LANDFORMS AND ASSOCIATED SURFICIAL MATERIALS OF YELLOWSTONE NATIONAL PARK

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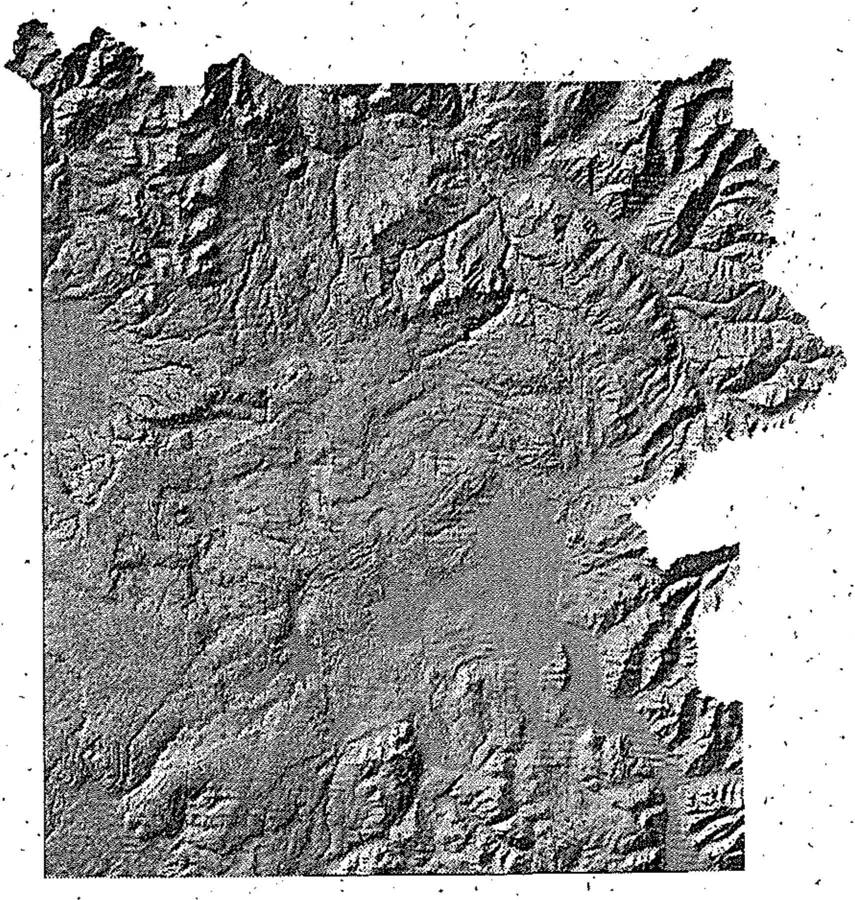
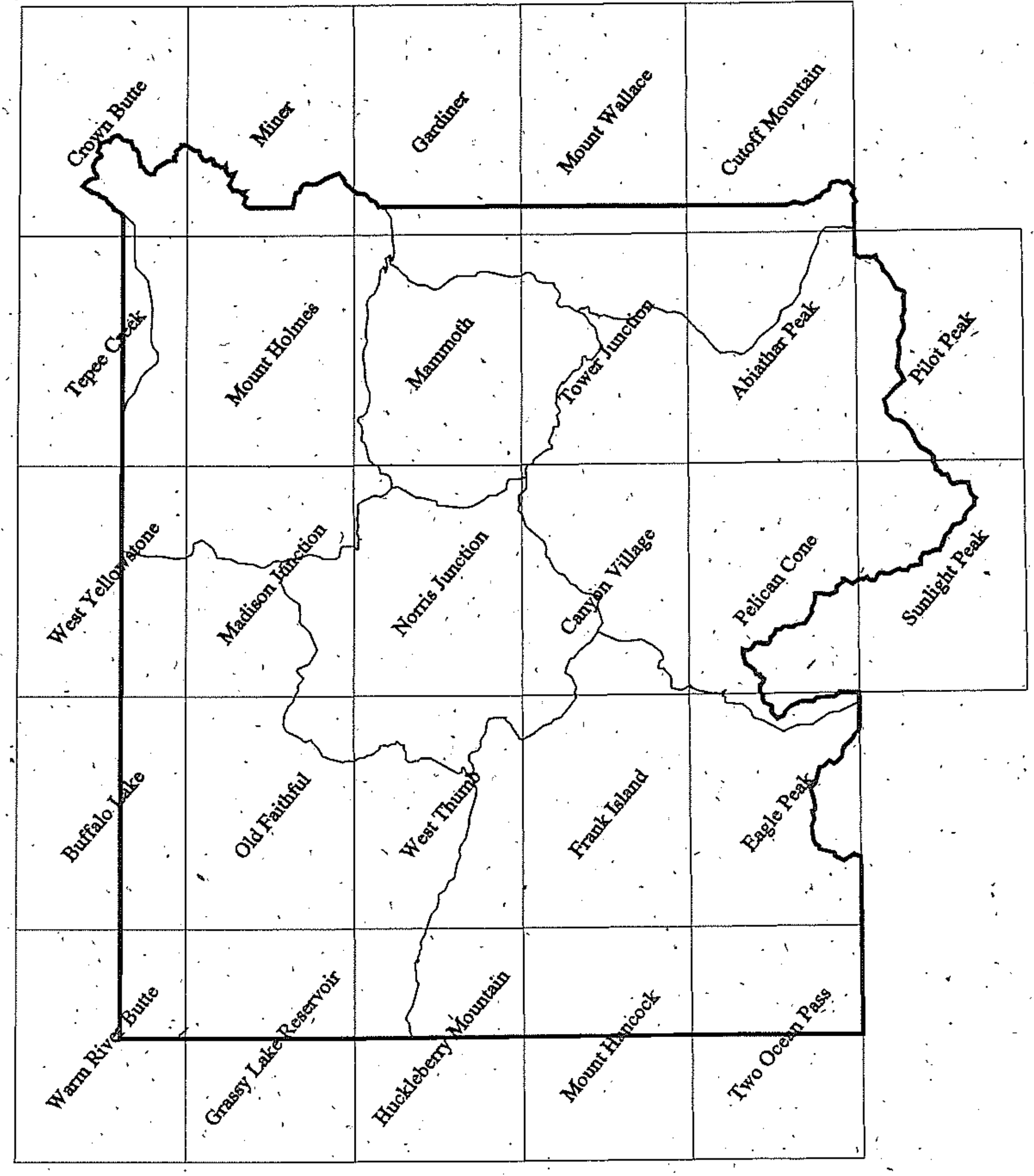


1996

INDEX TO MAP SHEETS



Map Sheets are based on USGS 15 minute 1:62,500 quadrangles.

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Front cover. The geomorphic form of Yellowstone National Park as depicted by a digital terrain model and derived from USGS data having 30-meter resolution, plotted using ARC/INFO software, at an approximate scale of 1:800,000.

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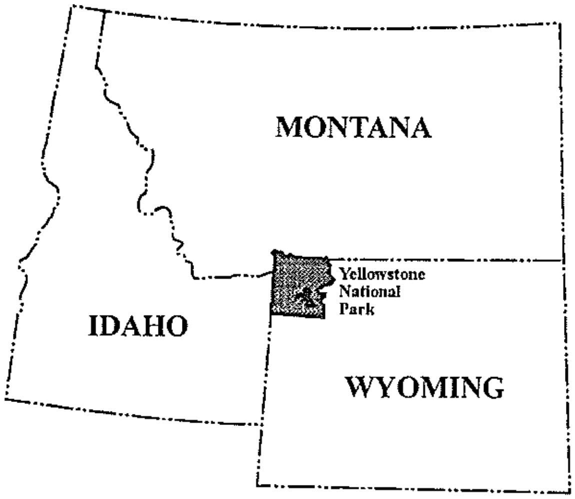
PREFACE

Yellowstone National Park is home to a spectacular community of life forms, from the uncounted unique microorganisms inhabiting the park's thousands of thermal features, to the "great piney woods" of mountain man lore, to the remarkable collection of large mammals that make up one of North America's last great predator-prey systems. The grizzly bear, the bald eagle, the cutthroat trout, and many other species share this landscape with a host of lesser-known but no less interesting and valuable creatures. Though humans have affected the park's ecological processes for thousands of years, and have changed it more significantly in the past century, Yellowstone National Park is still widely recognized as among our most pristine of wild settings, and as such is a great source of recreation, education, and wisdom.

LANDSCAPE AS THE STAGE FOR THE YELLOWSTONE DRAMA

However familiar they may be with the park's biological wonders, neither the public nor the scientific community has much appreciation of the role the landscape plays in shaping and maintaining these plants and animals. Although it is on a landscape scale that ecosystems and their many elements actually function and thrive, even the best educated and most interested people have had little opportunity to learn about nature on this scale. This is unfortunate, because it is on the landscape scale that we must understand nature reserves if we are to care for them with the sensitivity they require, and because it is often on this scale that we can gain the fullest connection to the park's wonders.

