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THE STUDY OF STONE TRAILS WITH PAINTED TRACERS ON UNSTABLE SLOPES IN THE SOUTHERN FRENCH ALPS PRELIMINARY RESULTS

Summary: DUMAS B. & RAFFY J., *The study of stone trails with painted tracers on unstable slopes in the Southern French Alps: preliminary results* (IT ISSN 0391-9838, 1993).

An experiment has been carrying out in the Baronnies Mountains at the altitude of 850 m since April 1988, with 6 lines of 100 painted tracers each, on a steep debris slope (21 to 32°) and on medium slope (12 to 20°). Stone trails are present among tufts of grass and small trees which represent the anthropic degradation of the original extensive oak forest. They more or less follow lines of maximum gradient. Some of the stone trails lead down into downcutting gullies in marls. Small steps are created by the tufts of grass which are covered with debris moving down the stone trails. The stone trails show landmark of runoff but back analysis on the painted stones over the past 2 years shows that runoff is not chiefly responsible for the movement of the coarse debris. Sometimes the correlation coefficients reflect positive correlations with the lenght of runoff and the sine of slope angle but there is not a significant correlation coefficient with the reverse of particle size. The processes belonging to what has been called rock creep by SCHUMM (1967) is largely responsible for the distance moved.

Among the possible processes of rock creep responsible for moving the debris along the stone trails in the mountainous climate of the Baronnies, needle ice transport has been eliminated because it has not been noted in the field study. But numerous freeze-thaw cycles a year have involved frost creep as it has been confirmed with the observation of frost-heaving figures. For different reasons one can justify the relative reliability of the back analysis results: the time elapsed after the beginning of the experiment is not sufficient to allow each variable to be on site expressed clearly in the distance moved; the lenght of runoff measured was not realistic because there has been no heavy rainstorms: other variables such as the roughness of the ground surface or the shape of the debris influence the distance moved; lastly animals, which consist in a random variable, move the stones too.

KEYWORDS: Slopes, Stone trails, Frost creep, Painted tracers, French Southern Alps.

Riassunto: DUMAS B. & RAFFY J., *Studio dei solchi dovuti al movimento di pietre con l'ausilio di ciottoli traccianti su pendii instabili delle Alpi Francesi meridionali. Risultati preliminari.* (IT ISSN 0391-9838, 1993).

Dall'Aprile 1988 è in corso un esperimento sui M. Baronnies, alla quota di 850 m, dove sono state posizionate sei linee di 100 ciottoli dipinti ciascuna su due pendii, uno molto acclive (21°-32°) e l'altro a media pendenza (12°-20°). Tra zolle erbose e piccoli alberi che rappresentano i relitti dell'originaria estesa foresta di querce, degradata per cause antropiche, sono presenti solchi dovuti al movimento di pietre. I solchi seguono grosso modo le linee di massima inclinazione. Alcuni confluiscono in solchi di ruscellamento incisi nelle marne del substrato. Presso le zolle erbose che vengono coperte dal detrito trasportato lungo i solchi si formano piccoli gradini. I solchi mostrano forme di ruscellamento, ma l'analisi delle pietre colorate mostra che il ruscellamento non è l'agente principale responsabile della rimozione del detrito grossolano. Talvolta i coefficienti di correlazione riflettono correlazioni positive con lo sviluppo lineare del ruscellamento ed il seno dell'angolo di inclinazione del pendio, ma non vi sono correlazioni positive con l'inverso delle dimensioni del clasti. Il movimento è in gran parte dovuto al processo indicato come *rock creep* da SCHUMM (1967).

Tra i possibili processi di *rock creep* responsabili della mobilizzazione del detrito lungo i solchi nel clima montano dei M. Baronnies, il movimento dovuto a ghiaccio aciculare è stato eliminato perché non è stato osservato nella zona. Numerosi cicli di gelo/disgelo hanno annualmente causato del geliflusso, come confermato da figure di crioturbazione. La relativa affidabilità delle analisi può essere spiegata in diverso modo. Il breve tempo trascorso dall'inizio dell'esperimento non è sufficiente per consentire ad ogni variabile in gioco una precisa espressione del ruolo svolto nella mobilizzazione dei clasti. Lo sviluppo del ruscellamento misurato non è realistico in quanto non si sono verificati rovesci eccezionali. Altre variabili quali l'irregolarità della superficie topografica o la forma del detrito influenzano la distanza percorsa. Infine, gli animali, che costituiscono una variabile casuale, contribuiscono anch'essi a rimobilizzare le pietre.

