

Proceedings of the Second Biennial Conference on Research in Colorado Plateau National Parks



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Editor

Charles van Riper III

National Biological Service

and

Department of Biological Sciences

P.O. Box 5614

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Flagstaff, Arizona 86011

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Foreword

The papers in this volume are contributions from National Biological Service (NBS) scientists, university students, and resource managers throughout the Colorado Plateau. The focus of all studies in this volume is on providing baseline scientific information on the physical, cultural, and natural resources of the Colorado Plateau. Support for these studies came from a myriad of federal, state, and private partners concerned about the well-being of the Plateau's resources.

The rich variety of the 68 presentations given at the conference and the 16 papers included here reflects the diversity of science presently being carried out on the Colorado Plateau. I applaud the effort of the contributors who, with modest funding and a broad base of public and institutional support, have pursued important lines of work in the four states that make up this vast biogeographic region.

All across America, we face the prospect of extensive environmental changes that will continue to affect the physical, cultural, and natural resources on our federal lands. As the biological and ecological research branch of the Department of the Interior, we in the NBS are committed to providing sound scientific information that can be used by both public lands managers and private landowners to conserve and manage natural resources.

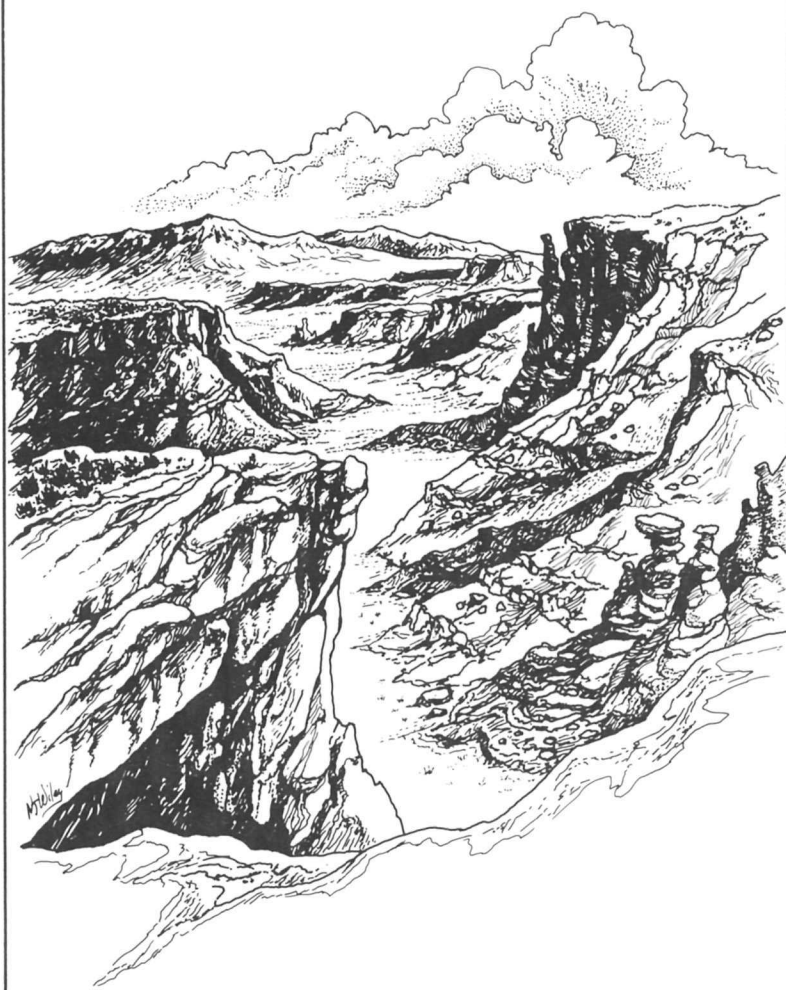
National parks represent the best remaining examples of America's natural ecosystems and, as such, are baselines for measuring future change. To protect parks and other federal lands, we must increase our efforts to inventory and monitor their biological resources, to understand the factors, both natural and human-induced, that threaten them, and to assist with the design of resource management programs that will ensure that future generations can use and enjoy them as we have.

In short, we must provide the sound science needed to conserve and manage the natural resources that sustain us, inspire us, and represent our biological and environmental heritage.

H. RONALD PULLIAM

Director
National Biological Service

Introduction



Introduction to the Proceedings of the Second Biennial Conference on Research in Colorado Plateau National Parks

On 25–28 October 1993 in Flagstaff, Arizona, the National Biological Service Colorado Plateau Research Station (formerly National Park Service Cooperative Park Studies Unit) and Northern Arizona University hosted the Second Biennial Conference of Research on the Colorado Plateau. The conference theme focused on research, inventory, and monitoring on federal, state, and private lands in the Colorado Plateau biogeographic province.

This is the second volume (see Rowlands et al. 1993) of a planned series of Colorado Plateau Research Station proceedings that highlights research and resource management efforts related to physical, cultural, and natural resources within the Colorado Plateau biogeographic province. The 16 papers in this volume were selected from 68 posters and research papers presented at the Second Biennial Conference. Each paper represents original research and has been reviewed anonymously by three peers in that particular research discipline. This volume of proceedings, like the products of other symposia centered around particular themes, will focus attention on some of the salient research being conducted within the Colorado Plateau. I expect this information to stimulate additional support for work on resources of the Colorado Plateau. If the expectation is achieved, the organizational and editorial efforts of the past several years will have paid dividends.

The papers naturally divide themselves into physical resources, cultural resources, and biological resources.

Physical Resources

Hanging gardens are one unique aspect of the Colorado Plateau. May, Fowler, and Stanton describe the geomorphology and community structure of hanging gardens and point out that these gardens occur over sections of the plateau because of unique geologic and hydrologic features. The hanging gardens in each national park on the Colorado Plateau are identified, and a brief classification is provided.

The second paper, by Netoff, Cooper, and Shroba, addresses weathering pits (also known as tanks, caldrons, huecos, dew holes, potholes, water pockets,

and tinajas) in sandstone substrate—another unique facet of the Colorado Plateau. The authors discuss weathering pits in the Glen Canyon National Recreation Area, specifically the series of pits near Cookie Jar Butte. The paper focuses on causes of formation of the pits.

Brown and Davila provide, in the next paper, an insight into how a large-scale mapping project can be beneficial to land managers on the Colorado Plateau. The authors mapped geologic features of Great Basin National Park. The integration of scientific expertise with management needs can benefit all involved parties.

In the final paper of the first section, Dexter, Cluer, and Manone report on the development of a method to monitor sandbar stability along rivers. This research was part of the multimillion dollar Bureau of Reclamation–Glen Canyon Environmental Studies research effort to examine the potential effects of fluctuating flows from Glen Canyon Dam on the down-river resources of Grand Canyon National Park.

Cultural Resources

The four papers in this section were chosen to represent a cross section of cultural and social research being carried out over the Colorado Plateau. The topics presented span a time interval from the archaic (9000 BP) through the Fremont culture (1000 BP) to historical fires in Mesa Verde and a 1993 telephone survey of Arizona residents on perceptions about preservation of Grand Canyon National Park. This section provides the reader with a representative spectrum of research and management alternatives that cultural resource managers can utilize to better know, protect, and preserve archeological, cultural, and social resources over the Colorado Plateau.

One of the continuing controversies that exists on archaic occupation of the Colorado Plateau is whether it has been continually occupied or if humans have moved in and out of the region (e.g., see Berry 1982). The paper by Geib presents an argument, through radiocarbon dating of artifacts, that the central Colorado Plateau has been continuously occupied since 9000 BP.

Some of the most frequently encountered artifacts at archaeological sites on the Colorado Plateau are ceramic potsherds (Colton and Hargrave 1937). In many instances, archaic cultures have been identified as having unique ceramic pottery styles, and the Fremont culture is no exception (Gunnerson 1957). In the second paper of this section, Spurr presents an examination of the compo-

sition of Emery Gray ceramics of the Fremont culture to support the contention that the present classification is not adequate because of inaccurate and inconsistent temper designations.

The third paper provides an example of how research can cross disciplines. Floyd-Hanna, Romme, Loy, and Hanna provide managers with a model that predicts fires and, ultimately, their effects on cultural resources. Because no trees with fire scars were present in their Mesa Verde study area, the authors developed a technique with which to date vegetation recovery.

The fourth paper addresses social research on the Colorado Plateau. Solop and Rodriquez present the results of a telephone survey of Arizona residents that examines public attitudes toward protecting resources of Grand Canyon National Park. Specifically, the authors attempted to gauge frequency of use, levels of concern for protecting Grand Canyon resources, and finally at what level people were willing to endure financial costs to support public policies of park preservation.

Biological Resources

The final section addresses research that has been carried out on biological resources across the Colorado Plateau. The section is subdivided into plant and animal groupings. The plant papers encompass a vegetation scheme for the Colorado Plateau, an analysis of hanging gardens, and a chapter on tissue culture techniques for ponderosa pine (*Pinus ponderosa*). The animal papers are organized by taxonomic level, beginning with amphibian surveys and reptile body temperatures as related to movement patterns, through several papers on birds, and ending with a paper on a mammalian reproductive cycle.

The initial paper might ultimately prove to be one of the most important of this volume. Spence, Romme, Floyd-Hanna, and Rowlands provide a vegetation classification scheme for scientists and managers on the Colorado Plateau. This paper is an accumulation of several years of work by the Colorado Plateau Vegetation Advisory Committee (CPVAC), whose charge was to construct a standardized vegetation theme on the Colorado Plateau for managers.

The second paper revisits hanging gardens to address the endemicity of plants. Fowler, Stanton, Hartman, and May examined 48 hanging gardens in Zion and Capital Reef national parks and Glen Canyon National Recreation Area to provide evidence of the importance of these plant species to hanging gardens.

Ponderosa pine is probably the most important economic tree species on the Colorado Plateau. For this reason, silviculturists have paid considerable attention to the production of young trees that would ultimately prove most suitable for timber production. Lin and Wagner, in the third paper, discuss the methodologies they developed to produce plantlets of ponderosa pine from callus induction and differentiation.

The initial animal paper of this proceedings is by Drost and Sogge and deals with a survey of northern leopard frogs (*Rana pipiens*) along the Colorado River in Glen Canyon National Recreation Area. This paper is important because of the serious declines of anuran amphibians throughout much of North America (see the 1990 paper by Barinaga for a succinct overview of this problem).

The fifth paper features reptiles: Graham, Persons, Schaedla, and Moore relate a study of body temperature patterns of western rattlesnakes (*Crotalus viridis*) at Natural Bridges National Monument. Twelve snakes were implanted with temperature-sensitive radios that revealed lower body temperatures than reported from other species of rattlesnakes.

Johnson and Sogge present the first paper on birds—about the influence that livestock corrals and associated food items have on the abundance and distribution of brown-headed cowbirds (*Molothrus ater*) in Grand Canyon National Park. The authors examined five locations where livestock concentrate in the park and found cowbirds frequenting three sites (two in Grand Canyon village and one at Yaqui Point).

The second bird paper is from a 7-year study reporting on observations at a great blue heron (*Ardea herodias*) colony adjacent to Curecanti National Recreation Area in Gunnison, Colorado. Graham and Meyer documented the gradual movement of heron nests west from Gunnison's city borders as the human population expanded and documented the expansion of the heron colony, which doubled in 5 years.

The last paper pertains to the reproductive cycle of Abert's squirrels (*Sciurus aberti*). This mammal is, much like hanging gardens, a unique aspect of the Colorado Plateau (Hoffmeister 1971). Pogany and Allred relate their research in which, from 1992 through 1994, they collected squirrels killed on roads in Grand Canyon National Park and Walnut Canyon National Monument. Each specimen was examined histologically to determine the phenology of the species' reproductive cycle.

Acknowledgments

The Second Biennial Conference and resulting publication result from the efforts of numerous agencies and individuals. In the planning stages, Northern Arizona University Vice President H. Hooper and personnel from du Bois Conference Center provided advice and assistance in structuring the conference. E. Deshler and M. Sogge (Conference Co-chairs) planned, organized, and directed conference logistics. The Colorado Plateau Research Station (CPRS) staff provided support in areas of registration (M. Rasmussen, J. Henderson), paper and poster presentations (P. Deshler, H. McCutchen, P. Rowlands, N. Brian), editorial (C. Cole), and transportation services (C. Drost). Northern Arizona University graduate students (L. Ellison, M. Johnson, J. Bright, D. Willey, P. Hodgetts, E. Nowak), directed by E. Deshler, assisted with logistics at the meeting, operated slide projectors, and provided general assistance with the paper sessions. I thank the many reviewers who unselfishly devoted their time and efforts to improving each paper. A special thanks to D. O'Leary for providing financial support for this publication from the Washington Office Servicewide Publications Program of the National Park Service.

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Editor

Physical Resources



Geomorphology of the Hanging Gardens of the Colorado Plateau

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Abstract. A roughly J-shaped archipelago of island habitats is distributed within the drainage system of the Colorado Plateau from the Zion area at the southwest to the canyons of the Green and Yampa rivers in the northeast. This is the hanging garden habitat. Hanging gardens are isolated mesophytic communities physically and biologically distinct from surrounding xerophytic or riparian communities. Geologic and hydrologic parameters control the existence, distribution, and physical attributes of the hanging-garden habitat. Attributes vary with the sedimentologic type of the different aquifer-bearing geologic formations in which gardens develop. Within a given formation, garden habitat attributes are relatively consistent. This observation allows a simple, informative, and predictive model of garden geomorphology to be applied across the geographic range of the system. The sandstone aquifers of the Colorado Plateau provide the necessary condition for hanging garden development—a perennial, seep-delivered water supply and an absence of significant fluvial processes. An erosional process called groundwater sapping yields protective geomorphology that shields the habitat from the aridity of the region as well as extrinsic erosional processes. Discharge rate and the lithology of the seep-supplying geologic formation determine the size, shape, distribution, and abundance of microhabitats within a hanging garden. Colonization of microhabitats is determined by the ecological requirements and by the biogeographic and evolutionary history of individual species making up the hanging-garden community. Diversion of the seep supply and erosion of colluvial soil by human foot traffic and livestock use affect garden ecology negatively. Hanging gardens should be protected

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from both activities. Local and regional alteration of patterns of aquifer flow may affect the hanging-garden ecosystem.

Key words: Biogeography, ecology, groundwater sapping, hydrology, mesophytic community.

The Colorado Plateau physiographic province of North America is characterized by areally extensive sedimentary rocks of Paleozoic through Recent ages that are generally flat-lying and are dissected by the Colorado River drainage system. Several transmissive sandstone formations on the plateau, underlain by relatively impermeable strata, are effective aquifers (Taylor and Hood 1988). Large-scale geologic structures (e.g., the Waterpocket Fold monocline and San Rafael Swell upwarp) yield broad dip planes and extensive joint systems within sedimentary strata and control groundwater movement at local and regional scales (Heath 1988). Subject to structural flow controls, groundwater exits from perched aquifers as seeps and springs on the walls of the incised plateau drainage system.

Groundwater erosional processes are land-shaping agents on the arid Colorado Plateau where bedrock is frequently exposed and soil cover is minimal over large areas. For example, the familiar theatre-headed canyons with steep side walls, arch-roofed alcoves, and hanging valleys found in plateau sandstones are the result of a process called sapping (Laity and Malin 1985). Sapping occurs where groundwater flow is concentrated and exits as a seep, eroding rock in that zone and removing the basal support of overlying rock (Dunne 1990). Canyons both widen and lengthen when the unsupported rock collapses. Until this collapse, however, cliffward erosion at the seep zone produces a concave-inward geometry that provides protection from sun and from surface erosion. The hanging gardens of the Colorado Plateau are found in such concavities with active seeps.

The geographic distribution of aquifer sandstones and the drainages that expose seeps control the distribution of the hanging-garden ecosystem. The lithologic and structural character of the aquifer formation, flow dynamics at the seep zone (Kochel et al. 1985), and extent of headward erosion determine which of three basic microhabitats are present and the geomorphology of the whole garden habitat. Our purpose in delimiting the fundamental parameters of garden habitat development is to provide a context for ecological and biogeographic research that distinguishes physical variability from biological variability in the

hanging-garden ecosystem. This distinction will constrain that research to best estimates of biological process and pattern.

Stanton et al. (1991^{*2}, 1992a*, 1992b*) present preliminary results of the community ecology research done on this system. Fowler (1995) discusses endemism in the Zion-area and Glen Canyon hanging-garden communities. We limit the following discussion to the physical character of the habitat of hanging gardens for the purpose described above.

Literature Review

Welsh (1989) and Welsh and Toft (1972) list geologic formations in which hanging gardens are found and classify garden types. Although descriptive and internally consistent, their typing of gardens centers largely on an ontogenetic description of garden development through time. Of course, a temporal component to the geomorphic processes involved exists; however, we find the change is almost entirely one of size. Size is related to the composition of the garden community only by the addition of microhabitat types. Basic microhabitat types are limited to three. Those that characterize a particular geomorphology are determined very early in the erosional sequence; thereafter, size alone does not significantly influence community composition or diversity (Stanton et al. 1992a*, 1992b*). Welsh and Toft (1972) also include both physical and taxonomic criteria in their classification scheme. This does not suit our purpose, because biogeographic and ecologic research require a distinction between geomorphic and biological processes. Where relevant in the following discussion, we correct some geological misinterpretations and misidentifications found in Welsh (1989) and Welsh and Toft (1972).

Little information dealing explicitly with geomorphic processes relating to this unique habitat exists in the literature, though the work of Laity and Malin (1985) describes canyon growth by groundwater sapping. Hamilton (1992) describes geologic processes in the Zion area thoroughly and with strong emphasis on the geomorphology of hanging gardens.

The senior author reviewed pertinent geological literature including stratigraphy, tectonics, sedimentology, geomorphology, and groundwater hydrology to

²Asterisk indicates unpublished material.

provide a regional and site-specific context for the field study of the hanging-garden system (e.g., Cooley 1965; Untermann and Untermann 1965; Huntoon 1982; Doelling 1985; Laity and Malin 1985; Nations 1986; Billingsley et al. 1987; Hamilton 1987; Hintze 1988; Taylor and Hood 1988; Blakey 1989; Bromley 1991; Marzolf 1991; Patton et al. 1991; and others).

Field Methods

In addition to relating the distribution of the hanging-garden ecosystem to the regional geology of the plateau, field study included three levels of analysis. The most inclusive level comprised the geology surrounding that portion of the drainage system containing gardens studied in each of the national parks involved in the project. The intermediate level consisted of observations within individual drainages—both those containing gardens and those where the appropriate geomorphology does not exist—to determine where and how garden development occurs. The most detailed level comprised on-site characterization of the particular geomorphology and lithologic and structural geology at each of the 75 hanging-garden sites that were used for the data base on community ecology. Information gathered and used to derive the following conclusions included location relative to local geological structure, relative location within the drainage, identification of aquifer and aquitard formations or intraformational facies, characterization of the contact between the two, relative estimation of seep discharge, characterization of weathering processes at the seep face and colluvial sedimentation below, and determination of the lateral control on groundwater seepage. Measured parameters included length of primary seep line and number of secondary seeps, dip of slope beneath seep zone, size of microhabitats (i.e., size of vegetation patches used in analysis of canopy coverage), and aspect of the axis perpendicular to the strike of the seep. The information most pertinent to the community ecology and biogeography of the system is in the 1993 annual report to the National Park Service and will also be in future publications.

