Sand Bar and Terrace Erosion Between 1964 and 1996 at the Tin Shed and Camp Creek Cultural Resource Sites on the Snake River in Hells Canyon

FINAL REPORT

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INTRODUCTION AND PURPOSE

The objective of this report is to describe terrace erosion and sand bar change at two localities with significant cultural resources within the Hells Canyon National Recreation Area. The Tin Shed Archeological site is located at mile 215.5 and the Camp Creek Archeological site is located at mile 209.5 (Figure 1). Both of these sites contain cultural deposits in the terraces adjacent to the Snake River. These sites have been listed on the National Register of Historic Places and contain information significant in our prehistory.

The fluvial landforms of the Snake River in Hells Canyon include sand bars, gravel bars, and alluvial terraces. Grams (1991; reported in Schmidt et al., 1995, and Collier et al., 1998) documented erosion of channel-side sand bars and alluvial terraces between Hells Canyon Dam and the Salmon River confluence. The number of sand bars and the total area of sand exposed at low flow decreased significantly, based on analysis of aerial photography and a field inventory. Bank erosion of terraces in this reach was documented by analysis of historical aerial photographs at three study sites. At these sites, 10 to 40 m of bank retreat occurred between 1955 and 1990. Continued erosion through 1998 of the sand bars and terraces at Salt Creek Bar and Fish Trap Bar was documented by Grams and Schmidt (1999).

METHODS

The primary goal of this project was to map surficial geology on aerial photographs and to use that mapping to evaluate changes in the sand bars and terraces at the two study sites. Each photograph was mapped individually and these maps were then compared to determine areas of erosion and deposition. Several series of aerial photographs that include the study sites are available and most were analyzed. We did not analyze those photos that are of poor quality (Table 1).

The analysis was conducted on a computer-based geographic information system, which provides a powerful and efficient means to compare maps developed from aerial photographs that are of different scale. The mapping and analysis process that we followed consisted of seven steps:

1. scanning the aerial photographs;
2. rectification (and geo-referencing of photographs);
3. mapping of surficial geology on each rectified photograph;
4. calculation of areas of erosion and deposition;
5. field verification of mapping;
6. revision of maps based on field data; and ,
7. re-calculation of areas of erosion and deposition.

All of the images were scanned from color or black-and-white photographic prints on a conventional flatbed scanner at a resolution of 1200 dpi. For the photos with a nominal scale of 1:1200 this equates to a pixel size of approximately 0.25 m. The TIF image files were imported into ERDAS Imagine version 8.3 image processing software and were converted into Imagine image files. To reduce the amount of storage space required and to expedite the rectification process, each image was cropped to include only the region of interest. This procedure reduced the size of each image file from more than 100 MB to an average of 15 MB.

An image-to-image photo-rectification process was used to register and geo-reference the photographs for the two sites. The images at the Camp Creek site were geo-referenced to 1990 digital orthophotographs (DOQ) that were provided by the U.S. Forest Service. The 1982 image was registered to the DOQ using a 2nd order polynomial transformation. Small trees, bushes, and rock outcrops were used as control points. Only points that could be positively identified on both images were used. The root-mean square (RMS) error on this transformation was 1.7 m. Because the resolution of the DOQ was much coarser than the resolution of the photographs, precisely identifying control points was difficult. For this reason, the other photographs were referenced to the geo-referenced 1982 photo rather than the DOQ. Control points were much easier to precisely identify between two photographs than between the 1982 photograph and the DOQ. A different set of control points was used for each transformation because not all of the points used were distinct on all images. The number of control points used and the RMS error for each transformation are listed in Table 2. The transformation error is approximately 1.0 m or less for each of the image-to-image rectifications. Thus, changes in bank location or sand bar margin less than 2 m could result from transformation errors and are not considered in our analysis.

Because DOQ's were not available to us at the time the Tin Shed site analysis was conducted, the aerial photographs were registered to the 1982 aerial photograph and were not geo-referenced. The RMS errors for the transformation of each image to the 1982 image are listed in Table 2. The GIS images and maps for this site, therefore, are in the pixel units of the 1982 air photos. The scale of these maps was determined using the DOQ's once they became available. The distance between several pairs of trees was measured on the DOQ's in meters and on the registered photographs. These values were used to calculate the ratio of pixel units on the images to meters. This conversion was used to place the scale bar on the maps and images and to convert the areas of map units from pixels to square meters.

Photographs were examined in stereo and mapping was first done on mylar overlays on the photographs. Mapping was then redone on the computer, directly on the geo-referenced photograph images on the computer screen, thereby eliminating digitizing errors and allowing magnification of the images. This method worked well because features identified in stereo, such as near vertical banks, usually occurred where there were distinct color differences that could be identified on the scanned image. The surficial geologic maps are Arc/INFO and Arcview format vector coverages. Each polygon in the coverages was attributed according to its surficial geology. Map units are described in the results section of this report.

The area of surficial geologic features exposed above the water surface is partly a function of the river's stage. When the area of features in two different years of photographs are compared, one must correct for differences in river stage. Otherwise, comparisons where a later photograph has a higher discharge will indicate apparent erosion since the time of the earlier photograph. Conversely, if the later photograph is taken when the river is of lower discharge than the earlier photograph, then the analysis will be biased to show deposition because the area of exposed deposits increases at lower river stages. We accounted for these biases in our analysis and discounted changes that might be caused by these biases. We only show erosion of deposits along the water's edge when the discharge at the time of the two compared photographs was approximately equal or when the discharge during the later photograph was the lower of the two. Similarly, we only show deposition along the water's edge when the discharge of the later photograph was higher than or equal to the discharge during the earlier photograph. Thus, we computed erosion or deposition in the analysis only when there was no bias introduced by stage differences or when the bias was opposite the computed change.

HYDROLOGY

Streamflow for the study reach is currently measured at the US Geological Survey gage, Snake River at Hells Canyon Dam (station number 13290450), which has been in operation since 1965. Between 1923 and 1971, streamflow was measured at two other locations: Snake River at Oxbow, Oregon (13290000) and Snake River below Pine Creek near Oxbow, Oregon (13290200). These gages were located approximately 35 km upstream from Hells Canyon Dam (Figure 1). Grams (1991) analyzed the historic streamflow data and extended the record for the Hells Canyon Dam gage back to 1923 by correlation between the Hells Canyon and Oxbow gages for the six-year period of overlap. The 75-yr record of annual peak discharges shows a period of low-magnitude floods in the early 1960's during the filling of Brownlee Reservoir and another period of low-magnitude floods in the late 1980's and early 1990's (Figure 2). The magnitude of the mean annual flood is 1,332 m^3/s (47,000 ft^3/s) and is the same for the pre- and post-Brownlee periods (Figure 3). The magnitudes of the most common and the rarest mean daily flows, those equaled or exceeded more than 50% of the time or less than 5% of the time, are unchanged for the period of record (Figure 4a). There has been an increase in the duration of time that mean daily flows have been between 500 and 1,600 m^3/s (17,700 and 56,500 ft^3/s). For example, the length of time that discharge has equaled or exceeded the magnitude of the mean annual flood has increased from 7 to 18 days per yr.

The times of aerial photography are indicated on the plot of mean daily discharge for the period of record (Figure 4b). At least three floods larger than the mean annual flood occurred in every interval between photographs, and the maximum flood was greater than 2000 m^3/s (70,600 ft^3/s) in every interval (Table 1). The largest floods in the intervals between air photos mapped in this study were 2486 m^3/s (87,782 ft^3/s), which occurred in February 1982, and 2325 m^3/s (82,107 ft^3/s), which occurred in December 1964. The flood of record is 2917 m^3/s (103,000 ft^3/s) and occurred in January 1997, after our most recent photo series.

RESULTS

Map Unit Descriptions

Preliminary map units were identified in the lab and were used to conduct the mapping from aerial photographs. The map units were revised based on field inspection of the deposits. Following the map units names, below, are the abbreviations that are used to identify the map units in the GIS database and the figures.

Sand [sand]

This map unit is bare and unvegetated Snake River fluvial sand deposits. Higher elevation, partially vegetated sand was not included in this category. This unit may occur as either eddy or channel-margin deposits.

Gravel [g]

This map unit is bare and unvegetated deposits that are more that approximately 75% gravel by surface area. The deposits include well-rounded particles that are Snake River deposits and angular particles that are likely derived from adjacent hillslopes.

Sand and Gravel [s-g]

This map unit is the bare and unvegetated deposits that are more than approximately 25% gravel, by surface area. The deposits include well-rounded particles that are Snake River deposits and angular particles that are likely derived from adjacent hillslopes.

Terrace [ter]

This map unit is fine-grained Snake River fluvial sand deposits. The surfaces of the terraces are typically flat or gently sloping towards the river. The terraces are vegetated and typically have hackberry trees, upland grasses and shrubs as vegetation cover. Sedimentary structures are rare but are horizontally bedded where they occur, indicating that the terraces built by vertical accretion. Deposits are typically compacted or affected by bio-turbation. Individual depositional units were distinguished by abrupt changes in grain size. Lines of recent (1997 or 1998) driftwood indicate that flows of approximately 2,500 m^3/s (88,300 ft^3/s) reach the edge of the terrace but do not completely inundate the surface of the terrace.

High Terrace [h_ter]

This map unit is fine-grained Snake River fluvial sand deposits similar to terrace deposits but that occur 2 to 3 m higher in elevation. This unit occurs only at the Camp Creek site.

Debris Fan [df]

This map unit is poorly-sorted to unsorted deposits of clay to boulder size material derived from tributaries to the Snake River. These deposits typically have a fan-like shape and may be mantled by fine-grained Snake River deposits less than 0.3 m thick **[df-ter]**. Reworked debris-fan deposits along the water's edge were mapped as a separate unit **[df-shore]**.

Alluvial Fan [fan]

This map unit is poorly-sorted to unsorted deposits of angular sand to cobble size material derived from local hillslopes. These deposits typically have a fan-like shape with a convex-upward surface topography. The angle of slope is always steeper than that of nearby terraces. These deposits are much more abundant at the Tin Shed site than at the Camp Creek site. At Tin Shed, exposed cutbanks in this deposit show that the unit is often interbedded with Snake River fluvial terrace deposits. These interbedded fluvial terrace and alluvial fan deposits are herein referred to as fan-terrace deposits **[fan-ter]**.

