DETERMINATION OF LONG-TERM SEDIMENT GENERATION RATES OF LARGE STEEP-SLOPED CANYONS WITH HETEROGENEOUS STRATIGRAPHY USING IN SITU ^{10}BE, GRAND CANYON, ARIZONA

Abstract

Study of the Colorado River in Grand Canyon, Arizona, has very direct applications to the relationship between sedimentation and regulation of the river system. Studies of sediment yield in this river stretch are well documented, however, the rates of sediment introduction into the system are not well known. This study provides a long-term average sediment yield of the Colorado River and its tributaries as a function of distance in the Grand Canyon using cosmogenic ^{10}Be. By gaining a four dimensional understanding, in space and time, of the movement of sediment within the Grand Canyon we will better understand the dynamic sediment system. The advantage of long-term averages presents the ability to compare and improve short-term sediment flux averages that may be skewed by short-term climatic or sediment yield cycles.

Introduction

Exposing two billion years of geologic history and serving as the life-blood of the Southwest, the degree of richness and dynamics of the Colorado River in the Grand Canyon is unparallel. The Grand Canyon extends 448 km (278 miles) across the northwestern part of Arizona (Fig. 1), stretching between Lake Powell on the east end and Lake Mead on the west. The Grand Canyon was formed when the Colorado River cut into the southwestern region of the Colorado Plateau (Fig. 2). Over the course of its path through the Grand Canyon, the Colorado River drops approximately 610 m (Beus and Morales, 1990).

The water that flows through the Grand Canyon embodies the union of four major rivers, the Green, San Juan, Little Colorado, and Colorado, as well as many minor tributaries (Beus and Morales, 1990). Following a major flood in 1905, regulation first began on the Colorado River. Since that time, regulation has become quite extensive (Kieffer, 1990).

Monitoring between 1921 and 1962 at Phantom Ranch shows that prior to regulation of the Colorado River in Grand Canyon, the average discharge was 17,000 cubic feet per second (cfs). The mean annual flood was 77,500 cfs, with many larger floods; an 1884 flood measured 300,000 cfs. At the same location, the sediment load was measured at over 275 Mg per day. Upon the closure and the filling of Glen Canyon Dam reservoir in 1963, the average discharge dropped to 11,000 cfs and sediment load to only about 45

Mg per day. The Colorado River, Spanish for “colored red” due its amount of sediment, began to often run clear following regulation (Kieffer, 1990).

Due to the inherent importance of sediment transport to the river, the Colorado River sediment yield has been an important topic of research. There exist short-term estimates of sediment yield and transportation rates of the Colorado River in Grand Canyon (such as Graf et al., 1991; Howard and Dolan, 1981; Webb et al., 2000), however, this study will provide a long-term sediment production rate by measuring the average erosion rate within the Colorado River basin in the Grand Canyon region. A long-term average will effectively cancel out periodic cycles or fluctuations that could skew a short-term average, providing a clear standardized understanding of the systems sediment yield.

Justification

This study will provide a dynamic and diverse understanding to the Colorado River basin system in the Grand Canyon, Arizona. Prior studies have investigated contemporary sediment yield and sediment transportation of the Colorado system in Grand Canyon (such as Graf et al., 1991; Howard and Dolan, 1981; Webb et al., 2000); however, no long-term average sediment yield rates are known. The scope of this study is threefold, it will (1) provide a rate at which sediment is delivered to the system; (2) enable understanding of the spatial distribution of tributary erosion; and (3) model rates at which sediment is delivered downstream. The importance of a firm understanding of sediment yield is understood considering the degree of regulation that exists on the Colorado River.

The regulation of the Colorado River has been a significant source of study. Since the dams closure in 1963, there have been many studies investigating the impact of the regulation on sediment yield, transportation, and deposition within Grand Canyon. Further, the rate at which sediment is being delivered to Lake Mead is also a source of concern. Monitoring of the Colorado River through this stretch only dates back to the late 1800’s using photographic comparison, with quantitative measurements much more recently (Webb, 1996; Melis et al., 1995). Considering the amount of interannual and interdecadal precipitation variability (Figs. 3 and 4), one begins to appreciate the importance of a long-term sediment influx rate of the Colorado River if understanding of the effects of regulation is to be effective. Such long-term understanding is highlighted in the Grand Canyon where cyclic erosion and deposition are present in the Colorado River below Glen Canyon Dam. Due to this cyclic quality, “data biasing” is a risk depending on study duration and recurrence period (Cluer, 1995). Consequently, a long-term understanding would compensate for any possible micro- or macro-cycling of sediment load.

