Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
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Denudation of the Piceance Creek basin, Colorado

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ABSTRACT An analysis of hydrological and geomorphological data collected in the Piceance Creek basin provides detailed information concerning the transport of dissolved solids and suspended sediment in seven small semiarid drainage basins. Chemical weathering within the zone of shallow groundwater circulation contributes more than 13 400 t $year^{-1}$ (46%) of the mean annual dissolved solids load at the mouth of Piceance Creek. Measured suspended sediment yields are very small (2.35-35.6 t $km^{-2}year^{-1}$) compared to most semiarid drainage basins. Nevertheless, measured hillslope erosion rates are locally quite large, up to ∿4000 t $km^{-2}year^{-1}$. Repeated profile surveys of selected hillslopes and ephemeral channels show that large quantities of sediment are being deposited in some areas. Compared to most semiarid drainage basins, a large percentage (36%) of the total denudation is removed from the basin as dissolved load. Rapid dissolution of carbonate cement in the near-surface rock material and deposition of a large quantity of sediment within and adjacent to ephemeral tributaries appear to account for this anomalous condition.

Erosion chimique du bassin du ruisseau Piceance, Colorado

RESUME Une analyse des mesures hydrologiques et géomorphologiques faites dans le bassin du ruisseau Piceance fournit des informations détaillées sur le transport des solides dissous et des sédiments en suspension dans sept petits systèmes d'écoulement d'une région semi-aride. L'altération chimique dans la zone de circulation superficielle des eaux souterraines contribue pour plus de 13 400 t an^{-1}, soit 46%, à la moyenne annuelle des matières solides dissoutes, déposées à l'embouchure du ruisseau Piceance. Les quantités mesurées de sédiments en suspension sont très faibles, de l'ordre de 2.35 à 35.6 t km^2an^{-1}, lorsqu'on les compare aux mesures faites dans la plupart des systèmes d'écoulement des régions semi-arides. Toutefois les taux d'érosion observés sur les flancs de coteau sont localement considérables, de l'ordre de 4000 t km^2an^{-1}. De nombreux relevés de profil faits sur des flancs de coteau choisis comme témoins et dans les lits des cours d'eau indiquent que de grandes quantités de matières sédimentaires sont déposées dans certaines régions. Comparé à la plupart des systèmes d'écoulement de régions semi-arides, le bassin de la Piceance revèle qu'un grand pourcentage, 36%, des pertes totales sont transportées en dehors du basin en tant que matière dissoute. La dissolution rapide du ciment de carbonate contenu dans les matériaux rocheux localises près de la surface du sol et le dépot de grandes quantités de sédiments dans les tributaires temporaires et dans les régions qui leur sont adjacentes, paraissent expliquer ces conditions anormales.

INTRODUCTION

The Piceance Creek drainage basin is located in northwestern Colorado, along the western slope of the Rocky Mountains (Fig.1). The hydrological characteristics of this basin have been studied intensively during the past decade as a result of proposed development of underlying rich oil shale deposits, estimated at 400 billion t. Piceance Creek drains approximately 1632 km^2 and occupies approximately 70% of a structural basin known by the same name. As used in this paper, the Piceance Creek basin will refer to the drainage basin.

The Uinta Formation of Eocene age is the uppermost bedrock unit and underlies nearly the entire drainage area (Donnell, 1961). The formation consists of primarily calcareous sandstone with some shale. The average thickness is 250 m. Underlying the Uinta Formation is

