Morphological, Sedimentological, and Rheological Study of Debris Flow and Hyperconcentrated Flow Deposits on Index Creek Northwest, Wyoming

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Introduction

Index Creek is located in Shoshone National Forest, in Wyoming just south of Colter Pass on the Beartooth Highway. The creek's drainage lies in the small and steep basin between the glacially carved Pilot and Index Peaks. The creek originates in the deeply eroded Eocene andesitic volcanic breccia of the Absoraka Volcanic Supergroup and works its way across exposures of Cambrian sediments and Pleistocene morainal deposits into uplifted glacially-scoured granitic rocks. Here Index Creek converges with the Clarks Fork of the Yellowstone River. Also exposed along the creek bed, particularly in the cutbanks, are poorly sorted matrix- to clast-supported alluvial deposits. Nine of these deposits are exposed well enough to allow detailed study.

Morphological, sedimentological, and rheological work has been done on similar deposits around the world in an effort to determine their origins. Generally, the deposits come from water floods, hyperconcentrated flows, and debris flows. The difficulty lies in determining which of these processes, which are really just contrived boundaries within a continuum of sediment-water mixtures, is responsible for which deposits. Morphologically, water flood and hyperconcentrated flow deposits are very similar, both forming bars, fans, sheets, and splays (Costa, 1987). Debris flows on the other hand form lateral levees and steep lobate snouts making their deposits easier to distinguish (Johnson, 1970). Deposits of water floods and hyperconcentrated flows also have similar sedimentological characteristics; both are clast-supported and contain a wide range of particle sizes. However, hyperconcentrated flow deposits are more poorly sorted, have less well developed stratification and imbrication, and may have reverse-graded subunits (Costa, 1987). Debris flow deposits are matrix-supported, have no stratification, show weak to non-existant imbrication, are even more poorly sorted than the waterlain deposits, and may contain light-weight organic material that would have floated away in a water flood or hyperconcentrated flow (Costa, 1984).

The flow mechanics of these three different flow types are directly responsible for the differences in their deposits. In water floods and hyperconcentrated flows the sediment is a distinct phase from the water and is supported and transported mainly by turbulence. Hyperconcentrated flows differ only in that they contain more sediment, which thus adds buoyancy and dispersive forces as support mechanisms (Costa 1987). During debris flows the entire mass, water and debris, moves as a whole and the entire mass stops when the internal friction is exceeded by the shear strength of the flow (Costa, 1984).

The purpose of this study is to classify the nine Index Creek deposits using properties like those described above, to calculate some of the flow properties, and to determine the frequency of the flows using stratigraphic and dendrochronological data. In addition, this study should be helpful in determining the effectiveness of existing classification techniques.

Field and Laboratory Methods

The field work for this study entailed detailed description of the deposits, data collection, and sampling for supplemental work in the lab. The morphology of the deposits and the imbrication, stratification, clast orientation, fabric, and stratigraphic relations of the deposits were noted in the field descriptions. In addition, pebble and grain size counts were performed; measurements of bed thickness, maximum clast size, and slopes were taken; and samples of fine and coarse-grained portions of the deposits were collected. Also, over fifty trees were cored for tree-ring dating.

Lab work was conducted to supplement and help interpret field data. Grain size analyses of the coarse and fine portions of the deposits were used to describe sorting and to develop a CM diagram (coarsest one percent against median grain size). These were used in conjunction with the field descriptions to determine whether deposits are of hyperconcentrated flow or debris flow origin. Matrix samples and measurements of slope, bed thickness, and largest clast size were used in calculating the density and shear strength of certain flows according to the techniques of Johnson (1984). The tree cores were counted and analyzed and the ages were used in conjunction with the stratigraphic data to provide a rough estimate of the frequency of the hyperconcentrated and debris flow events.

Results

The deposits in the study area consist primarily of greenish-gray diamicton, gray diamicton, brown diamicton, and darker- colored stratified gravel.

Although morphology was not helpful in determining the origin of the greenish-gray diamicton, sedimentology was. These deposits have no stratification, show no apparent clast orientation, and are very poorly sorted. The sorting, expressed in terms of inclusive graphic deviation, ranges between 1.9 and 3.5 phi for these deposits which is very similar to the values for debris flows described by Scott (1971). They consist of a fine-grained clayey matrix containing clasts ranging in intermediate diameter from 0.8 up to 80 centimeters. The clasts are dispersed throughout this matrix-supported deposit with no apparent concentrations in either the upper or lower portions. Although these deposits are much too coarse to plot in Figure 1 within the mudflow envelope as defined by Bull (1972), they do plot to the left of the better sorted fluvial sediments that cluster near the C=M line. Taking into account the CM diagram and the sedimentological characteristics these deposits are considered to have been formed by debris flows.

