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## Rates of Surficial Rock Creep on Hillslopes in Western Colorado

Abstract. *The average rate of downslope movement of rock fragments on shale hillslopes is directly proportional to the sine of the slope angle or that component of the gravitational force which acts parallel to the hillslope. The rates of surficial rock creep range from a few millimeters per year on a 3-degree slope to almost 70 millimeters per year on a 40-degree slope, but these rates vary with natural variations in soil characteristics and microclimate, as well as with accidental disturbances.*

Information on rates of landform erosion and evolution has been increasing steadily during recent years; however, it is rare that the data are adequate to establish a statistical relation between the rate at which erosion progresses on hillslopes and the factors determining these rates (*1*). A 7-year record of the downslope creep of rock fragments on eight hillslopes has been obtained as part of a study of the erosion and hydrology of landforms developed on the Mancos shale of Late Cretaceous age in western Colorado (*2, 3*), and these data illustrate the relation that exists between rates of rock creep and hillslope inclination, as well as the great variability that occurs among data collected in this manner.

Thin platy fragments of sandstone weather out of the Mancos shale and occur scattered over the shale hillslopes. One hundred and ten of these rock fragments, which ranged in thickness from 3 to 6 mm, and from 25 to 75 mm in maximum dimension, were marked with a small dot of aluminum paint. These rocks were then placed along transects normal to the hillslope contours, and the position of each rock was established with reference to metal stakes driven into the slopes. Hillslope angles were measured over a 30.5-cm (1-foot) length of slope extending downslope from each marker. The downslope movement of each rock was obtained by repeated measurements of its progressively increasing distance from a reference stake, which remained fixed in bedrock. The positions of the stakes did not change during the study, and therefore the bedrock was stable. The marked rocks were placed on the transects in 1958 and measurements of rock movement were made yearly in the spring and autumn between September 1958 and September 1962. A final measurement was made in September 1965.

The hillslopes on which the rocks were placed are located in two small drainage basins about 8 km northeast of Montrose in western Colorado. These basins drain to the west from a divide which forms the western edge of Bostwick Park (U.S. Geological Survey, Red Rock Canyon, 7½ minutes topographic map).

The Montrose study area has been described in some detail in previous publications (*3*). Annual precipitation at the Montrose (No. 2) weather station is 23.1 cm (9.1 inches). During the 7-year period of investigation 172.7 cm (68 inches) of precipitation fell at this station (*4*). Maximum relief within the drainage basins is about 76 m. The slopes are sparsely vegetated with shadscale, saltbush, and forbs. All hillslopes have a convex summit, and where they are not graded directly to a channel, they have a lower concave segment which is separated from the summit convexity by a straight segment.

The Mancos shale, which underlies all of the hillslopes, is a saline marine shale. Frost action in the weathered shale mantle is the major factor causing downslope creep of the weathered shale lithosol and the rocks. During the winter the surface of the slopes is loosened and heaved by the formation of granular ice crystals in the upper few inches of the lithosol. The loosened surface is subsequently compacted by summer rainbeat. This annual cycle of heaving and compaction is an effective mechanism causing episodic creep of the soil surface (*3*). Some disturbance of the slopes also occurs when sheep move through the area enroute to seasonal pastures.

Of the original 110 rocks placed on the slopes in 1958, 30 could not be located in 1965. Some of these were lost by burial, others were displaced from the profile by the trampling of livestock, humans, or other animals, and some undoubtedly were lost because their identifying paint mark was obliterated. Of the remaining 80 rocks, eight were eliminated from this analysis either because they showed an unusually large amount of movement during one measurement period, which suggested a disturbance other than that caused by the natural processes that generate creep, or because they showed a negative or upslope movement, which was considered adequate proof of disturbance.

The average rates of rock creep (velocity in millimeters per year), as measured for the 7-year period from September 1958 to September 1965, for each of the remaining 72 rocks are plotted against the sine of the angle of slope inclination in Fig. 1.

The rate of rock creep is directly proportional to the sine of hillslope inclination ($s$): velocity $= 102\ s - 0.7$, or essentially velocity $= 100\ s$. The coefficient of correlation is .77, indicating that 59 percent of the total variation is explained by slope inclination alone. The coefficient of correlation is significant at well above the .001 level. The sine of the hillslope angle is used because it is proportional to that part of the total gravitational force which acts along the surface of the slope (*5*).

Earlier I had concluded that the relation between slope angle and marker movement was exponential (*3*). That relation was derived from an analysis of the data obtained during the period 1958 to 1961. I now consider it incorrect, because I calculated the relation by averaging the rates of movement of various types of markers (painted rock fragments, metal washers, and wooden blocks) which behaved differently. Raindrop impact accelerated the rate of movement of the wooden blocks, whereas many of the washers were buried and therefore moved more slowly than the rocks. No attempt was made at that time to consider each measurement separately, as the objective then was to demonstrate the episodic or seasonal rates of movement (*3*).