Colluvial Hillslope Deposits [col]

This map unit is poorly-sorted to unsorted deposits of sand to angular cobble size material derived from local hillslopes. These deposits typically slope towards the Snake River. The angle of slope is always steeper than that of nearby terraces. These deposits are much more abundant at the Tin Shed site than at the Camp Creek site.

Bedrock and Talus [br-tal]

This map unit is undifferentiated bedrock, often covered by talus.

Talus and Colluvium [tal-col]

This map unit is undifferentiated talus and hillslope colluvial deposits.

Erosion and Deposition

Camp Creek

The net change at the Camp Creek site between 1964 and 1996 has been erosion of alluvial terrace deposits, debris fan-terrace deposits, and bare sand bars (Figure 5). Most of the areas where erosion of sand bars occurred are now armored by coarse-grained deposits of gravel or talus, that presumably have been exposed beneath the sand (areas that are mapped red in Figure 5). Net deposition of sand has occurred at a few locations adjacent to eroding terrace deposits, but these areas are small (areas that are mapped bright green in Figure 5). Erosion of the alluvial terraces has occurred by retreat of steep cutbanks (Figure 6). Approximately 50% of the length of these cutbanks show evidence of recent erosion in 1999 (Figure 5), the remainder are less steep and do not appear to be actively eroding. The debris fan-terrace deposits consist of coarse, angular tributary fan deposits mantled by a thin veneer of Snake River sand that is typically between 10 and 20 cm thick. Where erosion of these deposits has occurred since 1964, the veneer of sand has been eroded and only the armored debris fan is now exposed (Figure 5). These features do not have active cutbanks and continued erosion is probably not occurring.

Comparison of changes between each of the years of photography provides an opportunity to assess the rate and style of erosion at Camp Creek. In 1964, the Camp Creek site contained many large sand deposits at the upstream end of the reach, just downstream from the Camp Creek debris fan (Figure 5). These were primarily eddy deposits, located in the lee of the Camp Creek debris fan and bedrock outcrops downstream from the fan. By 1977, much of this sand had been eroded and these deposits were armored by gravel (Figure 7). Erosion of the terrace occurred at several locations. Much of this erosion occurred adjacent to eroding sand bars (areas where terrace erosion is next to sand erosion in Figure 7). In some locations, the eroded terrace deposits became bare sand deposits, increasing the area of bare sand (Figure 7). The total area of erosion of sand bars exceeded the area of deposition (Table 3).

Between 1977 and 1982, the margins of some of the larger sand bars eroded and the area armored by gravel increased (the areas mapped red in Figure 8). Deposition of sand occurred in a few places where sand bars had eroded between 1964 and 1977. Between 1982 and 1996, there was continued erosion of the terraces and sand bars (Figure 9). Deposition of sand occurred at a few locations, usually adjacent to terrace deposits.

These data demonstrate that most of the erosion of the alluvial terrace deposits occurred between 1964 and 1977 (Figure 7). In only a few locations did erosion occur both in the 1964 to 1977 period and in the 1982 to 1996 period. The persistence of erosion in recent years is indicated by the widespread active cutbanks, but the present rates of cutbank retreat are unknown (Figure 5). The majority of the erosion of bare sand bars that we measured occurred in the same period as the period of terrace erosion (1964 to 1977), although a large area was also eroded between 1982 and 1996 (Table 3).

Erosion of the terraces occurred along the edges of nearly all the terrace deposits in the reach. These deposits are concentrated in the center of the study reach (Figure 5). Sand bar erosion has been greatest at the upstream end of the reach where there has been very little compensating deposition (Figure 5). Most of the areas where sand bars occurred in 1996 were adjacent to eroding terraces. Thus, these bars may be composed of sand from the eroding terraces and persist in these locations primarily because the eroding terraces supply sediment to the bars.

Tin Shed

The setting of the Tin Shed site is very different from the Camp Creek site. Although the reach is wider and there is a much broader band of flat and gently sloping "terrace-like" deposits, the extent of homogeneous fine-grained fluvial deposits is less than at Camp Creek. Most of the "terrace-like" deposits are in fact interbedded colluvial hillslope deposits and Snake River fluvial deposits (Figure 10). Some of the hillslope deposits are fan-shaped and convex-upwards and were mapped as "alluvial fans." Where these deposits are not fan-shaped they were mapped as "colluvium." The interbedded hillslope and fluvial deposits are referred to as "fan-terrace" deposits in the discussion below.

Alluvial terraces and fan-terraces at the Tin Shed site have extensively eroded by cutbank retreat since 1964; bare sand deposits have eroded as well (Figure 11). In contrast to Camp Creek, significant erosion of the terrace deposits did not begin until after 1982, but sand bar erosion began much earlier. Erosion of the terrace upstream from the tin shed itself (mapped as "shed") occurred between 1982 and 1991 (Figure 12), and erosion downstream from the shed occurred between 1991 and 1996 (Figure 13). The greatest area of sand bar erosion occurred between 1964 and 1982 (Figure 14); continued erosion occurred between 1982 and 1991 (Figure 12).

DISCUSSION AND CONCLUSIONS

At both the Camp Creek and Tin Shed study sites, the terrace deposits eroded by bank retreat. The primary periods of erosion were when moderately large peak discharges with recurrence intervals of about 5 to 7 yrs occurred. At Camp Creek, most erosion of the terrace deposits occurred between 1964 and 1977 (Figure 15). During this period there were five floods larger than the mean annual flood and the largest of these was 2112 m^3/s (74,600 ft^3/s). The highest rate of erosion of the terrace and fan-terrace at the Tin Shed site occurred between 1991 and 1996 (Figure 15). During this period, three floods exceeded the mean annual flood and the largest was 2078 m^3/s (73,400 ft^3/s). This flood was the lowest peak that occurred in any of the intervals between air photos used in this study. The highest rates of erosion did not occur during the periods of the highest floods. Rather, these data suggest that terrace bank retreat rates are highest during moderate floods that occurred in the initial period of erosion.

Erosion of the bare sand deposits has been extensive at both sites and occurred in the first interval between air photos (Figure 15). As the locations of sand deposition became armored, the rate of erosion declined. This pattern is similar to the pattern of sand bar erosion described by Grams (1991) for all sand bars in Hells Canyon upstream from the Salmon River confluence. At the Tin Shed site, erosion of the sand deposits preceded the erosion of the terrace deposits while the bare sand and adjacent terrace deposits eroded during the same interval at Camp Creek. There is no evidence to suggest that terrace erosion preceded sand bar erosion at either site.

The mechanisms of erosion of bare sand deposits and the terrace or fan-terrace deposits are very different. The terraces have vertical or near-vertical cutbanks and erode by bank failure during or following high flows. The sand bars, however, likely erode by direct entrainment of the particles that comprise each bar. An important distinction between these mechanisms is that bank failure is not dependent upon the sediment concentration in the Snake River, but the entrainment of sand in the adjacent bars is a function of sediment concentration during the period that the deposit is inundated. The terraces need not be inundated for erosion to occur by bank failure.

Regulation of the Snake River by the dams of the Hells Canyon Complex has not significantly changed the magnitude or frequency of occurrence of floods in Hells Canyon (Figure 3). The dams do, however, block all sediment that would otherwise be transported into Hells Canyon. The rapid erosion of sand deposits in Hells Canyon is most likely caused by the lowered sediment concentration coupled with an unaltered flood regime. When sediment concentrations in the channel are relatively high, such as occurs on the Salmon River and on the Snake River downstream from the Salmon River confluence, sand in suspension tends to be deposited in eddies and along the banks. When sediment concentrations are low, very little or no deposition occurs. Rates of bar erosion may not necessarily be related to dam operations; erosion of bars also occurs in unregulated systems but is balanced by regular deposition. Low sediment concentrations downstream from Hells Canyon Dam severely limit the amount of deposition that can occur. And for active sand bars, successive years of low deposition rates results in net erosion.

Erosion of the terraces may be related to erosion of the adjacent sand deposits. Most of the eroding terraces are adjacent to sand bars or locations where sand has been eroded. Loss of sand deposits may remove buttress-type support from the terrace and exposes a greater height of the bank. Removal of the sand bar support would increase the likelihood of bank failure and would expose the base of the terrace to streamflow at a lower discharge, increasing the time of exposure to potentially erosive flows.

FUTURE RESEARCH

We have measured two styles of cutbank retreat of alluvial terraces in Hells Canyon. One style is a steadily declining rate of erosion with time and the second style has several such discrete periods (Figure 16).

The first style is consistent with the data presented in this report for Camp Creek. Erosion of the terraces began at Camp Creek after 1964 and declined with time. Grams and Schmidt (1999) showed that bank retreat at Fish Trap Bar was similar to that measured at Camp Creek. The second style of erosion was measured at Salt Creek Bar where there were two episodes of high rates of erosion separated by a period of less erosion (Figure 17). Erosion of the terraces at Tin Shed did not begin until after 1982, and it is too soon to determine whether the erosion rate is increasing or decreasing. The difference between the Camp Creek and Tin Shed sites is that there was a period of no response between 1964 and 1982 before erosion began at Tin Shed. The Tin Shed site, therefore, may be following either style of erosion.

We do not know which of these erosion styles is most representative of Hells Canyon, and we therefore cannot predict whether the reach-average rate of terrace cutbank erosion will increase or decrease in the future. If most of Hells Canyon fits style

I-A, then terrace erosion rates will decline with time. However, if style I-B is most representative, then much of Hells Canyon may not yet have begun to erode. If style II is most applicable, then renewed erosion may occur during moderate to large floods, such as occurred at Salt Creek Bar between 1982 and 1990. It is likely that each style of cutbank erosion represents some of the geomorphic settings of Hells Canyon, and that future response can only be determined by a comprehensive investigation of the geomorphic and hydraulic settings in which each style of cutbank erosion occurs.

