Timing and patterns of basin infilling as documented in Lake Powell during a drought

Lincoln Pratson[1], John Hughes-Clarke[2], Mark Anderson[3], Thomas Gerber[1*], David Twichell[4], Ronald Ferrari[5], Charles Nittrouer[6], Jonathan Beaudoin[2], Jesse Granet[3], John Crockett[6†]

[1]Nicholas School of the Environment, Duke University, P.O. Box 90227, Durham, North Carolina 27708, USA
[2]Ocean Mapping Group, University of New Brunswick, P.O. Box 4400, Fredericton, New Brunswick E3B 5A3, Canada
[3]National Park Service, Glen Canyon NRA, P.O. Box 1507, Page, Arizona 86040, USA
[4]U.S. Geological Survey, 384 Woods Hole Road, Quissett Campus, Woods Hole, Massachusetts 02543-1598, USA
[5]Bureau of Reclamation, P.O. Box 25007, Denver, Colorado 80225, USA
[6]School of Oceanography, University of Washington, P.O. Box 357940, Seattle, Washington 98195-7940, USA

ABSTRACT

Between 1999 and 2005, drought in the western United States led to a >44 m fall in the level of Lake Powell (Arizona-Utah), the nation's second-largest reservoir. River discharges to the reservoir were halved, yet the rivers still incised the tops of deltas left exposed along the rim of the reservoir by the lake-level fall. Erosion of the deltas enriched the rivers in sediment such that upon entering the reservoir they discharged plunging subaqueous gravity flows, one of which was imaged acoustically. Repeat bathymetric surveys of the reservoir show that the gravity flows overtopped rockfalls and formed small subaqueous fans, locally raising sediment accumulation rates 10–100-fold. The timing of deep-basin deposition differed regionally across the reservoir with respect to lake-level change. Total mass of sediment transferred from the lake perimeter to its bottom equates to ~22 yr of river input.

INTRODUCTION

The timing, location, and nature of deposition in a basin are largely dictated by base (i.e., water) level, basin-floor subsidence, and sediment supply (Posamentier et al., 1988). The impacts of base-level change and subsidence on basin infilling have been explored extensively through modeling (Paola, 2000), experiments (e.g., Heller et al., 2001), and analyses of basin stratigraphy (e.g., Van Wagoner et al., 1990). These same methods have also been used to evaluate the effects of sediment supply (e.g., Perlmutter and Matthews, 1989), but to a much lesser extent and with fewer conclusive and generally applicable results. This is because of uncertainties over (1) how sediment flux to a basin varies with respect to base-level change (e.g., are changes in the two in or out of phase?), and (2) the source of the sediments, from inside or outside the basin (Pratson et al., 2007).

Here we present new insights on these issues gained through repeat bathymetric surveys of Lake Powell (Arizona-Utah) (Fig. 1A) during a fall and rise in reservoir level between 1999 and 2005 (Fig. 1B). Lake Powell proved exceptional for this purpose because its physiography, time of operation, and water and sediment input are so well constrained. Water outflow occurs through penstocks (i.e., pipes) embedded in the Glen Canyon Dam >80 m above the adjacent reservoir floor (Fig. 2A), so essentially all sediments that enter the reservoir are trapped within it. This trapping began when the dam was completed 11 April 1963. Pre-reservoir topography was accurately surveyed beforehand (United States, 1963) and lake level has been recorded since (Fig. 1B). Input to the reservoir is gauged and dominated by the Colorado and San Juan Rivers, which supply ~95% of the water and ~90% of the sediment (Potter and Drake, 1989). Deltas have been rapidly growing beyond the mouths of both rivers (Fig. 2A), with maximum sediment accumulation rates through 1986 being measured in meters per year (Ferrari, 1988). The narrowness of the lake (generally ≤1.5 km wide) (Fig. 1A) prevents significant lateral sediment movement, so the deltas are essentially two-dimensional.