The following discussion, prospectus, and conclusions resulted from 9 months of field work on the hanging-garden system in 1991, 1992, and 1993 in Zion National Park, Glen Canyon National Recreation Area, Capitol Reef National Park, Natural Bridges National Monument, Arches National Park, Canyonlands National Park, and Dinosaur National Monument.

Discussion

We define the hanging-garden community by its assemblage of mesophytic vascular plants—characterization is made at the community level (Stanton et al. 1991*, 1992a*, 1992b*). Whereas the garden habitat may support some xerophytic and riparian species, the converse is less likely for most garden species—that is, the garden community occupies a distinct habitat and, as a whole, may not survive in either xeric or riparian conditions. We define this habitat by the extent of the primary seep and seep-moistened colluvial soil as described below. The garden habitat is the product of groundwater seepage. Seeps provide perennial, drought-resistant localized water supplies. The associated sapping process creates the protective geometry that allows for colluvial soil development and shields the habitat from the general aridity of the region.

The seep is the necessary—though not sufficient—condition for hanging garden development. Additional primary conditions include the absence of significant fluvial processes and protection from excessive sun and wind in the driest parts of the plateau. These few critical physical parameters determine whether appropriate habitat develops and whether colonization by garden species will be successful. The biogeographic history and dispersal and colonization characteristics of garden species determine the community composition of individual hanging gardens.

Groundwater Sapping and Garden Geomorphology

Sapping occurs where groundwater exits as a seep—not as a spring or point source. At the seep line, water that has moved through the aquifer formation encounters an impermeable layer that prevents its continued downward movement. The impermeable layer, or aquitard, may be the contact with the underlying formation or a stratigraphic facies of lower permeability within the aquifer formation or simply a lense or lamina of lower permeability within the aquifer. A seep zone develops above the aquitard; the rock at the cliff face is virtually water-saturated in this zone, and groundwater exits at a regular rate. Chemical weathering of the aquifer rock occurs in the seep zone, dissolving the cement that consolidates the material. Mechanical weathering—such as expansion by ice formation in colder areas and the precipitation of salt crystals whose growth further deconsolidates aquifer rock—also occurs in the seep zone. The loosened material

falls away from the weathering face. The cliffward erosion of rock at the seep line creates overhead protection for as long as the overhanging rock remains in place, and a concave-headward geometry develops on the strike axis of the seep. Gravity-deposited material, or colluvium, accumulates where slope beneath the seep line is less than the angle of repose of the colluvium and where it is sufficiently protected overhead from precipitation and erosion by fluvial processes.

Seep delivery ensures that water cycles through the garden habitat at a relatively slow rate. Discharge rate is a product of the hydraulic head or pressure of the groundwater at the air–rock interface, the number of seep lines in the seep zone, and the number of secondary seep lines at the site. Beyond a certain discharge rate—the fluvial threshold—water is lost to runoff and may support riparian habitat on alluvial soils beneath the garden.

The absence of significant fluvial processes means that most of the moisture available to garden vegetation moves to root systems laterally and upward by capillary action rather than downward by precipitation. Whereas precipitation and surface water flow are not themselves detrimental to vegetation, they erode the colluvial soil in which garden vegetation takes root.

Hanging-garden Microhabitats

We use *microhabitat* to distinguish specific kinds of places within gardens from the whole hanging-garden habitat. We identify three microhabitats that may exist singly or multiply within hanging gardens: seep-line, wet-wall, and colluvial-soil. The colluvial-soil microhabitat is further divided for increased precision into soil slope and soil ledge in measuring canopy coverage and describing the vascular community. We do not, however, employ the distinction in this paper.

Seep-line Microhabitat

The seep line is the fundamental microhabitat of a hanging garden—seep occupied by garden species is defined as a garden, regardless of size or the presence of other microhabitats. Drainages where groundwater sapping is the primary agent of erosion may contain a large number of individual seep-line gardens. Where these are stacked vertically at one site, we identify one garden with a primary seep and one or more secondary seeps. Where the seep-line microhabitat exists without the other microhabitats, discharge is relatively low, colluvium does not support garden vegetation, and there is insufficient water to maintain a wet-wall microhabitat. Vascular plants root directly in the seep zone. Vegetation uses all water

that is not lost to evaporation. Garden species that can tolerate the driest conditions—*Petrophytum caespitosum*, for example—tend to occupy seep-line gardens with low discharge.

Where discharge rates are higher, the seep-line is but one of the two or three microhabitats present. In these instances, garden species that are also found on colluvial soil and the wet wall occupy the seep-line microhabitat, and the transition into the colluvial-soil microhabitat can be continuous and without a distinct edge.

The seep-line microhabitat is linear. Some overhead protection, if only centimeters deep, is associated with headward erosion by sapping. Orientation of primary seep lines is generally horizontal, though they may exist at any angle—including the vertical—when water movement through joints of the aquifer sandstone is slow (i.e., not greater than the fluvial threshold). In eolian sandstone aquifers like the Navajo and Entrada formations, the high-angle cross-bedding of ancient dunes creates planes of differential permeability that can perch water long enough for its exit as a seep. In these situations, garden vegetation occupies seeps whose geometry mimics the slip-face angle of the original sand dune.

Wet-wall Microhabitat

Where there is sufficient discharge, water flows slowly across bare rock at slopes too steep for the accumulation of colluvium. This is the wet-wall microhabitat, best exemplified by the giant weeping walls in Zion Canyon. The wet-wall microhabitat supports the clinging vascular plants commonly associated with the name and notion of a hanging garden as well as algal and bacterial colonies and bryophytes. Vegetation roots directly in rock fractures or on small clumps of colluvium that accumulate on the irregular wet-wall face.

The wet wall is a zone of active weathering of parent aquifer rock and, because it is sparsely colonized, the erosional process of sapping is most visible here. Wet walls exhibit a continuum of the weathering cycle from well indurated rock (i.e., fresh shear surfaces) to unconsolidated sand that is saturated to depths of several centimeters. Unconsolidated material is held at the face of the wet wall by a gelatinous slime of colonial cyanobacteria. This mass eventually sloughs off with increased weight and becomes part of the colluvial sediment below the seep zone, leaving a fresh shear face on the wet wall. Mineral precipitates and evaporites are common at the air-rock interface of the wet wall, especially on gardens whose aquifer recharge area includes overlying limestones. Groundwater picks up additional mineral compounds that are not degraded before reaching the rock-air

interface. Much of what Welsh (1989) describes as *tufa* precipitates, however, are neither chemical precipitates nor evaporites. Rather, they are a dried crust made up of the sand–cyanobacterial combination described above. These crusts can be quite extensive on some gardens, especially in Zion where the wet-wall microhabitat is common. Broken apart, the alternating substrate and bacterial laminae give the appearance of stromatolite. This crust is abrasive when dry, as is travertine. Though this is a property of its sand content, it probably partly led to the misinterpretation that it is a precipitate.

Wet walls are usually close to vertical in orientation and frequently are super-vertical with either parallel concave or convex geometry relative to the cliff face as a function of site-specific structure. Clinging species are able to take root even on the underside of a garden roof, providing the seep zone continues overhead. Wet-wall microhabitat may also exist at substantially lower slopes though, when approaching the horizontal, water tends to flow faster, and fewer plants are able to take root. This microhabitat is subject to perturbation by ice shear in some areas.

Colluvial-soil Microhabitat

The colluvial-soil microhabitat supports both the greatest abundance and the greatest diversity of hanging-garden vascular species (Stanton et al. 1992a). Soil development on colluvium results from direct weathering of parent material. Colluvial soils in the protective geometry of hanging gardens are moistened by lateral and upward wicking of seep-delivered water. A drip line from overhanging rock is a slow, steady supply in most instances and does not result in significant erosion.

Species found on the seep line and wet wall also colonize the colluvial-soil microhabitat, with the exception of the least mesophytic (e.g., *P. caespitosum*). Additional forbs, grasses, sedges, and woody species colonize colluvial soil and increase the diversity of gardens with this microhabitat. Those xerophytic and riparian species that are able to colonize hanging gardens usually do so at the corresponding edges of colluvial-soil vegetation patches. Edges with transitional species are defined at either the point at which colluvium is no longer moist (in the instance of a xeric edge) or where alluvial sediments begin and colluvial sediments end (in the instance of a riparian edge).

The geometry of the colluvial-soil microhabitat may be triangular or tabular (i.e., quadrilateral), depending on the structure of the aquifer formation. Gardens

that form in eolian sandstones generally have triangular colluvial slopes, with the broad edge high and extending the length of the primary seep line and tapering inward downslope with the movement of water through the soil. Triangular shape is associated with a concave-inward geometry on the axis perpendicular to the strike of the seep. This is especially true for obvious reasons at the drainage head, even in noneolian aquifer formations. Welsh and Toft's (1972) classic alcoves exhibit this geometry. Tabular shape is associated with near-shore marine and fluvially deposited sandstones with strong horizontal bedding. The soil extends downslope at relatively equal depths all along the lateral extent of the primary seep. These slopes may also be concave-inward parallel to strike but not perpendicularly, and they do not taper downslope.

Unlike the other two microhabitats, the colluvial-soil slope is located almost entirely below the seep zone, developing largely in the aquitard formation or facies. Aquitard facies are finer-grained sandstones, siltstones, or mudstones of fluvial or lacustrine origin—hence their lower transmissivity and water-perching ability. They are horizontally bedded and so weather into alternating slopes and ledges above which colluvial sediments can accumulate. The colluvial soil that develops on the aquitard is thus composed not only of weathered sandstone but also has a component of the aquitard petrology as the result of in situ weathering of that parent material. The higher the mudstone percentage composition of the aquitard, the higher the clay content of colluvial soils that develop on it.

Colluvial soils on hanging gardens tend to be water saturated. Slopes are frequently greater than 65° . Neither unconsolidated sand nor suspended clay is particularly stable at steep slopes, so this microhabitat is exceptionally sensitive to disturbance and may be easily eroded.

Hanging-garden Classification

Hanging gardens may be described in terms of their shape and geometry and the microhabitats present. This specifies relative discharge rate of the seeps and implies the overall geomorphology of the habitat and its sedimentological origin. A classification built on microhabitats is descriptive and predictive, yet it serves to minimize physical variability that does not relate to biological variation. This is an important distinction for ecological research.

Gardens are either simple or complex; that is, they consist of either the seep-line microhabitat alone or that microhabitat plus either or both the wet-wall and colluvial-soil microhabitats.

The overall shape and geometry of complex gardens is strongly associated with the sedimentologic type of the aquifer formation. Those that are triangular and strongly concave-inward perpendicular to strike are associated eolian sandstones such as the Navajo Sandstone (Ss). We refer to gardens with this overall geometry as *Navajo-type* complexes. These generally exhibit strong lateral control on the seep zone by either jointing or structural concentration of groundwater flow. When headward erosion has undercut overlying rock that is still in place, these gardens are roofed and correspond with Welsh’s classic alcove (Welsh and Toft 1972.)

Tabular-shaped gardens are associated with sandstones that are strongly horizontally bedded, like the Cedar Mesa Ss. The Cedar Mesa is of near-shore marine and fluvial origin, with alternating facies of differential permeability. Lateral control on the seep line is weak—groundwater is translated horizontally for long distances above aquitard facies. Colluvial-soil slopes are long and shallow with slight strike-parallel concave-inward geometry, except at drainage headwalls. We refer to gardens with this geometry as *Cedar Mesa-type* complexes.

Thus we describe gardens as one of four possible combinations of microhabitats in one of three categories as follows:

Simple (linear)	Navajo-type complex (triangular)	Cedar Mesa-type complex (tabular)
(1) seep-line	(2) seep-line + wet-wall	
	(3) seep-line + colluvial-soil	
	(4) seep-line + colluvial-soil + wet-wall	

Diversity of the garden community does not increase substantially with the addition of the wet-wall microhabitat. The presence of the colluvial-soil microhabitat does correlate, however, with increased diversity (Stanton et al. 1991*, 1992a*, 1992b*). Multiple instances of different microhabitats within a single garden, though a measure of increased physical complexity, do not correlate significantly with diversity trends in the vegetative community (contra Welsh and Toft 1972).

We do not distinguish gardens associated with plunge pools from those that are not. Vegetation surrounding such pools is normally riparian and is not counted in the garden community unless it is obviously on colluvial soil rather than alluvial. Plunge pools are the geomorphic results of intense, periodic surface runoff. Though both surface and groundwater tend to concentrate at the heads of drainages (indeed, the topographic concentration creates the drainage), hanging gardens and plunge pools at headwalls are coincidentally linked by location. Seeps are a groundwater process—plunge pools are the product of surface flow.

Hanging Gardens in Colorado Plateau National Parks

The following is a general physical characterization of hanging gardens in each of the seven national park jurisdictions included for research in this study. Gardens in each are treated collectively. (Please see reports to the National Park Service [Stanton et al. 1991*, 1992a*, 1992b*] for descriptions of individual garden morphology and community ecology.)

Zion National Park

We studied hanging gardens in Zion National Park in 1991 and 1992. Pine Creek Hanging Garden is developed in the Springdale Sandstone Member (Mbr) of the Early Jurassic Moenave Formation, above the clay-rich mudstone of the Whitmore Point Mbr. It is a complex Cedar Mesa-type hanging garden, with a tabular colluvial-soil slope. The small wet-wall microhabitat is saturated up to 3 cm cliffward. Precipitates, evaporites, and dried cyanobacterial crust are prevalent at this garden and elsewhere at seep zones in Pine Creek.

All other gardens studied in Zion are developed in the Jurassic Navajo Ss. The Navajo Ss reaches its greatest stratigraphic thickness here (more than 600 m) and contains a large volume of groundwater. Gardens in Zion Canyon have surplus discharge that runs off the garden and is frequently held in plunge pools below (e.g., Upper Emerald Pool) before discharging into perennial tributaries to the Virgin River. Amphitheatre-shaped bowls at the heads of these tributaries support well developed hanging gardens. These are complexes of all three microhabitats, which frequently exist in multiple. Gardens that develop on the sidewalls of Zion Canyon and tributaries tend to have extensive wet walls. This is due partly to the hydraulic head of groundwater in this thickest section of the Navajo Ss, which results in large seep zones with high discharge rates. Frequently, however, a joint in the Navajo Ss lies in a plane parallel to the canyon wall so that groundwater

exiting high simply flows over the edge of the joint onto the cliff face (e.g., Weeping Rock Hanging Garden). Eventually the outer slab of suspended rock spalls away from the face, exposing even more wet wall.

The base of the Navajo Ss is exposed throughout much of Zion Canyon, and it is at this basal [gradational] contact with the underlying Kayenta Formation (Fm) siltstones–mudstones that most primary seep microhabitats are located. The wet-wall microhabitat above develops in the Navajo Ss and is supplied by higher secondary seeps. The colluvial-soil microhabitat occupies slopes and ledges in the Kayenta Fm below. The Emerald Pools in Heap’s Canyon are a curiosity in which two Navajo–Kayenta couplets are vertically stacked. The Navajo and Kayenta formations intertongue extensively in the southwest portion of the Colorado Plateau (Blakey 1989). In this locality, a tongue of Navajo Ss separates the Kayenta siltstone–mudstone into upper and lower aquitards (Hamilton 1992). The hanging gardens above Upper and Lower Emerald pools develop at the base of the main body and the tongue of the Navajo, respectively (contra Welsh 1989; the Springdale Mbr of the Moenave Fm is not exposed in this portion of the canyon). Welsh describes a *boulder [hanging] garden* between Upper and Lower Emerald pools; we identify this habitat as riparian with colonization by some garden species and do not recognize a Middle Emerald hanging garden.

Garden habitat along the Narrows Trail in Zion National Park is also a complex of the three microhabitats. In this locality, the basal Navajo seep line extends laterally for several hundred meters, and multiple patches of wet-wall and colluvial-soil microhabitat are distributed where the seep follows an inward curve of the canyon wall.

We also studied gardens found high up-section in the Navajo Ss on the Overlook Trail at the east end of the highway tunnel. Seeps here are perched on an intraformational horizontal bedding plane. Less groundwater is available this high in the section—these gardens have lower relative discharge rates than stratigraphically lower gardens. Interestingly, these drier gardens have higher species-to-area ratios than the large, wet gardens in Zion Canyon and were our first evidence for the inverse relation between overall wetness and diversity on hanging gardens.

Glen Canyon National Recreation Area

We studied gardens on the Colorado River and on tributaries to the San Juan and Escalante rivers of Glen Canyon in 1991 and 1992. These 27 gardens are all

developed within the Navajo Ss, at its base, or within the 12–21-m-thick transitional zone that exists between it and the underlying Kayenta Fm in some areas of Glen Canyon (Cooley 1965). The Navajo Ss is between 120 and 245 m thick in the Glen Canyon area and is largely flat-lying and exposed at its surface with little soil development or vegetative cover. The contrast between the surrounding slickrock and the hanging-garden community is striking in Glen Canyon. This area is the hottest and most arid of those in this study, and protection from both sun and drying wind is a critical geomorphic parameter. The shade line at midday in July virtually prescribes the edge of the garden community. Gardens on sidewalls are frequently developed in distinct, relatively compact alcoves with deep roofs—a very protective geomorphology. Simple seep-line gardens of low diversity are ubiquitous on those drainages growing by groundwater sapping. These exist anywhere on canyon walls along cross-bed laminae and horizontal bedding planes. Many are monospecific—inhabited only by *Petrophytum caespitosum*.

Gardens located in drainage headwalls exhibit the typical complex of three microhabitats, concave-inward geometry on both axes, and triangular colluvial-soil slopes. Secondary seep lines above the primary seep zone are common. The wet-wall microhabitat in Glen Canyon is generally small relative to total garden size and moist rather than covered with sheet flow. Plunge pools are common below the garden. Their formation by periodic intense surface runoff from the canyon rim above the garden is obvious here in the slickrock.

Although the thickness of the Navajo Ss here is half of that in Zion, it has greater surface exposure to recharge. Runoff of excess water is common here as well, extending seasonal persistence of intermittent streams below and providing reproductive habitat for several amphibian species. *Bufo punctatus*, *B. woodhousei*, *Hyla arenicolor*, and *Rana pipiens* utilize the plunge pool habitat below gardens at a number of our Glen Canyon sites. Water loss to evaporation, however, is high at all points in the cycle from seep to runoff and probably masks the true discharge volume.

Capitol Reef National Park

Hall's Creek and the east side of Waterpocket Fold were surveyed for gardens in the 1992 and 1993 field seasons. This monoclinal structure largely precludes the geomorphology necessary for hanging garden development. The Navajo Ss dips at so strong an angle over the east side of Waterpocket Fold that there is almost no low-angle exposure to charge the interstitial space of the

sandstone. Water entering the sandstone at its upper exposure is quickly shunted downward through the joints and fractures associated with the strong monocline. Surface water flowing over the sandstone simply runs right over the slickrock fold. During intense summer storms, this runoff shoots outward off the fold to free fall almost 245 m into Hall's Creek—a powerful sight from the bottom of the drainage. Furthermore, the contact with the Kayenta aquitard is buried at the bottom of the fold so that what groundwater does move through the sandstone does not encounter an impermeable layer while exposed.

Nevertheless, some hanging garden development exists in Capitol Reef National Park. At the bottom of the fold, in the Hall's Creek Narrows, seep lines just above the riparian zone support low-diversity gardens primarily composed of *Adiantum capillus-veneris*. The seeps are intraformational on horizontal bedding planes and cross-bed laminae within the Navajo Ss. The recharge is probably the upstream water table of Hall's Creek. One low garden, Sidewall Hanging Garden, seems to be supplied by water moving down an extensive vertical joint and charging laminar seeps above the garden.