Fortunately, Yellowstone National Park has been the site of a vast amount of scientific research in many disciplines. Although much remains to be learned, the 124 years of study that have passed since the park's establishment have provided a wealth of knowledge about many aspects of its landscape. Generations of scientists have worked to identify the patterns and "personality" of Yellowstone, such as the distribution of vegetation types, soils, or



Tri-state map showing the location of Yellowstone National Park.

climate; the seasonal movements of the large ungulates; or the processes of geyser formation. These disparate studies have a common linkage through the landscape. The scientific study of the landscape provides a structure for that linkage.

Forman and Godron (1986) suggest that the elements of a landscape are soils, vegetation, the disturbance regime, and landforms. As these elements are defined and mapped, the day comes closer when investigators can simulate landscape functions and their effects on particular resources, and predict the effects of human activities in the park (Shovic et al. 1994). But an important element in this exciting work has been missing: we lacked a clear understanding of the landforms upon which all these organic and inorganic actions take place. We know many of the actors, but we do not have a blueprint for the stage.

WHY LEARN ABOUT LANDFORMS?

Over the last few centuries, we have advanced from thinking of natural resources as individual items (such as a deer or a tree), to thinking in terms of large numbers or populations of these items, to thinking in terms of communities and their environments, which we now call "ecosystems." We have learned to perceive landscapes as scenes of great, inevitable, and necessary change, where predators and prey constantly affect each other's abundance, where fire, wind, and other forces frequently reshape vegetation communities, and where humans are a long-standing and ever-increasing presence in the ecosystem's dynamics. But, strange as it seems, we have given surprisingly little thought to the stage upon which all these dramas are played out.

Most people are aware of the more obvious landforms: mountains, river valleys, canyons, and foothills are among the informal labels commonly given to some parts of our landscape. But few people have had the opportunity to learn just how many other landforms there are, much less to appreciate the ways in which they interrelate in a wild, unmanipulated setting such as a national park. Hence this study, which aims to introduce readers to the diversity and complexity of Yellowstone's surface features. All we traditionally have admired and treasured about the park, from the famous wildlife herds to the fantasy landscapes of the geyser basins, are influenced by, if not the product of, the landforms upon which they rest.

Henry Shovic
Paul Schullery

STUDY OBJECTIVES

Like animals, plants, and soils, landforms have been defined by centuries of study, so we can identify the landforms of Yellowstone just as we would identify species of plants or types of soils. The science of landform description, classification, delineation, and interpretation is known as applied geomorphology (Thornbury 1969). Within this science, a landform is defined as "any physical, recognizable form or feature of the Earth's surface having a characteristic shape, and produced by natural causes; it includes major forms such as a plain, plateau, or mountain, and minor forms such as a hill, valley, slope, esker, or dune. Taken together, landforms make up the surface configuration of the Earth." (Gary et al., eds. 1974).

The surface configuration of Yellowstone National Park is a complex continuum of slopes and surficial materials, as represented schematically by the terrain model in Figure 1. To make sense of this complexity, we classify groups of slopes and materials into a set of relatively homogeneous classes, represented schematically in Figure 2. Note that this scheme reduces the continuous landscape picture to a set of classes (albeit a large number of them) within each of which surface features are relatively similar. These classes are termed "landforms."

The surface features in the park are only a small subset of Earth's wide variety of landforms. Therefore the landform groupings described in this study and their implied formative processes were developed only for local conditions and are not a comprehensive listing of all possible landforms or their genetic processes.

The objective of this study was to characterize the nature and distribution of "meso" level landforms (Dikau 1989) and associated features for the entire park (2,196,480 acres (889,574 ha)). "Meso" level landforms are on the order of 2.5 to 250 acres (10,000 to 1,000,000 m^2), and include valleys, moraine, hills, and scarps. "Micro" level landforms of 0.0025 to 2.5 acres (10 to 10,000 m^2) include features such as footslopes, kettles, small terrace scarps. We judged these too detailed for the kinds of landscape level work needed in the park. We selected a mapping scale of 1:62,500 to give the best combination of readability, publication practicality, and appropriate use of available data.

Figure 3 illustrates our conception of a "meso" level study. Rolling glaciated uplands occur on the higher slopes and are terminated by a steep, concave bluff. A single hill occurs in the mid-ground. A glaciofluvial outwash terrace is in the foreground, bordered by a glaciated plateau. Although the outwash terrace and the plateau are similar in appearance, they are differentiated by the nature of included surficial materials (glacial outwash sands and gravels vs. glacial till, respectively). The glacial troughwall in the background is differentiated from the nearby streambreak by its profile slope curvature and probable origin (concave, glacial erosion vs. straight, stream downcutting, respectively). These landforms are on the order of 50 to 400 acres (200,000 to 1,600,000 m^2) in size, the scale at which most landforms are mapped in this study.

We characterized landforms in terms of both visible and inferred characteristics. These characteristics include: genetic origin, kind and degree of stream drainage dissection, slope gradient distribution, slope curvature (profile and plan), relief, proportion and shape of bedrock exposure, and the nature of included surficial materials. These terms are described in Differentiation of Landforms. Their definitions follow concepts used in geomorphology (Thornbury 1969), as modified by mapping specialists (Soil Conservation Service 1985). All technical terms are also defined in the Glossary, to facilitate use by specialists and others in fields outside of geomorphology.

Although landforms and their differentiating characteristics are very useful in themselves for the prediction of landscape behavior, knowledge of accessory properties can enhance their value. If we know the dominant rock type and the regolith (surficial, unconsolidated material mantling unweathered bedrock), we can infer information about soil properties. For example, if the surficial material is glacial till (assumed from knowing the landform is a glaciated valley) and the regolith composition is dominated by rhyolitic rocks, then we can infer that the soil parent material is glacial till derived from rhyolite-flow bedrock, and the soil properties will reflect the nature of that bedrock composition. Likewise, if two otherwise similar landforms are differentiated by the presence of seasonally wet depressions, interpretations can be made about the possible presence of wetlands, which may influence habitat potential for species that use wetlands or depend on species that do.

The considered use of a geographic information system (GIS) is a valuable complement to any resource inventory process. We used it at all stages of the process: for quantified description and analysis, input, storage, cartography, display and visualization, and publication. Its use is summarized under Methods.

PREVIOUS WORK

Previous work in the subject area is as follows:

- A reconnaissance survey of major landforms is available for northern Yellowstone National Park (Shovic et al. 1987). A draft version has been completed for the remainder (Shovic, H., Preliminary Landscape Groups for Yellowstone National Park, unpublished map).

- A detailed inventory of landscapes for about 5% of the park has been published (Shovic et al. 1991).

- Surficial geology maps are available at 1:125,000 (U.S. Geological Survey 1972b) for the entire park, and at a scale of 1:62,500 (Pierce 1973a, 1973b, 1974a, 1974b; Richmond and Pierce 1971, 1972; Richmond 1973a, 1973b, 1973c, 1973d, 1974, 1977; Richmond and Waldrop 1972, 1975; Waldrop 1975a, 1975b; Waldrop and Pierce 1975) with the exception of the Buffalo Lake quadrangle.

The surficial geology maps were designed to depict surficial deposits and, with a few exceptions, generally do not describe landform characteristics or the nature of the underlying bedrock. Subsequent work has shown the extent of the Pinedale glaciation to be greater than previously thought (Kenneth Pierce, USGS, personal communication). This information was used to update the outer limit of the Pinedale glaciation. Hilltops previously thought to be former nunataks (Richmond 1977) were probably under glacial ice during Pinedale time. Also, the area south of West Yellowstone, Montana, which has been mapped as Bull Lake glacial till (Richmond 1973b), is likely of Pinedale age.

- We used a bedrock geology map covering the entire park at a scale of 1:125,000 (U.S. Geological Survey 1972a) rather than more detailed 1:62,500 maps because of better coverage when viewing across topographic quads and uniformity in scale and legend across the study area. We used this map to determine the nature of the bedrock underlying landforms and make inferences about materials in the regolith. The bedrock map was not designed to account for surficial processes of erosion, deposition, and weathering that form the landscapes we see. The character of the bedrock, however, influences the effectiveness of these processes and some rock types have strong correlations to certain kinds of landforms.

We used other geological publications describing various features and their geologic relationships (e.g., Keefer 1971, Parsons 1978, Harris 1980, Reid and Foote 1982, White et al. 1988). Some of these address landforms in specific areas and others cover parkwide but generalized surface features.