The three styles of erosion all involve the progressive erosion of terraces from Hells Canyon. We have not measured deposition of new terrace deposits anywhere in the canyon at any time between 1964 and 1996. This could be due to the fact that cycles of deposition or erosion occur over time frames longer than decades and we have been in a cycle of erosion since before 1964. Alternatively, terrace erosion could be accelerating due to operations of the Hells Canyon Complex. We cannot discount either alternative, but it is important to note that operations of the Hells Canyon Complex cannot be unequivocally linked to terrace erosion. For example, even the largest magnitude floods that have occurred since 1964 have not overtopped terrace surfaces. Thus, cutbank erosion must be related to the physical properties of the terrace deposit, river bank shear stress, rates of flood rise and recession, and sedimentation characteristics in eddy bars offshore from terrace cutbanks. The process linkages that control cutbank retreat in Hells Canyon are poorly known. Research on less impacted reaches, such as the unregulated lower Salmon River and the Snake River downstream from the Salmon River, provide an excellent opportunity to study geomorphic processes and rates of change in settings more similar to those that existed before completion of the dams of the Hells Canyon Complex.

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Collier, M. Webb, R.H., and Schmidt, J.C., 1996, Dams and Rivers: US Geological Survey Circular 1126, 94 p.

Grams, P. E., 1991, Degradation of alluvial sand bars along the Snake River below Hells Canyon Dam, Hells Canyon National Recreation Area, Idaho, Middlebury College 98 p.

Grams, P.E., and Schmidt, J. C., Sand bar erosion and deposition on the Snake River in Hells Canyon between 1990 and 1998, 1999: Draft Final Report to Wallowa-Whitman National Forest and Hells Canyon Preservation Council.

Schmidt, J. C., Grams, P. E., and Webb, R. H., 1995, Comparison of the magnitude of erosion along two large regulated rivers: Water Resources Bulletin, v. 31, p. 617-631.

Table 1. Aerial photographs analyzed in this study and discharge of the Snake River at Hells Canyon Dam for the day the photographs were taken. The table also includes the number of floods exceeding the mean annual flood and the magnitude of the largest flood for each interval between analyzed aerial phottographs.

Date*	Scale of Photos	Discharge# (m^3/s)	Discharge# (ft^3/s)	Number of floods larger than the mean annual flood that occurred since the previous photo series	Highest discharge that occurred since the previous photo series (m^3/s)
1955 (Aug 21)	1:20000	306 - 314	10,800 - 11,100		
1964 (Aug 17)	1:12000	292 - 311	10,300 - 11,000	5	2112
1970 (Jul 31)	1:14000	292 - 337	10,300 - 11,900	3	2325
1973 (Mar 25)	1:12000	218	7700	2	2146
1977 (Sep 9)	1:12000	150	5310	3	1792
1980 (Sep 17)	est. 1:20000	439	15500	1	1376
1982 (Aug 19)	1:12000	399	14100	1	2486
1991 (Jul 27)	est. 1:16000	191	12000	4	2226
1996 (Jul 10)	est. 1:16000	413	6760	3	2078
1999 field work	–	–	14600	2	2917

* The 1955 photographs were taken on August 20-21 and September 3-4, 1955. The 1964 photographs were taken on August 17-18, and 24, 1964. The 1970 photographs were taken on July 31 and August 10, 1970.

Mean daily discharge of the Snake River at Hells Canyon Dam for the date indicated or the range for the period indicated.

Table 2. Number of control points and root-mean square (RMS) errors for each image rectification.

Site	Input image	Reference Image*	Number of Control Points	RMS error, in meters**
Camp Creek	1955	1982-GR	14	1.1
	1964	1982-GR	14	0.7
	1977	1982-GR	32	0.7
	1982	DOQ	12	1.7
	1991	1982-GR	22	0.9
	1996	1982-GR	20	0.8
Tin Shed	1955	1982	11	0.2
	1964	1982	12	0.2
	1982	na	na	na
	1991	1982	11	0.2
	1996	1982	13	1.2

* The images for the Camp Creek site were referenced to the 1982 geo-referenced image (1982-GR), which was geo-referenced to the digital-orthophotograph (DOQ). The images for the Tin Shed site were registered to the non-geo-referenced 1982 photograph.

** The image rectification software provides the RMS error for each transformation in the units of the image that is being rectified. The RMS error was converted into meters by multiplying the value by the number of meters per pixel of the respective scanned image.

Table 3. Erosion and deposition of sand bar and terrace deposits during intervals between mapped air photos and the area of the deposits remaining in each year expressed as a percentage of the area of the deposits in 1964.

Tin Shed	Sand Bar			Terrace	
Year	Erosion (m^2)	Deposition (m^2)	Percent of 1964 area	Erosion (m^2)	Percent of 1964 area
1964	--	--	100%	--	100%
1964 - 1982	7927	265	29%	0	100%
1982 - 1991	5822	0	0%	7300	96%
1991 - 1996	0	2110	23%	15399	92.2%
Camp Creek					
1964	--	--	100%	--	100%
1964 - 1977	1894	644	53%	956	82%
1977 - 1982	244	284	40%	1005	81%
1982 - 1996	616	273	32%	1271	76%

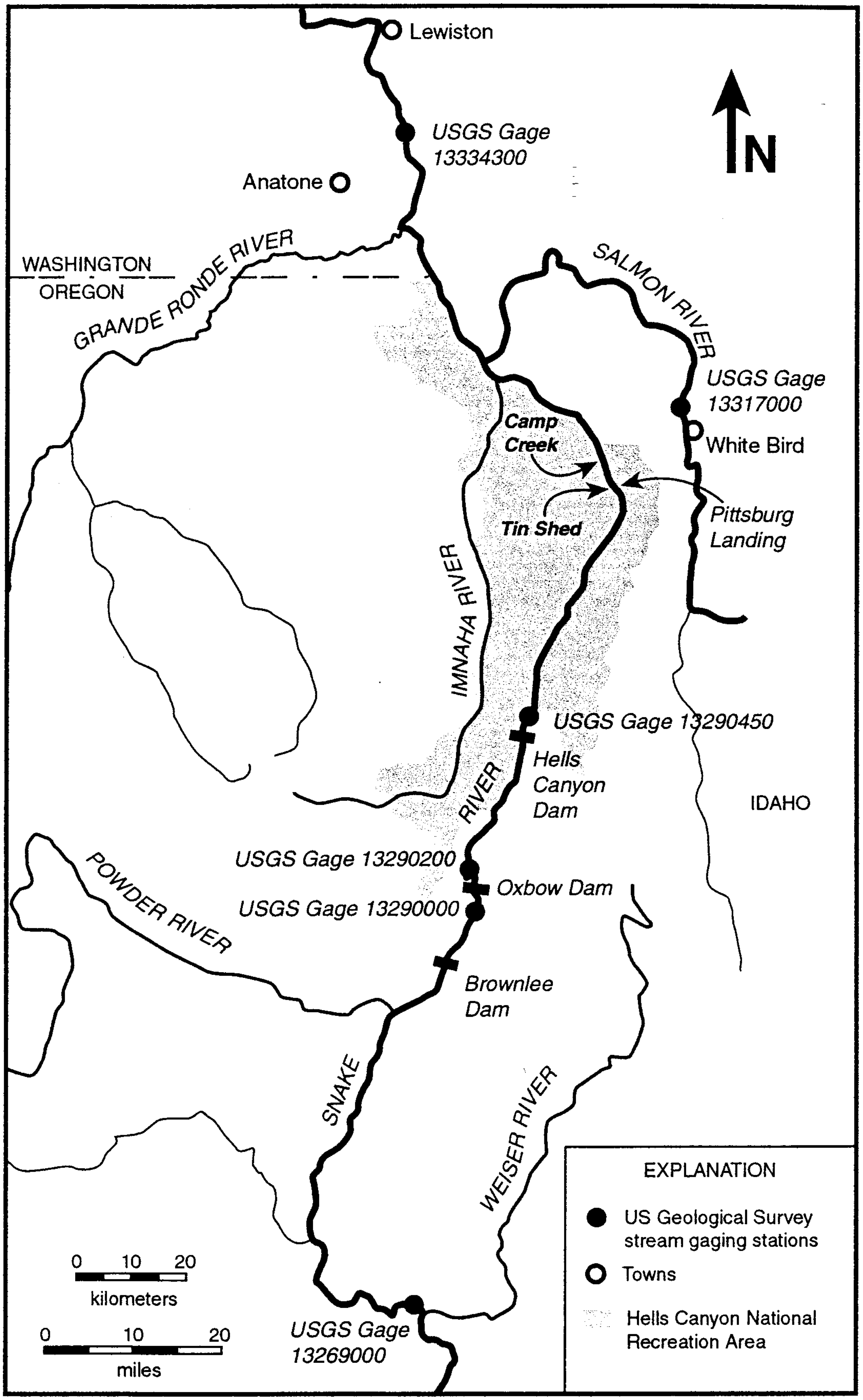

Figure 1. Map of the study area location showing locations of study sites, stream gaging stations, and major tributaries to the Snake River.