*Current address: ChevronTexaco Energy Technology Company, 1500 Louisiana St., Bellaire, Texas 77002, USA.

†Current address: San Diego State University Research Foundation, 5250 Campanile Dr., San Diego, California 92182, USA.

BACKGROUND AND METHODS

Between fall 1999 and fall 2004, average river inflow to Lake Powell was approximately halved by a drought in the southwestern U.S. (Fig. 1B). As withdrawals from the reservoir exceeded the inflow, lake level fell >44 m (Fig. 1B). Inflow then returned to its historical norm in spring 2005, raising lake level >9 m by early summer (Fig. 1B).

Within this period, three bathymetric surveys of Lake Powell were carried out. The surveys were conducted early (April 2001) and late (May 2004) during the fall in lake level, and (June 2005) when lake level had risen >9 m from its lowest point two months prior (Figs. 1B and 2A). Note that all the surveys were done as snowmelt from the Colorado watershed was arriving at Lake Powell and inflow was at its yearly maximum (Fig. 1B).

The surveys were of varying extent and used different high-resolution mapping systems capable of detecting lake bottom to within <3 cm. In 2001, the main axis of the Colorado arm was surveyed using a Garmin 240B single-beam 50/200 kHz fathometer integrated with a P-CODE global positioning system (GPS) receiver. In 2004, the main axes of both the Colorado and San Juan arms were surveyed with an EdgeTech 512i 0.5–12 kHz Chirp (compressed high-intensity radar pulse) sonar and a GPS receiver. In 2005, a Kongsberg EM3002 300 kHz multibeam sonar system, coupled with short-baseline differential GPS, was used to completely map the Colorado, San Juan, and Escalante arms of the reservoir. A 500 kHz SonTek acoustic Doppler profiler, with GPS, was used to profile the topsets of the Colorado and San Juan deltas, where water depths were too shallow to take the EM3002 (i.e., <10 m).

The EM3002 automatically applied sound speed corrections to the soundings and translated them into georeferenced depths. For the other surveys, depths were computed by multiplying the bottom echo traveltimes with an average water sound speed for each survey. The average sound speeds were derived from control points with known elevations located throughout the reservoir. Finally, depth measurements from all the surveys were converted into elevations using the appropriate daily reservoir levels posted by the U.S. Bureau of Reclamation (USBR).

The surveys were placed within the longer-term context of reservoir infilling by coregistering them in the geographic information system (GIS) with the few previous surveys of Lake Powell: (1) a detailed topographic survey made by the USBR before the Glen Canyon Dam was built (United States, 1963); (2) a bathymetric profile up the axes of the Colorado and San Juan arms compiled in 1976 by Potter and Drake (1989); and (3) a series of cross-lake bathymetric profiles measured by the USBR every few kilometers up each waterway of the reservoir in 1986 (Ferrari, 1988).

