both the preparation of a photomosaic and the preliminary examination of the photographs led to the compilation of geotechnical units of the area. These units are the ordinary geological units with their recurring surface parameters which complemented by erosional processes, developed upon the rock type. Thethick and extensive superficial materials over the same geological unit produce a different geotechnical unit (Photo I, Unit C), because they play an important role from the geotechnical point of view. In the area a number of examples were observed covering the Paleocene Red Marls which encountered numerous instability conditions. Each unit displays a different pattern and is easily recognised and delineated through the photographic densities (Photo I).

After the recognition and delineation of geotechnical units a more detailed interpretation of each unit was carried out using the stereomodel primarily to conform and finalize the boundary-of the geotechnical units and secondarily to acquire information about the erosional processes and the types of instability conditions in each unit. At the end of this preliminary interpretation it has been possible to devise a sampling scheme to select the typical unstable areas for detailed observations. It is mainly based on the characteristic terrain attributes which made it possible to avoid working in areas of similar unstable conditions.

Within the sample areas special attention was concentrated along the valleys, erosional scars, gullys and badlands using maximum optical magnification, to provide measured parameters of sampled instability features. There were some features which were not clear enough for significant identification at the scale of 1:30,000. For this reason, two-times enlargement of these photographs, for the sampled areas, were made to improve the interpretability of the smaller features (Photo 2 and 3). The result was extremely useful to the extent that it had been possible to detect some aspects of the causes and mechanisms of each visible instability. It showed that a mass movement is a landform deformation which sticks to the eye of the interpreter in stereomodel; that is, it is an anomaly within a valley or on any landform (e.g. an abrupt cut off the side of a hill or an interfluve). From the interpretation of various mass movement types it was concluded that a mass movement in stereomodel, in most cases, occurred as the unit displacement of a mass. This mass was removed from a part of the earth resulting in a void and an irregular hummocky surface which appeared below a distinctive scar accumulated at the end of a sliding way. As a result, the terrain pattern and land-use-vegetation will show a sharp change, in which case it is reflected in the photographic densities (Ta liang & Belcher, 1958).

This massive displacement will deform the landforms in different geometry and form in different geotechnical units such as flow, slide and fall controlled by the material, rock type, slope angle and geological situation. The geometry of these media is effectively identifiable from the aerial photographs due to their three-dimensional significance in stereovision. It is mostly because of this significance that the color aerial photographs have no superiority over the black and white photographs in mass movement investigations.

The creep, the imperceptible mass movement phenomenon, which has no significant aerial photographic indications, has been inferenced on the basis of the undulated, bulging and ruptured morphology of the slopes and mottled dark gray photo tones. A dark photo tone is usually the indication of a high moisture content which is one of the important agents to induce the creep in the soil. During the field work in the area it was proved that the dark photo tone together with proper slope conditions indicated the existence of creep. However, infrared color aerial photographs may be more useful in identification of creeps, solifluction and the tension cracks (Norman et *al.,* 1975).

In conclusion, each instability type portrays a particular configuration in photographic imagery. Their interpretation is basically concerned with making inferences and deductions from the geometrical attributes of landforms and gray tone levels appearing in the stereoscopic image (Table I).

Table I - The type of mass movements and their photographic characteristics with other relevant information found in the area

Type	*Photo characteristics*	*Probable causes identified from the aerial photographs*	*Geotechnical description*	*Material and geology*
Slump	Characterized with its two directional cylindrical scar and stepped parallel ridges with a backward inclination to it. They show distinctive topographic anomalies and also reflected in photo tones.	Removal of the lateral support at the toe of the slope by natural erosion or artificial excavation.	Rapid downward movement of poorly consolidated earth mass with a cylindrical slide surface on a horizontal axis parallel to its scar. Commonly occurs in the materials of possessing the isotropic shear strength.	Regularly stratified poorly consolidated rock formations.
Slab slide	They are characterized by the sudden change in the bedding surface which also reflects in the gray tone levels. The slide bed usually spread in the end of the sliding ways.	The removal of the support of the slide slab at the toe in the inclined edge of the beds.	Sliding of a rock bed parallel to bedding plane. Common when hard and permeable rock beds overlying the marls.	Inclined, stratified sandstone or limestone marl intercalated rock formations.
Rock fall	Mostly associated with steep rock faces of massive formations. The talus formation and individual rock blocks are also identifiable at the foot of the slope.	Production of overhanging rock walls by the removal of the underlying soft layers.	Free falling rock blocks of various size from the overhanging slopes.	Resistant and jointed rock layers intercalated with soft layers and/or a hard layer overlying soft erodable marls.
Rock avalanche	It shows an irregular steep detachment scar. The detached debris form an irregular fragmentary pattern of accumulated boulders. It is also reflected in the photographic densities.	The removal of the support of the blocky formation by retrogressive gulley erosion and the existence of overhanging rock slopes.	The cumulative rock fall from the jointed limestone walls interbedded with soft plastic marls. Detachment surfaces are the predisposed joints.	Stratified, compact limestone with dislocation planes interbedded with marls.
Earth flow	They resemble glacier flows forming a lobe-shaped bulge at the foot of the slope. They show large scarp when superficial. The flow is also well visible in the gray tone levels when especially fresh.	The overloaded slope and high water content inferenced by the gray tone levels. And gulley erosion at the foot of the slope	They usually occur in debris material and unconsolidated marls. Initially it may start as a slump afterwards transferred to earthflow by adopting themselves predetermined topography. They were mainly triggered by excessive water.	Thick debris material and unconsolidated pelitic formations.
Mud flow	They are more extensive and show lighter gray tones with larger bulge compared to earth flows. The old mudflows outlined by land use and other environmental factors.	Excessive water.	Mudflows are usually the retransportation of slide masses or the other loose materials by excessive water.	Any debris material.
Creep	No significant photographic characteristics. Inferencible on the basis of bulging and ruptured morphology of slopes with dark photographic densities.	Detection of colluvial slope with its irregular surface morphology and undermining at the foot of the slope.	The imperceptible movement of superficial material which usually does not exceed the thickness of the material. The movement initiated due to the different physical characteristics of the creeping layer leading to a long-term plastic deformation.	Soil and rock fragments over the marl formation with a slope of 15°.