Literature Review

Rate of erosion using cosmogenic isotopes

The constant exposure of cosmic radiation causes fast moving nuclides to collide into Earth’s surface forming cosmogenically produced isotopes. Cosmogenic isotope dating is based upon the accumulation of certain nuclides that form due to this interaction of cosmic radiation with exposed surface matter. The isotopes are only produced in the top few meters of crust, allowing for applications to landform ages and geomorphic evolution. The accumulation of these cosmogenic nuclides is proportional to cosmic ray intensity and the concentration of target nuclides in material. Consequently, the amount of cosmogenic isotopes relates to the duration that materials have been exposed to cosmic radiation (Zreda and Phillips, 2000).

Due to the production method, the dosing of cosmogenic rays is not constant for all latitudes, elevations, and burial depths. The nuclides producing cosmogenic isotopes are deflected by Earth’s magnetic field and interact with Earth’s atmosphere. Consequently, cosmic flux is greatest at high latitudes and high elevations (Bierman, 1994). Production rates also decrease exponentially with depth (Lal, 1988). For these reason corrections to cosmogenic production rates must be made accordingly to the specific latitude, elevation, and burial depth parameters (Fig. 6) (Bierman, 1994).

While cosmogenic isotopes are effective for evaluating point location erosion rates, analysis of isotope concentration in alluvial sediment enables calculation of basin-wide erosion rate. Bierman and Steig (1996) provide a model for such analysis. This model assumes an isotopic steady state for the sediment isotope budget within the study basin (Fig. 7); the in-going isotope flux (I_{IN}) is equal to the out-going isotope flux (I_{OUT}). Accordingly, the isotope reservoir (N_{RES}) would remain constant, as well as the flux of mass within the basin (M_{OUT}). I_{IN} is a function of cosmogenic bombardment, while I_{OUT} is equal to isotope loss due to decay (I_D) and isotope transport out of the basin (I_{TRAN}).

Isotopes are transported out of the basin through isotopes in sediment (I_{SED}) and isotopes in solution (I_{SOL}). Consequently, the relationship established is such that:

$$I_{IN} = I_{OUT} = I_D + I_{TRAN} = I_D + I_{SOL} + I_{SED} \quad (1)$$

$$M_{IN} = M_{OUT} = \text{constant} \quad (2)$$

(Bierman and Steig).

An inverse relationship exists between the flux of cosmogenic isotopes leaving a basin and the rate of basin erosion. The longer sediment is exposed to cosmic rays, longer dosage time, the higher the isotope concentration; consequently the higher the dose, the slower the erosion rate (Bierman and Steig).

Bierman and Steig present a model for calculating average rate of basin-wide mass loss (m^*):

$$m^* = [\Lambda(P^J_{0\,eff} - C^J_{SED}\,\lambda)] / C^J_{SED}, \quad (3)$$

where average rate of basin-wide mass loss (m^*) is a function of attenuation factor (Λ), effective basin-wide production rate at ground surface ($P^J_{0\,eff}$), average isotope concentration in sediment leaving basin (C^J_{SED}), and decay constant (λ). Depending on the rate of transport within the basin, the decay constant (λ), may become negligibly low, changing the equation to:

$$m^* = [\Lambda\, P^J_{0\,eff}\,] / C^J_{SED}. \quad (4)$$

This model is only applicable if $C^J_{SED} = C^J_{SOL}$ and a set of assumptions are accepted. These assumptions, outlined by Bierman and Steig, include:

> (1) the rate of erosion is constant but not necessarily spatially uniform; (2) the basin is in isotopic steady state, (3) sampled sediment is spatially and temporally representative of all sediment leaving the basin, i.e. it is well mixed; (4) mass loss from the basin is occurring primarily by surface lowering; (5) the mineral selected for isotopic analysis is uniformly distributed through the basin.

Climate variability

The climatic variability of the Grand Canyon contributes noticeable effect on the sediment load and flow volume of the Colorado River and its tributaries (Graf et al., 1991). Graf et al. suggests that the sediment storage in tributary flood plains has been related to sediment load of the Colorado, tying the flood-plain storage also to the climatic variability. A recent study measures the mean annual precipitation of the Grand Canyon region ranges from 148 to 655 mm, with the total average at 316 mm. Winter (November-March) precipitation accounts for about 37 percent of the total, and summer (July-September) accounts for 35 percent (Table 1). Looking at interannual and interdecadal precipitation over the last century (Figs. 3 and 4), one finds fairly significant variability (Webb et al., 2000). Furthermore, year to year sediment load and flow volume variations have been most significant in the fall. This correlates to the period of greatest variability in regional climatic, significantly influenced by ENSO conditions (Graf et al., 1991).

