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Applicability of Paleoflood Surveys to the Black Hills of Western South Dakota

Study SD2005-12
Final Report

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DISCLAIMER

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16. Abstract

Flood-frequency analyses for the Black Hills area have large uncertainties because of several complicating factors, including effects of the massive 1972 storm near Rapid City; geologic influences; and potential influences of topography on precipitation patterns. The objective of this study was to assess the applicability of paleoflood hydrology techniques to generate better historical records on the magnitude and frequency of peak-flood events in the Black Hills area.

As the study evolved, it became apparent that the paleohydrologic approach of greatest potential utility is detailed stratigraphic analysis of sequential deposits of slackwater flood sediments in caves, alcoves, and rock shelters, along with radiocarbon dating of entrained organic materials. This approach has been used worldwide in suitable environments to assess the frequency of large and infrequent floods and was applied at French Creek and Spring Creek, where detailed analyses demonstrated the regional applicability of this approach. Stratigraphic records for multiple sites in each stream reach provided excellent chronologies of previous large floods, indicating various flood events within the previous several millennia approaching or exceeding the approximate magnitude of 1972 flooding. Ensuing regional reconnaissance efforts indicated that local conditions are ideal for formation and preservation of flood slackwater deposits, especially within Paleozoic carbonate rocks ringing the periphery of the Black Hills, where abundant caves and alcoves protect deposits from erosion. Generally arid conditions aid in preservation of stratigraphic boundaries and detrital organic materials necessary for reconstructing flood chronologies.

The overall conclusion of this reconnaissance-level study is that improved understanding of flood frequencies for the Black Hills region would result from implementation of future studies using established paleoflood techniques. Flood slackwater deposits have been identified in canyon sections of most major drainages in the Black Hills. These deposits show stratigraphic records of large floods that can be effectively used with radiocarbon dating and hydraulic analysis to determine the approximate timing and discharge of previous large floods. Specific flood issues that could be addressed by Black Hills paleoflood studies include (1) determination of the frequency, magnitude, and spatial characteristics of 1972-scale floods for several or all of the major Black Hills drainages; and (2) evaluation of spatial patterns of large-flood generation that owe to topography, geology, and climatology.

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1.0 PROBLEM DESCRIPTION

Flood-frequency analyses for the Black Hills area have large uncertainties because of several complicating factors, including (1) effects of the extraordinary 1972 storm near Rapid City; (2) geologic influences; and (3) potential influences of topography on precipitation patterns. Methods relying on analysis of existing peak-flow data (numbers of sites and available periods of record) are insufficient to address these complications. An efficient means of reducing these uncertainties is to extend peak-flow records by applying paleohydrologic techniques—approaches using geologic and paleobotanic evidence of floods to determine the age and size of flood events that occurred before the advent of systematic flood records. This study addresses the potential of such paleohydrologic approaches in the Black Hills region.

Large floods that occurred at numerous streamflow-gaging locations on June 9–10, 1972, are a primary complicating factor for flood-frequency analysis in the Black Hills area. The 1972 storm produced as much as 10–15 inches of rainfall in about 6 hours over an area of about 60 square miles (mi^2) (Schwarz et al., 1975), with rainfall totals exceeding 6 inches over about 300 mi^2. This is one of the largest and most intense rainstorms recorded within similar climatic regimes in the United States. Resulting flood flows for various affected U.S. Geological Survey (USGS) streamflow-gaging stations constitute high outliers when using the standard log-Pearson III frequency analysis recommended in Bulletin 17B of the U.S. Interagency Advisory Committee on Water Data (1982). Results of frequency analyses for affected gages also are highly inconsistent with frequency analyses for other area gages that were unaffected by the 1972 storm, but may be subject to similar extreme events.

A second complicating factor is the influence of extensive outcrops of the Paleozoic-age Madison Limestone and Minnelusa Formation, which dominate the geology of the “Limestone Plateau” area of the western Black Hills (fig. 1-1). High infiltration capacity for these formations results in peak-flow characteristics that are distinctively suppressed for small recurrence-interval flood events for several gaging stations that are located primarily within this geologic setting. Combined available record lengths are insufficient, however, to determine whether peak-flow characteristics are truly suppressed for large recurrence intervals. It is plausible that a general threshold in rainfall intensity and duration may exist, above which peak-flow characteristics would no longer be suppressed. This hypothesis is supported by a large 1972 peak that was documented by Schwarz et al. (1975) for Cleghorn Canyon, which is located just northwest of Rapid City, and has large outcrop areas of these formations. However, existing information is insufficient to quantify potential effects of geology on extreme flood events.

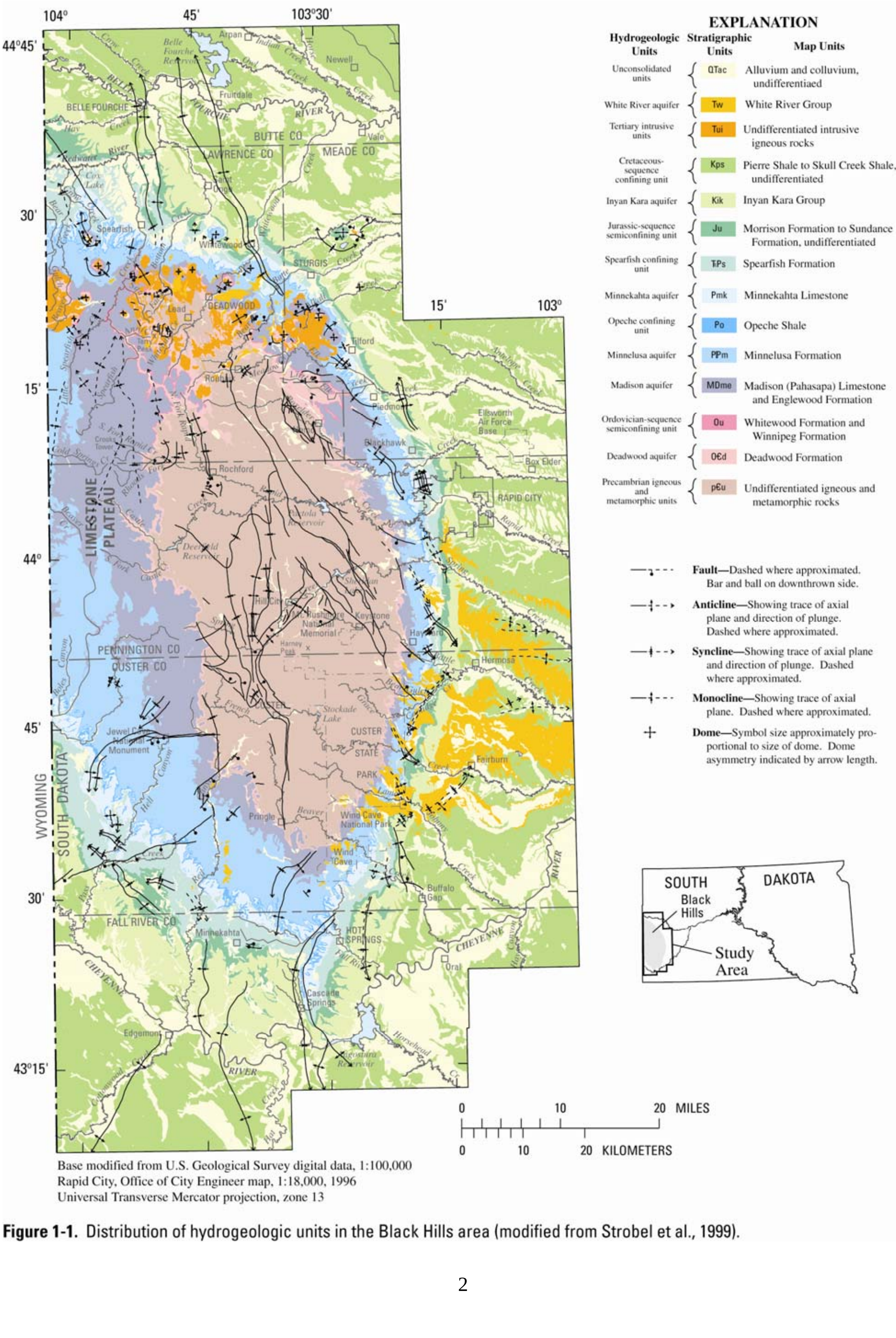


Figure 1-1. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel et al., 1999).

A third complicating factor is the possible influence of topography on precipitation patterns for the Black Hills area. Decreasing potential with increasing elevation for high intensity and duration rainstorms has been documented for other mountainous areas generally above an elevation of about 7,500 feet (ft); however, documentation for the Black Hills area is minimal (Jarrett and Costa, 1988; Jarrett, 1993). Thus, it currently (2007) is not known whether differences in precipitation patterns contribute substantially to suppression of peak-flow characteristics for large recurrence-interval flood events in the Limestone Plateau area, which occurs at elevations of about 6,000 ft and higher. This question has important implications for both the Limestone Plateau area and for other nearby high-elevation areas, where suppression of peak-flow characteristics from geologic influences is not as apparent.

2.0 RESEARCH OBJECTIVES

2.1 PROJECT OBJECTIVES

Flood frequencies are poorly defined for the Black Hills area for the three primary reasons noted in Section 1.0. Existing peak-flow data (numbers of sites and available periods of record) are insufficient to address various complicating factors for frequency analyses in the area. Paleoflood hydrology techniques have been used successfully to improve peak-flow frequency relations in various areas; however, the applicability of such techniques is unknown for the Black Hills area. To address these needs, a cooperative study was initiated between the South Dakota Department of Transportation (SDDOT) and USGS.

SDDOT Research Project SD2005–12 was implemented as a reconnaissance-level study to evaluate the utility of various potential techniques for this area. The study was designed to address a single objective, specifically to assess the applicability of paleoflood survey techniques to generate better historical records on the magnitude and frequency of peak-flood events in the Black Hills area. This objective was designed to address two primary study purposes: (1) to evaluate the suitability of various paleoflood survey techniques for conditions within the Black Hills area; and (2) to provide a mechanism for scoping of potential future study phases, assuming that suitable paleoflood survey techniques are determined to be applicable for the area.

2.2 PROJECT SCOPE

Thirteen specific research tasks were identified within the SDDOT Research Project Statement (SD2005–12) to guide research directions. These 13 tasks are:

1. Meet with the project's technical panel to review the project scope and work plan.
2. Review and summarize paleoflood literature that can be directly related to the conceptual performance of paleoflood surveys in the Black Hills.
3. Perform interviews with individuals from the South Dakota School of Mines and Technology (SDSM&T), scientific entities, and other government agencies that may have intimate knowledge of the Black Hills relative to flooding, hydrology, geology, and other disciplines that could be directly related to the performance of paleoflood surveys in the area.
4. Scrutinize the estimation of the peak-flood data for the Rapid City storm event of 1972 in efforts to more fully affirm said data.
5. Investigate records of flooding and gaging stations unaffiliated with USGS to assess the applicability of any stage indicators arising from that data.

6. Based on a set of well conceived criteria that includes streams with historical gage records, select sites around the entire Black Hills area deemed as likely candidates for successful paleoflood surveys.
7. Meet with the project's technical panel to present findings and propose the list of candidate survey sites for review and approval.
8. From the list approved by the project's technical panel, sample the most promising sites through field investigations aimed at defining the select locations where comprehensive paleoflood surveys will be instigated.
9. At the selected locations, conduct comprehensive paleoflood surveys that include finding distinct paleostage indicators (PSIs), gathering discernible paleoflood evidence, recording surveyed cross sections of the drainage basins, and permanently documenting locations that demark critical features unveiled during the field work using Global Positioning System (GPS) referencing.
10. Through accepted state-of-the-practice methods, perform absolute and relative dating techniques on the paleoflood evidence gathered during the field surveys to gain the best possible timeframe estimates for past significant flood events.
11. Develop a data set that combines the historical flood-frequency estimates, including stage indicators, for all locations selected during the study and perform cross-analyses to determine if preliminary conclusions can be drawn as to whether Black Hills paleoflood data appear to be viable for improving the flood-frequency estimates within individual drainage basins, groups of drainage basins with characteristics deemed worthy of common classification, and the Black Hills region as a whole.
12. Prepare a final report summarizing research methodology, findings, preliminary conclusions, and recommendations relative to subsequent phases of the planned research efforts.
13. Make an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the project.

Task 1 was designed to review the project scope and work plan. Tasks 2 through 5 were designed to locate and review existing information that might be relevant to initiation of a paleoflood study specifically for the Black Hills area. Tasks 6 and 7 were designed to identify candidate sites for trial application of appropriate paleoflood techniques. Tasks 8 through 11 were designed for testing of applicable techniques. Tasks 12 and 13 were designed for communication of results.

3.0 TASK DESCRIPTIONS

This section provides descriptions of activities and information relevant to accomplishment of the 13 specific research tasks. Running summaries of project activities were maintained for tasks 2 through 6. These running summaries were updated as appropriate, and were appended as attachments to quarterly progress reports. Final summary documents for these tasks were transmitted to SDDOT in a technical memorandum dated Aug. 7, 2007. These final summary documents are referred to, as appropriate, within this section; however, discussions for the associated tasks generally are limited to brief overviews.

3.1 MEET WITH THE PROJECT'S TECHNICAL PANEL

Task 1: Meet with the project's technical panel to review the project scope and work plan.

An initial meeting with the SDDOT project technical panel was held on Sept. 26, 2005. An overview was provided to panel members regarding factors that complicate flood-frequency analyses for the Black Hills area. Discussions were held regarding the scope of the study and planned approaches for addressing the research tasks that were identified. A field trip was taken to Little Elk Creek (northwest of Piedmont) and Stagebarn Canyon (south of Piedmont) to view evidence of previously undocumented flood events that apparently were extraordinarily large.

3.2 LITERATURE REVIEW

Task 2: Review and summarize paleoflood literature that can be directly related to the conceptual performance of paleoflood surveys in the Black Hills.

The SDDOT Research Project Statement (SD2005–12) stated that an initial literature search indicated an abundance of general paleoflood hydrology literature, but little literature specific to the Black Hills area. A subsequent detailed search produced only two documents that addressed paleoflood hydrology for the area, and neither document provided substantial insights for this study. These two documents are (1) a master's thesis by Michael R. Ainsworth (1981) done through the Geology Department at SDSM&T; and (2) a report by the Bureau of Reclamation (2005) titled "Issue Evaluation Pactola Dam, South Dakota, Hydrologic Hazard" that described a cursory paleoflood survey for Rapid Creek near Pactola Dam. Both documents are included in a bibliographic listing transmitted in the Aug. 7, 2007 Technical Memorandum.