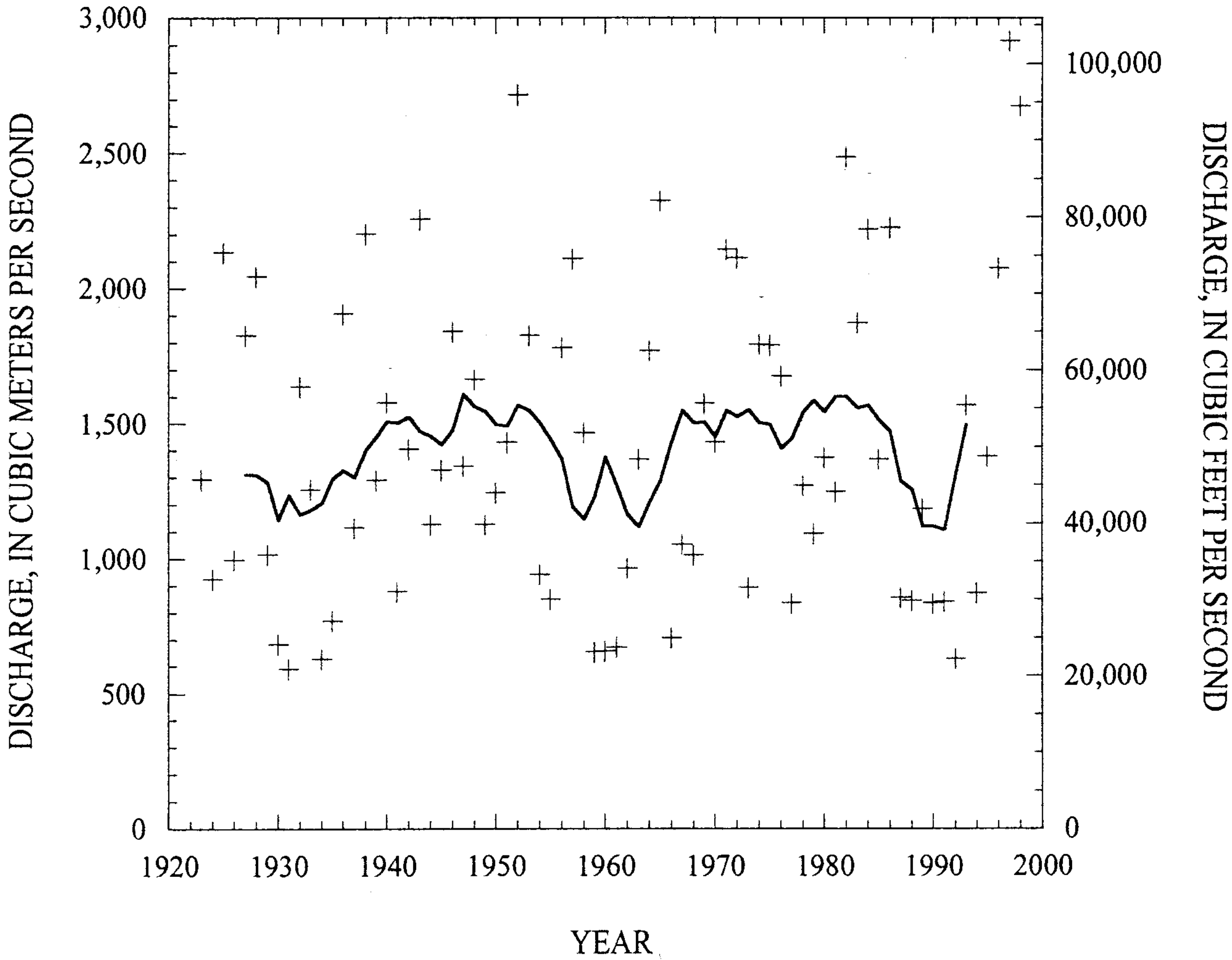

Figure 2. Annual maximum instantaneous discharge of the Snake River at Hells Canyon Dam, 1923 to 1998. Streamflow has been measured at Hells Canyon dam since 1965. The values for 1923 to 1964 were determined by correlation with upstream gages.

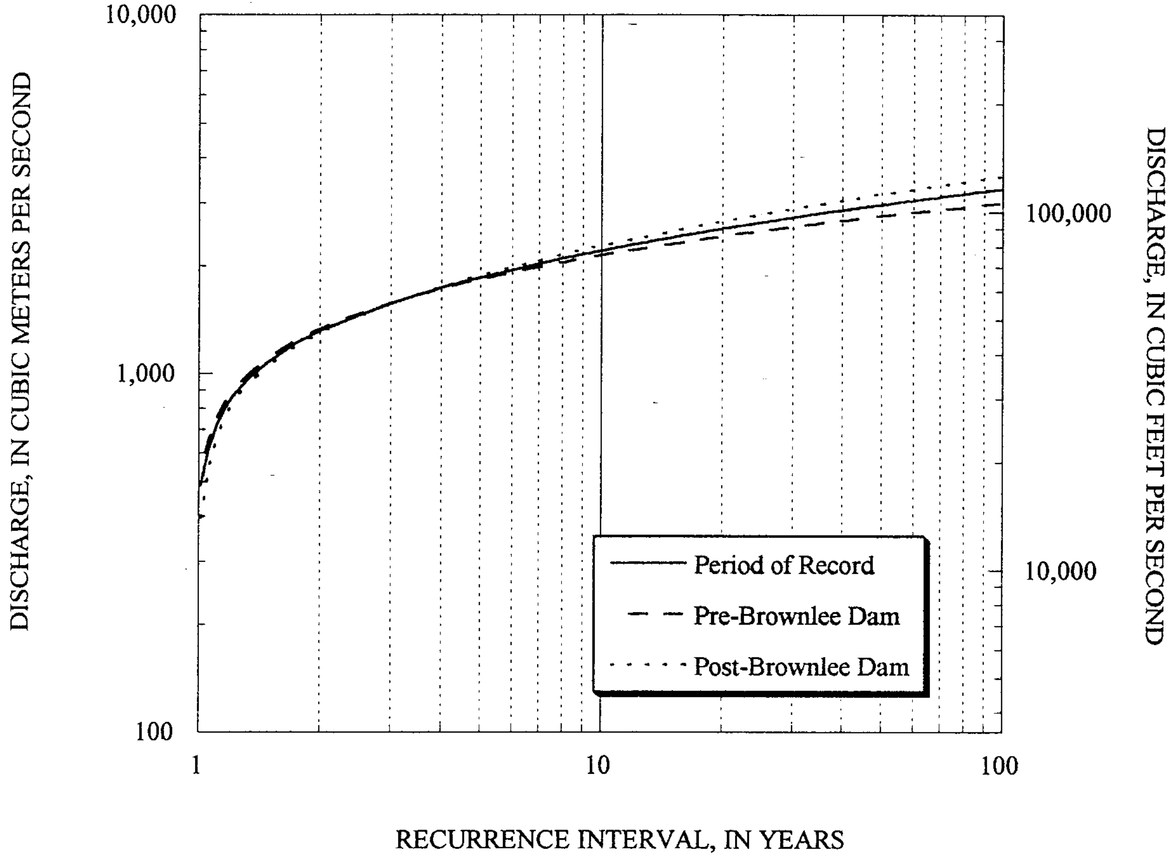

Figure 3. Recurrence interval of annual peak discharges for the Snake River at Hells Canyon Dam, 1923 to 1998.

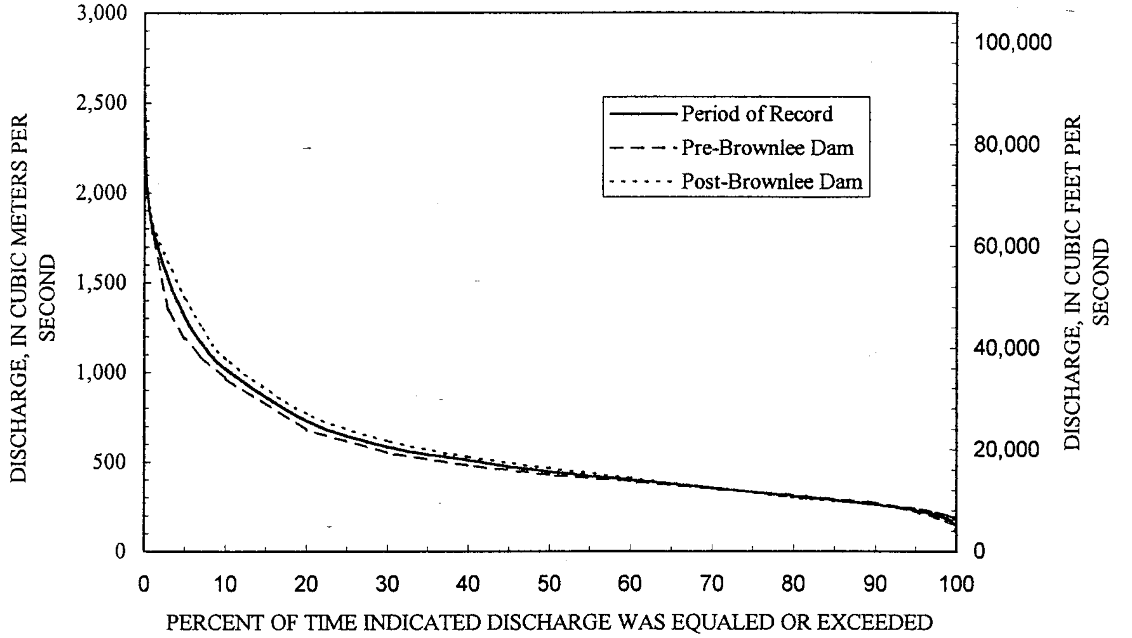

Figure 4a. Duration of mean daily discharges for the indicated time periods.

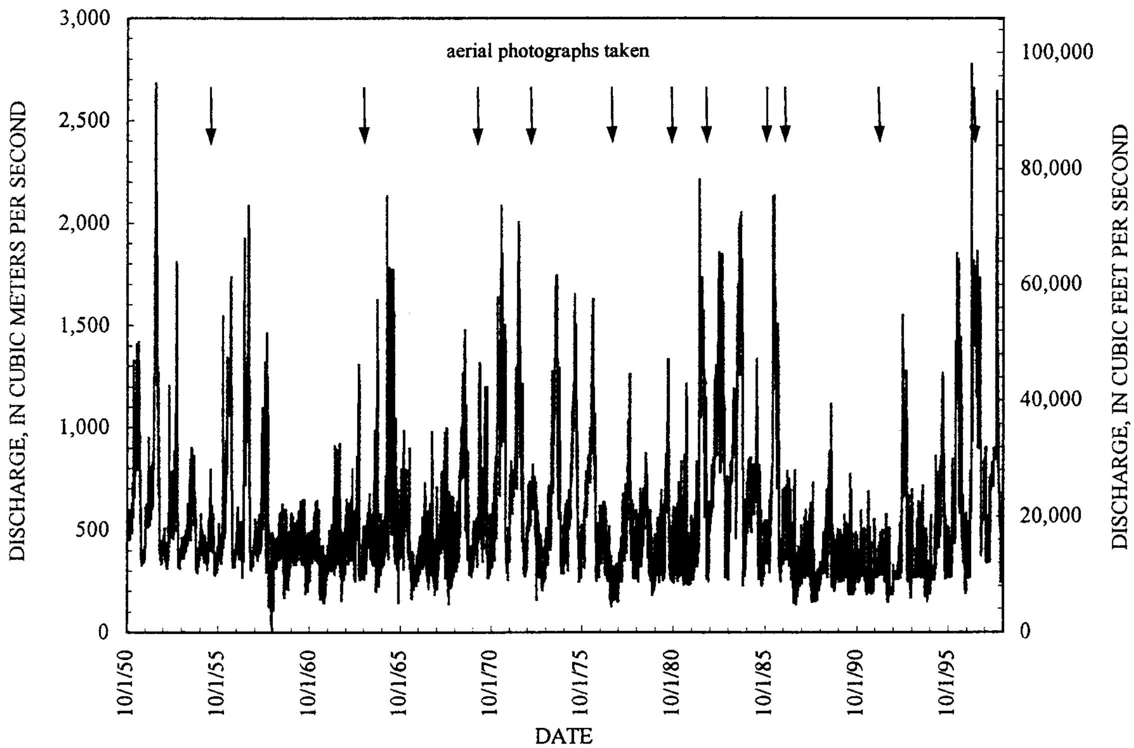

Figure 4b. Mean daily discharge of the Snake River at Hells Canyon Dam between 1950 and present. The times of aerial photographs are indicated by arrows.