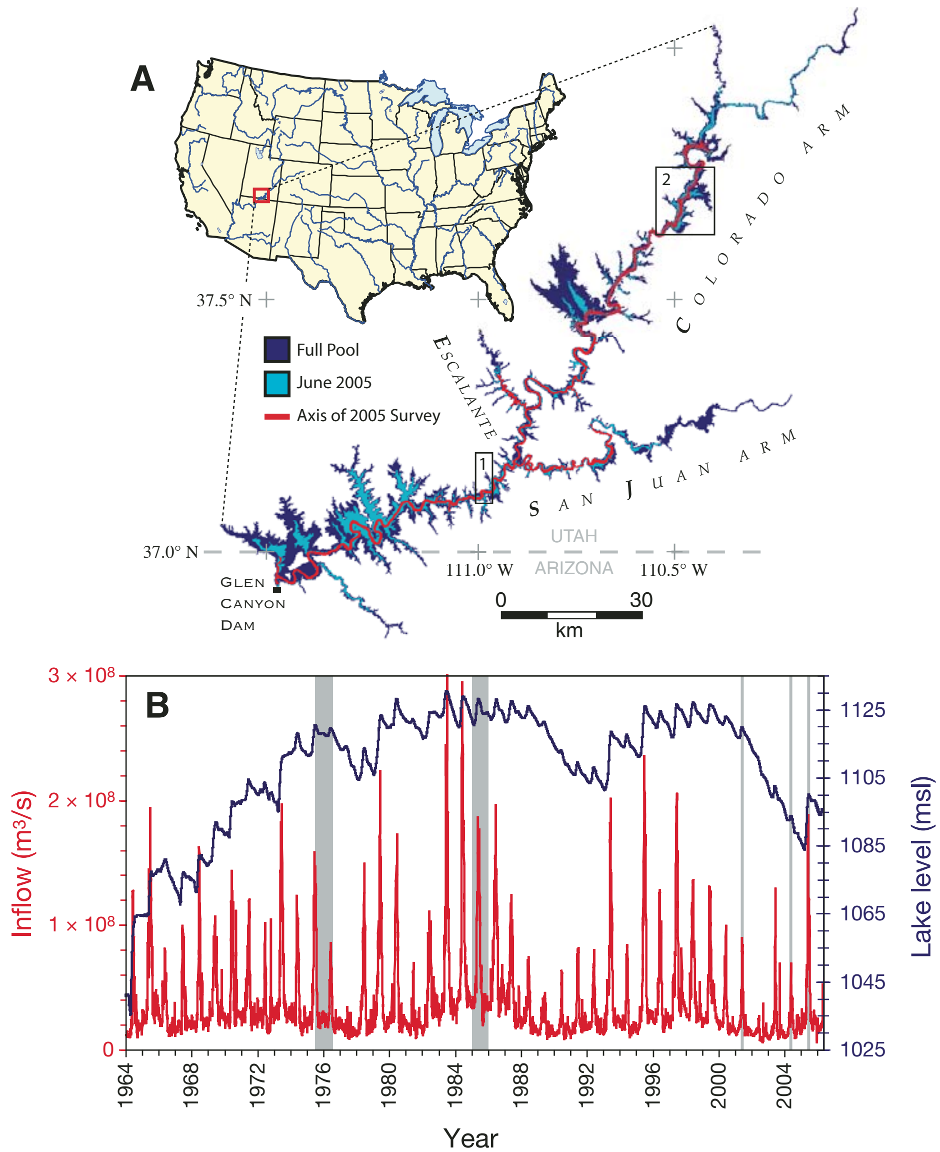

Figure 1. A: Map of Lake Powell. Full pool is maximum reservoir level (1141 m). Regions 1 and 2 correspond to Figures 3A and 3B, respectively. B: Inflow to Powell and lake level (msl—meters above sea level) since closure of Glen Canyon Dam (http://www.usbr.gov/uc/crsp/GetSiteInfo). Gray bars indicate when reservoir was surveyed.

RESULTS

The earlier bathymetric surveys of Lake Powell (Fig. 2A) show that prior to the 1999–2004 drought, sedimentation was greatest on the foresets of deltas building out from the Colorado and San Juan Rivers, with accumulation rates at these sites reaching 2–3 m/yr (Ferrari, 1988). As lake level fell during the drought, deposition shifted to the deeper part of the reservoir (Figs. 2A–2C). However, the location and extent of this deposition varied basinward of the two rivers, the differences persisting through the subsequent lake-level rise.

In the Colorado arm of the reservoir, the delta foreset continued to prograde and steepen even as lake level fell and the delta top was incised by the Colorado River (Fig. 2A). During the lake-level fall between 2001 and 2004, mean accumulation rates remained highest on the delta foreset, but sediments were deposited >70 km basinward at an average rate of 0.75 m/yr (Fig. 2B). A significant fraction of this deposition became ponded behind three large rockfalls that cross the reservoir floor (RF1–3, Fig. 2A). These were created decades before by failures of the sandstone cliffs that border much of the lake (Potter and Drake, 1989). The sediment ponding was greatest behind the rockfalls closest to the delta (RF1 and RF2; Fig. 2A, and 1 in Fig. 3A), but sediments were also carried over these obstacles to at least as far as a third rockfall near where the Colorado and San Juan arms meet (RF3, Fig. 2A). The bathymetric changes show that sediment accumulation then waned in the deep part of the lake during lake-level rise, and deposition shifted back up onto the delta foreset, where the maximum accumulation rate jumped to >13 m/yr (Fig. 2B).