TERMINI CHIAVE: Esperimenti di campagna, Erosione dei versanti, Scivolamento superficiale in roccia, M. Baronnies, Alpi Francesi.

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The research started in the Southern French Alps (fig. 1) on slopes in the Baronnies Mountains brought about the observation of existing stone trails. The tracks that were studied are at between 800 and 860 m altitude and belong to a standard mountain of Mediterranean climate. They develop, following more or less the lines of the maximum slope gradient.

The stone trails appear either on medium debris slopes (10 to 21°) or on steeper ones (22 to 35°) but not on slopes of less than 10°. The tracks are gathered on deforested

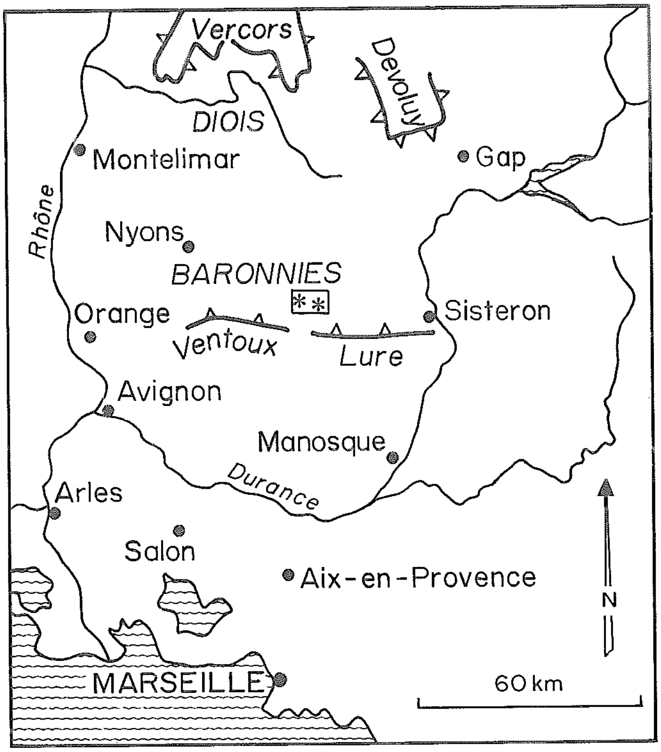


FIG. 1 - Location sketch map of the experiment area.

land which has suffered from soil erosion and gullying due to overgrazing. A low, woody formation dominated by *Genista cinerea* and a large grass plant (*Calamagrostis argentea*) has replaced the climassic association which is an oak *Quercus pubescens* forest.

The stone tracks are for the most part made up of coarse debris a lot of which is produced by winter frost. We have tried to determine which processes actually allow the debris to move. Among the possible transport processes which are able to move coarse debris downward, there include overland flow, rock creep, frost creep and needle ice transport. These processes do not necessarily exclude each other. We must primarily try to recognize the signature of these processes or group of processes in land marks in our field area. Secondly we have to hid out using back analysis what is the significance of each process in the transport of the coarse debris and which transport process is dominant in generating stone trails on the hillslopes.