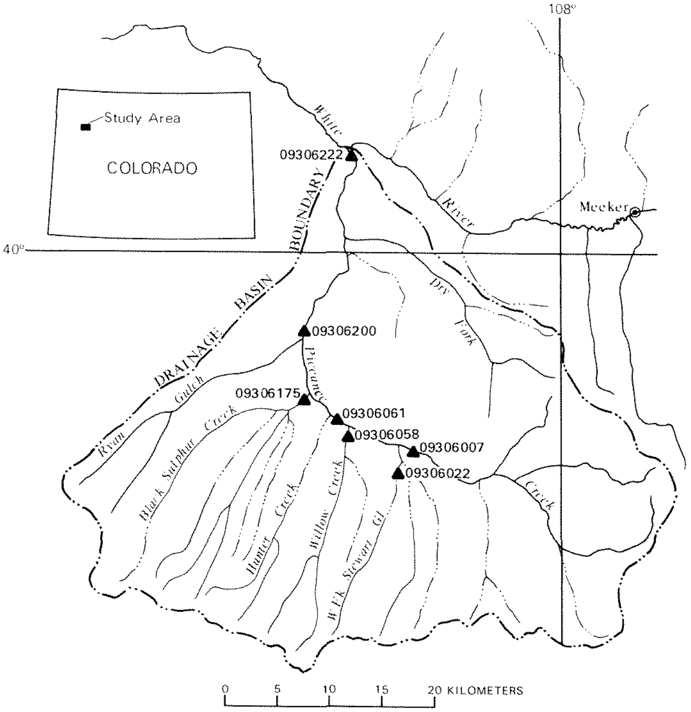

FIG.1 Map showing the Piceance Creek basin and location of gauging stations.

approximately 400 m of a kerogen-rich marlstone comprising the Parachute Creek Member of the Green River Formation of Eocene age. The Green River Formation was deposited in a playa-lake complex (Surdam & Wolfbauer, 1975). Throughout the formation, horizons with significant quantities of saline minerals exist. The largest percentage of saline minerals occurs near the bottom of the Parachute Creek Member, and is termed the saline zone. The principal saline minerals in this unit are nahcolite ($NaHCO_3$), halite (NaCl), and dawsonite ($NaAl(OH)_2CO_3$). These minerals are very soluble. Samples of groundwater collected from the saline zone of the Green River Formation have dissolved solids concentrations as large as 50 000 mg l^{-1}.

The Piceance creek basin has a semiarid climate. Precipitation is distributed nearly uniformly throughout the year and ranges from approximately 800 mm $year^{-1}$ in the southern part of the basin, at an elevation of 3000 m, to 250 mm $year^{-1}$ at the mouth of the basin, at an elevation of 1650 m (Wymore, 1974). Mean annual precipitation for the entire basin is approximately 440 mm $year^{-1}$. Mean monthly temperatures near the geographical centre of the basin range from -7°C during January to 16.5°C during July. The broad interfluvial and hillslope areas are vegetated with juniper and pinyon trees. Ground cover is sparse grass. Valley flats primarily are vegetated with sage, except along the perennial streams, where irrigated hay meadows are common.

Soil is predominantly thin and poorly developed throughout the basin except on the alluvial valley fills. On hillslopes, the soil consists of 0-50 cm of rocky material, d_{50} about 5 mm. Chemical weathering other than by dissolution appears to be slight. On the relatively flat, broad interfluves, soil consists of finer material and is somewhat thicker, although the profile is still poorly developed. Soil permeability, especially on the hillslopes, appears to be relatively large compared to rainfall rates, as evidence of surface runoff is uncommon.

HYDROLOGY OF PICEANCE CREEK

In the spring of 1974, 15 gauging stations were constructed along Piceance Creek and its tributaries in order to determine discharge and water quality characteristics. Several of these gauges are located on small, ephemeral tributary channels that have had only a few days of flow during the period of record, April 1974 to September 1981. The hydrological characteristics of these tributaries will not be considered in this report, because the data are too limited to make conclusions regarding mean annual suspended sediment and dissolved solids loads. The location of the seven gauging stations whose records were analysed are shown in Fig.1. Each gauging station consists of a rated cross section, a continuous water-stage recorder, an automatic pumping sediment sampler, and a specific conductance monitor. In addition, monthly water samples are collected and analysed for chemical compositon. The daily mean discharge, suspended sediment, and dissolved solids loads were computed from these measurements, and have been published annually by the US Geological Survey.

A summary of surface water characteristics in the Piceance Creek basin is given in Table 1. Mean annual values for hydrological characteristics were computed by summing the daily values for the seven complete water years of record, October 1974 to September 1981. Missing values of daily suspended sediment and dissolved solids concentration were calculated from linear, least-squares regressions, using water discharge as the independent variable. Annual runoff is a very small part of the annual precipitation (2.8-5.0%) at all gauging stations. The percentage of runoff dominated by groundwater-return flow was determined from the daily flow duration relation. This analysis shows that virtually all of the runoff (≧95% at all gauging stations) was groundwater dominated. Thus, virtually all surface runoff in the Piceance Creek basin has been in contact with the soil and bedrock for an appreciable length of time. The prominence of groundwater-dominated runoff also tends to confirm the observation that overland flow is infrequent. Flood peaks in the Piceance Creek basin are associated with spring snowmelt, primarily above an elevation of 2300 m, and intense, localized convectional storms during the summer. Overland flow due to snowmelt is limited to areas of frozen ground or bedrock. Similarly, overland flow due to intense rainfall is limited in both areal and temporal extent.