METHODS

INVENTORY PROCESS

Our primary data sources were vertical aerial photography and surficial geologic mapping, as described in the previous section.

Photography

Aerial photography was taken at a nominal scale of 1:44,000, using near-infrared film, in the late summers of 1982 and 1983 (Project 41009 HAP 82). We used standard stereo interpretive methods (Ray 1960, Way 1973, Wolf 1974) using a 2x to 4x stereoscope. The choice of near-infrared film enhanced our ability to effectively interpret transpiring vegetation, exposed bedrock, and talus (Wolf 1974).

Mapping

U.S. Geological Survey surficial geologic maps (scale 1:62,500) were used as the mapping base to give a consistent scale, provide high-quality georegistration, and make the best use of their information. We mapped delineations on mylar registered directly to those quadrangles, hereinafter referred to as "quads," first mounted on ¼-inch foamboard for maximum stability and uniformity of scale. Spatial data for each quad was digitized directly from this mylar/foamboard map combination. Arcs and labels of polygons on quad edges were then edgematched to their respective adjoining quads, their boundaries dissolved, and the data appended to a master coverage.

Software

We used UNIX-based ARC/INFO software for spatial database construction and management. Windows-based Paradox relational database management software was used for the legend and attribute databases. Both were used for spatial analysis, with data transfer between systems in dBase format. UNIX based ARCVIEW was used for examples of data use in spatial analysis. Final maps were produced with ARC/INFO and ALPS (automated labeling software provided by the Natural Resource Conservation Service, USDA).

Note: Trade names used in this publication do not imply endorsement by Yellowstone National Park or any government entity.

Pilot Study

We developed a conceptual perspective on the range and character of landforms in the study area through a pilot study that used three quads representing a wide range of landform groups as given by Shovic (Preliminary Landscape Groups for Yellowstone National Park, unpublished map). From this initial work, we identified 65 landforms which were organized and grouped to make subsequent mapping more efficient and consistent. After field review, we mapped nine more quads and re-mapped the original three using the current legend to ensure consistent application of concepts modified by the additional data. Concurrent field investigations, fixed-wing overflights, and ground-based oblique photographs were used for quality control.

Each of the remaining 16 map sheets was processed within a week after completion of rough drafts; thus the digital spatial database was kept current with project progress. We used it as a "live" draft, making changes iteratively as mapping proceeded, printing hard copy for review and using a number of quality control procedures to assure consistency and error control. Final maps were plotted directly from the spatial database.

We kept relational attribute databases current for the landform, regolith composition, and wet area parameters; i.e., as new mapping concepts were identified, they were added "on the fly" to the appropriate database and hard copies were made in the appropriate format for use in mapping. These databases were related to the spatial database before each mapping session so we could use the most up-to-date legends and flag obsolete or misnamed delineations as mapping proceeded. Since slope was an important differentiating characteristic, we intersected digital slope maps with delineations to spot outliers and help characterize map unit concepts.

Quality Control

We produced interim maps showing spatial arrangement of map units to assure the reality of our mapping concepts. We compared our maps to other published data to spot outliers and delineations that did not fit with accepted concepts of local geomorphological relationships. For example, the maximum extent of Pinedale glaciation has been revised since the publication of most of the surficial maps (Ken Pierce, USGS, personal communication). To use the newest data, we compared the latest glacial boundary maps with the limits derived from our spatial data, adjusting ours where necessary for consistency.

We tracked statistics on areal extent and distribution throughout the mapping process. We reviewed map units that were small in total extent to make sure we were delineating realistic landscape features. Delineations that were too small to be depicted because of physical size or cartographic constraints were eliminated electronically. For example, water bodies were delineated to a minimum of 0.1 acres (0.04 ha) because we had no other coverage of small lakes available and this was an opportunity to produce a detailed, accurate assessment of lakes in the park. But because we wanted to avoid duplication of small water bodies with the topographic quad publication base, we eliminated all delineations < 50 acres (20 ha) from the cartographic coverages while retaining them in the spatial database for later inclusion in a lakes coverage.

Database queries also identified delineation names that were potentially inconsistent with geomorphic concepts. When draft mapping was completed, we reviewed the entire digital map using queries from the attribute databases to assure all map units were included in the legend, and that all legend items were delineated on the map. We also used spatial queries to highlight various combinations of features on screen, which helped to assure that areal extent and distribution were reasonable, and to identify outliers and bad labels. For example, a glaciated upland landform was identified having lake sediments as regolith instead of the expected glacial till. Using the spatial database, we found the delineations and reviewed each one. In this case, the map unit was kept in the spatial database because it was a lake basin subsequently overridden by glacial ice, resulting in topographic features consistent with glaciation over a regolith of lake sediments.

Final Map Sheets

The final cartographic symbology was produced electronically, including label placement, size, neatlines, names of adjoining quads, border labels, and titles. Manual editing on-screen was still necessary, but most of the work in producing photo-ready mylar overlays was done electronically. The final map-unit descriptive legend and associated descriptive tables were printed directly from the relational databases in photo-ready format. Final statistics on areal extent were produced from the spatial data. Final quad-based maps were electronically clipped from the continuous master spatial database, minimizing label and line errors between the borders of final map sheets. We manually reviewed every quad map to assure readability, accuracy of mapping concepts and their application on the landscape, and proper placement of annotation.

LEGEND DEVELOPMENT AND MAP UNIT VARIABILITY

The Closed Legend Method

Inventory studies of this nature are usually done with what is called a "closed legend," which is a relatively complete legend that is developed using the results of a preliminary investigation. This legend is used to map the remainder of the study area, with new units added only after weighing the additional cost against the potential benefits, which are usually related to some defined potential uses. For a large study area like Yellowstone, the cost of adding units can be large, reflecting the time involved in reviewing included properties, remapping or redefining unit concepts, finding previously mapped units, and the need for multiple revisions and publications.

Use of a closed legend necessarily makes map unit concept precision (and variability) subject to the practicality of maintaining map unit accuracy. We wanted to avoid this limitation in our study so that we could recognize the many unique but small landforms present in Yellowstone National Park (e.g., the hydrothermal areas), while minimizing the variability in units and retaining the maximum flexibility of use.

The Open Legend Method

When the open legend method is used, unique landforms are given names in the sub-legend as they are discovered and mapped, regardless of their areal extent, with a minimum of fitting to previously recognized landforms or modification of existing landform definitions to include the new properties. Although theoretically preferable, an open legend is usually impossible to use for large areas, because the number of map units quickly becomes too large to comprehend and the theoretical improvement in mapping accuracy is lost because of large potential errors in map naming and areal mapping consistency. The landform sub-legend has more than 90 landform types, and the regolith composition sub-legend about 60 items. Since any matrix material may be appended with any landform, and any combination may have a wet area designation, an enormous number of possible combinations exist. Also, with more than

7,000 separate delineations of these units in the park, manual retrieval of previously mapped units is nearly impossible.

We believe that we were able to overcome these limitations with the interactive, iterative use of GIS and associated databases throughout the mapping process. We therefore completed this inventory using an open legend.

Scale and Variability

Unlike traditional hard-copy maps which are published at a fixed scale, digital spatial data is essentially "scaleless" in that it can be used (or misused) at scales larger or smaller than that for which it was initially designed. However, at some scale it becomes not only inappropriate for interpretation, but also cartographically inaccurate. The information presented here was conceptually designed for use at the acquired scale of 1:62,500. However, with appropriate interpretive care, it can be used at scales up to 1:24,000, and in certain situations up to 1:6,000. Although the delineations will appear somewhat broadly defined at larger scales, polygon boundaries match topographic features on base maps.

The descriptions of landforms given below represent central concepts. Since we have imposed a discontinuous classification on what is essentially a continuously varying landscape, each delineation has some unavoidable variation around these concepts. We describe this variability through the ranges in descriptions (e.g., drainage density and slope), and in the comments relating to similar landforms. As a general rule, up to 15% of any one delineation may be significantly different from that described.

DIFFERENTIATION OF LANDFORMS

Differentiating and Accessory Characteristics

Each landform is defined by a unique combination of "differentiating" characteristics that make it visually different from all other landforms. Although all associated characteristics are "accessory" to that landform, only a few are "differentiating." For example, one strongly associated characteristic of a glacial trough bottom with weak dissection is the occurrence of glacial till as a surficial material. As such it is accessory to that landform. But because other glacial landforms may also be covered with glacial till, this characteristic is not differentiating for a glacial trough bottom. However, no other glacial trough bottom landform has weak dissection (given that all other characteristics are equal) because degree of stream dissection is differentiating, as well as accessory.