In the San Juan arm of the lake, a different pattern of deposition ensued. The delta here prograded no more than 1 km during the fall and subsequent rise in lake level with little if any steepening (Fig. 2A). Sediments tended to bypass the entire delta and deposit beyond its foreset all the way to the Glen Canyon Dam, ~165 km beyond the inflow (Figs. 2A and 2C). Sedimentation in this deep, lowermost stretch of Lake Powell did not increase significantly until well into the drought. The ^{210}Pb measurements from a core collected in the lower lake in 2001 (Figs. 2A and 2C) indicate that for more than 10 yr sediment accumulation rates at the site were 0.01 m/yr. This rate agrees with an average rate of 0.04 m/yr determined ~1 km away by differencing soundings from the 1986 and 2001 bathymetric surveys. However, by the 2004 survey, mean sediment accumulation rates in the lower part of the lake increased almost two orders of magnitude, to meters per year (Fig. 2C). Furthermore, small subaqueous fans had formed at the mouths of at least two side canyons, Antelope (SF3) and Forbidden (SF1) (Fig. 2A). The Forbidden fan was imaged in the 2004 and 2005 surveys (1 in Fig. 3B). It was not present during the earlier 1986 survey and was not mapped in 2001, but the 2004 Chirp subbottom profile reveals a reflection at an equivalent depth to the lake floor in 2001 that can be traced under the fan (3 in Fig. 3B). This suggests that the fan formed during the 3 yr period when lake level fell. Fan formation may have then ceased; 1.5 m of sediment ponded behind the up-lake levee of the fan as sediment continued to come down the main axis of the lake (3 in Fig. 3B). Unlike in the Colorado arm, deep-water deposition below the San Juan arm did not decline during the subsequent lake-level rise. Instead, accumulation rates through the 2005 survey remained as high as during the period of lake-level fall (Fig. 2C).

The deep-water deposits were laid down by subaqueous gravity flows. Such events are not restricted to periods of low lake level. Turbid, bottom-hugging density currents commonly emanate from the Colorado and San Juan Rivers (http://www.gcmrc.gov/products/water_quality/; Johnson and Merritt, 1979). These hyperpycnal flows were probably frequent between 1995 and 2000 when lake-level was high, for suspended-sediment concentrations averaged ≥0.5 g/L at the Green River, Cisco, and Bluff, Utah, gauging stations 100–150 km upriver of the reservoir (http://co.water.usgs.gov/sediment/seddatabase.cfm). However, the jumps in deep-reservoir sediment accumulation rates (Figs. 2B