Debris flow and sediment yield

The Grand Canyon debris flows are characterized as short-duration, high-magnitude floods (Melis and Webb, 1993). Historically, debris flows have occurred when monthly precipitation is high. The monthly precipitation does not always have to be consistently high, nor is a season-long buildup of antecedent soil moisture required for debris flow conditions (Webb et al., 2000). Debris flows from the tributary systems of the Grand Canyon present a significant source of sediment to the Colorado River system. Sediment contribution varies per reach, according to the frequency of debris flows within the reach’s tributaries (Webb et al., 2000). Size of debris flow can also be highly variable (Table 2) (Melis et al., 1995).

Debris flows occur in 525 Colorado River tributaries between Lees Ferry (river mile 0) and Diamond Creek (river mile 225). There have been many studies of their frequency in the Grand Canyon tributaries (including Melis and Webb, 1993; Melis et al., 1995; and Webb et al., 2000). The frequency ranges from under 1 to 10 or more per century depending on the tributary. There is the highest frequency between river miles 61.5 to 77.0, of which 95 percent of the tributaries have had at least one debris flow in the last century. Between river miles 132 to 160 is the lowest frequency, only 50 percent of the tributaries have had a debris flow in the last century. The average frequency for any tributary is 1 to 4 per century (Melis and Webb, 1993).

Using a probability approach, Webb et al. (2000) found that 60 percent of all tributaries have a frequency of debris flow of one or greater per century. Further, about 5 percent of all tributaries have a frequency of more than 2 per century, and all have a probability greater than zero of having one every century. On average for any tributary, there is a 30-50 year recurrence interval of debris flow (Melis et al., 1995).

Debris flows travel 1 to 20 km from their initial source (Melis and Webb, 1993). These flows are characterized as being composed of 15 to 20 percent water by-weight and poorly sorted sediment. The sediment composition typically including fewer than 2 percent clay, 10 percent boulder (Melis et al., 1995), and sand may have between 10 to 40 percent by content (Webb et al., 1989); (Table 3).

Prior to regulation by the closure of the Glen Canyon Dam in 1963, the Colorado River in Grand Canyon was characterized by a high inter-annual variability of flooding (Melis et al., 1995). While regulation has not affected the total sediment flux from tributary debris, reduced peak discharge and lower river stages produced by the regulation has caused the sediment-transport rates away from debris fans to attenuate (Melis and Webb, 1993). This has limited the river's ability to completely erode new debris accumulating on debris fans (Melis et al., 1995). In fact, studies have reported that the decrease in size of flood flows due to regulation has produced decrease in sediment-transport potential of the Colorado River by a factor of 3.9 (Howard and Dolan, 1981).

Prior to the closure of the Glen Canyon Dam in 1963, the debris fans were fully reworked; all particles except large boulders were removed (Melis and Webb, 1993). Since regulation, only about 25 percent of the debris-fan is reworked (Webb et al., 2000). This has resulted in the accumulation of finer-grained sediment in rapids and debris fans (Melis and Webb, 1993).

Of the 772 Colorado tributaries in Grand Canyon, only four major tributaries are gaged. Webb et al. (2000) reports that of the total sediment yield by ungaged tributaries in the Grand Canyon, between 4 to 23 percent is delivered by debris flows (Table 4). In addition, this study estimated the total sediment yield and sand delivery from ungaged tributaries to the Colorado River in Grand Canyon to be $2.8\text{-}3.0 \cdot 10^6$ Mg/yr and $0.4\text{-}2.0 \times 10^6$ Mg/yr, respectively (Table 5). The total sediment yield is a function of the sediment flux contributed by debris flow in addition to sediment flux produced from streamflow floods. Accounting for storage in debris fans, ungaged tributaries contribute 0.1×10^6 and 0.5×10^6 Mg/yr of sand between the critical section of Glen Canyon Dam and the Little Colorado. This is 33 percent of the only other source of sand in this section, the

Paria River. This underlines the importance of the small ungaged tributaries to the total sediment budget of the Grand Canyon (Webb et al., 2000).

Methods

Sample collection

In order to understand the nuclide distribution of the Colorado River basin in Grand Canyon, we selectively collected a suite of sediment samples along the Colorado River. We collected samples from both the confluence of tributaries with the Colorado River and mainstream sediment. The tributary samples provide the sediment yield, while the mainstream sediment will provide the distribution of ^{10}Be down the channel. These two combined allow calculation of the sediment budget. We sampled both major and minor tributaries, as well as an even distribution of tributaries from river right and river left. The sampled tributaries include: Paria, Nankoweap, Vishnu, Kanab, Tiger, Little Colorado, Red Canyon, Monument, and Mohawk Rivers. In total, we collected 20 samples will be collected.

Laboratory methods

Each sample will be sieved and weighed. We will analyze out sediment of grain sizes between 500 to 841 μm or 250 to 500 μm, optimizing the preparation process and removing aeolian input. This selection of each sample will then be cleaned to remove dust and organic matter, etched with HCl to remove carbonate and remaining organics, then etched up to four times with HF and HNO_3 to obtain pure quartz and remove atmospheric ^{10}Be. Further processes will then utilized to obtain purified Be and Al. We will then determine $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios using accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory, California.