TYPE OF INSTABILITIES OBSERVED IN THE AREA

At the end of the laboratory analysis of the aerial photographs a series of preliminary maps and diagrams were compiled which were subsequently taken to the field. The result of the field work has shown that, in most cases, the field observations confirmed the information obtained in the laboratory. Most of the significant landslides for mapping were interpreted directly from the aerial photographs which date from 1957. During the fourteen years since the aerial photographs were taken, there has been a considerable amount of slope destruction as a result of mass movements which were recorded during the field work.

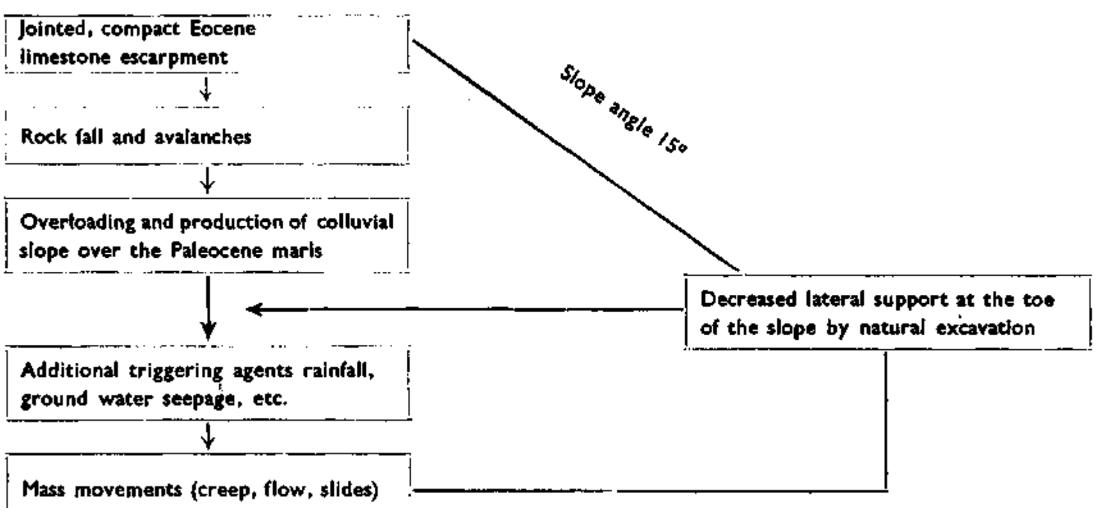
After the field work a comparative analysis of all the information and reinterpretation of the aerial photographs was carried out to compile the geotechnical map (Fig. 7).

Four instability conditions were selected as typical for a detailed study. There are several geological and geomorphological factors in the creation of these instabilities occurring in the area. These are as follows:

1. Instabilities in superficial materials.
2. Instabilities between Eocene limestones and Paleocene Red Marls.
3. Instabilities within the Paleocene Red Marls.
4. Instabilities in the permeable and impermeable intercalated layers.

The first three situations are closely related processes which circulate within a peculiar area (Photo 3 and Fig. 2). The development of these instabilities is shown in the flow chart below.

Instability development chart of the area



GEOTECHNICAL EXPLANATION

The Eocene limestones are compact, intensely jointed and also marl intercalated rocks (Photo 4). The infiltration of water, through the joints, during the heavy rainfalls expands the intercalated plastic marls and disturbs the stability of the unit. The underlyihg formation consists of the Paleocene Red Marls which are easily eroded and removed. As a result the blocks of jointed Eocene limestone fall down and/or, if the zone of instability is large, rock avalanches occur along the Eocene-Paleocene contact (Photo 5). This fragmentation from Eocene limestone escarpment overloads the Paleocene Red Marls and produces a colluvial slope by accumulating a variable thickness (approximately 2-4 m) of colluvial material. These are light gray, clayey silt with angular gravels and blocks, and boulders of the Eocene limestones. The laboratory analysis of a representative sample from the matrix of this materials yielded a high moisture content (43 %) and a high plasticity (39 %).

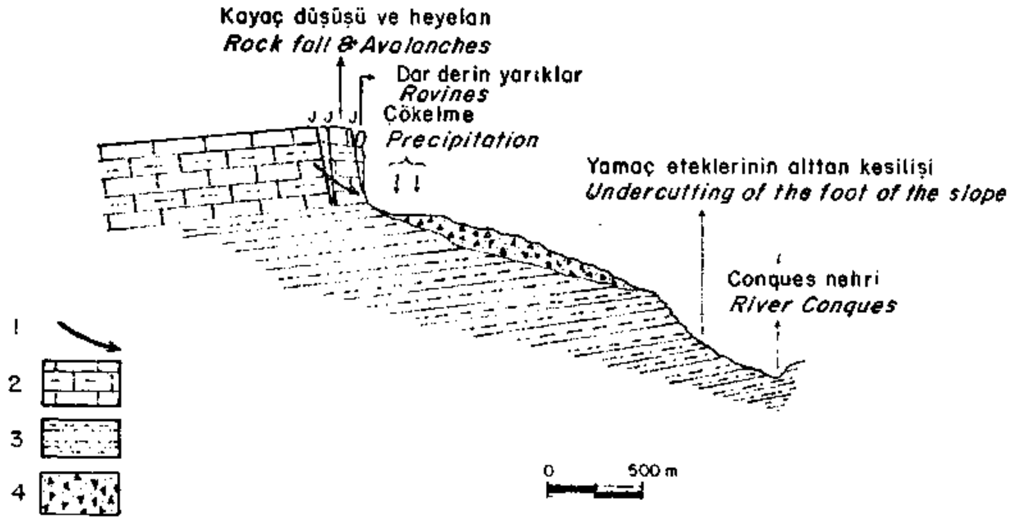


Fig. 2 - Factors affecting the instability conditions prevailing between the Eocene limestone-marl and Paleocene Red Marls.
1 - Ground water; 2 - Limestone-marl (Eocene); 3 - Red marls (Paleocene); 4 - Colluvial material.