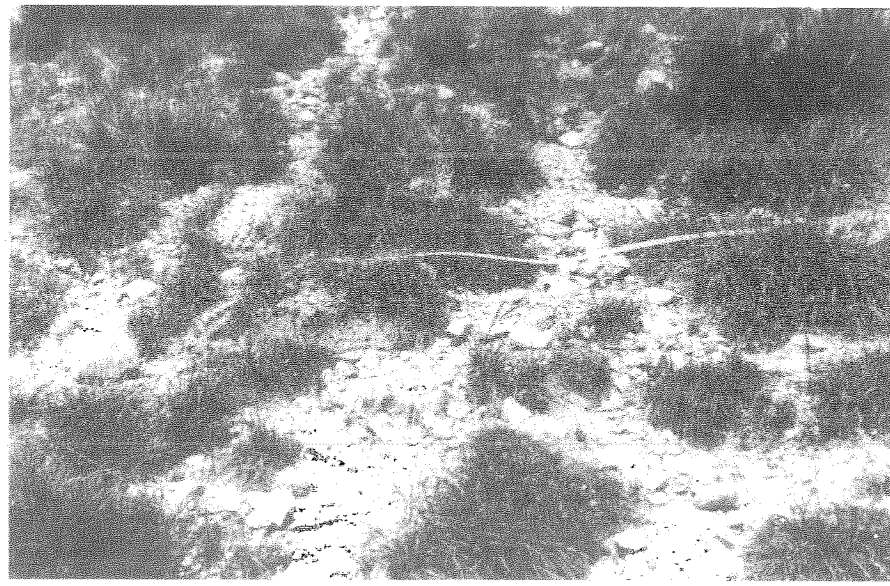
As it is possible that the transport processes or the respective parts of these processes are not similar on medium slopes and on steep slopes, we are going to distinguish the two different types of slopes in the following study. Two separate sites display stone trails, one with gradients between 14 and 17° (860 m high) and the other with gradients between 24 and 32° (837 m high).

The 860 m site (fig. 2) is a concave slope. It is controled by tectonics and lithology which is represented by interbedding marls and limestones. The stone trails do not come down from the crest of the hillslope. They are not perfectly straight line but make some sinuosities for they are obstructed by small terraces (terrassettes in french). These small terraces are caused by tufts of vegetation, particularly grass and mediterranean plants like thyme and lavande which interrupt the downward flow of stones and coarse debris, therefore acting as dams. Thus the tufts full of debris constitute small terraces which are of gentle slope in comparison with the stone trails. Downslope the trails end up surrounded by denser vegetation.

The 837 m site (fig. 4) is the mountain front of a homoclinal scarp. It has been shaped in a straight profile. In the central part of the scarp (fig. 5) the straight upper segment merges into a glacis with a short concavity. The glacis cuts the Cenomanian marls outcropping in the lower segment of the hillslope. On both sides this glacis has been destroyed by gullying.

FIG. 2 - The 860 m site. Deforested concave hillslope. White marls appear in several areas where gullying is developing. In the background there is the original oak forest. The experiment area is in the centre.

FIG. 3 - Stone trails at the 860 m site. Two stone trails move down the slope between vegetation tufts. Sometimes they are obstructed by small terraces.



SURVEYING THE LAND MARKS OF THE TRANSPORT PROCESSES

Are there any land marks of the movement of coarse debris by overland flow along the stone trails and is the climate in the Baronnies Mountains favourable to the creation of a transporting runoff on the slopes? These are the two questions.

We set up a climatic station at the end of 1986. The rainfall diagram (fig. 6) shows an important difference in the 1987 rainfall amount (1211 mm) and in the 1989 one (649 mm). Spring and Autumn have the greatest rainfalls.

Rainfall intensity and landmarks of overland flow:

Two facts permit us to believe that rainstorms can bring about a check on the stone tracks in the 837 m site which is a steep slope. Firstly, 20% of the stone tracks whose general direction falls in with the lines of the maximum gradient slope culminate downward in gullies which dissect the outcropping Cenomanian marls. They seem to represent an erosion stage which precedes the gullying stage. In their lower part, 30% of the stone trails are slightly cut below the straight segment of the hillslope.

The second fact is that after the summer rainstorms we observed landmarks of overland flow paths along some of the stone trails (fig. 8 and 9). These paths were revealed by different granulometrical assemblages. In figure 7 one can see the 2 parts of a transversal cross-section of a stone strail. One stone trail bears cobbles and pebbles while another shows the transport of many debris which go down except some big stones left behind in places. These observations were made twice, once in Spring 1988 after a heavy rain and the second in summer 1990 after rain-

FIG. 4 - The 837 m site: a steep slope. White marls are dissected on the left and on the right. In the centre, the thicker vegetation area corresponds to the root of a glacis with pine trees. Above the glacis, white landmarks represent stone trails.

