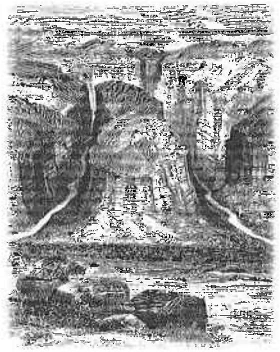

Chapter Twenty-Four

Rates of Downcutting of the Colorado River in the Grand Canyon Region

Ivo Lucchitta, Garniss H. Curtis, Marie E. Davis, Sidney W. Davis, Thomas C. Hanks, Robert C. Finkel, Brent Turrin

Abstract: Precisely dated Pleistocene basalt flows and associated deposits and surfaces in the Granite Park area of western Grand Canyon yield local downcutting rates for the Colorado River for the past 600 ka. These range from 8.7 to 16 cm/ka. In eastern Grand Canyon and the Lake Powell area, rates over the same time interval are in the 31 to 50 cm/ka range, and gravel deposits of the same age as those at Granite Park are three or more times higher in elevation. The discrepancy can be accounted for partly through movement along the Hurricane and Toroweap Faults, partly through upstream migration of a knickpoint along the river.

The rate at which the Colorado River has been cutting down in Grand Canyon sheds light on the manner and timing of formation of Grand Canyon, the rate at which accompanying erosional processes take place, the history of uplift of the Colorado Plateau, and the lithospheric processes responsible for the uplift.

The downcutting rate for the past 600 ka has been determined successfully at river mile 209 near Granite Park, western Grand Canyon (Lucchitta and others, 2000). Here, two precisely dated basalt flows, which together correspond to Hamblin's (1994) Black Ledge flow, are associated with planation surfaces and carbonate soils whose ages are thus calibrated. Unfortunately, our previously published downcutting rate derived from these relations is incorrect owing to an unnoticed typographic error. (We are thankful to Joel Pederson, who pointed out the discrepancy, personal communication, 2000). The purpose of this brief report is to rectify the error and amplify the analysis of erosion rates. The data summarized below are reported in detail in Lucchitta and others (2000).

Setting

As shown in Figure 1, the lowest and most massive of the two basalt flow sequences at mile 209 of the Colorado River [by convention, measured downstream from Lees Ferry] is ~30 m thick as preserved; its base occupies a channel carved in bedrock. Basalt and bedrock are separated in places by a few meters of river gravel. The base of the channel is ~30 m above present river grade. The top of the sequence is at ~60 m above present grade. The $^{39}Ar/^{40}Ar$ age is 604 ± 8 ka (complete geochronologic data are given in Lucchitta and others, 2000). This basalt flowed down the Colorado River for 54 km beyond the Granite Park area.

The thin upper basalt flow is just above the top of the lower unit, and embedded near the base of 23 m of monolithologic basalt-cobble gravel and basalt sand. This flow has an age of 524 ± 7 ka. The basalt sand is interpreted as the product of volcanic eruptions whose products choked the river, whereas the cobble gravel probably was produced by the breaching of basalt dams. In either case, aggradation is likely to have been very rapid during the catastrophic events, as would the subsequent downcutting through the unconsolidated sediments once the overload disappeared.

The basaltic gravel and sand are at a maximum height of 83 m above present grade. This is the highest elevation attained by Quaternary river deposits preserved here. The gravel and sand are truncated by a pediment surface that is graded to the top of the massive lower flow sequence and has Stage V carbonate soil. The pediment was formed after the river had cut back down through the basalt gravel and sand

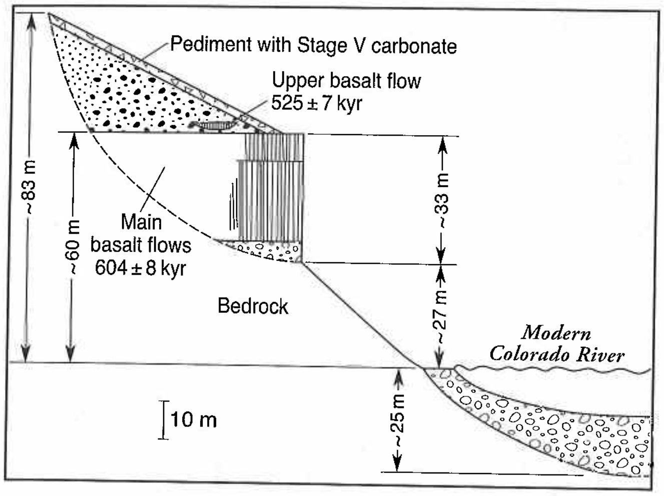

Figure 1. Characteristics of Quaternary deposits at Granite Park (mile 209), western Grand Canyon, as used to determine downcutting rates of the Colorado River