TABLE 1 Summary of hydrological characteristics at selected gauging stations in the Piceance Creek basin

Station number	*Drainage area (km^2)*	*Mean annual discharge ($m^3 s^{-1}$)*	*Runoff/ precipitation*
09306007	458	0.348	0.050
09306022	114	0.045	0.028
09306058	125	0.058	0.033
09306061	800	0.479	0.041
09306175	267	0.182	0.047
09306200	1310	0.569	0.030
09306222	1632	0.708	0.030

Station number	*Mean annual load ($t\ year^{-1}$)*		*Mean annual basin denudation ($t\ km^{-2} year^{-1}$)*		
	Dissolved solids	*Suspended sediment*	*Dissolved solids*	*Suspended sediment*	*Total*
09306007	7 970	16 300	15.0	35.6	50.6
09306022	1 500	268	11.0	2.35	13.4
09306058	1 780	602	12.1	4.79	16.9
09306061	14 130	13 700	-	17.1	-
09306175	6 650	3 860	-	14.5	-
09306200	20 500	19 000	-	14.5	-
09306222	32 900	24 400	8.2	15.0	23.2

Estimated 2-h rainfall with a recurrence interval of 50 years is only 50 mm (Miller *et al.*, 1973).

TRANSPORT OF DISSOLVED SOLIDS

The mean annual load of dissolved solids at each gauge is listed in Table 1. The mean annual load of dissolved solids from the Piceance Creek basin is 20.2 t $km^{-2}year^{-1}$, and varies from 13.2 to 24.9 t $km^{-2}year^{-1}$ at individual gauges. Compared to other drainage basins in the western USA with similar volumes of runoff per unit area (Langbein & Dawdy, 1964), the transport of dissolved solids by Piceance Creek is almost 100% greater than expected. The dissolved solids load per unit area in the Piceance Creek basin, however, is quite similar to the regional value of approximately 20.9 t $km^{-2}year^{-1}$ determined for the White River basin downstream from the town of Meeker. Because the Uinta and Green River Formations underlie most of this contributing area, agreement is to be expected. No clear trend of increasing dissolved solids load per unit area with either increasing drainage area or decreasing elevation exists in the Piceance Creek basin. There is, however, a definite increase in the mean annual concentration of dissolved solids with increasing drainage area. These two observations are reconcilable unit runoff decreases downstream.

Robson & Saulnier (1981) developed a numerical model describing groundwater flow and solute transport in the Piceance Creek basin. Results of this investigation provide an explanation for the downstream increase of dissolved solids concentration as well as an estimate of the quantity of the dissolved solids derived from dissolution near the ground surface. Groundwater flow paths are generally from south to north in the Piceance Creek basin, and the depth of circulation increases with path length. As noted previously, the concentration of dissolved solids in the groundwater increases greatly with depth. Underlying the central and northern part of the basin at a depth of about 600 m, there is a saline zone where concentrations attain 50 000 mg l^{-1}. Finally, the middle and lower reaches of Piceance Creek are in an area of upward groundwater flow. Thus, the proportion of deep circulating groundwater in Piceance Creek increases downstream. Model computations indicate that approximately 54% of the non-atmospheric dissolved solids load of Piceance Creek is contributed by deep circulating groundwater. Virtually all of this contribution appears to be derived from dissolution in the Parachute Creek Member of the Green River Formation.