The accessory characteristics are genetic origin, kind and degree of stream drainage dissection, slope gradient distribution, slope curvature (profile and plan), relief, proportion and shape of bedrock exposure, and included surficial materials. Any of the selected characteristics may be differentiating, but the most commonly used are those directly visible in aerial photography. Surficial materials and genetic origin are occasionally used if landforms that are similar in differentiating characteristics need to be separated for interpretive purposes, or if aerial photos are not sensitive enough to segregate landforms that field investigations show need to be distinct. The accessory characteristics and our methods for measurement are described below.

Genetic Origin

We assigned each landform a probable genetic origin which represents the dominant formative process responsible for its physical characteristics. The major processes occurring in Yellowstone National Park are glaciation, glaciofluvial alluviation, non-glaciofluvial alluviation, fluviation, mass wasting, and hydrothermal modification. Although the formative processes are more often complex than simple, and most of Yellowstone's landforms have been determined by multiple processes acting at different times with differing intensities, the most visibly dominant process was used for this study. Evidence for each kind of process came from information on the surficial and bedrock geologic maps, topographic maps, existing publications, aerial photography, and field investigations.

Glaciation includes the direct effects of glacial erosion and deposition, and peri-glacial processes such as frost churning and solifluction. Aerial photos showed glacial troughs, cirques, flow features, scour and deposition on uplands, or other evidence of glacial activity. Surficial maps showed presence of glacial till, solifluction or frost-affected deposits with estimated thickness, as well as the relative age of deposits. Field investigations, consultation, topographic data, and geologic literature confirmed that all landforms having these processes fall within accepted geographic and elevational limits of glaciation.

Glaciofluvial alluviation is directly related to the movement of glacial meltwater, either during glaciation or relatively soon thereafter. Surficial maps showed presence of glaciofluvial materials (e.g., kame material, outwash deposits, flood deposits, or lake sediments) and landform characteristics that are consistent with their glaciofluvial origin (e.g., kames, outwash plains, flood bars, or lake beds). If near present streams, the glaciofluvial materials are significantly higher in elevation than the present stream flood plain or channel. In cases where these materials have been strongly modified by post-glacial fluvial processes, recent alluvial processes, or mass wasting, the landform was assigned the process that appeared to dominate its characteristics (e.g., fluvial hills, stream flood plain).

Non-glaciofluvial alluviation refers to recent sub-aerial deposition or formation of alluvium (stratified stream sediments) in or near stream courses, excluding sediments deposited during or immediately after glacial time periods. Deposits are near or at the elevation of the present stream level.

Fluviation pertains to the effects of precipitation and the associated long-term weathering of materials in place, yearly snowmelt, rain, and the downhill movement of material by gully, rill, or sheet erosion, as well as slow surface-mantle creep with attendant removal of material by streams. Any surficial material may have these characteristics, regardless of its initial origin. The term "fluviation" is not entirely satisfactory since it emphasizes the actions of rivers, but it is used as the nearest approximation to the processes involved (Thornbury 1969).

Mass wasting is a general term that refers to the dislodgment and down-slope transport of soil and rock material as a direct result of gravity. Unlike other erosion processes, the debris removed by mass wasting is not carried within, on, or under another medium possessing contrasting processes. It includes slow displacements such as the formation of colluvial slopes and solifluction, and rapid movements such as landslides. Slow soil-mantle creep is not included because it is considered a fluvial process.

Hydrothermal modification has been occurring since long before the last glaciation, and is characterized by variability in space, time, intensity, and effects. Yellowstone has a high concentration of hydrothermal activity (Keefer 1971, White et al. 1988). Some areas have been modified to such an extent that the erosional or depositional effects of hydrothermal processes apparently dominate the landform's characteristics. These areas often take on the characteristics of other landforms (e.g., breaklands, valleys, uplands, basins), but they are largely composed of hydrothermally altered surficial materials or bedrock and apparently originated in hydrothermal activity.

Stream Dissection

The degree to which streams have modified the landscape is important and highly visible, both in terms of identification of landforms and for many interpretations (Thornbury 1969). We considered glaciated landforms "dissected" by post-glacial fluvial processes only if 1) evidence of post-glacial stream modification was visible, or 2) there was evidence of pre-glacial fluvial dissection that had not been erased by glacial processes. Such evidence includes entrenchment of stream channels, breaks in slope consistent with stream downcutting, presence of V-shaped valleys cut into those having a glacial U-shape, and drainage patterns that are inconsistent with apparent glacial dynamics. We used stream drainage pattern type, stream drainage texture, and degree of dissection as measures of fluvial modification.

Stream drainage patterns follow those described in Way (1973). Patterns occurring in the study area are arboreal, dendritic, deranged, angulate, pinnate, parallel, rectangular, or braided (see Glossary). Examples of dendritic and parallel patterns are given in Figures 4 and 5. These patterns are determined by climate, underlying rock type and structure, soil texture, glacial history, and slope. At this scale of mapping, drainage system patterns are sometimes not visibly definitive. We assumed a dendritic pattern in cases where too few drainageways occur in a particular delineation for classification.

Stream drainage texture is the relative spacing of drainageways on a land surface (Figures 4, 5, 6, and 7). Stream drainage texture and degree of dissection are two measures of the degree to which streams have "dissected" or divided a preexisting landform. Stream drainage texture is a measure of average stream drainageway spacing. It does not imply there is an active stream in each drainage.

- Fine texture means that spacing is < 900 ft (ca. 240 m), and typically indicates high levels of surface runoff, impervious bedrock which may be relatively nonresistant, and soils of low permeability.

- Medium texture is 900 ft to 2100 ft (ca. 240 m to 560 m), and implies the presence of soils and rock of intermediate composition.

- Coarse spacing is where drainageways are > 2100 ft (ca. 560 m) apart. Coarse texture implies there is relatively little runoff, relatively resistant bedrock which may be permeable, and/or coarse-textured soils.

Degree of dissection is a measure of the depth of drainageway bottoms versus adjacent uplands or ridgetops. It is most apparent in landforms that have a previously flat or planar surface (Figures 4, 5, 6, and 7). The degree of stream dissection is related to the influence of running water. Where landforms are weakly dissected, little stream downcutting has probably occurred since the landform was created (usually in the Pleistocene). Strong dissection implies a drainage system which has had high stream energy or stream volume, a relatively long period of exposure to these processes, relatively nonresistant bedrock, or structural movements favoring stream downcutting.

- Not dissected indicates there is no discernible dissection on aerial photos at a scale of 1:22,000.

- Weakly dissected refers to stream drainageways that are < 20 ft (ca. 6 m) below adjacent uplands or surface ridges perpendicular to the drainageway.

- Moderate dissection is 30 to 90 ft (ca. 10 to 30 m).

- Strong dissection is > 90 ft (ca. 30 m).

- Entrenched dissection refers to stream drainageways that have steep (> 40 %) slopes and flat bottoms, and are 90 ft (ca. 30 m) or deeper.

Relief

Relief refers to the difference between the lowest and highest elevations in an individual landform delineation. Most landforms are differentiated on this criterion. High relief uplands or "mountains" have relief > 1000 ft (305 m), while other lands have less relief (Figure 37). Most landforms are differentiated on maximum or minimum relief, but a few may not have any relief, and some have minimum relief because of mapping limitations (e.g., 120 ft (37 m) for stream breaks or breaklands). Breakland-like forms with relief less than that value cannot be reliably identified and delineated at the scale of mapping.

Slope

Slope (i.e., slope gradient) is the inclination of the land surface from the horizontal. Percentage of slope is the vertical distance divided by the horizontal distance, then multiplied by 100. Thus, a slope of 20% is a drop of 20 ft (ca 6 m) in 100 ft (ca 30 m) of horizontal distance. Most landforms are differentiated on slope groups. For example, gently sloping plateaus (Figure 54) have overall slopes of < 15% over most of the map unit. There may be drainageways or scarps that have higher slopes, but they make up < 10% of the entire surface area. A slope of 40% was used to differentiate stream breaks (breaklands) (Figure 55). Slope classifications represent natural groupings based on which slopes commonly occur in the study area.

Plan and Profile Slope Curvature

Slope curvature is one of the most important characteristics of the landscape (Dikau 1989). In this study, plan and profile curvature are described on a meso-scale , roughly 1000 to 1600 ft (305 to 487 m) (Dikau 1989.) Local (micro) scale curvature may be considerably different. For example, a glaciated valley may have a profile slope concavity overall, but on a local scale its curvature is highly variable because of depositional variation and postglacial erosion.

Plan slope curvature (horizontal slope shape) is measured along the slope contour, or perpendicular to the fall line.

- Convex curvature implies the land surface resembles the curved outside of a sphere.

- Concave curvature implies the surface resembles the inside surface of a sphere.

- Straight curvature implies a relatively planar surface.

- Complex curvature implies a repeating sequence of convex and concave slopes.

- Variable curvature implies that any combination of slope curvature may occur.