The plotted points of Fig. 1 scatter widely about the regression line, but when the data are averaged for 0.10 increments of the sine of hillslope inclination, these points fall near the regression line. When only these average values are considered, hillslope inclination explains 99 percent of the variation of the rate of rock creep. However, the scatter is not surprising in view of the accidents that can befall a given marker as it moves down the slope. For example, its movement can be retarded by the growth of annual vegetation or by being tipped into the desiccation cracks, which are common on the barren slopes. When trapped in the soil cracks, the markers assume the rate of creep of the soil; whereas the markers which rest on the surface move individually in direct response to surface heaving and compaction. Therefore, although the rate of marker movement reflects the movement of the soil, the surface markers undoubtedly move more rapidly than the soil itself.

Notes were taken on circumstances which could have affected the movement of each marker, but there are no consistent relations between the nearness of vegetation or the orientation and the size of each marker on marker movement. All markers were located on slopes which faced to the south; thus a significant microclimatic variable was eliminated. The variability of the rates of rock creep, therefore, was assumed to be the result of variations in soil properties and microclimate at each marker location. For example, if at any given location on the hillslopes the soil was more susceptible to swelling, or if that part of the hillslope remained moister and was, as a result, more susceptible to frost action, then a marker at that location should move more rapidly than its neighbors.