3.3 PERFORM INTERVIEWS

Task 3: Perform interviews with individuals from the South Dakota School of Mines and Technology (SDSM&T), scientific entities, and other government agencies that may have intimate knowledge of the Black Hills relative to flooding, hydrology, geology, and other disciplines that could be directly related to the performance of paleoflood surveys in the area.

Numerous interviews were conducted for this task. A summary document for interviews conducted was transmitted in the Aug. 7, 2007 Technical Memorandum. In general, the interviews did not yield much definitive information regarding the performance of paleoflood surveys in the area; however, many contacts with possible utility for future potential study phases were made. The following provides a brief overview of the most useful contacts:

- The South Dakota State Archaeological Society (SAS) could be a very useful partner for future collaborative efforts. Many of the sites with valuable paleoflood evidence are in sheltered alcoves where archaeological evidence could be preserved. Thus, archaeological oversight would be required for many detailed paleoflood site investigations. The SAS has a keen interest in our work owing to (1) the abundance of archaeological evidence; and (2) the dating that is performed in association with paleoflood investigations. Hence, future collaborations could be very valuable. For example, it was discovered that an SAS site along Lame Johnny Creek in Custer State Park is located in an alcove containing paleoflood evidence.
- Useful contacts have been made with the Black Hills Grotto Club, which has been very involved with exploration of caves within the area. Many of the sites with valuable paleoflood evidence are within small caves or are located in areas where caves are abundant. Thus, coordination with the Grotto Club would be very useful for future potential study phases.
- Numerous contacts were made with area residents and landowners during the course of this study. Although most such contacts are not listed in the summary document for interviews, communications with residents and landowners were very important and would be a critical component of future potential study phases for several reasons. Landowner permission is an absolute necessity when working within private land holdings. In addition, landowners often can provide information regarding access and noteworthy flow events that have occurred in local streams.

Public interest in this study is high because of the interesting nature of the subject matter and the relevance to important public issues. A specific example involves ongoing interactions of USGS staff (Dan Driscoll) with a floodplain advisory committee dealing with floodplain issues in the Rapid City area. Public visibility has large potential to provide many important benefits (and possible collaborations) for potential future study phases.

3.4 SCRUTINIZE 1972 PEAK-FLOOD DATA

Task 4: Scrutinize the estimation of the peak-flood data for the Rapid City storm event of 1972 in efforts to more fully affirm said data.

A summary document for 1972 data scrutiny was transmitted in the Aug. 7, 2007 Technical Memorandum. It was determined that the 1972 peak-flood estimates have been thoroughly examined by various USGS hydraulic experts as part of the standard review process and as part of various subsequent efforts. Cursory additional examination of all measurement files available in the Rapid City USGS office indicated that sound procedures were consistently used in processing and reviewing the original data sets, and that confidence should be high that resulting estimates are reasonably reliable. Reasonable reliability does not necessarily imply a high level of accuracy, given the inherent uncertainty of indirect discharge determinations, especially within high-gradient mountain streams.

Additional examination of individual measurements for selected sites would be useful as part of potential future study phases. Data available for any stream reaches where detailed future investigations might occur would be useful for hydraulic analyses of such reaches, and closer examination of all applicable files would be appropriate.

3.5 INVESTIGATE FLOOD RECORDS FOR STATIONS UNAFFILIATED WITH USGS

Task 5: Investigate records of flooding and gaging stations unaffiliated with USGS to assess the applicability of any stage indicators arising from that data.

A summary document with information regarding flooding at stations unaffiliated with USGS was transmitted in the Aug. 7, 2007 Technical Memorandum. It was determined that no relevant information is available for gaging stations operated by entities other than USGS. However, a wide variety of information is available regarding historical flooding in various locations. Most of the historical accounts tend to be somewhat sketchy, however, and much of the information would be useful only for documenting dates and general magnitudes of flood events. More exhaustive investigations of historical accounts would be very useful for detailed paleoflood surveys for specific stream reaches, and additional efforts in this area would be appropriate for potential future study phases.

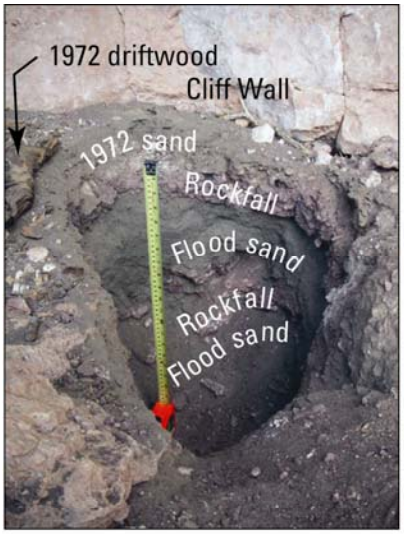
3.6 SELECT CANDIDATE SITES FOR PALEOFLOOD SURVEYS

Task 6: Based on a set of well conceived criteria that includes streams with historical gage records, select sites around the entire Black Hills area deemed as likely candidates for successful paleoflood surveys.

This task initially focused on identifying locations where various forms of paleoflood evidence might exist that could be amenable for testing various possible techniques of paleohydrologic analysis. An initial activity was development of a spreadsheet containing a comprehensive list of potential candidate sites that consisted primarily of USGS streamflow-gaging station locations in the Black Hills area where systematic peak-flow records have been collected. This spreadsheet was modified throughout the course of the study to include updated information regarding priorities established for reconnaissance and general results of reconnaissance efforts. A companion document containing more detailed notes regarding reconnaissance efforts also was developed, and collectively the two documents provide comprehensive information regarding reconnaissance efforts. Final versions of both documents were transmitted in the Aug. 7, 2007 Technical Memorandum.

As the study evolved, it became apparent that the paleohydrologic approach of greatest potential utility is detailed stratigraphic analysis of sequential deposits of slackwater flood sediments in caves, alcoves, and rock shelters, along with radiocarbon dating of entrained organic materials. This is an approach used worldwide in suitable environments to assess the frequency of large and infrequent floods (e.g. Jacobsen et al., 2003). This technique was applied at French Creek and Spring Creek, where detailed analyses demonstrated the regional applicability of this approach (as described in Sections 3.7 to 3.10). Thus, later efforts of site selection focused on evaluating the potential for application of this highly successful approach on a regional scale throughout the Black Hills area and resulted in a list of visited stream reaches throughout the area where fully implemented application would address the key issues of flood frequency and spatial and topographic controls on flood generation noted in Section 1.0.

The evolution of this task resulted from discovery of well-preserved flood slackwater deposits (fig. 3.6-1) in many Black Hills drainages. Flood slackwater deposits are composed of sand and silt deposited from the suspended load of individual floods. These deposits form and are preserved along margins of canyon bottoms, typically in zones of flow separation (e.g. Kochel and Baker, 1982, 1988). Within caves and alcoves, or where otherwise protected from erosion or extensive disturbance by plants and animals, successive floods may leave a sequence of deposits forming a stratigraphic record of large flow events encompassing many hundreds or thousands of years (e.g. O'Connor et al., 1994; Hosman et al., 2003). Individual flood deposits typically are separated by rockfall, organic duff, or local tributary sediment (which commonly has distinctly different grain size and mineral composition than other deposits), commonly allowing for determination of the number of floods that left deposits at a particular site. Organic detritus, including charcoal, driftwood, and blown-in leaf fall within and between individual flood deposits, can be dated using radiocarbon techniques, allowing for determination of the approximate timing of individual floods as well as the length of record represented by a sequence of flood deposits. The elevations of individual flood deposits indicate a minimum value for the elevation or stage attained by the flow. By combining stratigraphic and chronologic records of multiple depositional sites with hydraulic flow modeling techniques for obtaining corresponding discharge estimates, robust flood-frequency analyses are possible that vastly improve recurrence interval estimates for large, low-frequency floods (e.g. O'Connor et al., 1994; Hosman et al., 2003). This approach is by far the most effective paleohydrologic means of substantially improving frequency estimates of rare, high-magnitude floods (Stedinger and Baker, 1987).



a. Pit 3A at Hailstorm Alcove, Spring Creek. Pit is 1.7 feet deep and exposes gray sand deposited by three separate flood deposits, including capping 1972 deposit and two older flood deposits, underlying Spring Creek flood deposits separated by red rockfall. Lowermost flood deposit dates from ~400–200 B.C.

b. Pit 1B at Superscour Alcove, Spring Creek. Pit is 2.0 feet deep and exposes alternating flood sand and driftwood of three Spring Creek flood deposits, including capping 1972 flood sand and flotsam.

c. Olympia Alcove, Spring Creek. Pit is 3.5 feet deep and exposes five gray flood sand deposits, including capping 1972 deposits and driftwood, separated by redder slopewash. Basal radiocarbon date indicates that this stratigraphic record encompasses the last 700–800 years. Shovel handle is 1.5 feet.

d. View of entrance to Pratt Cave and Pit A, French Creek.

e. Upper part of Pit A in floor of Pratt Cave. View shows two flood deposits, separated by driftwood and rockfall. Shovel handle is 1.5 feet.

f. Pit B at Pratt Cave site, exposing 11–13 French Creek flood deposits interbedded with redder slopewash sediment. Pit is 3.5 feet deep. Basal radiocarbon date indicates that this stratigraphic record encompasses the last 600–700 years.

Figure 3.6-1. Photographs of slackwater sediment accumulations at selected sites along Spring Creek and French Creek.

A key finding of this study is that local conditions in the Black Hills are ideal for formation, preservation, and analysis of flood slackwater deposits. The Paleozoic carbonate rocks ringing the periphery of the range form resistant-walled canyons bounding the larger creeks that drain radially from the range core. In particular, the uplift history of these rock units resulted in extensive dissolution and lateral erosion, forming caves, alcoves, and ledgy overhangs that shelter slackwater deposits from erosion. The Precambrian metamorphic rocks and Tertiary intrusive rocks of the central Black Hills provide abundant sand carried in suspension by larger floods, with mineral compositions distinct from those of slopewash and fluvial sediment derived from local drainages and hillslopes. The generally arid conditions within rock shelters aid in preservation of stratigraphic boundaries and detrital organic materials necessary for reconstructing flood chronologies. The general absence of flow during many periods of most years in the stream reaches within the Paleozoic carbonate rocks resulted in little human disturbance of deposits within the caves and alcoves. The ideal conditions in the Black Hills for the formation and preservation of flood slackwater deposits provide an unparalleled opportunity for reconstructing flood histories.

Given the demonstrated utility of flood slackwater deposits, additional reconnaissance as part of this task was focused, where feasible, on identifying alcoves containing deposits of flood sediments suitable for detailed stratigraphic analysis. For purposes of evaluating the applicability of various stream reaches as candidates for future potential paleoflood surveys, two categories of drainage basins were identified: (1) relatively large drainage basins having stream reaches entrenched in canyons within outcrops of the Paleozoic carbonate rocks around the periphery of the Black Hills—sites in these basins have potential for providing improved frequency estimates of 1972-scale floods; and (2) drainage basins in the vicinity of the Limestone Plateau area within the higher elevations of the Black Hills, which would be useful for addressing the role of topography and geology in producing large runoff events. A list of stream reaches in both categories where paleoflood evidence (predominantly within alcoves) has been identified through extensive reconnaissance efforts is provided in table 3.6-1. Locations of alcoves (or other relevant paleoflood evidence) are shown in figure 3.6-2, along with locations of USGS gaging stations for which comprehensive paleoflood surveys could have applicability. A primary finding from these extensive reconnaissance efforts (in combination with other results of this study) is that the probability is high that the flood-frequency issues identified in Section 1.0 could be substantially resolved through full implementation of comprehensive paleoflood studies in strategic locations.

The suitability of any particular slackwater deposit for a comprehensive paleoflood survey (e.g. number of flood layers and availability of organic material for radiocarbon dating) cannot be determined until it has been excavated to full depth; however, the detailed analyses in the two sampled reaches (described in Sections 3.8 to 3.10) indicate that appropriate alcoves commonly contain deposits of several large floods that occurred during the last several hundred to several thousand years. Many of the canyon areas with excellent potential for alcoves are relatively large, and more extensive searches would be needed in combination with preliminary excavations to locate the most ideal combinations of alcoves for comprehensive paleoflood surveys. However, these reconnaissance efforts have clearly demonstrated that alcoves with good potential for conducting successful paleoflood surveys are available within most if not all of the largest drainages around the periphery of the Black Hills area.

Table 3.6-1. Locations where flood slackwater deposits or other paleoflood evidence have been identified through reconnaissance efforts.

Stream reach	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Comments
			Stream reaches categorized as large-drainage-area setting
Fall River	43 26 27	103 28 47	High alcoves above courthouse on right bank noted by Thomson (1961)
	43 26 06	103 28 50	High left bank alcoves east of main street businesses
	43 26 04	103 28 52	Right bank alcoves across from City Hall
Beaver Creek	43 34 55	103 28 09	Fairly low right bank alcove
	43 34 53	103 28 09	Much higher right bank alcove
Lame Johnny Creek	43 38 37	103 22 42	State Archaeological Society excavation in left bank alcove
French Creek	43 42 49	103 21 55	Detailed stratigraphy performed in and near "Pratt" cave
	43 42 47	103 21 13	Detailed stratigraphy performed at "Riviera" site
Battle Creek	43 51 28	103 19 21	Fairly low right bank alcove; more alcoves and various other flood evidence continuing downstream
	43 51 18	103 19 07	Two low right bank alcoves with various other flood evidence just upstream
	43 51 19	103 18 33	High left bank "Crystal" Alcove (clearly higher than 1972 flood evidence); lower alcoves just downstream
	43 50 58	103 18 32	High left bank alcoves along bench just west of "Hole in Wall"
	43 50 42	103 18 20	Fairly high alcoves along right bank cliff southwest of "Hole in Wall"
Grace Coolidge Creek	43 45 44	103 21 08	Promising alcove on left bank – fairly high
	43 45 54	103 20 55	Alcove along cliff section on left bank
Spring Creek	43 59 33	103 19 01	Very high driftwood and sands at "Temple of Doom" Alcove
	43 59 30	103 18 09	Detailed stratigraphy performed at "Hailstorm" Alcove
	43 59 37	103 17 55	Detailed stratigraphy performed at "Superscour" Alcove
	43 59 47	103 17 41	Detailed stratigraphy performed at "Olympia" Alcove
	43 59 25	103 16 25	Various alcoves that may have future utility
Rapid Creek	44 02 38	103 19 50	Large left bank alcove near county road
	44 02 40	103 19 42	Right bank alcoves upstream from railroad cut
	44 02 45	103 19 44	Right bank alcoves downstream from railroad cut
Boxelder Creek	44 07 50	103 25 22	Very large right bank alcove – fairly high
	44 06 57	103 22 48	Very high left bank alcoves
	44 07 02	103 22 31	Left bank alcove
Stagebarn Canyon	44 11 58	103 22 54	Excellent alcove on right bank
	44 12 03	103 22 53	Excellent high alcove on left bank
Little Elk Creek	44 14 18	103 26 07	High left bank alcove near "White Gate"
	44 14 45	103 25 50	Left bank alcove on high ledge
	44 14 38	103 25 41	Lower right bank alcove
Elk Creek	44 16 59	103 29 03	High left bank alcove
	44 17 00	103 28 54	Left bank alcove
Lower Spearfish Creek	44 26 40	103 52 07	Right bank alcove
Whitewood Creek	44 25 43	103 38 54	Right bank alcove
Bear Butte Creek	44 23 37	103 34 53	Low right bank slackwater deposits
	44 24 14	103 34 39	Several high right bank alcoves, various elevations

Table 3.6-1. Locations where flood slackwater deposits or other paleoflood evidence have been identified through reconnaissance efforts (Continued).