and the thin 524 ka upper flow, when it was stuck on top of the resistant lower flow unit. Inasmuch as the deposition of basalt gravel and sand and the subsequent downcutting are both likely to have taken an amount of time insignificant in comparison with the 524 ka age of the upper basalt (Lucchitta and others, 2000), we can take this figure to represent the time when the river was parked on top of the lower flow and the carbonate soil began to form in the pediment. The ~524 ka age for Stage V carbonate agrees well with ages obtained in the Rio Grande region by Seager and others (1995), and elsewhere (Gile and others, 1981).

Rates of Downcutting

The geologic relations at mile 209 enable us to calculate three possible rates of downcutting.

1. The first is obtained by dividing the maximum height of the basaltic sand and gravel (83 m) by the age of the deposit, which is taken to be essentially identical with the 524 ka age of the upper basalt (see above). This yields a rate of ~16 cm/ka (erroneously given as 1.6 cm/ka by Lucchitta and others, 2000). The rate is likely to be too high because it involves cutting through 53 m of section (basalt flows and basaltic sediments) deposited catastrophically above the level to which the river had already cut down by about 600 ka.

2. The second rate is obtained by ignoring the relatively short time taken to accumulate and then cut through the upper basalt and basaltic gravel and sand, focusing instead on the time (~524 ka) it took to cut through the 60 m between the top of the massive lower basalt sequence and the modern floodplain. This yields a rate of ~11.5 cm/ka. This rate is affected by the 33 m of basalt and gravel that the river had to cut through to get back to the level of its 600 ka channel. This might be seen as introducing a major discrepancy. However, the rate at which the river cut through the basalt probably was comparable to the rate at which it had previously cut through local bedrock to its 600 ka channel, so the 11.5 cm/ka rate may be a reasonable approximation to the river's undisturbed rate of downcutting through bedrock in this area.

3. The third rate is obtained by arguing that the bottom of the channel had already eroded down to about 27 m above the present floodplain when the older lava flowed down the channel ~600 ka. This allows us to determine the effective overall downcutting rate for the past 600 ka. That is, we divide 600 ka by the distance between the bottom of the 600 ka channel and the bottom of the modern channel, ignoring the time taken to accumulate the upper basalt flow and the basaltic sediments, then cutting back down through them. We do not know how far the bottom of the modern channel is below the modern floodplain. This distance includes the depth of the water and the thickness of gravel in the river bed.

Leopold and Maddock (1953) give a water depth in the channel at Grand Canyon gage of about 8 m when the river flow is 30,000 cfs. This is also the discharge rate we have used for our reference level at Granite Park. Schmidt and Graf (1990) report water depths of 6 to 9 m for western Grand Canyon at a discharge of 24,000 cfs. On the basis of these data, 8 m is a reasonable estimate of water depth at the Granite Park location.

Regarding the thickness of alluvium in the channel, Leopold (1969) reports that a sawed plank was found at 17 m below normal streambed elevation during excavations for Hoover Dam, indicating that alluvium is at least that thick at the dam site (western end of Lake Mead). Adding 8 m of water to 17 m of alluvium gives 25 m to bedrock in the river channel. The figure agrees with river-bed profiles in Leopold (1969), which show maximum water depths in this range. Bedrock must be at least as far down as the water is deep.

Using the estimate of 25 m for depth to bedrock in the channel, the separation between the bottom of the lava paleochannel and that of the modern channel is about 52 m, and the overall rate of downcutting over the past 600 ka works out at about 8.7 cm/ka. This is a minimum rate because it incorporates in the denominator the time required to deposit the volcanic material above the 600 ka paleochannel (600 to 524 ka), and then cut back down through it.

