The Moab Mill Project

A technical report towards reclaiming uranium mill tailings along the Colorado River in Grand County, Utah

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This report is available on the World Wide Web: http://www.livingrivers.org/MoabMillProject.pdf

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Purpose: This study evaluates the analyses by the Department of Energy (DOE) concerning flood flows on the Colorado River in the vicinity of the Moab Mill Project Site at Moab, Utah (former Atlas Uranium Mill), and other relevant information regarding the erosional potential of the Colorado River during an extreme flood event. Specifically, the evaluations address probable maximum floods by investigating paleoflood deposits upstream of the uranium mill tailings pile, in addition to historic river channel migration in the vicinity of the pile.

Need: Concerned citizens of Moab and Grand County understood the uranium tailings pile (12 million tons) adjacent to the Colorado River posed a serious health hazard for residents, visitors, downstream water consumers, and endangered species. In 2004 it appeared certain that the DOE would mitigate this hazardous material by stabilizing and armoring the tailings pile in place alongside the Colorado River.

To these citizens, knowing the variable extremes in the natural flow of the Colorado River, such a decision seemed irresponsible. There seemed to be no sound basis for a DOE determination that the integrity of the tailings from 200 to 1,000 years could be reasonably guaranteed; such a determination is required by federal regulation. Funding was sought to retain experts to evaluate the scientific assumptions related to the historic flood and channel migration behavior of the Colorado River in the vicinity of Moab. Further scientific study, including fieldwork, was required to address some of the many uncertainties associated with the historic flood potential and, thus, the future flood potential of the river in the vicinity of the site.

Results: Two reports were commissioned and are contained herein.

The first, prepared by Dr. John C. Dohrenwend (University of Arizona), is an evaluation of the scientific investigations as presented in the 2004 DOE Draft Environmental Impact Statement (DEIS). Though the DEIS did not specifically include a preferred alternative for tailings reclamation, the findings suggested that capping the waste pile in place along the Colorado River remained a viable consideration. Dr. Dohrenwend's findings challenged the assumptions of the DOE relating to floodplain meanders of the Colorado River adjacent to the Moab site. In the context of the National Environmental Policy Act (NEPA) process, the DOE responded to Dr. Dohrenwend's findings and additional new information relating to the behavior of the Colorado River. The DOE finally concluded that, indeed, too many uncertainties were associated with the long-term stability of the tailings on the floodplain and chose an off-site disposal alternative.

The second, prepared by Dr. Noam Greenbaum (University of Haifa), represents the first-ever professional paleoflood study on the main stem Colorado River above Lee's Ferry, Arizona. His findings bring forth new scientific data that challenge assumptions regarding the probable maximum flood and the number and intensity of floods over the past several thousand years. The results of his study provide further justification for the DOE decision to relocate the tailings to an off-site location. The paleoflood study also has important implications for research on of the long-term hazards associated with potential floods in the upper Colorado River and its tributaries.

Recommendation: Continue paleoflood research on the Colorado River, Green River, and San Juan River above Lake Powell for future resource management planning.

Editors: John S. Weisheit and Sarah M. Fields (July, 2006)

Cover photo: Floodplain before development of the Moab Uranium Mill. Whitman Cross, 1905. USGS Library, Denver.
Inside cover photo: Tailings pile at Moab Project Site from the Colorado River. John Weisheit, 2005.

Table of Contents

List of Figures, Photos, and Tables

A Review: Department of Energy's Assessment of Potential Flood Hazards at the Moab Project Site

Paleofloods in the Upper Colorado River near Moab, Utah

A Review: Department of Energy's Assessment of Potential Flood Hazards at the Moab Project Site (Atlas Tailings Pile), January 2005

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Introduction

For almost 25 years, the City of Moab, Grand County, and the State of Utah have all been faced with a difficult and contentious problem: what to do with the former Atlas Uranium Mill tailings pile located on the Colorado River floodplain just north of town? On the one hand, an impressive number of scientists and engineers working for Atlas Minerals Corporation, the Nuclear Regulatory Commission, and the Department of Energy (DOE) have written reports suggesting that the pile is safe and will not be compromised by even the largest of floods that could possibly occur in the area. Common sense suggests that the location of the pile isn't safe, because the Colorado River is notorious for the extreme variability of its flows.

Flows in historic times have ranged from base flows of 2,500 to 4,000 cubic feet per second (cfs) during the dry months of late summer, fall, and winter to as much as 125,000 cfs during the snowmelt floods of late spring and early summer. Moreover, the site of the mill and tailings pile is located on the Colorado River floodplain on the outside of a large bend in the river channel.

The potential impact of an extreme flood is considered by many people to be one of the key issues relating to the safety of the mill site. However, this possibility is not adequately considered in the Draft Environmental Impact Statement (DEIS) on "Remediation of the Moab Uranium Mill Tailings" released by the DOE on November 3, 2004. Instead, limited references are made to four previous reports that discount flooding as a serious problem. These reports are:

Harvey, M. D., and S. A. Schumm, 1982, Geomorphic evaluation of the long term stability of the below grade disposal system site, Atlas Minerals Uranium Extraction Facilities, Moab, Utah: Water Engineering and Technology, Inc., Shreveport, Louisiana, unpublished report, 30 p.

Mussetter, R. A., and M. D. Harvey, 1994, Geomorphic, hydraulic and lateral migration characteristics of the Colorado River, Moab, Utah, Final Report: Mussetter Engineering, Inc., Ft. Collins, Colorado, unpublished report to Canonie Environmental and Atlas Corporation (MEI Ref. No, 9402), 102 p.

U. S. Department of Energy (Grand Junction Office), 2002, Lithologic, well construction and field sampling results from the 2002 field investigation: Report, October 2002, 60 p.

U. S. Department of Energy (Grand Junction Office), 2003, Migration potential of the Colorado River channel adjacent to the Moab Project site: Letter Report, November 2003, Revision 2, 11 p. + Figures

The last of these reports draws heavily from the data and interpretations presented in the previous reports and summarizes the position of the DOE regarding the flood hazard potential at the Moab Mill site. This 19-page document claims that,

> Although a conclusive prediction of future river movement is not possible, evidence suggests that the river is and will continue migrating to the south and east away from the existing tailings pile.

In support of this claim, the November 2003 letter report presents several technical arguments. These arguments include consideration of:

1) Historical evidence of river migration,

2) Sediment input from Courthouse Wash and Moab Wash,

3) Location and age of river terrace gravels at the north end of Moab Valley,

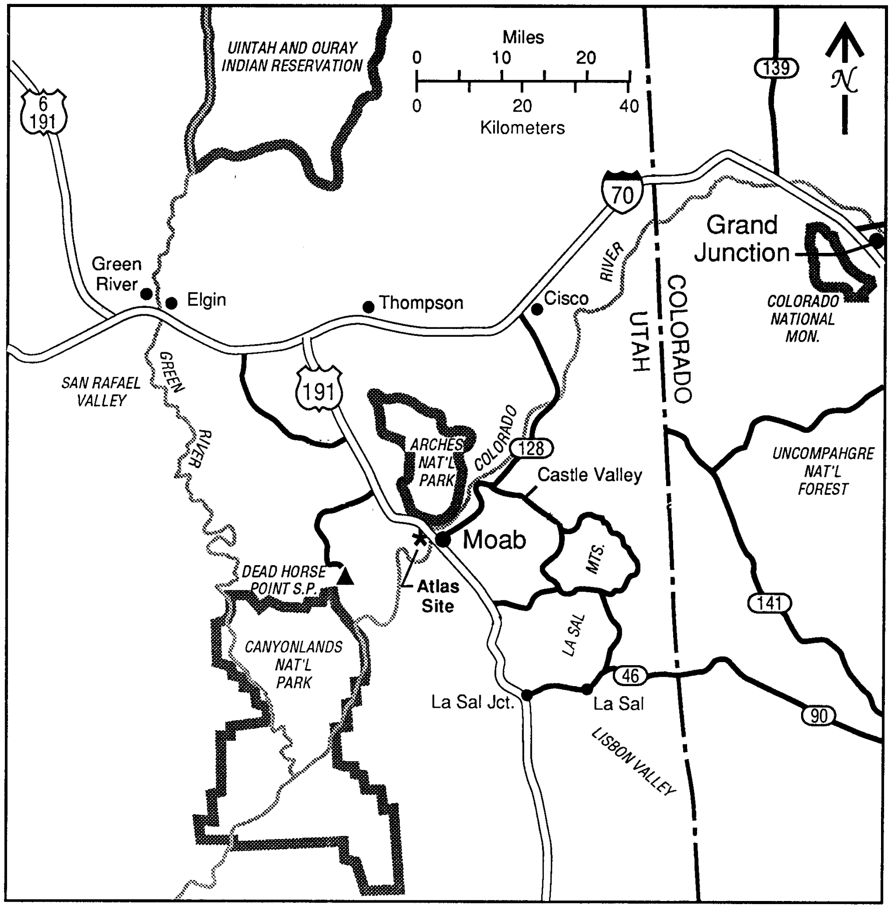
4) Thickness and distribution of basin fill sediments in the Moab Valley,

5) Rate and character of salt dissolution in the Moab Valley area, and

6) Absence of a cobble gravel bedload downstream of the Portal.

Historical evidence of river migration

Because of the potential impact of an extreme flood on the stability of the Atlas tailings pile, the Colorado River and its floodplain between the US 191 bridge and the Portal (Figures 1a and 1b) have become one of the most intensively studied areas in the upper Colorado River basin. This area has been measured, modeled, drilled, and sampled throughout the past two decades in an effort to predict future changes in the river's channel.



Fiqure 1a. Generalized regional map showing the location of the Moab Project Site (Atlas Site) in east-central Utah. Department of Energy, 2003.

Fiqure 1b. Aerial photograph showing the location of the Moab Project Site at the north end of the Moab Valley. Department of Energy, 2003.

Historic maps, aerial photos, and satellite images have been examined to document changes in channel form and position over the past 80 years.

According to the analysis included in the November 2003 report, the Colorado River is moving south and east towards Moab. However, this is highly unlikely, because Moab is on the inside of a river bend aimed away from town. In fact, the historical analysis presented in this DOE report is seriously flawed. Several of the maps and aerial photographs used in this analysis were not accurately registered to each other. These inaccuracies are most conspicuous for the DOE interpreted positions of the channel in 1944 and 1953. Downriver from the pile, the southwest bank of the river is shown in the DOE analysis to be located in 1944 and in 1953 near the present position of the river's northeast bank. Also, conspicuously inconsistent are the different channel positions attributed to 1953 (based on aerial photos) and 1959 (based on the 1959 US Geological Survey topographic map). This is particularly revealing because the 1959 topographic map was produced from the 1953 photos.

By accurately registering all the historic maps and photographs, reliable comparisons between one time and another can be made, and the picture summarized in Figure 2 emerges clearly. Since 1924 (historic map not shown), the south and east bank (river left, looking downstream) has moved progressively north, west, and southwest away from Moab. From the bridge to the pile, the south bank has moved north and northwest an average of 320 feet since 1944. Downstream from the pile, this bank has moved west and southwest an average of 175 feet during this same period. In contrast, most of the north and west bank (river right) has remained in essentially the same position since 1914. The only significant exception is the area immediately adjacent to the pile where the channel appears relatively unstable. In this area, the west bank shifted rapidly eastward between 1962 and 1983, only to shift westward again sometime before 2001. The net result of all of these changes has been a conspicuous 37% narrowing of the channel that occurred mostly between 1962 and 1983. These findings are directly contrary to the statement in the November 2003 letter report that "the river is and will continue migrating to the south and east away from the existing tailings pile," and they cast considerable doubt on the overall integrity of the DOE report. Moreover, the progressive narrowing of the channel between 1944 and the present implies that the river's past behavior may not be a reliable predictor of future channel changes.

Sediment input from Courthouse Wash and Moab Wash

According to the November 2003 letter report: (a) the tailings pile and former mill site are sited on an alluvial fan developed from Moab Wash and Courthouse Wash; (b) both washes have delivered significant quantities of

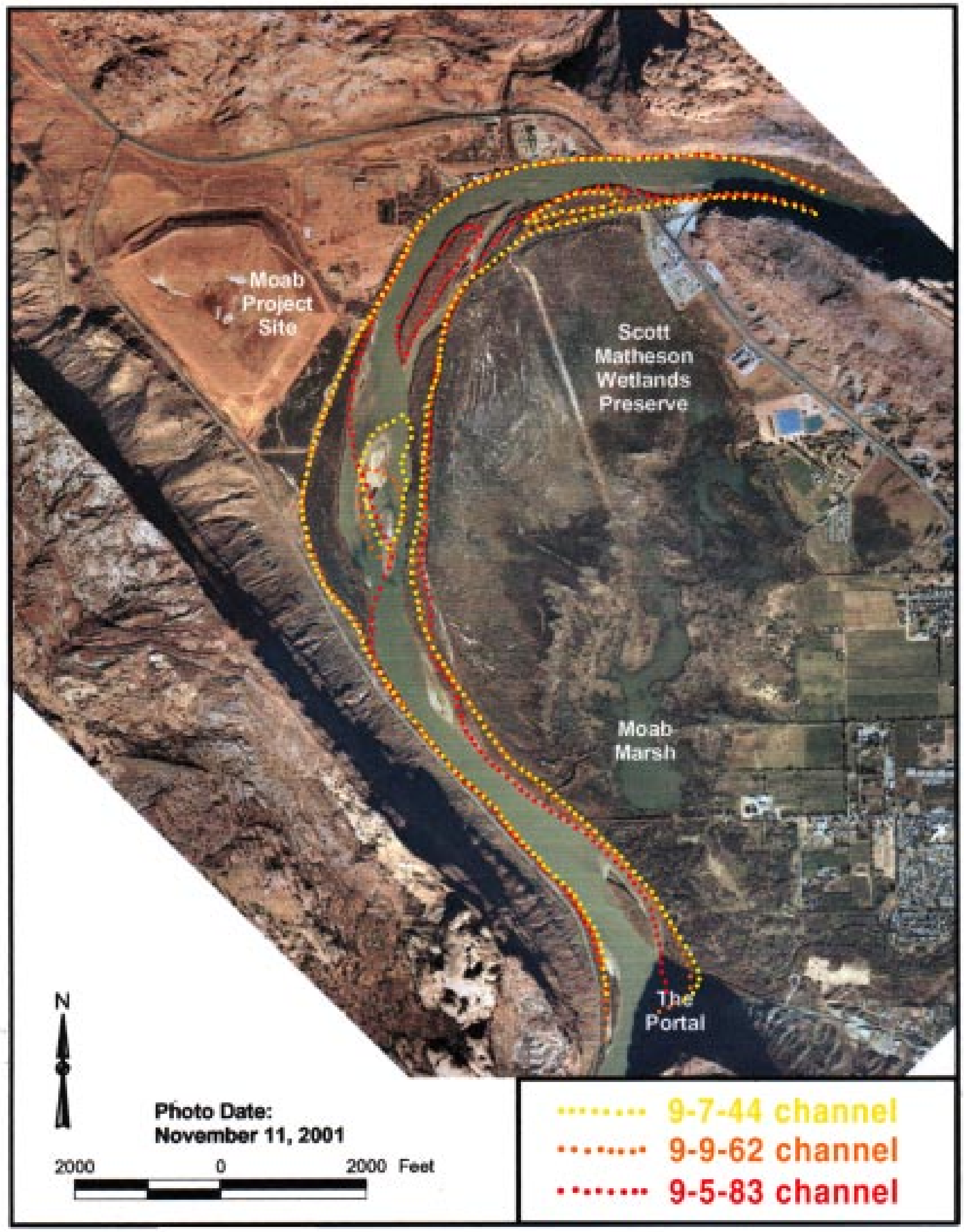


Figure 2: Channel positions of the Colorado River in the vicinity of the Moab Project Site in 1944, 1962, 1983, and 2001. John C. Dohrenwend, 2005.

sediment to the area in the past, and deposition will continue unless significant changes occur in the upstream watersheds; and (c) sediment input from Courthouse Wash and Moab Wash tends to push the river south and prevents lateral migration to the north.

However, as inspection of historical aerial photographs clearly shows the Colorado River channel has, in fact, moved more than 300 feet north and northwestward between 1944 and the present time (Figures 3a and 3b). In direct contradiction to DOE's argument, most of this movement occurred directly opposite and immediately downstream from the mouth of Courthouse Wash.

It has long been recognized that the alluvial fans of desert streams typically build outwards from their valley (or canyon) mouths. However, in some important ways, Courthouse Wash is not a typical desert stream. It joins the Colorado River less than a quarter mile after leaving the mouth of its narrow, steep-walled canyon. During low flows, the much larger flow of the Colorado quickly carries away most of the sediment that might otherwise be deposited at the mouth of the wash. During high flows a very different situation may occur.

Like many of the washes that drain the slickrock country in the Moab area, Courthouse Wash is ephemeral, and its flow is highly variable. The wash seldom flows with any volume for more than a few days, even after a heavy rain. Flash flooding is common and typically occurs during the southwest monsoon in mid to late summer. During flash floods, flows down the wash may exceed several thousand cfs and, in extreme cases, may peak at flows greater than 10,000 cfs.

Most of the water flowing down the Colorado River comes from the snowfields of the southern Rocky Mountains. Consequently, the highest flows on the river almost always occur during the snowmelt floods of late spring. By mid summer, flow in the river typically drops to somewhere between 2,500 and 4,000 cfs. Therefore, whenever a large flash flood occurs on a tributary wash, the result is that for a short time the flow of the tributary exceeds the flow of the main stream. When this happens, the tributary flow may jet all the way across the main stream channel to the opposite bank.

This unusual role reversal between tributary and main stream can be truly spectacular. For example, consider this eyewitness account of an event that occurred near the downstream end of Westwater Canyon in the late summer of 2002, when washes started running red over the black rocks of the canyon's walls: "At the end of the rapids and around the corner, a side canyon at Big Hole was spewing water, rocks, and debris across the river and effectively preventing the rafts from passing the side canyon. The flow

Figure 3a. Vertical aerial photograph of the Colorado River in the vicinity of the Moab Project Site in 1962. Department of Energy, 2003.

Figure 3b. Vertical aerial photograph of the Colorado River in the vicinity of the Moab Project Site in 1983. Department of Energy, 2003.

Supplemental photograph of Courthouse Wash before the development of main stem reservoirs. Dan O'Laurie Museum of Moab. Photographer unknown.

Supplemental photograph of Courthouse Wash as it appears today. Photographer unknown.

from the side canyon had enough force to shower the rafters upstream with a rain of mud."

Courthouse Wash has been witnessed to behave in a similar fashion during late summer floods, shooting water and debris across the Colorado and sometimes into the sloughs. Firsthand observations of the effects of a powerful flash flood on Courthouse Wash in the mid-1960s provide insight into the effect of such floods: "The alluvial fan deposited by this flood was large enough to temporarily block and divert the flow of the Colorado River." This incident is a compelling demonstration of the possible short-term dominance of the wash during the summer monsoon season, when the river is low.