Stream reach	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Comments
Stream reaches categorized as higher-elevation setting			
Hell Canyon	43 46 48	103 48 12	Square-cornered alcove upstream from Windmill Draw
	43 44 10	103 50 43	Upstream extent of large debris flow
	43 44 10	103 50 45	High right bank alcove downstream from U.S. 16
	43 43 53	103 50 25	High right bank alcove with large drift log
	43 43 50	103 50 20	More good alcoves in downstream reach – both banks
	43 43 45	103 50 22	Left bank alcove below thalweg grade
Castle Creek	43 58 48	103 51 40	Left and right bank alcoves
	43 58 42	103 50 41	Left bank alcove
	44 00 50	103 50 10	Left bank alcove by footbridge
Rhoads Fork	44 07 38	103 53 22	Right bank alcove
	44 07 42	103 53 19	High left bank alcove
Upper Spearfish Creek	44 13 57	103 55 20	Very high left bank alcove at parking area. Flood sands not definitive
	44 15 36	103 55 06	Low “Driftwood” Alcove along right bank
	44 15 38	103 55 06	Higher “White Flag” Alcove along right bank
	44 15 40	103 55 06	High “Tin Can” Alcove along right bank
	44 15 53	103 55 12	High left bank alcove
	44 16 02	103 54 59	High left bank alcove

Table 3.6-1 provides a summary of selected information for 15 streams within the category of “large drainage basins” that could be useful for future paleoflood studies addressing the magnitude and frequency of 1972-scale floods. All of these streams have relatively large drainage areas, which is advantageous from several standpoints. First, paleoflood evidence typically is more abundant in larger drainages because larger flood flows typically are generated in larger basins. A relatively small number of large drainages compose a substantial part of the entire Black Hills area; thus, high-resolution data could be obtained for much of the area with surveys in relatively few basins. In addition, systematic peak-flow records are available for one or more applicable gaging stations within most of these drainage basins (fig. 3.6-2), which would allow incorporation of paleoflood results with existing peak-flow data. Relatively extensive reconnaissance was conducted in all of the 15 larger drainages listed in table 3.6-1 and one or more alcoves potentially containing stratigraphic records of large floods were located in each of these drainages. Various evidence from 1972 flooding (including slackwater deposits and deposits of coarse sediments, flotsam, and other debris) is available in about one-half of the larger drainages. Such evidence provides an excellent point of reference for both stratigraphic and hydraulic analyses and would be useful in conducting future paleoflood studies in affected stream reaches.

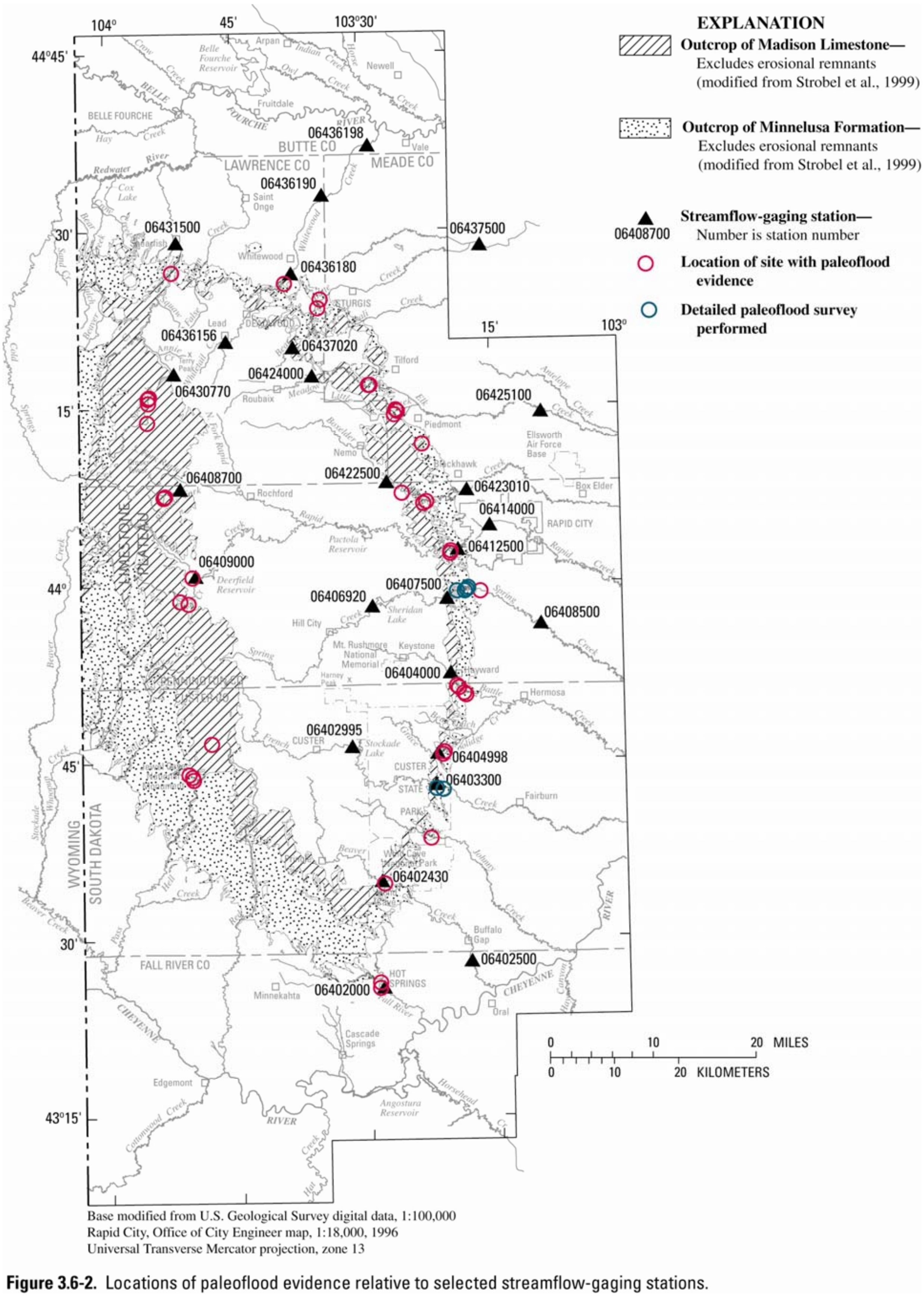


Figure 3.6-2. Locations of paleoflood evidence relative to selected streamflow-gaging stations.

Substantial reconnaissance also was conducted for the second general category of drainage basins in high-elevation areas near or within the Limestone Plateau. High resolution paleoflood evidence is less common within these settings because (1) drainage areas within these headwater areas generally are small, which tends to limit the potential for large floods and associated paleoflood evidence; and (2) geologic conditions generally are much less favorable for the existence of suitable alcoves than in locations around the periphery of the Black Hills. Several drainages eventually were located (fig. 3.6-2) where sufficient paleoflood evidence was found (including some alcoves with flood sediments) to conclude that a future paleoflood study to address the questions regarding the higher-elevation areas could be successfully implemented.

The best candidate basin found so far in this category is Hell Canyon, where at least one relatively large peak flow has occurred since large parts of the drainage were severely burned by the Jasper Fire in 2000. During reconnaissance, recent flood flotsam was observed high in the basin and continuing throughout the length of the drainage. Freshly deposited sediments and freshly exposed sediment deposits also were observed in many locations. A relatively large number of alcoves with flood sediments also were located in several reaches. This combination of flood evidence could provide an excellent working environment for a comprehensive survey. Good potential also exists within a headwater reach of Spearfish Creek, where several alcoves were located. Additional areas with reasonable potential also were located within Rhoads Fork and Castle Creek.

3.7 MEET AGAIN WITH THE PROJECT’S TECHNICAL PANEL

Task 7: Meet with the project’s technical panel to present findings and propose the list of candidate survey sites for review and approval.

The second planned meeting with the technical panel was held on May 10, 2006. The prioritized list of candidate sites described in Section 3.6 was presented to the panel members, and discussions followed regarding the logic used for assembling the list and for assigning general priorities for consideration of candidate sites for future surveys. Additional discussions focused on general approaches for selecting sites and carrying out field surveys, as summarized herein. Two general approaches for full-scale paleoflood study implementation (future phases) were discussed: (1) to focus strictly on locations where gaging stations have been operated such that systematic peak-flow records are available; and (2) to use a more “regional” approach that would not be restricted to gaged locations. The panel members concurred that for the current study phase, the primary focus should be on sites in the general proximity of gages; however, ungaged locations should be considered for reconnaissance for evaluating the potential utility of various sites for future study phases. In particular, it might be necessary to consider some ungaged locations to evaluate peak-flow characteristics in the vicinity of the Limestone Plateau. Two general at-site methods were discussed: (1) a “more-detailed” method that can yield chronologies of multiple flood events and is based on detailed stratigraphic analyses and radiocarbon dating of organic material from layered sequences of deposits; and (2) “less-detailed” methods that tend to focus on a singular identifiable paleoflood at any given site and typically require much less time at each site. Two general site types were discussed: (1) sites where extremely large peaks have occurred relatively recently, such as during 1972; and (2) sites where extremely large peaks have not been recorded by systematic gaging. The panel concurred that (1) testing of the more-detailed method for two stream reaches would be the highest short-term priority, including one stream with substantial flooding from the 1972 storm and one stream for which especially large peaks have not been measured; and (2) additional exploration of the less-detailed method also would be appropriate, and that potential stream reaches for testing would be based on availability of paleoflood evidence that might be found through reconnaissance efforts. This meeting and subsequent field investigations resulted in selection of two sites for more detailed paleoflood analyses described in Sections 3.8 and 3.9: (1) a reach on Spring Creek that had substantial flow during the 1972 flood; and (2) a reach on French Creek, where particularly large flows have not occurred during the last several decades.

Two subsequent meetings with the technical panel also were held. The first was on June 6, 2006, which included a field trip to Spring Creek and French Creek where comprehensive field surveys were underway (task 9). Spring Creek provided a good opportunity to view flotsam, tree scarring, and geomorphic features (such as slackwater and coarse-grained deposits) from the 1972 flood. French Creek was chosen to represent a stream reach for which exceptionally large peaks were absent from the systematic record. Well-preserved deposits of slackwater flood sands had been located in alcoves in both stream reaches, and French Creek had deposits of well-preserved driftwood at three elevations substantially above the primary sand deposits.

Another meeting with the technical panel was held on June 7, 2007, with an original intent of viewing results from 2 weeks of additional field efforts that were initiated on May 29, 2007. The primary focus of these efforts was on reconnaissance for locations where (1) applications of the less-detailed method (described previously in this section) might be warranted; and (2) meaningful investigations could be made to address the questions regarding (A) peak-flow characteristics in the vicinity of the Limestone Plateau; and (B) potential differences in precipitation regimes in the highest elevations of the Black Hills. Weather conditions prevented the planned field trip, so results of the prior field efforts were communicated during an indoor meeting. Primary findings from these field efforts were that: (1) the primary utility of less-detailed approaches would be to provide broadly distributed corroborative evidence supporting detailed analyses at specific sites, but such evidence generally would be unable to provide chronologies of multiple floods that can be obtained from slackwater deposits; and (2) sufficient paleoflood evidence had been located (primarily in the form of slackwater deposits in alcoves) that meaningful future investigations probably could be conducted within the higher-elevation areas of the Black Hills to address the questions regarding items 2A and 2B described above.

3.8 SAMPLE THE MOST PROMISING SITES

Task 8: From the list approved by the project's Technical Panel, sample the most promising sites through field investigations aimed at defining the select locations where comprehensive paleoflood surveys will be instigated.

On the basis of reconnaissance investigations and guidance from the technical panel, more detailed analyses were conducted on two reaches (fig. 3.6-2): (1) a ~1-mile-long segment upstream from U.S. Highway 16 where Spring Creek flows across the Minnelusa Formation; and (2) a ~1-mile-long segment of French Creek within Custer State Park. These sites were selected because they each contained numerous alcoves and caves that had floors composed of slackwater deposits, met the criteria of being variously affected by the 1972 flow, were readily accessible, and had landowners willing to allow access for the study. The analyses at each of these two sites, as elaborated in the following two sections (Sections 3.9 and 3.10), included the following:

- Detailed searches along canyon walls for slackwater deposits in areas protected from erosion or other disturbance.
- Preliminary shallow excavations to tentatively evaluate the clarity of stratigraphic records and number of preserved events.
- Selection of multiple alcoves at different elevations for detailed stratigraphic analysis.
- Excavation and detailed stratigraphic description and recording of slackwater deposits and preserved flood flotsam.
- Samples of organic materials for radiocarbon dating.
- Site surveys to document elevations of deposits and cross-section geometry for preliminary discharge estimations.