The atmospheric contribution of dissolved solids to Piceance Creek upstream from gauge 09306222 is estimated to be 3670 t $year^{-1}$, by using a runoff coefficient of 0.030 and an average concentration of 5 mg l^{-1}, as determined from 11 chemical analyses of bulk precipitation samples collected in the basin. The annual quantity of dissolved solids contributed by dissolution of near-surface rock material is estimated to be 13 400 t $year^{-1}$ or 46% of the non-atmospheric load. Thus, a reasonable measure of chemical denudation of the land surface in the Piceance Creek basin appears to be 8.2 t $km^{-2}year^{-1}$. Three gauging stations (09306022, 09306007 and 09306058) are located upstream and upgradient from the saline zone. Consequently, the contribution of deep circulating groundwater with a large concentration of dissolved solids to these gauges probably is small. If it is assumed that the non-atmospheric, dissolved solids load at these gauges is derived entirely from dissolution of near-surface rock material, the estimated rates of chemical denudation range from 11 to 15 t $km^{-2}year^{-1}$. The range of chemical denudation rates results from both uncertainty due to simplifying assumptions and model errors as well as the physical characteristics of the Piceance Creek basin. The concentration of dissolved solids in the near-surface groundwater increases only gradually, ~ 30%, from the head to the mouth of the basin (Saulnier, 1978). Surface runoff per unit area, virtually all of which is groundwater dominated, however, decreases by approximately 50% downstream along Piceance Creek. Consequently, the chemical denudation rate appears to decrease gradually from the headwaters to the mouth of the basin.

Further evidence for the significant impact of deep circulating groundwater on the dissolved load of surface water is indicated by a longitudinal comparison of the relation between dissolved solids concentration and water discharge at the four mainstem gauges (Fig.2).

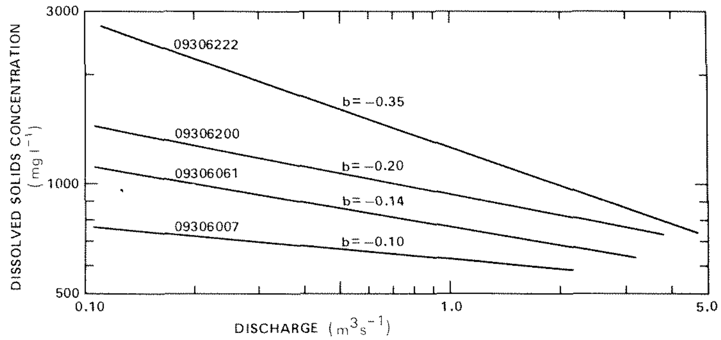

FIG.2 Graph comparing the variation of dissolved solids concentration as a function of water discharge measured at mainstem Piceance Creek gauging stations, October 1974 to September 1981.

These relations were determined for approximately 80 measurements by a least-squares regression of the log-transformed values. The standard error of estimate for the regression relations range from ±10 to 15%. From the upstream gauge (09306007) to the furthest downstream gauge (09306222), a progressive increase occurs in: (1) the concentration of dissolved solids at any given discharge, and (2) the slope of the relation (b) between the dissolved solids concentration and water discharge. As described above, virtually all streamflow in the Piceance Creek basin has at least passed through the soil profile and upper part of the unsaturated zone. Such flow has a dissolved solids concentration ranging between 500 and 700 mg l^{-1}. Streamflow at the upstream gauge (09306007) consists almost entirely of such water, as shown by the nearly constant dissolved solids concentration throughout a wide range of discharge (Fig.2). That is, deep circulating groundwater with a large concentration of dissolved solids does not contribute significantly to the surface discharge at gauge 09306007 at any rate of flow. The quantity of deep circulating groundwater, however, increases downstream and, therefore, contributes a progressively greater portion of the surface discharge. Consequently, the dissolved solids concentration of surface discharge increases downstream at any rate of flow. The result is most apparent when the surface discharge is small, because then the contribution of shallow circulating groundwater with a relatively small concentration of dissolved solids is the least. Conversely, the concentration of dissolved solids tends to become similar at all gauge sites, as the contribution of shallow circulating groundwater increases the surface discharge.