Discussion & Conclusions

Possible problems

Bierman and Steig (1996) outline a series of assumptions that are inherent in the structure of their model, including:

> (1) the rate of erosion is constant but not necessarily spatially uniform; (2) the basin is in isotopic steady state, (3) sampled sediment is spatially and temporally representative of all sediment leaving the basin, i.e. it is well mixed; (4) mass loss from the basin is occurring primarily by surface

lowering; (5) the mineral selected for isotopic analysis is uniformly distributed through the basin.

While it is difficult to test or constrain each individually, most can be intuitively verified. Use of a large basin with sediment supply from many tributary systems, as is the case of this study, effectively averages spatial and temporal heterogeneity in isotope concentrations (Bierman and Steig, 1996). This prevents the ability of single tributary or sediment sources from biasing the results.

The sampling method acquires sediment directly from tributaries and from along the Colorado River mainstream. This provides quantified understanding of how isotope concentration is being added to the system and how the existing isotope concentration is distributed downstream. Under these constrains, there are three possible outcomes for isotopic concentration as a function of distance downstream (Fig. 8). If isotopic concentration remains constant downstream, it indicates erosion rate is constant through the entire distance and sediment transport is rapid, not allowing for isotopic production while in transport. An increase in concentration would indicate either slow transportation, allowing for isotopic accumulation while in transport, or a decrease in tributary erosion rates, thus supplying higher dosed sediment. Finally, a decrease in net concentration would indicate higher tributary erosion rates, introducing sediment with lower isotopic concentration.

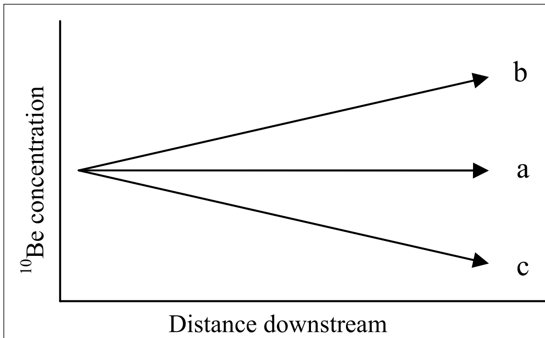

Figure 7: Possible outcomes for ^{10}Be concentration as a function of distance downstream show either (a) erosion rate is constant through the entire distance and sediment was transported rapidly; (b) slow transportation rate or decreased erosion rate; or (c) increased erosion rate.

A final possible problem could be the introduction of immaturely exposed sediment through debris flow. Debris flows are a major source of sediment into the Colorado River system in Grand Canyon. The process of this mass wasting causes sediment below surface level to be immediately introduced into the sediment flux of the system. Since this sediment is from below the surface it received a lower dosage of cosmic ray exposure, introducing “under-exposed” sediment. This would result in lowering the net isotopic concentration. A lower isotopic concentration indicates an increase in erosion rate, which is exactly what is occurring. Consequently, the effect of the debris flow on the system's isotopic concentration accurately depicts the erosion rate.

Possible impact of study

By providing a long-term average erosion rate, one will have a strong grasp of the volume of sediment influx introduced to the Colorado River system. The major impact of this is twofold. First, one can compare this long-term average with trends of current averages, specifically since regulation in 1963, to begin to fully understand sediment impact of regulation. Further, this will also provide a strong understanding of the volume and rate of sediment transport below Glen Canyon Dam. This would be directly applicable in understanding the volume of sediment entering Lake Mead. The long-term average is more effective than current averages because it dampens the effect of climatic variability and cyclic fluctuations in sediment yield.

Time Line

Sediment samples are currently in the etching process in Skidmore College Geosciences Cosmogenic Isotope Laboratory to be refined to pure quartz. They will be completed and sent to University of Vermont Cosmogenic Isotope Laboratory in November. Here the samples will undergo final refinement to acquire pure Be and Al and be packed into targets. Once this is done, the targets will be sent to Lawrence Livermore National Laboratory, Livermore, California. The results of $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios will then be acquired by March. Upon receiving these data, analysis and conclusions can be made, allowing for presentation of this paper in late April.

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Appendix

m^* = basin-wide average rate of mass loss (g cm^{-2}a^{-1})

Λ = attenuation factor (g cm^{-2})

$P^J_{0\ \mathrm{eff}}$ = effective basin-wide production rate at ground surface (atoms a^{-1}g^{-1})

C^J_{SED} = average isotope concentration in sediment in mineral *J* leaving basin (atoms g^{-1})

C^J_{SOL} = average isotope concentration in solution in mineral *J* leaving basin (atoms g^{-1})

λ = decay constant (a-1)