3.9 CONDUCT COMPREHENSIVE PALEOFLOOD SURVEYS

Task 9: At the selected locations, conduct comprehensive paleoflood surveys that include: finding distinct paleostage indicators (PSIs), gathering discernible paleoflood evidence, recording surveyed cross sections of the drainage basins, and permanently documenting locations that demark critical features unveiled during the field work using Global Positioning System (GPS) referencing.

Comprehensive paleoflood surveys were conducted along two stream reaches where USGS streamflow-gaging stations have been operated, including Spring Creek, for which substantial flooding occurred in 1972, and French Creek, for which a large peak has not occurred within the period of systematic record (fig. 3.9-1). These surveys consisted primarily of excavating, describing, and sampling flood sediments at selected sites along each of the two stream reaches, as described in Subsections 3.9.1 and 3.9.2. A discussion of preliminary discharge estimates at the detailed study sites is provided in Subsection 3.9.3.

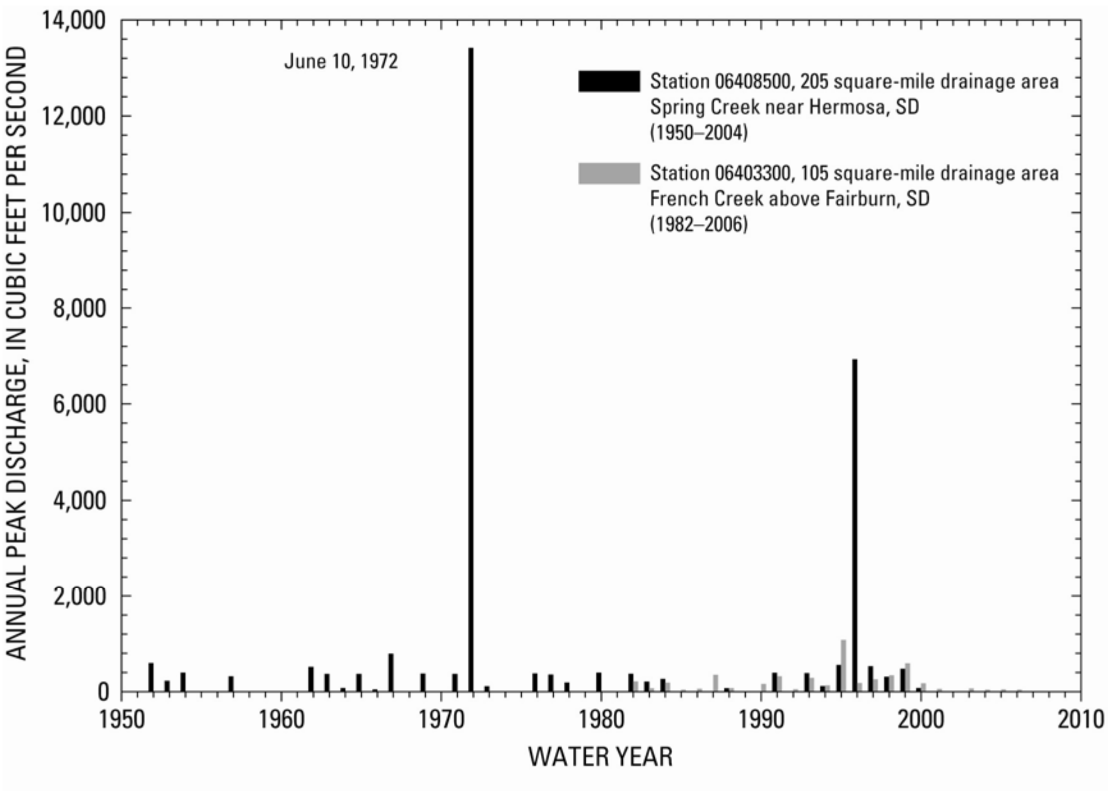


Figure 3.9-1. Annual peak discharges for U.S. Geological Survey streamflow-gaging stations on Spring Creek and French Creek.

3.9.1 Spring Creek Flood Deposits and Stratigraphic Descriptions

The reach of Spring Creek selected for detailed analysis extends from about 1.5 to 2.5 miles west (upstream) of the U.S. 16 Highway crossing of Spring Creek. This reach is within sections 4 and 5 of Township 1S, Range 7E and section 32 of Township 1N, Range 7E. This reach is between USGS gaging stations 06407500 and 06408500 (fig. 3.6-2). Spring Creek here is incised within steeply sloping canyon walls formed of limestone and sandstone of the Minnelusa Formation. The canyon meanders easterly with a valley bottom typically between about 100 and 300 ft wide. The study reach is within a "streamflow loss zone" where streamflow losses as much as a "threshold" of about 30 cubic feet per second (ft^3/s) (Hortness and Driscoll, 1998) provide recharge to the Madison and Minnelusa aquifers downstream from station 06407500. Thus, the stream channel generally is dry in this reach, except during sustained periods of runoff. Within this reach of Spring Creek, three sets of alcoves were found suitable for excavation and detailed analysis. The 1972 peak discharge at U.S. 16 Highway was 21,800 ft^3/s (Schwarz et al., 1975), which is a good approximation of the peak discharge within the study reach.

Hailstorm Alcove (all names are informal designations to facilitate communication), the most upstream of the intensely studied sites, is a series of shallow, ledgy overhangs in the Minnelusa Formation along the right (facing downstream) valley wall adjacent to an overflow channel and about 140 ft east of the present main channel. Sheltered areas extend about 100 ft along the canyon wall, and typically have floors composed of large rockfall with pockets of Spring Creek flood sediment and local slopewash from adjacent hillslope and cliff faces. Abundant flotsam from the 1972 flood lies on top of most of the deposits, and is as high as 13.9 ft above the channel thalweg. Two excavations were described in detail for alcoves inundated in 1972 and covered by sand and flotsam deposited by that flood (figs. 3.6-1a and 3.9.1-1). Both of these shallow pits revealed earlier Spring Creek flood deposits beneath the 1972 deposits, separated from the 1972 deposits by 4 to 8 inches of rockfall from the overhanging alcove walls and ledges. In the highest pit, 12.2 ft above the thalweg, the pre-1972 Spring Creek flood deposits are markedly thicker and coarser than the 1972 deposits (fig. 3.6-1a), indicating that this previous flow probably was larger than that of 1972 at this location. Older slackwater deposits found ~4 ft higher than the maximum level of 1972 flotsam (~18 ft above the channel thalweg) at this site (not shown on fig. 3.9.1-1) are consistent with this interpretation.

Superscour Alcove is ~0.4 mile downstream from Hailstorm Alcove, and is formed where Spring Creek abuts sharply against a prow of rock jutting out from the right (facing downstream) canyon wall. During large flows, the main current scours deeply at the base of this prow as most flow is forced left, but a large clockwise eddy forms upstream along the right canyon wall. Within this eddy, sand and flotsam are deposited and are preserved under the overhanging ledges of Minnelusa Formation limestone and sandstone. At Superscour Alcove, the highest 1972 flotsam is 16.7 ft above the scoured thalweg, with 1972 flood deposits being preserved to within ~1 ft of the maximum flotsam elevation (fig. 3.9.1-2). Three pits were excavated and described at varying elevations along ~50 ft of this alcove wall. Pits 1A and 1B (figs. 3.6-1b and 3.9.1-2) were deeper than the third pit and contained records of 3 to 5 floods, including the capping deposits of the 1972 flood. The highest excavation exposed a single flood deposit in addition to the deposits left in 1972.

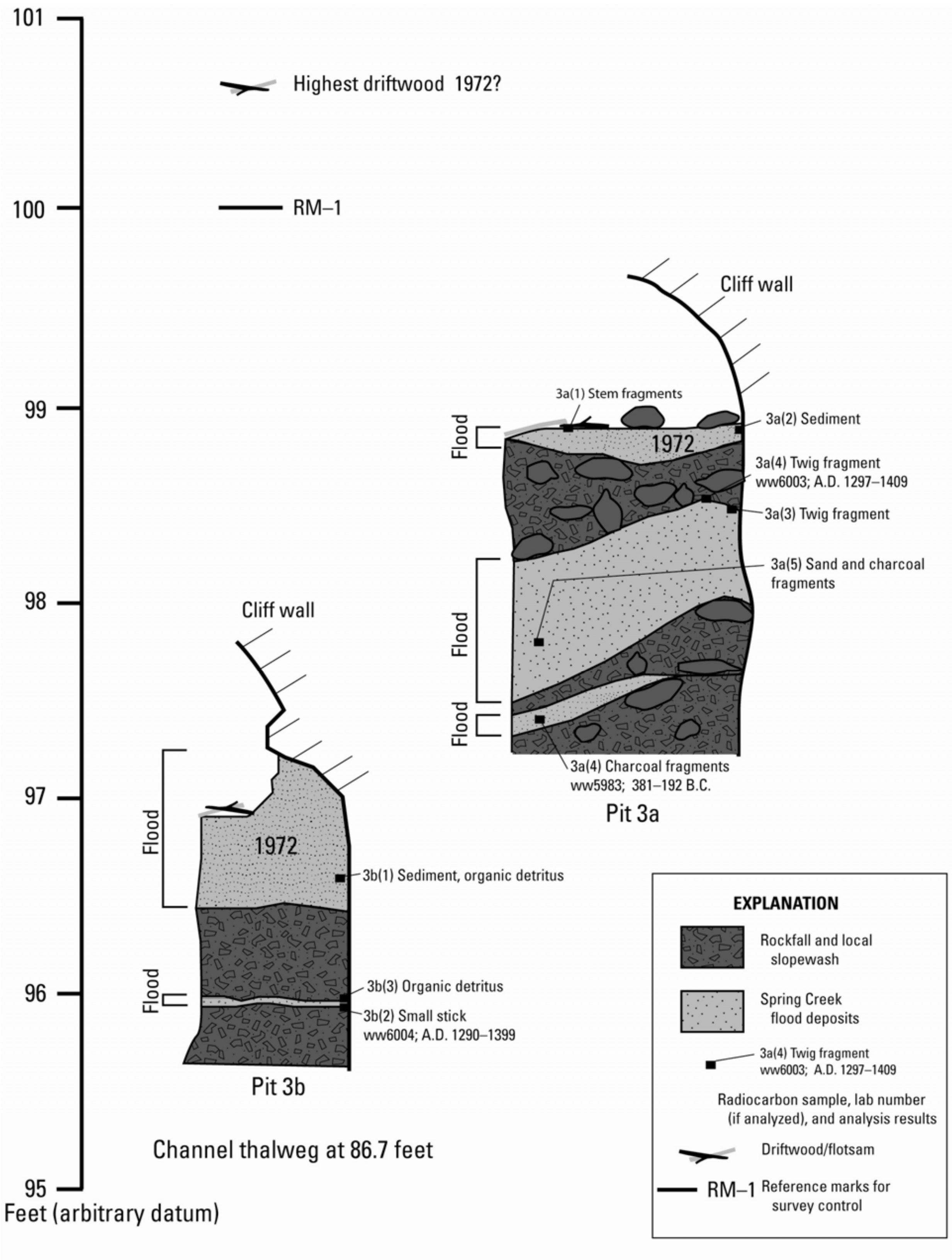


Figure 3.9.1-1. Schematic of stratigraphy, interpretation of flood units, and radiocarbon sample locations and results for excavations at Hailstorm Alcove, Spring Creek.

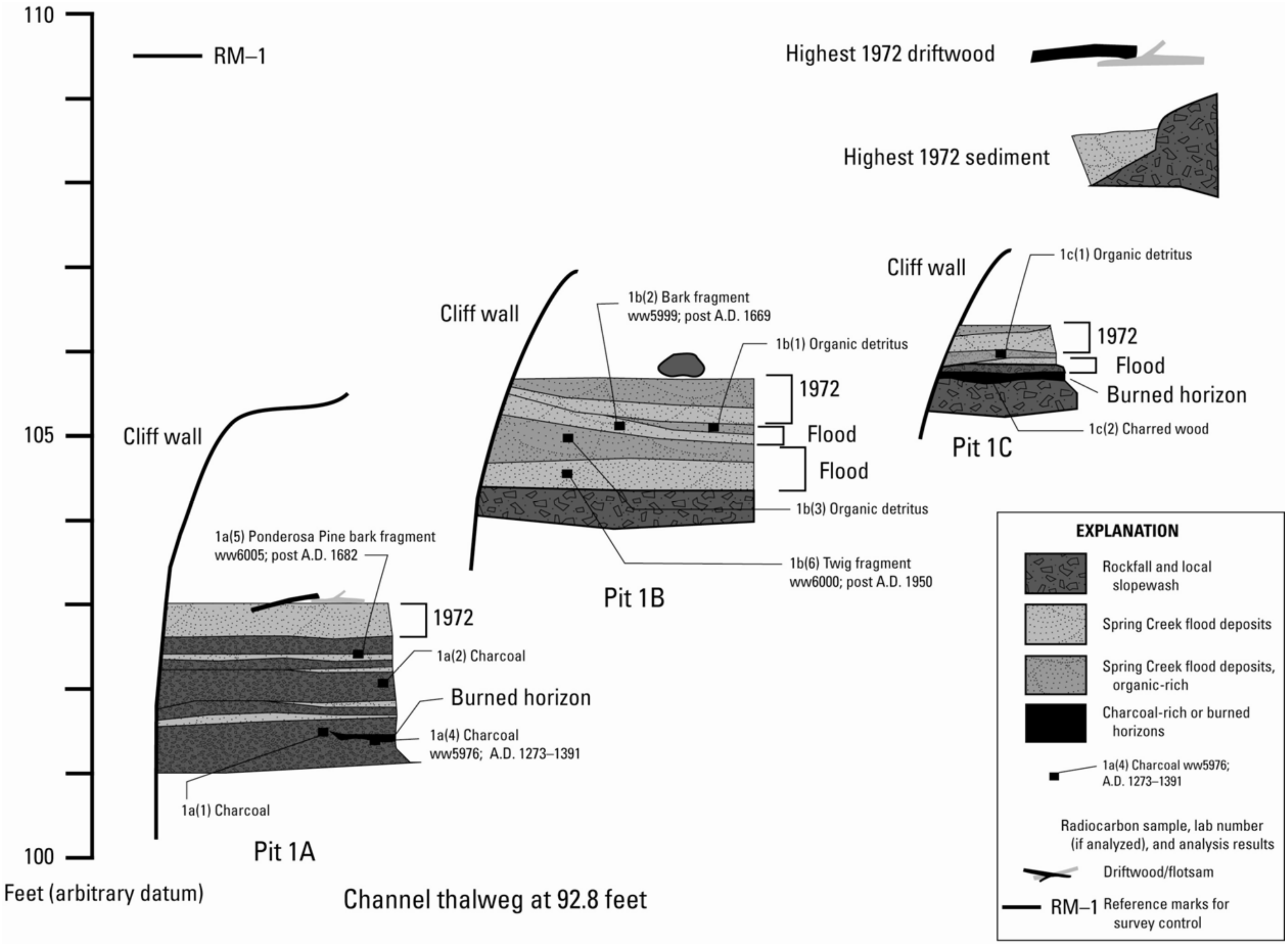


Figure 3.9.1-2. Schematic of stratigraphy, interpretation of flood units, and radiocarbon sample locations and results for excavations at Superscour Alcove, Spring Creek.