FIG. 5 - A stone trail at the 837 m site. In the foreground the alignment of boulders is due to a limestone outcrop. Tufts of vegetation involve a slight sinuosity.

storms. All in all, the paths followed by overland flow are only a part of the transversal cross-section of the stone trails; the landmarks do not extend over the whole length of the stone trails; they do not affect all the stone trails and do not appear as scouring the whole width of the trails.

The figure 7 shows that the average time intensity was greatest in the summer of 1887 and 1988, the maximum (44 mm per hour) taking place in summer 1988 during half an hour and the second highest in May 1988 with 30 mm per hour only during 10 minutes. Thus it is the observations made by YAIR & KLEIN (1973) that an intensity threshold equal to 1 mm per 3 minutes, that is 20 mm per hour, must be reached so that runoff would appear on debris slopes. From the opening of our climatic station in the Baronnies Mountains, this threshold was reached 9 times.

Freeze and thaw cycles and frost creep.

The Baronnies Mountains experience winters with numerous frost thaw cycles which may involve downslope movements by frost creep. The frequency diagram of frost days (fig. 10) shows that the number of frost days during 3 winters since 1986 in between 73 and 84. Indeed we often found on site a crumbly texture which ressembles something that has been called nubbins by WASHBURN (1980) and PEREZ (1987), particularly in areas where soil water content is high. According to these two authors the nubbins reflect the effect of frost heaving which generates stone transport. This movements is caused by freeze and thaw cycles of ice in soil.

Needle ice transport.

It is a fact that neither WASHBURN (1980) nor PISSART (1987) distinguished needle ice transport and frost creep. The first author who introduced a difference between frost creep and needle ice transport is BENEDICT (1970). He wrote that frost creep is «the net of downward displacement that occurs when the soil, during a freeze — thaw cycle, expands normal to the surface and settles in more nearly vertical direction». Needle ice is not exactly identified with frost creep because ice is present at the surficial part of the soil with ice columns some centimeters long heaving stones and matrix. It is why needle ice transport is now considered as an extreme case of periglacial creep. Following PEREZ (1987) needle ice can be a very active process transporting stones.

We have had the opportunity to see needle ice activity in certain parts of our study area, in December and January. But we have noted that there were not needle ice along the stone trails while there were really fine examples in other sites of our field area. Nevertheless one cannot exclude a slight occurence of this process.

Rock creep.

The fourth kind of process able to transport the stones is what has been called rock creep by SCHUMM (1967) and WILLIAMS (1974). However it is not really known today what processes exactly are hidden behind this word: transport by alternate wetting and drying processes by simple temperature variations, or by other processes. Rock creep does not leave particular landmarks on the soil surface. Consequently it is possible that this modality has been active but this cannot be confirmed.

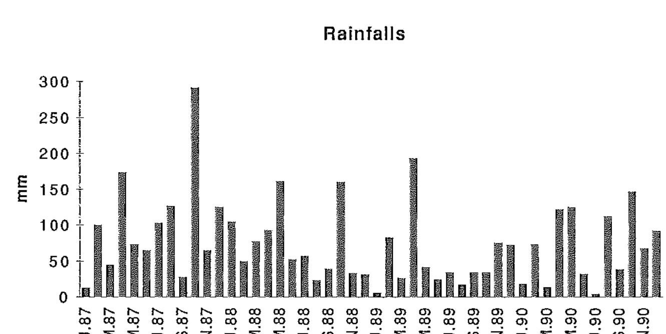


FIG. 6 - Rainfall diagram.

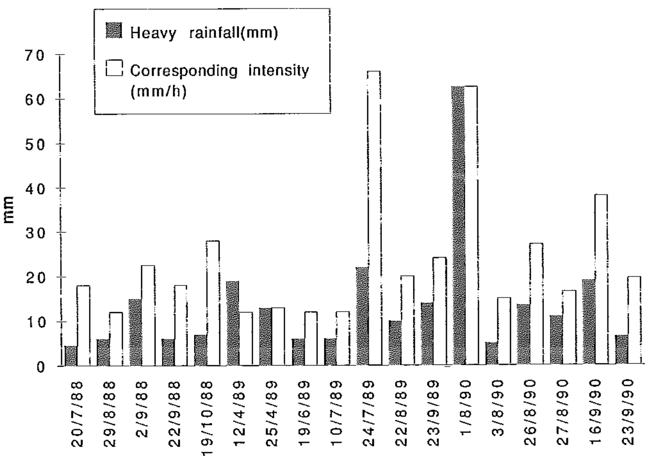


FIG. 7 - Heavy rainfalls and corresponding intensities.