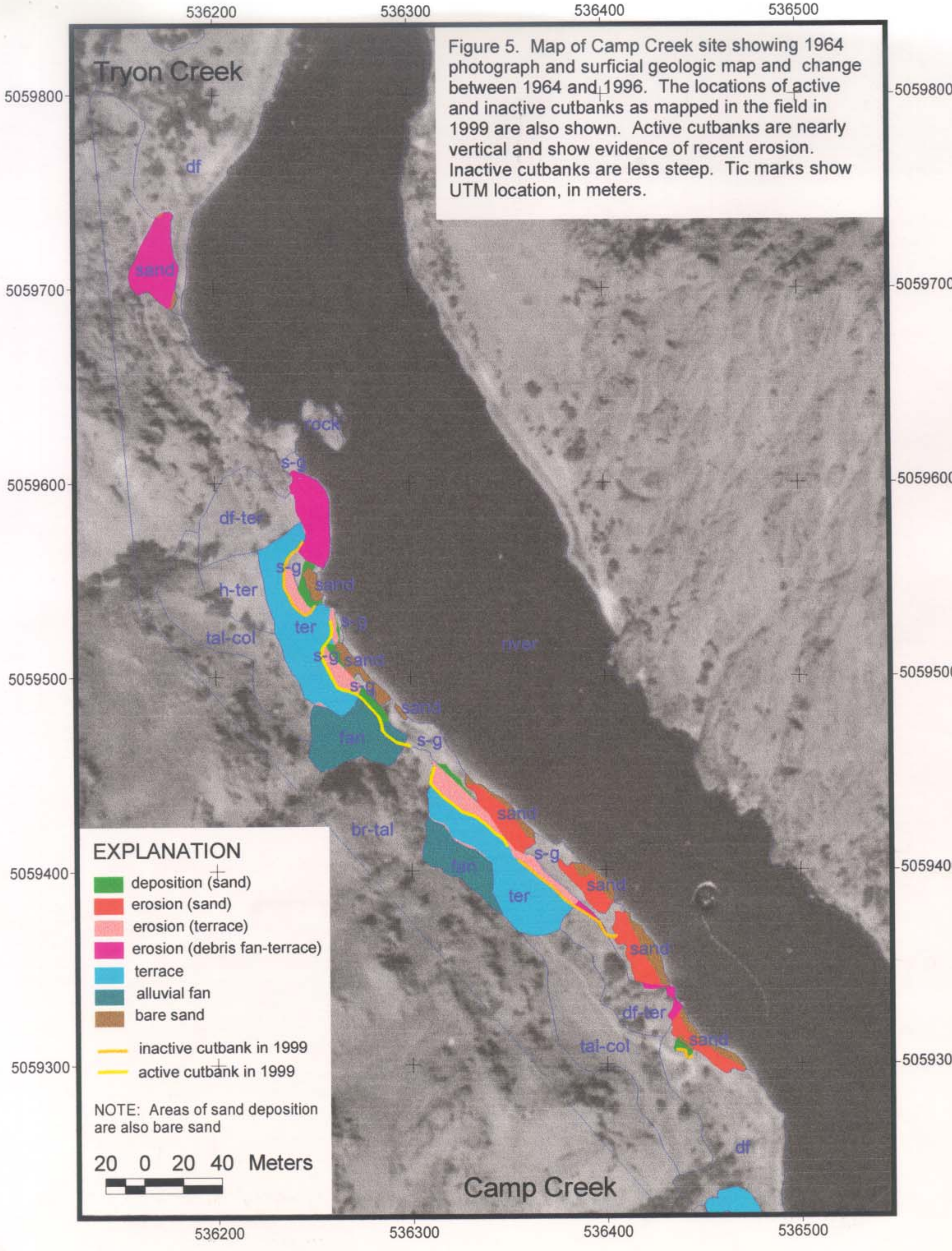

Figure 5. Map of Camp Creek site showing 1964 photograph and surficial geologic map and change between 1964 and 1996. The locations of active and inactive cutbanks as mapped in the field in 1999 are also shown. Active cutbanks are nearly vertical and show evidence of recent erosion. Inactive cutbanks are less steep. Tic marks show UTM location, in meters.

Figure 6. Photograph of eroding cutbank on the edge of the terrace at Camp Creek.

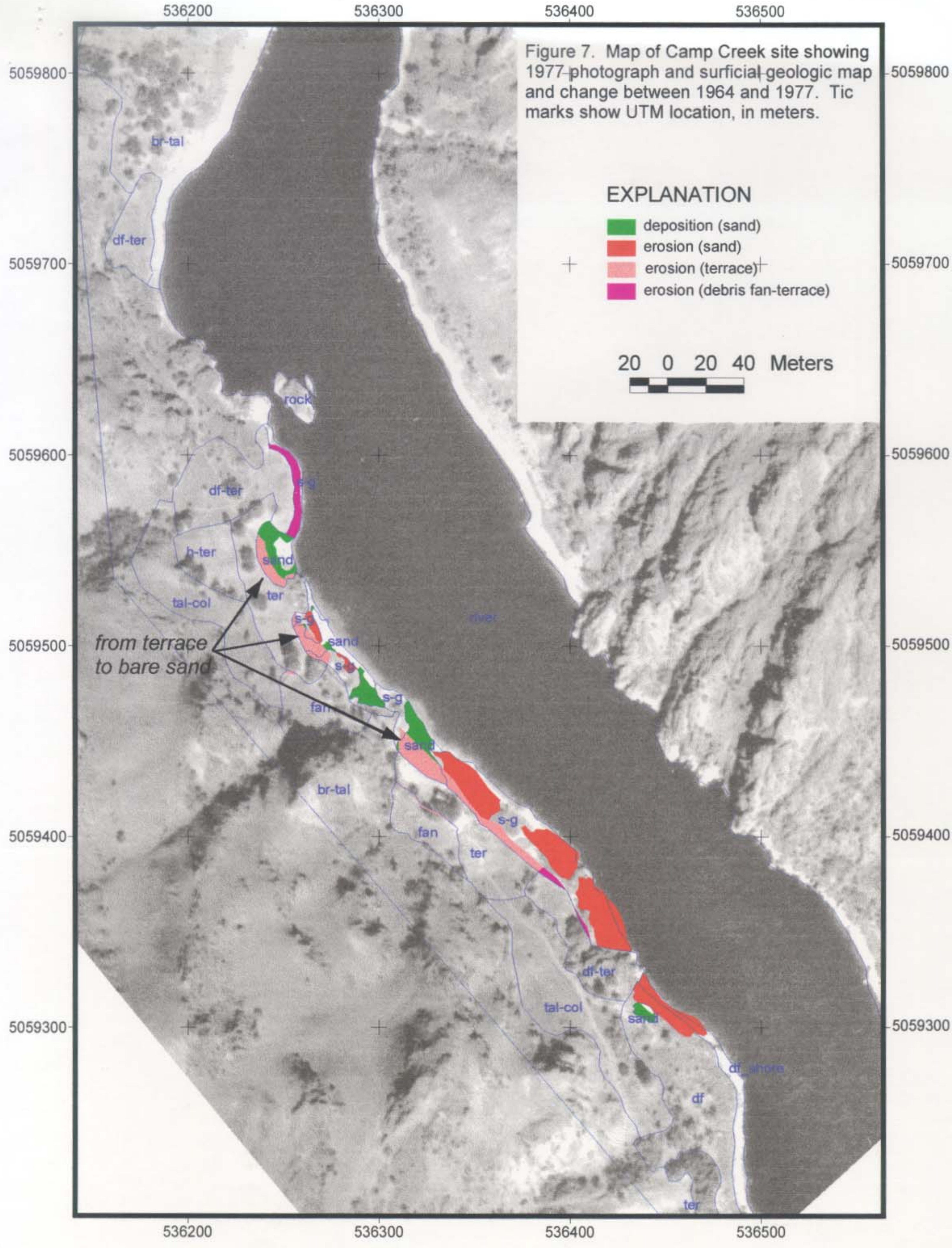

Figure 7. Map of Camp Creek site showing 1977 photograph and surficial geologic map and change between 1964 and 1977. Tic marks show UTM location, in meters.