For example, Figure 34 shows a straight plan curvature; Figure 37, convex; Figure 30, concave; Figure 38, straight; and Figure 41, complex.

Profile slope curvature (vertical slope shape) is measured down the fall line (perpendicular to the contour.)

- Convex curvature implies slope angle increases.

- Concave curvature implies slope angle decreases.

- Straight curvature implies slope angle stays relatively constant.

- Complex curvature implies a repeating sequence of convex and concave slopes.

- Variable curvature implies any combination of slope curvature is possible.

For example, Figure 34 shows a concave profile curvature; Figure 37, convex; Figure 38, straight; and Figure 41, complex.

Slope Arrangement

Some landforms have an apparently random slope pattern, due to glacial processes or lack of controlling structure in bedrock (Figure 40). Other landforms have a repeating pattern of hills and valleys related to erosional processes, bedrock faulting, or bedrock characteristics such as flow ridges on lava or tuff plateaus (Figure 41). Some landforms are defined by single slopes, such as fluvial bluffs (Figure 67).

Proportion and Shape of Exposed Bedrock

Exposed bedrock affects vegetative productivity, erosion potential, construction, and hydrologic function. We estimated the proportion and shape of exposed bedrock with aerial photography and field investigations. To be included as a characteristic, bedrock had to be consistently > 5% by area and occur consistently between delineations. Where bedrock is not mentioned, it occurs in a small part of the map unit, or does not occur consistently between delineations. In non-glaciated areas, bedrock is probably exposed because of relatively rapid erosional events, relatively weak weathering processes, or the presence of hard, well consolidated bedrock. In glaciated areas, exposures indicate that glacial processes favored scour rather than deposition, or the presence of resistant bedrock.

Surficial Materials

The nature of the regolith (unconsolidated material mantling unweathered bedrock) was determined from the surficial and bedrock geologic maps, topographic maps, existing publications, aerial photography, and field investigations. The types of regolith are: *alluvial fan deposits* (cobbly to sandy, locally with loess in surface layers); *stream alluvium* (relatively coarse-textured stream deposits, stratified deposits of sand, gravel, and cobbles); *fine textured alluvium* (stratified, relatively fine deposits of silt, sand, and fine gravel deposited by slow-moving streams); *colluvium-talus* (angular gravel, cobbles, and boulders; fragmented soil material with few fine materials); *colluvium-talus/soil* (angular gravel, cobbles, and boulders, with soil material filling interstices in rocks); *colluvium-soil* (a mantle of loose material that is primarily soil, with some rock fragments); *glacial till* (also includes glacial rubble); *flood deposits; glaciofluvial deposits; lake sediments* (silty); *beach sediments* (sandy); *loess mixed with frost rubble; landslide debris; loess and sandy outwash,* and *residuum* (material weathered in place from bedrock). Further details are in the Glossary.

LANDFORM GROUPINGS

Though each landform has a unique set of characteristics, we found that placing the landforms in a genetic hierarchy was useful for three reasons. First, a conceptual framework is vital to transmit the maximum information to the user. Through association with glacial processes, the term "glacial outwash plain" conveys much more than does the description, "flat, finely dissected plain." Secondly, since we anticipated identifying many different landforms, we were concerned about the difficulty of keeping them all in mind as each new area is reviewed for classification. Use of a hierarchical grouping provides relatively few choices at each level, making it possible to quickly select the right landform class or create a new one as needed. Finally, classification of mode of development (genesis) has a high predictive value for important accessory characteristics. For example, a landform described as a trough-shaped valley indicates a general hydrologic character and surficial bedrock occurrence. However, if it is also known that it has a recent glacial genesis, we can infer the character of the regolith and the probable stability of stream channels.

The classification hierarchy was based on a subset of differentiating characteristics that group landforms having similar formative modes. We chose a structure that reflects formative processes that are dominant in the study area and arranged the characteristics in a deductive order. The hierarchy is made up of "Divisions," "Groups," and "Subgroups."

The Division level is made up of two classes relating to major landforming processes (Glacial and Non-Glacial). Within these two divisions, groups are defined according to the basic characteristics of the landscape. Process is considered as well as the overall shape of the landforms. Figure 8 shows the divisions and groups and their hierarchical structure. Within these groups, the subgroups further divide characteristics, leaving a manageable number of choices for the selection of individual landforms. See Results and Discussion for a summary of included landforms.

Glacial Division

In this division, surface appearance is dominated by features associated with glaciation or glaciofluvial alluviation (Figure 8). The surface arrangement of included materials is glacial in origin, though the nature of the materials themselves may have resulted from non-glacial processes such as mass wasting. Post-glacial fluviation has affected these landforms to varying degrees, evidenced by stream dissection.

Glacial Troughs and Cirques Group

This group includes areas that have been under glacial ice and reflect a relatively strong influence of glacial erosional and depositional processes (Figure 8), due to relatively nonresistant bedrock type or structure, relatively rapid movement or large volume of glacial ice, or the effects of preexisting topography. Glacial erosion has produced concave slopes and basins, with characteristic U-shaped trough valleys. Plan slopes are generally straight. Bedrock exposures are scoured or rounded. Local glacial deposition has occurred in trough bottoms. Subgroups are differentiated on shape, slope, and degree of glacial expression (Figure 9).

Glacial Cirques Subgroup includes semicircular, concave, bowl-like areas that have steep faces, primarily resulting from glacial ice and snow abrasion (Figures 30 and 31). Profile and plan curvatures are concave.

Glacial Trough Valley Bottoms Subgroup includes the floors and lower side slopes of glacially eroded valleys (Figure 33). The valley profile is commonly U-shaped. Profile slope is concave and plan slope is straight. Slope gradients are < 30%. Stream pattern is arboreal with weak dissection.

Glacial Trough Valley Walls Subgroup includes the steep side slopes of glacially eroded valleys (Figure 34). The valley profile is commonly U-shaped. Profile slope is concave and plan slope is straight. Slope gradients are > 30%. Stream pattern is parallel, with weak to moderate dissection.

Glacial Complexes Subgroup includes complexes of cirques headwalls and basins, trough valley walls and bottoms, or glacial headslopes. Cirque complexes and trough valleys are used to combine landforms that are too small to delineate separately at this scale of mapping. Glacial headslopes are valley headslopes or valley walls that have evidence of glacial scouring and deposition in a direction perpendicular to the valley headslope or wall, but no well-defined cirque basins (Figure 35).

Glaciated Uplands Group

This group includes areas that have been under glacial ice and are at least partially mantled with glacial till (Figure 8). However, the mechanisms of glacial erosion and deposition were probably relatively less effective than those in the Glacial Troughs and Cirques group. This may be due to presence of resistant bedrock type or structure, relatively slow movement or low volume of glacial ice, or the effects of preexisting topography. Therefore, the landforms lack well-defined trough or cirque development. They have a concave, convex, or planar appearance, depending on preexisting landforms, degree of glacial influence, and bedrock structure. Slopes are locally complex. Bedrock exposures are rounded with glacial striations (scour marks) present in some places. Subgroups are differentiated on the basis of slope and slope shape, slope arrangement, underlying bedrock shape, and maximum relief (Figure 10).

Glaciated Plateaus Subgroup includes glaciated lands having a planar appearance due to the shape of the underlying bedrock structure, usually lava or ash flow tuff flows (Figures 36 and 54). Slopes are < 15%.

Concave Glaciated Uplands Subgroup includes glaciated lands that have a large-scale bowl shape with slightly concave profile slopes, complex plan slopes, and dendritic drainage patterns (Figure 39).

High Relief Glaciated Uplands Subgroup includes glaciated lands that have convex slopes and high relief (> 1000 feet or 305 m) (Figure 37).

Glaciated Hills Subgroup includes glaciated lands that have low to moderate relief (< 1000 feet or 305 m) with complex slopes and an overall convex appearance in profile and in plan (Figure 41). They have a strongly repeating pattern of hill slopes and ridges. They have low to moderate relief, and slope gradients < 40%.

Glaciated Ridgetops Subgroup includes glaciated lands that have convex slopes with gradients < 25% (Figure 42). They have weak or no dissection. They are mapped when large enough to be accurately delineated at the scale used in this project.

Rolling Glaciated Uplands Subgroup includes glaciated lands that have a complex of concave and convex slopes, with no strongly repeating pattern of hill slopes and ridges and low to moderate relief (Figure 40).

Glaciofluvial Landforms Group

This group includes areas that reflect the effects of meltwater flows, floods, and lakes related to glaciation (Figure 8). Local topography may be a mixture of terraces, flats, kames, hills, and channels, plains, or flood bars. Subgroups are differentiated on the basis of slope profile shape (Figure 11).