As it not possible to include with the help of field observations (fig. 11) alone, either runoff, frost creep, needle ice and rock creep could be responsible for the movement of coarse debris along stone trails. And therefore we used a tracer method and made a back analysis to understand the distance moved by the tracers.

BACK ANALYSIS: THE DISTANCE MOVED BY THE TRACERS IN PROPORTION TO THEIR PARTICLE SIZE, SLOPE ANGLE AND THE LENGTH OF RUNOFF

Monitoring procedure:

On the slopes we displayed and have followed 6 lines each of 100 painted stones. The lines are perpendicular to the contours. Three lines are set on the 837 m site and 3 on the 860 m one. The particle size corresponds with an intermediate axis larger than 1 cm. The stones were sampled in situ. The painted stones are placed at 10 cm intervals. We measured the displacement of the tracers periodically, in 2 coordinates, one perpendicular and the other parallel to the line. It so happened that some of the tracers were buried and disappeared. In this case, they must be taken out of the back analysis.

Measuring the displacements: the order of magnitude.

The painted stones were lined up from April to September 1988. Table 1 gives the distance moved 2 years and 19 months later. The main results are as follows:

— The average distance moved is greater on the steeper slope (837 m site) than on the medium slope 860 m site); the average distance moved over 2 years of elapsed time was in general twice or three times greater on the 837 m site than on the 860 m site;

— only on the 860 site certain tracers have not moved at all;

— The maximum displacement on the 860 m site is 30 cm for 14 months, on the 837 m site it is 178 cm for 19 months from September 1988 to April 1990, on a 27°3 slope angle; the average displacement on the 837 m site (13.1 cm) was equal to twice the average distance moved (6.5 cm) on a 14°1 slope angle (860 m site).

This last result is in keeping with the order of magnitude of distances moved by rock creep. The annual rates in the Baronnies Mountains on medium slopes (see table 2: between 2.6 and 4.1 cm) and on steep slopes (between 5.5 cm and 9 cm) are similar to those found by SCHUMM (1967) and WILLIAMS (1974), that is to say equal to about 5 cm per year on medium slope. This means that rock creep is probably the predominant cause of transport process along the stone trails. However rock creep cannot account for the largest displacements and other processes must be found. Following the annual rate found by PEREZ (1987) which is equal to about 50 cm per year on a 25° slope angle in the Andes where needle ice is very active, the comparison with the Baronnies does not permit the exclusion

FIG. 8 - Landmarks of overland flow along stone trails. In the axis of the stone trail, overland flow has removed all the debris, except the biggest stones located near the pen, while the whole coarse debris stands on both sides.

TABLE 1 - Distance moved and tracer particle size on different slopes (measured in April 1990, since April 1988*, since september 1988).

Sites	837 m site			860 m site		
Tracer line	Yellow	Blue	Green*	Red	Blue	Yellow*
Slope angle	30° 1	27° 3	26° 5	16° 1	16° 3	14° 3
Distance moved (cm)						
Mean	18	11	13.1	5.3	6.3	6.5
Minimum	0.3	0.2	0.8	0	0.5	0
Maximum	178.2	95.3	169.5	23.5	19	30.3
Annual rate	9	5.5	8.3	2.6	3.2	4.1
Particle size (mm)						
Mean	34.4	29.3	36	30	23.8	22.1
Minimum	13	15	19	12	11	12
Maximum	95	84	114	128	91	52

FIG. 9 - Debris covers on grass tufts. Mixed fine and coarse debris spread over grass. They come from the stone trail. Centimeter scale.

of this process, considering that it is slower here due to less freeze — thaw cycles: form 73 to 84 against 335 in the Perez's study area.

Back analysis: the principles of the method applied in this study

In order to determine which process is dominant in transporting the coarse debris along the stone trails, we asked the 3 following questions:

— 1° If overland flow is responsible for the transport of the debris, then there is a correlation between the displacement of the tracers and three parameters, namely the sine of slope angle, the length of overland flow and the reverse of particle size. The slope angle was measured for each tracer under or near each painted stone and it did not correspond with the average gradient of the hillslope. The length of overland flow was measured on site as the maximum possible runoff all along the trails. It is shorter than the distance from the divide.