Olympia Alcove is a single-chambered deep alcove formed in Minnelusa Formation rocks on the left canyon wall. The alcove has a floor composed of Spring Creek flood sediment and much redder sediment washed in from the adjacent cliff. The floor of the alcove is only about 8.7 ft above and 20 ft away from the channel thalweg, so this alcove probably is inundated more frequently and energetically than either Hailstorm or Superscour Alcove. A 3.5-ft excavation exposed five Spring Creek flood deposits, including a capping deposit of sand and driftwood from the 1972 flood (figs. 3.6-1c and 3.9.1-3). These Spring Creek deposits contain abundant charcoal and wood detritus, and were separated from each other by varying thicknesses of local slopewash sediment. The 1972 flood deposit is 8.7 ft above the thalweg, but the highest flotsam across the channel from the alcove is 13.4 ft above the thalweg, indicating that the alcove floor was inundated by about 4.7 ft of water in 1972.

In addition to these three sites, a more limited analysis was conducted within a narrower canyon segment approximately 1 mile upstream from Hailstorm Alcove, where Spring Creek is incised into the Madison Limestone. This reach contains many small caves and dissolution caverns at a range of elevations high above the channel thalweg, including a pair of small connected caverns informally named the Temple of Doom Alcove. A driftwood sample was collected for radiocarbon dating (described in Section 3.10.1 and determined to be about 700 years old) at a location 19.9 ft above the thalweg. A singular sequence of slackwater flood deposits also was found in a connected alcove more than 5 ft above this driftwood.

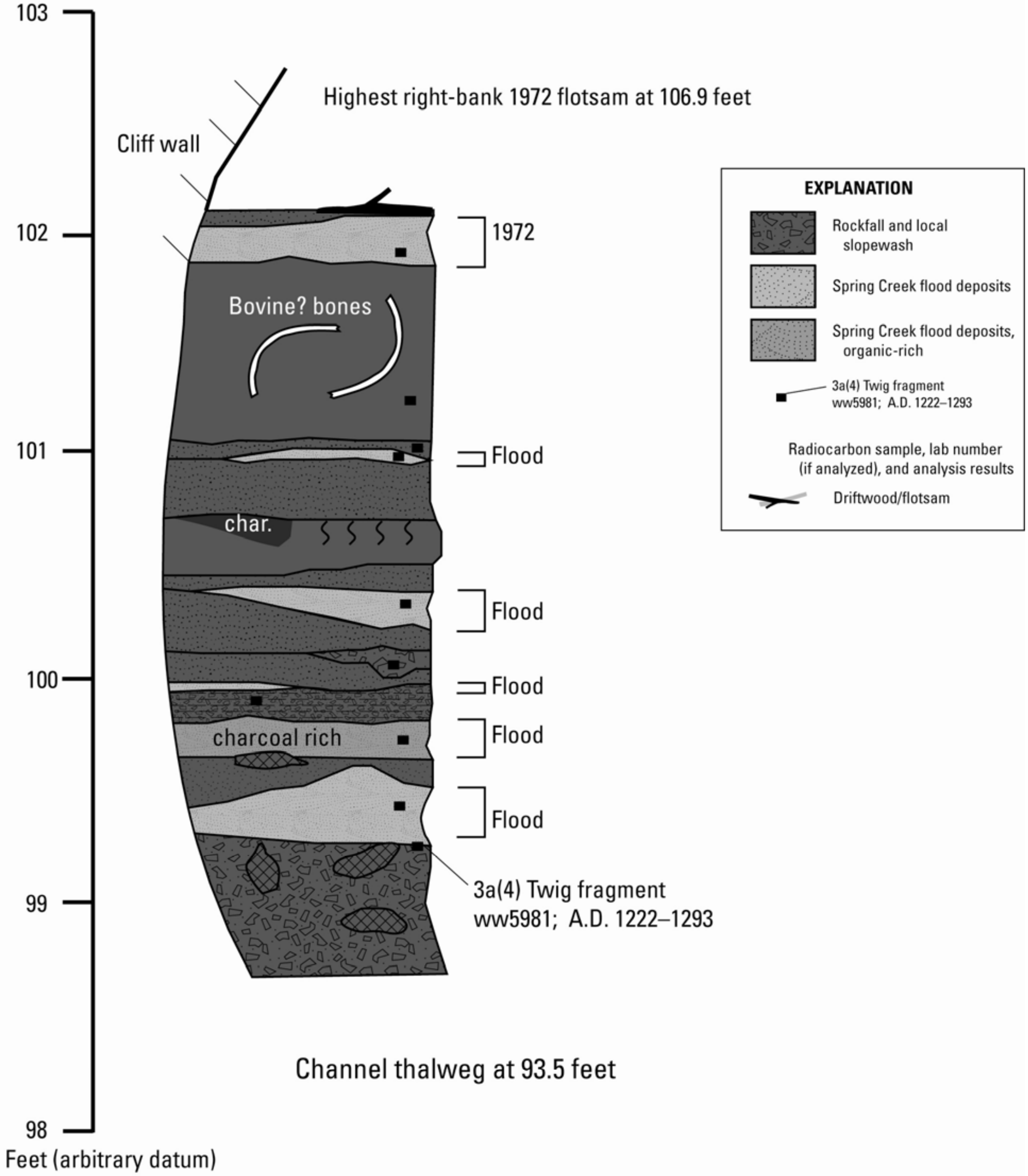


Figure 3.9.1-3. Schematic of stratigraphy, interpretation of flood units, and radiocarbon sample locations and results for excavations at Olympia Alcove, Spring Creek.

3.9.2 French Creek Flood Deposits and Stratigraphic Descriptions

The French Creek study reach is within Custer State Park, within the French Creek Natural Area upstream from the Wildlife Loop Road. This reach is within sections 11 and 12 of Township 4S and Range 6E. The study reach extends for about 1.0 mile downstream from gaging station 06403300 (fig. 3.6-2) and is within a streamflow loss zone ("loss threshold" of about 30 ft^3/s) that begins near the contact with the Madison Limestone, just downstream from this station (Hortness and Driscoll, 1998). Thus, the stream channel generally is dry in this reach, except during sustained periods of runoff. This station was not operated during 1972; however, documentation provided by Schwarz et al. (1975) indicates that precipitation in the drainage area was relatively small and that a large peak was not associated with the June 9–10, 1972, storm. The largest recorded peak discharge in the period of record (since 1982) was 1,060 ft^3/s in 1995 (fig. 3.9-1). Within this reach of French Creek, efforts were focused primarily on a single cave complex (Pratt Cave), but stratigraphic descriptions also were conducted at an eroded tributary fan (Riviera site) where slackwater flood sediments provided evidence of very large previous flows.

Pratt Cave is a multi-chambered cave complex extending several tens of feet away and above the French Creek channel from a narrow opening on the right canyon wall, about 35 ft south of the channel thalweg. The canyon bottom is approximately 125 ft wide and densely vegetated with ash and box elder, which has effectively hid the cave entrance and protected it from excessive human disturbance. A large chamber immediately inside the entrance has a floor composed of flood deposits and driftwood, and smaller caverns connected to this chamber have flood sediment and driftwood at higher elevations (figs. 3.9.2-1, 3.6-1d, and 3.9.1e). The cave entrance is partly blocked by a cone of rockfall debris; the present geometry would allow water in the cave only when flow stages exceeded 12.5 ft relative to the French Creek thalweg, although this threshold elevation probably has varied because the blocking cone of debris has changed with time. A small alcove 30 ft downstream ('Pit B" of fig. 3.9.2-1) also has a floor composed of French Creek flood sediment and drift wood, but is substantially lower with an upper surface only 6.0 ft above the French Creek thalweg.

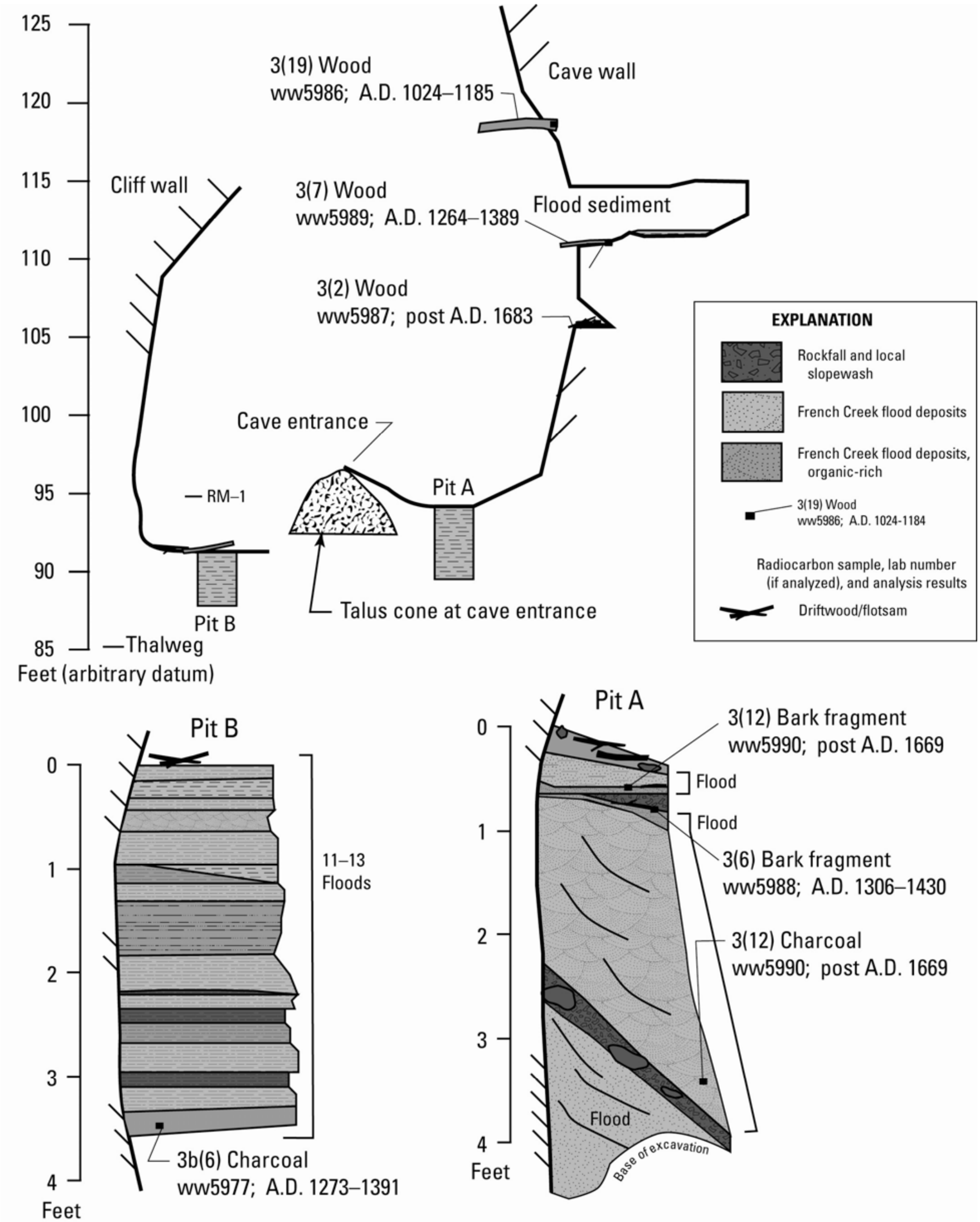


Figure 3.9.2-1. Schematic of stratigraphy, interpretation of flood units, location of driftwood accumulations, and radiocarbon sample locations and results for Pratt Cave site, French Creek.

The excavation into the flood sediment that composes the main chamber floor of Pratt Cave exposed deposits of three French Creek floods, each separated and capped by flotsam, wind-blown organic debris, and rockfall (fig. 3.6-1e). The top of the deposit is 9.0 ft above the channel thalweg, although the present cave opening geometry would require flow 3.5 ft higher for spillage into the cave, as described previously in this section. In addition, small caverns with floors at 20.6 ft and 25.7 ft above the thalweg contained French Creek flood sediment and driftwood. A water-worn log, 10 ft long with a diameter of 0.7 ft, is wedged into a narrow crevice about 33 ft above the thalweg, indicating an exceptionally high flood stage at some point in the past.

The lower downstream alcove at the Pratt Cave site also contained about 3.5 ft of thinly bedded French Creek flood deposits and intervening layers of local slopewash and rockfall, in sum representing 11–13 French Creek floods (figs. 3.6-1f and 3.9.2-1). Here, like Olympia Alcove on Spring Creek, the greater number of floods reflects the lower elevation of the alcove and its consequent more frequent inundation.

About 0.6 mile downstream from Pratt Cave, where the canyon is substantially wider, a small tributary from the north (with a drainage area of ~0.3 mi^2) has built out a small alluvial fan into the French Creek valley bottom. Grading for an old roadbed at the toe of the fan exposes a stratigraphy of coarse-grained tributary deposits interbedded with two sandy French Creek flood deposits, informally termed the Riviera site. The highest of the two flood deposits is as much as 0.7 ft thick (fig. 3.9.2-2) and traceable for approximately 20 ft along the road cut and where the fan has been incised by tributary downcutting. This flood deposit is 15.7 ft above the channel thalweg at a location where the valley bottom is ~250 ft wide.