This role reversal has contributed to the accumulation of large quantities of sediment along the south bank of the Colorado River directly opposite and immediately downstream from the mouth of the wash. This, in turn, has contributed to the northward migration of the south bank and a significant narrowing of the river channel.

Location and age of river terrace gravels at the north end of Moab Valley

River gravels are exposed on a strath terrace surface at the mouth of Courtwash Wash. This terrace surface is an erosional feature cut in bedrock. The elevation of this terrace is about 4,012 feet, approximately 54 feet above the present level of the Colorado River channel (Figure 4a). The age of this terrace has been estimated to be about 12,000 to 30,000 years old. This age estimate is based on a comparative analysis of soil development. However, the terrace surface is significantly degraded. Therefore, this age estimate should be considered as very imprecise and is probably much too young.

The November 2003 letter report argues that the location and estimated age of this terrace suggests that the river has migrated southward over the last 12,000 to 30,000 years. However, there are two significant problems with this suggestion:

(1) This terrace is located within the mouth of Courthouse Wash and, therefore, is more a product of Courthouse Wash than the Colorado River. Colorado River gravels are preserved on the terrace surface. However, these gravels could have been deposited during a large flood on the Colorado River, and, therefore, they do not necessarily indicate the exact position of the Colorado River channel at the time of deposition.

Assuming the age estimate based on relative soil development is correct, the height of this terrace would suggest that the Colorado River has been downcutting at a rate somewhere between 1.8 and 4.5 feet per thousand years during the past 12,000 to 30,000 years. This is the only terrace on the Colorado River that is preserved in Moab Valley. However, preliminary age estimates based on exposure age dating techniques upstream from Moab Valley indicate downcutting rates more on the order of 0.7 feet per thousand years. If this estimate is correct, then the age of the Courthouse Wash terrace would be closer to 75,000 years.

(2) A wood sample was recovered from DOE bore hole 435 at an elevation of about 3,853 feet, approximately 105 feet below the level of the present river

Figure 4a: Locations and ages of Colorado River gravels adjacent to the Moab Project Site at north end of Moab Valley. A vertical aerial photograph of the area between the Atlas tailings pile and the mouth of Courthouse Wash showing the locations of river gravels cited in the DOE 2003 letter report. John C. Dohrenwend, 2005.

channel. Bore hole 435 is located about 600 feet from bedrock outcrop at the north end of Moab Valley and about 1,200 feet from the terrace at the mouth of Courthouse Wash (Figure 4b). The age of the wood sample has been estimated by radiocarbon analysis to be about 45,000 years old. Unfortunately, reliable radiocarbon age dating is limited to the last 45,000 years. Therefore, this age estimate must also be considered to be very imprecise. That is, the age of this sample must be considered to be 45,000 years or older, and exactly how much older cannot be determined by radiocarbon analysis.

If one assumes that these two age estimates are both precise and correct, then these two occurrences suggest either (1) a minimum of 159 feet of displacement between the mouth of Courthouse Wash and the site of bore hole 435 within the past 45,000 years; or (2) extremely deep scour by the Colorado River sometime during the past 45,000 years at this location and very likely on through the center of the site of the Atlas tailings pile.

Of more significance is the fact that similar river gravels are widely distributed beneath the surface of Moab Valley (Figure 5), demonstrating that the Colorado River channel has, in the past, flowed directly through the site of the tailings pile.

None of these observations indicate a unidirectional migration of the Colorado River channel. However, they do prove that the Colorado River

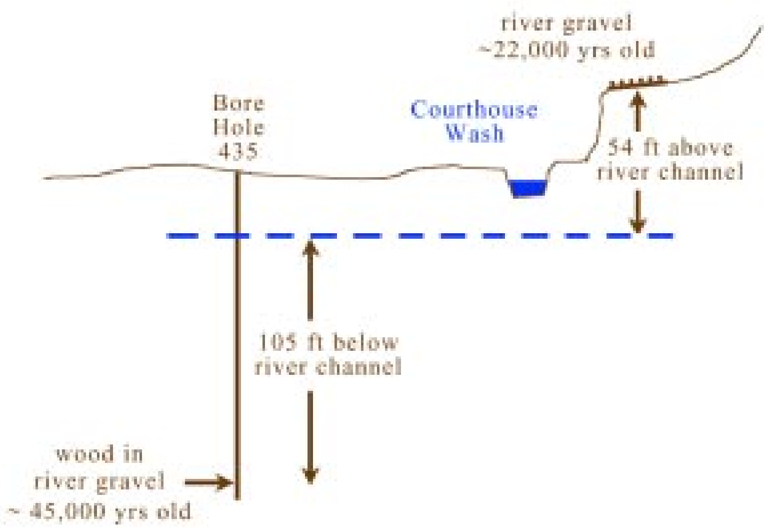


Figure 4b: Schematic diagram showing the difference in elevation between river gravel locations shown in Figure 4a. John C. Dohrenwend, 2005.

has flowed through the site in the past, and they suggest the possibility of either significant subsurface instability or extreme channel scour in the vicinity of the Moab Project site at sometime during the recent geologic past.

Thickness and distribution of basin fill sediments in the Moab Valley

The reports cited in the DEIS to substantiate the contention that the Colorado River is moving away from the tailings pile have not reported or considered all available data regarding the thickness and distribution of valley filling deposits in the Moab Valley.

For example, the data developed by the groundwater studies of Gardner and Solomon and the results of subsurface investigations conducted by the DOE in 2002 have not been consistently or carefully considered in DOE's subsequent reports. Specifically, the thickness and distribution of valley fill deposits beneath the tailings pile and mill site are certainly much more complex than reported in the November 2003 letter report. Figure 8 of this report (NESW diagrammatic cross-section, copied from Doelling et. al., 2002) does not include any of these data and shows only a very simplistic interpretation of the thickness and distribution of the valley fill. Yet no attempt has been made to correct this interpretation to show the implications of the additional bore hole data. Also, the November 2003 letter report neglected to mention Doelling's cautionary note regarding his cross-section: "The exact position or trend of this fault (?) is unknown. In fact it may not be a fault at all, but a dramatic thinning of units northwest of the bend in the Colorado River." Moreover, Gardner and Solomon's bore hole data for areas south and east of the river also are not included in 2003 letter report.

When all of the data are compiled, what they actually show is that the subsurface conditions directly beneath the tailings pile are much more complex than the highly simplistic and relatively benign picture presented by the November 2003 letter report. Indeed, these data indicate that localized subsidence of the valley floor directly beneath the tailings pile must be considered as a possible and potentially serious geologic hazard (Figure 6).

Moreover, available well log and bore hole data indicate that the valley fill is not thickest and deepest south of the present location of the river channel. Rather, these data show that the valley fill is thickest and deepest beneath or, perhaps, as much as several hundred feet north of the present river channel. Consequently, the position of the sloughs in the Matheson Wetlands is not directly related to salt-induced subsidence of the valley filling sediments. Instead, the sloughs merely mark the lowland boundary between the Mill Creek fan and the Colorado River fan. Therefore, even if the relatively slow subsurface subsidence of Moab Valley were to affect the valley's surface, there is no reason to suppose that continuing subsidence of the valley floor would cause the river channel to migrate away from the tailings pile. Indeed, if one assumes that the thickest and deepest valley fill deposits mark the position of maximum valley subsidence, then there would be, in actual fact, strong reason to suppose that continuing subsurface subsidence could cause the river to move closer to the pile.

Rate and character of salt dissolution in the Moab Valley area

Recent measurements of the ages of the isolated remnants of multiple paleosurfaces, using cosmogenic isotopic dating techniques, have determined that even some of the highest mesa surfaces between Capitol Reef and Caineville Reef (west of Moab Valley and south of the San Rafael Swell)

Figure 5: Vertical aerial photograph of the northern end of Moab Valley showing the minimum extent of the Colorado River gravels beneath the valley floor. Modified from Gardner and Solomon, 2003.

are little more than one million years old. All of the buttes, monuments, ridges, and canyons below these mesa tops have been formed by erosional processes during the past one million years. When this information is put into the context of the results of other geologic research, including radiometric age measurements of the volcanic caprock on Grand Mesa (about 6 million years old) and the igneous dikes in Cathedral Valley (about 4 million years old), these findings enable the compilation of a much more precise description of the erosional history of the Colorado Plateau.

The area of the central Colorado Plateau (and Moab Valley) has been subjected to more or less continuous erosion during the past 5 to 6 million years. During this time, the rocks and sediments that once covered the region to the tops of today's highest mountains have been eroding away at an average rate approaching one foot per thousand years. By comparison, average erosion rates in many areas of the American Southwest are only one or two inches per thousand years. The Colorado Plateau is, therefore, one of the youngest, most rapidly changing landscapes in all of North America, and the principal agent of all of this erosion is, of course, the Colorado River system.

The Moab Valley is the surface expression of a collapsing salt-cored anticline. The salt beds beneath the valley's subsiding floor are almost 2 miles thick. As the Colorado River and its tributaries cut down through the thousands of feet of rock that once covered this salt-cored anticline, tremendous volumes of rock were removed and the land surface gradually lowered. Eventually, probably about two million years ago, circulating groundwater reached the level of the uppermost salt beds. As the salt dissolved, the crest of the anticline began to collapse forming the Moab Valley. As the river continues to cut down through the plateau, the valley continues to subside.

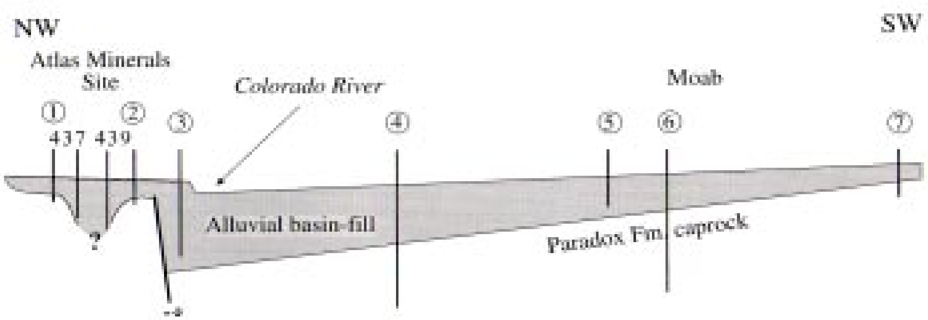
The rates of valley subsidence and river downcutting are closely related. Most of the groundwater beneath the valley surface is a dense salt brine. As the river continues to downcut, fresh near-surface groundwater continues to mix with the brine, promoting continued dissolution of the salt. Thus, it is the river's downcutting that controls the erosional evolution of the Colorado Plateau and all of its component parts, including Moab Valley and the site of the Atlas tailings pile.

Absence of a cobble gravel bedload downstream of the Portal

The November 2003 letter report regarding the potential flood hazard at the Atlas tailings pile observes that large gravels and cobbles are not found in the active river channel downstream of the Portal, except near side canyons. This report also maintains that the surface of Moab Valley is subsiding and that, because of this subsidence, coarse river sediments are being trapped in the valley. This reasoning is used to suggest that continuing subsidence will force the Colorado River channel to migrate south and east, away from the Atlas tailings pile and towards Moab.

Groundwater dissolving the massive salt layers far beneath the valley floor is, in fact, causing the slow subsidence of the valley's alluvial fill. But, the surface of Moab Valley is not dropping because of this subsidence. The Colorado River and its local tributaries deliver far more sediment to the valley floor than could ever be accommodated by the valley's slow subsidence. Therefore, ongoing deposition by the Colorado River and by Mill Creek and Pack Creek are the principal processes controlling the surficial geology and geomorphology of Moab Valley. The correct explanation for the lack of cobbles and gravels in the active channel downstream from the Portal is quite different.

Of course, the steepness of a riverbed plays a central role in a river's ability to move sediment. Other things being equal, the flatter a river's slope, the smaller the size of the bedload sediment it can move. From Moab Valley all the way downstream to Cataract Canyon the average slope of the river is very low, averaging only 15 inches per mile (0.025%). In contrast, the river gradient upstream from Moab Valley (between Dewey Bridge and Negro Bill Canyon) drops an average of five feet per mile (about 0.1%), and downstream in Cataract Canyon, the average drop is almost 12.5 feet per mile (0.25%). Therefore, channel sediments in and downstream of Moab Valley are mostly fine-grained. Cobbles and other coarse materials are only moved during large floods. At all other times, only fine sediments are moved through this flat water section.



Fiqure 6: Northeast to southwest diagrammatic cross-section of the northern end of Moab Valley showing the approximate thickness of the valley fill. Fiqure modified from Doelling et al., 2002.

The sequence of fine-grained deposits overlying coarse grained deposits is typical of many late Quaternary (less than 50,000 year old) valley fill sequences in the Southwest. Generally speaking, the gravels were mostly deposited during late glacial times when precipitation was greater and river flows were larger (and/or very large floods were more frequent). The finer-grained sediments were deposited during postglacial (Holocene) times when precipitation was less (and/or very large floods were less frequent). This change in the grain size of alluvial deposits is typically most pronounced in those areas where river gradients are relatively low. Other things being equal, alluvial deposits in low gradient areas are a more sensitive indicator of changes in river flow. This is because declining river flows will first lose their ability to carry larger, heavier bed load materials in low gradient (low energy) river reaches. The result is the typical alluvial fill sequence where glacial age river gravels are overlain by post glacial age river sands.

Summary

The suitability of the Atlas mill and tailings site for the long-term disposal of radioactive waste has not been established by the November 2004 DEIS. The site was not originally selected out of concerns for human health and safety or for the preservation of environmental quality. Rather, it was selected as a convenient place for the milling of uranium ore and a cheap place for dumping the enormous quantities of chemical and radioactive waste generated by that milling process. Therefore, there is no *a priori* reason to suppose that the site is suitable for long-term waste disposal.

Analyses of the DEIS and supporting reports clearly show that these documents do not present a realistic picture of the geologic and hydrologic conditions at the Atlas mill and tailings site. Careful and consistent analyses of available scientific data concerning the suitability of the site must be made within the context of accurate perceptions of how the Colorado River really interacts with the Moab Valley. Such analyses clearly show that the flood hazard potential at the Atlas tailings site is not diminishing, as the reports cited by the DEIS claim, due to a theorized southward and eastward migration of the Colorado River. Rather, the river has flowed across the tailings site in the past and very possibly could return to that course in the future. Furthermore, because the river's inner channel has, over the past 80 years, shifted closer to the pile and has become narrower and deeper, the potential for deep channel scour, sudden channel shifting, and catastrophic failure of the pile during large floods may well have increased significantly.

Contrary to the claims and speculations contained in the reports used by the DOE to support the inferences and conclusions presented in the DEIS, the following points are clear:

(1) An 80-year history documented by accurate registration of historic maps and aerial photographs clearly shows that the Colorado River is not migrating south and east away from the tailings pile. The high flood levees bordering the main channel have not shifted measurably. However, the south and east bank of the active channel between these levees have moved north and west. It is now 150 to 300 feet closer to the mill site, and the channel has narrowed and deepened in its new position.

(2) Courthouse Wash and Moab Wash have not caused the Colorado River channel to migrate away from the mill site. Rather, analysis and direct observation of high energy flows from Courthouse Wash demonstrate unquestionably that these floods have deposited sediments on the south side of the Colorado River channel and, therefore, have actively contributed to the northward migration of the river channel.

(3) Available well log and bore hole data indicate that the valley fill is not thickest and deepest south of the present location of the river channel. Rather, these data show that the valley fill is thickest and deepest beneath or, perhaps, as much as several hundred feet north of the present river channel. Therefore, there is no reason to suppose that continuing subsidence of the valley floor would cause the river channel to migrate away from the tailings pile. Indeed, if the thickest and deepest valley fill deposits mark the position of maximum valley subsidence, there would, instead, be strong reason to suppose that continuing subsidence could cause the river to move closer to the pile.

(4) Available subsurface data also show that conditions directly beneath the tailings pile are much more complex than the highly simplistic and relatively benign picture presented by the DOE. Indeed, these data indicate that localized subsidence of the valley floor directly beneath the tailings pile must be considered as a possible and potentially serious geologic hazard. Moreover, comparison of surface and subsurface data along the northern margin of Moab Valley between Courthouse Wash and the mill site suggest the possibility that localized subsidence or extremely deep channel scour has occurred in this area sometime during the past 45,000 years.

(5) Although dissolution of the massive salt layers beneath Moab Valley is causing the slow subsidence of the alluvial fill within the valley, the valley's surface is not dropping because of this subsurface subsidence. The Colorado River and its local tributaries deliver far more sediment to the valley floor than could ever be accommodated by the valley's slow subsidence. Therefore, ongoing deposition by the Colorado River and by Mill Creek and Pack Creek are the principal processes controlling the surficial geology and geomorphology of Moab Valley.

(6) Finally, the geometry and position of ancient Colorado River gravels buried beneath the surface of Moab Valley clearly show that the Colorado River has, in fact, shifted back and forth across mill and tailings site in the recent geologic past.

In summary, there is considerable scientific evidence that important flaws exist in those studies indicating suitability of the Moab Mill site for the long-term storage of radioactive waste. Particularly flawed is the contention that the Colorado River is presently migrating and will continue to migrate away from the site. This contention is completely incorrect. The Colorado River channel has not migrated south and east away from the Moab Mill site at any time in the past 80 years, and there is no reason to suppose that it will start to do so at any time in the immediate future.