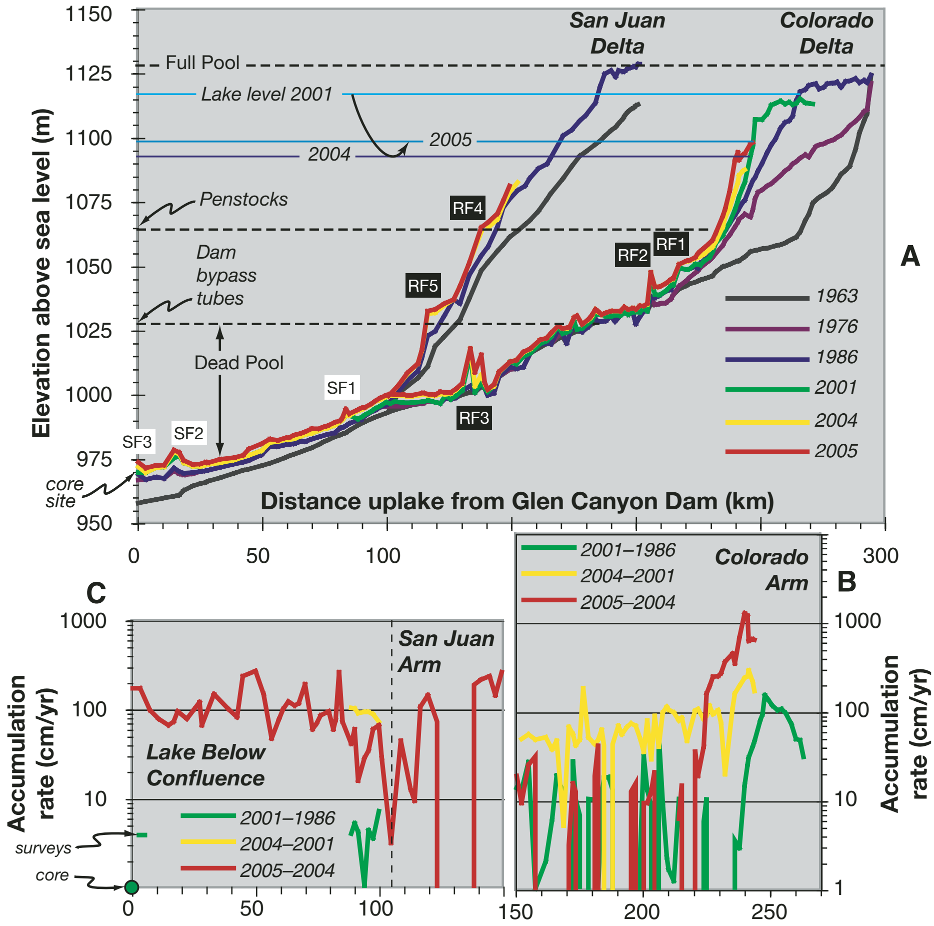

Figure 2. A: Successive bathymetric profiles along main axes of Powell. RF—rock fall; SF—subaqueous fan. Profiles portrayed at same irregular several-kilometer sample spacing as 1986 survey (Ferrari, 1988). Note that RF3 separates floor of Colorado arm from that of San Juan arm to Glen Canyon Dam. B, C: Sediment accumulation rates from differencing surveys indicated and dividing by elapsed time. Except for soundings adjacent to dam, 2001 survey stops ~80 km up reservoir of dam. Dead pool is unusable water, defined by elevation of tubes for bypassing water around dam.

and 2C) clearly point to increased deposition by subaqueous gravity flows during the drought.

At least one of these subaqueous gravity flows was imaged in the 2005 survey (Fig. 3A). Adjacent multibeam bathymetry swaths collected over five days captured the progress of the flow as it moved down the Colorado Delta foreset (2 in Fig. 3A). The type of flow is unclear. It could have been a viscous debris flow or just the bedload component of a slow-moving turbidity current. In either case, its sediment concentration was great enough to produce a distinct acoustic reflection delineating the front of the flow as an abrupt 20–40 cm rise above the reservoir floor (3 in Fig. 3A). Differences in the position of the front over time (2 in Fig. 3A) indicate that the flow was progressing down the 0.1° incline at 6 m/h.

DISCUSSION

As in natural basins, water and sediment supply to Lake Powell are coupled through the tie between regional climate and hydrology (Scholz, 2001). Because of this coupling, our observations of change in Lake Powell offer new insights on sediment supply to basins during climate-driven base-level change.