This reach of French Creek also contains abundant evidence of much older and larger floods. Immense boulder bars partly fill the valley bottom at many wide places and at bends. These deposits are in locations consistent with deposition by extreme floods, such as where point bars would form and in areas of reduced flow velocity (e.g. O'Connor, 1993). The deposits are composed of subangular to well-rounded clasts of granite, limestone, quartzite, and dolomite. Individual clasts have diameters as large as 12 ft. Across the channel from Pratt Cave, a deposit of these boulders ranges from 20 to 45 ft above the present thalweg, and a large point bar deposit near the Riviera site has a surface 34 ft above the present thalweg. The limestone and dolomite clasts of these deposits are substantially pitted and weathered, indicating that these deposits are perhaps tens of thousands of years old and probably are related to the distinctively different hydrologic and geomorphic regimes during the last glacial period.

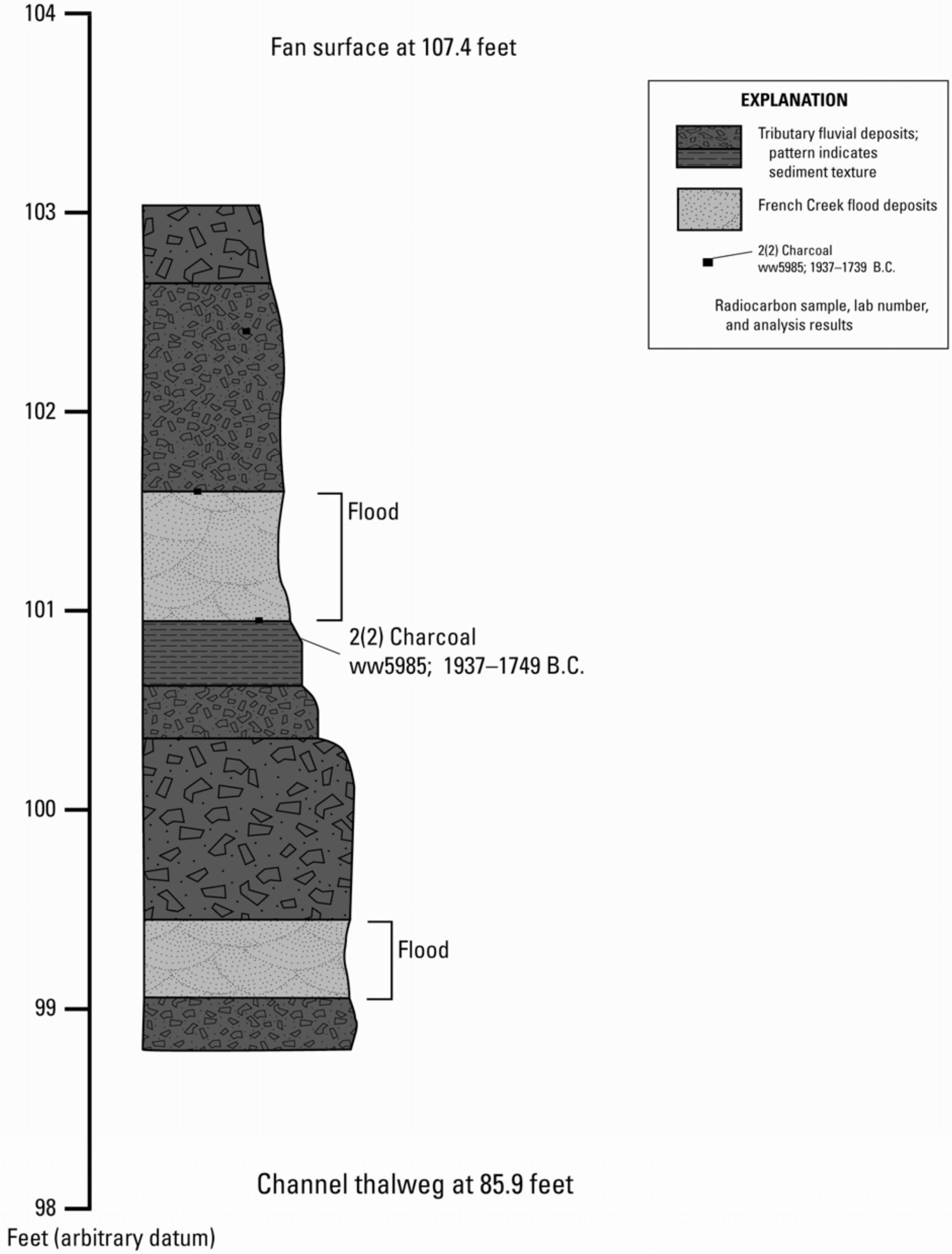


Figure 3.9.2-2. Schematic of stratigraphy, interpretation of flood units, and radiocarbon sample locations and results for excavation at Riviera site, French Creek.

3.9.3 Preliminary discharge estimates at the detailed study sites

Channel cross sections were surveyed at all stratigraphic analysis locations to allow calculation of preliminary discharge estimates associated with flood deposits. The basic premise of discharge estimation is that flood stage must have been at least as high as the elevation of the preserved flood deposits or flotsam. Hence, ignoring hydraulic and other geomorphic uncertainties, the resulting discharge estimate will be a minimum value. Other uncertainties are important, however, including (1) possible changes in overall channel geometry in the interim between deposit emplacement and the cross-section survey; and (2) hydraulic issues, such uncertainty in energy loss coefficients (e.g. Manning *n*) or the fidelity of the surveyed cross sections for characterizing flow conditions within the reach. In a fully implemented study, these issues can be systematically addressed to provide estimates of uncertainty associated with paleohydrologic discharge values (e.g. O'Connor and Webb, 1988; O'Connor et al., 1994; Hosman et al., 2003). O'Connor and Webb (1988) and Webb and Jarrett (2002) described methods of hydraulic analysis for paleoflood studies.

The preliminary analyses reported herein rely on applying the Manning equation or critical flow equation to a single cross section at each site of stratigraphic analysis. The Manning equation (Barnes, 1967) is an established relation for estimating discharge; $Q = 1.49n^{-1}AS^{1/2}R^{2/3}$, where Q is discharge, n is the Manning roughness coefficient, A is the cross section area, S is the energy gradient (typically assumed equivalent to channel slope), and R is the hydraulic radius (all units in feet and seconds). Roughness estimates are typically assigned on the basis of analyst experience, aided by guides such as Barnes (1967). The critical flow relation is based on the observation that flows in steep environments tend toward a state of minimum specific energy (Grant, 1997). This condition is satisfied for $Q = (gA^3T^{-1})^{1/2}$, where g is the acceleration of gravity, and T is flow top width, in any consistent set of units. The main advantage of the critical flow equation is that it does not rely on estimates of Manning *n*, which can be subjective, and on the assumption that measured channel slope is closely equivalent to the energy gradient; the shortcoming is that there may be uncertainty as to whether the flow is indeed close to critical conditions—an uncertainty that can only be addressed by more sophisticated hydraulic analysis. Jarrett and England (2002) indicated that peak discharge computed as critical flow generally is within about +/- 15 percent of the discharge computed by direct current meter measurement for mountain streams similar to those in the Black Hills area.

Both techniques (Manning equation and critical flow) were applied for four alcove sites along Spring Creek. Likewise, both techniques were applied for the Pratt Cave and Riviera sites along French Creek. The results are summarized in figure 3.9.3-1 and table 3.9.3-1.

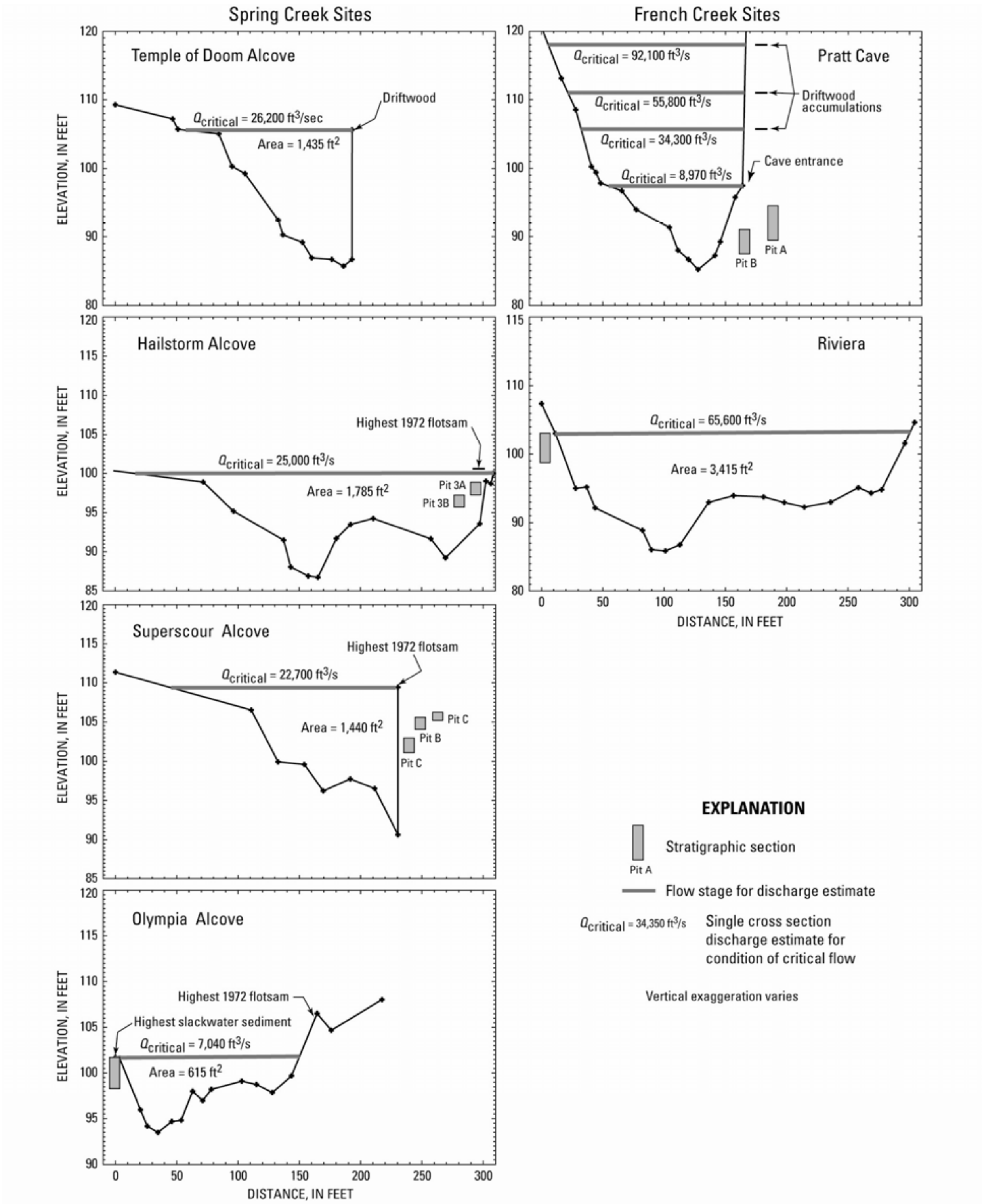


Figure 3.9.3-1. Surveyed cross sections and related data for detailed stratigraphic analysis sites. Related data include flow stages and relative locations of stratigraphic sections and sampled driftwood deposits. Survey datum is arbitrary for all cross sections, but same as elevation datum for associated stratigraphic sections. Discharge estimates derived using critical flow equation (table 3.9.3-1) for flow stages shown.

Table 3.9.3-1. Summary of hydraulic data and computations for estimation of discharge at selected paleoflood sites.

[--, not determined]

Discharge point	Area (square feet)	Wetted perimeter (feet)	Hydraulic radius (feet)	Top width (feet)	Slope[a] (feet per foot)	Rough-ness coef-ficient	Estimated discharge (cubic feet per second) Manning equation	Estimated discharge (cubic feet per second) Critical flow equation[b]
Spring Creek sites								
Highest driftwood, Temple of Doom Alcove	1,435	160.4	8.9	138.6	0.0130	0.025	42,200	--
	--	--	--	--	--	0.030	35,100	--
	--	--	--	--	--	0.035	30,100	--
	--	--	--	--	--	0.040	26,300	26,200
	--	--	--	--	--	0.045	23,400	--
	--	--	--	--	--	0.050	21,100	--
Excavation, Hailstorm Alcove	1,785	298.5	6.0	292.7	0.0072	0.025	29,800	--
	--	--	--	--	--	0.030	24,800	25,000
	--	--	--	--	--	0.035	21,300	--
	--	--	--	--	--	0.040	18,600	--
	--	--	--	--	--	0.045	16,500	--
	--	--	--	--	--	0.050	14,900	--
Excavation, Superscour Alcove	1,440	207.6	6.9	186.5	0.0072	0.025	26,400	--
	--	--	--	--	--	0.030	22,000	22,700
	--	--	--	--	--	0.035	18,800	--
	--	--	--	--	--	0.040	16,500	--
	--	--	--	--	--	0.045	14,700	--
	--	--	--	--	--	0.050	13,200	--
Excavation, Olympia Alcove	615	152.3	4.0	149.8	0.0072	0.025	7,840	--
	--	--	--	--	--	0.030	6,530	7,040
	--	--	--	--	--	0.035	5,600	--
	--	--	--	--	--	0.040	4,900	--
	--	--	--	--	--	0.045	4,350	--
	--	--	--	--	--	0.050	3,920	--
French Creek sites								
Cave mouth, Pratt Cave	--	--	--	--	--	--	17,400	--
	--	--	--	--	--	0.030	14,500	--
	--	--	--	--	--	0.035	12,400	--
	--	--	--	--	--	0.040	10,900	--
	--	--	--	--	--	0.045	9,670	--
	--	--	--	--	--	0.050	8,700	8,970
Lower cavern, Pratt Cave	1,695	146.2	11.6	132.8	0.0198	0.025	72,700	--
	--	--	--	--	--	0.030	60,600	--
	--	--	--	--	--	0.035	51,900	--
	--	--	--	--	--	0.040	45,400	--
	--	--	--	--	--	0.045	40,400	--
	--	--	--	--	--	0.050	36,300	34,300
Small log, Pratt Cave	2,405	163.2	14.7	144.0	0.0198	0.025	121,000	--
	--	--	--	--	--	0.030	101,000	--
	--	--	--	--	--	0.035	86,600	--
	--	--	--	--	--	0.040	75,700	--
	--	--	--	--	--	0.045	67,300	--
	--	--	--	--	--	0.050	60,600	55,800

Table 3.9.3-1. Summary of hydraulic data and computations for estimation of discharge at selected paleoflood sites (Continued).