Additional scientific study

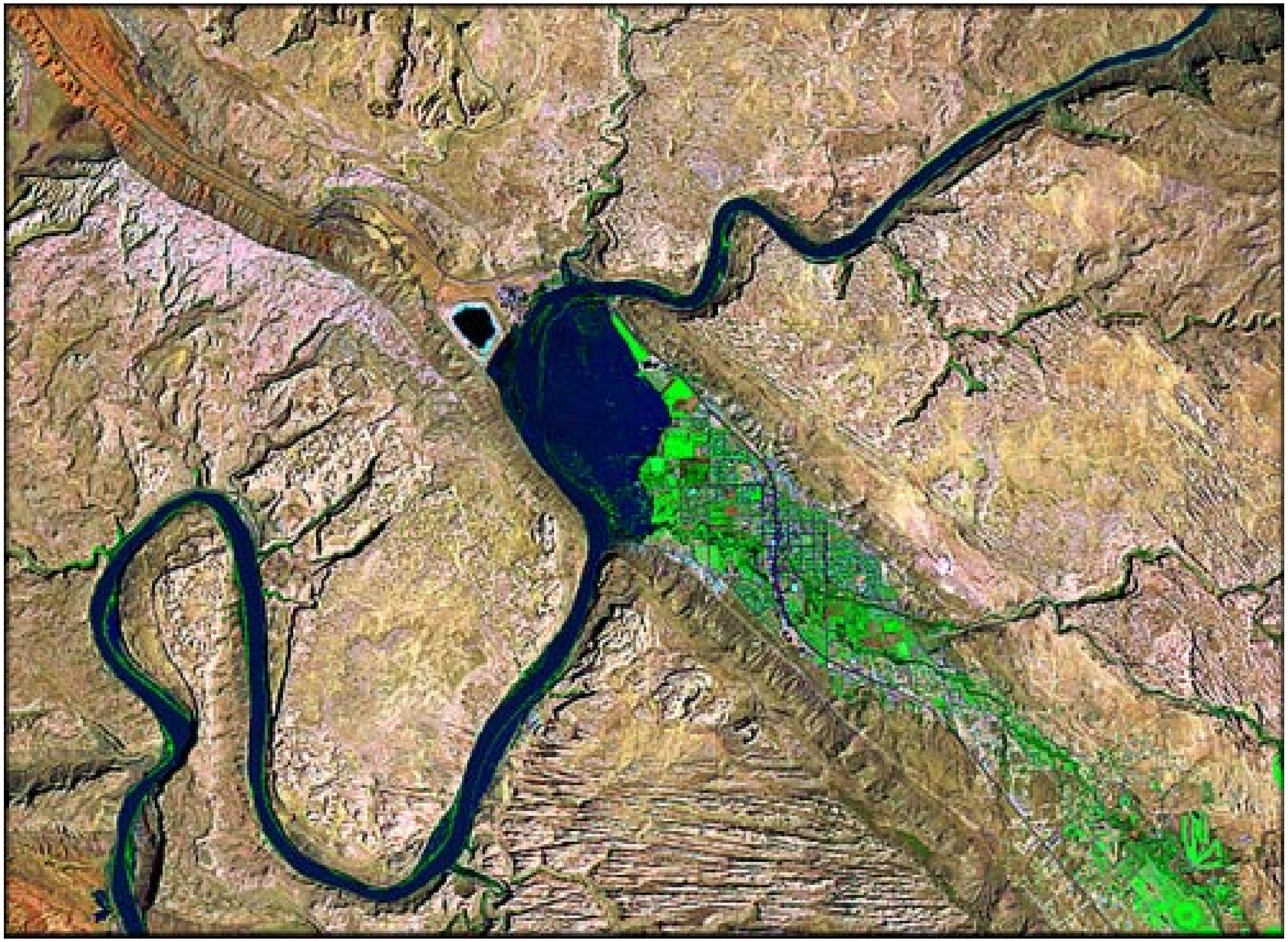
Additional scientific studies focused on the potential flood hazard at the Moab Mill are needed to determine whether the site is a suitable place for the long-term disposal of uranium mill waste. To be useful, additional studies must significantly reduce the uncertainties that surround and confound our understanding of the complex relationship between the Colorado River and the Atlas tailings site. Specifically, such studies should determine whether or not there is significant potential for catastrophic flooding that could compromise the stability and integrity of the tailings pile. They should also address the uncertainties related to the downstream impacts of such an event.

The Moab Valley is a very unusual place, essentially one-of-a-kind on the Colorado Plateau, in North America, and perhaps anywhere in the world. The formation of the Moab Valley is in large part the result of salt tectonics. The folding, flow, and diapiric rise of massive salt deposits from far beneath the earth's surface and the dissolution of these deposits as the earth's surface is eroded down to the level of the rising salt are the principal processes that have shaped most of the large valleys of the Paradox Basin. Of all these breached anticlinal valleys, the Moab Valley appears to be the only one where the Colorado River or any of its tributaries are downcutting more slowly than the valley is subsiding. This, in and of itself, makes the Moab Valley practically unique.

Moreover, the valley is located in the east central part of the Colorado Plateau, a region of very rapid erosion and landscape change. This part of the Plateau is one of the youngest landscapes in North America. As the principal agent of this rapid erosion, the Colorado River is, quite literally, one of the dirtiest rivers in the world. That is to say, it carries more dirt or sediment per unit of flow than all but a few of the world's major rivers.

There is probably no other place on earth that is truly comparable to the Moab Valley. This makes the scientific study of this very unusual place all the more difficult. Earth science works best when there are many places where similar phenomena and relationships can be used for comparison with the area being studied. Without the ability to make such comparisons, it is very difficult to test or verify the results and conclusions of the study.

Further complicating the issue is the fact that recent geologic times have been and continue to be times of changing climate. Since the waning stages of the last great ice age to the present time, climate change has been the norm. Generally speaking, climatic conditions on the Colorado Plateau have become progressively warmer and drier throughout this time. However, conditions have also fluctuated dramatically between periods of relative moisture and extended drought. These changes and fluctuations have strongly influenced extremes of river flow and rates of landscape change throughout the region. Continuous measurements of river flow on the Colorado River have only been made for the past 91 years, and this limited record does not provide a sufficient base for predicting the future frequency or magnitude of very large floods.



Supplemental photo of Moab Valley, May 26, 1984. Landsat 5 satellite image showing the extent of the second largest flood of record on the Colorado River in Moab Valley. This satellite image was acquired one day prior to the flood peak when the flow rate was approximately 66,500 cfs. The 1984 flood inundated the toe of the Atlas tailings pile to a depth of about four feet.

We also lack much of the basic scientific data that is necessary to understand the complex relationship between the Colorado River and the Moab Valley. We do not have a clear picture of the rate of downcutting of the Colorado River. The many well preserved river terraces both upstream and downstream from Moab Valley have not yet been carefully studied, and the ages of these terraces have not been determined. We also lack a clear understanding of the subsidence and filling of Moab Valley. The thickness and extent of the valley filling deposits are only approximately known, particularly on the Moab side of the river. Moreover, the depth of scour within these deposits during very large floods is not well established. More importantly, the ages of these deposits are only very imprecisely known, even though several attempts have been made to date them. Therefore, we do not have (and perhaps may never have) sufficient subsurface data to understand anything more than the general details of the dissolution, subsidence, and valley filling processes.

Consequently, we do not know how rapidly the river is eroding downward, how rapidly the valley filling deposits are subsiding, or whether downward erosion and valley subsidence vary in time and space. In short, we have yet to learn very much at all about the natural system that immediately surrounds, supports, and potentially threatens the site of the Atlas tailings pile.

Studies Related to Potential for Catastrophic Flooding

Among the areas of uncertainty identified by the DEIS for on-site disposal of the mill tailings, that of "Catastrophic Floods" is of particular concern because of the possibility of channel migration into the tailings pile and flood erosion of the tailings. The assumption is made in the DEIS that a catastrophic discharge of 300,000 cubic feet per second will occur no more than once in 500 years. It is also presumed in the DEIS that the much smaller, once-in-100-year flood will reach 3 to 4 feet above the base of the tailings pile. Because these are only estimates, based on extrapolations from very limited stream gauging data, we will be applying a technique over the next few months to directly test these figures by documentation of actual long-term flood behavior of the Colorado River at Moab.

During several days of field investigations in January of 2005 we identified multiple study sites along the Colorado River that preserve sand and silt deposited by the highest past flood stages of the river. The sites were located by an aerial survey on January 16. The sites include areas near Dewey Bridge and Salt Wash, which are upstream of Moab, and Shafer, Buck and Lathrop Canyons, all of which are downstream of Moab. Several sites were briefly observed from the ground and determined to be appropriate for a subsequent slackwater deposit paleostage indicator (SWDPSI), paleoflood hydrology (PFH) investigation. The investigation at the chosen site will follow this report and will include surveys of elevations, geometry of the adjacent flood channelways, stratigraphy of the flood deposits, geochronology, and hydraulic calculations of the associated paleoflood discharges. The end result will be an estimate of the flood frequency hazard for the Colorado River in the vicinity of Moab.

Data from the SWDPSI-PFH investigation will form the basis for estimating the potential for flood erosion and inundation of the tailings pile. This potential is critical because of the as-yet-unknown possibility for catastrophic flooding to distribute eroded tailings over the entire inundated region, including much of the City of Moab.

Editor's Epilogue: DOE Final Environmental Impact Statement

The above report was submitted to the DOE in January 2005 as part of public comment on the DEIS. The Final Environmental Impact Statement (FEIS) for the Remediation of the Moab Uranium Mill Tailings (DOE/EIS-0355) was released in July 2005. The FEIS concluded that the preferred alternative for the reclamation of the former Atlas mill site was to remove the approximately 12 million tons of tailings and other contaminated materials from the floodplain (now estimated by DOE to be 16 million tons) of the Colorado River to a new disposal cell near Crescent Junction, Utah, 30 miles north. **The FEIS discusses Responsible Opposing Views on River Migration in Section 2.6.4.1.**

The DOE announced its final determination to relocate the tailings to Crescent Junction in the Moab Uranium Mill Tailings Remedial Action Project Site Record of Decision (ROD) (70 Fed. Reg. 55358, September 21, 2005). The ROD states that **"DOE identified off-site disposal as its preferred alternative for the disposal of tailings, primarily because of the uncertainties related to long-term performance of a capped pile at the Moab site. Issues, such as the potential for river migration and severe flooding, contribute to this uncertainty."**

The paleoflood study herein (next page) indicates that the FEIS and the study by the US Geological Survey (Kenny, 2005), have underestimated the number of large floods that can occur within the reclamation standard of 200- to 1000-years. Hence, there continues to be significant risk that flood erosion at the tailings pile could occur in the time period between the present and the eventual removal of the pile.

The FEIS and ROD are available at:
http://gj.em.doe.gov/moab/eis/eis_info.htm

The USGS Scientific Investigations Report, 2005-5022, is available at:
http://pubs.usgs.gov/sir/2005/5022/pdf/SIR2005_5022.pdf

The Gardner and Solomon, Matheson Wetland Preserve Study, 2003 and 2004, is available at:
http://www.radiationcontrol.utah.gov/MILLS/ATLAS/mmgroundw_com.htm

Paleofloods in the Upper Colorado River near Moab, Utah, May 2006

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Introduction

Paleoflood hydrology was first applied in the late 1970s and beginning of the 1980s in the larger Colorado River tributaries: Verde River – with a drainage area of 14,240 km^2 (Ely and Baker, 1985), Salt River – 11,150 km^2 (Partridge and Baker, 1987), Salt River – 33,650 km^2, (Fuller, 1987), Virgin River – 10,306 km^2 (Enzel et al., 1994), Escalante River – 820-4,430 km^2 (Webb et al., 1988), and the entire Colorado River at the Grand Canyon – 279,350 km^2 (O'Connor et al., 1994). In the larger catchments the maximum paleoflood discharges are usually larger than the maximum measured values at gauging sites. **Note:** See metric conversion table on page 29.

The most detailed and relevant paleoflood study on the Colorado River to the present study is the one by O'Connor et al. (1994). This study was carried out in the Grand Canyon downstream of Glen Canyon Dam and close to the US Geological Survey (USGS) Lee's Ferry (Fig. 1) gauging station (1921-2005). At this site the largest historical flood, with an estimated peak discharge 8,500 m^3 s^{-1}, occurred in July 1884, and a larger flood, with an estimated peak discharge of about 11,300 m^3 s^{-1}, probably occurred in 1862 (Dickinson, 1944). The largest flood on the measured record (6,250 m^3 s^{-1}) occurred in 1921. The paleoflood record provides evidence of at least 15 large floods during the last 4,500 years. Ten floods during the last 2,000-2,300 years had discharges > 6,800 m^3 s^{-1}; one flood, which occurred between about 1,600 and 1,200 years BP, was as high as 24 m above present water level and had a discharge > 14,000 m^3 s^{-1} (O'Connor et al., 1994).

Enzel et al. (1993) collected all measured, historical, and paleoflood peak discharges for all tributaries of the Colorado River and generated an envelope curve for the Colorado River Basin. Specific peak discharges for drainage basins with an area >10,000 km^2 vary between 0.165 and 0.412 m^3 s^{-1} km^{-2}. The only paleoflood data for a drainage area >100,000 km^2 (0.05 m^3 s^{-1} km^{-2}) is based on O'Connor et al. (1994).

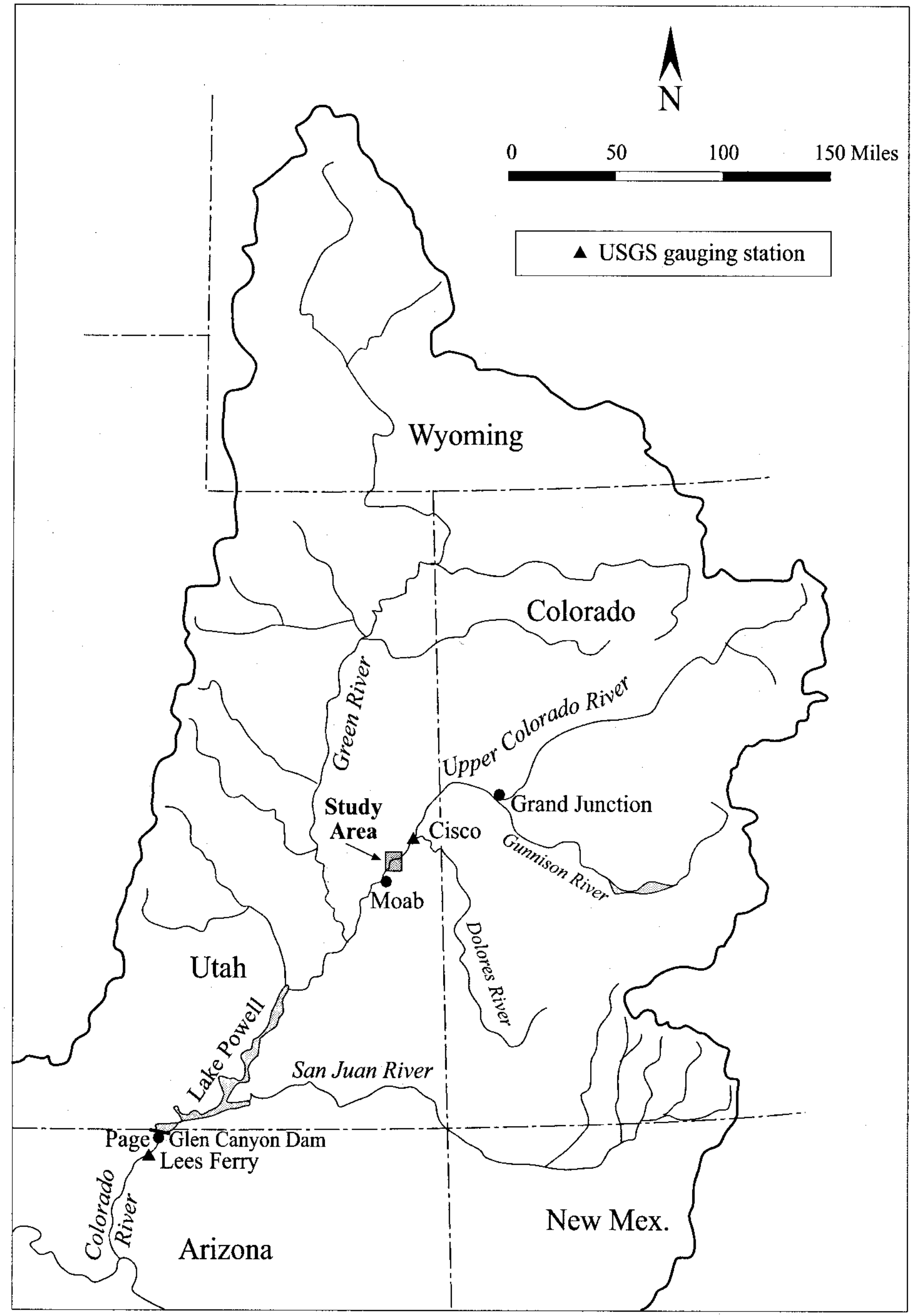

Figure 1: The upper Colorado River Basin including the larger tributaries, USGS gauging stations, and the present study area.

Study Area

Precipitation

The region is hyperarid: annual rainfall at the Moab gauging station (1889-2005), at an elevation of about 1,280 m, ranges between 11 cm y^{-1} in 1898 to 41.7 cm y^{-1} in 1983; mean annual rainfall for the period 1889-2000 is 22.8 cm y^{-1}. Precipitation is evenly distributed throughout the year, some of which falls as snow during the winter. Maximum monthly rainfall (2.9 cm) occurs in October, whereas the minimum monthly amount (1.3 cm) occurs in February. Some of the wettest years on record (1905, 1941, 1965, and 1983) are related to El Nino Southern Oscillation activity. Others are related to positive values of the Pacific Decadal Oscillation index (Webb et al., 2004).

Hydrology

Floods in the upper Colorado River are caused mainly by: (a) melting of the annual snowpack during the first waves of relatively high temperatures in the spring. Therefore, the annual peak discharges occur usually between May and June. These flows are characterized by a relatively moderate rise and similar moderate recession. And, (b) summer thunderstorms, which are typical of July and August and produce localized intense rainstorms with relatively steep rising climb and short recession. The largest floods are the product of spring rainstorms falling over the melting snowpack.

Hydrological data

The relevant hydrological data for our study area are derived from the USGS Cisco gaging station above Dewey Bridge (30 km upstream of the study area) (Fig. 1). The drainage area of the Colorado River at the Cisco station is 62,470 km^2. The flood record in this station is 87-years long (1914-2005) and is almost continuous (Fig. 2). Maximum annual peak discharges range from 185 $m^3 s^{-1}$ (in 2002) to 2,175 $m^3 s^{-1}$ (in 1917), with an average of 992 $m^3 s^{-1}$. The maximal measured peak discharge (3,540 $m^3 s^{-1}$) is historical and occurred on July 4, 1884. The daily mean flow ranges between 61 and 1,932 $m^3 s^{-1}$, with an average of 650 $m^3 s^{-1}$. About 50% of the maximal annual discharge occurs in May and another 44% in June.

In Cataract Canyon, where the upper Colorado River meets the Green River, the 1884 flood had an an estimated peak discharge of about 6,370 $m^3 s^{-1}$. It is unclear how large these floods were in the upper Colorado River near Moab prior to 1884, as Moab did not have an established post office until 1879 and the first Moab newspaper was printed in 1896.

The existing flood records in the upper Colorado River indicate that numerous large floods occurred between the 1880s and the 1930s and that a general trend of decrease is documented (Fig. 2). This trend was explained mainly by the decrease in the frequency of large flood-producing rainstorms since the early 1940s and partly by the abrupt reduction in grazing since 1932 (Webb et al., 2004). Large floods (>1,700 $m^3 s^{-1}$) (60,000 cfs) later than the 1930s occurred in 1941, 1957, 1983, and 1984 (Fig. 2). Mean annual flow volume in the upper Colorado River at the Cisco gauging station is about 6,660 10^6 m^3.