Glaciofluvial Kame/Outwash Complexes Subgroup includes deposits resulting from relatively high-energy glacial meltwater flows (Figures 44 and 45). They have concave profile and concave or straight plan slope curvatures. Slope gradients are < 25%. Local topography is a mixture of kames, hills, channels, and terraces.

Glaciofluvial Kames and Bars Subgroup includes deposits formed from glacial meltwater flows and related floods (Figure 47). Slope gradients are < 25%. Local topography is convex with steep scarps and small terraces.

Glaciofluvial Terraces, Plains, and Flats Subgroup includes deposits resulting from relatively low-energy glacial meltwater flows and impoundments (Figures 46 and 49). Slope profile curvature is straight. Slope gradients are < 10%.

Non-Glacial Division

This division includes lands dominated by features associated with non-glacial processes such as fluviation, alluviation, post-glacial hydrothermal activity, or mass wasting. The present arrangement of surficial materials is not glacial in origin, but their character materials may have some glacial influence (Figure 8).

Alluvial Landforms Group

This group is comprised of deposits of recent (Holocene) alluviation (Figure 8), including alluvial fans, alluvial basins, and flood plains (Figures 50, 51, 58, and 59). Stream erosional landforms are not included if at a scale larger than small terrace formation and channel downcutting. There are no subgroups.

Fluvial Uplands Group

Lands in this group mirror the effects of non-glacial fluviation (Figure 8), including unconcentrated runoff, slow weathering in place, slow downslope movement of the regolith or weathered mantle with removal by streams, and domination by bedrock structural characteristics, (e.g., rhyolite-flow boundaries or relatively rapid stream downcutting). Excluded are relatively rapid downslope movement and talus movement, recent streamflow depositional processes, or landforms strongly influenced by hydrothermal activity.

These lands were probably not covered with glacial ice during the most recent (Pinedale) glaciation, shown by lack of glacial features or location above or outside the maximum Pinedale ice limits. Most were probably covered by earlier (Bull Lake) glaciers. If they were glaciated during some period, either no visible evidence remains (probably because of removal by subsequent processes), or little glacial erosion/deposition occurred, possibly due to slow ice movement. The formation of an ice dam by a dominant glacier downvalley could produce the latter conditions. Evidence for fluviation includes V-shaped valley profiles, straight profile slope curvature, lack of recognizable till cover, and lack of glacial striations on bedrock exposures. Subgroups are differentiated on the basis of relief, slope gradient, slope curvature, and slope arrangement (Figure 12).

Fluvial Plateaus Subgroup includes glaciated lands that have a planar appearance due to the shape of the underlying bedrock structure, usually lava or ash flow tuff flows (Figure 53). Slopes are < 15%.

High Relief Fluvial Uplands Subgroup includes lands that have straight to slightly convex slopes and high relief (> 1000 feet or 305 m). Slope gradients are < 40%.

Fluvial Hills and Bluffs Subgroup includes lands that have low to moderate relief (< 1000 feet or 305 m) with an overall convex or straight appearance in profile and in plan (Figure 67). Hills have a strongly repeating pattern of hill slopes and ridges. They have low to moderate relief, and slope gradients are < 40%. Bluffs are single slopes, generally on the edges of lava or tuff flows.

Rolling Fluvial Uplands Subgroup includes lands that have a complex of concave, straight, and convex slopes (Figures 56 and 57) with no strongly repeating pattern of hill slopes and ridges and low to moderate relief.

Stream Breaks (Breaklands) Subgroup includes lands that have slope gradients > 40% (Figure 55). Profile curvature is straight on lower to mid slopes and convex on head slopes.

Hydrothermal Group

Lands in this group are differentiated on the basis of formation mode (Figure 8). A hydrothermal landform's characteristics are apparently due to hydrothermal activity, either erosional, due to acid-sulfate processes (Figures 48, 60, 61, 62, and 63); or constructional (i.e., primarily from neutral-chloride or carbonate processes) (Figures 64 and 65). Hydrothermal explosions have created some features (Figure 66). All these lands appear quite different from surrounding areas, although hydrothermal processes may not necessarily be active at the present time. We developed this group because of the importance of these small but unique areas. Not included are areas which are influenced by hydrothermal processes but whose characteristics are relatively unchanged by them. See Regolith composition for these. There are no subgroups.

Mass Wasting Group

Lands in this group reflect the effects of gravity, as either relatively rapid mass movement or slow downhill movement of rock fragments (Figure 8). Slow downhill movement of the soil mantle is not included. These lands were formed either during or shortly after the end of the Pleistocene, and some movement continues today. Subgroups are differentiated on the basis of relative speed of movement and morphology (Figure 13).

Coarse Textured Colluvium Subgroup includes lands formed by relatively slow downslope movement of rock fragments (Figures 38 and 43). Only coarse-textured material is included. These lands are differentiated from stream breaks by the nature of the associated surficial materials and profile slope shape.

Landslides Subgroup includes the erosional and depositional parts of landslides, resulting from relatively rapid downslope movement of rock fragments or soil material (Figures 32 and 52).

Water Bodies Group includes water bodies (Figure 49) not including streams.

DIFFERENTIATION OF OTHER MAP UNIT CHARACTERISTICS

Wet Areas

The term "wet areas" refers to areas that show evidence of wetness for at least the latter part of the growing season and that may support wetland vegetation. We judged this a conservative criterion, because additional areas are wet earlier in the growing season, and most of the park's soils are wet in the spring and early summer before the active growing season. Evidence comes from field investigations and from the evaluation of aerial photography with near-infrared film, looking for the presence of depressional or stream-bottom topography and colors indicating actively transpiring vegetation in late September of 1982.

Regolith Composition

Regolith composition modifiers fell into ten general groups: alluvial materials, rock rubble, frost rubble, rubble veneer (glacial rubble), certain kinds of glacial till, rock types in regolith, hydrothermal or hydrothermally modified materials, lake sediments, residuum, and colluvium. Regolith composition was mapped using information available from surficial and bedrock geology maps, aerial photography, and field investigation.

RESULTS

Map unit symbols, map unit names, and areal statistics are given in Tables 1 and 2. Each map unit symbol is a combination of symbol entries in the landform sub-legend (Table 3) and the regolith composition sub-legend (Table 4). Each map unit name in Table 1 is a combination of landform name entries in the two sub-legends.

The landform sub-legend (Table 3) includes the landform symbol, landform name, and areal extent of each. The landform name is a descriptive term using the group, subgroup, and a brief listing of characteristics that separate it from other landforms. Areal extent is calculated by summing the data in Table 2 by landform, across classes of regolith composition.

Complete landform descriptions are in Table 5 (sorted alphabetically) and Table 6 (sorted by Group and Subgroup). This table repeats landform symbols and landform names given in Table 1, but includes descriptions of all differentiating and accessory characteristics. Terms are defined in the Glossary. Proportions of surficial materials are averages. The type-location entry refers to where the landform was first recognized and represents a central concept of its character. The regolith composition sub-legend (Table 4) includes the symbols and descriptions for each map unit in Table 1. These are sorted by general regolith grouping in Table 7 to more easily illustrate their nature and interrelationships.

The symbol “w” is appended on map unit symbols where seasonal wet areas make up > 5% of the map unit’s area. Because the presence of wet areas is an important feature in the behavior of map units, statistics in Table 2 are repeated in Table 8, broken out by the "w" suffix.

Mapsheets showing the spatial distribution of map units are in a separate envelope. Each map is a 1:62,500 (15-minute) USGS topographic quadrangle overlaid with map unit delineations. We eliminated all units of < 5 acres (ca. 20,000 m^2), except for those with a hydrothermal origin or regolith, stream bottoms, and alluvial basins, all of which can be accurately depicted at sizes down to one acre (4,000 m^2). We eliminated all “WATER” delineations of < 50 acres (ca. 200,000 m^2) to improve the maps' readability.

Table 6 illustrates all described landform symbols and characteristics arranged in our hierarchy of Divisions, Groups, and Subgroups. Tables 9 and 10 give a perspective on the occurrence and importance of the different groupings and their relative contributions to the landscapes of the study area.

As shown in Tables 4 and 7, the regolith composition sub-legend is relatively straightforward. During mapping this part of the legend was appended after landforms had been defined. The delineation of landforms was more difficult because differentia for landforms were considerably more complex. Under Methods we described a hierarchy of Divisions, Groups, and Subgroups that aggregated lands in terms of similar characteristics. This was done to provide a conceptual framework and as a mapping aid. However, we purposely left out any discussion of individual landforms and their relationships to the hierarchy. Use of the open legend process dictates that landforms are defined in the results of our study, not in the design portion. The conceptual design process represented by our groupings is essential to provide a structure for mapping, but does not restrict the number or kinds of landforms discovered. The difference between these two concepts is illustrated below.