We found two gardens higher in the Navajo Ss formed at intraformational seep lines. These are small (long axis <10 m) with little colluvial soil development and low discharge rates. The diversity-to-area ratio is high for one of these gardens. This habitat also supported one canyon treefrog (*H. arenicolor*) far from any other source of permanent moisture. The scarcity of hanging gardens in Capitol Reef National Park makes those that are developed a rare and important resource.

Natural Bridges National Monument

White Canyon and its tributary drainages cut through the Permian Cedar Mesa Formation in Natural Bridges. The Cedar Mesa Fm consists of fluvial and nearshore marine dune sands interbedded with less permeable finer-grained interdunal, lacustrine, and overbank facies. The sandstone facies are up to 10 m thick, and the silty facies are usually less than 3 m thick in the outcrop area studied. Low-angle cross-bedding and significant horizontal bedding characterize the sandy facies, and horizontal structure is primary in the silty facies. This sedimentology yields a different geomorphology than that seen in the eolian sandstones of the plateau. Eolian sandstones are characterized by high-angle cross-bedding, little horizontal structure, and relatively homogeneous, amorphous lithology. When undercut, eolian rock masses spall off along curved planes that frequently correspond to the angle of repose of the slip face of the original dune. This angle is

harmoniously repeated all over the slickrock country of the plateau in alcoves, arches, and other nonlinear landforms. Noneolian sandstones like the Cedar Mesa do not exhibit this weathering pattern. The Cedar Mesa Fm is strongly structured horizontally, is more heterogeneous in lithology, and weathers into steplike, linear, laterally extensive geometries by both fluvial and groundwater processes.

The gardens that form in the Cedar Mesa Fm are long laterally and short vertically. We estimated that one garden in Tuwa Canyon, while not included in this study, extended laterally more than 500 m, but its width never exceeded about 10 m. Gardens are concentrated in the upper third of the Cedar Mesa section; most groundwater volume is translated laterally before reaching the lower two-thirds of the section.

The wet-wall microhabitat is not common on Cedar Mesa gardens. Bicarbonate is an abundant evaporite on colluvium. Except at drainage heads, the colluvial-soil microhabitat is generally tabular shaped with slight, concave-inward geometry parallel to strike. Overhanging ledges protect colluvial soils from erosion by precipitation. These are higher-elevation gardens than those in Zion and Glen Canyon, and shade seems to be less important to the garden community (determined by the correlation between aspect and vascular community attributes). Gardens are concentrated on the east side of White Canyon because groundwater follows the shallow west dip of the formation until it exits at the canyon intersection.

Arches and Canyonlands National Parks

Gardens in these parks, studied in the 1993 field season, are treated collectively here because there is no significant geomorphic difference between them. The Jurassic Wingate, Navajo, and Entrada sandstones (the Glen Canyon group) are all well exposed in this area. All are considered to be primarily eolian dune deposits, though this interpretation for the Navajo further west has been debated (e.g., Marzolf 1976). All are characterized by high-angle cross-stratification and the weathering pattern described above. While the Wingate is a potential aquifer, it is largely overlain by the Kayenta Fm and is seldom exposed to recharge at the surface. May surveyed the top of the Chinle Fm (i.e., the base of the Wingate) in 1993 in the Upheaval Dome area of the Island in the Sky district and identified no hanging gardens. The large alcove supporting garden species off the first switch-back of the Schafer Trail reported by Welsh (1989) as forming in the Wingate is actually in the Navajo Ss.

The Navajo Ss is the primary garden-forming aquifer in this region. At Island in the Sky in Canyonlands National Park, seeps on the Neck Springs Trail form at the base of the Navajo (contra Welsh 1989) above a fairly distinct contact with the underlying Kayenta Fm. The Navajo Ss is less than 100 m thick here, and the recharge area at Island in the Sky is restricted, so seeps here are probably more subject to seasonal fluctuations in discharge rate. Nevertheless, there is sufficient flow through the aquifer to support gardens of moderate to large size with excess runoff. These are typical Navajo-type gardens, much like those found in Glen Canyon.

Navajo-type hanging gardens develop in the eolian Entrada Ss in Arches National Park as well. We sampled gardens developed on south-facing walls on the north side of the Salt Valley in the Delicate Arch vicinity. Vertical displacement on a more or less west–east trending fault creates two slickrock benches that expose the contact between the Moab Tongue Mbr above and the Slickrock Mbr (below) of the Entrada Fm. The seep line runs much of the length of this contact on both benches. Navajo-type gardens form in the drainage nickpoints of a series of joints that run perpendicular to the fault line. The seep line in between these larger gardens supports laterally extensive gardens that grade outward from complex to simple.

Dinosaur National Monument

We studied gardens on the Green and Yampa rivers and tributary canyons in the 1993 field season. The primary garden-forming aquifer in this region is the Pennsylvanian–Permian Weber Ss. The Weber exhibits variable facies lithologies. Gardens high in the section (e.g., up Bull, Johnson, and Red Rock canyons and up Ely Creek) are of the Cedar Mesa-type geomorphology. Signature Cave hanging garden, however, developed at the base of the Weber Ss beneath a deep classic alcove. It is a Navajo-type garden with a triangular colluvial-soil slope and pronounced strike-perpendicular concave-inward geometry. The seep seems to exit from the base of the Weber at its contact with the underlying Morgan Fm, though the seep line itself is largely obscured by colluvium. This far north on the plateau, and at this elevation, shade becomes relatively unimportant.

An anomalous situation exists at Limestone Hanging Garden up Limestone Draw on the Green River. Groundwater moves down through about 245 m of Morgan Fm and Round Valley Limestone and is slowed at the top of the Mississippian Doughnut shale. It exits and flows over the sloping Doughnut Fm

and the sandier Humbug Fm. The groundwater exit at this site is laterally small, yet a large volume of water is discharged onto a narrow, deep, vegetated slope. Close to the seep line, the garden is typically concave-inward, with a wet-wall microhabitat, secondary seeps, and a protected triangular colluvial-soil slope. Below the seep zone, however, are several vegetated slopes that are fully exposed to fluvial processes. These slopes support hanging-garden species, though a channel through the larger slope contains running water and supports riparian species. In this instance only, the authors disagree on how to delimit the garden. One of us (J.F.F.) defines the anomalous slopes as in-garden based on the presence of the hanging-garden plant community. The senior author (C.L.M.) cannot distinguish a sedimentologic difference between these slopes and the surrounding talus slopes with which they are continuous (other than their colonization by garden vegetation) and would limit this garden to the edge of typical fine-grained, well sorted colluvial sedimentation and protective geomorphology. This site includes point-source flow in addition to seepage and accompanying alluvial sedimentation on the talus beneath the colluvial slope.

Aquifers on the Colorado Plateau and the Age of the Hanging-garden Ecosystem

The sandstones of the Colorado Plateau are the region's major aquifers. The Early Jurassic Glen Canyon group in particular is both laterally and stratigraphically extensive. In fact, the Navajo Sandstone is the largest eolian unit of the Earth's rock record. These aquifers hold an immense volume of water. However, due to fine grain size, alteration of mineralogy during diagenesis, overburden loading, and secondary infilling of joints and fractures, the primary permeability of these sandstones is minimal (Hood and Patterson 1984; Taylor and Hood 1988). Furthermore, the Colorado Plateau-Wyoming Basins hydrologic region has the lowest recharge rate on the North American continent (Heath 1988). Considering, then, that these formations are not easily charged with groundwater, how is it that they are such effective aquifers? Logically, if recharge is slow, then a significant amount of time is required to account for the present volume of water stored in these sandstones. Likewise, the rate of discharge must not have significantly exceeded recharge rate during the time elapsed since downcutting exposed perched aquifers.

Downcutting on the Colorado Plateau began with its initial uplift as early as the middle Eocene (+43 million years ago [m.y.a.]). The Colorado River and its tributaries seem to have evolved separately in individual areas and at slightly different times (Patton et al. 1991). The modern Colorado drainage was established between 11 and 5 m.y.a. (Larson et al. 1975a, 1975b; Lucchitta and Young 1986; Lucchitta 1990). Given the Recent arid climate regime on the Colorado Plateau, it seems likely that aquifers exposed to surface recharge during Pleistocene wet cycles were fully charged at that time and that recharge has more or less kept up with discharge to maintain the current volume for about 1.8 million years.

The age of the hanging-garden ecosystem is not known. We may parsimoniously assume that as soon as downcutting exposed perched aquifers, the processes that develop garden geomorphology could proceed. Based on estimated ages of paleodrainages, it is conceivable that appropriate garden geomorphology has existed in some areas for as long as 15 million years. A safer assumption, based on the estimated age of the modern drainage system, would allow garden geomorphology since about 5 m.y.a. Certainly the process of groundwater sapping on the Colorado Plateau was well under way by the early Pleistocene (~1.8 m.y.a.). Quaternary paleontologists and paleoecologists use fossil data collected in dry alcoves and caves formed by this geomorphic process to reconstruct post-Pleistocene climate and ecosystem history.

The presence of the appropriate geomorphology, however, does not necessarily imply the historical presence of hanging gardens. A strong possibility exists that discharge rates from perched aquifers before the current arid regime were too high to allow colluvial sediments to accumulate. The garden community is supported by slow-delivery seeps—not by springs. Furthermore, we do not know whether the early vegetation that occupied this geomorphic habitat was similar to the modern assemblages. Direct evidence is unavailable because the saturated soils of the garden habitat do not preserve plant megafossils. Palynomorph analysis of sediments from dry alcoves or fossil evidence from packrat (*Neotoma* spp.) middens can tell us what the vegetation of the region was like at a particular time, but that does not necessarily inform us of the community composition of a hanging garden from the same stratigraphic horizon. Certainly the modern garden community is dissimilar from its surrounding flora. Also, alcoves and caves in the canyon system of the plateau are formed by fluvial processes as well as groundwater processes. As downcutting proceeds, channel widening performs the same removal of basal support as the seep does on a canyon wall or headwall. So even

evidence from dry alcoves at the same stratigraphic level does not assure the historical presence of a hanging garden (contra Welsh 1989; gardens are consequent on their geomorphology, not the converse).

We may deduce only that the distinct ecosystem we identify as hanging gardens on the basis of the vegetative community is maximally as old as charged aquifers exposed by downcutting and likely no older than the current arid climate regime (i.e., the system probably dates from the Pleistocene). The senior author further postulates that a significant portion of the current plateau aquifer volume is Pleistocene in age and that post-Pleistocene aridity and the low recharge rate of these aquifers combine to make this groundwater system extremely susceptible to permanent draw down. The hanging-garden ecosystem is necessarily equally susceptible to degradation.

Prospectus

Whether the modern garden community is a relict of a previously widespread flora or the product of dispersal from other source areas—or both—is a central question currently being addressed by the authors. The hanging-garden system naturally lends itself to longitudinal ecological investigation; indeed, monitoring the status of its endemics requires continued research. Additional primary research should include a comprehensive soil analysis with sufficient geographic distribution to ensure sampling the variability. The Grand Canyon section of the Colorado drainage system should be surveyed for hanging gardens.

Conclusions

The importance of groundwater geomorphology to the hanging-garden ecosystem cannot be overstated. The first condition for both habitat development and initial colonization is the seep. Habitat and community evolution are linked to seep-controlled geomorphic processes. A fluctuation-resistant water delivery system with no fluvial component is critical to the persistence and stability of the garden ecosystem.

Aridity is a primary feature of the Colorado Plateau, affecting geomorphic and biologic processes in both ecological and evolutionary time. The aquifers of the plateau mitigate aridity constraints for the hanging gardens. These aquifers are

likely older than the current climatic regime and recharge at a very slow rate. Long-term persistence of the hanging gardens depends on maintenance of aquifer volumes.

The physical attributes of hanging gardens are a product of the sedimentology, lithology, and structure of the geological formations in which they develop and the corresponding geomorphology produced by groundwater sapping. Similar sedimentologies yield gardens that are geomorphically similar. Community similarity or difference is a function of the biogeographic and evolutionary history of component species.

Management of the hanging-garden ecosystem should include preventing the erosional effects of humans and livestock, preventing or removing local seep diversions, and consideration of the potential long-term effects of both drawdown and reservoirs on aquifer flow patterns.

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Giant Sandstone Weathering Pits Near Cookie Jar Butte, Southeastern Utah

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Abstract. In arid southeastern Utah, giant weathering pits in the lower member of the Entrada Sandstone of the Middle Jurassic age are striking features of the landscape near Cookie Jar Butte in Glen Canyon. The pits are larger than most of those described in the geologic literature (as wide as 38 m and as deep as 16.5 m). Four pit types identified on the basis of cross-sectional form are cylinders (the most abundant type), bowls, armchairs, and pans. Sandy sediment commonly veneers the bedrock floor of all pit types. The sediment is similar in character to the adjacent sandstone and is probably locally derived. Many of the deeper pits retain water from months to years, and water temperature and pH values vary considerably by season. Vegetation in pits that are not periodically inundated with water differs by type and amount; pits with the thickest sediment tend to have the densest cover. Laboratory analyses of sandstone from pit walls, floors, and rims reveal a fine-grained (\bar{x} diameter about 90–100 μ) arkosic sandstone that is weakly cemented with CaCO_3 (2.7–9.1% by weight) and lesser amounts of clay. Thin-section analyses of the sandstone cores reveal quartz, plagioclase, and potassium feldspars that are relatively unweathered, and examination using a scanning electron microscope indicates that most grains are coated with variable thicknesses (0–5 μ) of clays and iron oxides—interstitial clays constitute 1–6% of the total sample. Physical weathering such as spalling, salt crystal growth, and clay mineral hydration and dissolution of carbonate cement weaken the sandstone. The sediment produced by these processes is probably removed by wind, plunge-pool action, and perhaps dissolution and piping. The cause of the removal of pit sediment is unknown.

Key words: Entrada Sandstone, Glen Canyon National Recreation Area, pothole, tinaja, water pocket.

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Weathering pits are typically broad, shallow depressions formed on flat to gently-sloping outcrops of bare rock. They are commonly flat-floored, as wide as a few meters, and a few tens of centimeters deep. Theories on their origin usually propose a combination of physical, chemical, and biological weathering processes that promote mineral decomposition and the action of wind or water that removes the decomposed material. Little is known about the age of weathering pits.

Weathering pits have attracted special attention in arid regions, where they have been watering holes for people and animals for millennia. This accounts for many of the local names given to them, such as cisterns, tanks, caldrons, huecos, dew holes, potholes, water pockets, and tinajas. Pits develop on diverse lithologies; intermittent ponds have been reported on quartzite ridges in North Carolina (Reed et al. 1963), in limestone in Texas (Udden 1925), in arkose at Ayers Rock in Australia (Twidale 1982), and unusually deep (8 m) pits in granite-gneiss in Brazil (Twidale 1968). Weathering pits are nearly ubiquitous on gently-sloping outcrops of weathered granite and sandstone. Weathering pits are so abundant on friable sandstones of the Colorado Plateau that they locally create a distinctive dome-and-pit landscape.

Previous investigators focused on pits with high width-to-depth ratios and on processes that weather rock rather than those that remove the weathered material. The limited quantitative data on pit morphology indicate that pits are typically circular to elliptical in plan view, flat-floored, have widths of 0.5 to 3.0 or 4.0 m, depths of 5 to 60 cm, and average width-to-depth ratios of 6:1 to 10:1 (Udden 1925; Twidale 1982; Ollier 1984; Alexandrowicz 1989). Angeby (1951) and Jennings (1967) reported much deeper holes, but the origin of these depressions seems related to plunge-pool action at the base of waterfalls and to collapse into subterranean voids and not solely to weathering. Weathering processes proposed for pit development emphasize the role of water, which, partly because of reduced rates of evaporation, probably remains for progressively longer periods as the pit deepens. Reference is made to some combination of physical, chemical, and biochemical activity that accounts for weathering of pit walls and floors (Udden 1925; Matthes 1930; LeGrande 1952; Reed et al. 1963; Jennings 1967; Roberts 1968; Twidale and Bourne 1975; Godfrey 1980; Jennings 1983; Goudie 1986; Young 1987a; Howard and Kochel 1988; Alexandrowicz 1989). Authors do not agree, however, on the role and relative importance of specific weathering processes—salt crystal growth, spalling, hydration and desiccation, solution, hydrolysis, attack by organic acids, frost

weathering, and colloidal plucking in pit initiation and growth. Although the existence of salts and calcite is frequently cited as evidence of crystal wedging (Bradley et al. 1978; Laity and Malin 1985), it is difficult to demonstrate that these minerals are the direct cause of grain dislodgement (Young and Young 1992). Howard and Kochel (1988) and others stated that solutions of calcite cement locally created karstic landforms on barren, smooth outcrops of friable sandstone (i.e., slickrock) slopes in the Glen Canyon region, but they provided little evidence to support their statement. Goudie (1991) summarized the most recent literature on pan development and supports the idea that the initial depressions are largely the result of solution. He also concludes that aridity contributes to pan development by limiting vegetation cover (permitting deflation), and by localizing salts (promoting rock disintegration).

Several mechanisms have been proposed to account for the removal of weathered sediment from pits (Barnes 1978). Wind deflation is thought by some to be effective, although Twidale (1982) de-emphasized its importance. Where pits are in or near intermittent water courses, fluvial action may abrade bedrock and remove sediment. In deeper pits, especially those that are not integrated into water courses, subsurface removal by dissolution or piping has been proposed, particularly for pits that are obviously connected to underground conduits (Twidale 1990). Extensive underground tubes and cavities in quartz sandstones have been reported in Venezuela and Australia (Jennings 1983; Young 1987b).

Some of the most conspicuous gaps in the literature concern the age and rate of development of weathering pits. Matthes (1930) noted that weathering pits in the Sierra Nevada are present on older glaciated surfaces but are absent on recently (less than 10,000 years?) glaciated surfaces. In the Colorado Front Range, incipient pits have developed on boulders in glacial deposits of Holocene age (Birkeland 1984; Birkeland et al. 1987). The Mistor Pan in Dartmoor, England, is a large, well known pit that was first described in 1291; its depth did not significantly change between 1828 and 1929 (Twidale 1982). The rate of pit growth may be highly variable, depending on factors such as climate, lithology, and rate of sediment removal.

Clusters of giant sandstone weathering pits are known at three sites in southeastern Utah; two are in the lower part of Glen Canyon, which is partially inundated by Lake Powell (Fig. 1). The pits near Cookie Jar Butte and Rock Creek Bay are formed in outcrops of the lower member of the Entrada Sandstone of Middle Jurassic age.