Study Reach

The Colorado River canyon at the study area flows, in general, from northeast to southwest. The northwestern bank is undisturbed and is already a part of Arches National Park. The southeastern bank is Bureau of Land Management (BLM) land disturbed only by the road along the river and by a boat put-in and take-out site (Fig.4). The study area is located about 17 km upstream of Moab at a large bend of the canyon. The elevation of the river bed at the study area is about 1,300 m above sea level (asl). The canyon is entrenched between 300-350 m (320 m on average) deep into the sandstones of the plateau. The width of the canyon at the top varies between 600 and 800 m, whereas the width of the channel varies between 70 and

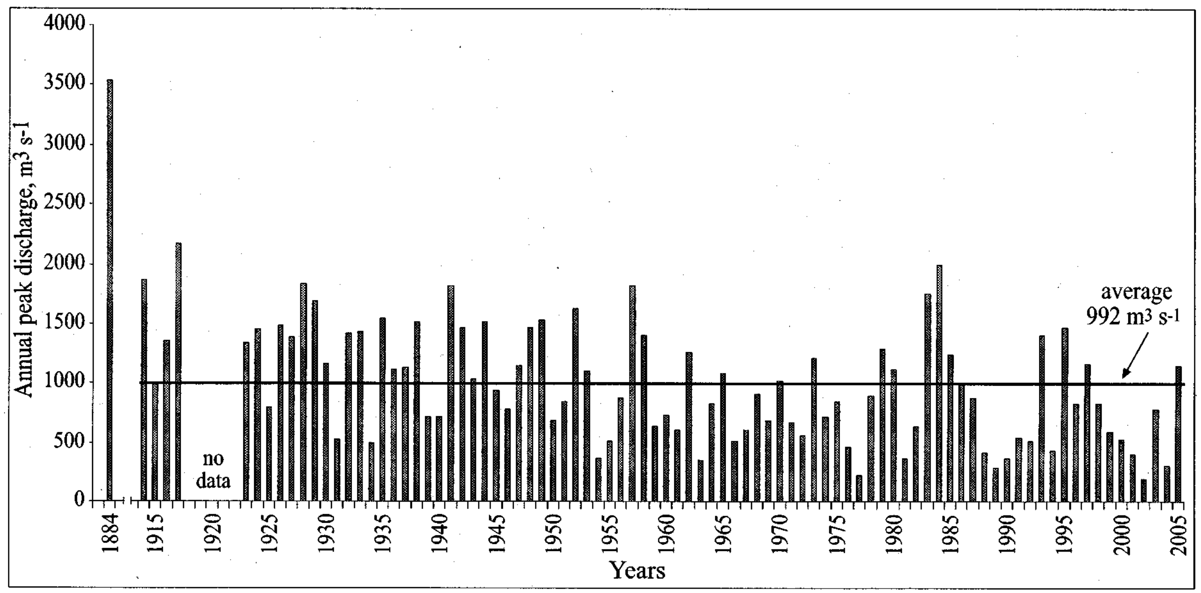

Figure 2: Annual maximum peak discharges for the Colorado River at Cisco, Utah, gauging station, 1914-2005.

150 m, depending on the geometry of the cross-section and discharge. The constrictions in the channel are usually caused by very coarse debris flow deposits from the steep slopes of the canyon, which also cause formation of small rapids (Webb et al., 1988). Based on topographical maps in the scale of 1:24,000, the general gradient along this section is about 0.0032. The drainage area of the Colorado River at the Cisco gauging station, about 30 km upstream, is 62,470 km^2.

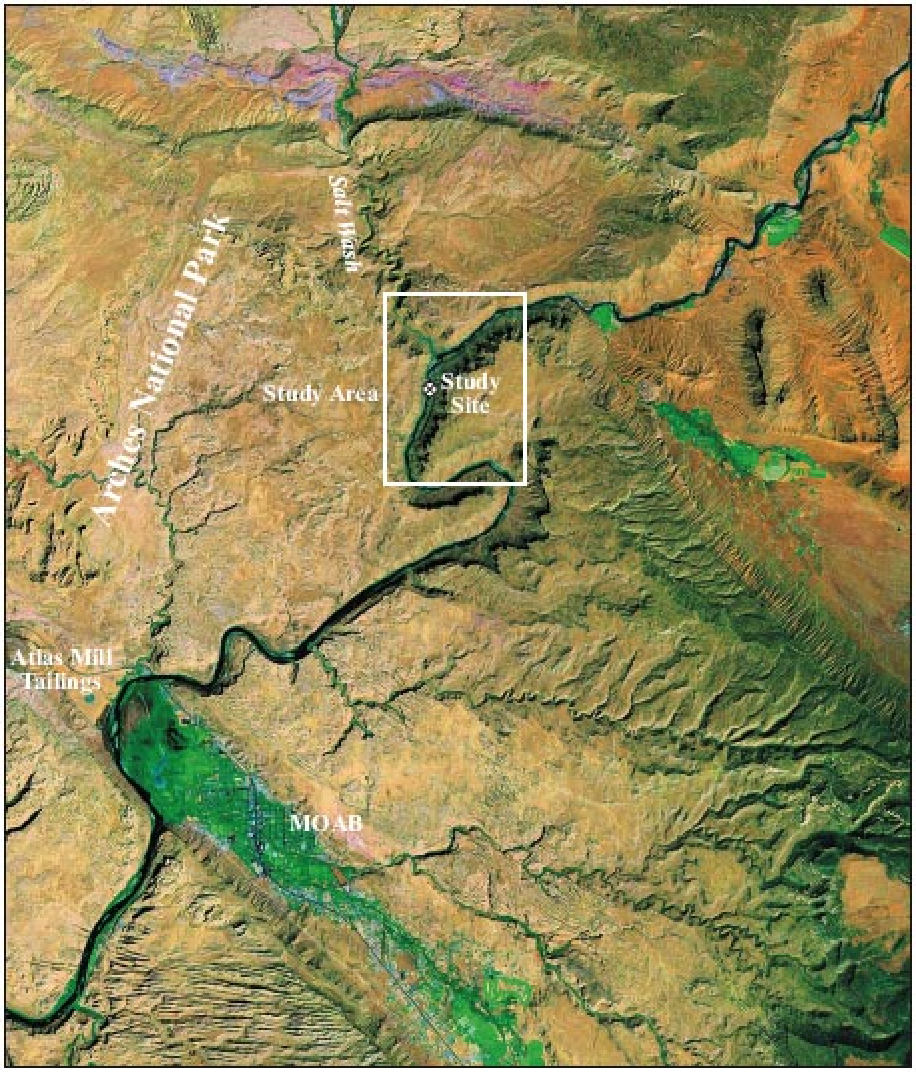

Figure 3: Satellite photo of the region including Moab, the Atlas Mill Tailings, and the study area.

Paleoflood Hydrology

Paleoflood hydrology reconstructs the magnitude and frequency of past floods, provides long-term flood records for ungauged basins, and extends short systematic flood records to the past (Kochel and Baker, 1982; Baker, 2003). The reconstruction of the paleofloods includes determination of their peak discharge and the time of occurrence, usually based on radiocarbon dating. The paleoflood data reconstruct the largest floods that occurred in a basin and enhance the frequency analyses of the flood records by an improved fitting of the probability functions (e.g., Stedinger and Cohn, 1986; Webb et al., 1988; Thorndycraft et al., 2003). A review of various methods of incorporating paleoflood data and other non-systematic information is provided by Frances (2004).

Paleoflood hydrology can be applied in bedrock canyons where the cross-section and the course of the river are stable and, therefore, it is assumed that their geometry has not changed much during the last several thousand years. The paleoflood reconstruction uses fine-grained slackwater flood deposits (SWDs) and other paleostage indicators (PSIs), such as driftwood lines deposited rapidly from suspension in sites where flow velocities are significantly reduced (Patton et al., 1979; Kochel et al., 1982; Ely and Baker, 1985; Baker, 1987; Baker and Kochel, 1988). These indicators represent the high stage of the flood and provide the best natural record of large flood magnitude. Such sites include back-flooded tributary mouths, caves and alcoves in canyon walls, channel expansions where flow separation causes eddies, and overbank floodplain deposits. Ideal paleoflood sites preserve multiple flood stratigraphic records, which can be separated into individual flow events using sedimentological criteria (Baker, 1987; Benito et al., 2003). Paleodischarge estimates are obtained using the HEC-RAS (Hydrologic Engineering Center, 1997) procedure, which generates water surface profiles for various discharge values (O'Connor and Webb, 1988). Comparison between the elevation of SWDs and driftwood lines to the elevations of the water surface profiles provides a peak discharge value to the flood at the site (Baker, 1987; O'Connor et al., 1986). Ages of paleofloods are obtained using radiocarbon dating of fine organic debris: wood and charcoal that floated over the floodwaters and were deposited over the flood SWDs or as a driftwood line.

Field Methods

Field reconnaissance

A field reconnaissance along the upper Colorado River upstream of Moab was carried out during late March 2005. Three potential paleflood sites were located along a study reach of about 5 km between Sandy Beach and Big Bend (Fig. 4). The upper site, COL-1, is an overbank flood SWD

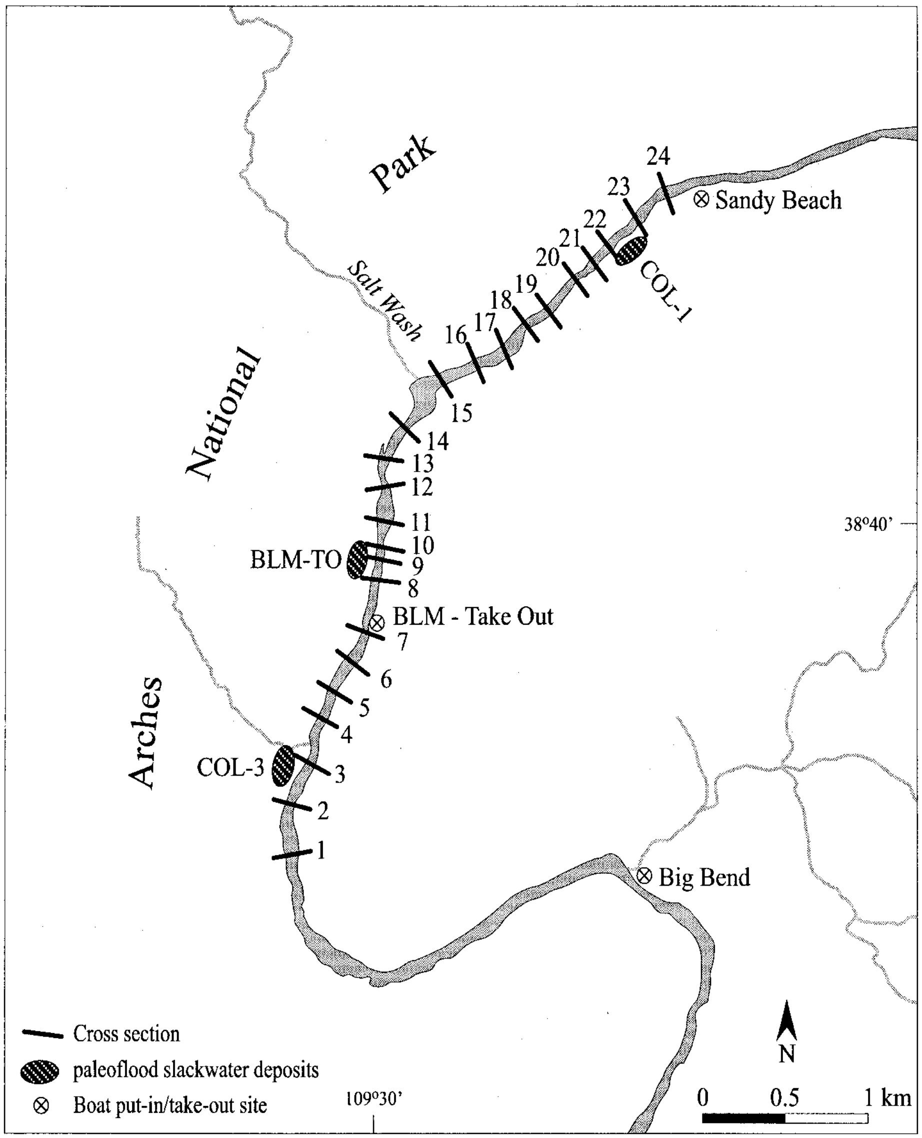

Figure 4: The study reach of the present study including the main SWD accumulations, the cross-section of the survey, and the paleoflood BLM-TO study site.

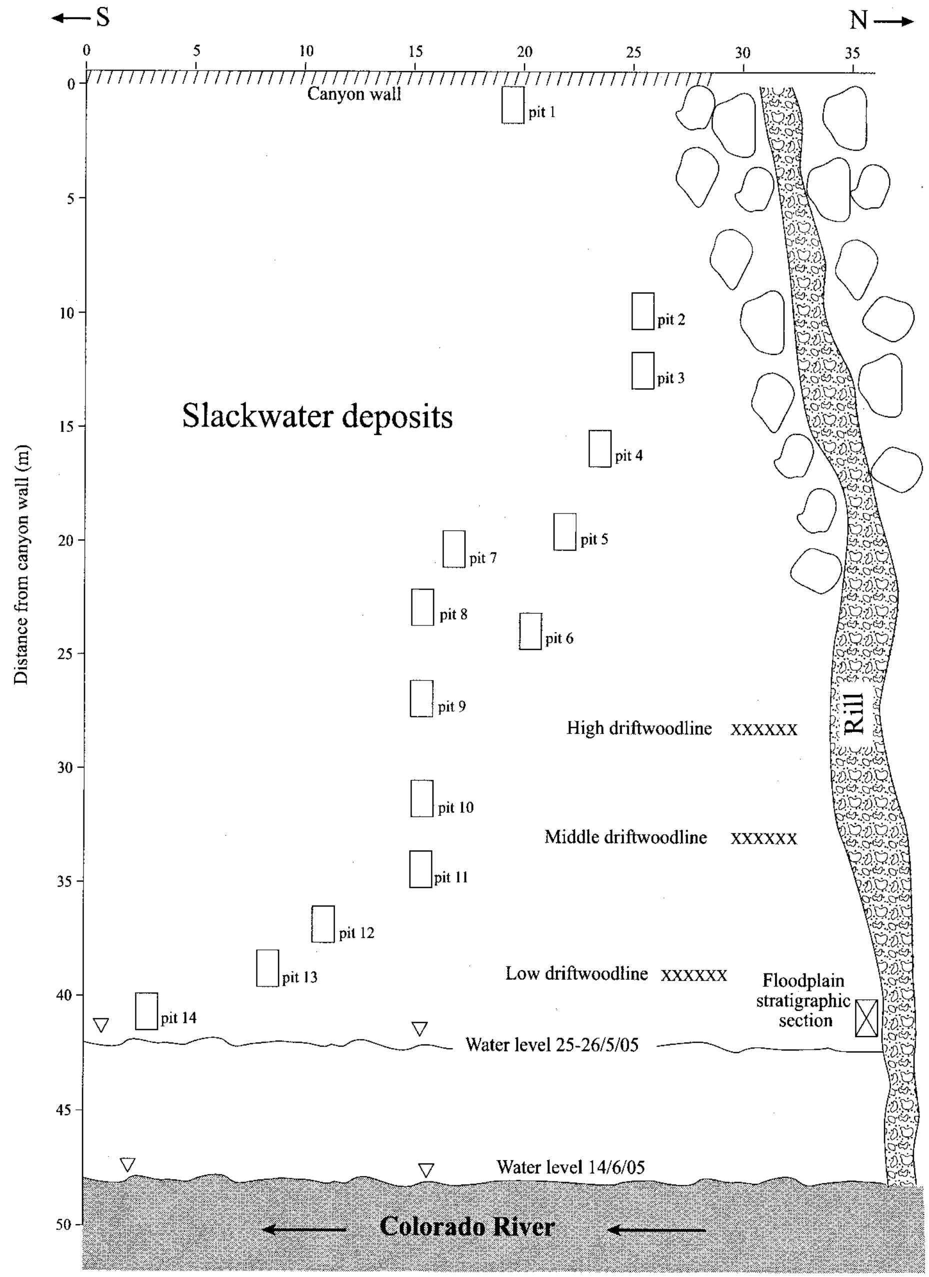

Figure 5: A map showing the location of the pits that were dug at the BLM-TO study site at the right bank of the Colorado River for studying the flood deposit stratigraphy. Other paleostage indicators, such as driftwood lines and actual winter and summer water levels during the study period, are shown as well.

located at the left bank a few hundred meters downstream of Sandy Beach. The second site, BLM-TO, is located opposite to the BLM take-out site (a few hundred meters upstream) at the right bank of the river in the area, which is a part of Arches National Park. It is also an overbank SWD site located over an alluvial terrace composed of coarse gravel – mainly cobbles and up to large boulders. The lower site, COL-3, is located at the right bank in a very small tributary mouth. The tops of sites COL-1 and COL-3 are covered by a thick layer of eolian sand, which is probably derived from flood deposits reworked by the strong winds that flow upstream within the Colorado River canyon. Site COL-1 may also be disturbed by the road.

Therefore, we concluded that the best site, deserving minimum digging and trenching, was the BLM-TO site, which finally served as our research site for the detailed paleoflood study.

Survey

A detailed survey was conducted during the period May 23-31, 2005, along the study reach of the Colorado River (Fig. 3). The study reach is 4.5 km long and extends from Sandy Beach and downstream almost to Big Bend (Fig. 4) (See also Appendix). The survey used an EDM total station with a laser rangefinder to form a series of 24 cross-sections every 180-190 m in average along the study segment of the upper Colorado River. The measurements include all geometric parameters of the channel and the entire canyon of the Colorado River, such as width, depth, present water level, and gradient; hydraulic parameters, such as roughness coefficient, and sinuosity; and the elevations and locations of all PSIs, such as driftwood lines, SWDs, and high imbricated boulders. These indicators serve as evidence for the actual or minimal water stages of past floods. The measured water elevations at the site can be transformed into discharge by the daily or hourly discharges measured at the Cisco gauging station.

Sedimentological methods

During the period June 10-19, 2005, 14 pits were dug in the flood deposits at the BLM-TO site (Fig. 5; Pictures 1, 2). Arches National Park provided an official permit to dig theses pits and also arranged for an archaeological inspection by Pat Flanigan during the digging phase. The pits were dug with the help of the staff of Wildland Scapes (Moab). The digging of each pit was down to the underlying boulders of the alluvial terrace, and their depth was up to 2 m (Fig. 6). The pits were dug close to each other, with a vertical overlapping of the exposures. This enabled a staircase exposure of the entire section of the SWD relic from top to bottom, as well as correlation between sedimentary units in adjacent pits. The sequence of deposits exposed in each pit was separated into flood deposits associated with flood events using well-established sedimentological criteria (Baker, 1987; Benito et al., 2003) (Figs. 7, 8). This sedimentological separation enabled the reconstruction of the stratigraphy at each pit. Each of the deposits at each pit was documented in detail and sampled for optional future laboratory analyses. For color determination we used the Munsel color chart.

Organic debris, wood and charcoal, which floated over the floodwaters and were deposited over the flood SWDs, usually in the form of discontinuous thin layer at the top of the deposit, were sampled for radiocarbon dating. Because of the very limited amounts of organic matter, we initiated systematic sampling for Optical Stimulation Luminescence (OSL) dating, which uses fine, sandy samples unexposed to daylight. A 2 m exposure in the

Picture 1: Flood site at the BLM-TO site.

floodplain sedimentary units located at a rill that cuts into the floodplain close to the site (Fig. 5) was described and documented in detail (including OSL samples) in order to reconstruct the floodplain stratigraphy (Fig. 9).

Photos of the site and the pits were taken before the pits were covered a few days after the field work was done.

Dating Methods

Radiocarbon

Ages of paleofloods that contained organic material were obtained using radiocarbon dating. In most pits (pits 4, 10, and 13) the organic material is usually in the form of a discontinuous thin layer at the top of the deposit. The organic material in pit 14 was extracted from an incipient soil, which overtops the flood deposit.