At the foot of the slope the lateral river erosion and the other erosional processes such as gulleying, badlands and rills are rather active. This situation leads to increased shearing stress by overloading and undercutting by which in turn the strength of the materials is reduced, especially when saturated. Consequently, the colluvial material moves downwards in the different forms of mass movements. For instance, the creep is a constant phenomenon on this slope which does not exceed the thickness of the colluvial material (Photo 6 and 7).

The creep is favorably affected by the loosening and upheaval of soil and rock fragments caused by frost action or the roots of low-growing vegetation. Due to the upheaval the porosity of these layers will increase and the masses will become heavier as a result of a higher water content. Consequently, these layers obtain particular physical properties inducing the phenomenon «creep» under the influence of gravity. Photograph 6 is exteremely interesting in that it shows a straight growing healthy tree slowly moving down-slope with its roots trailing behind it. Furthermore, the more common indications of creep activity, such as bend tree trunks (Photo 8) and tilted fence posts were frequently observed.

Sheet and debris-slides and earth flows have also been observed and are detrimental to the cultivation of this fertile slope. The earth flows are one of the commen features that occur in the colluvial slope. They usually have a large scar at the upper part, the flow adjust itself to the topographic situation and follows gulleys or valleys or spreads out at the lower part of the slope (Zaruba & Mencl, 1969), (Photo 12). The weight of the colluvial materials also disturbs the stability of underlying marl formation which causes deep-lying mass movements due to increased shearing stress by overloading and, natural and artificial, undermining at the foot of the slope (Photo.9). Photo 10 shows a slide in superficial material which tends to be a deep-seated rotational slide along the dashed lines. But the sliding circle is broken by the resisting forces of the underlying compact rock formation and thus transferred into a superficial slide. In this situation the road is safe as it is constructed on the solid rock. It was determined that, more often then not, slumping was the initial stage of earth and mud flows on the colluvial slope (Photo II, 12 and 13).

The mass movements which occurred in the Upper Cretaceous Sandstone-Limestone-Marl intercalated formation falls in the fourth instability group. An example of this type, is seen in Photo 14, which slipped into the Tremp reservoir lake. The movement has taken place with a slip surface parallel to the bedding plane between the calcareous sandstone (above) and marl layers (below) of Cretaceous series. The slide might have been due to the penetration of water through the permeable sandstone layer into the expansive plastic marl layer. Thus a slide surface developed between the marl and sandstone inducing the movement. Probably the sliding was also provoked by the undermining of the lake waves. Furthermore, Two villages (Tendruy and Puigcergos) have been destroyed by mass movements and sections of several roads had to be reconstructed after each wet season in the area.

Tendruy situation

The interpretation of the aerial photographs in the laboratories, dating from 1957, showed convincingly that a village was in danger and that its relocation was urgently necessary. But it was only in 1969 that the coming disaster announced itself clearly enough to convince the villagers and the government to abandon the site. Thus a twelve year prediction was made by photo interpretation on the basis of the three dimensional significance of stereomodel by detecting the lateral river erosion which was aggravating the instability of the slope where the village was erected.

Geotechnical explanation. — The former village of Tendruy was erected on a hill near the river side edge of a shallow fossil river channel which overlies the Paleocene Red Marls. The material of the fossil channel is unconsolidated sandy gravel which crumbles when touched by hand. At the lowest part of the gravel - deposit a new stream is formed which cut approximately 30 m into the surface of the fossil channel. To the west of the village a moderately deep abandoned valley occurs, as can be seen on the plan and section. The village with its gravelly base over the marls is thus completely isolated (Fig. 3 and 4).

The contact between the gravel and underlying marls has an inclination of approximately 7 degrees east. This situation creates instabilities due to lateral sapping and vertical cutting of the existing stream which prevail all along the east side of this gravel formation and the underlying marls. It is also a well known fact that infiltration of water through the overlying permeable layer may produce a slip surface in the lower impermeable formation. As a result of these combined unstable conditions the hill and the village started to move (creep) slowly eastward, towards the river.

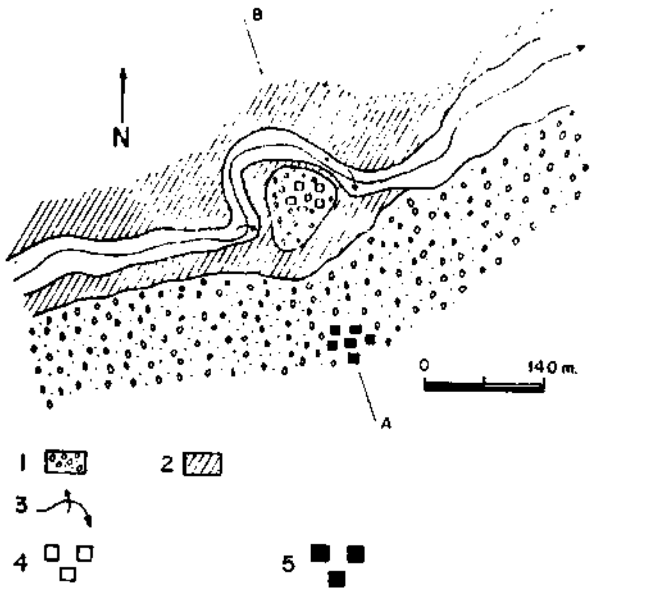


Fig. 3 - Plan view of Tendruy situation.
1 - Gravel; 2 - Marls; 3 - Lateral river erosion;
4 - Old village; 5 - New village.