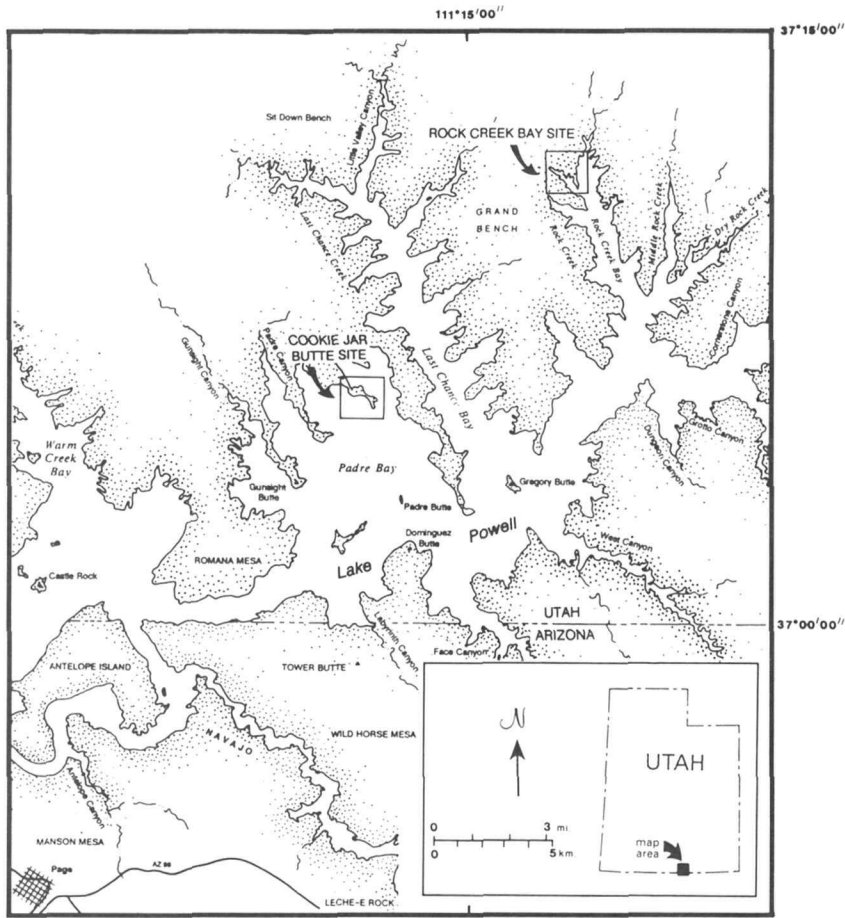


Fig. 1. Map of the giant weathering pits near Cookie Jar Butte and Rock Creek Bay, Utah.

Field and laboratory analyses of the pits near Cookie Jar Butte were done in 1992 and 1993. Measurements indicate that these pits are much deeper than typical weathering pits; they may be among the deepest in sandstone on earth (Netoff and Shroba 1993). They are of considerable geomorphological interest because of their immense size and because their origin is difficult to explain by conventional theories.

The major objectives of this report are to describe the geologic occurrence, dimensions, and geometry of the weathering pits at Cookie Jar Butte and to evaluate several hypotheses that might account for their origin.

Study Area

Cookie Jar Butte is on the north side of Padre Bay (Fig. 1; Sec. 7, T. 45 S., R. 6 E. of the Gunsight Butte 7.5-minute quadrangle, Utah) in an approximately 30-ha area of pitted terrain on gently to moderately-sloping surfaces. Clusters of giant weathering pits in the Entrada Sandstone also exist at two other sites: one is on a mesa top near the head of Rock Creek Bay, and the other is at Dance Hall Rock, about 30 km northeast of Cookie Jar Butte. Neither was examined in detail.

The bedrock of this part of the Colorado Plateau consists of horizontal to gently-dipping Mesozoic and Cenozoic sedimentary strata, locally deformed in monoclinal folds and broad upwarps and downwarps. Cookie Jar Butte lies along the southeastern margin of the Kaiparowits Downwarp, which has regional dips of about 1° toward the northwest (Hackman and Wyant 1973).

The bedrock at and near Cookie Jar Butte is described in detail by Peterson and Barnum (1973) and Sargent and Hansen (1982) and is briefly summarized here. From bottom to top, the rock units include the Navajo Sandstone (Lower Jurassic), the upper member of the Carmel Formation (Middle Jurassic), the lower member of the Entrada Sandstone, the middle member of the Entrada, the sandstone at Romana Mesa, and the Salt Wash Member of the Morrison Formation (Upper Jurassic).

The lower member of the Entrada Sandstone, in which all of the giant pits have formed, is an orange, reddish-brown to buff, very fine-grained sandstone that is thinly to thickly cross-bedded. It has been described as a quartz-rich sandstone (quartz arenite), composed predominantly of subrounded to subangular quartz grains (Harshbarger et al. 1957; Witkind 1964; Davidson 1967; Peterson and Pipiringos 1979). Our laboratory analyses, however, reveal abundant (20–29%) feldspars and lithic fragments (3–14%), indicating an arkosic sandstone. It is approximately 170 m thick near Cookie Jar Butte. Large, irregular masses of structureless sandstone exist locally at the study site, some of which are partially exposed in pit walls and rims. The lower member of the

Entrada is thought to be of eolian and nearshore marine origin (Peterson and Barnum 1973).

The layer-cake structure of the rocks in the Glen Canyon region and their deep dissection by the Colorado River and its tributaries have produced a stair-step landscape, including mesas, buttes, structural terraces, steep-walled canyons, and talus-mantled ledgy slopes at the base of steep slopes. The Salt Wash Member forms the resistant caprock on the mesas and buttes that rise above Cookie Jar Butte. Distinctive topographic features that have developed on both the Navajo and Entrada sandstones include alcoves, varnished cliffs with rounded shoulders, pitted uplands, and slickrock slopes (Fig. 2). These features are in marked contrast to the flat-topped bedrock terraces and sharp, angular cliffs that characterize the landforms on more competent units such as the Wingate Sandstone (Lower Jurassic) and the Dakota Sandstone (Upper Cretaceous).

The climate of the lower part of the Glen Canyon region is arid to semiarid and is characterized by considerable variations in temperature and precipitation that are caused by differences in elevation and aspect. The average July temperature at Wahweap, near Page, Arizona (Fig. 1), is 28° C, whereas the average January temperature is 0° C (National Park Service, 1958–80, unpublished data). Diurnal temperature variations are marked, especially during spring and summer when they often exceed 20° C. Mean annual precipitation at Wahweap is a meager 15 cm (National Park Service, 1958–80, unpublished

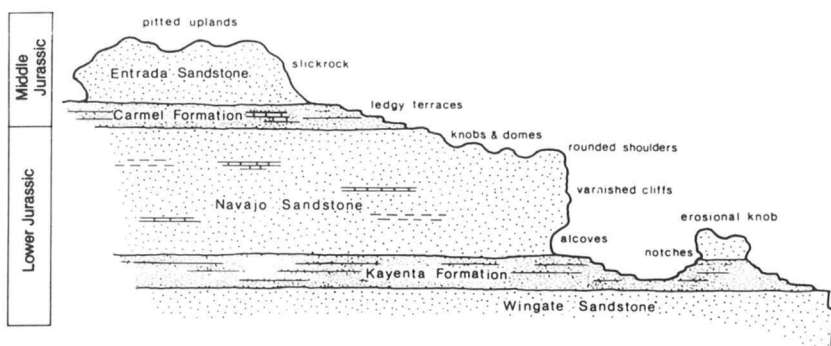


Fig. 2. Schematic diagram of erosional landforms that typically develop on the friable sandstones and mudstones in the lower part of the Glen Canyon region, Utah. The sandstone at Romana Mesa is only present locally and is not shown. At high pool (1,128 m), the surface of Lake Powell is just above the Carmel–Entrada contact at Cookie Jar Butte.

data), with significant year-to-year variations. Prevailing winds are from the southwest and are commonly strongest during spring. Severe winds are often associated with thunderstorms and squall lines, which also commonly approach from the southwest.

Vegetation and soils are sparse. They are limited to small areas where moisture is concentrated, such as along seeps and stream courses, and in weathering pits. Soil development is not only restricted by aridity and sparse vegetation but also by the meager amount of unconsolidated parent material.

Methods

Field and laboratory studies began in May 1992 with a reconnaissance of the Cookie Jar Butte site. Preliminary field maps (scale approximately 1:1,000) showing the distribution of weathering pits were prepared with the aid of 1:12,000-scale color aerial photographs provided by the Bureau of Reclamation, 1:24,000-scale topographic maps (U.S. Geological Survey), and 1:4,000-scale topographic maps prepared by the Bureau of Reclamation for the National Park Service. Thirty-one pits were described and measured, and 9 bedrock core samples were extracted. Loose sediment on the floors of selected pits was described and sampled for laboratory analysis. Additional bedrock cores and four pit water samples were collected in December 1992.

More detailed field investigations of the pits at Cookie Jar Butte were conducted during March 1993. The large, accessible pits were measured and described to determine the width and depth of closure (lowest part of pit rim to top of sediment or to bedrock floor in pit), pit-wall morphology, pit-floor sediments, pit-floor vegetation, and other pertinent site factors. Additional samples of bedrock cores, loose pit-floor sediment, weathered rock, and water in pits were collected for laboratory analyses. Visits to Cookie Jar Butte were made again in May and July 1993 to collect water samples and selected bedrock samples.

The laboratory analyses were conducted to determine the nature of the sandstone in which the pits formed and the nature of the pit-floor sediment and pit water. Thin sections of bedrock cores were examined by petrographic microscope to determine the mineralogy of grains, the type and amount of cement, and the percent pore space. Selected samples of weathered bedrock were examined with the scanning electron microscope and in thin section to

determine the degree of alteration of the sandstone by diagenesis or near-surface weathering. The particle size of pit-floor sediments was analyzed, and selected samples were examined for the presence of distinctive tracer grains that were emplaced in December 1992. The CaCO_3 content of selected sandstone cores was analyzed to determine whether systematic variations in CaCO_3 content reflect selective dissolution of the calcite cement. Water samples from selected pits were collected in December 1992 and in March, May, and July 1993 to determine the magnitude of seasonal fluctuations in water temperature and pH.

Results

The giant weathering pits near Cookie Jar Butte are usually circular in plan view, cylindrical in shape, have low width-to-depth ratios, and depths of closure of as much as 16.5 m (Fig. 3). Single pits exist, but pits commonly exist



Fig. 3. Low oblique aerial photograph of a cluster of pits southeast of Cookie Jar Butte, Utah. Note the circular shape of most pits and the large mass of structureless sandstone *left (south) of center*. The pit at the base of the structureless sandstone (*at head of arrow*) is CJ-24, which has a diameter of 27.1 m and a depth of closure of 14.9 m (photograph by D. I. Netoff 1992).

in clusters; some are so closely spaced that they coalesce. Weathering pits exist on flat outcrops and on gentle to moderate slopes (30° or more) that face north, south, east, and west (Fig. 4). Some are on ridge crests and near isolated hilltops. Several are aligned along drainage courses.

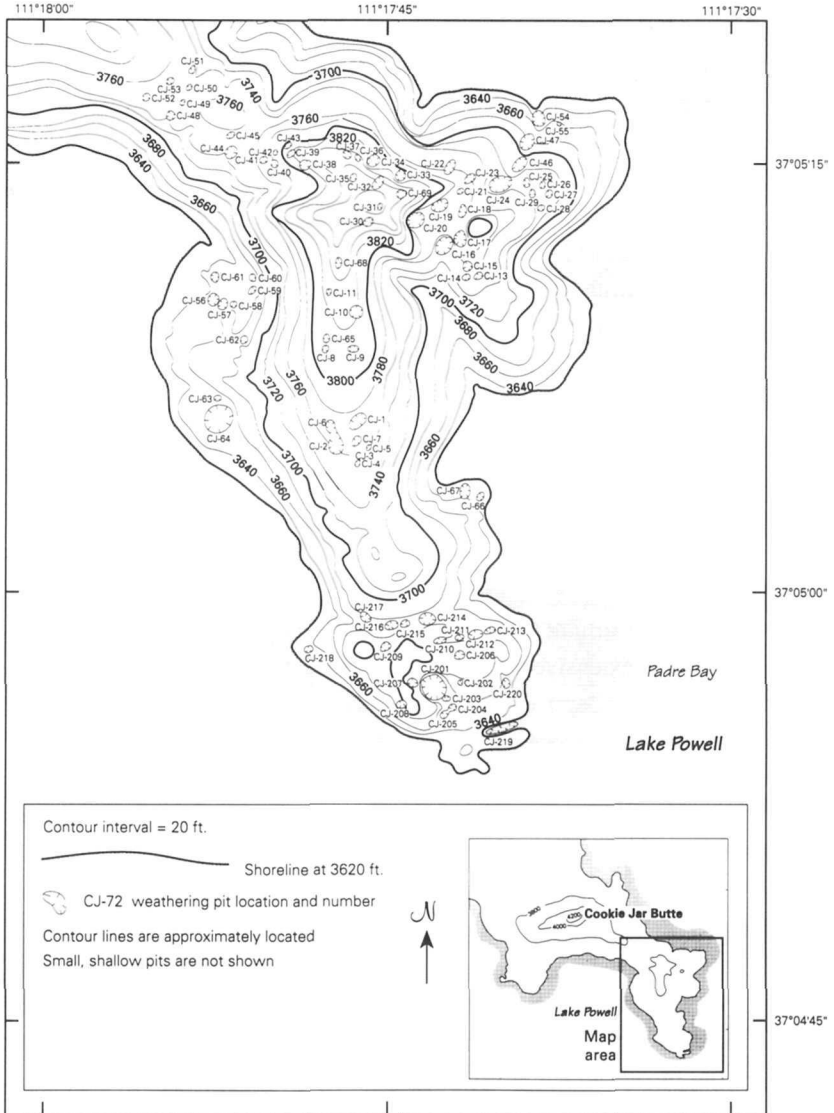


Fig. 4. Giant weathering pits southeast of Cookie Jar Butte, Utah.

Four distinct types of pits were identified on the basis of their cross-sectional form. The following nomenclature was modified from that of Twidale's (1982). Pans are broad, flat-floored, steep-sided, and have high width-to-depth ratios (Fig. 5; Tables 1 and 2). They are similar in form to pits commonly described in the literature but differ significantly from them because of their large dimensions. Only three pan-shaped pits were identified (Fig. 5; Tables 1 and 2). Two of these contained loose sediment veneers on their floors that were thick enough to support sparse vegetation, and the other one seems to have contained water continuously for at least the past 3 years. How much of the water in the pit was supplied by rainfall and how much remained from when the pit was inundated by high lake levels are not known.

Bowls have gently-sloping sides and are roughly parabolic in cross-section. Most bowls have flat floors and a very thin layer of sediment that overlies the bedrock. Their widths range from about 2 to nearly 26 m and width-to-depth ratios are low ($\bar{x} = 7$; Tables 1 and 2).

Cylinders have vertical or nearly vertical walls, flat floors, moderate to great depths (as deep as 16.5 m), and have the lowest width-to-depth ratios of any pit type, commonly less than 4 (Table 2). Loose sediment veneers the floors of most pits, and the sediment is as thick as 1 m. The pits resemble giant drill holes and have an average depth of about 6 m (Fig. 6). Many cylinders contain several meters of water that may remain for months or years when moist weather prevails.

Armchairs are similar to cylinders, except that part of the pit wall of the armchair has been extensively breached by slope retreat or pit enlargement. Breaching reduces the depth of pit closure and results in higher width-to-depth ratios than for similarly-shaped unbreached pits (Table 2). Armchairs exist on slopes of 30° or less.

Pit walls show varying degrees of development of morphological features such as tafoni, small alcoves, rock varnish, spalls, and lichen cover regardless of pit type. Tafoni and alcoves tend to concentrate along lithologic discontinuities such as bedding planes, joints, and small-scale faults (displacement of a few centimeters to a few meters; Fig. 7). Salt-crystal growth is most obvious following periods of wet weather, such as the winter of 1992–93, and seems to promote the formation of tafoni and alcoves in many of the pits, particularly along bedding planes where moisture is concentrated. Many near-vertical pit walls display the effects of spalling, especially on exposures that receive long periods of direct sunlight. Near-vertical walls on the north-facing sides of many

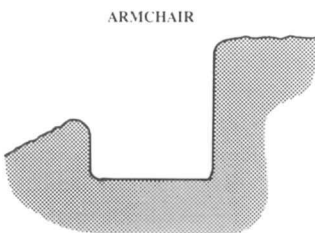
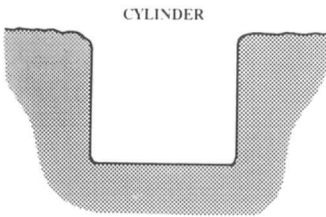
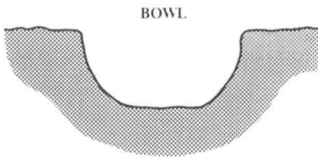
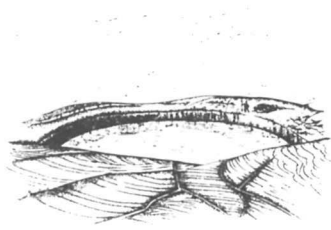
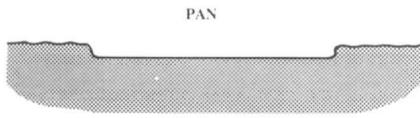


Fig. 5. Types of weathering pits near Cookie Jar Butte, Utah. Diagrams on the left are schematic cross sections; sketches on the right are oblique views of actual pits (sketches by Gary Durant).

Table 1. Summary of width, depth, width-to-depth ratio, and type of pit for the giant weathering pits near Cookie Jar Butte, Utah.

Pit number	Width ^a (m)	Depth ^b (m)	Width– depth ^c	Pit type
CJ-1	15.1	3.7	4.1	Cylinder
CJ-2	18.1	1.9	9.5	Bowl
CJ-3	7.6	1.6	4.8	Bowl
CJ-4	5.9	2.1	2.8	Cylinder
CJ-5	n.d. ^d	0.0	n.d.	Armchair
CJ-6	11.9	1.5	7.9	Bowl
CJ-7	6.1	2.5	2.4	Cylinder
CJ-8	6.4	3.5	1.8	Bowl
CJ-9	8.7	0.8	10.9	Armchair
CJ-10	15.7	4.9	3.2	Cylinder
CJ-11	8.8	1.6	5.5	Armchair
CJ-13	11.9	3.3	3.6	Bowl
CJ-14	8.1	4.1	2.0	Cylinder
CJ-15	13.0	6.4	2.0	Cylinder
CJ-16	22.9	1.7	13.5	Pan
CJ-17	14.3	4.0	3.6	Cylinder
CJ-18	15.5	7.3	2.1	Cylinder
CJ-19	14.3	0.8	17.9	Pan
CJ-20	19.5	10.1	1.9	Cylinder
CJ-21	7.6	2.6	2.9	Cylinder
CJ-22	15.1	6.7	2.3	Cylinder
CJ-23	14.2	3.2	4.4	Armchair
CJ-24	27.1	14.9	1.8	Cylinder
CJ-25	9.4	5.4	1.7	Cylinder
CJ-26	6.6	3.4	1.9	Cylinder
CJ-27	7.5	3.3	2.3	Cylinder
CJ-28	7.5	2.2	3.4	Armchair
CJ-29	13.7	4.6	3.0	Cylinder
CJ-30	5.1	1.1	4.6	Bowl
CJ-31	4.0	0.5	8.0	Bowl
CJ-32	5.3	1.5	3.5	Armchair
CJ-46	15.8	5.8	2.7	Cylinder
CJ-47	19.6	4.3	4.6	Armchair
CJ-54	17.0	0.5	34.0	Armchair
CJ-56	13.6	3.1	4.4	Cylinder
CJ-57	13.3	1.6	8.3	Cylinder
CJ-58	15.9	0.0	n.d.	Bowl
CJ-64	37.5	4.6	8.2	Pan
CJ-65	8.4	4.1	2.0	Cylinder
CJ-68	5.4	0.6	9.0	Bowl
CJ-100	22.6	15.5	1.5	Cylinder
CJ-101	14.0	1.3	10.8	Bowl

Table 1. *Continued.*

Pit number	Width ^a (m)	Depth ^b (m)	Width– depth ^c	Pit type
CJ-102	14.3	n.d. ^d	n.d.	Bowl
CJ-103	14.0	1.6	8.8	Bowl
CJ-104	8.1	0.0	n.d.	Bowl
CJ-105	6.9	n.d.	n.d.	Bowl
CJ-106	8.2	0.8	10.3	Bowl
CJ-107	9.4	0.0	n.d.	Pan
CJ-108	6.9	3.1	2.2	Cylinder
CJ-109	6.4	2.3	2.8	Bowl
CJ-110	7.3	0.4	18.3	Bowl
CJ-114	20.6	5.5	3.7	Cylinder
CJ-201	21.3	16.5	1.3	Cylinder
CJ-202	7.8	2.6	3.0	Cylinder
CJ-203	6.8	2.6	2.6	Cylinder
CJ-204	12.4	0.0	n.d.	Bowl
CJ-205	11.1	4.7	2.4	Armchair
CJ-206	15.2	9.4	1.6	Cylinder
CJ-207	19.5	8.6	2.3	Bowl
CJ-208	10.8	1.5	7.2	Armchair
CJ-209	9.3	4.6	2.0	Cylinder
CJ-210	14.2	9.4	1.5	Cylinder
CJ-211	12.0	4.4	2.7	Cylinder
CJ-212	19.5	n.d.	n.d.	Armchair
CJ-213	15.5	n.d.	n.d.	n.d.
CJ-214	19.4	8.2	2.4	Cylinder
CJ-215	12.4	1.8	6.9	Bowl
CJ-216	17.2	8.8	2.0	Cylinder
CJ-217	25.9	4.6	5.6	Bowl
CJ-218	10.4	2.4	4.3	Cylinder
CJ-220	9.6	0.3	32.0	Armchair

^aWidth = average of maximum and minimum diameters measured at the inner part of the pit rim.