The radiocarbon dating techniques, including conventional counting, Accelerator Mass Spectrometry (AMS) (Baker, 1987), and post-atomic-bomb dating, were used for the modern floods, i.e., younger than 1950 AD (Baker et al., 1985; Ely et al., 1992). The samples of organic material were submitted during late June to the Radiocarbon and Isotope Laboratory at the Department of Geosciences, University of Arizona (2 samples), and to the AMS Laboratory, Department of Physics, University of Arizona (2 samples).

Luminescence dating

We found very little organic material for radiocarbon dating within the slackwater deposits of the Colorado River at the BLM-TO site, whereas the fine, sandy sediments of the SWDs of the Colorado River are suitable for systematic luminescence dating (Aitken, 1998). The luminescence methods date the last sunlight exposure episode in a mineral's history and use signals that are acquired by mineral grains, such as quartz or feldspar, from the natural environmental radiation. The magnitude of the OSL signal is related to the total radiation that the sample received. Since the OSL signal is sensitive to sunlight, exposure to the sun during transport and deposition of the sediment will reduce the previously acquired OSL signal to zero ("bleaching") and, after burial, it will grow again.

Picture 2: Flood site at the BLM-TO site.

Fine sand-size quartz was extracted using routine laboratory procedures (Porat, 2002). Briefly, after wet sieving to select the desired size fraction (125-150 μm), carbonates were dissolved using 8% hydrochloric acid, and the dried fraction was passed through a Franz magnetic separator at a high current (~1.5 Ampere) to remove heavy minerals and most feldspars. The non-magnetic fraction was then etched with concentrated (42%) hydrofluoric acid for 40 minutes to dissolve the remaining feldspars and etch the quartz. Subsequently, fluorides were removed with 16% hydrochloric acid.

About 5 mg of the purified quartz was deposited on 10 mm aluminum discs using silicon spray as an adhesive. Measurements were done on Risø DA-12 and DA-20 TL/OSL readers equipped with a calibrated ^{90}Sr β source. Stimulation was carried out with a green-filtered halogen bulb or blue LED diodes, and detection was through 7 mm U-340 filters. The equivalent dose (De) was measured using the OSL signal and the single aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000) on 12 aliquots for each sample. The signal was measured at 125°C to background level. The test dose was roughly 4.5 Gy, and a cut heat of 5 s @ 180°C was used to remove unstable signals.

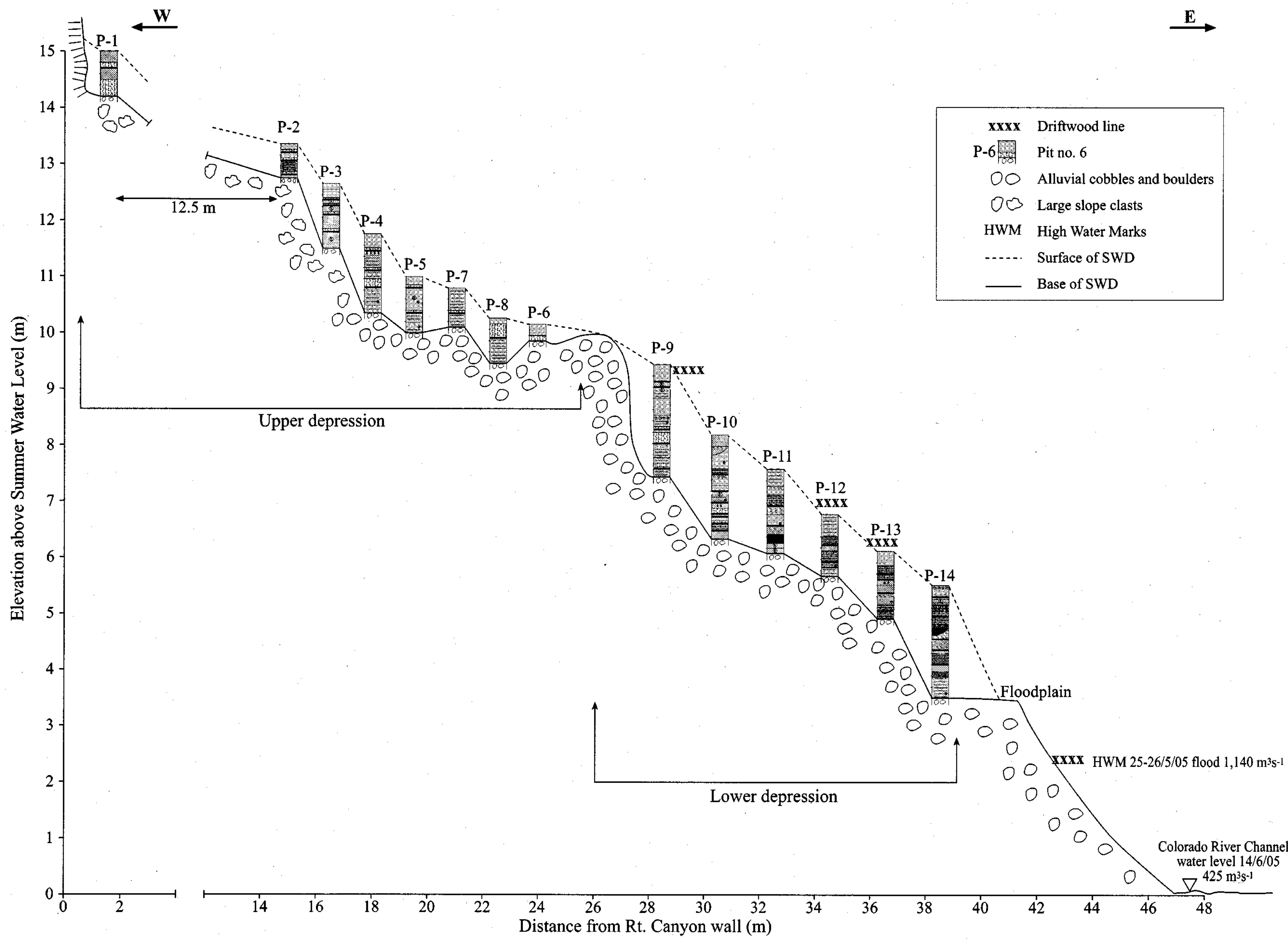

Figure 6: Vertical and horizontal locations of the pits in the SWDs at the BLM-TO study site in relation to the summer water levels of the Colorado River channel in June 2005. Note that the SWD trap is composed of 2 separate depressions: an upper depression (pits 2-8) and a lower depression (pits 9-14). Pit 1 is separated and located at the base of a rocky bench of the canyon wall.

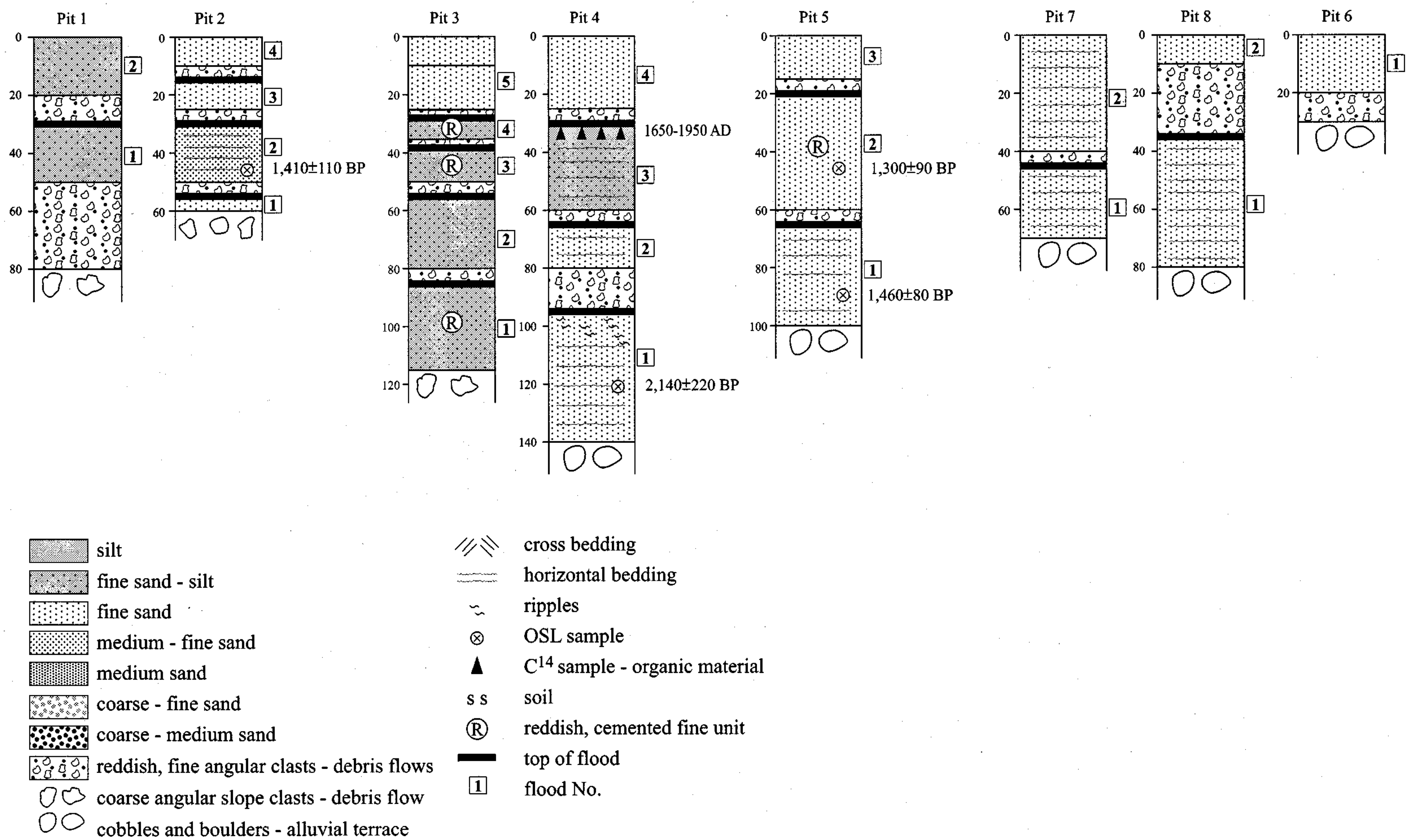

Figure 7: Stratigraphic sections of the pits at the upper depression of the BLM-TO site, including radiocarbon and OSL ages. The sections include a separation of the sedimentary units into flood-related deposits. Reddish deposits of fine angular clasts represent local slope flows that cover Colorado River flood deposits.

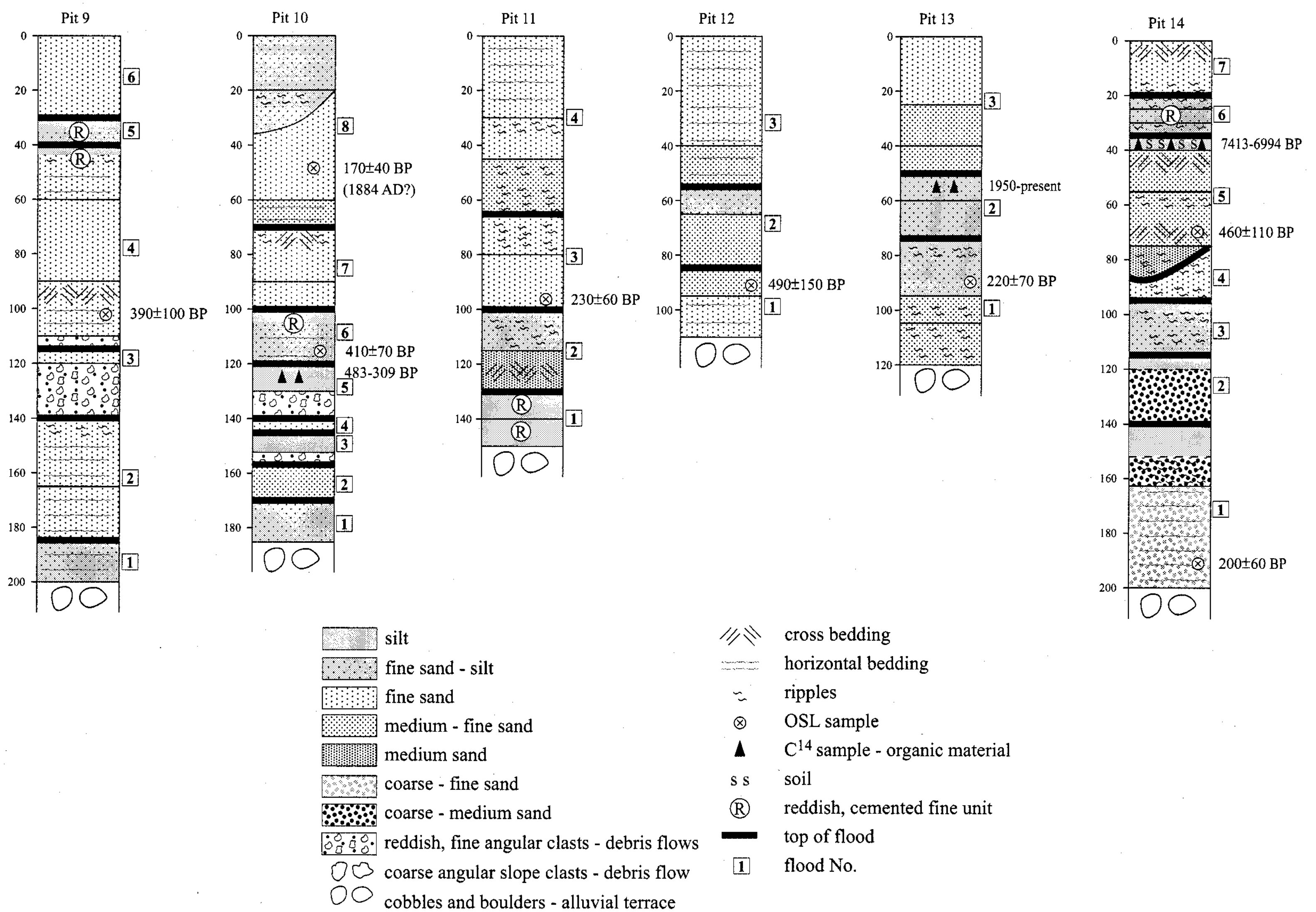

Figure 8: Stratigraphic sections of the pits at the lower depression of the BLM-TO site, including radiocarbon and OSL ages. The lowest pit (pit 14) is probably composed of the oldest deposits. The young OSL ages below the much older radiocarbon age were not considered.

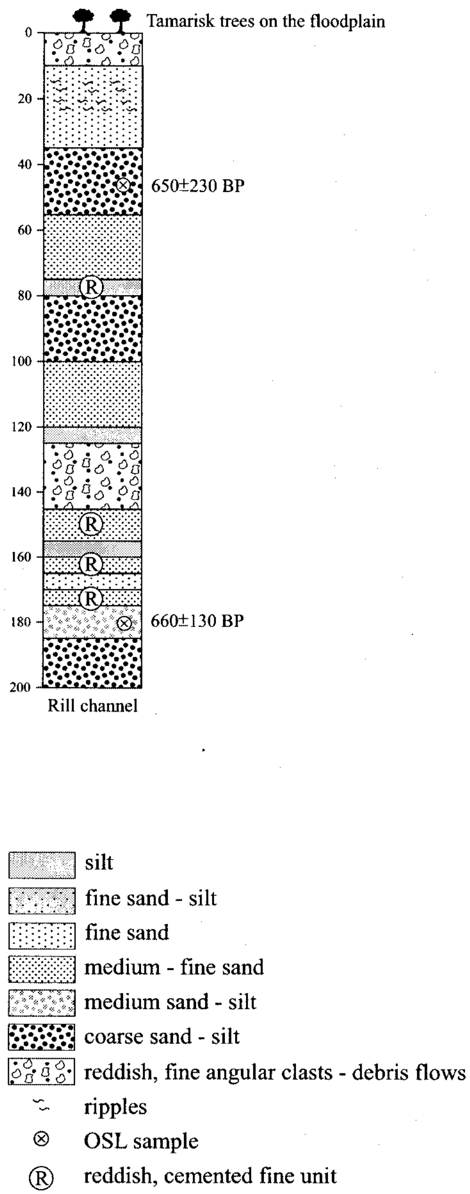

Figure 9: Stratigraphic section at the floodplain, including OSL ages.

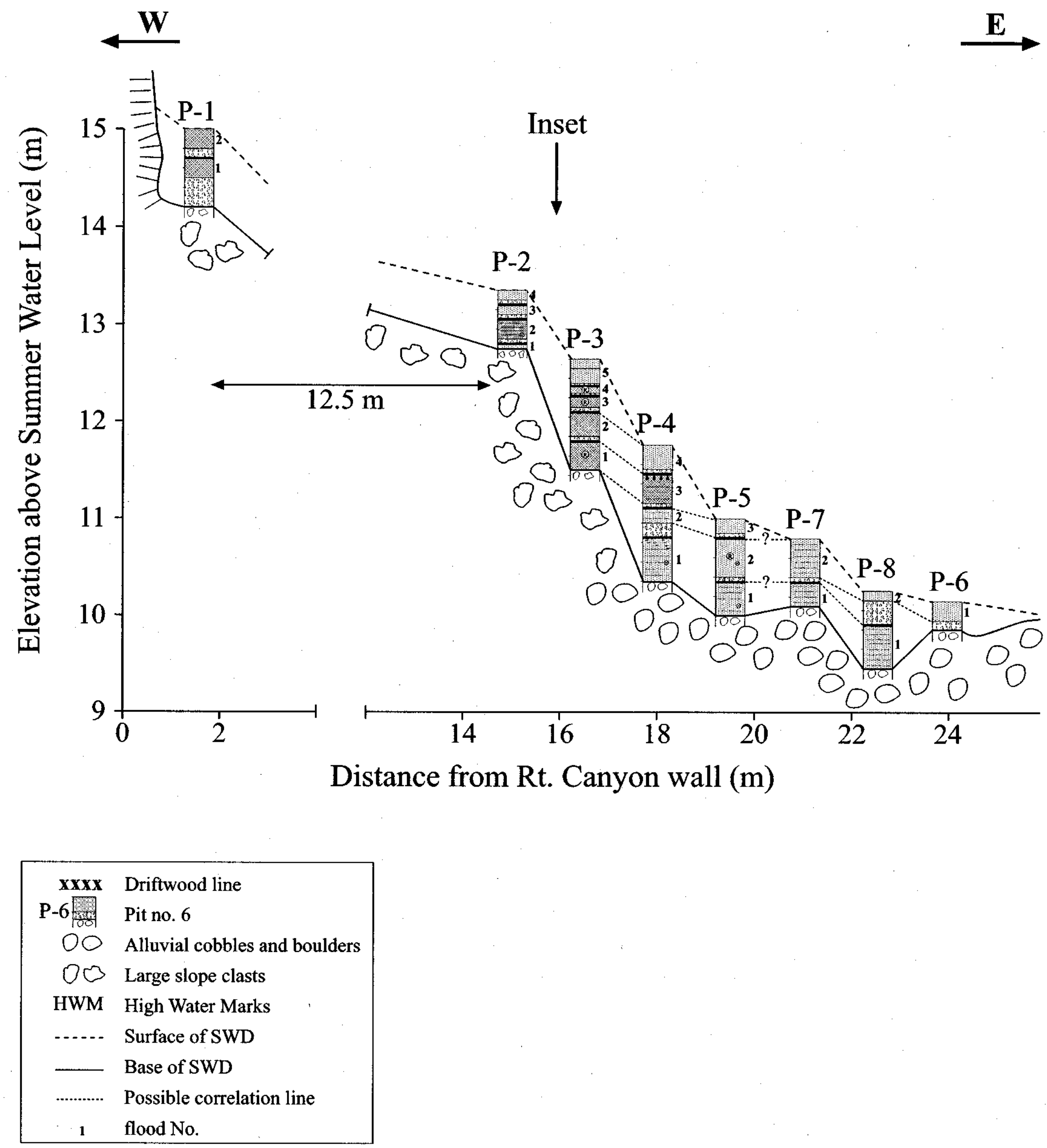

Figure 10: Proposed correlation between flood units at the upper depression of the BLM-TO paleoflood site based on both radiocarbon and OSL ages and other sedimentological and morphometrical properties of the SWDs.