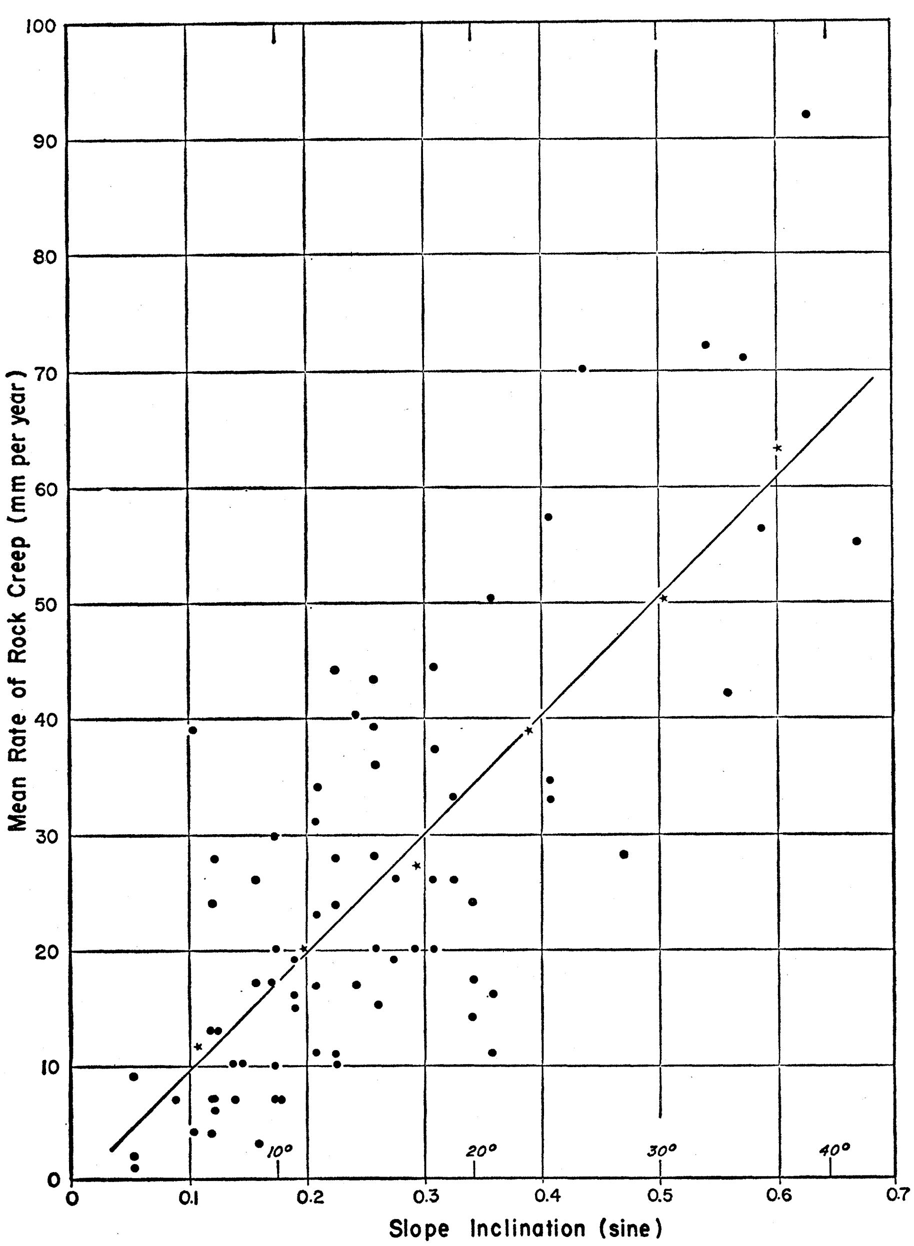


Fig. 1. Relation between the sine of slope inclination and the rate of movement of rock fragments on Mancos shale hillslopes in millimeters per year. Average rates of rock movement for 0.10 increments of the sine of slope inclination are shown as stars. Standard error is 11.8 mm. Correlation coefficient is .77.

To summarize, the measured rates of surficial rock creep on Mancos shale hillslopes are directly proportional to the component of gravitational force acting parallel to the hillslope. However, on slopes of identical inclination, a great range in the rate of movement occurs. This must be expected in any investigation of mass movement under natural conditions because of the variability of soil characteristics and microclimate, as well as the several accidental factors that can influence the rate of downslope movement. Perhaps this variability will always be greatest on poorly vegetated hillslopes; nevertheless, the scatter of the data indicate that if studies of rates of erosional processes are to be fruitful, not only must a large sample be obtained but also a large range of the independent variable must be included in the sample. For example, if only ten measurements of rock creep were obtained or if the markers were placed on slopes having only a 10-degree range in inclination, it is probable that no significant trend could be established from the data plotted in Fig. 1.

Finally, these rates of surficial rock creep, when compared with measurements of mass movement phenomena made elsewhere, indicate that the rates of rock creep occurring on the Mancos shale hillslopes in a region of low rainfall are more rapid than the very slow rates of soil creep measured in humid regions, but they are less rapid than the rates of talus creep and solifluction measured in the cold high latitudes (*5*).

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## Mouse Immunoglobulin Allotypes: Detection with Rabbit Antiserums

Abstract. *An antiserum with allotypic specificity for mouse $\gamma_{2a}$-globulins was prepared in a rabbit by injection of 7S $\gamma_2$-globulin of $C_{57}BL/6$ mice. The antibody reacted with an isoantigen in the 7S $\gamma_2$-globulins of normal serum of mouse strains belonging to the Ig-1$^b$ allotype class ($C_{57}BL/6$, $C_{57}BL/10$, and SJL strains). No precipitin reaction was observed with serum from 18 other inbred mice strains representing other Ig-1 allotype classes.*

Mouse immunoglobulin allotypes were first described by Kelus and Moor-Jankowski (*1*). Serums of Balb/c mice injected into $C_{57}BL$ mice induced an antibody response specific for a Balb/c globulin. Others (*2–5*) have approached the problem similarly, using various combinations of mouse donors and recipients. The mouse immunoglobulin allotype is a suitable model for study because: (i) a large number of inbred strains are available, and (ii) the protein containing the isoantigen is relatively easy to isolate. However, the mouse is not a convenient animal for preparing antiserums. I now describe a rabbit antibody with an allotypic specificity for an isoantigen of the $MuA_2$ (*2*) [$Asa^2$ (*4*), Ig-1$^b$ (*5*)] group.

A single New Zealand white rabbit was injected subcutaneously on day 0 and day 7 with a 7*S* $\gamma_2$-globulin preparation (*6*) obtained by the Pevikon method of block electrophoresis (*7*) of normal $C_{57}BL/6$ serum. The most cathodal globulin fraction was emulsified in Freund's adjuvant (Difco) containing 8 mg of *Mycobacterium tuberculosis* per milliliter. Rabbit serum obtained on day 31 was examined by agar diffusion techniques (*8*). This antiserum produced two distinct 7*S* $\gamma_2$ precipitin lines on the immunoelectrophoresis plate in the reaction with $C_{57}BL/6$ serum, but only one precipitin line when CBA serum was used as antigen (Fig. 1, trough *b*). The following technique was used to evaluate the relation of CBA serum to the aforesaid two precipitin lines of 7*S* $\gamma_2$ seen with $C_{57}BL/6$ antigen. After electrophoresis of the $C_{57}BL/6$ serum, coincident with charging the troughs with antibody, small wells were made at appropriate sites and filled with CBA serum. The outer precipitin line was deviated by the CBA serum, but the inner line was not affected (Fig. 1, trough *d*). Serums from 19 other inbred strains (Jackson Memorial Laboratory, Bar Harbor, Maine) were similarly evaluated and only $C_{57}BL/6$, $C_{57}BL/10$, and SJL strains deviated the inner line whereas those from A/J, A/HeJ, AKR/J, DBA/1J, DBA/2J, $C_{57}BR/cd$, $C_{58}/J$, $C_{57}L/J$, $C_3H/HeJ$, $C_3HeB/FeJ$, CE/J, MA/J, RF/J, ST/J, SWR/J, 129/J, Balb/c, and CBA affected the outer line exclusively. Similarly two myeloma proteins (LPC-1 and MPC-31) (*9*) obtained from Balb/c mice representing respectively, the 7*S* $\gamma_{2a}$- and 7*S* $\gamma_{2b}$-immunoglobulin subclasses (*10*) did not deviate the inner line. Both of these precipitin lines seen on immunoelectrophoresis represent immunoglobulins, because specific binding of radioactive antigen was observed by autoradiography (Fig. 2).