Discharge point	Area (square feet)	Wetted perimeter (feet)	Hydraulic radius (feet)	Top width (feet)	Slope[a] (feet per foot)	Rough-ness coef-ficient	Estimated discharge (cubic feet per second)	
							Manning equation	Critical flow equation[b]
French Creek sites (Continued)								
Highest log, Pratt Cave	3,485	188.0	18.5	161.0	0.0198	0.025	205,000	--
	--	--	--	--	--	0.030	171,000	--
	--	--	--	--	--	0.035	146,000	--
	--	--	--	--	--	0.040	128,000	--
	--	--	--	--	--	0.045	114,000	--
	--	--	--	--	--	0.050	102,000	92,100
Highest sands, Riviera site	3,415	303.6	11.3	297.3	0.0198	0.025	99,600	--
	--	--	--	--	--	0.030	83,000	--
	--	--	--	--	--	0.035	71,200	--
	--	--	--	--	--	0.040	62,300	65,600
	--	--	--	--	--	0.045	55,400	--
	--	--	--	--	--	0.050	49,800	--

[a]Channel slopes determined from 1:24,000 scale topographic maps.

[b]Critical flow discharge estimates placed adjacent to nearest corresponding Manning estimate.

The discharge estimates are mutually consistent and reasonable in consideration of the physical evidence and documentation regarding the magnitude of the 1972 flood in the Black Hills. The highest flood deposits at Hailstorm and Superscour Alcoves, which were similar to the maximum flotsam level of the 1972 flood, correspond to critical flow estimates of about 23,000 to 25,000 ft^3/s. These values are similar to a Manning equation estimate with a Manning *n* value of 0.03. The estimates of 23,000-25,000 ft^3/s are similar to the documented 1972 peak of 21,800 ft^3/s at U.S. Highway 16 (Schwarz et al., 1975). The critical flow estimate for the top of the deposits at Olympia Alcove is only about 7,000 ft^3/s, which is similar to an estimate of ~6,500 ft^3/s for the Manning equation estimate for a Manning *n* value of 0.03. These lower values reflect the lower elevation of the deposits in this alcove; therefore, this alcove is accumulating deposits from smaller floods than the higher Hailstorm and Superscour Alcoves. The older and higher deposits in the Temple of Doom Alcove required a discharge of at least 26,000 ft^3/s according to the critical flow discharge relation, which is similar to a Manning equation estimate with a Manning *n* value of 0.04.

At Pratt Cave on French Creek, which was not affected by the 1972 flooding, inundation of the cave could require as little as ~9,000 ft^3/s, based on the critical flow estimate. The various driftwood accumulations, in ascending order, would require ~34,000 ft^3/s, ~56,000 ft^3/s, and, for the highest driftwood log lodged in a high crevice about 33 ft above the thalweg, ~92,000 ft^3/s. In all settings, the critical flow estimates generally relate to Manning equation results for *n* values approaching or exceeding 0.05. The discharge value of ~92,000 ft^3/s associated with the highest driftwood exceeds any historical flows previously measured for comparable drainages in the Black Hills area. Many 1972 discharge values generally are comparable, however, relative to the French Creek drainage area of ~105 mi^2. Comparable examples for the unregulated portions of drainage areas along Rapid Creek include 31,200 ft^3/s for station 06412500 (above Canyon Lake, unregulated area of 51 mi^2) and 50,000 ft^3/s for station 06414000 (at Rapid City, unregulated area of 90 mi^2).

These discharges are preliminary estimates, calculated only to indicate that the deposits found in these two study reaches are of the same order of magnitude as the 1972 flooding that occurred in many stream reaches. These values are not intended to be used for further analysis. Discharge values that could be used for flood-frequency analysis would be calculated under full implementation and would entail more extensive surveying of channel geometry and sophisticated hydraulic flow modeling, either step-backwater calculations over multiple cross sections or full two-dimensional modeling. Modeling results, along with uncertainty and sensitivity analyses, would be registered to elevations of individual flood deposits, so as to provide a minimum estimate of peak discharge (and uncertainty) for each individual flood deposit. Correlation of deposits between sites, either by geochronology or sedimentologic characteristics, also would enable more accurate discharge estimates. Hosman et al. (2003) provide an example of such an analysis.

3.10 PERFORM DATING OF APPROPRIATE PALEOFLOOD EVIDENCE

Task 10: Through accepted state-of-the-practice methods, perform absolute and relative dating techniques on the paleoflood evidence gathered during the field surveys to gain the best possible timeframe estimates for past significant flood events.

A key aspect of paleoflood studies is documenting the timing and frequency of prehistoric flood deposits. Multiple approaches are possible, but radiocarbon analysis of detrital organic materials is the most expedient for the slackwater deposits in the Black Hills region. Radiocarbon analysis uses the naturally occurring isotope carbon-14 (^{14}C) to determine the age of carbonaceous materials. For this study, radiocarbon sampling was performed in conjunction with the stratigraphic and sedimentologic descriptions. Sampling and analysis in this Black Hills study followed procedures outlined in Ely and Baker (1985), O’Connor et al. (1986, 1994), and Hosman et al. (2003).

The goal for this scoping phase was primarily to determine the length of time represented by the sequences of deposits, rather than the specific ages and timing of individual flood events. Consequently, most submitted samples were from near the base of described stratigraphic sections (which would be the oldest deposits) as well as from individual perched driftwood accumulations. Full implementation aimed at confidently determining the age of individual flood deposits would require many more analyses. In total, more than 50 samples were collected for possible radiocarbon dating. Of these, 18 samples were submitted to the U.S. Geological Survey ^{14}C Laboratory in Reston, Virginia. All results were converted to calendar years by the calibration program CALIB REV5.0.2 using the intcal04.14c calibration data set (Stuiver and Reimer, 1986, 1993; Reimer et al., 2004). One sample, from the Riviera site, contained insufficient carbon for radiometric dating. The results for the 17 analyzed samples are summarized in table 3.10-1.

Table 3.10-1. Radiocarbon analysis results and calibrations to calendar year age estimates.

[--, not determined]

Date and field sample number	Site	Material	Lab identifi-cation number	Corrected conventional ^{14}C age[a] (Before Present)	^{14}C age error[a]	$\delta^{13}C$[b]	Calibrated age[c] [2-sigma range, in calendar years A.D./B.C. (with associated fraction of probability density function)]	Median calendar year probability	Comments
8/25/2006 - 1(1)	Temple of Doom Alcove	Twig fragment	WW6001	680	34	-24.7	A.D. 1268–1320 (0.61); A.D. 1350–1391 (0.43)	A.D. 1302	
5/31/2006 - 3a(4)	Hailstorm Alcove	Twig fragment	WW6003	599	33	-25.1	A.D. 1297–1409 (1.00)	A.D. 1347	
5/31/2006 - 3a(6)	Hailstorm Alcove	Charcoal	WW5983	2205	34	-24.6	381–192 B.C. (1.00)	285 B.C.	
5/31/2006 - 3b(2)	Hailstorm Alcove	Twig fragment	WW6004	625	32	-25	A.D. 1290–1399 (1.00)	A.D. 1349	
6/1/2006 - 1a(4)	Superscour Alcove	Bark fragment	WW5976	671	32	-24.2	A.D. 1273–1321 (0.56); A.D. 1349–1391 (0.44)	A.D. 1310	
6/1/2006 - 1a(5)	Superscour Alcove	Single charcoal clast	WW6005	98	32	-23.6	A.D. 1682–1737 (0.28); A.D. 1804–1936 (0.71)	A.D. 1839	
6/1/2006 - 1b(2)	Superscour Alcove	Bark fragment	WW5999	138	32	-23.2	A.D. 1669–1780 (0.44); A.D. 1798–1894 (0.39); A.D. 1907–1944 (0.16)	A.D. 1811	
6/1/2006 - 1b(6)	Superscour Alcove	Twig fragment	WW6000	Post A.D. 1950	--	-24.7	Post A.D. 1950	--	Out of stratigraphic order
6/2/2006 - 1(2)	Olympia Alcove	Charcoal	WW5981	738	32	-25.6	A.D. 1222–1293 (1.00)	A.D. 1269	
6/5/2006 - 3(2)	Pratt Cave	Twig fragment	WW5987	96	31	-25	A.D. 1683–1736 (0.28); A.D. 1805–1934 (0.71)	A.D. 1840	
6/5/2006 - 3(3)	Pratt Cave	Charcoal	WW5984	199	32	-25.4	A.D. 1646–1691 (0.27); A.D. 1728–1811 (0.55); A.D. 1920–1952 (0.18)	A.D. 1770	
6/5/2006 - 3(6)	Pratt Cave	Bark fragment	WW5988	560	32	-28.8	A.D. 1306–1363 (0.52); A.D. 1385–1430 (0.48)	A.D. 1358	
6/5/2006 - 3(7)	Pratt Cave	Twig fragment	WW5989	691	33	-25	A.D. 1264–1315 (0.70); A.D. 1355–1389 (0.30)	A.D. 1292	
6/5/2006 - 3(12)	Pratt Cave	Bark fragment	WW5990	140	31	-24.8	A.D. 1669–1750 (0.45); A.D. 1798–1891 (0.38); A.D. 1908–1945 (0.16)	A.D. 1808	Out of stratigraphic order

Table 3.10-1. Radiocarbon analysis results and calibrations to calendar year age estimates (Continued).

[--, not determined]

Date and field sample number	Site	Material	Lab identification number	Corrected conventional ^{14}C age[a] (Before Present)	^{14}C age error[a]	$\delta^{13}C$[b]	Calibrated age[c] [2-sigma range, in calendar years A.D./B.C. (with associated fraction of probability density function)]	Median calendar year probability	Comments
6/5/2006 - 3(19)	Pratt Cave	Wood from log	WW5986	926	34	-20.6	A.D. 1024–1185 (1.00)	A.D. 1100	
6/5/2006 - 3b(8)	Pratt Cave	Charcoal	WW5977	672	32	-24	A.D. 1273–1320 (0.57); A.D. 1350–1391 (0.43)	A.D. 1309	
6/7/2006 - 2(2)	Riviera site	Charcoal	WW5985	3520	35	-24.1	1937–1749 B.C. (1.00)	1837 B.C.	

[a]Radiocarbon ages (in ^{14}C years Before Present) are calculated on basis of Libby half-life of 5,568 years (Reimer et al., 2004). The error stated is +/- 1 sigma on basis of combined measurements of the sample, background, and modern reference standards. Age referenced to A.D. 1950. Where no measurements of $^{13}C/^{12}C$, a value of -25‰ assumed for determining corrected conventional age.

[b]$^{13}C/^{12}C$ ratio reported where measured (‰).

[c]Calibrated 2-sigma calendar year age intercepts, in calendar years B.C./A.D., on basis of CALIB REV5.0.2 using intcal04.14c calibration data set (Reimer et al., 2004) and a laboratory error multiplier of 1. Where multiple intercepts, solutions listed in order of greatest likelihood summing to greater than 90 percent of the probability density function.

3.10.1 Spring Creek Results

Three ^{14}C analyses were obtained on samples collected from the deposits at Hailstorm Alcove, which tentatively show that the three individual floods recorded by the stratigraphy span a time period extending back to about 400 to 200 B.C. Radiocarbon dates from the penultimate flood deposits (immediately below the 1972 deposits) at both pits 3A and 3B indicate that this flood, which probably was larger than the 1972 flood on the basis of deposit thickness and its coarse texturer, was sometime between A.D. 1300 and 1400 (fig. 3.9.1-1). The Hailstorm Alcove depositional site apparently is so high that it only rarely is inundated, thus recording only the largest floods of the last several thousand years on Spring Creek.

Four radiocarbon analyses at Superscour Alcove indicate that the record here is shorter than at Hailstorm Alcove, but contains evidence of more floods of smaller magnitude during the last several centuries (fig. 3.9.1-2). The basal ^{14}C date for Pit 1A indicates that the sequence of four thin Spring Creek flood deposits plus the overlying and thicker 1972 deposit accumulated since A.D. 1273–1391. Here, the penultimate flood deposits in both pits 1a and 1b were apparently emplaced sometime after A.D. 1670–1680. One result, the post A.D. 1950 date from the base of Pit 1B, is anomalous by its stratigraphic position relative to the post A.D. 1669 sample collected from above it. Such discrepancies typically can be resolved by additional dating, and commonly owe to (1) contamination by modern carbon, such as roots from live plants or by burrowing insects or animals (for the case of anomalously young ages), or to (2) old carbon being transported by the emplacing floods, such as if charcoal from a centuries-old forest fire was entrained and then deposited (in the case of anomalously old dates). For these reasons, full implementation would require multiple analyses of individual deposits and stratigraphic horizons for confident age assignations (e.g. O'Connor et al., 1994; Hosman et al., 2003).

A single radiocarbon analysis from near the base of Olympia Alcove gives a similar result as Pit 1A at Superscour Alcove—the record at Olympia Alcove tentatively shows that six floods (including 1972) left deposits in this relatively low alcove since A.D. 1222–1293 (fig. 3.9.1-3). The relatively thick and coarse deposit at the base of the Olympia Alcove pit may be equivalent to the similar-aged large-flood deposit preserved below the 1972 deposit at Pit 3A at Hailstorm Alcove.

An analysis of a twig within a driftwood accumulation above the highest 1972 flotsam near the Temple of Doom Alcove gave a calibrated age of A.D. 1268–1391. This evidence of a flood larger than the 1972 flood matches the evidence at Hailstorm Alcove, where there also is evidence of an exceptionally large flood sometime between about A.D. 1300 and 1400.

3.10.2 French Creek Results

Nine ^{14}C samples were submitted for analysis from sites along French Creek; seven from the deposits and driftwood accumulations at Pratt Cave (fig. 3.9.2-1), and two from the exposed tributary fan and French Creek flood deposits at the Riviera site (fig. 3.9.2-2). One sample, from the lowermost French Creek flood deposit at the Riviera site, had insufficient carbon remaining after pretreatment for analysis, so ultimately results were obtained for eight samples, all but one from the Pratt Cave site.