Preheat tests were carried out to evaluate the change of De as a function of varying preheat temperatures between 200° and 260° C. For some samples the De values increased with increasing temperature; more tests are needed to ascertain the cause for such behavior.

For dose rate evaluations, a representative sample of each sample was analyzed for the radioelements U, Th, and K, measured by ICP. Cosmic dose rates were calculated from burial depths. Water contents were estimated at 5%, except for the flood plain samples, for which a value of 10% was used. Table 5 (Appendix) lists the field and laboratory data.

The systematic sampling of the sandy units yielded, wherever possible, 1-2 OSL samples per pit: at the base of the pit and > 0.5 m below the surface. The sampled pits include pits 2, 4, 5, 9, 10, 11, 12, 13, and 14, altogether 12 samples (Figs. 7, 8). Also, 2 samples were taken from the floodplain exposure. Altogether, 14 samples were collected, shipped to Israel, and analyzed at the luminescence laboratory of the Geological Survey of Israel (GSI), in Jerusalem, by Dr. Naomi Porat.

Hydraulic Methods

Paleodischarge estimates were obtained by the slope-area method and will be compared to the results of HEC-RAS hydraulic computer model, which generates water surface profiles using step-backwater calculations for various discharge values (O'Connor and Webb, 1988; Webb and Jarrett, 2002). Comparing the elevations of the SWDs and PSIs to the computed elevations provides a minimal estimation of the peak discharge. A comparison of SWD elevations with other field observations, such as the elevation of driftwood lines of the same floods, historical water levels, and gauged discharges, indicates that heights of the flood deposits commonly are lower than the actual peak stage (Kochel, 1980; Ely and Baker, 1985; Baker, 1987; Partridge and Baker, 1987; O'Connor et al., 1986; Greenbaum et al., 2000). For example, in Nahal Zin, a 1,400 km^2 ephemeral stream channel in the hyperarid Central Negev, Israel, the observed differences between flood deposits and peak stage for large floods are 50-70 cm (Greenbaum et al., 2000). This would lead to an underestimation of the peak discharge (Kochel et al., 1982; Baker, 1987), and they should, therefore, be treated as a minimum value.

The water surface profiles for the study reach, calculated by the HEC-RAS, are expected to indicate subcritical flow regime, typical of large floods in bedrock-controlled streams (e.g., Ely and Baker, 1985; Partridge and Baker, 1987; O'Connor et al., 1986; Baker, 1987). Supercritical conditions are reached only rarely and at few locations where channel gradient increases abruptly, such as large cataracts and rapids.

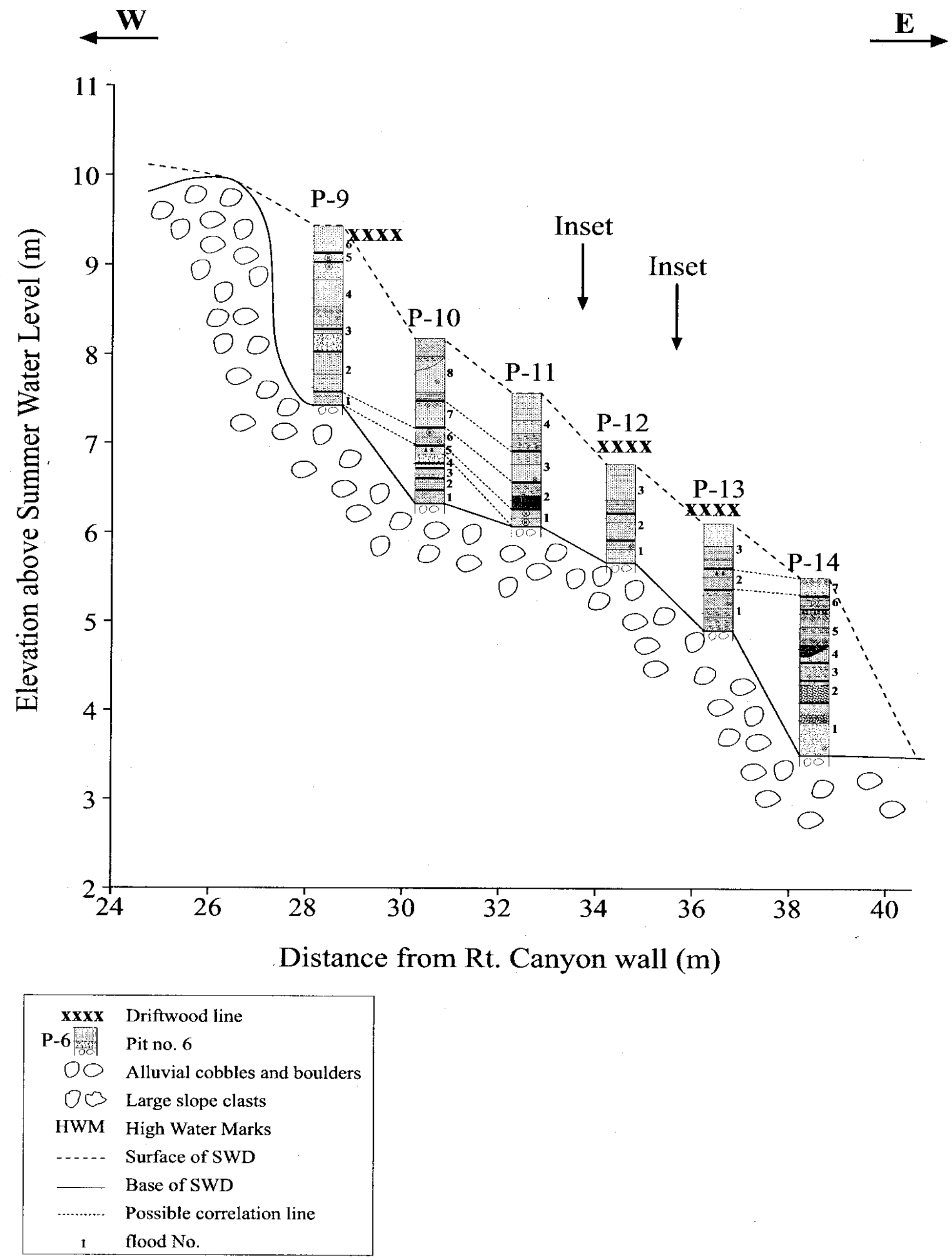

Figure 11: Proposed correlation between flood units at the lower depression at the BLM-TO paleoflood site based mainly on radiocarbon ages and other sedimentological and morphometrical properties of the SWDs.

Other uncertainties in the discharge calculations are presented in detail by O'Connor et al. (1994): (a) flow conditions downstream of the study reach and their effect on the local surface profiles, (b) values of energy loss coefficient, and (c) channel geometry during peak flow stages.

Additional inaccuracies in the discharge estimations may result from the selected hydraulic parameters. Manning's *n* is considered to be of low sensitivity when calculating flow discharges of large floods (O'Connor and Webb, 1988). Enzel et al. (1994) show that for large floods a change of ±20% in *n* values produces a change of < ±5% in the corresponding discharge. In the present study a generalized estimated Manning's *n* was adapted to the following parts of the cross sections: (a) the channel, characterized by low *n* value typical of 0.025 due to the low roughness of the water surface; and (b) the banks and slopes, characterized by high roughness values of 0.06 due to their ragged nature, since they consist of coarse cobbles and boulders and are rich with vegetation at the foot-slope and on the floodplain.

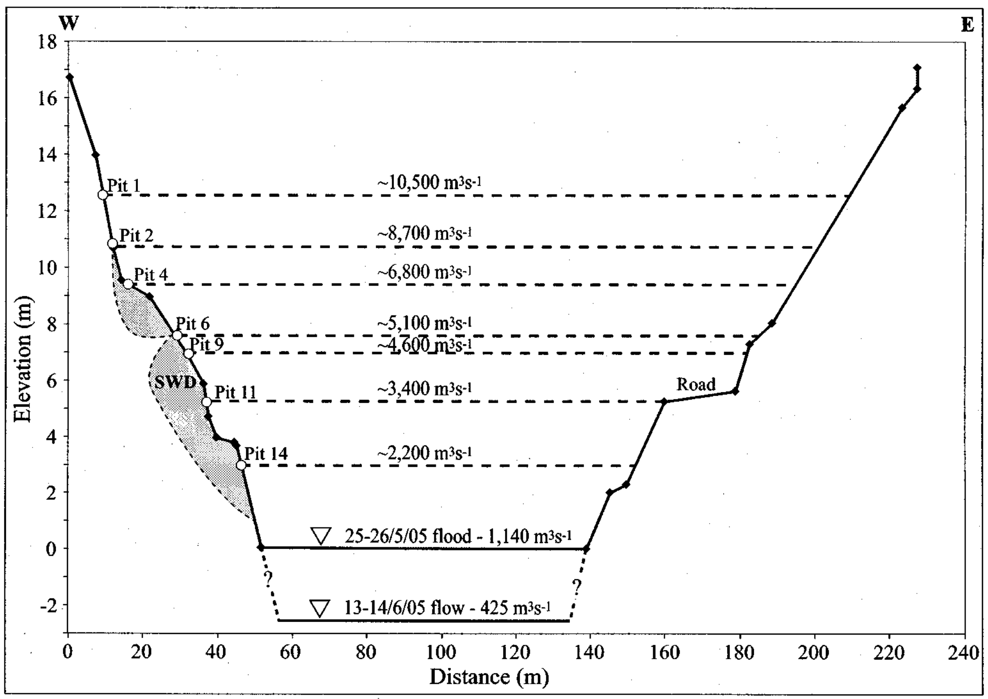

Figure 12: Cross-section No. 9 through the Colorado River at the BLM-TO paleoflood site, elevations of pits and associated peak discharges using slope-area calculations.

Since the channel bed topography and depth along the study reach is unknown, our discharge calculation uses the water surface during the survey as a smooth channel bed and the daily discharge, derived from the Cisco gauging station, was added to the discharge provided by the hydraulic program.

The elevation of the water levels during the survey and the field work were documented in the field (Fig. 6, Pics. 1, 2), and the associated discharges are available from the Cisco gauging station upstream. These discharges will help to calibrate the water surface profiles generated by the HEC-RAS hydraulic program.

Results

Sedimentological Results

The BLM-TO site composed of 2 depressions/traps, in which the SWDs accumulated. The higher trap, represented by pits 2-8 (Pics. 1, 2), is 9.6-13.5 m above summer water levels (SWL: water level on June 19, 2005) (Figs. 6, 7). This depression is relatively shallow, as indicated by the depth of the pits, which ranges between 0.3 and 1.4 m. The lower trap, represented by pits 9-14, is 3.5-9.7 m above SWL (Figs. 6, 8; Pics. 1, 2) and is deeper; the pits are 0.8-2.0 m deep. Pit 1 is located at the base of the rocky rim of the canyon (Pic. 1); other thin SWD accumulations are scattered between pit 1 and pit 2. The sediments in pits 1-3 are deposited over large boulders originating from debris flow, while the deposits in the other pits overlie boulders of an alluvial terrace. Each of the pits in the higher depression (pits 1-8; Fig. 7) include between 1 and 4 reddish, angular, clast-supported, gravelly deposits, which originate from the slope due to their proximity to the contributing canyon wall. In the lower depression (Fig. 8) these units occur only in pits 9 and 10, whereas, in lower pits they are absent. Some of the SWDs have reddish color, which may be related to: (a) different source of sediments, (b) fine sediments derive from the slope, or (c) development of incipient soil.

The sedimentary units were separated into flood-related deposits, which may combine several sedimentary units. The 14 pits, their stratigraphy and their relative position in the site, are shown in Figure 6 and Table 1.

The common texture of the SWDs of the floods at the site is medium-fine sand and up to silt. The structure of the sediments is usually finning upward, horizontally bedded or massive, but may also be cross-bedded or rippled. The typical color of the SWDs, as well as the present floods, is yellowish brown (10YR5/4), as documented in the flood deposits of pits 9-14. In the higher pits 1-8 the common color is somewhat darker brown (7.5YR5/4), possibly due to an increase in the amount of local reddish dust washed into the SWDs after their deposition. The common contacts that separate sedimentary units, are: (a) abrupt changes in texture, structure, or color; (b) presence of organic layer; and (c) presence of reddish, angular, clast-supported gravelly slope deposit. Pits 1-8 include 1-6 flood deposits, while pits 9-14 contain 6-15 deposits. Also, 3 driftwood lines, which present the actual stage of the flood, were documented and surveyed at the site, as well as high imbricated boulders, which indicates minimal water stage only. A paleosol, radiocarbon dated to 7413-6994 BP, was exposed in pit 14, indicating a temporal gap in deposition of flood deposits at similar or higher elevation.

Table 1: Properties of the SWDs at the pits.

Pit No.	No. of flood sedimentary units	No. of associated flood events	No. of gravelly slope deposits	Depth of pit (m)	Elevation above SWL* (m)
1	2	2	2	0.8	14.2-15.1
2	4	4	3	0.6	13.0-13.6
3	6	5	4	1.1	11.7-12.8
4	4	4	3	1.4	10.5-11.9
5	3	3	2	1.0	10.2-11.2
6	1	1	1	0.3	10.0-10.3
7	2	2	1	0.7	10.3-11.0
8	2	2	1	0.8	9.6-10.4
9	10	6	2	2.0	7.7-9.7
10	12	8	2	1.9	6.6-8.5
11	9	4	0	1.5	6.4-7.9
12	6	3	0	1.1	5.7-6.8
13	8	3	0	1.2	5.0-6.2
14	15	7	0	2.0	3.5-5.5
Floodplain	14	14	2	2.0	1.6-3.6

*SWL - Summer water level June 14, 2005

The floodplain section (Fig. 9) includes the following types of sedimentary units: (a) flood deposits similar to those exposed in the pits; (b) reddish, angular clast-supported gravelly slope deposits similar to the other pits; and (c) reddish sandy and silty units that may originate either from the slope, but, more likely, are flood deposits derived from tributaries that drain reddish sandy rocks, such as the Dolores River.

Dating Results

(a) Radiocarbon

The results of the radiocarbon dating at the various pits are presented in Table 2.

(b) Luminescence dating

The ages of the SWD range from several hundred years up to over 2,000 years before present (Figs. 7, 8; Table 2). The samples appear to cluster into two age groups: older than 1,300 years and younger than 660 years. The ages of the older samples, between 1,300 and 2,140 years, are well constrained, with small uncertainties (sample error is only 5-10%). However, the samples younger than 660 years show large scatter of De values (samples error is 17-35%), indicating that the sediments are not homogenous with respect to solar bleaching (Clarke, 1996). Ages for these samples were calculated without obviously outlying old aliquots. Even so, the insufficient bleaching implies that the ages presented in Table 2 are maximum ages, and the timing of SWD deposition could be more recent. Twelve samples from 11 pits and 2 samples from the exposure in the floodplain were dated by luminescence. The results of the OSL dating are shown in Table 3. The full results are presented in the Appendix.

Table 2: Results of radiocarbon dating of paleoflood deposits at the BLM-TO site.

Sample No.	Pit No.	Unit No. in pit	Flood no. in pit	Material	^{14}C age (years)	Calibrated age (years AD/BP)
A13878	4	2	3	Wood	135±35	1650-1950 AD
AA65420	10	4	5	Charcoal	340±34	1467-1641 AD
A13879	13	2	2	Wood	120.5±1.8	1950-present
A13877	14	3	5	Soil	6275±160	7413-6994 BP

Comparison of Radiocarbon and OSL dating results

The older OSL ages (> 1000 years BP) characterize the higher deposits in the upper depression (Fig. 10), whereas the younger ages (< 660 years BP) date the flood deposits at the lower depression and the floodplain (Fig. 11). This trend generally agrees with the radiocarbon ages (Figs. 7, 8, 10, 11). The certainty of the ages in the lower depression is lower and needs improvement and refinement. Nevertheless, the oldest radiocarbon age was found in the lowest pit (pit 14) at the base of the entire SWD relict (Figs. 8, 11). The underlying OSL ages are much younger and also do not agree with the order of the pit stratigraphy. Therefore, these ages were not taken into consideration. At the upper depression, the ages from both dating methods agree with each other. The stratigraphy based on the combination of the ages agrees in general with the startigraphy in the pits. In the lower depression (except for pit 14) the ages in each pit agree with the stratigraphy as well. In spite of the higher uncertainty, both dating methods also agree with each other. The large number of dates provides a higher chronological resolution, which indicates more insets of flood deposits aside of previous SWD accumulations and a more detailed flood stratigraphy, with a larger number of reconstructed flood events.

Table 3: Results of luminescence dating of paleoflood deposits at the BLM-TO site.

Sample No.	Pit No.	Unit no. in pit	Flood no. in pit	Age (years)
P2U5	2	3	2	1410±110
P4U4	4	4	1	2140±220
P5U1	5	2	2	1300±90
P5U2	5	3	1	1460±80
P9U5	9	3	4	390±100
P10U3	10	1	8	170±40
P10U7	10	3	6	410±70
P11U5	11	2	3	230±60
P12U5	12	2	1	490±150
P13U6	13	3	1	220±70
P14U7	14	3	5	460±110
P14U13	14	7	1	200±60
FPU3	**Floodplain**	2		650±230
FPU15	**Floodplain**	13		660±130

The relative older ages of the floodplain, about 650 years BP (Fig. 9), may suggest that it is relatively stable during the last several hundred years.

Number of paleofloods

The transformation of sedimentary units into associated flood events (Figs. 7, 8) is based on several sedimentological principles and criteria related to similarity/difference in sediment properties, such as structure, texture, color, contacts between units, and age. Presence of incipient soil overtopping flood deposits indicates a period of smaller floods that had not exceeded the elevation of the soil. Table 1, Column 3, presents an interpretation of the sedimentary sections exposed in the pits and their separation into flood-associated units that may combine several sedimentary units. The upper pits were separated into 1-5 floods at each pit, while each of the lower pits includes 3-8 reconstructed floods (Figs. 8, 9).