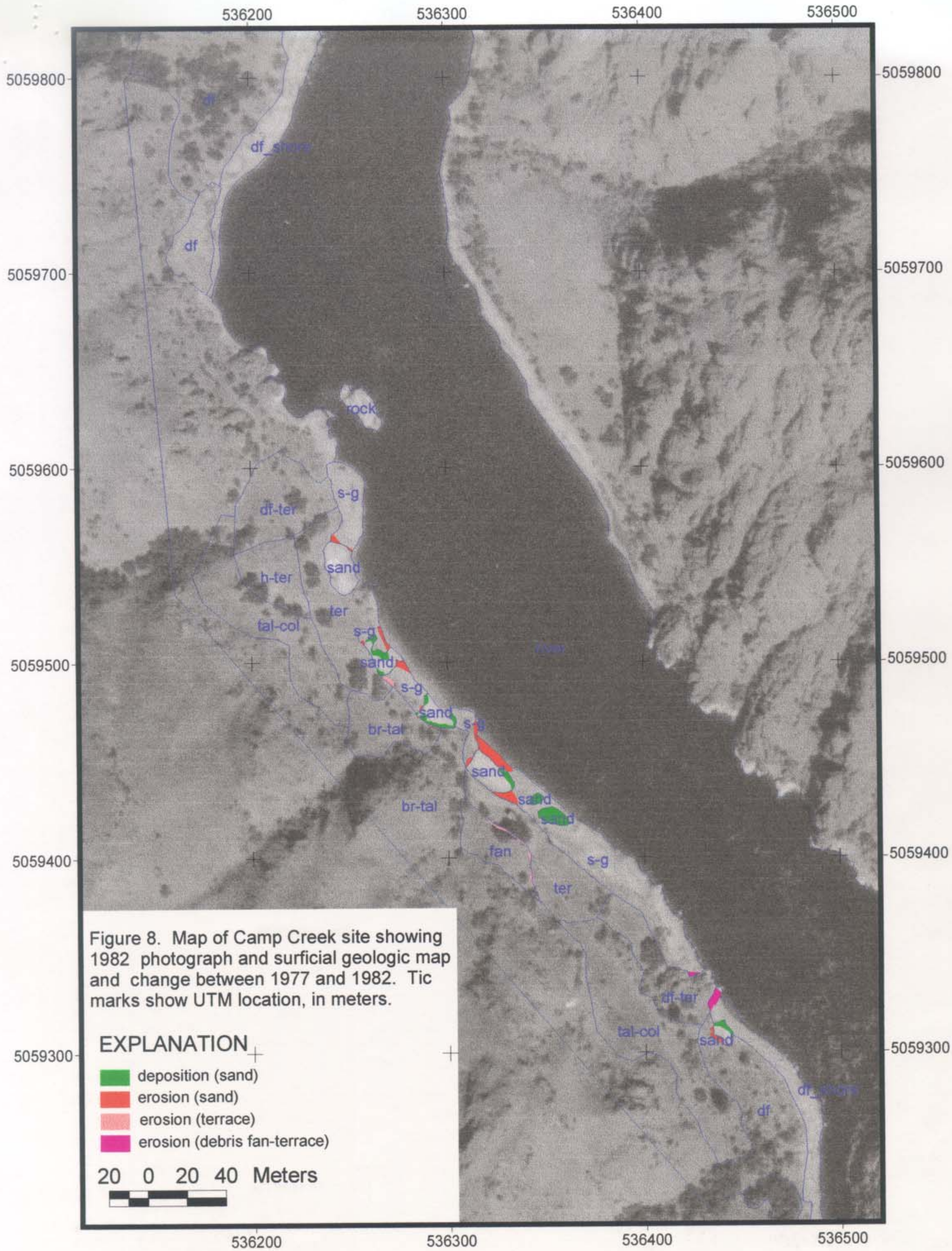

Figure 8. Map of Camp Creek site showing 1982 photograph and surficial geologic map and change between 1977 and 1982. Tic marks show UTM location, in meters.

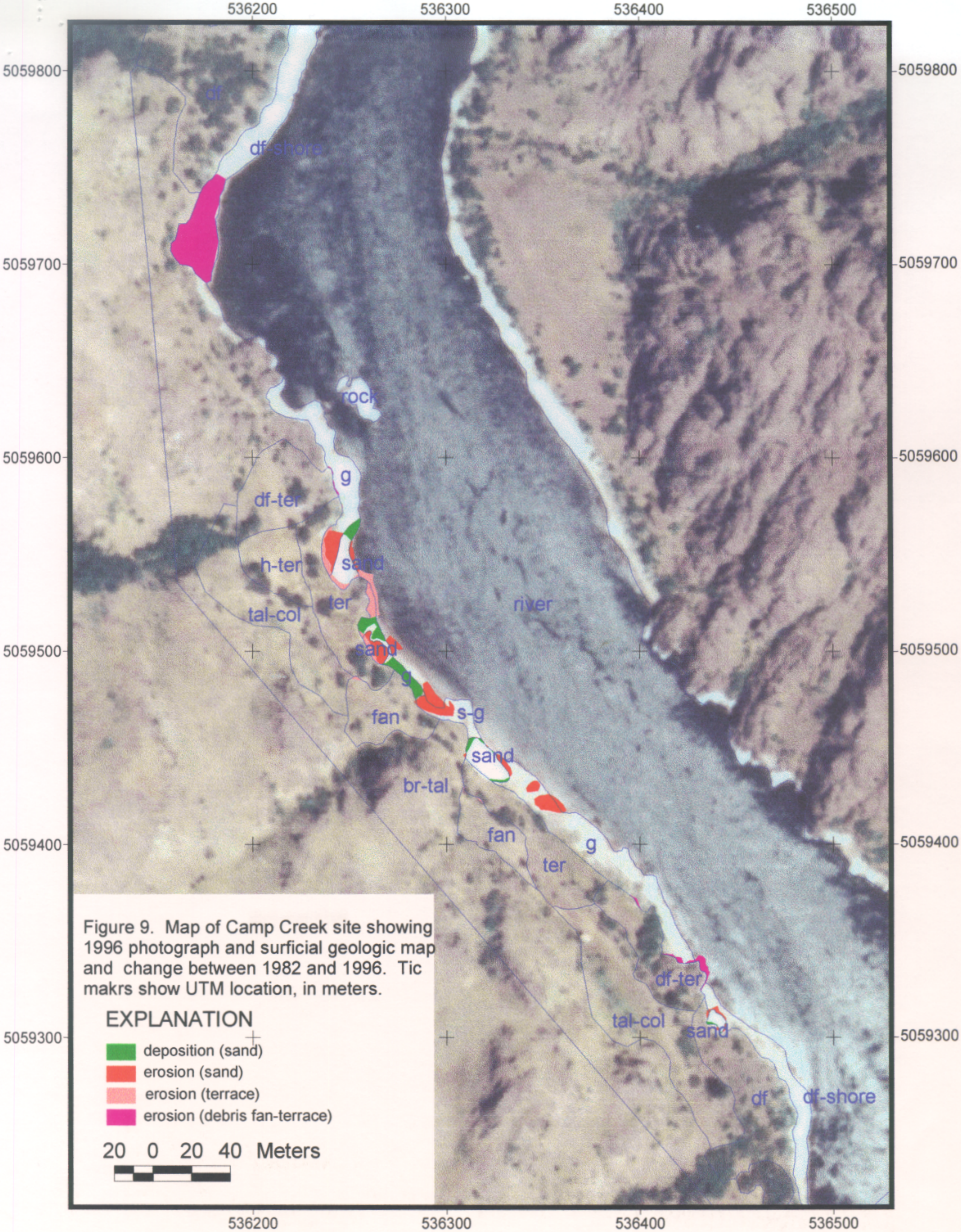

Figure 9. Map of Camp Creek site showing 1996 photograph and surficial geologic map and change between 1982 and 1996. Tic makrs show UTM location, in meters.

Figure 10. Photograph of exposed cutbank at Tin Shed site, showing interbedded Snake River fluvial deposits and hillslope deposits. In this photograph the hillslope deposits overlie the fluvial and sand deposits.

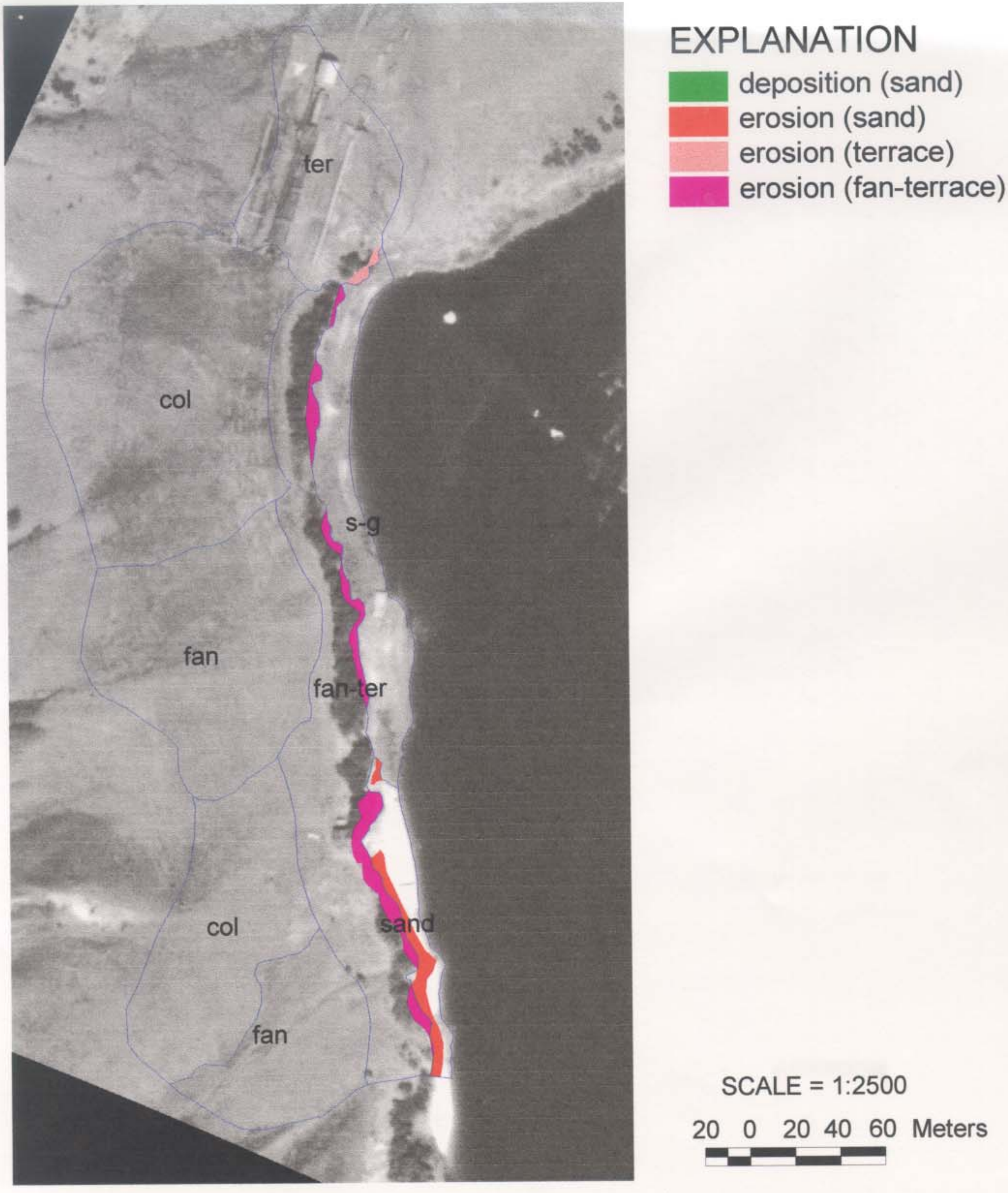

Figure 11. Map of Tin Shed site showing 1964 photograph and mapping and change between 1964 and 1996.