Three samples from Pit A (fig. 3.9.2-1) provide a tentative chronology of flooding broadly consistent with ages from driftwood sampled in higher caverns and crevices above the cave floor. A date from a fragment of Ponderosa Pine bark at the base of the uppermost flood deposit indicated that the emplacing flood was sometime after A.D. 1669. Thus, the last major flood on French Creek was sometime in the last 350 years. No historical accounts of exceptionally large floods along French Creek have been found; thus, this large flood probably pre-dates European settlement that commenced about A.D. 1880. Similar to the penultimate large flood at some of the Spring Creek sites, the thicker and coarser deposit at Pit A was capped by fine organic debris, including bark fragments, that gave an age of A.D. 1306–1430, although this result is complicated by the post A.D. 1669 result obtained from a charcoal clast sampled lower within this deposit. Samples from progressively higher driftwood accumulation in caverns and crevices gave progressively older ages. A twig in the lowest sampled cavern (fig. 3.9.2-1) is from post A.D. 1683, consistent with the result from the uppermost deposit in Pit A. Likewise, a stick that floated into a higher cavern and deposited with a thin layer of French Creek sediment gave an age of A.D. 1264–1389, consistent with the tentative age of the next-oldest deposit at Pit A. The highest driftwood at Pratt Cave, the 10-ft-long log 39.5 ft above the thalweg, gave a date of A.D. 1024–1185. Without additional analysis, it is not possible to determine if this log floated in during an older and larger flood, perhaps corresponding to the basal deposit in Pit A, or was perhaps a log already 200 years old when incorporated into the circa A.D. 1300 large flood.

The basal date from the much lower Pit B at Pratt Cave indicates 11–13 floods achieved stages of at least 3.6 to 6 ft above the French Creek thalweg since A.D. 1273–1391 (Fig. 3.9.2-1). Determining the relation between individual flood deposits in this sequence and the higher deposits and driftwood in the main part of Pratt Cave would require additional dating; however, this date does indicate there is an extensive stratigraphic record of multiple floods over the last several centuries.

The single radiocarbon date from the tributary fan deposits at the Riviera site (fig. 3.9.2-2) indicates that the uppermost French Creek flood deposit, interbedded with the tributary fan deposits, occurred after 1937–1749 B.C. The underlying French Creek flood deposit, for which a small piece of charcoal did not have sufficient carbon for analysis, is presumably older. Although more dating is necessary to refine the chronology at the Riviera site, the flood deposits at this site probably pre-date all of the deposits at the Pratt Cave site.

In sum, flood deposits in the Black Hills region contain abundant materials suitable for radiocarbon analysis and development of high-resolution flood chronologies. The radiocarbon results obtained during this reconnaissance study indicate that the stratigraphic record of flooding preserved along Black Hills streams extends back 3,000 to 4,000 years at some sites. The lower-elevation alcoves along both French and Spring Creeks contain stratigraphic records of multiple floods going back several centuries, and probably reliably record floods of 50- to 100-year return periods. The higher alcoves, such as Hailstorm, Temple of Doom, Pratt Cave, have accumulated sediment and driftwood from only the very largest events of the last few thousands of years. One specific tentative interpretation of flood history on the basis of this reconnaissance study is that there were exceptional floods (larger than the 1972 flood on Spring Creek) that affected both French and Spring Creeks sometime around A.D. 1300-1400. These floods could possibly have resulted from the same storm event, but the present resolution of the flood chronology is not yet sufficient to establish this.

3.11 FROM ALL LOCATIONS SAMPLED, DETERMINE APPLICABILITY OF PALEOFLOOD DATA FOR IMPROVING FLOOD-FREQUENCY ESTIMATES

Task 11: Develop a data set that combines the historical flood-frequency estimates, including stage indicators, for all locations selected during the study and perform cross-analyses to determine if preliminary conclusions can be drawn as to whether Black Hills paleoflood data appear to be viable for improving the flood-frequency estimates within individual drainage basins, groups of drainage basins with characteristics deemed worthy of common classification, and the Black Hills region as a whole.

The analysis of historical flood records (gaged and otherwise), in combination with regional reconnaissance of most large Black Hills drainages and subsequent detailed studies at the French Creek and Spring Creek sites, indicates that application of paleohydrologic techniques has excellent potential for substantial improvement of flood-frequency estimates for many streams in the Black Hills region. This finding is especially true for particularly large, low-frequency floods such as those that occurred in several drainages in 1972. This finding owes to several considerations and datasets and information sources obtained during this study:

1. The historical and gaged record of flooding shows that exceptional floods can result from large thunderstorm complexes affecting substantial portions of the Black Hills. The largest measured floods are associated with 1972 flooding, with flood peaks on the order of as much as about 50,000 ft^3/s for several different streams with drainage areas in the range of about 50 to 150 mi^2.
2. Such floods on individual drainages are rare, relative to systematic record lengths, with at most one or two major floods having affected the larger Black Hills drainages since the late 1800s (as determined from tasks 2, 3, 4, and 5). Some drainages have no record of major floods during this timeframe. The few historical occurrences of these events make it exceedingly difficult to reliably judge their frequency from gaged and historical observations alone. Additionally, their relative rarity inhibits reliable inferences of large-flood generation processes that may vary spatially (due to factors such as topography, geology, or climatology) over the Black Hills region.

3. Preliminary analysis of flood slackwater deposits at Spring Creek and French Creek (reported in Sections 3.8 to 3.10) show that these stratigraphic records of flooding are resolvable into confident interpretations of the number, timing, and magnitude of large floods, including discharges perhaps larger than the maximum discharges of the 1972 flood. Moreover, these stratigraphic records extend sufficiently far back in time (commonly more than 2,000 years) and contain records of enough floods so that robust flood-frequency estimates, particularly for large flows such as those of 1972, can be determined from established statistical techniques (e.g. O'Connell et al., 2002).
4. The availability of flood evidence from 1972 flooding, including slackwater deposits, deposits of coarse sediments, flotsam, and other debris, would be highly useful in conducting future paleoflood studies in affected stream reaches. Such evidence provides an excellent point of reference for both stratigraphic and hydraulic analyses.
5. The regional reconnaissance conducted in this study under task 6 (table 3.6-1) shows that alcoves, rock shelters, and caves within canyon sections of most major drainages and many smaller streams preserve stratigraphic records of large floods. The broad distribution of streams with such stratigraphic records could allow for addressing questions of spatial control of 1972-scale floods.
6. Paleoflood evidence is less abundant in the smaller drainage areas that dominate the higher-elevation parts of the Black Hills area. Sufficient paleoflood evidence, including flood slackwater deposits, does exist in strategic locations, however, such that questions regarding geologic and topographic controls in the higher-elevation areas probably could be successfully addressed.

3.12 PREPARE A FINAL REPORT

Task 12: Prepare a final report summarizing research methodology, findings, preliminary conclusions, and recommendations relative to subsequent phases of the planned research efforts.

This document represents the Project Final Report as called for in the description for this task.

3.13 MAKE EXECUTIVE PRESENTATION TO THE RESEARCH REVIEW BOARD

Task 13: Make an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the project.

An executive presentation was made at a regular meeting of the Research Review Board on August 30, 2007.

4.0 FINDINGS AND CONCLUSIONS

The overall conclusion of this reconnaissance-level study is that improved understanding of flood-frequency for the Black Hills region would result from implementation of future studies using established paleoflood techniques. Flood slackwater deposits are preserved in caves, alcoves, and rock shelters in canyon sections of most major drainages in the Black Hills. These deposits record stratigraphic records of large floods that can be effectively used with radiocarbon dating and hydraulic analysis to determine the approximate timing and discharge of previous large floods. Specific flood issues that could be addressed by Black Hills paleoflood studies include (1) determination of the frequency, magnitude, and spatial characteristics of 1972-scale floods for several or all of the major Black Hills drainages; and (2) evaluation of spatial patterns of large-flood generation that owe to topography, geology, and climatology. Addressing these issues would substantially improve understanding of processes for flood generation and the frequency of large floods in the Black Hills region.

The following are specific findings and conclusions of this study:

1. Rare and large floods such as the 1972 flooding leave distinctive suites of deposits, such as flotsam accumulations and slackwater deposits.
2. In protected environments such as caves, rock shelters, and alcoves, such deposits accumulate for several centuries or millennia, forming stratigraphic records of large floods that can substantially extend historical and gaged records of flooding.
3. At French Creek, for which the historical record of floods is sparse with no known flows of 1972 magnitude, slackwater deposits and driftwood accumulations at Pratt Cave recorded 11–13 relatively large flows over the last ~700 years, including at least two major floods with discharges exceeding ~35,000 ft^3/s and one flow 700 to 1,000 years ago with a discharge of ~90,000 ft^3/s.
4. At Spring Creek, where the 1972 flood attained a peak discharge of ~22,000 ft^3/s, there is evidence of at least three flows of 1972 magnitude during the last 2,400 years, including one larger flow 600–700 years ago.
5. At both Spring Creek and French Creek, slackwater deposits at different elevations contain stratigraphic records spanning different time periods, with low accumulations recording smaller floods over the last several hundred years, and higher deposits accumulating from only the largest floods over the last 2,000–4,000 years.
6. These types of results from the preliminary analyses at Spring and French Creeks, if additionally supported by more geochronology and precise hydraulic modeling, can be used in conjunction with established statistical analysis procedures to substantially improve flood-frequency estimates for floods of the general rarity and magnitude of the 1972 flooding.

7. Our regional reconnaissance (task 6) indicates that the types of flood deposits found along Spring and French Creeks are preserved in most, if not all, major drainages, indicating a high probability that robust flood-frequency estimates for large and infrequent floods—such as the 1972 flood—could be determined for many of the large drainages in the Black Hills region.
8. Additionally, our reconnaissance has located similar slackwater flood deposits in caves, alcoves, and rock shelters flanking many smaller and higher-elevation Black Hills drainages, indicating that paleohydrologic approaches, if applied widely across the region, have high potential to address questions of geologic and topographic controls on the frequency of large and rare floods in the Black Hills.

5.0 APPLICABILITY OF PALEOFLOOD METHODS FOR FUTURE STUDIES

The reviews, analyses, and conclusions arising from the task definitions for this research study resulted in the following summary of applicability of paleoflood methods for future studies and anticipated outcomes regarding potential implementation of future study phases:

(1) **Full implementation of future studies using established paleoflood analysis techniques would reduce uncertainty in frequency estimates for large-magnitude and infrequent floods for many applicable stream reaches in the Black Hills region.** Preliminary comprehensive paleoflood investigations for Spring Creek and French Creek demonstrated the quality of high-resolution flood chronologies that can be obtained in appropriate environments. Extensive reconnaissance efforts have shown that similar potential exists within many other applicable stream reaches.

(2) **The best approach for reconstructing high-resolution flood chronologies is by detailed stratigraphic analysis of flood slackwater deposits found in the abundant caves, alcoves, and rock shelters in canyon settings entrenched in Paleozoic carbonate rocks around the periphery of the Black Hills.** These sheltered areas preserve stratified flood deposits and entrained organic materials for hundreds and, locally, thousands of years. Stratigraphic interpretation and dating of these flood-deposit sequences can provide long-term chronologies of large flood events. Additionally, the wide range of alcove elevations provides stratigraphic records of large floods spanning different magnitude and age ranges, thus providing relatively comprehensive records of floods over a wide range of magnitudes. Various other forms of paleoflood evidence also can contribute useful information in many locations.

(3) **Future studies phases, if implemented, would warrant inclusion of detailed hydraulic and statistical analyses.** Detailed surveys of channel geometry throughout extensive stream reaches would be required to support rigorous hydraulic analyses needed to make adequate estimates of previous large flood discharges. Utilization of appropriate statistical analytical procedures incorporating infrequent large flood events would be needed for development of robust flood-frequency estimates.

(4) **Studies focused on the larger drainages where they flow through the carbonate rocks on the periphery of the Black Hills, such as the Spring Creek and French Creek sites studied in detail for this phase, would provide the most information on the size and frequency of 1972-scale flows.** Most if not all of these larger drainages in the Black Hills have sites with high potential for paleoflood analysis. Regional reconnaissance indicates that slackwater flood deposits are available in most of the larger drainages, and evidence from 1972 flooding would provide a valuable point of reference in many of these drainages. Results for this setting would be most meaningful for assessing hazards for the majority of populated areas and infrastructure concentrated along the flanks of the Black Hills.

(5) **Studies of higher-elevation and smaller drainages would provide important information regarding flood generation processes and controlling factors such as elevation, topography, and geology.** Smaller drainages in the higher elevations generally have few flood deposits preserved, but reconnaissance in the Black Hills indicates several possible sites for which detailed investigations probably would provide substantial information on flood-frequency and magnitude. Such information would contribute to site-specific flood-frequency analyses as well as broader frequency analyses within the Black Hills region that use regionalization techniques.

6.0 ANALYSIS OF RESEARCH BENEFITS

The primary benefit of this research is clear demonstration of the superb potential of paleoflood analysis techniques for improving flood-frequency estimates for the Black Hills region. The reconnaissance and detailed analyses conducted in this research show that excellent chronologies of large flood events (some exceeding 1972-scale floods) are preserved in flood slackwater deposits, and that detailed stratigraphic analysis of sequences of these flood deposits, coupled with dating of flood deposits and hydraulic flow modeling, are likely to substantially reduce uncertainty in the frequency of large floods such as the 1972 event. Such information ultimately has wide applicability to reducing costs and mortality due to flooding in the Black Hills region, as well as aiding in understanding of flood generation processes.

Because this research study was a reconnaissance-level scoping effort, with implementation of potential future phases to be considered subsequent to completion of this phase, analysis of the ultimate financial benefits is not yet possible. Nevertheless, preliminary perspectives on potential benefits of future implementation may be appropriate, because the results of this phase indicate that paleohydrologic analysis in the Black Hills regions would likely substantially improve understanding of the frequency and magnitude of large floods, especially in areas subject to flood damage.

One useful perspective comes from consideration of the cost and time required for otherwise obtaining such data on large flood discharges. Current (2007) cost for operation of a USGS crest stage gage in South Dakota is $1,430. Thus, an equivalent value for 100 years of peak-flow record for a single stream would be equivalent to $143,000 in un-inflated dollars and an equivalent value for 1,000 years of peak-flow record at a single site would be $1,430,000. For analysis of the frequency of rare floods, it is the few large floods in such a record that are important. If fully implemented, a paleoflood study would obtain such records at substantially less cost and time. Another obvious and useful perspective (although harder to quantify), arises from consideration of potential cost savings arising from better flood-frequency information, especially in how such information aids in better and more cost efficient determinations of design criteria for infrastructure and for more general purposes, such as zoning or flood hazard planning.

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