The chemical composition of shallow and deep circulating groundwater is different, especially in the relative concentrations of calcium and sodium. As noted previously, the Uinta Formation is relatively enriched in calcium carbonate. Groundwater percolating through the Uinta Formation becomes saturated with respect to calcium carbonate (Saulnier, 1978). Groundwater that circulates through the saline zone dissolves large quantities of nahcolite, halite and dawsonite. The concentration of sodium is increased greatly, and the calcium/sodium ratio decreases. The concentration of bicarbonate

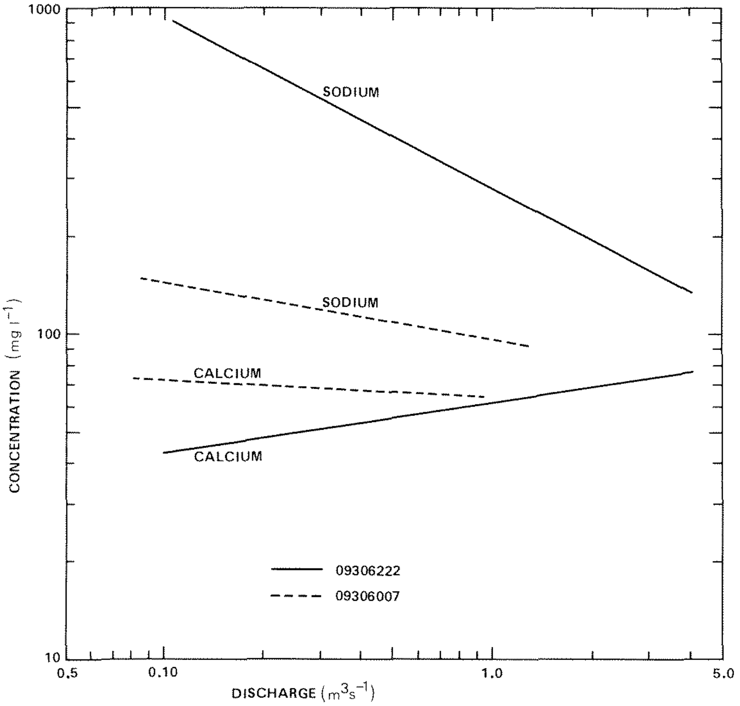

Fig. 3 Graph comparing the variation of sodium and calcium concentration as a function of water discharge measured at the furthest upstream gauging station (09306007) and the furthest downstream gauging station (09306222), October 1974 to September 1981.

also increases, which causes the precipitation of calcium carbonate along joint and fault zones as well as tufa deposits at the surface (Saulnier, 1978). Consequently, the calcium/sodium ratio as well as the absolute concentration of calcium are less in groundwater from the deep circulation system than the shallow circulation system. As a result, the chemical composition of streamflow at the upstream gauge, which is dominated by return flow from shallow circulation, is quite different from streamflow at the downstream gauge, which is dominated by return flow from deep circulation.

The variation in concentration of calcium and sodium as a function of discharge at the upstream gauge (09306007) and the downstream gauge (09306222) are compared in Fig.3. These relations were determined from approximately 80 measurements by a least-squares regression of the log-transformed values. The standard error of estimate for the regression relations ranges from ±15 to 20%. At the upstream gauge, the concentrations of calcium and sodium are nearly constant throughout a range of discharge, and the concentration of calcium is approximately 60% of the sodium concentration. At the downstream gauge, the sodium concentration is increased greatly whereas the calcium concentration is somewhat decreased. These differences are most prominent at low discharge when the relative proportion of return flow from deep circulation (saline zone) is greatest at the downstream gauge. As surface discharge increases due to a significant quantity of return flow from shallow circulation, the sodium and calcium concentrations tend toward the values determined at the upstream gauge.

TRANSPORT OF SUSPENDED SEDIMENT

The mean annual load of suspended sediment transported at each gauge is listed in Table 1. The mean annual load of suspended sediment per unit area at the mouth of Piceance Creek (gauge 09306222) is 15.0 t $km^{-2}year^{-1}$, and varies from 2.35 to 35.6 t $km^{-2}year^{-1}$ within the basin. At all gauges, the measured yield of suspended sediment is quite small compared to the vast majority of semiarid drainage basins. The regional suspended sediment yield computed for the White River basin downstream from the town of Meeker is 153 t $km^{-2}year^{-1}$. All of the contributing drainage area, of which the Piceance Creek basin comprises approximately 15%, is generally similar in climate, vegetation, and lithology. Nevertheless, the mean annual yield of suspended sediment from the Piceance Creek basin is less than one-tenth of the regional value.