Morphological and sedimentary characteristics were helpful in determining the origin of the gray diamicton. This deposit consists of portions exposed in two areas. One is along the main channel, along the southern channel, and along the west side of the Clarks Fork river. The other exposure area lies against the granite cliffs on the east side of the river. Just upstream of this is a wide spot in the river containing standing drown trees suggesting that this deposit once dammed the river. For it to have been able to damn the river it must have come from a source much more viscous than waterfloods or hyperconcentrated flows. The sedimentology of this deposit also suggests a debris flow origin. It has no stratification, no apparent clast orientation, very poor sorting (3.4 phi, which is within the range of values in Scott, 1971), and clast sizes ranging from 0.8 to 76cm dispersed throughout this matrix-supported deposit. This deposit also plots to the left of the better sorted sediments near the C=M line in Figure 1.

The brown diamicton deposits are also considered to be of debris flow origin. These deposits have distinct levee morphologies, in which the sediment at the side of the channel extends higher than the ground surface on the overbank side. Like the previously described deposits these have no stratification and no apparent clast orientation. They are extremely poorly sorted with values of 4.1 and 4.2 phi and have clast sizes ranging from 0.8 to 89 centimeters. The deposits are matrix-supported to clast-supported and plot within the same range as the previously described deposits on the CM diagram.

The darker-colored stratified gravel has a very different character than the diamicton. These deposits are found along cutbanks and as mid-channel bars. They have weak stratification, an open-framework clast-supported structure, and clasts oriented with long-axes parallel to the layering. One of these deposits plots farther to the right and closer to the C=M line than the previuosly described deposits on the CM diagram, but one of them plots within the same range as the other deposits. Also, these deposits are also extremely poorly sorted with values of 2.5 and 2.4 phi, well within Scott's range for debris flows and higher than some of the previously described deposits. However, their field characteristics are distinctly not those of a debris flow deposit. Therefore they are considered to be of hyperconcentrated flow origin and it seems as though sorting and the CM diagram may not always be helpful in distinguishing between deposits of debris flow and hyperconcentrated flow origin in this drainage basin.

Only two of the deposits are sufficiently exposed to make the measurements necessary to calculate flow properties. According to the technique of Johnson (1984), the density of the reconstituted debris of both the gray moderately well-lithified deposit and one of the brown poorly-lithified deposits were calculated and found to be 2.08g/cm^3 and 2.13g/cm^3 respectively. The shear strength of each deposit was then calculated using both the unusually large clast and critical thickness techniques (Johnson, 1984). The shear strength of the gray deposit was found to be 6,310dn/cm^2 according to clast size and 35,468dn/cm^2 according to critical thickness. The brown deposit's shear strength was calculated at 9,072dn/cm^2 using the clast size and 18,724dn/cm^2 using the critical thickness. The critical thickness technique is to be used with the lateral deposits of debris flows that overtopped the channel and then spread out. Neither of the sampled deposits fit this description. Therefore, the critical thickness technique is not appropriate in this case and the values are considered overestimates. The values obtained using the unusually large clast size technique are considered better estimates.

Only four deposits had a sufficient number of trees obviously growing on their top surfaces to be dated by dendrochronology. Two of these deposits, it turns out, had trees with ages too close to the oldest of the control trees (trees far enough away from the channel not to be affected by debris flows) to obtain anything other than the very minimum of ages. These are the two brown deposits which have similar field characteristics, DBa and DBc. They have trees growing on their surfaces with ages of 312 and 284 years old, whereas the control trees have ages of 333 years old and less. Also, one of the greenish- gray deposits had a 228 year old tree growing on its surface. Although this age seems to be quite younger than the oldest of the control trees, one cannot be certain that the tree is one of the original colonizers and so this age is also a very minimum one. However, the gray debris flow that crossed the Clarks Fork river was dated at

However, this calculated value is not truly comparable to measurements taken in the non-tor areas because the roadcuts used to examine the non-tor interval provide only a two-dimensional view of the rock.

Given the open ground of the Beartooth Plateau and the lack of obstruction to views on the summit, finding locations was not difficult and, given the desired level of accuracy of the locations of the tors, almost all of them were located using triangulation in coordination with a topographic map.

The outer circumference of each tor was mapped using a forty-meter tape measure and a Brunton compass to measure a series of rays that inscribed the individual tor. These rays were later re-plotted on graph paper with a scale of one meter to one centimeter. The interior area of the figure was then calculated and converted to establish the area covered by the tor.

It appeared in the field as if lithology might exert some control on the fracture spacing in the rock, so samples were collected from each tor in order to study the thin-section petrography.