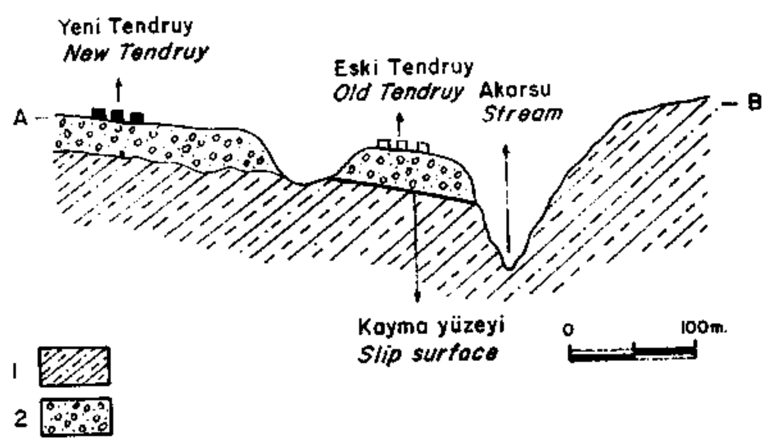


Fig. 4 - Cross section along A-B on the plan view of figure 3.
1 - Marl (Paleocene); 2 - Gravel.

The old village still exist. It has an irregular surface and many fissured and undulated walls can be seen. Although it is not ruined yet, it is dangerous to stroll in it. The village may completely slide down within a few years. The new village has been erected on a stable place further to the south.

Puigcergos situation.

A slump affecting the Eocene limestone-marl formation is the cause of this disaster. The former village of Puigcergos was located on a residual hill.

The relative height of the hill is approximately 100 m and the B^{co}. de Espona, which is flowing at its southwest side, carved the final form of the hill and separated it from the hills which occur further to the south. Lithologically the hill is the extention of the Eocene limestones in the south (Fig. 5). The vertical cutting of the B^{co}. de Espona is negligeble, since it has reached the mature stage and is characterized by a gentle gradient. Lateral sapping on the other hand is of great importance especially in the rainy periods when great discharges are observed as a result of its fairly large catchment area (apprx. 7 km^2).

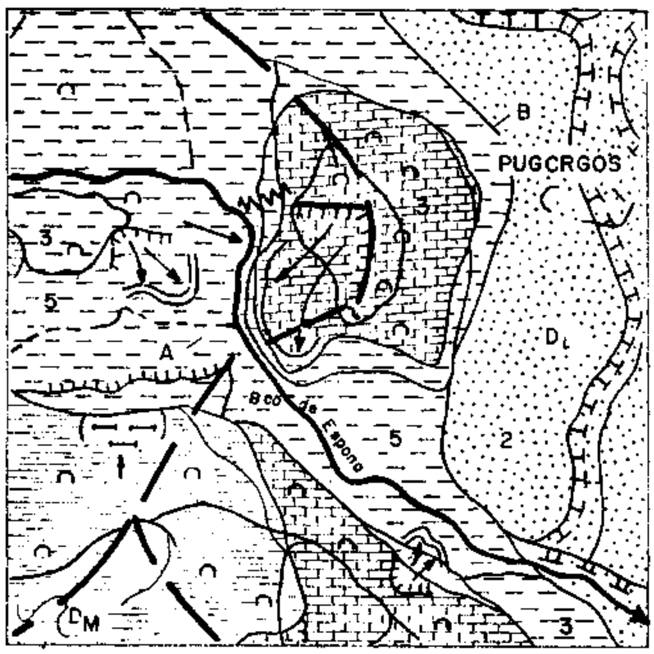


Fig. 5 - Plan view of the Puigcergos slump initiated by lateral river erosion.

The flow direction of B^{co}. de Espona is straight and almost eastward until it reaches the hill which forces the river to make a southward bend. At this point of the channel the lateral erosion is evidently maximum and the. current actively erodes the foot of the hill. With progressing lateral cutting the first sign of disequilibrium was the appearance of a number of cracks on top of the hill. Warned by these clear indications of imminent danger the villagers removed the settlement to a flat and stable place further to the east. Infiltration of rain water through the cracks and into the susceptible Paleocene marls below (Fig. 6). increased the instability and finally caused the slump (Photo 15). The resulting anomaly of the detached mass is great and well visible in the stereovision (Photo 2).

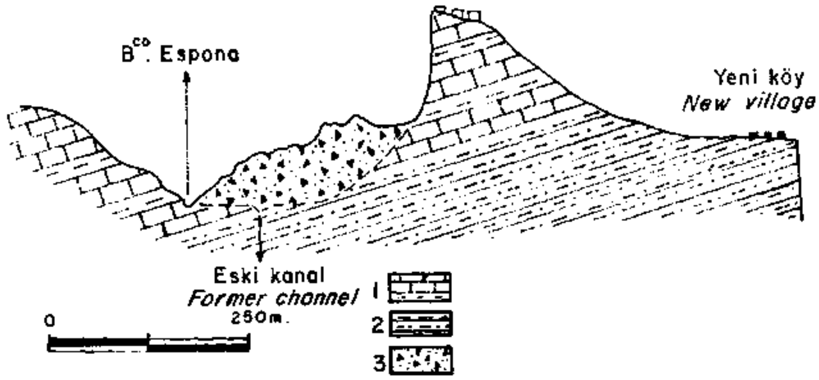


Fig. 6 - The cross section along A-B on the plan view of Figure 5.
1 - Limestone & marls (Eocene); 2 - Red marls (Paleocene);
3 - Debris.