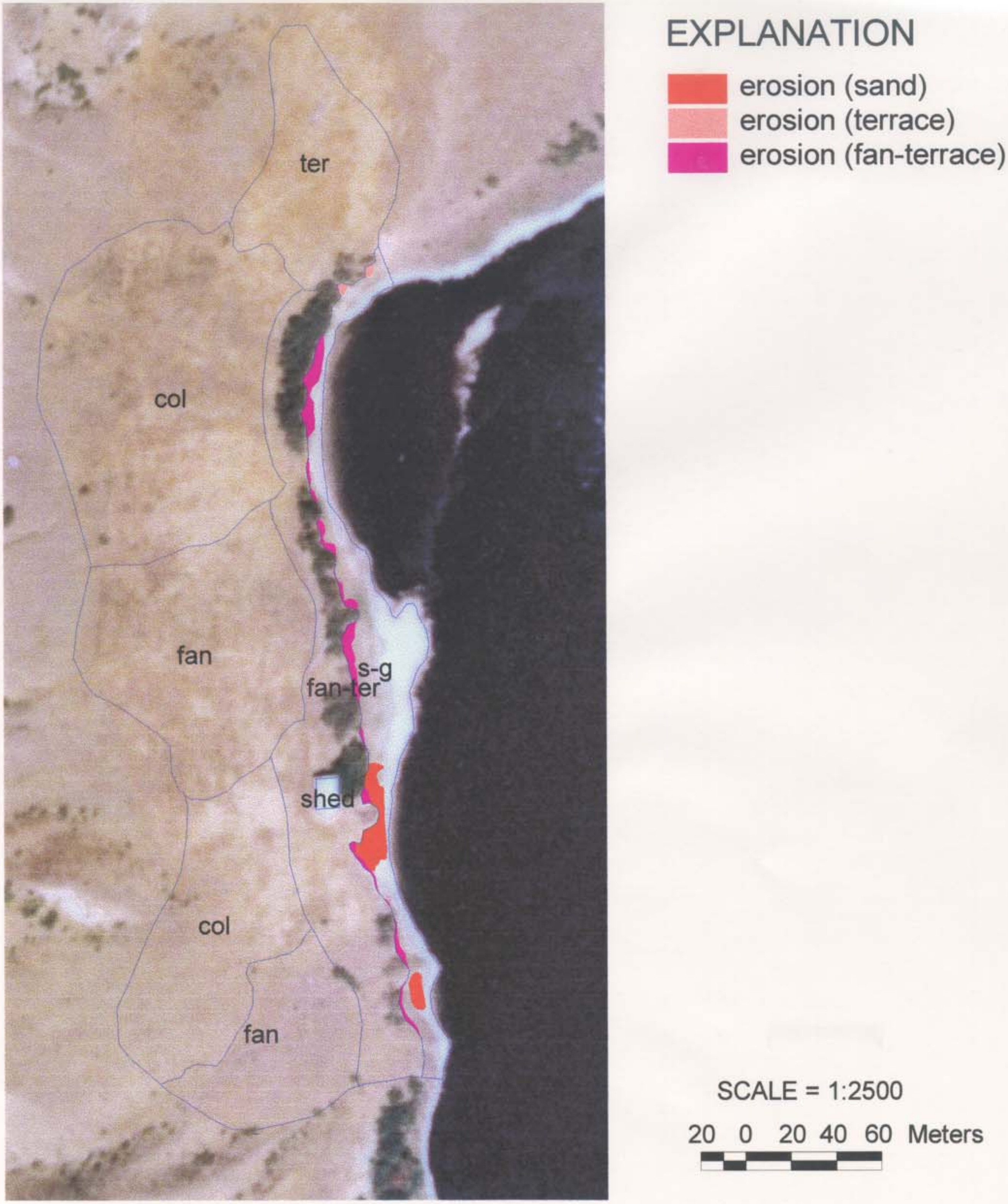

Figure 12. Map of Tin Shed site showing 1991 photograph and surficial geologic map and change between 1982 and 1991.

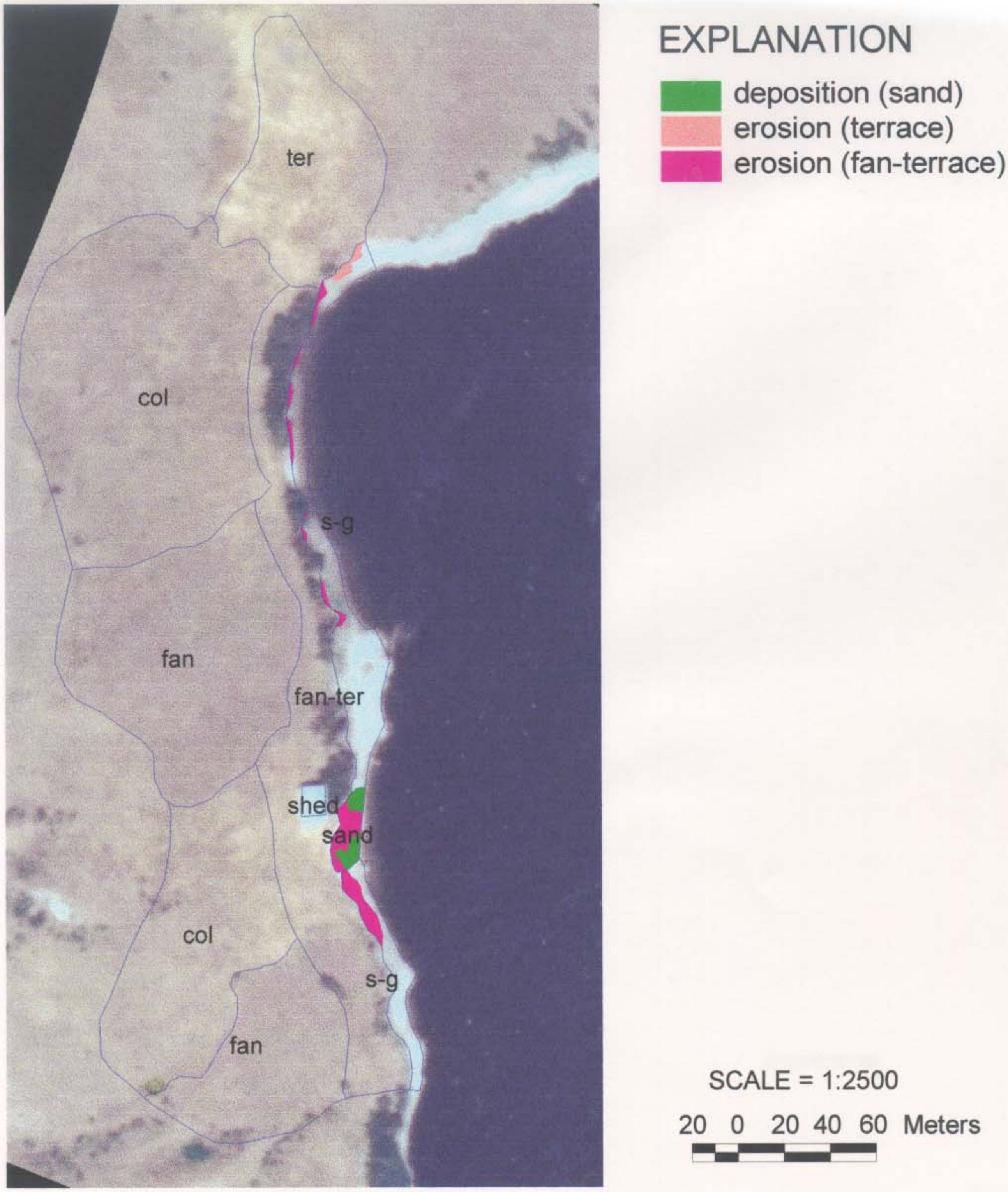

Figure 13. Map of Tin Shed site showing 1996 photograph and surficial geologic map and change between 1991 and 1996.

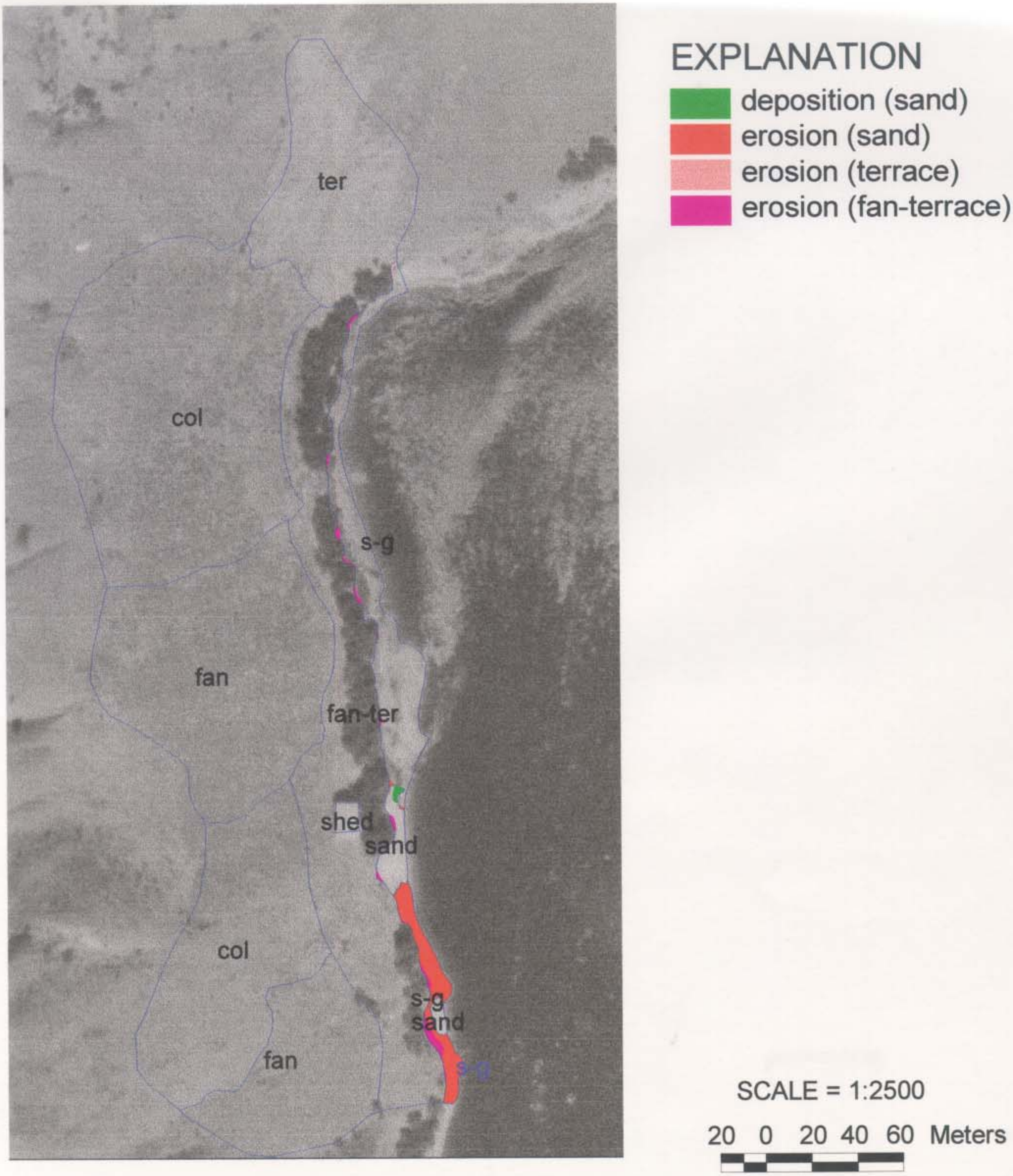

Figure 14. Map of Tin Shed site showing 1982 photograph and surficial geologic map and change between 1964 and 1982.