Two milliliters of the rabbit antiserum to 7*S* $\gamma_2$-globulin of $C_{57}BL/6$ mice were absorbed successively with 0.05-ml portions of CBA serum (40 : 1 ratio). After incubation overnight at 4°C, the resulting precipitate was removed by centrifugation, and 0.25 ml of supernatant was saved for testing prior to the addition of another 0.05 ml of CBA serum. A control antiserum was treated in a similar fashion except that saline was added. After the second absorption with CBA serum, the mixture of antiserum and CBA serum contained excess of antigen common to the CBA 7*S* $\gamma_2$-globulins (Fig. 3, top wells). However, the antiserum, even after three more absorptions, still formed a precipitin line with $C_{57}BL/6$ serums (Fig. 3, bottom wells). Figure 1 (troughs *a* and *c*) shows antiserum absorbed five times with CBA compared, on immunoelectrophoresis, with control antiserum (Fig. 1, troughs *b* and *d*).

The excess CBA serum in the absorbed antiserum forms a precipitin line with the control antiserum. This five-times-CBA-absorbed antiserum was tested by agar diffusion against the 21 serum samples from the inbred mice and the two myeloma proteins. A precipitin reaction was observed only with $C_{57}BL/6$, $C_{57}BL/10$, and SJL inbred serums, and these precipitin lines fused in a reaction of identity (*11*). A

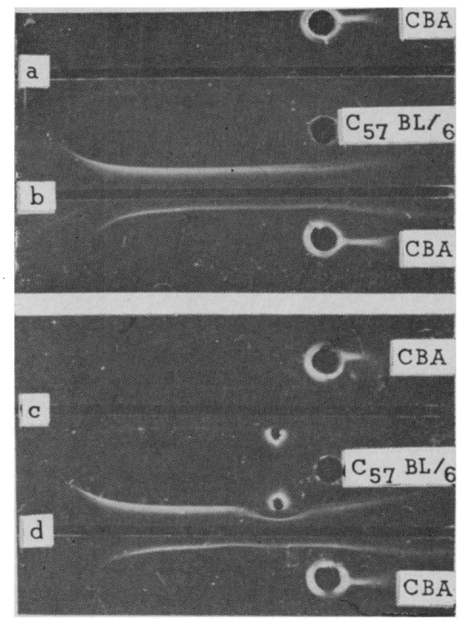


Fig. 1. Immunoelectrophoretic patterns of CBA and $C_{57}BL/6$ serums with rabbit antiserum to $C_{57}BL/6$ 7*S* $\gamma_2$-globulin absorbed with CBA serum and saline. Addition of CBA serum to the small wells shows that the external line contains common CBA antigens, whereas the internal line does not. Troughs *a* and *c* contain rabbit antibody to $C_{57}BL/6$ 7*S* $\gamma_2$ absorbed five times with CBA. Troughs *b* and *d* contain rabbit antibody to $C_{57}BL/6$ 7*S* $\gamma_2$ that had been absorbed five times with saline.

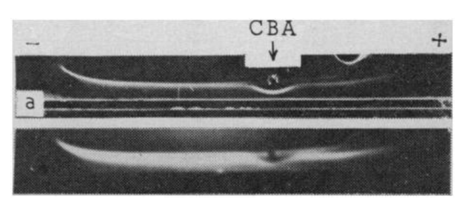


Fig. 2. Immunoelectrophoresis plate (top) and respective hen egg albumin (HEA) $I^{131}$ autoradiograph (bottom) of SJL serum containing antibody to HEA. Antigen-binding capacity can be seen in both precipitin lines. Autoradiography as follows: the developed immunoelectrophoresis slide was washed for 24 hours in saline and photographed; the troughs were then charged with HEA $I^{131}$. After 24 hours, the slide was washed with repeated changes of saline for 3 days, dried, stained, and affixed to Kodak projection slide plates for 1 week.