Table 4: Summary of paleofloods at the BLM-TO site, minimal peak stages and slope-area calculations of peak discharges.

Location	Pits no.	No. of floods	Stages above SWL* (m)	Peak discharge ($m^3 s^{-1}$)
Lower depression	12-14	12	4.2-6.3	2200-3000
Lower depression	10-11	8	6.5-8.5	3200-3800
Lower depression	9	5	8.5-9.7	4600
Upper depression	3-8	9	10.0-12.2	5100-8000
Upper depression	2	4	12.4-13.5	8700
Upper depression	1	2	14.8-15.1	10,500
Total	1-14	40	4.2-15.1	2200-10,500

*SWL - Summer water level on June 14, 2005.

Correlation between floods in adjacent pits (Figs. 10, 11) is based on the properties of the sediments, their thickness, lateral continuity, field relationships among the deposits, radiocarbon and OSL ages, and other principles in SWD sedimentation (Figs. 10, 11).

The following interpretation of the flood stratigraphy is based on both dating methods, which usually (except for pit 14) agree with each other. The results of the correlations (Table 4) provide a probable generalized paleoflood stratigraphy, which includes about 40 paleofloods at the BLM-TO site: 15 at the upper depression and 25 at the lower depression. The results of the luminescence dating, which were incorporated later, provide a more detailed and complicated stratigraphy and increase the number of floods relative to the stratigraphy, based on radiocarbon ages only.

Flood No. 4 in pit 11, which was correlated to flood No. 8 in pit 10, was OSL dated to 170±40. Its minimal age, then, is about 130 years. The peak discharge of this flood was calculated to about 3,800 m^3s^{-1} and may be correlated to the 1884 flood (3,540 m^3s^{-1}).

Magnitude of paleofloods

Slope-area calculations at the site indicate that the peak discharge reconstructed for floods associated with deposits at the top of pit 1 (15 m above SWL) is about 10,500 m^3s^{-1} and about 8,700 m^3s^{-1} for the top of pit 2 (13.5 m above SWL) (Figs. 6, 10, 12). Calculated peak paleovelocities for these floods are 5.1 and 5.3 m s^{-1}, respectively. The peak discharge for the top of pit 6, the lowest pit at the upper depression (10.2 m above SWL), is about 5,100 m^3s^{-1} (calculated velocity of 4.3 m s^{-1}) (Figs. 6, 11, 12). At the lower depression, peak discharges are from 4,600 m^3s^{-1} for the top of the uppermost pit (pit 9, elevation of 9.5 m above SWL), with a calculated velocity of 4.2 m s^{-1}. For the top of the lowest pit (pit 14), peak discharge is about 2,200 m^3s^{-1} (elevation of 5.5 m above SWL), and the velocity is 4.2 m s^{-1} (Fig. 6, 12). These calculations will be compared to water surface profiles produced by the HEC-RAS program.

Summary

Based on the slope-area method only, a gross estimation of the largest peak discharges calculated in this study indicate at least 3 floods that exceed about 8,500 m^3s^{-1} (about 300,000 cfs) during the last 1410±110 years B.P. The paleoflood record probably includes another 2 undated larger floods, with peak discharges exceeding 10,000 m^3s^{-1} (about 350,000 cfs), which may have occurred during the last 2140±220 years B.P. **The maximal peak discharge values need to be confirmed by the HEC-RAS procedure.** If correct, these values exceed the probable maximum flood (PMF) value of the USGS for the Moab Valley of 300,000 cfs (about 8,500 m^3s^{-1}) (Kenny, 2005). The 500-year flood for Cisco gauging station in this USGS report is 120,000 cfs (about 3,400 m^3s^{-1}), whereas the 100-year flood is 97,600 cfs (about 2,765 m^3s^{-1}). The similarity between the 100- and 500-year floods was explained by the flow regulation during the past half a century, which slightly reduced the peak magnitudes. The results of the present study indicate that the peak discharge of about 20 paleofloods during the last 2140±220 years exceeded 3,400 m^3s^{-1}, and over 25 paleofloods exceeded peak discharges of 2,765 m^3s^{-1}.

These results suggest that a further and more accurate paleoflood study is definitely needed in the future in order to improve the risk assessment for Moab area and Moab Valley.

Note: The cross-sections of the EDM total station/laser rangefinder along the study reach of the upper Colorado River (see Fig. 4, page 17) and close-up photos of the pits can be viewed in the report archived on the web at:
http://www.livingrivers.org/MoabMillProject.pdf

Editor's Epilogue:

It is clear that there are 2 undated flood deposits (pit 1) exceeding 350,000 cfs over the past 2,000 plus years. The data also shows (including pit 2) that at least 5 floods exceed the probable maximum flood of 300,000 cfs over the past 2,000 plus years. A very large number of paleofloods (20 plus) exceeded the 500-year flood value for Cisco (120,000 cfs) over the last 2,000 plus years. This indicates that the nature of 100- and 500-year floods are not yet fully understood in the Colorado River Basin. At a future time, the above data should be put into a full-up flood-frequency analysis, so that the 100- and 500-year magnitudes can be inferred directly from the paleoflood data alone.

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Appendix

Table 5: Results of luminescence dating of paleoflood deposits at the BLM-TO site.

Sample	Depth (m)	K (%)	U (ppm)	Th (ppm)	Ext. α (µGy/a)	Ext. β (µGy/a)	Ext. γ (µGy/a)	Cosmic (µGy/a)	Total dose (µGy/a)	Aliquots used	De (Gy)	Age (years)
P2U5	40-50	1.66	2.05	6.7	8	1492	903	214	2617±47	12/12	3.68±0.27	**1410±110**
P4U4	110-120	1.99	2.90	9.2	11	1870	1182	182	3245±56	11/12	6.95±0.71	**2140±220**
P5U1	40-50	1.74	2.50	8.4	10	1639	1046	214	2909±51	11/12	3.79±0.26	**1300±90**
P5U2	70-80	1.74	2.50	8.6	10	1643	1055	193	2901±51	10/12	4.24±0.22	**1460±80**
P9U5	90-100	1.58	1.97	5.8	7	1388	816	186	2397±64	12/12	0.92±0.24	390±100
P10U3	50-60	1.58	2.30	7.4	9	1487	942	207	2645±46	11/12	0.45±0.12	170±40
P10U7	100-110	1.66	1.80	5.5	7	1434	822	184	2447±45	9/12	1.01±0.18	410±70
P11U5	90-100	1.58	2.15	7.2	9	1464	917	186	2576±46	10/12	0.58±0.15	230±60
P12U5	90-100	1.74	2.58	8.3	10	1646	1050	186	2892±51	11/12	1.40±0.45	**490±150**
P13U6	70-80	1.49	2.53	7.5	10	1458	951	193	2611±47	11/12	0.57±0.19	220±70
P14U7	60-70	1.66	4.20	7.7	13	1779	1177	199	3168±55	12/12	1.46±0.34	**460±110**
P14U13	170-180	1.83	4.50	10.8	16	1998	1388	169	3570±61	11/12	0.73±0.22	200±60
FPU3	40-50	1.66	2.80	6.4	9	1490	920	169	2587±62	10/12	1.68±0.59	**650±230**
FPU15	170-180	1.58	3.80	5.4	10	1534	961	214	2720±78	8/12	1.80±0.34	**660±130**

Gamma dose rate was calculated from the radioelements and the cosmic dose estimated from burial depth. Water content was estimated at 5%, except for the floodplain samples, for which a value of 10% was used. Quartz with grain size 125-150 µm was etched by concentrated HF for 40 minutes following dissolution of carbonates by HCl. De was obtained using the single aliquot regeneration, using preheats of 10 s at 200-260°C. Test dose was ~4.5Gy, and a cut heat of 5s @180°C was used. Aliquots used: the number of aliquots used for the average De out of the aliquots measured (distinct outliers were removed).

Supplemental photo taken in 1905 looking downstream. The paleoflood study site is near the center of this view. Whitman Cross, USGS Denver.

Conversion Table
Metric to U.S. Customary

Multiply	**By**	**To obtain**
millimeters (mm)	0.03937	inches
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
kilometers (km)	0.6214	miles
square meters (m2)	10.76	square feet
square kilometers (km2)	0.3861	square miles
hectares (ha)	2.471	acres
liters (L)	0.2642	gallons
cubic meters (m3)	35.31	cubic feet
cubic meters (m3)	0.0008110	acre-feet
grams (g)	0.03527	ounces
kilograms (kg)	2.205	pounds
metric tons (t)	1.102	tons

Celsius (C) to degrees Fahrenheit (F): F = 1.8(C) + 32

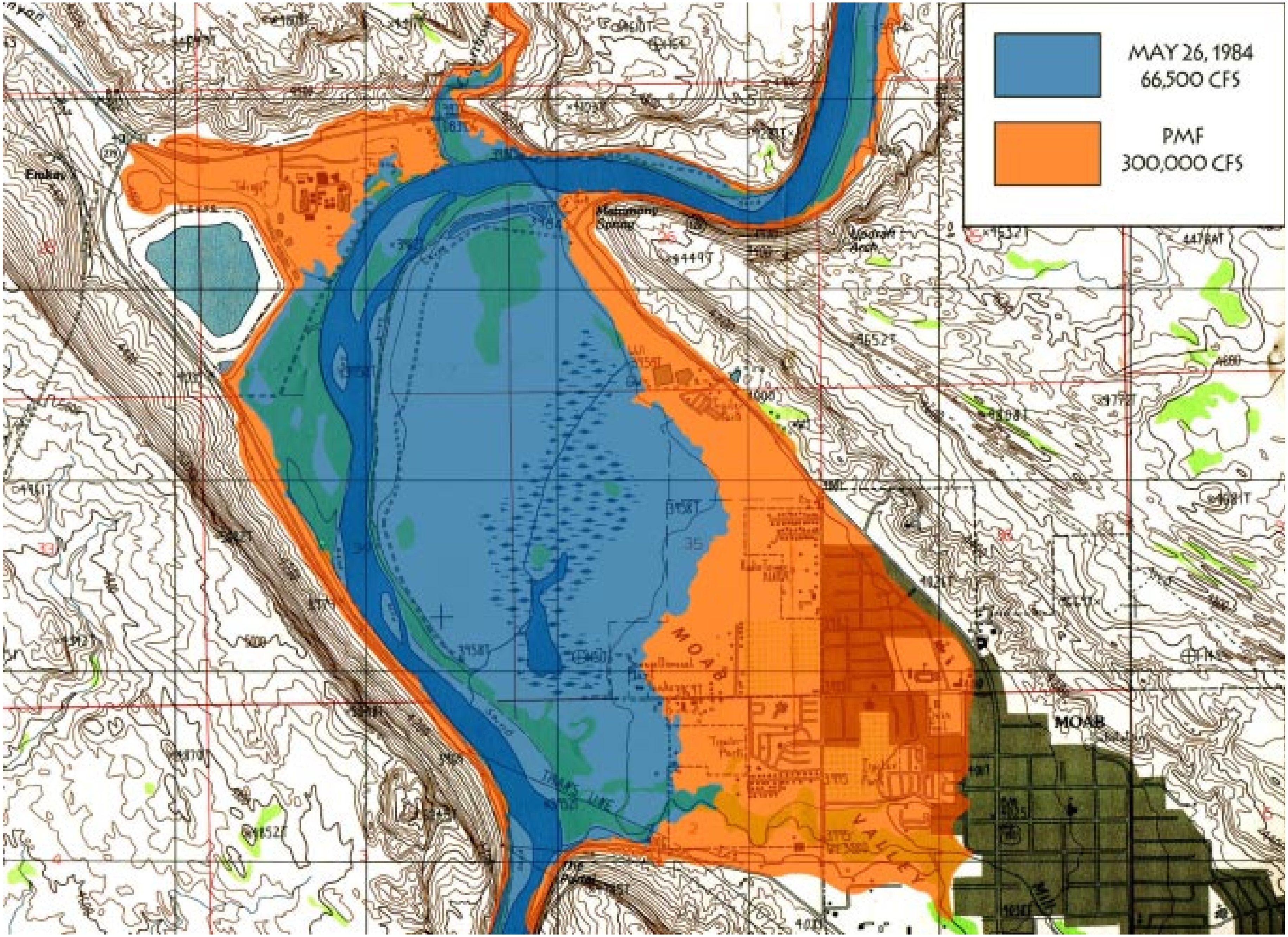
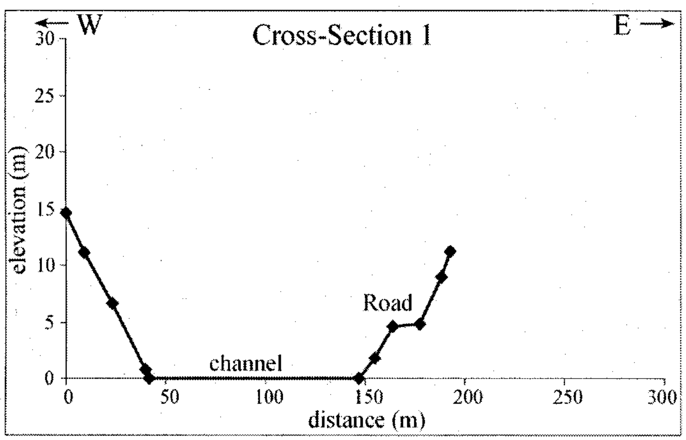
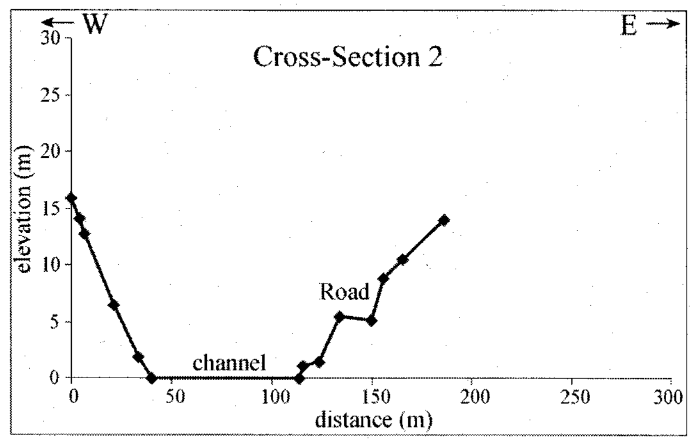


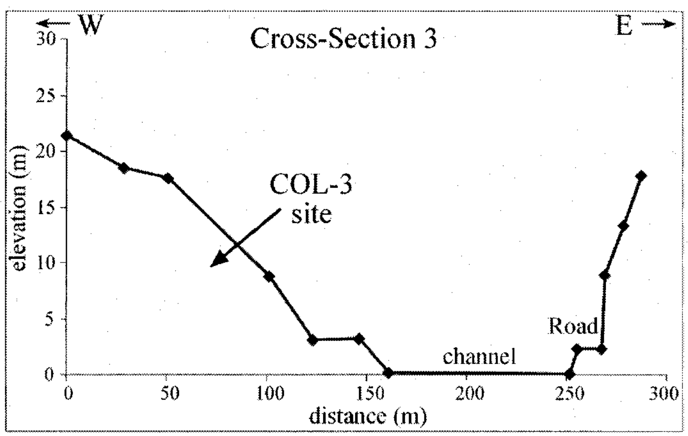
Photo page 30: Extent of a 300,000 cfs flood in the Moab Valley. John C. Dohrenwend.
Photo inside back cover: Aerial photo of Moab Mill Site. John C. Dohrenwend.
Photo back cover: Colorado River flood (circa 1920) taken near Courthouse Wash. Utah Historical Society. Photographer unknown.

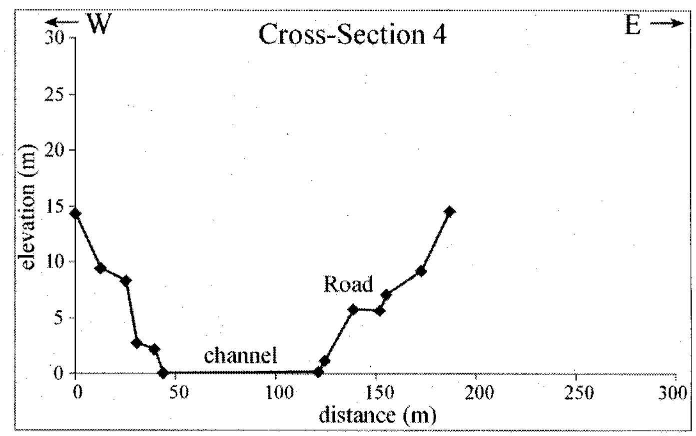
The following pages include supplemental information not provided in the formal publication:

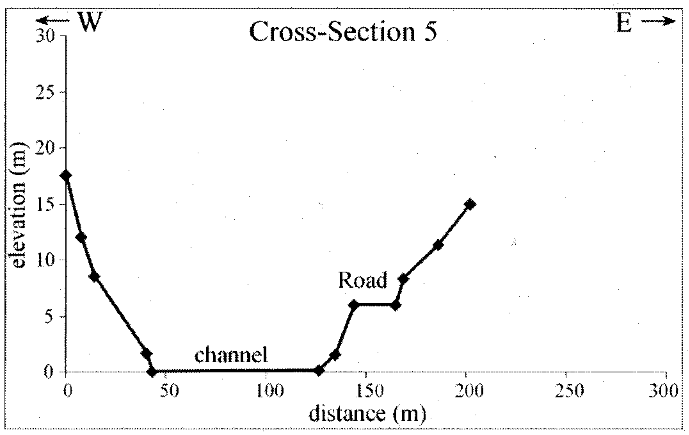
- **The cross-sections using a EDM total station/laser rangefinder**
- **Color photos of the pits prior to burial**