In spite of the many imprecisions, the three rates differ by a factor of less than two: 8.7 to 16 cm/ka. This range is much lower than the 35 to 100 cm/ka average rate proposed by Lucchitta (1966, 1988) for carving of Grand Canyon as a whole over the last 5 Ma. It is also much lower than the 31 to 48 cm/ka rates that can be calculated from Table 2 in Lucchitta and others (2000) for eastern Grand Canyon through Lees Ferry, the 40 to 50 cm/ka rate for the Glen Canyon area (Davis and others, this volume; Hanks and others, this volume), and the ~40 cm/ka calculated for the Fremont River (a tributary of the Colorado River) by Marchetti and Cerling (this volume). The highest and oldest river deposit at Lees Ferry, about 230 m above the bottom of the modern river channel nearby, gives a rate of about 44 cm/ka, which can be taken as the overall downcutting rate for that area over the past 500 ka. These rates are in decent agreement with the 24 cm/ka rate given by Kirkham and others, this volume for the overall downcutting rate of the river near Glenwood Springs over the past 3 Ma. Their data do not permit a more detailed apportionment of downcutting within that time interval, so it is entirely possible that downcutting occurred at a higher rate in only the later part of the interval.

Interpretations

One possible explanation for the discrepancy between downcutting rates in different parts of the river is that the block upstream from the Hurricane and Toroweap Faults (both upstream from Granite Park) has been uplifted by Quaternary movements on these faults. The river would cut back down through the uplift at a rate comparable to the uplift rate to maintain grade.

Fenton and Cerling (this volume), and Fenton (personal communication, 2001) give displacement rates of 7 to 19 cm/ka on the Toroweap Fault over the past ~400 ka, and 7 to 11 cm/ka for the Hurricane Fault over the past ~180 ka. The range of displacement rates therefore is 14 to 30 cm/ka for the two faults combined. This is substantially less than downcutting rates upstream. Furthermore, the cumulative displacement along the faults projected over the last 500 ka is about 90 m. Even assuming that displacement was consistently up-to-the-east (upstream), it is less than half of the measured height above present river grade of Stage V carbonate soils (~500 ka) in the Lees Ferry–Lake Powell region (Lucchitta and others, 2000, table 2; Davis and others, this volume; Hanks and others, this volume). This suggests that displacement on the Hurricane and Toroweap Faults is not by itself enough to account for the discrepancies between Granite Park and the river reach from Lees Ferry upstream.

Another possibility is that the rate of displacement on the faults has decreased with time, so movements responsible for some of the height of the Lees Ferry gravel would have happened early in the 500 ka interval, before the earliest displacement recorded by Fenton and others (2001). However, these authors (2001 and in press) indicate that displacement rates on both faults have been linear for at least the last 500 ka.

A fourth possibility is that the river has cut faster through the soft Mesozoic section from Lees Ferry upstream than through the resistant Paleozoic and Proterozoic rocks of Grand Canyon. This is unlikely because the Paleozoic rocks, which begin to form the canyon walls just downstream from Lees Ferry, would have set the incision rate for the upstream reach.

Finally, the discrepancy may be caused by a knickpoint migrating upstream through headward erosion. This would be in response to opening of the Gulf of California 5 to 6 Ma, young uplift of the Colorado Plateau, and capture of an ancestral upper Colorado River by a young and vigorous lower Colorado drainage (McKee and others, 1967; Lucchitta, 1966, 1989; Davis and others, this volume; Hanks and others, this volume). The knickpoint and its accelerated rate of downcutting would have passed the Granite Park area before 500 ka, and would have reached Lees Ferry and points upstream after that date.

Summary

At Granite Park, the bedrock floor of the Colorado River channel was about 52 m above the floor of the present channel at 600 ka. Subsequent aggradation due to volcanic events upstream caused the river to build up its bed to at least 83 m above present grade, then cut back down between 525 ka and today. The downcutting occurred at a rate of 8.7 to 16 cm/ka.

At Lees Ferry, 336 km upstream from Granite Park, the bottom of a ~500 ka paleochannel is about 230 m above the present bottom. Downcutting rates for various river deposits here are in the 31 to 48 cm/ka range. Rates for areas upstream as far as the vicinity of Glenwood Springs are similarly high.

Up-to-the-east movements on the Hurricane and Toroweap Faults can account for half to a third of the discrepancies between Granite Park and the areas upstream. The rest is best explained by a knickpoint migrating upstream in response to opening of the Gulf of California ~5 Ma, young uplift of the Colorado Plateau, and development of a young and vigorous Colorado River in the Grand Canyon region.

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