Data Analysis and Results

Statistical analysis of the field data was performed using Microsoft Excel version 5.0a and the program nodule "stereo" of the Rockware program suite, version 2.1. The average fracture spacing of all lithologies in a tor is 47.7cm. The standard deviation of the mean of the population is 48.4cm. The average fracture spacing in a non-tor area is 12.4cm with a standard deviation of the population of 13.0cm. The correlation coefficient between the average horizontal fracture spacing of a tor and the size of a tor is -0.06. The correlation value between the average horizontal fracture spacing of a tor multiplied by the average vertical fracture spacing of that tor and the size of that tor is -0.12. A Student's *t*-test performed on the fracture spacings between the tors and the non-tor areas yields a T-value of 21.576 versus a *t*-critical value of 2.581 for an expected variance of zero and an α=.01, giving a $P(T<=t)$=1.6E-84. Figure 1.a shows the percent frequency distributions of spacings between joints in tors and non-tor areas, and Figure 1.b shows the same percent frequency distribution over the range of zero to fifty centimeter spacings. Table 1 summarizes the major statistical values for the daughter population sampled during the field work.

Interpretations

A simple comparison of the two values above calculated for the average fracture spacings in tor and non-tor areas shows that they are significantly different. However, both are suspect due to the high standard deviation of both the population and of individual measurements. Nonetheless, if we look at the confidence interval of the mean rather than the standard deviation, the numbers are much more reasonable. Due to the high number of samples drawn from the daughter population of tor and non-tor spacings, we can say with a 99% confidence interval (α=.01) that the mean of the parent population of tor fracture spacings lies between 43.4975 cm and 51.9088 cm, whereas the mean of the parent population of fracture spacings in the non-tor area is 99% likely to fall within the range of 11.5261 cm and 13.2564 cm.

To explain the results from the Student's *t*-test above, barring the one chance in one hundred that the measurements taken in the field mark an "unusual coincidence", if we were to expect no difference in the average fracture spacing between tors and non-tor areas, we would have one chance in $6.23*10^{83}$ chances to explain the variance between the two as a result of random error. The results of the Student's *t*-test clearly show that the samples of the daughter populations drawn during the field work originated in two distinct parent populations. This implies that we can draw a discrete boundary between the spacings in a tor and the spacings in a non-tor area. While this does not necessarily imply that tors are the sole result of the structural geology of the regolith, it does reaffirm the assumption that the jointing in tors is more widely spaced than the jointing in non-tor areas.

The negative correlation between the size of a tor and the vertical-horizontal areal fracture density or the vertical-horizontal-horizontal cubic fracture density implies that there is actually an inverse relation between the size of a tor and its squared or cubed fracture spacings. This is in direct contrast to the results of the comparison of the averages of spacings in tor and non-tor areas. It may be that the precise boundaries of a tor are determined by a

Table 1

Deposit	Type of flow	Sorting	Shear strength	Age (minimum)
DB1 greenish- gray diamictite	debris flow	1.9 phi		236- 238 years old
DB2 greenish- gray diamictite	debris flow	3.3 phi- 3.5 phi	?	
DB4 greenish- gray diamictite	debris flow	2.2 phi		?
DB5 greenish- gray diamictite	debris flow	2.7 phi		
DB4 gray diamictite	debris flow	3.4 phi	6,310dn/cm2	131- 133 years old
DBa brown diamictite	debris flow	4.1 phi	9,072dn/cm2	292- 294 years old
DBc brown diamictite	debris flow	4.2 phi		320- 322 tears old
DT1 stratified gravels	hyperconcentrated flow	2.5 phi	?	?
DT2 stratified gravels	hyperconcentrated flow	2.4 phi		

References

Bull, W.B. 1972. Recognition of alluvial fan deposits in the stratigraphic record. In: Rigby, J.K. and Hamblin, W.K. (Eds.), Recognition of Ancient Sedimentary Environments. Society of Economic Paleontologists and Mineralogists, Special Publication 16, p.63-83.

Costa, J.E. 1984. Physical geomorphology of debris flows. In: Costa, J.E. and Fleisher, P.J. (Eds.), Developments and Applications in Geomorphology. Springer- Verlag, New York, p.268-312,

Costa, J.E. 1987. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R. (Ed.), Flood Geomorphology. Wiley & Sons, New York, p.113-122.

Johnson, A.M. 1970. Physical Processes in Geology. Freeman and Cooper, San Francisco, p.577.

Johnson, A.M. 1984. Debris flow. In: Brunsden, D. and Prior, D.B. (Eds.), Slope Instability, Wiley- Interscience Publication, Chichester, p.257-362.

Kochel, R.C. and Johnson, R.A. 1984. Geomorphologhy and sedimentology of humid- temperate alluvial fans, central Virginia. In: Koster, E.H. and Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary, p.109-122.

Meyer, G. A. Depatement of Geology, Middlebury College, Middlebury, Vermont, 05753 Personal Communication, 1994.

Scott, K.M. 1971. Origin and sedimentology of 1969 debris flows near Glendora, California. U.S. Geological Survey Proffesional Paper 750-C: C242-247.