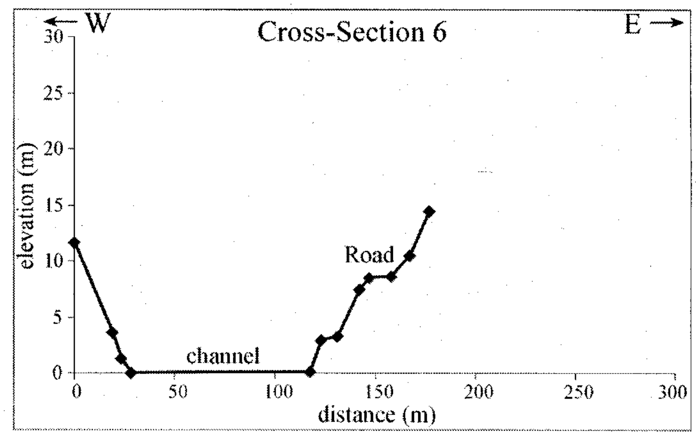




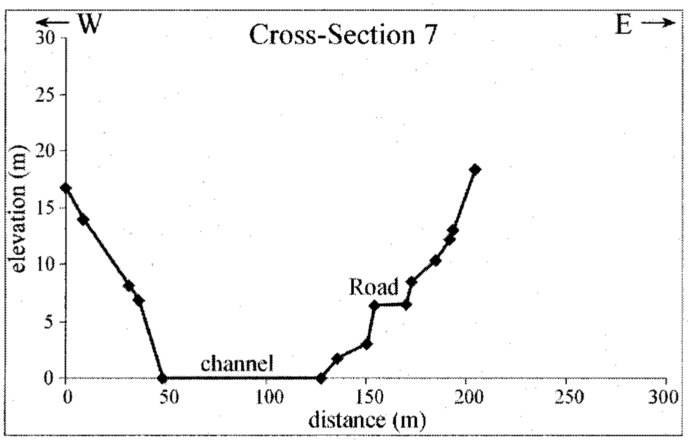




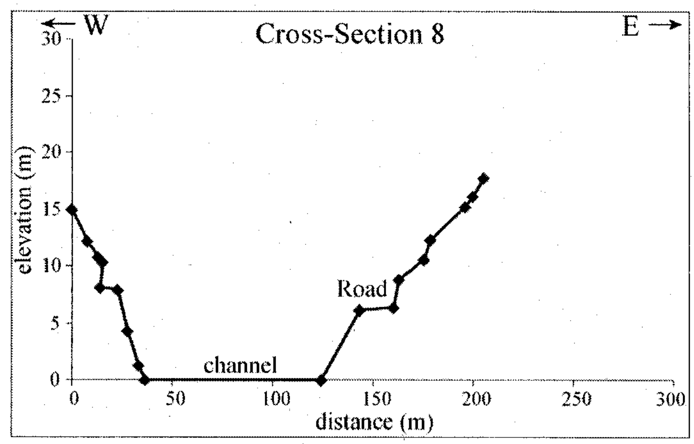
← W
Cross-Section 5
E →
elevation (m)
distance (m)
Road
channel



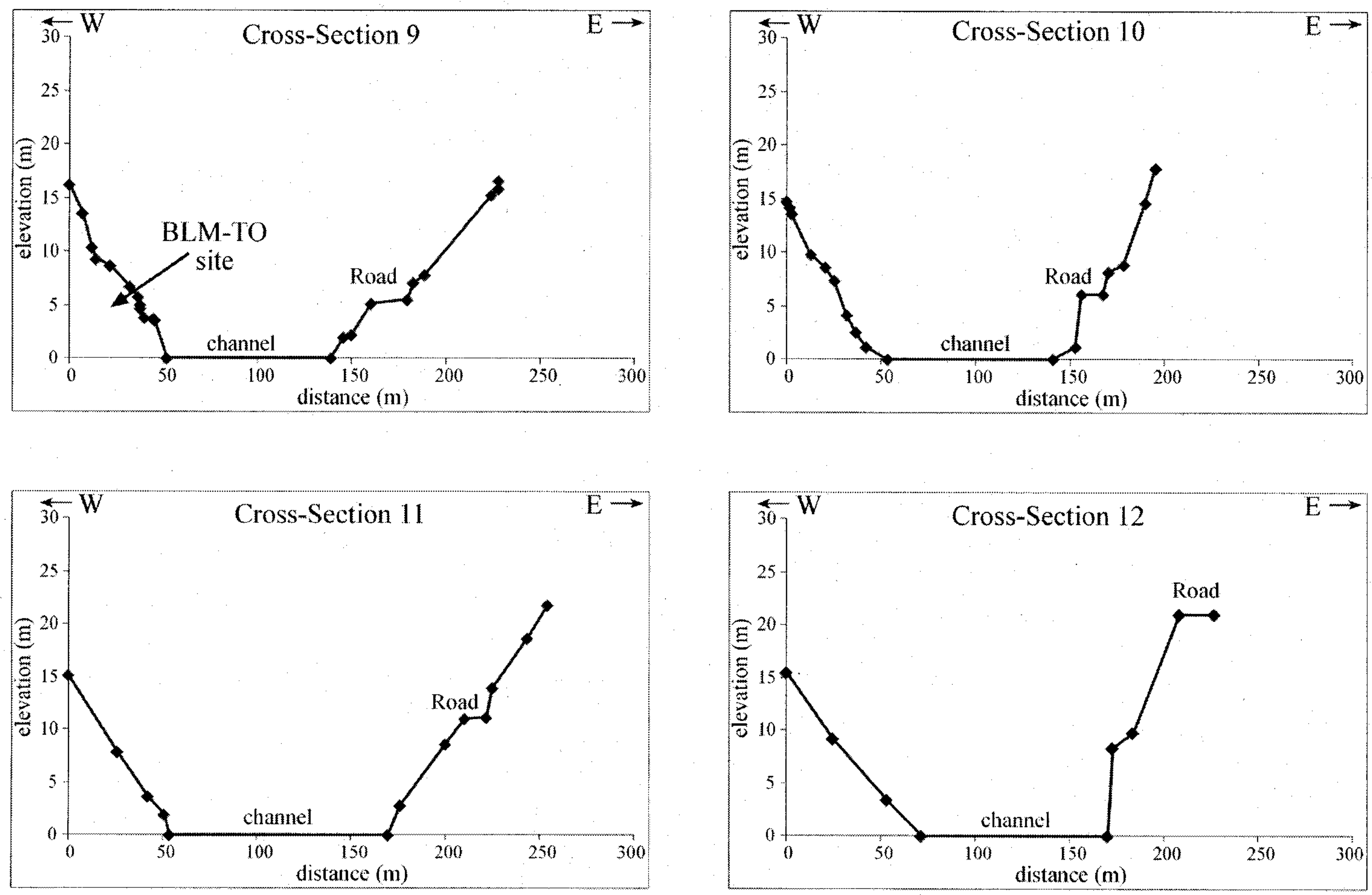
← W
Cross-Section 6
E →
elevation (m)
distance (m)
Road
channel



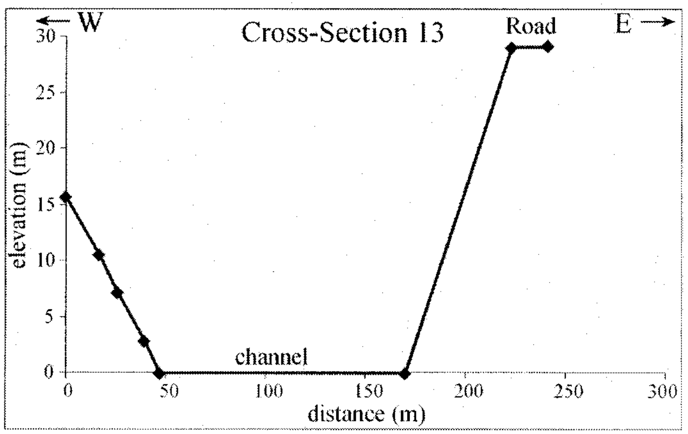
← W
Cross-Section 7
E →
elevation (m)
distance (m)
Road
channel



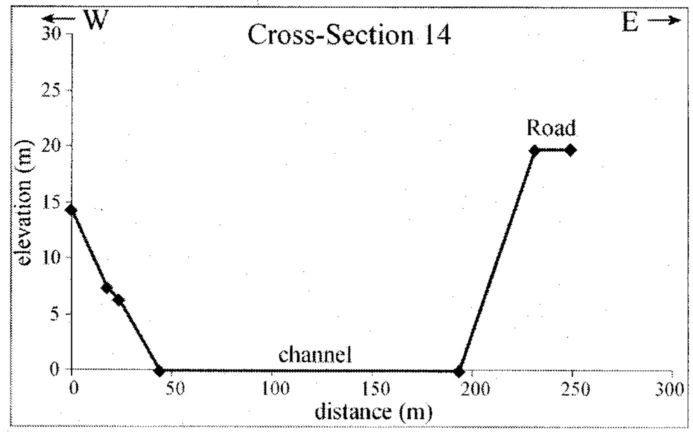
← W
Cross-Section 8
E →
elevation (m)
distance (m)
Road
channel



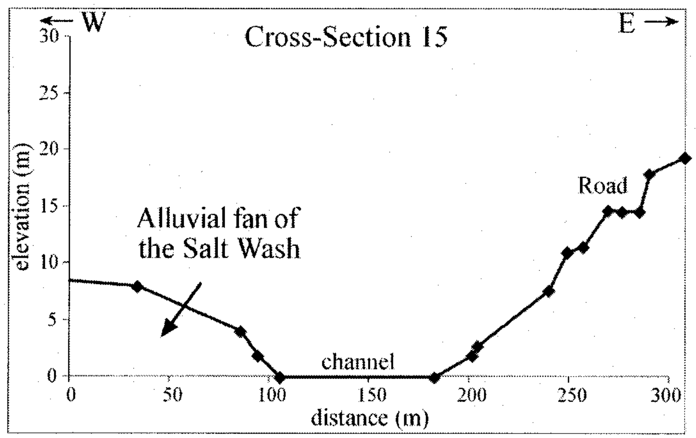
Cross-Section 9
W
E
BLM-TO site
Road
channel
elevation (m)
distance (m)
Cross-Section 10
W
E
Road
channel
elevation (m)
distance (m)
Cross-Section 11
W
E
Road
channel
elevation (m)
distance (m)
Cross-Section 12
W
E
Road
channel
elevation (m)
distance (m)



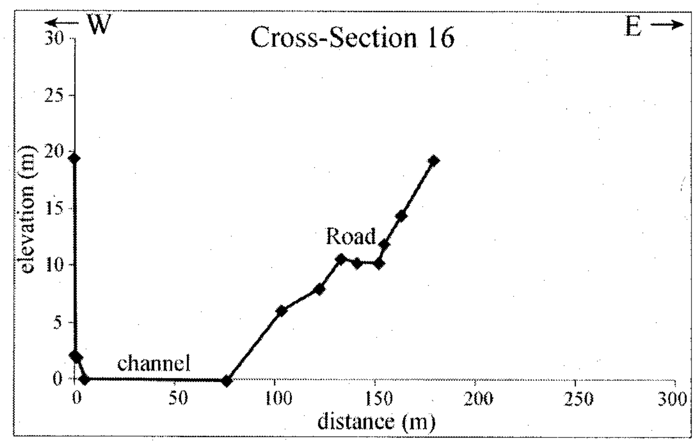
← W
Cross-Section 13
Road
E →
elevation (m)
channel
distance (m)



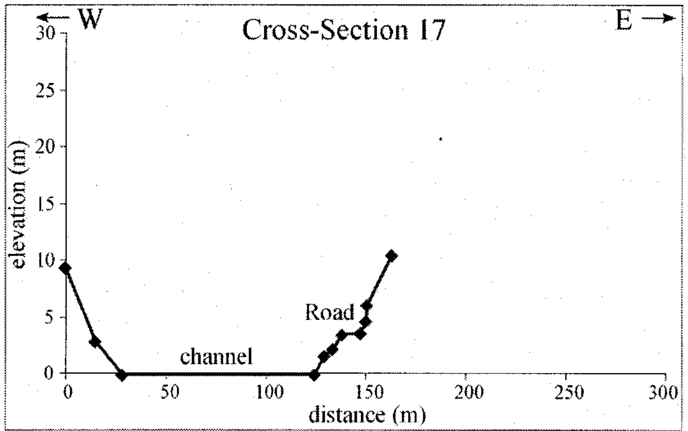
← W
Cross-Section 14
E →
Road
elevation (m)
channel
distance (m)

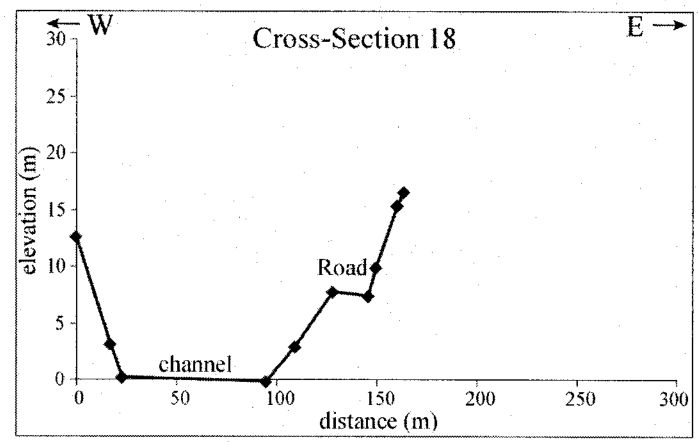


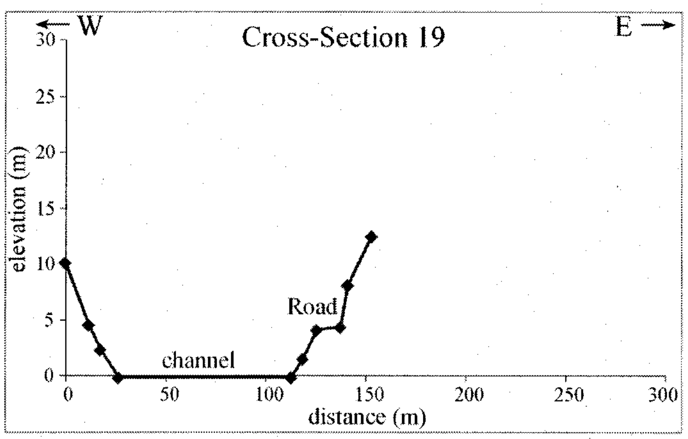
← W
Cross-Section 15
E →
Road
Alluvial fan of
the Salt Wash
elevation (m)
channel
distance (m)

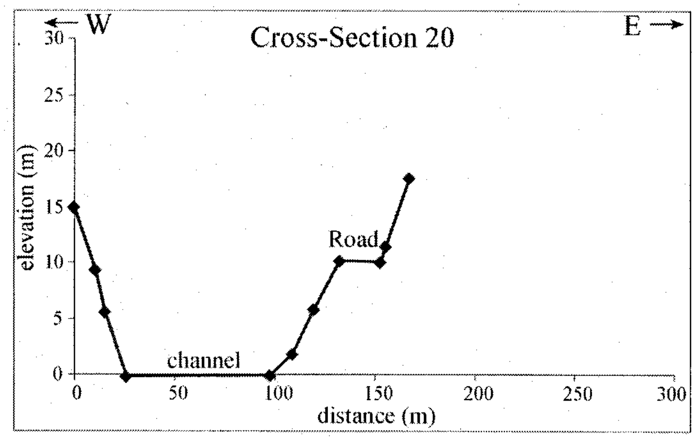


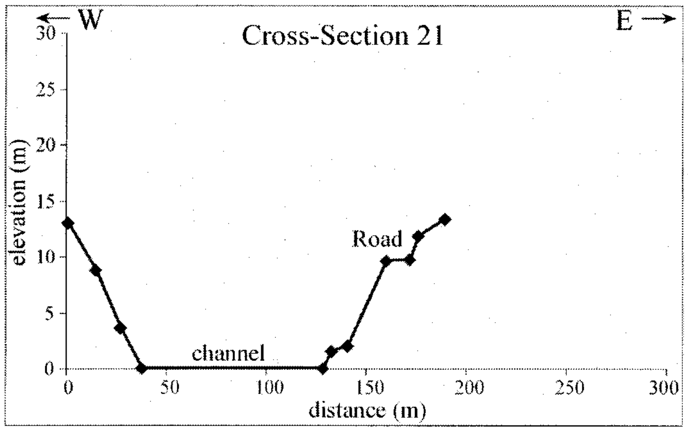
← W
Cross-Section 16
E →
Road
elevation (m)
channel
distance (m)

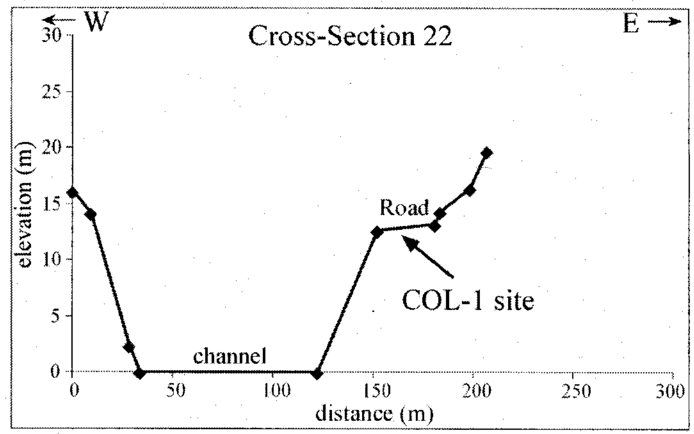

Cross-Section 17
W
E
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300

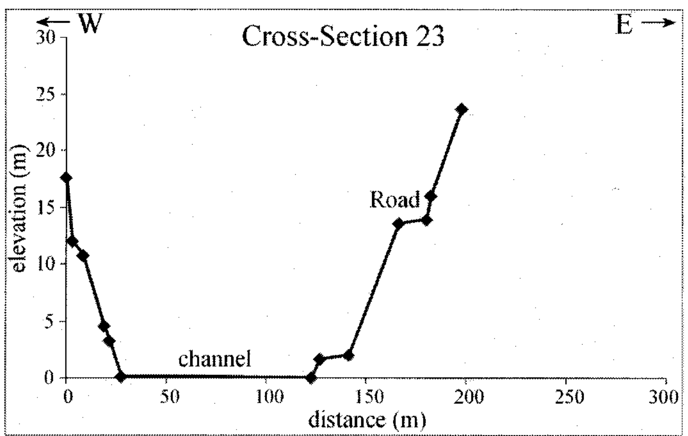

Cross-Section 18
W
E
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300

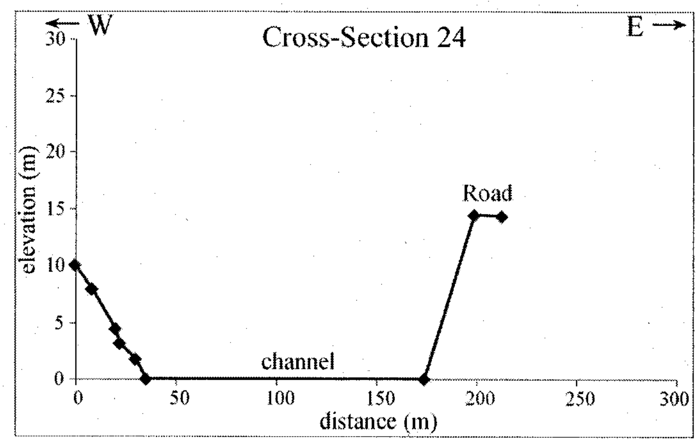

Cross-Section 19
W
E
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300


Cross-Section 20
W
E
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300


Cross-Section 21
← W
E →
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300


Cross-Section 22
← W
E →
elevation (m)
distance (m)
channel
Road
COL-1 site
0
5
10
15
20
25
30
0
50
100
150
200
250
300


Cross-Section 23
← W
E →
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300


Cross-Section 24
← W
E →
elevation (m)
distance (m)
channel
Road
0
5
10
15
20
25
30
0
50
100
150
200
250
300

Pit 1

Pit 2

Pit 3

Pit 4

Pit 5

Pit 6

Pit 7

Pit 8

Pit 9

Pit 10

Pit 11

Pit 12

Pit 13

Pit 14

End