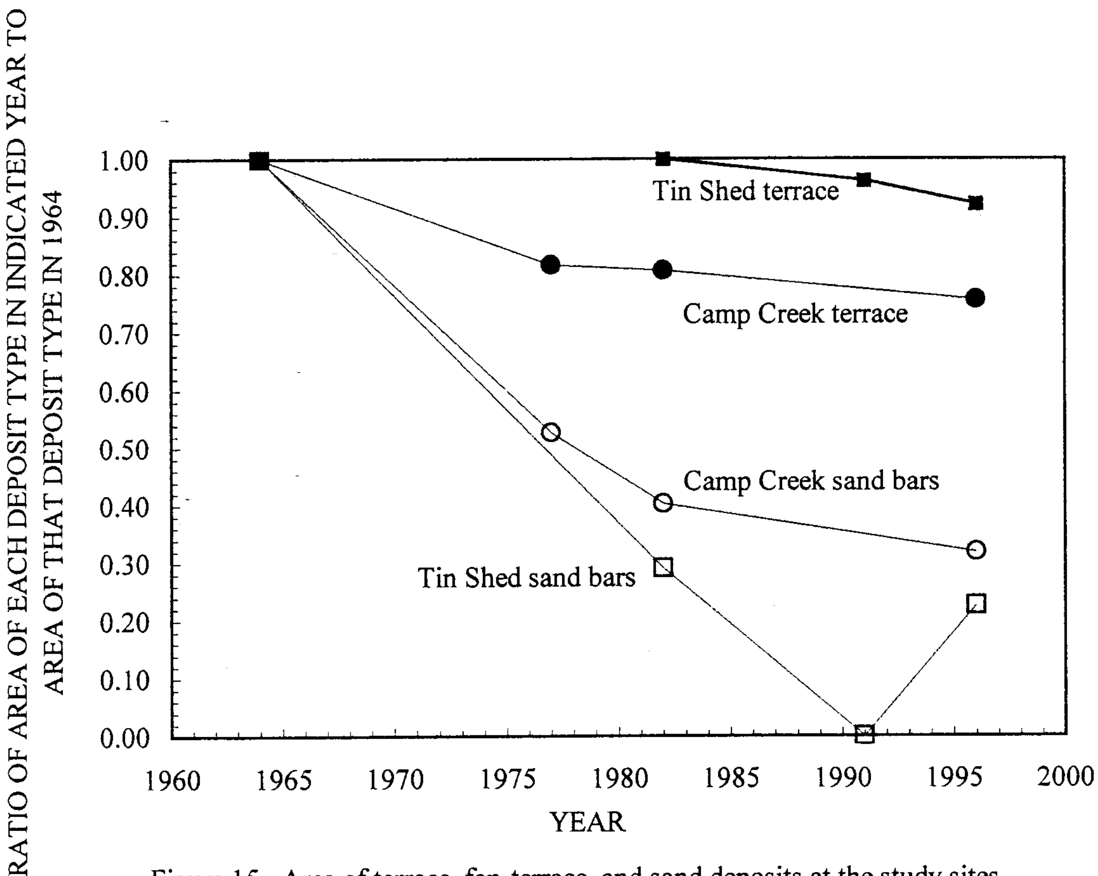

Figure 15. Area of terrace, fan-terrace, and sand deposits at the study sites between 1964 and 1996, expressed as a ratio of the area measured in a given year to the area measured in 1964.

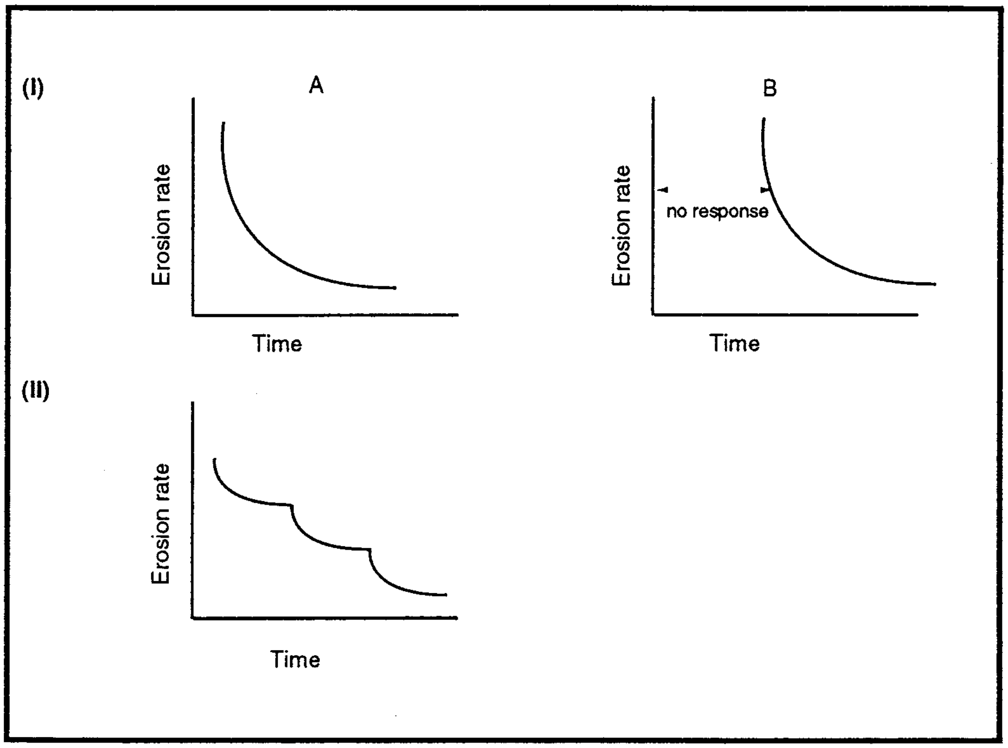

Figure 16. Conceptual model showing proposed alternative styles of terrace cutbank erosion. Style I is rapid initial erosion followed by decreasing rates of erosion. In style IA, the erosion is initiated soon after streamflow regulation; in style IB, there is an unknown lag between streamflow regulation and the inception of erosion. In style II, high rates of erosion recur following periods of low rates of erosion.

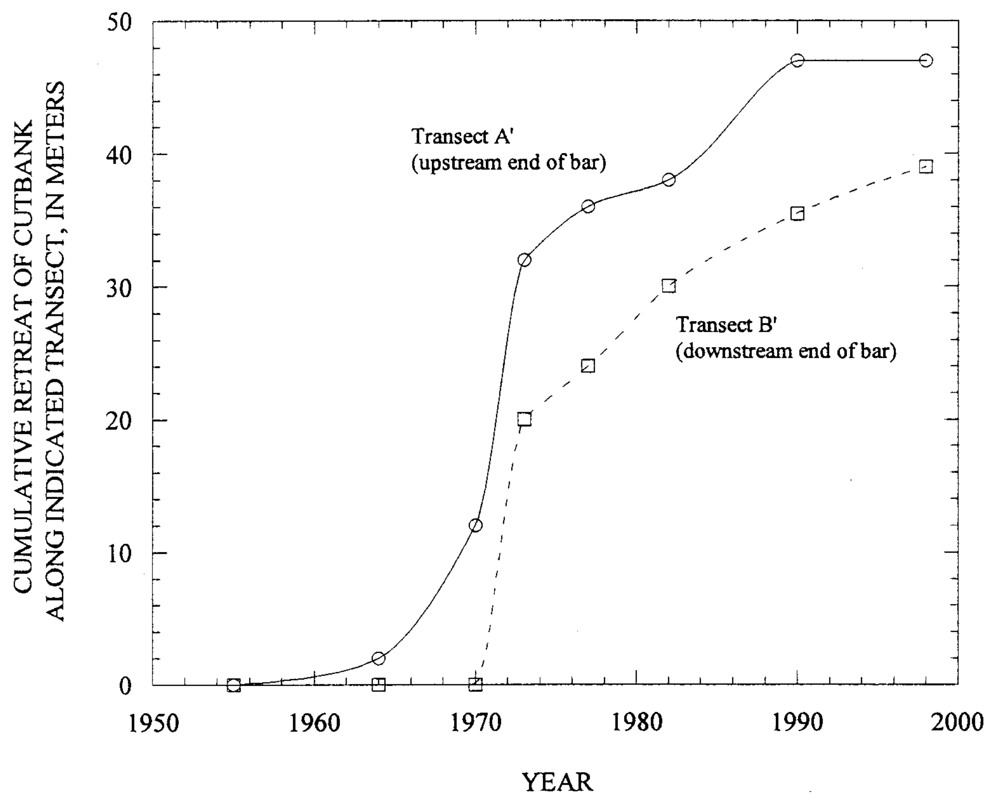

Figure 17. Episodic high rates of erosion (style II) measured at Salt Creek Bar (from Grams and Schmidt, 1999).