Figure 3 illustrates seven conceptual divisions of different land areas in the image. This represents the design and conceptual framework used before landforms were delineated. Figure 29 shows the differentiation of those areas into a set of 15 map units, each being separated by landform, regolith composition, and presence of wet areas. The latter represents the results of our study.

In Figure 29, map unit AOW39w appears similar to ALF39. The general look of the landscape is similar. Regolith composition is equivalent (stratified gravels and sands, #39 in Table 4). However, stream drainage patterns are different (AOW vs. ALF in Table 5) and wet areas are present in the former, meaning they must be differentiated into separate map units. The three steep areas in Figure 3 have been separated by slope profile shape, proportion of exposed bedrock, and genetic origin to form four landforms (TWD10, BTU10, TWM10, and ULT10). All these landforms have similar underlying rock types (rhyolite, # 10 in Table 4). The RMB05 is dominated by glacial rubble (rubble veneer) derived from rhyolite (#05 in Table 4), with deeper till and a significant proportion of wet areas in PGU10w.

The Division and Group levels of our hierarchy arrange landforms primarily by process. It is at the subgroup level where we illustrate the central differentiating characteristics between landforms and where landforms were defined. To better visualize the relationships between landforms at this level, we have included a set of graphics that show their relationships to other subgroups. Each figure is arranged as a key at the Subgroup level and shows the differentiating characteristics by landform. These fit into the Group and Division keys given in Figures 8 through 28. The Group is listed where there are no defined subgroups.

Glacial Cirques Subgroup. Landforms are differentiated on slope (Figure 14).

Glacial Trough Valley Bottoms Subgroup. Landforms are differentiated on stream dissection and nature of surficial materials (Figure 14).

Glacial Trough Valley Walls Subgroup. Landforms are differentiated on nature of surficial materials and stream dissection (Figure 14).

Glacial Complexes Subgroup. Landforms are differentiated on the kind of inclusions (Figure 14).

Glaciated Plateaus Subgroup. Landforms are differentiated by presence of outwash channels, loess-covered or lobate ridges, talus slopes, bedrock exposure, or degree of stream dissection (Figure 15).

Concave Glaciated Uplands Subgroup. Landforms are differentiated on texture and degree of dissection, and bedrock exposure (Figure 16).

High Relief Glaciated Uplands Subgroup. Landforms are differentiated by texture of stream dissection and bedrock exposure (Figure 17).

Glaciated Hills Subgroup. Landforms are differentiated by type of drainage pattern and degree of stream dissection (Figure 18).

Glaciated Ridgetops Subgroup. Landforms are differentiated on bedrock exposure and presence of active cryoturbation (Figure 19).

Rolling Glaciated Uplands Subgroup. Landforms are differentiated by degree and degree of stream dissection, topographical roughness, and bedrock exposure (Figure 20).

Glaciofluvial Kame/ Outwash Complexes Subgroup. Landforms are differentiated on overall plan shape (Figure 21).

Glaciofluvial Kames and Bars Subgroup. Landforms are differentiated on mode of deposition and slope curvature (Figure 21).

Glaciofluvial Terraces, Plains, and Flats Subgroup. Landforms are differentiated on degree and texture of dissection (Figure 21).

Alluvial Landforms Group. Landforms are differentiated on landform morphology (Figure 22). There are no subgroups in this group.

Fluvial Plateaus Subgroup. Landforms are differentiated by kind of drainage pattern, degree of stream dissection, or presence of flow ridges (Figure 23).

High Relief Fluvial Uplands Subgroup. Landforms are differentiated by bedrock exposure (Figure 23).

Fluvial Hills and Bluffs Subgroup. Hills a repeating pattern of slopes and valleys, low to moderate relief, and slope gradients < 40% with landforms differentiated by kind of drainage pattern. Bluffs are single slopes, generally on the edges of lava or tuff flows with landforms differentiated on slope profile curvature (Figure 24).

Rolling Fluvial Uplands Subgroup. Landforms are differentiated by degree and degree of stream dissection, topographical roughness, and bedrock exposure (Figure 25).

Stream Breaks (Breaklands) Subgroup. Landforms are differentiated on composition of surficial materials, bedrock exposure, and degree and texture of stream dissection (Figure 26).

Hydrothermal Group. Landforms are differentiated on slope gradient, slope curvature, and mode of deposition (Figure 27). Not included are landforms which have some hydrothermal influence but whose characteristics are relatively unchanged by those processes.

Coarse Textured Colluvium Subgroup. Landforms are differentiated on kind of talus slope and slope gradient. Active, unvegetated talus slopes or rock glaciers have slope gradients < 40%. Inactive talus slopes have gradients between 30 and 80% and slabby rock fragments (Figure 28).

Landslides Subgroup. Landforms are differentiated on process (erosional or depositional), and mix of included materials (Figure 28.)

CONCLUDING REMARKS

As in any applied scientific contribution, this study's value is measured in its potential for use. Knowledge of landforms and their associated characteristics can be used in a myriad of ways. This study could benefit those interested in wetland mapping, bighorn sheep habitat, wolf range, bison migration routes, glacial history interpretation, sedimentation patterns in Yellowstone Lake, visual effects of developments, forest regeneration potential, fire-spread modeling, and many other topics.

As a whimsical example, scientific study may show that talus slopes of certain kinds harbor moth species favored by certain bats. The distribution of these bats may become of interest to park managers. Using the landform/surficial material legends, a spatial analysis could produce Figure 68 that shows the distribution of talus slopes (areas that average > 30% talus or a mixture of talus and soil.) About 176,000 ac (71,000 ha) occur in the park. Further stratification shows only 12% of this occurs on steep slopes, having some soil, and slabby or platy rock fragments (which are important factors in moth habitat). We could use other spatial characteristics to refine the results, such as slope, aspect, elevation or vegetation types. Spatially explicit results could be plotted at an appropriate scale to help a scientist or manager find study sites for further work on the bats of interest.

The above example is a simplified view of the wealth of information contained in this study. It is obvious, and even daunting, that the source maps are highly detailed, the tables are extensive, and the legend stretches on for pages. However, this illustrates the complexity of the nature and distribution of the landforms and surficial materials in Yellowstone National Park, the "stage" for the landscapes we see. This hard copy is merely a benchmark of our progress to date. One benefit of this study is the electronic database, capable of being generalized and interpreted in the future to meet specific needs. This allows users to concentrate on learning and predicting the effects of alternative futures, rather than attempting to interpret a document fixed in time or fixed in level of detail.

Yellowstone National Park is like a play of epic proportions. The stage on which we and our fellow creatures act out our dramas is indeed diverse and complex. This document is a window on a part of that diversity, making our view a little larger, a little more considered, and possibly a little wiser. As the human population expands and demands more from our landscapes, we will need that wisdom. The outcome of the play and of the wild creatures on the stage depend on it.

LITERATURE CITED AND REFERENCES

Chorley, R. J. 1972. Spatial analysis in geomorphology. Methuen and Co., London.

Christiansen, R. L. 1984. Yellowstone magmatic evolution: its bearing on understanding large-volume explosive volcanism. Pages 84-95 *in* Studies in geophysics, explosive volcanism: inception, evolution, and hazards. National Academy Press, Wash., D.C.

Davis, C., and H. F. Shovic. 1996. Gallatin National Forest Soil Survey. National Resource Conservation Service, USDA.

Despain, D. G. 1987. The two climates of Yellowstone National Park. Pages 11-20 *in* Proc. Mont. Acad. Sci. 47:11-20.

Despain, D. G. 1990. Yellowstone vegetation. Roberts Rinehart, Inc., Boulder, Colo.

Dikau, R. 1989. The application of a digital relief model to landform analysis in geomorphology. Pages 51-79 *in* J. Raper, ed. Three dimensional applications in geographic information systems. Taylor and Francis, London.

Dirks, R. A., and B. E. Martner. 1982. The climate of Yellowstone and Grand Teton National Parks. National Park Service Occasional Paper No. 6., Wash., D.C.

Dixon, J. B., and S. B. Weed. 1977. Minerals in soil environments. Soil Sci. Soc. of Amer., Madison, Wis.

Dorn, R. D. 1992. Vascular plants of Wyoming. 2nd ed. Mountain West Publ., Cheyenne, Wyo.

Forman, R. T., and M. Godron. 1986. Landscape ecology. John Wiley and Sons, New York, N.Y.

Fournier, R. O. 1985. The behavior of silica in hydrothermal solutions. Pages 45-61 *in* Berger, B.R. and P.M. Bethke, eds. Reviews in economic geology, Vol. 2: geology and geochemistry of epithermal systems. Soc. of Econ. Geo., Chelsea, Mich.