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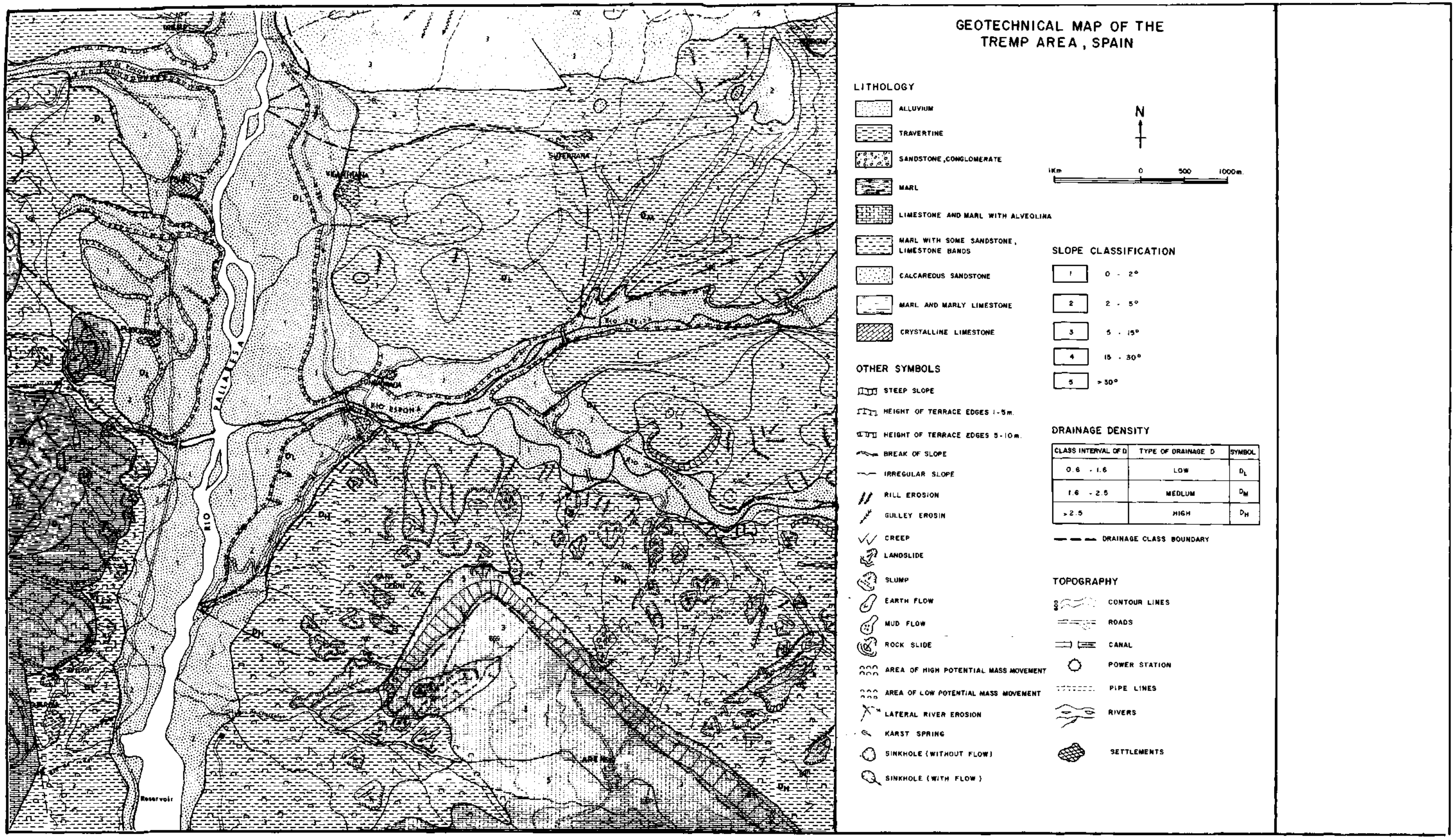

Fig. 7 - Geotechnical map of the Tremp Area, Spain.

Photo 1 - The stereogram shows how surface configurations are delimiting the geotechnical boundaries as at A (Eocene limestones), B (Paleocene Red Marls) and C (Superficial materials covering the Red Marls).

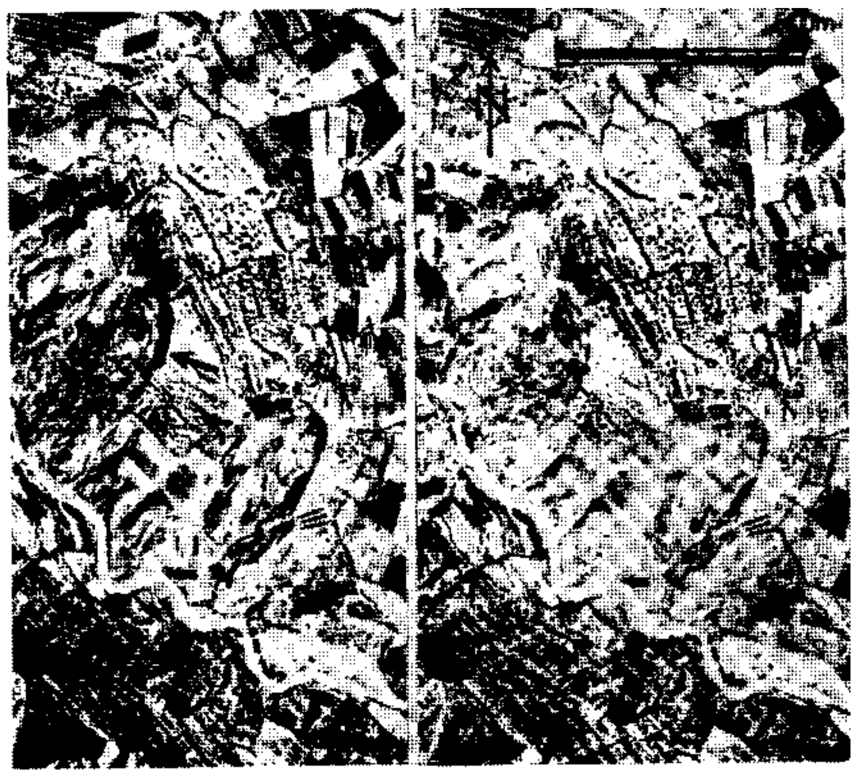

Photo 2 - Stereogram showing the Puigcergos slump of Figure 3 arrowed.