Suspended sediment yields in the Piceance Creek basin also are quite small compared to similar basins throughout the western USA. Langbein & Schumm (1958) developed a relation between mean annual suspended sediment yield and precipitation for drainage basins in the USA. For a mean annual precipitation of 440 mm $year^{-1}$, the predicted yield is approximately 200 t $km^{-2}year^{-1}$. Frickel *et al.* (1975) estimated a suspended sediment yield of approximately 220 t km^{-2} $year^{-1}$ using the Pacific Southwest Inter-Agency Committee method (1968). Thus, there is good agreement between the measured regional value and analytically computed values of suspended sediment yield. Measured suspended sediment yields in the Piceance Creek basin, however, are approximately an order of magnitude smaller.

Measurements of hillslope transects and channel cross sections in the Piceance Creek basin by Frickel *et al.* (1975) indicate extensive and widespread storage of sediment along the base of hillslopes and in ephemeral stream channels. Fifteen of 17 hillslopes and 13 of 19 channel cross sections studied in the period July 1972 to September 1973 exhibited aggradation. Similar measurements elsewhere in semiarid parts of western USA also have recorded aggradation in stream channels and along the base of hillslopes (Emmett, 1974; Leopold, 1978). Thus, it is not possible to ascertain the extent to which a large rate of sediment storage may account for the anomalously small sediment yields measured at stream gauges in the Piceance Creek basin.

TOTAL DENUDATION IN THE PICEANCE CREEK BASIN

The denudation rate of the land surface in the Piceance Creek basin may be estimated by summing the rates of mechanical and near-surface chemical erosion. As described above, the rate of near-surface chemical weathering was computed for only four of the seven gauging stations studied. The rates of chemical, mechanical, and total erosion are summarized in Table 1. Estimated denudation for the entire Piceance Creek basin is 23.2 t $km^{-2}year^{-1}$, and varies from 13.4 to 50.6 t $km^{-2}year^{-1}$ in the sub-basins. Mechanical and chemical erosion appear to be almost equally important. In contrast, the estimated denudation rate for the White River basin downstream from the town of Meeker is approximately 174 t $km^{-2}year^{-1}$, of which approximately 88% is suspended sediment produced by mechanical erosion. Thus, present rates of denudation in the Piceance Creek basin are significantly less than in hydrologically similar, nearby basins. Although the rate of material removal by dissolved-phase transport exceeds the mean condition for comparable basins in the western USA by almost 100%, the rate of sediment removal is approximately a factor of 10 less than the norm.

Substantial evidence exists for relatively large denudation rates in parts of Piceance Creek basin at present or at least in the recent past. Carrara & Carroll (1979) estimated hillslope erosion rates in the Piceance Creek basin by measuring the height of root exposure for trees growing on steep south-facing slopes. Average erosion in such locations corresponds to a denudation rate of 4250 t $km^{-2}year^{-1}$ and has increased by nearly an order of magnitude during the past 400 years. These measurements probably represent near-maximum denudation rates and apply to only about 2% of the basin. The average denudation rate determined for north-facing hillslopes, approximately 2000 t $km^{-2}year^{-1}$, was slightly less than one half of the rate for south facing hillslopes, although it was still quite significant.

CONCLUSIONS

Dissolved solids loads measured at gauging stations in the Piceance Creek basin and corrected for atmospheric contributions show that the rate of chemical denudation is approximately twice the average rate for semiarid drainage basins in the western USA. Approximately 50% of the mean annual load of dissolved solids at the mouth of Piceance Creek is contributed by chemical weathering within the zone of shallow groundwater circulation.

Suspended sediment loads measured at seven gauging stations in the Piceance Creek basin show that the rate of mechanical denudation is approximately 10% of the average rate for similar semiarid drainage basins in the western USA. Even nearby basins with similar climate, vegetation, and lithology have much larger rates of mechanical denudation. Studies of hillslope erosion and sediment transport in small basins (<10 km^2) indicate that whereas hillslope erosion is substantial, relatively large quantities of the eroded debris are being deposited along the base of hillslopes, on alluvial fans, and in small stream channels.

Compared to most semiarid drainage basins, a large percentage (36%) of the total denudation is removed from the Piceance Creek basin as dissolved solids. Rapid dissolution of carbonate cement in the near-surface rock material and the deposition of a large quantity of sediment within and adjacent to small tributaries appear to account for the anomalous denudation rate.

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