^bDepth of closure = vertical distance from the lowest part of the pit rim to the pit floor (bedrock or top of sediment).

^cWidth–depth = the ratio of width to depth of closure.

^dn.d. = not determined.

of the pits seem to be the most stable; they display the least amount of granular disintegration, have the least amount of loose detritus at their base, and have by far the greatest percentage of lichen cover, which averages about 17% versus less than 1% lichen cover on pit walls that are not north-facing.

Table 2. Comparison of width-to-depth ratios of the four kinds of weathering pits at Cookie Jar Butte, Utah.

Cylinder		Bowl		Armchair		Pan	
Pit number	Width–depth	Pit number	Width–depth	Pit number	Width–depth	Pit number	Width–depth
CJ-1	4.1	CJ-2	9.5	CJ-9	10.9	CJ-16	13.5
CJ-4	2.8	CJ-3	4.8	CJ-11	5.5	CJ-19	17.9
CJ-7	2.4	CJ-6	7.9	CJ-23	4.4	CJ-64	8.2
CJ-10	3.2	CJ-8	1.8	CJ-28	3.4		
CJ-14	2.0	CJ-13	3.6	CJ-32	3.5		
CJ-15	2.0	CJ-30	4.6	CJ-47	4.6		
CJ-17	3.6	CJ-31	8.0	CJ-54	34.0		
CJ-18	2.1	CJ-68	9.0	CJ-205	2.4		
CJ-20	1.9	CJ-101	10.8	CJ-208	7.2		
CJ-21	2.9	CJ-103	8.8	CJ-220	32.0		
CJ-22	2.3	CJ-106	10.3				
CJ-24	1.8	CJ-109	2.8				
CJ-25	1.7	CJ-110	18.3				
CJ-26	1.9	CJ-207	2.3				
CJ-27	2.3	CJ-215	6.9				
CJ-29	3.0	CJ-217	5.6				
CJ-46	2.7						
CJ-56	4.4						
CJ-57	8.3						
CJ-65	2.0						
CJ-100	1.5						
CJ-108	2.2						
CJ-114	3.7						
CJ-201	1.3						
CJ-202	3.0						
CJ-203	2.6						
CJ-206	1.6						
CJ-209	2.0						
CJ-210	1.5						
CJ-211	2.7						
CJ-214	2.4						
CJ-216	2.0						
CJ-218	4.3						
T ^a = 33		T ^a = 16		T ^a = 10		T ^a = 3	
avg. ^b = 2.7		avg. ^b = 7.2		avg. ^b = 10.8		avg. ^b = 13.2	

^aT = total number of weathering pits.
^bavg. = average value of width–depth ratios.



Fig. 6. The cylindrical-shaped pit at CJ-100, located about 550 m southwest of Cookie Jar Butte, has a diameter of 22.6 m and a depth of 15.5 m. Water remained in the pit from at least December 1991 (about 2 m) until July 1993 (almost dry). Calcium carbonate bathtub rings on the pit walls suggest that the pit may have recently been half full of water (photograph by D. I. Netoff 1992).

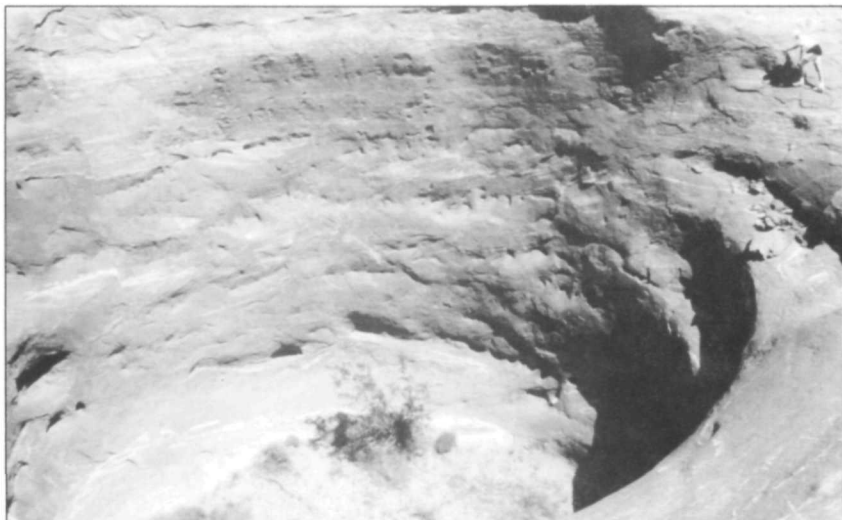


Fig. 7. Tafoni (pitting in vertical bedrock walls) aligned along bedding planes at pit CJ-20 (Fig. 4). Although joints and bedding planes influence the locations of the tafoni, they do not seem to exert a strong control on the location or shape of pits near Cookie Jar Butte. This cylindrical pit is 19.5 m wide and 10.1 m deep. Note person in *upper right* for scale (photograph by D. I. Netoff 1992)

All pit types commonly have a thin veneer of loose, sandy sediment that covers their bedrock floors. The mineralogy, particle size, color, and grain shape of the sediment are similar to that of the sandstone bedrock; therefore, the sediment is probably derived largely from the local bedrock. In some pits, the sandy sediment consists of thin layers of organic-rich material alternating with yellowish-red (5 YR 5/6; Munsell Color 1973) layers that are low in organic material. In some pits, the sediment is thicker than 1 m and unstratified. The upper surfaces of these sediments are undulatory and were probably reworked by the wind (Fig. 8). No artifacts or fossils were found in pit-floor sediment, nor have any buried soils been identified. Abrasive fragments that are larger than sand grains are rare in pit-floor sediments, except in pits with rock fragments from the Morrison Formation, which is exposed in nearby cliffs.

Pits with the thickest pit-floor sediment tend to support the densest plant cover. Plant communities generally consist of grasses, shrubs, herbs, and forbs, although the species composition varies considerably. Grasses such as the foxtail chess (*Bromus rubens*), sand dropseed (*Sporobolus cryptandros*), and blue grama (*Bouteloua barbata*) are common dominants or codominants.



Fig. 8. A cluster of giant pits, two of which contain moderately thick pit-floor sediment and a relatively dense vegetation community. The pit in the *lower left* (CJ-19, Fig. 4) is 14.3 m wide, and the pit in the *far upper right* (CJ-16, Fig. 4) is 22.9 m wide. Both are classified as pans (photograph by D. I. Netoff 1993).

Herbs and shrubs such as the tamarisk (*Tamarix ramosissima*), narrow-leaved yucca (*Yucca angustissima*), Mormon tea (*Ephedra viridis*), and matchbrush (*Gutierrezia microcephala*) vary in abundance and achieve dominance or codominance in some pits. Annuals such as the Russian thistle (*Salsola australis*) are present but are not as common as the other species. Many other annuals are present in some pits.

No obvious lithologic or structural controls determine the shape or location of most pits near Cookie Jar Butte. Joints and small-scale faults are present throughout the lower Entrada Sandstone outcrops. Most, however, are cemented with varying amounts of CaCO_3 , which seems to strengthen the sandstone along these zones.

Thin-section analyses of near-surface sandstone cores at depths of 0–12 cm from pit rims, walls, and floors indicate that quartz accounts for 65–74% of the detrital grains (Tables 3 and 4). The remaining grains are mostly potassium feldspar with lesser amounts of lithic fragments and plagioclase feldspar. The total amount of pore space between sand grains (excluding calcite cement), based on point counts, is about 19–25%. Grains are typically subangular to subrounded, and the dominant grain sizes are medium to very fine sand (average

Table 3. Point-count summaries of stained thin sections of selected sandstone cores from pit rims, walls, and floors.^a

Constituent (%)	CJ-17 A2 ^b	CJ-17 B2 ^c	CJ-101 A2 ^d	CJ-101 B2 ^e
Quartz	46	50	44	48
Potassium feldspar	12	14	13	11
Plagioclase	3	5	8	4
Calcite	4	3	9	9
Pore space	25	20	24	26
Lithic fragments ^f	10	8	3	2
Q/Q + K + P + L ^g	65	65	65	74
K/Q + K + P + L	16	18	18	16
P/Q + K + P + L	4	7	11	7
L/Q + K + P + L	14	11	5	3
Grain size (μ)				
Maximum	158	210	225	162
Minimum	30	32	35	37
Average	90	95	97	92
1s ^h	26	35	30	23
Total counts	208	208	208	208

^aPit CJ-101 is located 500 m southwest of Cookie Jar Butte, and pit CJ-17 is located 800 m southeast of Cookie Jar Butte (Fig. 4).

^bPit CJ-17 A2 is sample from pit wall at a depth of 3.8–5.1 cm.

^cPit CJ-17 B2 is sample from pit floor at a depth of 1.9–4.4 cm.

^dPit CJ-101 A2 is sample from pit rim at a depth of 1.9–3.2 cm.

^ePit CJ-101 B2 is sample from pit wall at a depth of 2.5–5.1 cm.

^fLithic fragments: fine-grained rock fragments + biotite and amphibole.

^gQ = monocrystalline + polycrystalline quartz; K = potassium feldspar; P = plagioclase; L = lithic fragments.

^h1s = one sample standard deviation.

90–100 μ, based on point counts and sieve analyses). Most quartz grains have distinct grain boundaries and show little or no evidence of dissolution (pitting or embayments). The feldspar grains are either slightly weathered or unweathered in roughly equal proportions. A reddish-orange to yellowish-orange coating as thick as 5μ covers most grains. These coatings are probably a combination of iron oxides and clay minerals (Fig. 9). Grains are loosely cemented with CaCO₃ (2.7–9.1 wt.% based on Chittick gasomatic determinations) and clays (1–6 wt.% based on particle-size analysis). No consistent trends in CaCO₃ content were detected among samples from pit floors, walls, and rims, nor were significant differences in CaCO₃ content observed between surface and near-

Table 4. Point-count summaries of unstained thin sections of selected sandstone cores from pit rims, walls, and floors.^a

Constituent (%)	CJ-101 A3 ^b	CJ-101 B1 ^c	CJ-101 B5 ^d	CJ-101 C2 ^e	CJ-103 C1 ^f
Quartz and feldspars	67	73	68	69	70
Calcite	13	9	10	5	7
Pore space	15	12	17	19	19
Lithic fragments ^g	5	5	4	7	5
Total counts	276	240	268	212	204

^aPits CJ-101 and CJ-103 are located about 500 m southwest of Cookie Jar Butte.

^bPit CJ-101 A3 is sample from pit rim at a depth of 3.2–4.4 cm.

^cPit CJ-101 B1 is sample from pit wall at a depth of 0–2.5 cm.

^dPit CJ-101 B5 is sample from pit wall at a depth of 10.2–12.1 cm.

^ePit CJ-101 C2 is sample from pit floor at a depth of 1.9–4.4 cm.

^fPit CJ-103 C1 is sample from pit floor at a depth of 0–3.2 cm.

^gLithic fragments: fine-grained rock fragments + biotite and amphibole.

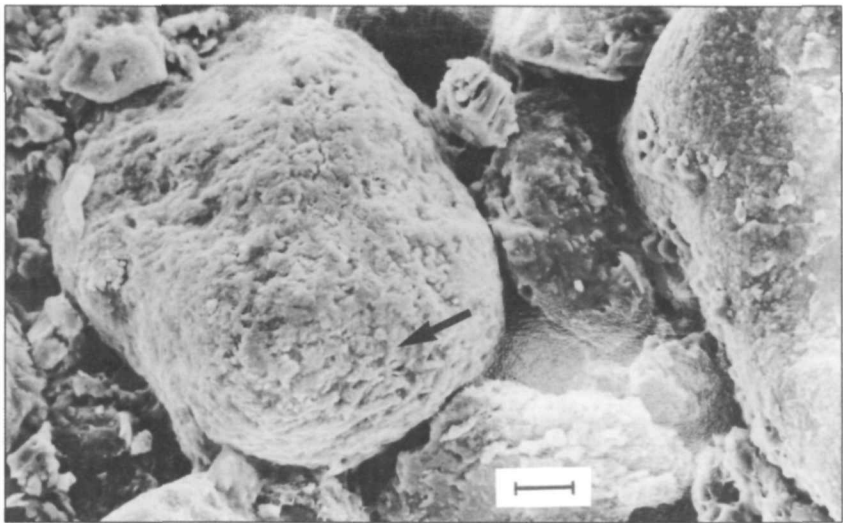


Fig. 9. Scanning electron microscope photomicrograph of a sandstone core (CJ-101 C3, located about 500 m southwest of Cookie Jar Butte) showing clay coatings on a quartz grain (arrow). Bar scale is 10 μ .

surface (0–12 cm) sandstone core samples. The borders of the calcite cement may be convex, possibly the result of dissolution, or may show sharp crystal faces (T. R. Walker, 1993, personal communication), indicating a lack of etching or dissolution. Small (<1%) amounts of gypsum cement were also observed.

Water sampled from selected weathering pits near Cookie Jar Butte in December 1992, March 1993, and May 1993 indicate significant seasonal variations in pH (Table 5). The average pH value of pit water samples in December was 8.2; the average in March was 7.5; and the average in May was 9.0. Two water samples in May gave unusually high pH values of 9.4 and 9.5.

Discussion

Weathering Processes

Several weathering processes are thought to be important in pit initiation and growth; many are accentuated by the presence of discontinuities such as bedding planes, joints, and small-scale faults. Pit wall recesses such as tafoni

Table 5. Water temperature and pH values measured at selected weathering pits during December 1992, March 1993, and May 1993.^a

Pit number	December		March		May	
	pH	Temp.(° C)	pH	Temp.(° C)	pH	Temp.(° C)
CJ-6	d. ^b	d.	7.6	19	d.	d.
CJ-10	d.	d.	7.0	n.d. ^c	d.	d.
CJ-15	n.d.	n.d.	7.4	11	n.d.	n.d.
CJ-30	d.	d.	7.6	n.d.	d.	d.
CJ-32	n.d.	n.d.	n.d.	n.d.	9.5	21
CJ-57	8.5	0	7.7	18	8.9	23
CJ-64	8.0	0	7.8	15	8.7	23
CJ-100	n.d.	n.d.	7.5	9	9.1	18
CJ-108	8.4	0	7.4	9	9.4	20
CJ-109	d.	d.	8.4	12	d.	d.
CJ-201	8.0	6	7.4	n.d.	8.7	19
CJ-214	n.d.	n.d.	7.6	n.d.	8.7	20

^aPits CJ-100, CJ-108, and CJ-109 are located 500–600 m southwest of Cookie Jar Butte; the remaining pits listed are located southeast of Cookie Jar Butte (Fig. 4).

^bPit was dry, and values were not determined.

^cPit contained water, but values were not determined.

and small alcoves are commonly aligned along bedding planes and to a lesser extent along joints and small-scale faults. These are sites where moisture is localized, which in turn accelerates moisture-dependent weathering processes. Salts are commonly concentrated in these recesses, and salt crystal growth may cause granular disintegration of pit walls. Salts may also catalyze quartz dissolution (Young 1987a), although we did not detect thin-section evidence of this process.

Other soluble substances may migrate by capillary action to the rock surface, crystallize, and create enough stress to induce granular disintegration. Calcite and gypsum have been suspected of causing granular disintegration in friable sandstone (Laity and Malin 1985), and we observed minor calcite wedging in one of the sandstone cores. Scanning electron microscope examination of a salt-encrusted, weathered bedrock sample at pit CJ-3 revealed nearly pure gypsum crystals.

Clay mineral hydration and desiccation may also exert disruptive forces in some sandstones (Netoff 1971). Particle size analysis of a crushed core sample from pit CJ-13 indicated that clay-size material is a significant component (5.7%) of the CaCO_3 -free portion of the sample. Moreover, we observed well-developed cracks in dry pit-floor sediment in many pits, suggesting the presence of expandable material in these sediments. Contraction of pit-floor sediment suggests that sandstone bedrock in contact with the sediment may be subject to colloidal plucking.

Spalling of pit walls is common on all except north-facing exposures. Spalls parallel the pit walls; at some sites, sets of closely spaced, face-parallel joints exist in the wall rock. The cause of spalling is not known, but the joint pattern resembles expansion-induced exfoliation. Thermal expansion caused by solar radiation may initiate spalling, especially after the rock has been weakened by other weathering processes. The effectiveness of solar radiation, however, has been debated for decades (Griggs 1936; Ollier 1969).

Freezing and thawing may be effective weathering agents where water is abundant, such as at seeps, alcoves, and tafoni. Pit waters may freeze and form surface ice as thick as several centimeters during cold winters, and expansion and contraction of ice in contact with pit walls may promote disintegration.

Chemical weathering processes that may contribute to pit development include carbonation, dissolution, and hydrolysis. Dissolution of calcite cement should free quartz and feldspar grains and promote pit enlargement. Thin-section analysis revealed at least some calcite dissolution in sandstone exposed in

pit walls and floors, although some samples showed no signs of dissolution (T. R. Walker, 1993, personal communication). Karst landforms on quartzose sandstones formed by dissolution of quartz grains have been reported by many geologists (e.g., Jennings 1983; Young 1987b; Young and Young 1992), but most of their examples were from much wetter present or past environments, and the landscapes that they studied are extremely old. We found no evidence of extensive dissolution of quartz grains, and we therefore discounted solution as a major weathering process in pit development. The slight alteration of plagioclase and potassium feldspar is probably the result of hydrolysis and perhaps dissolution, but many of these grains seem to be fresh, and consequently feldspar weathering is not believed to play an important role in pit development or in the formation of diagenetic clays.

Biological activity has been advocated by several investigators as a causative process in the development of weathering pits; they cite evidence such as the dark organic stains that often coat bare bedrock pit floors and the presence of lichens on pit walls and rims. The pea-soup color of the water in several of the pits that we observed when surface water temperatures exceeded about 18° C illustrates the intensity of organic activity in these miniature aquatic systems. Biological activity is probably partly responsible for seasonal variations in pit-water pH values. The high pH (9.5) in some pit waters should be conducive to silica dissolution (Birkeland 1984). The lack of obvious dissolution features in thin-section analysis, however, argues against this mechanism.