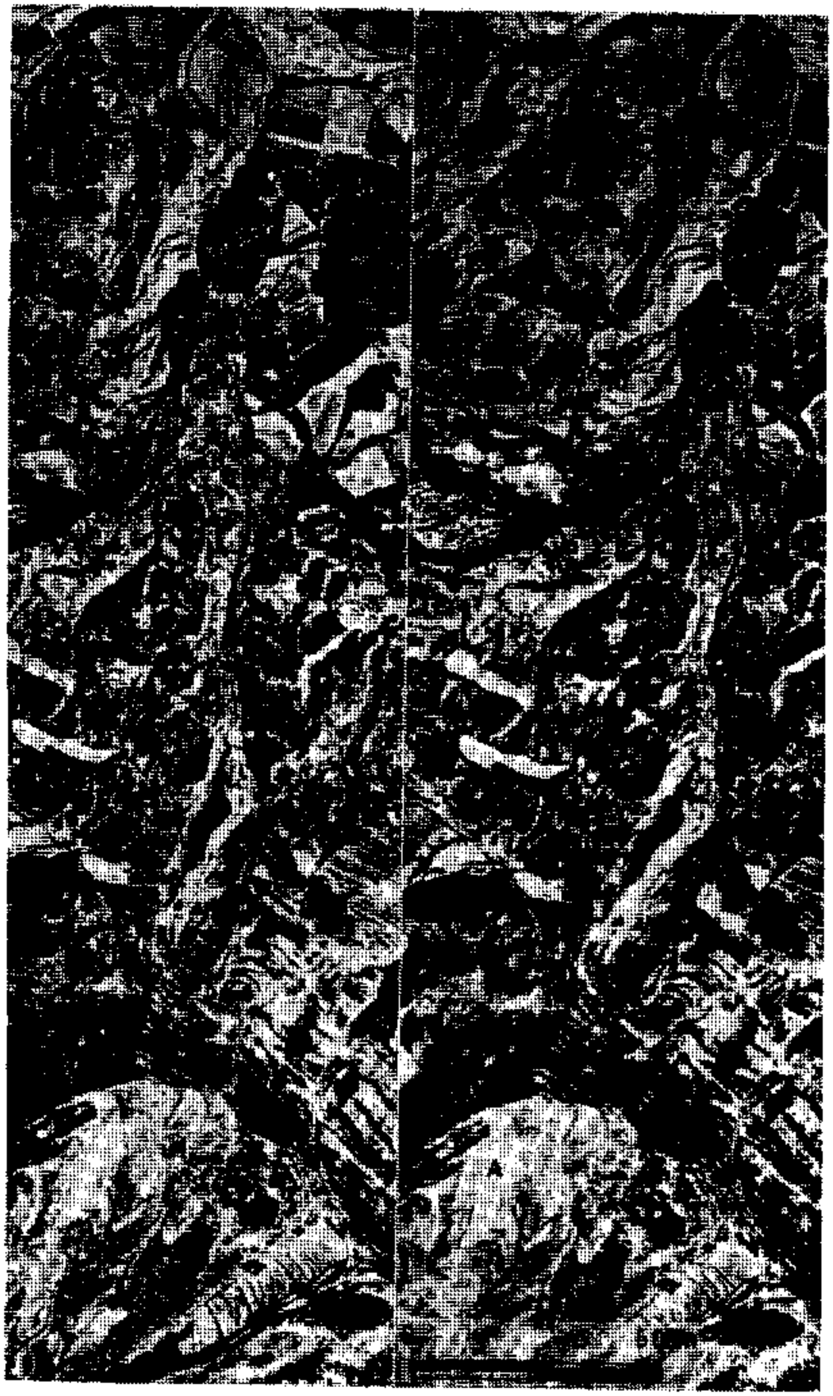

Photo 3 - Stereogram showing the slope destructions between the Eocene Limestones (A) and Paleocene Marls (B). The arrow indicating the earth flow of Fig. 9 and 10.

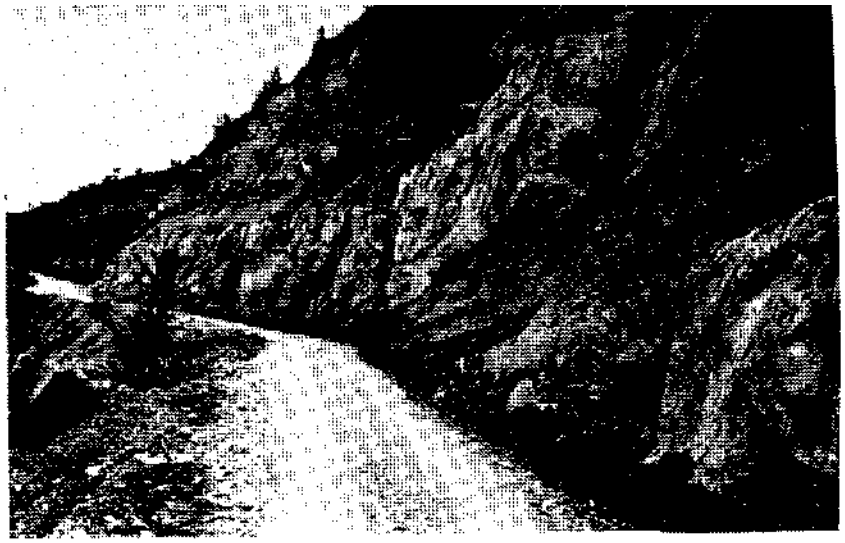

Photo 4 - Photograph of the Eocene limestone-marl intercalated formation. The road reconstructed after the rock avalanche of figure 5.