— 2° If needle ice transport is responsible, then there is a closer correlation between the displacement and the tangent of the slope than the sine of the slope angle (PEREZ, 1987).

— 3° Finally, if frost creep is responsible, there is a positive correlation with the sine of the slope angle, according to SCHUMM (1967) and WILLIAMS (1974), and there is no correlation with the length of runoff and with the reverse of particle size. Although it does probably exist a correlation law between the displacement by frost creep and slope angle, unfortunately it is not known at present-day.

Results

The linear regressions relate to painted tracers set up on the 2 sites. From the 100 painted stones we selected

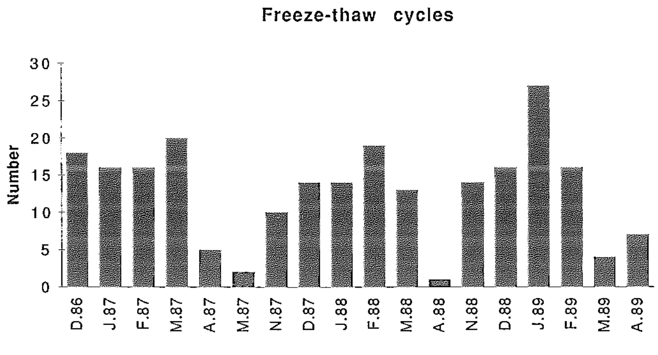


FIG. 10 - Number of frost days during 3 years.

the tracers used on the stone trails as well as those found on the small terraces which sometimes obstruct the trails.

On the 337 m site, which is the steep slope (table 2), the correlation coefficients of the regressions are highly variable from one line to the next. The best correlation is with small terraces as in the case of the blue tracers: the correlation coefficients are 0.54 and 0.235 for the sine of slope angle and the length of runoff respectively. These two variables explain almost 54% of the variance of the displacement ($R^2 = 0.539$). It does not appear to be a general law of hierarchy on the correlation coefficients linking the distance moved with the three variables. The worst correlation links the movement with the tracer size, except as far as the yellow tracers are concerned, whose correlation coefficient - 0.317 testifies reverse correlation, but the sample size is only 21.

The best correlation with stone trails is obtained with the length or runoff (R = 0.408). As for the other lines the best correlation is sometimes with slope angle. The interpretation of this back analysis is that runoff is not responsible for the displacement of the stone except in the case of the yellow tracers, although there is no correlation with the sine of the slope angle (0.056). The sine of the slope angle correlation coefficient is not significant enough to be proof of intervening rock creep (which includes frost creep: see p. 6).

On an average slope angle (the 860 m site), with the stone trails of the yellow tracers (table 3) we have an example of two good positive correlations with the length of runoff (R = 0.827) and the sine of slope angle (R = 0.658). As the correlation coefficients with the length of runoff are very low and no significant in both other lines of this site we must conclude that runoff does not move the tracers along the stone trails. But in the case of the stone trails and the small terraces of the red tracers, there is only a correlation with the slope angle (R = 0.35 and 0.32 respectively). This indicates that rock creep including frost creep is responsible for the movement but it only explains a small part of the variance (11 and 25%).

Is needle ice transport responsible for the movement? We attempted to answer this question by comparing the correlation coefficients with both the sine of slope angle and the tangent (table 4). We used 2 lines from the 837 m site and 1 from the 860 m site. In all three cases the sine

TABLE 2 - Correlation table of the 837 m site with linear regressions.