Rock varnish on the north-facing walls of many pits may be due in part to organic stains from microorganisms (Fig. 10). The presence of lichens and rock varnish on north-facing pit walls and the relative lack of spalling, salt crystal growth, and granular disintegration on those walls suggests that either some types of biological activity promote pit-wall stability or pit-wall stability permits the establishment of some types of biological activity.

Removal of Weathering Products

The removal of sandstone weathering products from weathering pits is probably accomplished by some combination of plunge-pool action, wind deflation, and perhaps dissolution or piping. Although evidence at selected pits supports one or more of these mechanisms, preliminary field and laboratory data do not clearly identify any single process or group of processes that accounts for the removal of weathering products from the pits.

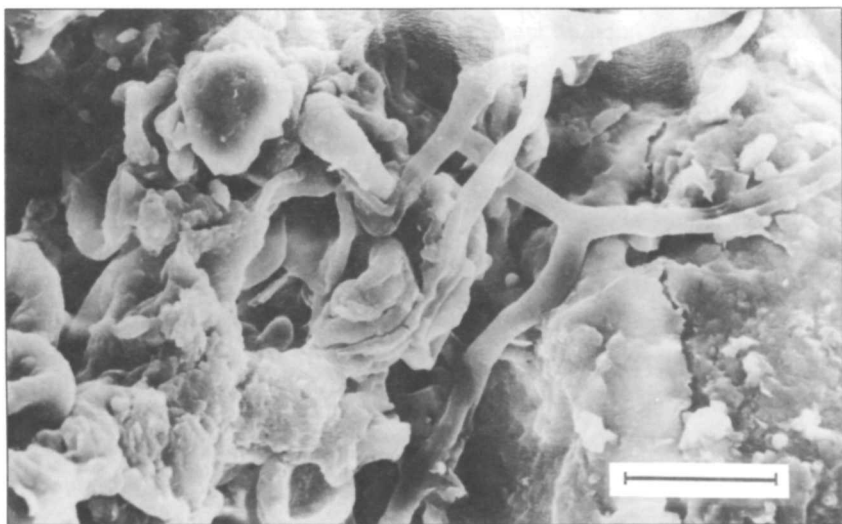


Fig. 10. Scanning electron microscope photomicrograph of rock varnish on the north-facing pit wall at CJ-13 (Fig. 4). The filaments and spherical structures are largely organic, most likely a combination of bacteria and fungi. Bar scale is 10 μ .

Plunge-pool erosion is the combined effect of the hydraulic force of water and the abrasive action of sand and gravel in swirling pools; perhaps erosion is enhanced by solution of the calcite cement. Plunge-pool erosion requires channelized flow and stream gradients sufficient to generate at least moderate flow velocities; it is most effective where resistant, abrasive tools are present. Countless examples of large, multiple plunge pools along many of the tributaries of the Colorado River in the Glen Canyon region illustrate the intensity of plunge-pool action, even along intermittent streams (Fig. 11).

Several giant weathering pits near Cookie Jar Butte are roughly aligned along bedrock channels that have sufficient drainage areas and gradients to induce plunge-pool erosion, which at least at one site may eventually produce a natural bridge (Fig. 3). Many pits, however, are not in an organized drainage system, and several pits are on ridge crests or near isolated hills. Whether paleochannels contributed to pit enlargement at these sites is difficult to determine. The absence of abrasive fragments on the floors of these pits also suggests that plunge-pool erosion does not account for pit enlargement.

Little doubt exists that wind deflation is capable of removing loose, dry sand from shallow pits. In May 1993, a thin veneer of loose sand on the floor

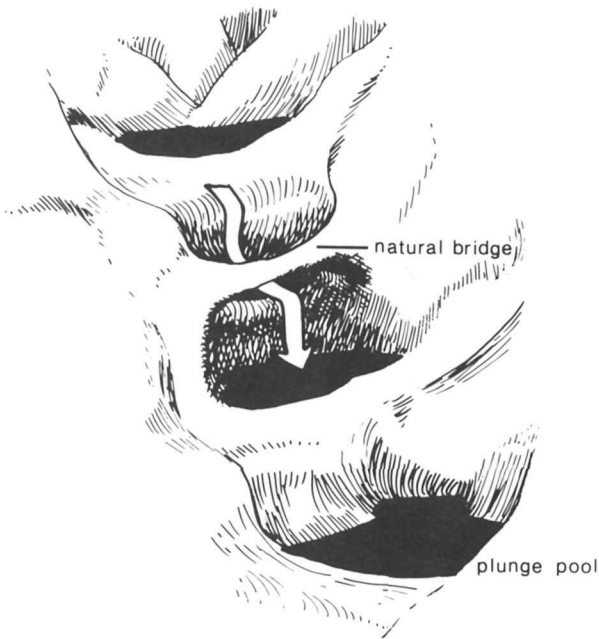


Fig. 11. Sketch of plunge-pool basins of the type that commonly form in many of the tributary valleys of the Glen Canyon region (sketch by Nancy Stonington). A natural bridge similar to the one depicted here will soon develop at pit CJ-24 (Fig. 3).

of a bowl-shaped, 1.6-m-deep pit near Cookie Jar Butte was rapidly removed by wind with a velocity of 56 km/h measured at the pit rim. Eolian sediment removal is halted when weathering pit depth exceeds the capacity of the strongest winds to remove the sediment from the pit floor.

Whether winds can deflate 100- μ -size quartz and feldspar grains from deep and narrow cylindrical depressions is a critical question. Wind gusts as strong as 130 km/h have been recorded on Lake Powell (John Ritenour, 1992, personal communication), and episodic winds on favorable topographic sites could be of far greater velocity. Winds may have been even stronger in the Pleistocene when presumably high-pressure gradients existed between the warm, low canyon floors and the nearby ice-capped, high plateaus to the north of Glen Canyon. Moreover, large areas of exposed sandstone in the Canyonlands region of southeastern Utah have been proposed as a possible source of eolian silt in the Piceance Creek basin of northwestern Colorado (Whitney and Andrews 1983).

Arguments against the removal of sediment by wind from the floors of deep pits include the lack of wind scour features on pit walls, pit floors, and other bedrock surfaces, as well as the fact that the giant pits formed on both the windward and leeward slopes of Cookie Jar Butte. Whether paleowinds removed sediment from the floors of deep and narrow cylindrical pits is not known and would be difficult to prove.

Two plausible hypotheses for the removal of quartz grains include removal by dissolution and removal by piping, but we did not detect obvious dissolution features in thin-section analysis. Joints and small-scale faults that intersect pits near Cookie Jar Butte may have been large and open enough at one time to serve as conduits for the removal of sand, but they are now completely cemented with CaCO_3 and are less likely to transmit water than the surrounding sandstone. Retention of water for months or years in many of the deeper pits suggests that the walls and floors of these pits are relatively impermeable. The conduits may have been wide enough to transport sand in the past and have since been sealed by sand and CaCO_3 , but no convincing evidence has been observed that supports this supposition.

Antiquity of Weathering Pits

Two other key questions are, How old are the pits? and Are they relict features or are they still forming? The maximum limiting age of the pits is the time when the pit-bearing sandstone was exposed to surficial processes, which is controlled by the time when the Colorado River and its tributaries cut down to the level of the existing pits. Estimated downcutting rates based on terrace heights above Bullfrog Creek (a tributary of the Colorado River in Glen Canyon about 117 km [channel distance] northeast of our study site) range from 80 to 250 m/m.y. (meters per million years; Biggar and Patton 1991). If this range is used to estimate when the Colorado River was at the elevation of the highest of the giant weathering pits near Cookie Jar Butte (134 m above the modern channel of the Colorado River), the estimated age range of the highest (possibly the oldest) weathering pits would be 0.5–1.7 Ma (million years ago). These values are in general agreement with estimates of downcutting rates by Hunt (1969) and Machette and Rosholt (1991). Hunt (1969) determined an average rate of downcutting of the Colorado River of 165 m/m.y. based on the river's present sediment load. Machette and Rosholt (1991) used uranium-trend dating to determine an average rate of downcutting in the upper part of the Grand

Canyon—about 140 km southwest of our study site—of at least 190 m/m.y. These rates yield estimated ages of the highest pits of about 0.8 to 0.7 Ma. We infer, therefore, that the oldest pits are no older than early Pleistocene.

Considerable antiquity of armchair pits is suggested by their presence on moderate slopes; nearly level bedrock outcrops promote pit development because ponded water localizes weathering processes and accelerates pit deepening. The formation of armchairs predates the breaching of the pit rims by slope retreat. The rate of pit deepening must have at least kept pace with slope retreat to maintain closed bedrock depressions.

Evidence of present-day pit-wall weathering includes abundant spalls, salt-crystal growth, and loose debris along the base of pit walls and on pit floors. Indirect evidence of the recency of pit excavation includes the lack of thick sediment on pit floors. Alternatively, the presence of local rock varnish and lichen cover on pit walls implies temporary pit wall stability. Pit development may have begun as far back as early Pleistocene and may have continued through the Holocene.

One of the fundamental questions about pit development remains unanswered: Why is the distribution of giant sandstone weathering pits so restricted, especially considering the vast expanse of exposed friable sandstones throughout the Colorado Plateau? We see nothing unique in the bedrock structure, topography, or climate at Cookie Jar Butte that would account for the limited distribution. Perhaps unique environmental conditions set the stage for and fostered the development of the giant pits, and these or other conditions remain conducive to their continued development.

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Large-scale Geologic Mapping in Great Basin National Park, Nevada

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Abstract. Great Basin National Park is located in the southern Snake Range, White Pine County, Nevada, near the ranching community of Baker, Nevada. The Great Basin National Park project began in June 1992 through an interagency agreement between the U.S. Geological Survey (USGS) and the National Park Service (NPS) and was completed in March 1995. The project delivers large-scale geologic maps of the park, a Geographic Information System data base shared between the USGS and NPS, USGS Open-file and Geologic Quadrangle geologic maps, reports on topical studies, and a USGS bulletin on the geologic evolution of the park. The park includes the southern Snake Range, recognized as a metamorphic core complex and exposing the Snake Range decollement, a large-scale, low-angle fault plane surface. Studies are conducted on important regional problems like the age, time of initiation, style, and kinematics of extension in the Basin and Range Geologic Province. Results to date conclude that extension in the Snake Range began from 20 to 15 Ma (million years; early to middle Miocene) earlier than had been previously thought. Products from this project provide data to develop responses to preservation and management issues, to answer requests for public information, and to provide a basis for continued scientific research in the region.

Key words: Extension tectonics, geographic information systems, Snake Range decollement, southern Snake Range.

Great Basin National Park (GBNP) in east-central Nevada is in the southern Snake Range, White Pine County, part of the northern Basin and Range Geologic Province (Figure). The park headquarters and the entrance to the

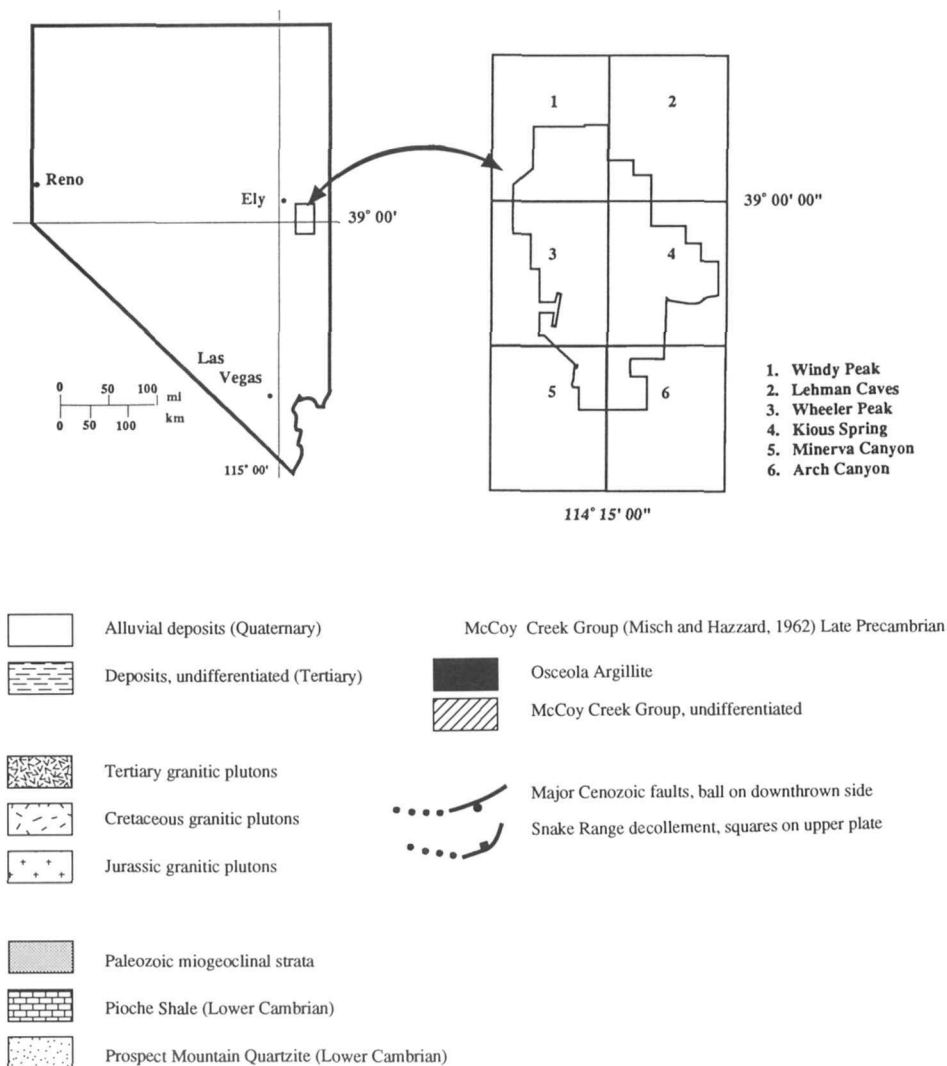
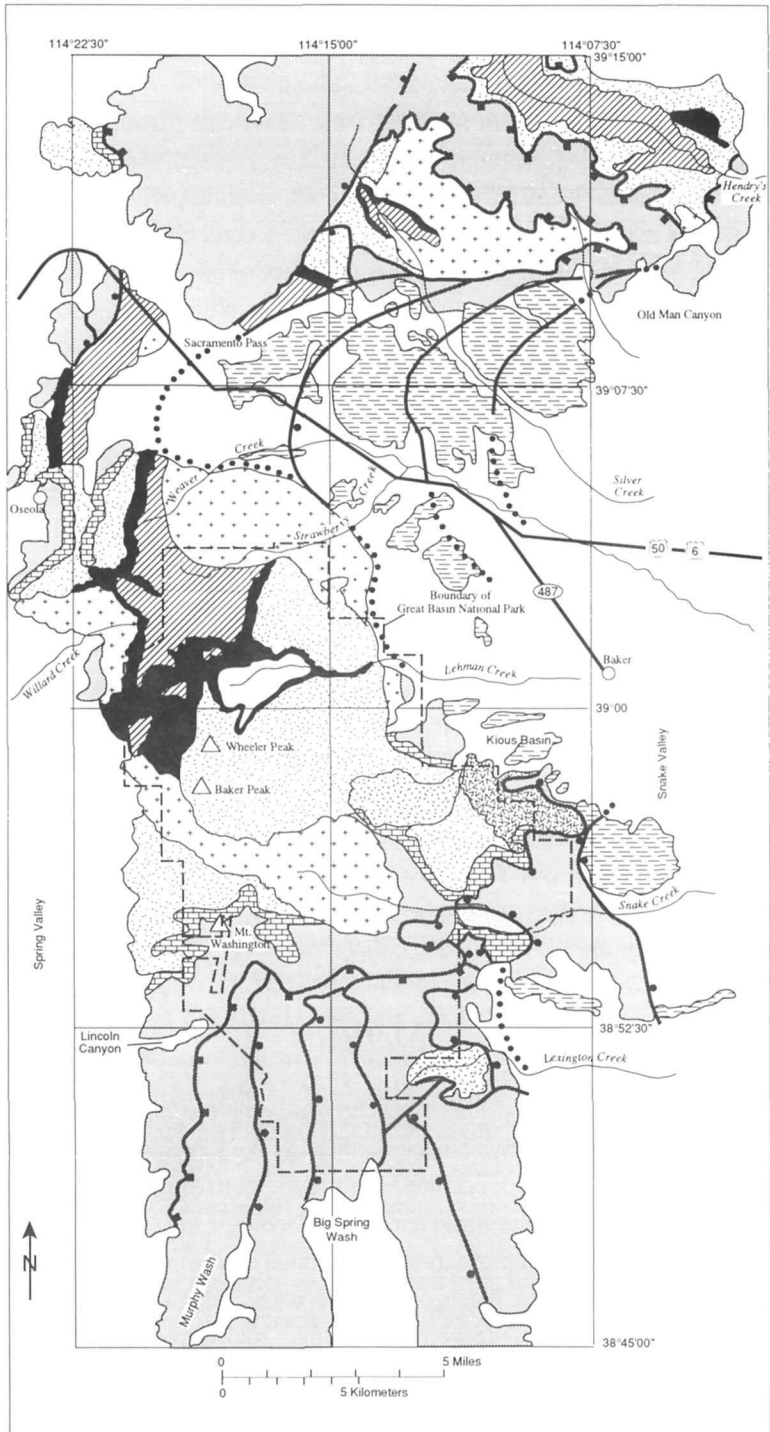


Figure. Generalized geologic map of the central Snake Range, Nevada. Map emphasizes the distribution of variably metamorphosed upper Precambrian and Cambrian miogeoclinal strata and the various plutons that intrude these rocks. Geologic map modified after Miller et al. (1988). Small index map shows boundary of Great Basin National Park and the six 7.5' topographic quadrangles encompassing the park.



Lehman Caves are located about 8 km west of the ranching community of Baker, Nevada, near the eastern border of Nevada and Utah.

In 1986, Great Basin National Park was created from portions of the Humboldt National Forest and the Lehman Caves National Monument. The park includes Wheeler Peak in the Wheeler Peak quadrangle (Figure), which at 3,982 m is the highest peak in the park and the second highest peak in Nevada. In 1964, the world's oldest known tree, a bristlecone pine (*Pinus longaeva*), was discovered near Wheeler Peak and was estimated to be about 4,950 years old.

The general management plan of the Great Basin National Park calls for development in several locations in the Kious Spring and Lehman Caves topographic quadrangles. The plans include a new visitor's center, parking lot, and access road located south of the present location and require geologic evaluation before construction. Therefore, current, large-scale geologic maps of the entire park are needed.

The project provides a geologic survey of GBNP and a Geologic Information System (GIS) data base shared between the U.S. Geological Survey (USGS) and National Park Service (NPS) as well as with local, state, and national data users. The project also provides USGS Open-file geologic maps, formal USGS Geologic Quadrangle (GQ) maps, topical studies, and associated reports. The GIS data set provides a powerful and cost-effective tool to develop responses to preservation and management issues, to answer requests for public information, and to provide a basis for continued scientific research in the region. The project meets the Department of the Interior's national mandate (Economy Act of 1932) to authorize, encourage, and implement interagency agreements for mutual benefit and cooperation.