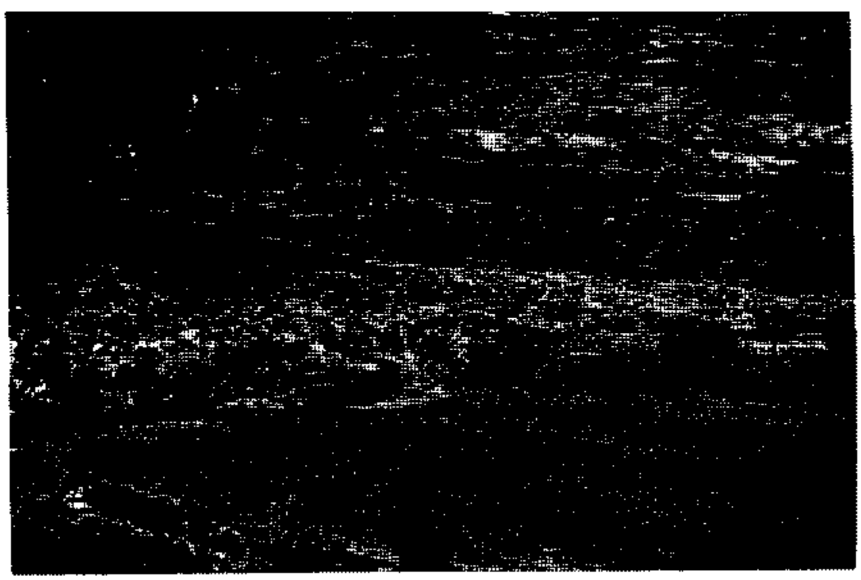

Photo 5 - The rock avalanche detached from the scar in Figure 4.

Photo 6 - Photograph showing the roots of the trees which indicate the creep of soil in the colluvial material over the Paleocene Red Marls.

Photo 7 - Photograph showing the overhanging vegetative cover which indicates that the creeping layer is to a depth of up to the end of the roots over the Paleocene Red Marls.

Photo 8 - Photograph showing the bended tree trunks indicating the existence of creep.

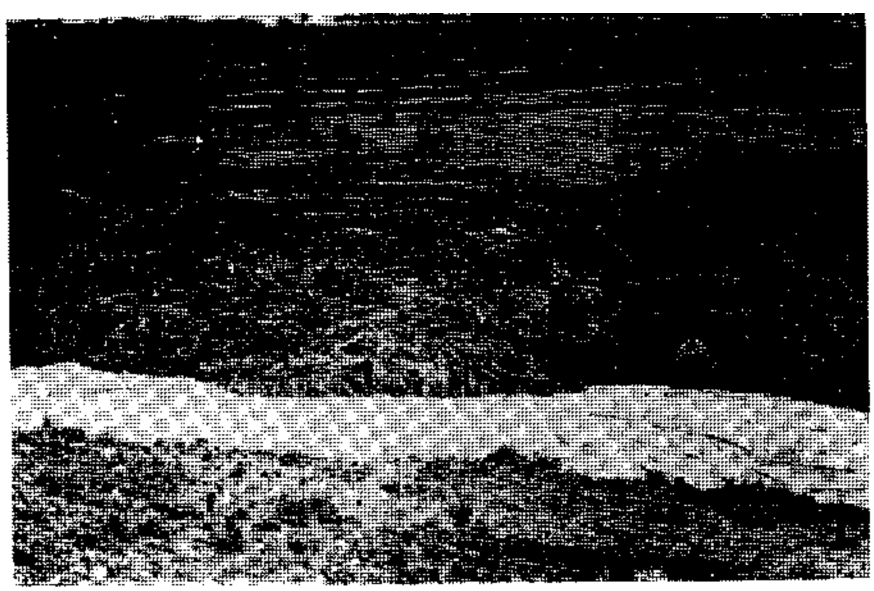

Photo 9 - Double slumping due to overloading and lateral river erosion in the Paleocene Red Marls.

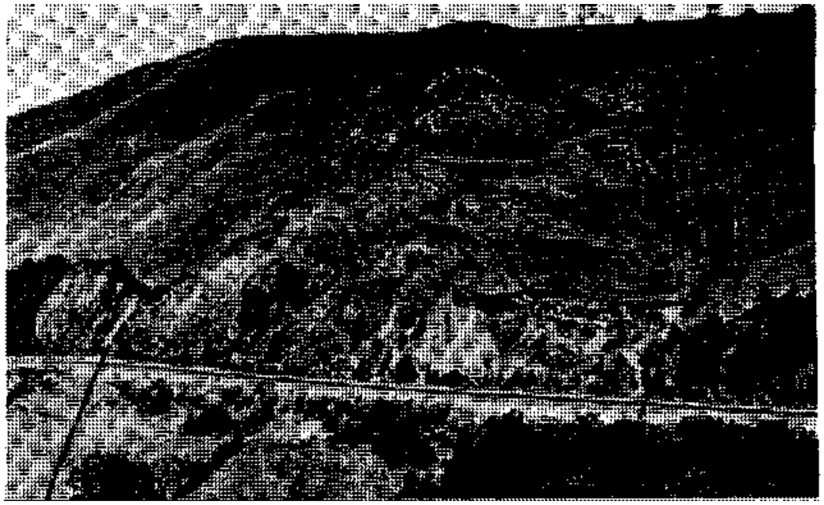

Photo 10 - Photograph showing a superficial slide which tends to be deep-seated rotational slide along the dashed lines.