The first of these insights is that subaqueous gravity-flow dynamics may affect the timing and distribution of basin sedimentation during base-level change. In Lake Powell, a far greater fraction of incoming sediment bypassed the San Juan Delta foreset than the Colorado, and the bypassing was not limited to falling base level, but continued into the lake-level rise, although why this occurred is unclear. Until recently, the San Juan Delta foreset had always been steeper than the Colorado, but by spring 2005 the latter had achieved the same 0.1° dip (Fig. 2A, and 1 in Fig. 3A). While the mean water discharge from the San Juan River is little more than 15% that of the Colorado, sediment discharge from the two rivers is roughly equivalent (Potter and Drake, 1989). The higher concentration of suspended sediment in the San Juan River could imbue gravity flows with greater excess density to move beyond the delta foreset. Whatever the reason, the timing and extent of deep-basin sedimentation in Lake Powell were not simply a function of lake level or its rate of change, as sequence stratigraphic concepts postulate (Posamentier et al., 1988). The character and dynamics of the subaqueous gravity flows involved were also factors.

The second insight is that base-level falls that expose unconsolidated strata can lead to increased hyperpycnal flows in a basin even when river inflow is reduced. Whereas hyperpycnal flows are common in lakes (Fan and Morris, 1992), long-term recordings of coastal river discharges have suggested that such flows require floods to initiate where rivers empty into the ocean (e.g., Dadson et al., 2005; Johnson et al., 2001; Mulder and Syvitski, 1995). Like all rivers, sediment discharge in the Colorado and San Juan Rivers is directly proportional to water discharge, which declines during droughts (Committee to Review the Glen Canyon Environmental Studies, 1991). Consequently, the halving of water discharge to Lake Powell during the 1999–2004 drought should have also reduced sediment discharge to the lake and presumably hyperpycnal flows. However, our observations indicate that such flows increased over this period. The primary sediment sources for these flows were the local unconsolidated delta topsets exposed by the lake-level fall. Although diminished, river-mouth water discharges incised these strata with relative ease, becoming rich in suspended sediment and thus negatively buoyant as they crossed into the reservoir. It seems feasible that marine hyperpycnal flows could be similarly generated at river mouths during sea-level lowstands if exposed basin strata are easily eroded, even when river water discharges are lower than those needed for the phenomena to occur today.

Finally, the vast majority of sediments moved deep into a basin over the course of low base level may actually come from erosion of strata within the basin exposed by the base-level fall, and not from an up-river source. In Lake Powell, the drought triggered the redistribution of ~1 km^3 of sediments from along the lake perimeter to below the elevation of tubes that can bypass water around the Glen Canyon Dam, i.e., the "dead pool" level (Fig. 2A). Assuming that the average porosity and grain density of the strata in Lake Powell are 60% and 2500 kg/m^3, respectively, the volume of sediments moved below the dead pool level equates to a mass of 1000×10^6 Mt. Combined, the Colorado and San Juan rivers annually deliver ~41×10^6 Mt of sediment into Lake Powell, which represents 90% of the total sediment load to the lake (Potter and Drake, 1989). This suggests that possibly as much as 22 yr of river sediment input to Lake