Methods

The project began in June 1992 and was completed in March 1995. Great Basin National Park is located in the southern Snake Range, White Pine County, Nevada (Figure). The park encompasses the southern Snake Range, a structurally complex region in the Basin and Range Geologic Province. In general, the southern Snake Range represents a gentle domal antiform, uplifting and exposing late Precambrian to Paleozoic marine clastic strata that are themselves complexly faulted. The Paleozoic and younger rocks overlie the Snake Range decollement, a low angle, east-dipping normal fault system on the eastern flank

of the range. The uplifted strata are variably metamorphosed and intruded by plutons of Jurassic, Cretaceous, and Tertiary age. The Lehman Caves are developed in the Middle Cambrian Pole Canyon Limestone. The modern landscape was further sculpted by Pleistocene glaciations, and the most dramatic glacial features in the central Great Basin are preserved on the north flank of Wheeler Peak.

Because no large-scale geologic mapping of the study site existed, new mapping was needed in the area. The park includes six large-scale (1:24,000) topographic quadrangles: Windy Peak, Lehman Caves, Wheeler Peak, Kious Spring, Minerva Canyon, and Arch Canyon. J. L. Brown served as project chief—functions included collaboration with Park Service personnel, management of schedules and products for mapping and topical studies, and coordination and production of GIS products.

The first summer field season (1992) involved geologic mapping and field examination in three quadrangles: Windy Peak, Lehman Caves, and Kious Spring. The second summer field season (1993) involved geologic mapping and field examination in Arch Canyon and Wheeler Peak quadrangles. The final summer field season (1994) involved mapping in Minerva Canyon and Arch Canyon.

The quadrangles are prioritized according to complexity. Published and unpublished geologic data are compiled onto registered stable base greenline topographic mylars. The greenlines are required base material for further map publishing processes and digitizing. Digital elevation models of the topography were acquired for the six quadrangles at 1:24,000 scale. New data were compiled from recent aerial photography of the park using the Kern computerized photogrammetric mapper (PG-2). The compilations served as working drafts for the actual on-the-ground field work and were finalized after field mapping was completed. The field work follows standard geologic field mapping methods as described in Compton (1962). The geologic map is first published as an author-prepared, black and white, USGS Open-file Map and Report, which is quickly available to the NPS and the geologic community. The final product is a full-color USGS GQ map. All six quadrangles in Great Basin National Park will be published in the GQ format.

Ten samples for age dates were collected from selected plutons and flows and were analyzed by fission track and $^{40}\text{Ar}/^{39}\text{Ar}$ methods in laboratories at Stanford University and at the University of California at Santa Barbara. Fission track dating methods determine the age of a rock from microscopic paths of

radiation damage caused by uranium fission. Dating methods ($^{40}\text{Ar}/^{39}\text{Ar}$) determine the age of a rock from the known radioactive decay rates of argon isotopes.

Clear film blackline copies of the completed geologic greenlines are scanned on a Textronix drum scanner and the data converted into ARC INFO coverage. The ARC INFO coverage is edited to eliminate errors and other features attributed with elevations. A triangulated irregular network (TIN) is created to facilitate edge mapping and mosaicking of the six completed quadrangles into a geologic map of the whole park.

Study Site

The southern Snake Range, as part of the Basin and Range Geologic Province, represents the transition between the unextended Confusion Range structural block to the east and the more highly extended region encompassing the Snake, Schell Creek, and Egan ranges to the west (Gans and Miller 1983; Dumitru et al. 1993; Miller et al. 1993). The Snake Range decollement (Drewes and Palmer 1957; Misch and Hazzard 1962; Whitebread 1969; McGrew 1993) is exposed in the park and is recognized as a large-scale, low-angle, fault plane surface. In addition, the central portion of the southern Snake Range is recognized as a metamorphic core complex from mineralogical and microstructural fabric in the rocks (Misch and Hazzard 1962; Miller et al. 1989). Controversy abounds about the direction of movement (compressional or extensional) on the Snake Range decollement (Coward et al. 1987; Lee et al. 1987; McGrew 1993) and on the origin of metamorphic core complexes in general (Crittenden et al. 1980; Armstrong 1982; Coney and Harms 1984).

Following the development of plate tectonic theory and Atwater's (1970) reconstruction of the evolution of western North America using plate tectonic motion, most geologists have interpreted Basin and Range Geologic Province evolution within the context of plate tectonics. Subduction along the continental margin during the time of the Sevier orogeny (middle Cretaceous) in Nevada caused compression, eastward thrusting, and overthickening of the crust along a narrow welt bordering the eastern edge of the miogeocline. In Nevada, the location of the overthickened crustal welt approximated the Nevada-Utah state line and later became the locus for the development of metamorphic core complexes. The core complexes are unique mid-Tertiary features that represent

rare glimpses of continental crustal rocks that have been deformed and metamorphosed by stretching, extension, doming, and denudation. Structural and metamorphic relics of both the compressional and extensional phases of core complexes are preserved but are not easily interpreted.

The Snake Range decollement and its associated metamorphic core complex, together with recent seismic reflection profiles, suggest a regional crustal extension model at mid-Tertiary time (Wernicke 1981; Miller et al. 1983; Bartley and Wernicke 1984; McGrew 1993). In addition, extension in the eastern Basin and Range Geologic Province was preceded by a flux of magmatism into the crust and then was followed by low-angle, core-complex-style (extension) faulting (Gans et al. 1989). In the study area, extension began in the early Oligocene and resulted in approximately 95 km of west-northwest and east-southeast directed crustal stretching (Gans and Miller 1983). Because extension terrains appear to be compartmentalized and alternated with areas of much less deformation along the welt, they are not related in a simple way to plate-boundary forces. Therefore, the ultimate cause and regional tectonic setting of the park remains poorly understood.

The southern Snake Range is underlain by upper Precambrian to Triassic (540 to 240 Ma [million years ago]) sandstones, shales, and carbonates with cumulative thicknesses possibly greater than 15 km. They form part of a shallow-marine, miogeoclinal sequence deposited on the subsiding margin of North America. In the park, this sequence is represented by the Late Proterozoic and Lower Cambrian Prospect Mountain quartzite (Hague 1892), the Lower and Middle Cambrian pioche shale (Walcott 1908), and the Middle Cambrian Pole Canyon Limestone (Misch and Hazzard 1962). Spectacular exposures of the miogeoclinal strata are seen in the head wall of the Wheeler Peak cirque and at the north face of Mount Washington. Formational designations, thicknesses, and regional facies variations have been described by Drewes and Palmer (1957), Whitebread (1969), Hose and Blake (1976), and Stewart (1980). This sequence was intruded by granitic to dioritic plutons during Jurassic (160–155 Ma), mid-Cretaceous (110–90 Ma), and Late Cretaceous (90–70 Ma) time (Miller et al. 1983, 1988, 1990; Lee et al. 1986). The intrusion of the plutons caused deformation and metamorphism of the shallow marine shelf sequence.

The most recent faulting in the area took place about 12 to 5 Ma ago (late Miocene) and served to block out the mountains and flat valleys (horst and graben structure) distinctive of today's Basin and Range Geologic Province topography. Examples of tilt blocks formed from faulting and tilting of the

northern and southern Snake Range and the Sacramento Pass strata (Grier 1983, 1984) during the late Miocene are visible looking north from the Wheeler Peak park road. Modern landforms such as fault bounded escarpments, triangular facets on mountain spurs, linear mountain fronts of high relief, and narrow V-shaped valleys suggest continuing active vertical uplift in the park in response to ongoing Basin and Range Geologic Province mountain-building (Dohrenwend 1987).

Results

Six geologic maps were prepared and digitized: Lehman Caves, Windy Peak, Kious Spring, Garrison, Wheeler Peak, and Minerva Canyon. The Lehman Caves quadrangle was published as USGS Open-file report 93-209 (Brown 1993) and is also available as a USGS Geologic Quadrangle (GQ-1758; Brown 1994a). Windy Peak was published as USGS Open-file report 94-687 (Brown 1994b); Kious Spring and Garrison quadrangles were published as USGS Open-file report 95-010 (Brown 1995). Mapping in Arch Canyon, Wheeler Peak, and Minerva Canyon quadrangles was completed in summer 1994. Because of the structural complexity, mapping of Arch Canyon and Minerva Canyon was the most challenging part of the project. The Great Basin National Park research project has resulted in other papers and abstracts (Brown et al. 1993; Dumitru et al. 1993; McGrew 1993; Miller et al. 1993).

Through GIS applications, we have produced colored geologic maps and three-dimensional, aerial perspective maps of the south Snake Range showing the geologic formations draped over the topography. These posters are on display at Stanford University, at the Visitor's Center of Great Basin National Park, and at the USGS National Center in Reston, Virginia. The digitized geologic maps are archived with the USGS National Mapping geologic data base and with the Nevada Bureau of Mines and Geology in Reno.

Discussion

Our purpose is to provide basic geologic mapping, GIS data sets, and results of geologic research to the newly established Great Basin National Park in the southern Snake Range, Nevada. The results help NPS develop responses to preservation and management issues and provide a basis for continued

scientific research in the region. In addition, published products that interpret research allow visitors to explore the value of parks as laboratories for natural resource studies.

We provide new data on the late Precambrian and Paleozoic depositional history of the region; illustrate the Mesozoic and Cenozoic structural, metamorphic, and intrusive history of rocks in the southern Snake Range; and detail the geometry and history of the fault systems that evolved during the formation of the southern Snake Range. Previous mapping provided information on stratigraphic succession, regional extents, and correlations of specific units at a small scale. Because much of the early mapping was done before the dissemination of modern petrologic concepts, structural and geochemical analyses and details of the correlation, ages, and compositions of geologic units were not well known.

Mapping objectives included providing greater detail on certain critical geologic relations, exploration for additional structures, and relating local fundamental deformational features to a regional scheme. This included determination of amounts of extension in the southern Snake Range; time of emplacement, composition, and source of plutons; nature and timing of movement on the Snake Range decollement; and interpreting the ultimate cause of thrusting.

Results of new apatite fission track dates from our study, supplemented by other information, point to significant extension and uplift from 20 to 15 Ma (early to middle Miocene) in the southern Snake Range, which was earlier than previously thought (Dumitru et al. 1993). New age dates are anticipated from the analyses of 10 samples collected in summer 1992 in the southern two quadrangles (Arch Canyon and Minerva Canyon) and will provide more detail on the timing of this extension event.

Previous work on the intrusive rocks in the southern Snake Range revealed three types of distinctive granitoids clustered in a small area, an association different from the rest of the Great Basin (Lee et al. 1986). Three of these plutons (Willard Creek, Osceola, and Snake Creek–Williams Canyon) are oldest (Middle Jurassic) and are derived from the deepest source. Two plutons (Pole Canyon–Young Canyon and Lexington Creek) are Late Cretaceous in age and are derived from shallower depth. The youngest pluton (Young Canyon–Kious Basin) is 37 Ma in age (Eocene) and is emplaced at the shallowest depth. Latest movement on the southern Snake Range decollement is believed to be younger than Eocene because the Young Canyon–Kious Basin and Lexington plutons

were affected. In addition, pluton emplacement migrated from northwest to southeast, and migration was accompanied by shallowing of the magmatic source. A conclusion drawn from our studies to date shows that recent movement on the southern Snake Range decollement is extensional and was initiated after middle Miocene time.

Unsettled problems of Basin and Range Geologic Province extension include determining driving mechanisms of low-angle faulting; relating extension with plate-boundary forces; evaluating the role of magmatic intrusion as a possible driving mechanism for extension; understanding isostatic rebound, doming, and flattening of the footwalls of normal faults; evaluating the location, amount, and timing of extension; determining the significance of the flat mantle–crustal boundary (Moho) beneath basins and ranges; and detailing the significance of the association of decollement surfaces with metamorphic core complexes.

Acknowledgments

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Using Land-based Photogrammetry to Monitor Sandbar Stability in Grand Canyon on a Daily Time Scale

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Abstract. We report on the development of a method used to monitor spatial characteristics of subaerial alluvial sediment storage using automatic, time-lapse, 35-mm cameras. The cameras are fixed to bedrock in a protective canister, aimed at low oblique angles toward alluvial deposits of interest, and set to trigger once every 24 h. Presently, 43 sandbars are monitored with single cameras, and one sandbar is monitored with two cameras arranged to give stereographic coverage. The color 35-mm images are scanned electronically for input into PC ERDAS for digital manipulation and analysis, and the original transparencies are archived. Digital images are then sequenced and written to compact disk or video tape to produce time-lapse visualizations. Methods were developed to transform the digital image from oblique to planimetric. Aerial extent of sediment cover could then be estimated by several methods. Error analysis of transformed images showed that third-order transformations provided the optimal balance between control and accuracy. Third-order transforms were within ± 1 m to 95% confidence. We captured significant changes in 28 separate sandbar deposits in at least 79 separate events displaying typical return intervals of 105 to 110 days. Most beach failures recorded by these methods occurred following low-flow discharges on weekends. We document rapid erosion (typically complete within 1 day) followed by slower deposition (typically lasting 2 weeks).

Key words: Colorado River, fluvial erosion, image analysis.

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Until recently, water resource management policies in the West were not evaluated for effect on the downstream riparian environment (Ingram et al. 1991). The construction and operation of Glen Canyon Dam seems to have profoundly influenced the downstream riparian environment throughout Grand Canyon (Dolan et al. 1974; Andrews 1991; Dawdy 1991; Johnson 1991). The task of assessing the types and magnitudes of these changes has fallen to the Glen Canyon Environmental Studies (GCES; Committee to Review the Glen Canyon Environmental Studies 1987).

A major research emphasis of the GCES has been sediment in the Colorado River system in Grand Canyon. The amount of sediment, the dynamics of sediment transport, and the resulting deposit morphology of sediment are components of the overall river ecosystem. Sediments serve as substrates for plants, as water-stilling structures and water-warming structures for various plants and animals, and as camping sites for river runners (Johnson 1991; Valdez and Williams 1993).

Most sandbars form in predictable locations based on the interaction between river hydraulics and landform features of bedrock or boulders. Typically, runoff from intense localized storms drains down steep-gradient tributary canyons and produces bouldery debris fans at the mainstem confluence. The debris fan constricts the mainstem channel and creates supercritical or shooting flow of the rapid. The supercritical flow separates from the bank near the toe of the debris fan and leaves a low velocity, recirculating eddy zone downstream of the fan and a bounding shear zone between the shooting flow and the eddy zone called the eddy fence. As the shooting flow of the rapid decelerates, the flow reattaches to the bank at some point downstream (Fig. 1; Schmidt and Graf 1990; Bauer and Schmidt 1993).

Sand and finer grain clastics are within the critical particle size range for erosion, transportation, and deposition in these types of hydraulic environments. The usual resulting deposits are visible (Fig. 1) under low-stage conditions. Typically, sandbars are found along the upstream face of the debris fan (upper pool bars), along the downstream face of the fan in the quiet water of the eddy (separation bars), and at the stagnation zone of the flow attachment (reattachment bars). Other depositional environments include point bars on the insides of meanders and thin channel margin deposits not otherwise associated with debris fans or meanders. In addition, a poorly quantified volume of sediment is stored subaqueously on the channel bottom (Schmidt and Graf 1990; Bauer and Schmidt 1993).

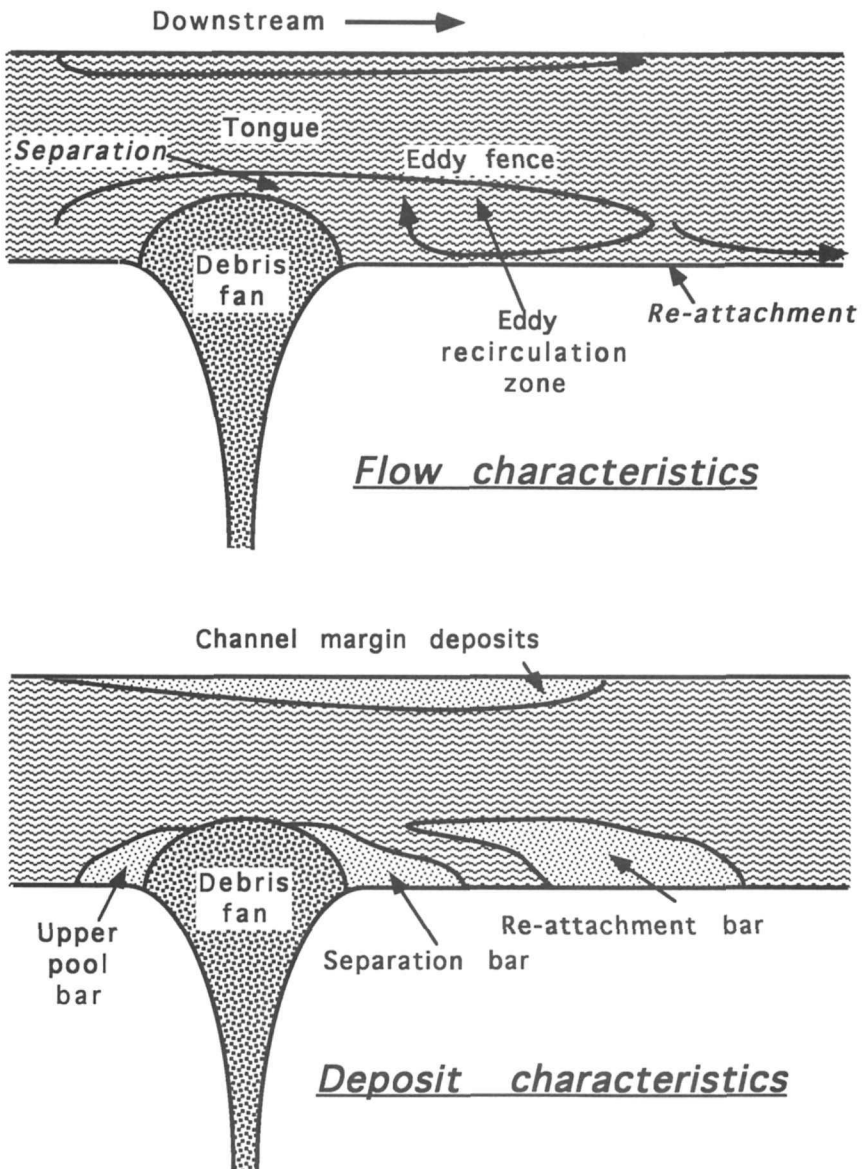


Fig. 1. The major hydraulic components of a Grand Canyon rapid (*top*) and the resulting alluvial deposits (*bottom*).

The mechanisms by which these deposits can change form and volume are of interest to researchers and planners, especially because the flow regime of the postdam Colorado River in Grand Canyon is so much different than in predam times. The most notable difference includes the change from an annual flow cycle (100,000–2,000 cfs) dominated by snowmelt runoff to a diurnal flow cycle dominated by peak power generation demand (30,000–8,000 cfs). The following three major mechanisms seem to be active in the reworking of sandbars (Budhu 1992):

1. seepage induced failure during low flow;
2. wave induced erosion from surface turbulence, wind, and boats;
and
3. drag forces from bottom turbulence and downstream flow.

Early efforts of the GCES researchers were directed at obtaining baseline volumetric estimates and short term volumetric changes of sandbars within the Grand Canyon. One early method involved inserting thin wire cables of known length vertically into the sandbar at node points of a precisely surveyed grid. In theory, the wires in this grid could be remeasured quickly on subsequent trips and supply data necessary for volumetric estimates. Quite often, however, subsequent survey trips would find the sandbar had changed so much in just 2 weeks that large portions of the wire grid could not be found. This technique was replaced out of necessity by a much more labor intensive approach using total station plane surveying at biweekly intervals.

Hypothesis

The volumetric survey work showed that major changes had occurred in sandbar morphology in between survey visits. We feel these changes are neither gradual nor consistent from sandbar to sandbar. We hypothesize that significant changes in sandbar morphology and volume can occur over a period of several hours to several days.