Fournier, R. O. 1989. Geochemistry and dynamics of the Yellowstone National Park hydrothermal system. Ann. Rev. Earth Planet. Sci. 17:13-53.

Gary, M. R., C. McAfee, Jr., and R. Wolf, eds. 1974. Glossary of geology. American Geological Institute, Wash., D.C.

Harmon, P. and D. King. 1985. Expert systems: artificial intelligence in business. John Wiley and Sons, Inc., New York, N.Y.

Harris, D. V. 1980. The geologic story of the national parks and monuments. John Wiley and Sons, New York, N.Y.

Hausenbuiller, R. 1972. Soil science: principles and practices. Wm. C. Brown, Dubuque, Iowa.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill Book Company, Inc., New York, N.Y.

Jones, J. B., and E. R. Segnit. 1971. The nature of opal. I: Nomenclature and constituent phases. J. Geo. Soc. Aust. 18:57-68.

Keefer, W. R. 1971. The geologic story of Yellowstone National Park. U.S. Geol.

Surv. Bull. 1347.

McNab, W. H., and P. E. Avers. 1994. Ecological subregions of the United States: section descriptions and map. U.S.D.A. For. Serv., Wash. D.C.

Nordin, J., and M. Blackwell. 1984. Soil survey of the Teton National Forest. U.S.D.A., Soil Conserv. Serv., Casper, Wyo.

Parsons, W. H. 1978. Field guide: middle Rockies and Yellowstone. Kendall Hunt, Dubuque, Iowa.

Pierce, K. L. 1973a. Surficial geologic map of the Mammoth quadrangle, and part of the Gardiner quadrangle, Yellowstone National Park, Wyoming and Montana. Map I-641. U.S. Geol. Surv., Wash., D.C.

Pierce, K. L. 1973b. Surficial geologic map of the Mount Holmes quadrangle, and parts of the Tepee Creek, Crown Butte, and Miner quadrangles, Yellowstone National Park, Wyoming and Montana. Map I-640. U.S. Geol. Surv., Wash., D.C.

Pierce, K. L. 1974a. Surficial geologic map of the Abiathar Peak quadrangle, and parts adjacent quadrangles, Yellowstone National Park, Wyoming and Montana. Map I-646. U.S. Geol. Surv., Wash., D.C.

Pierce, K. L. 1974b. Surficial geologic map of the Tower Junction quadrangle, and part of the Mount Wallace quadrangle, Yellowstone National Park, Wyoming and Montana. Map I-647. U.S. Geol. Surv., Wash., D.C.

Pierce, K. L. 1979. History and dynamics of glaciation in the northern Yellowstone National Park area. U.S. Geol. Surv. Prof. Paper 729-F. U.S.G.P.O., Wash. D.C.

Ray, R. G. 1984. Aerial photographs in geologic interpretations and mapping. U.S. Geol. Surv. Prof. Paper 373, Seventh printing, U.S.G.P.O., Wash., D.C.

Reid, S. G., and D. J. Foote. 1982. Geology of Yellowstone Park area. Wyoming Geological Association, 33rd Annual Field Conference Guidebook. Casper, Wyo.

Richmond, G. M. 1973a. Surficial geologic map of the Huckleberry Mountain quadrangle, Yellowstone National Park and adjoining area, Wyoming. Map I-639. U.S. Geol. Surv., Wash., D.C.

Richmond, G. M. 1973b. Surficial geologic map of the Grassy Lake quadrangle, Yellowstone National Park and adjoining area, Wyoming. Map I-644. U.S. Geol. Surv.,Wash., D.C.

Richmond, G. M. 1973c. Surficial geologic map of the Warm River Butte quadrangle, Yellowstone National Park and adjoining area, Idaho and Wyoming. Map I-645. U.S. Geol. Surv., Wash., D.C.

Richmond, G. M. 1973d. Surficial geologic map of the West Thumb quadrangle, Yellowstone National Park, Wyoming. Map I-643. U.S. Geol. Surv., Wash., D.C.

Richmond, G. M. 1974. Surficial geologic map of the Frank Island quadrangle, Yellowstone National Park, Wyoming. Map I-642. U. S. Geol. Surv., Wash., D.C.

Richmond, G. M. 1977. Surficial geologic map of the Canyon Village quadrangle, Yellowstone National Park, Wyoming. Map I-652. U. S. Geol. Surv., Wash., D.C.

Richmond, G. M., and K. L. Pierce. 1971. Surficial geologic map of the Mount Hancock quadrangle, Yellowstone National Park, and adjoining area, Wyoming. Map I-636. U.S. Geol. Surv., Wash., D.C.

Richmond, G. M., and K. L. Pierce. 1971. Surficial geologic map of the Two Ocean Pass quadrangle, Yellowstone National Park and adjoining area, Wyoming. Map I-635, U.S. Geol. Surv., Wash, D.C.

Richmond, G. M., and K. L. Pierce. 1972. Surficial geologic map of the Eagle Peak quadrangle, Yellowstone National Park and adjoining area, Wyoming. Map I-637. U.S.

Geol. Surv.,Wash., D.C.

Richmond, G. M., and H. A. Waldrop. 1972. Surficial geologic map of the Pelican Cone quadrangle, Yellowstone National Park and adjoining area, Wyoming. Map I-638. U.S. Geol. Surv., Wash., D.C.

Richmond, G. M., and H. A. Waldrop. 1975. Surficial geologic map of the Norris Junction quadrangle, Yellowstone National Park, Wyoming. Map I-650. U.S. Geol. Surv., Wash., D.C.

Rodman, A, D. Thoma, and H. F. Shovic. 1992. John D. Rockefeller, Jr. Memorial Parkway draft soil survey. Yellowstone Center for Resources, Yellowstone National Park, Wyo.

Ross, C. S., and R. L. Smith. 1960. Ash-flow tuffs: their origin, geologic relations, and identification. Geol. Survey Professional Paper 366. U.S.G.P.O., Wash.,D.C.

Schultz-Lam, S. F., G. Ferris, K. O. Konhauser, and R. G. Wiese. 1995. In situ silicification of an Icelandic hot spring microbial mat: implications for microfossil formation. Can. J. Earth Sci. 32: 2021-2026.

Shepard, J. S. 1971. The influence of geothermal temperature gradients upon vegetation patterns in Yellowstone National Park. Ph.D. thesis. Colo. State Univ., Ft. Collins, Colo.

Shovic, H. F. 1994. Landscapes of northwestern Yellowstone National Park: soils, landforms, and vegetation characteristics with interpretations for erosion potential and productivity. Pages 273-283 *in* Plants and their environments: proceedings of the first biennial scientific conference on the Greater Yellowstone Ecosystem. Tech. Rept. NPS/NRYELL/NRTR. U.S.D.I., NPS, Nat Res. Pub. Office, Denver, Colo.

Shovic, H. F., M. Johnson, and H. H. Porter. 1994. A new view of an old land. Yellowstone Science. 1(2):2-6. Yellowstone National Park, Wyo.

Shovic, H. F., J. Mohrman, and R. Ewing. 1987. Major erosive lands in the upper Yellowstone River drainage basin from Livingston, Montana to Yellowstone Lake outlet, Yellowstone National Park. Yellowstone Center for Resources, Yellowstone National Park, Wyo.

Shovic, H. F. and C. Montagne. 1985. Application of a statistical soil-landscape model to an order III wildland soil survey. Soil Sci. Soc. Am. Jour. 49: 961-968.

Shovic, H. F, A. Rodman, and D. Neprud. 1991. Soils investigation of the Reese Creek-McMinn Bench-Mammoth area: northwestern Yellowstone National Park, Wyoming. Yellowstone Center for Resources, Yellowstone National Park, Wyo.

Soil Conservation Service. 1985. Glossary of landform and geologic terms. National Soils Handbook 430-VI. U.S.G.P.O., Wash. D.C.

Soil Conservation Service. 1993. Soil survey manual. U.S. Dept. Agri. Handbook 18, U.S.G.P.O.,Wash. D.C.

Soil Science Society of America. 1987. Glossary of soil science terms. Soil Sci. Soc.of Am., Madison, Wis.

Soil Survey Staff. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Soil Conserv. Serv., U.S. Dept. Agric. Handbook 436, Wash., D.C.

Soil Survey Staff. 1994. Keys to soil taxonomy, 6th Ed. SMSS Tech. Monograph No. 19., Natural Resources Conservation Service, U.S.G.P.O., Wash. D.C.

Thornbury, W. D. 1965. Regional geomorphology of the United States. John Wiley and Sons, New York, N.Y.

Thornbury, W. D. 1969. Principles of geomorphology. John Wiley and Sons, New York, N.Y.

Trettin, C. C. 1986. Characterization of soils in Yellowstone National Park- Project Report CX-1200-1B027. Ford Forestry