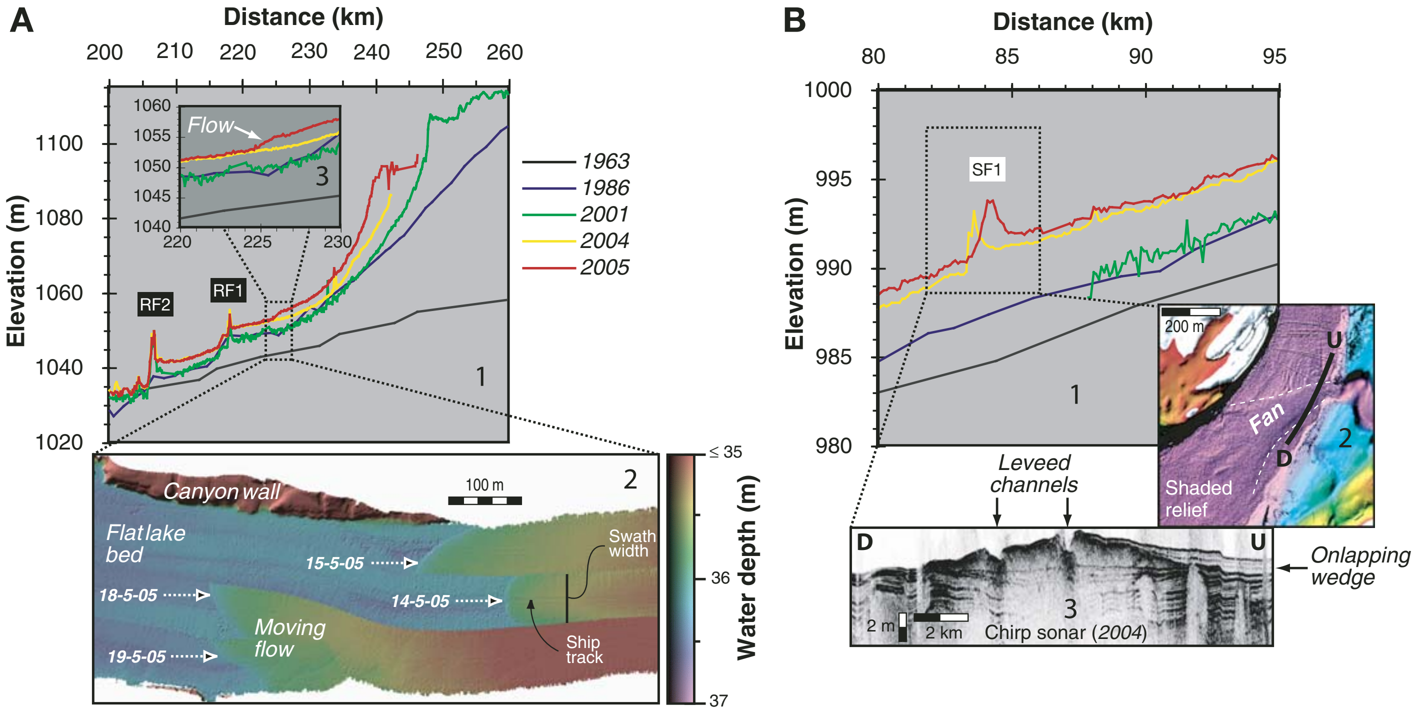

Figure 3. A: 1—Colorado Delta profile (100 m horizontal sample spacing); note filling behind RF1 (RF—rockfall) and 2 between 2001 and 2004. 2—Moving subaqueous gravity flow evident in shaded relief imagery. Arrows point to locations of flow front on successive dates (day, month, year). 3—Flow is evident in 2005 bathymetric profile of Colorado Delta, rising 3 m above surrounding reservoir floor. B: 1–2—Subaqueous fan (dashed outline) emanating from Forbidden Canyon into Lake Powell. SF—subaqueous fan. Fan formed by 2004. 3—Chirp (compressed high intensity radar pulse) sonar profile, collected in 2004.

Powell was remobilized to the deepest parts of the lake in ~20% of the time. While the speed and scale of this redistribution are undoubtedly tied to the rate and magnitude of the base-level fall in Lake Powell as well as to the erodability of the exposed strata, our estimates suggest that deep-water sediments deposited in many basins during low base level could be overwhelmingly derived from erosion of shallow-water strata in the basin exposed by the fall.

ACKNOWLEDGMENTS

Grants to Pratson from the U.S. Office of Naval Research (N00014-03-1-0141) and the U.S. National Science Foundation (EAR-98-96392 and OCE-04-05515) helped support data collection, analysis, and manuscript preparation. The 2005 multibeam survey was made possible by a Natural Sciences and Engineering Research Council Discovery grant to Hughes-Clarke. We thank Carlos Pirmez and an anonymous reviewer, whose comments greatly improved the manuscript.

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Manuscript received 11 January 2008
Revised manuscript received 8 July 2008
Manuscript accepted 19 July 2008

Printed in USA