Line and selected tracers	Sample size	Slope angle	Simple regression: Correlation coefficient R with significant level (p)			Determination Coefficient R^2 (multiple regression)
Variables			Length of runoff	Sine of slope angle	Particle size	
837 Blue stone trails	40	27° 3	0.213 (0.1865)	0.165 (0.31)	0.089 (0.5844)	0.069
837 Green stone trails	72	26° 5	−0.096 (0.4248)	0.042 (0.7279)	0.079 (0.5119)	0.021
837 Yellow stone trails	21	30° 1	0.408 (0.0663)	0.056 (0.8092)	−0.317 (0.1611)	0.244
837 Blue small terraces	15	27° 3	0.235 (0.399)	0.54 (0.0377)	0.098 (0.7283)	0.539
837 Green small terraces	14	26° 5	0.011 (0.9697)	0.36 (0.2056)	0.237 (0.4151)	0.145
837 Yellow small terraces	24	30° 1	0.039 (0.8621)	0.188 (0.4025)	0.298 (0.1785)	0.152

FIG. 11 - Example of tracer movements. Six painted stones seen in black are moved at the 837 m site. Average slope is 28°. The distance moved from the string corresponds to one year and 3 months of elapsed time after the beginning of the experiment. Centimeter scale.

of slope angle gives slightly better correlation coefficients than the tangent. This indicates that in the time elapsed during the experiment needle ice was not significantly responsible for the transport, which is in keeping with the fact that needle ice was neither frequent nor rather long in the stone trails.

We can conclude that a general meaning cannot be given to the back analysis results. Sometimes the rock creep including frost creep seems to be responsible for the transport of the stones. The main difficulty lies in the fact that there are certain important differences in the correlation coefficients for the 3 same variables between the lines. The question now is how to explain these great differences between the lines.

TABLE 3 - Correlation table of the 860 m site with linear regressions.

Line and selected tracers	Sample size	Slope angle	Simple regression: Correlation coefficient R with significant level (p)			Determination Coefficient R^2 (multiple regression)
Variables			Length of runoff	Sine of slope angle	Particle size	
860 Yellow stone trails	50	14° 3	−0.396 (0.0044)	0.316 (0.0293)	0.145 (0.3167)	0.284
860 Red stone trails	40	16° 1	−0.106 (0.5146)	0.351 (0.0262)	−0.23 (0.1525)	0.251
860 Blue stone trails	29	16° 3	0.224 (0.243)	0.245 (0.1998)	0.078 (0.6876)	0.142
860 Yellow small terraces	49	14° 3	−0.129 (0.3764)	0.129 (0.3777)	−0.162 (0.2668)	0.065
860 Red small terraces	29	16° 1	−0.016 (0.9379)	0.32 (0.1035)	−0.105 (0.6031)	0.112
860 Blue small terraces	54	16° 3	0.165 (0.232)	0.335 (0.0132)	0.029 (0.8341)	0.136

TABLE 4 - Comparison between correlation coefficients of the displacements in relation to the tangent and the sine of the angle.

Site and line tracers	Sample size	Slope angle	Correlation coefficient (p = significant level)	
			Tracer slope angle	
			Tan	Sine
837 Green	72	26° 5	0.035 (0.7713)	0.042 (0.7239)
837 Blue	40	27° 3	0.163 (0.3161)	0.165 (0.31)
837 Yellow	21	30° 1	0.046 (0.8434)	0.056 (0.8092)
860 Red	40	16° 1	0.348 (0.278)	0.351 (0.0262)
860 Blue	29	16° 3	0.25 (0.1905)	0.245 (0.1998)
860 Yellow	50	14° 3	0.324 (0.0216)	0.316 (0.0253)

CONCLUSION AND DISCUSSION

The rock creep including frost creep appears to have been mainly responsible for the movement along certain stone trails. Runoff and needle ice were not responsible for the movement during the experiment period. However the back analysis results are not reliable because of the great differences between the lines. Apart from in one case, the explicable part of the variance is too insignificant.

There are 4 reasons which explain why the back analysis results are not reliable:

1°) The results are only preliminary results and the time elapsed after the slopes were set up was too short, and all the more so since there were not any heavy rainstorms.

2°) The variable length of runoff introduced in the calculations is the measurement of the maximum length possible of runoff along the slope. Indeed runoff did not appear all along this length because the tracers had only been in existence for 2 years.

3°) It is necessary to introduce other variables in the back analysis, such as the roughness of the ground surface and the shape of the painted stones because these two variables could interfere in the transport. They probably play quite an important part in the variance.

4°) Animals such as field mice, foxes, rabbits, vipers and even magpies that roam about on the slopes can move the painted stones. They represent a random phenomenon which cannot possibly be taken into account in the back analysis.

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