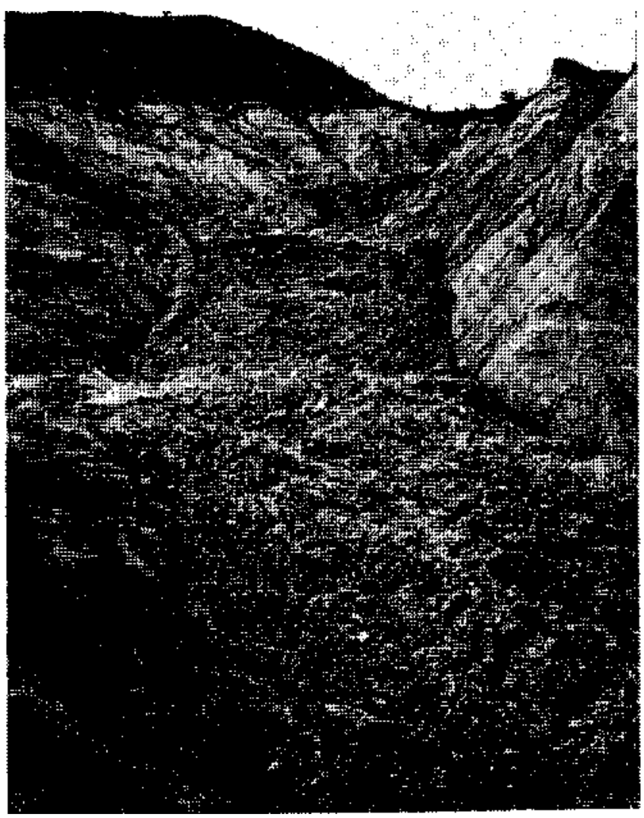

Photo 11 - A slump in the Paleocene Red Marls formation transferred to an earth flow due to retrogressive gulley erosion.

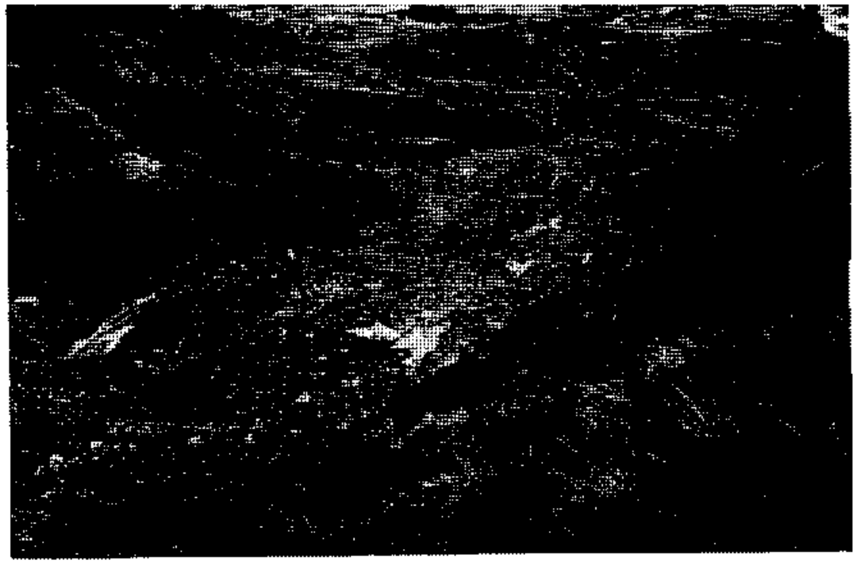

Photo 12 - The lower part of the earth flow in Photo 11.

Photo 13 - Photograph showing the mudflow which resulted from the retransportation of the slide material detached from the scar at the top of the flow.

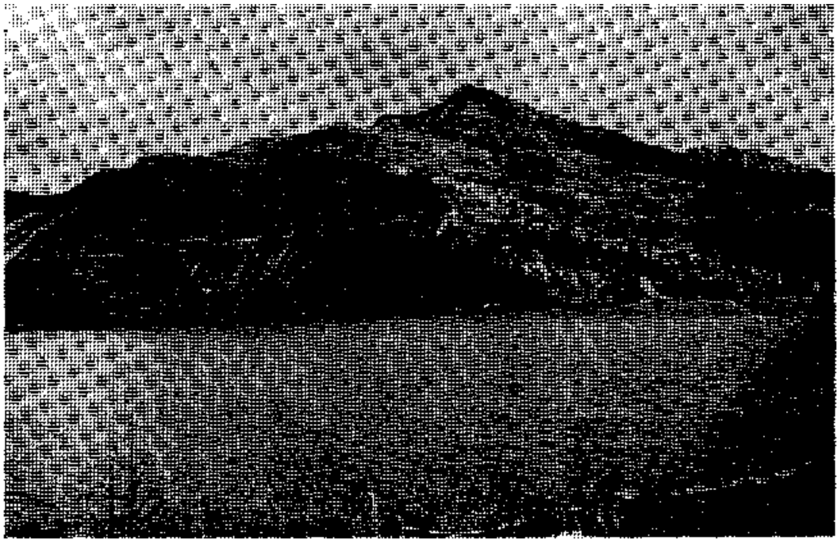

Photo 14 - A slide parallel to bedding plane in the Cretaceous series.

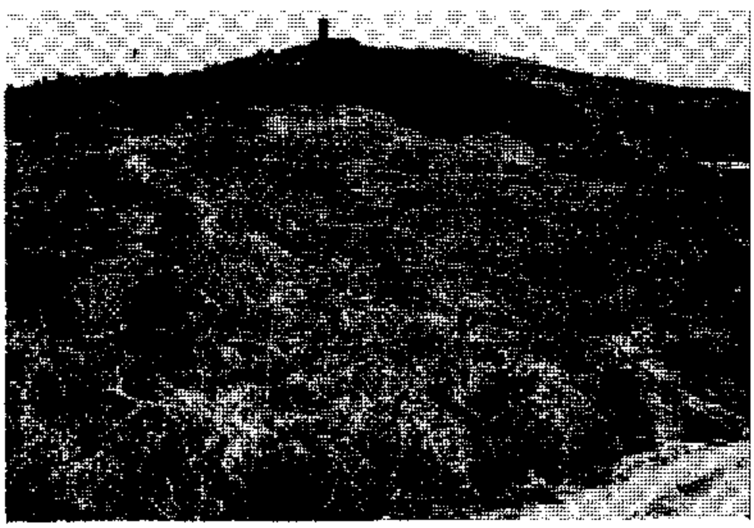

Photo 15 - Photograph showing the Puigcergos slump affecting the Eocene limestone-marl intercalated formation.