Objectives

Our objectives are

1. to obtain daily photographs for a year of 43 sandbars along the Colorado River between Lees Ferry and Diamond Creek;
2. to digitize some of the photographs for analytical and other purposes;
3. to develop procedures to assess the errors involved and rectify these images from oblique to planimetric views;
4. to develop animated visualization to help assess short time step changes in sandbar morphology over the sampling period; and
5. to use the results of the previous objectives to analyze the nature, timing, and extent of short term change in sandbar morphology.

Methods

Field Methods

We needed an inexpensive replacement for precision aerial photogrammetry because aerial photography is expensive even for a single time step. Also, we needed daily photography, but daily aerial photography is intrusive on wilderness and dependent on favorable flying conditions.

We used a land-based camera system built from relatively inexpensive off-the-shelf products. We chose Pentax IQ 105 programmable cameras as the core of the system. The microprocessor-controlled cameras allow the built-in timer to be set for repeat exposures once every 24 h at a preset time of day. Each camera was secured to a base, which was fastened snugly inside a standard military ammunition can. A large, round hole was cut into the side of the can congruent with the position of the camera lens and fitted with glass. A small metal gable was fashioned to protect the glass from the elements. The boxes were painted in earth tones to make them inconspicuous.

At each sandbar site, a camera box was located a sufficient distance away to allow photographing the entire beach. A single camera was used except at site 172.3L where two cameras were used to test stereographic coverage. Usually, the camera was located across, and elevated above, the river to provide a low oblique view of the sandbar. The camera box was attached with silicon sealant to a large boulder or to bedrock.

The timer was set to expose the film daily at a predetermined time selected to take advantage of local low river stage and to avoid local shading. Each camera was loaded with 36-exposure, ASA 64, color slide film, attached to the base, and sealed in the box along with a packet of desiccant. Forty-three sandbars

were included in the sample, and each of the five major geomorphic reaches (Schmidt and Graf 1990) was represented (Fig. 2).

While the camera was being sited, control panels were temporarily fixed at points around the beach. A surveying crew then located the positional coordinates of the panels and the camera box using total station plane surveying techniques. Once the camera had photographed the sandbar with the control panels in place, the panels were removed. Subsequently, the film was recovered approximately monthly. Virtually no mechanical failures occurred with the cameras.

Image Processing

Film was processed conventionally and left in strips to facilitate scanning. A Nikon high-resolution slide scanner was used to convert the image to digital form. The digital tagged image format file (TIFF) created by the scanner was controlled by using Picture Publisher software. The image was imported into ERDAS V.7.5 for image rectification and analysis (Fig. 3; ERDAS 1992).

The image had to be rectified from an oblique view to a planimetric view. The pixel locations of the control panels in the image were matched with the precisely surveyed coordinates of the same panels on the ground through a transformation equation. A variety of transformation equation orders or exponential powers may be applied. The benefit of higher order equations is a reduced root mean square (RMS) error between image and ground (Fig. 4).

Each higher order equation requires an increase in the number of ground-control points. Control panels were no longer necessary once the desired transformation equation had been established. Fixed natural features in the image were used to control subsequent transformations. Typically, these natural features were chosen from the bedrock or debris fans surrounding the sandbar deposit.

Once the images were rectified to approximate the planimetric view, various area and outline shape related analyses were performed. These analyses include total area of subaerial sand cover and daily lateral erosion or deposition rates based on a comparison of sequential images (Fig. 5). Estimates of height change and sand volume cannot be made with single-camera photogrammetry. In addition to the measurements, the original oblique views or the rectified views were sequenced into high-speed video loops for improved visualization and understanding of sandbar dynamics.

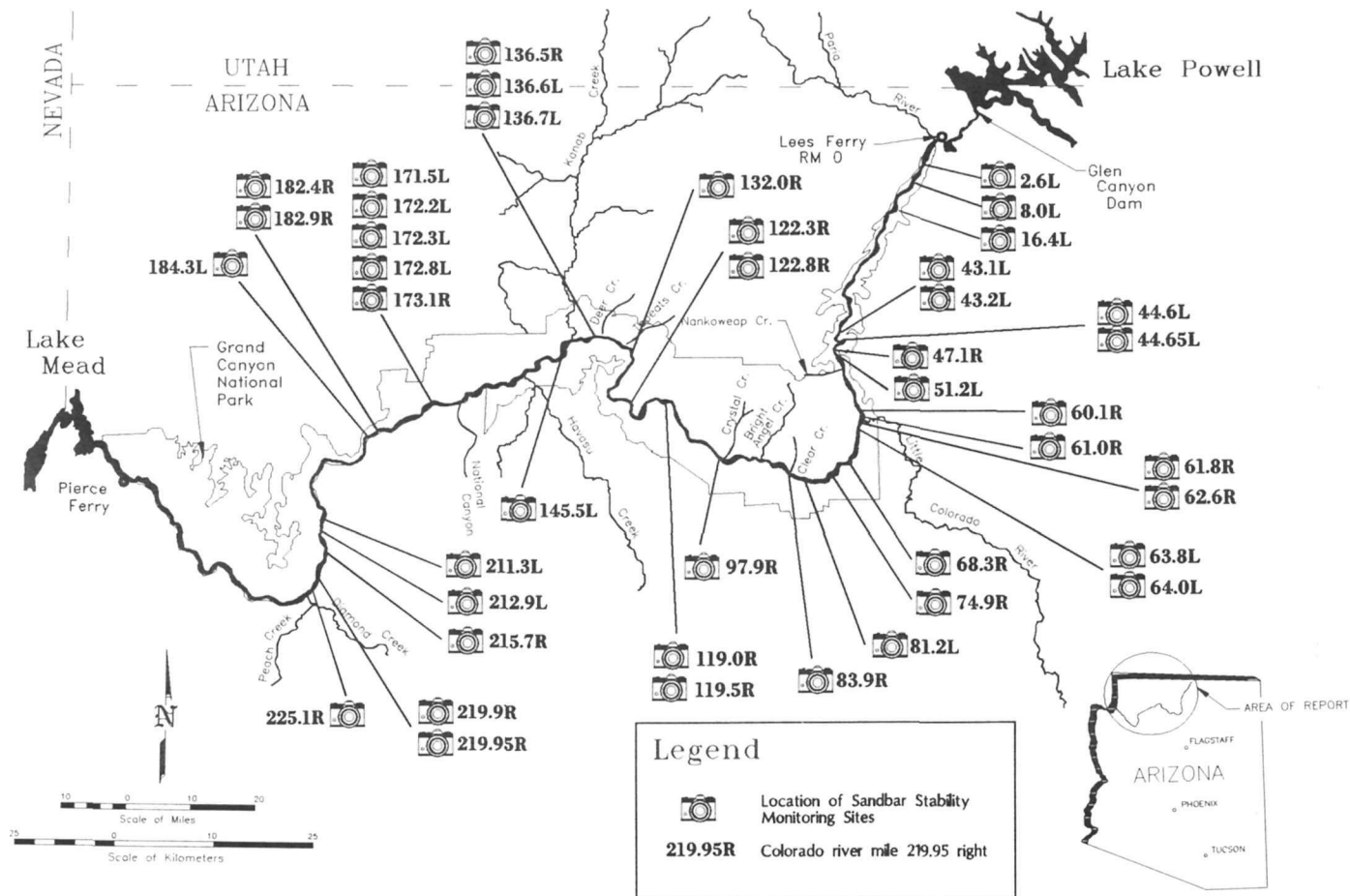


Fig. 2. Site index map for sandbars and camera stations used in this study.

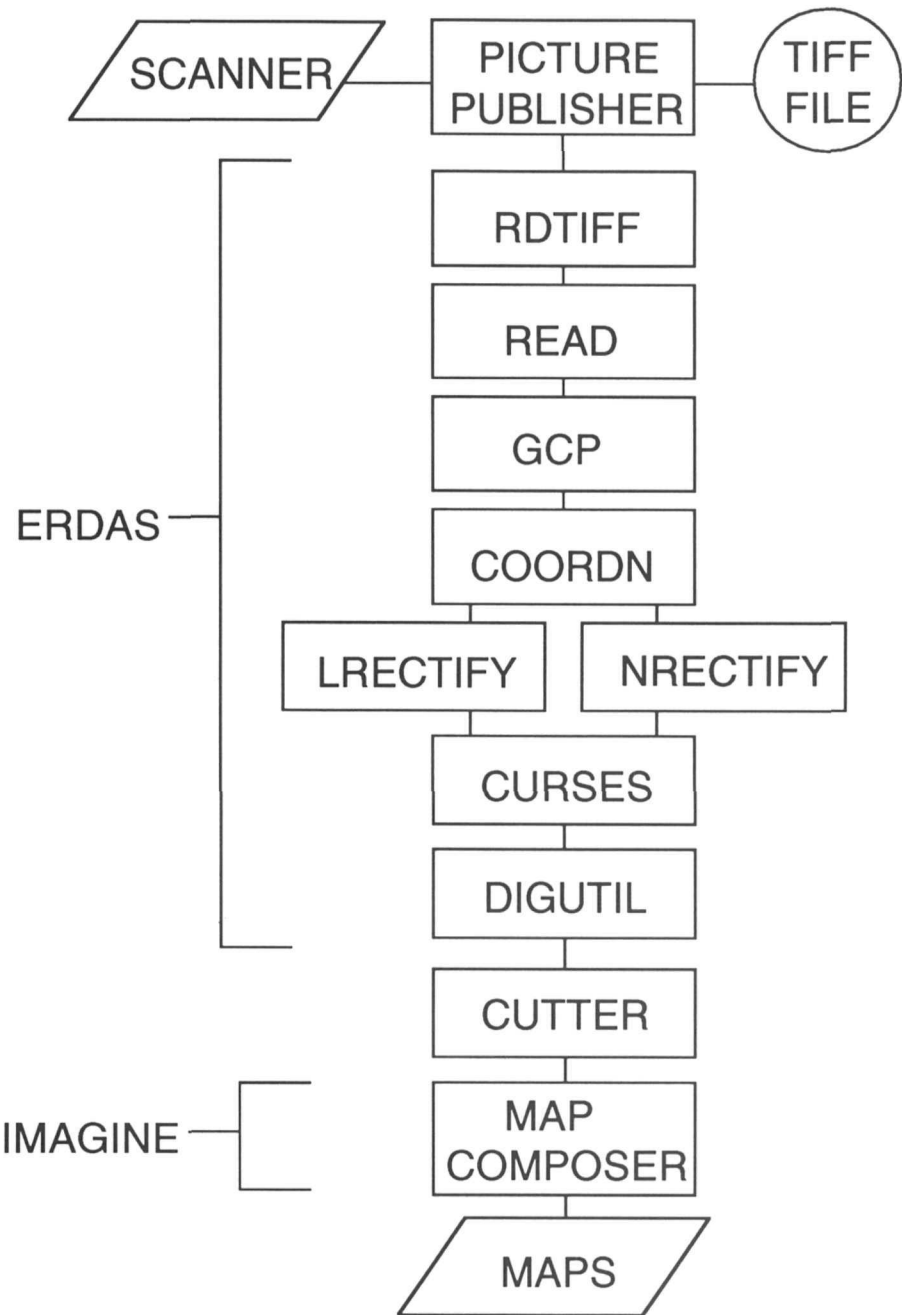


Fig. 3. Major image processing procedures and modules used in this study.

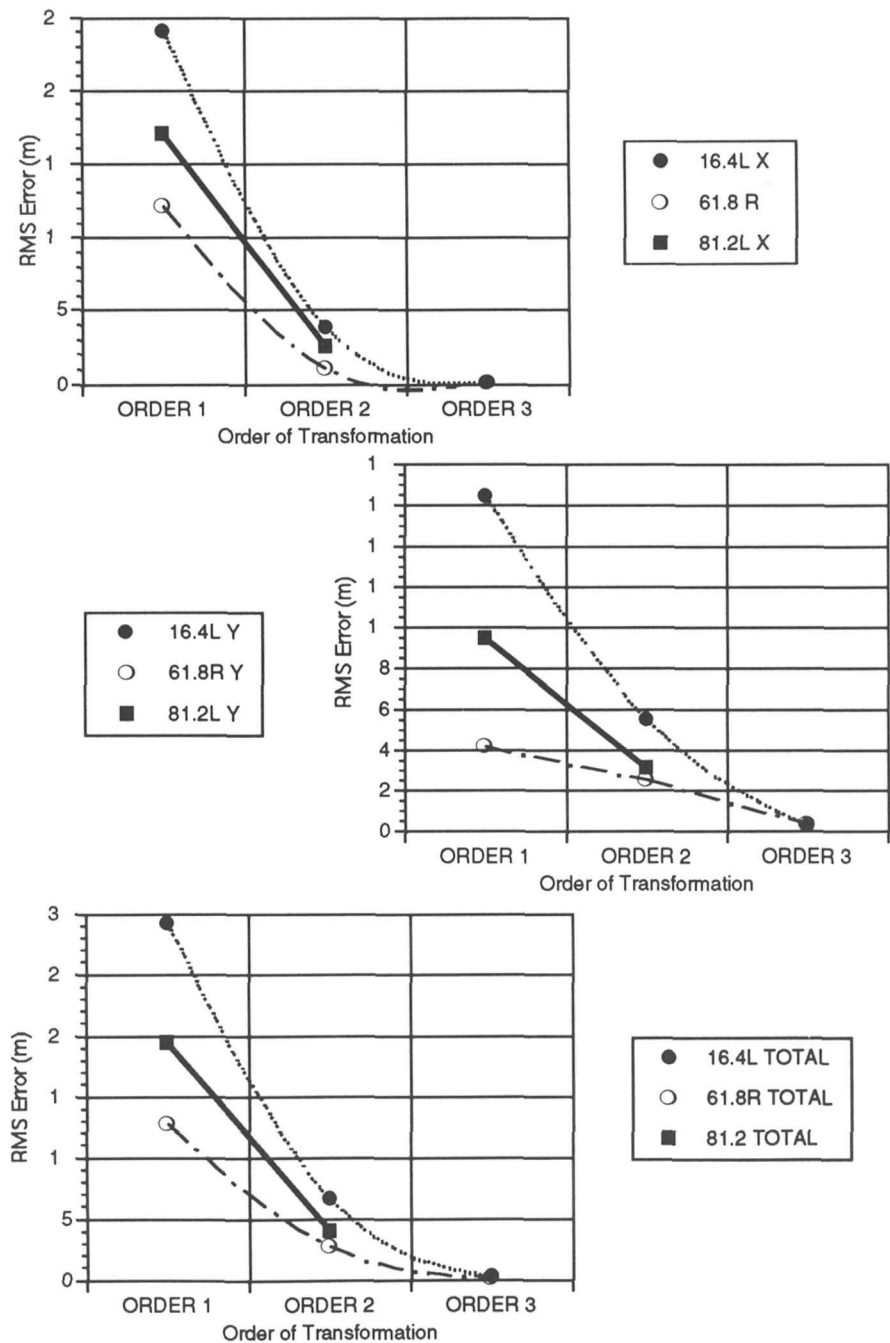


Fig. 4. Transformation order versus RMS error as reported by ERDAS.

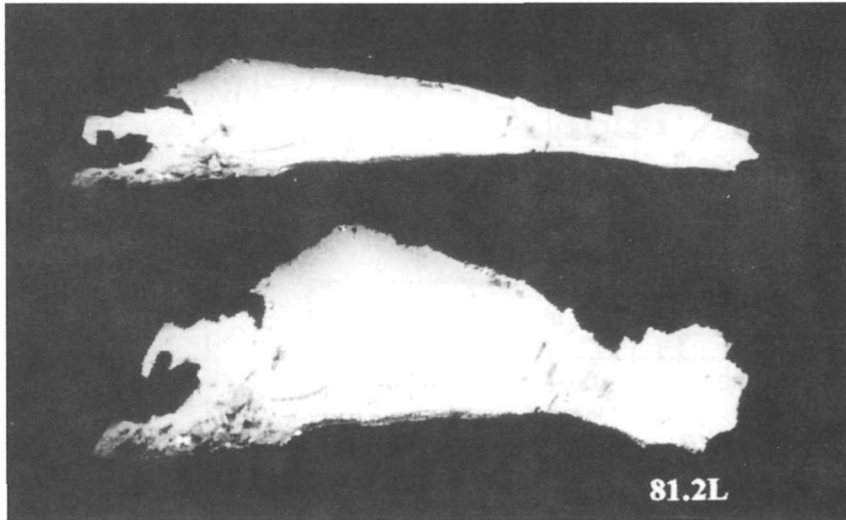


Fig. 5. Pretransformation (*top*) and post-transformation (*bottom*) images in ERDAS of 81.2L showing control panels in place.

Results

Methodologic

One of our objectives related to analysis of the spatial accuracy of the techniques used. The simplicity of the technique and the ability to vary the repeat interval of the photography makes these methods usable in a wide variety of environmental assessments using image analysis or Geographic Information System (GIS) applications.

Possible sources of error accrued through the image processing steps included nonplanar sandbar surfaces and abrupt changes in elevation, slight shifts in camera position during maintenance, diurnal environmental heat flux, scanning error (e.g., film curl); manual identification of control points, and limitations in masking target image in batch processing. To assess the cumulative spatial error involved in our procedures, we selected three sandbars of about the same linear extent (approximately 100 m long) but with different amounts of vertical relief. The sandbars selected were 16.4L (Hot Na Na), 61.8R (first site below the Little Colorado River confluence), and 81.2L (Grapevine Camp). The sandbar at 61.8 was included because of its high relief, whereas 16.4L and 81.2L represented more typical relief. We withheld several of the control panels

from the transformation, then ran the transformation operation using the remaining control points, and finally queried the transformed image for the location of the withheld panels.

The resulting queried coordinates reflected a cumulation of all errors propagated through the system when used in a manner we were likely to employ in our spatial analyses. These queried coordinates were obtained using the CURSES module of ERDAS (Fig. 3). When the queried coordinates were compared to the surveyed coordinates for the panels, a Euclidean distance error could be computed for each panel withheld.

ERDAS internally computes an RMS error for the transformed image compared to the control points used. It would be convenient if the transformation RMS value could be used as an estimate of error for any point on the transformed image. We set out to evaluate the validity of that possibility by comparing the RMS error to Pythagorean distance errors for the control points that were withheld. The salient statistics for the individual sandbar error analyses is illustrated in Table 1. When performing the error analysis, we must withhold so many points that third order transforms are not possible, so our results are derived using second order transforms and subsequently extrapolated to third order transforms (Table 2).

Results of the error analysis suggest that the RMS value is typically (but not always) a conservative estimation of Pythagorean distance error (Table 1), hence confidence intervals should be applied. Order three transforms seem to be the optimal choice considering a balance between accuracy and surveying effort.

Order three transform RMS suggests better than 1 in 100 spatial accuracy at an alpha level of 0.05 or 95% confidence (Fig. 4). Therefore, the techniques used here allow us to come within 1 m of planimetric position for 95% of the point positions sampled.

Environmental

Some initial analysis was completed but more is needed. By combining the photogrammetry from this project and the pilot project, we had usable records for selected sandbars to August 1990. Since August 1990, significant changes have occurred at least 79 times in the morphology of 28 sandbars. Two long-running records showed 10 failures from August 1990 to July 1993 (68.3R) with a mean return time of 110 days and 9 failures from January 1991 to July

Table 1. Error analysis for images of three Grand Canyon sandbars using second-order transformations.

16.4L Hot Na Na (approx. 100 m long)			
Point number	Error in X (m)	Error in Y (m)	ΔZ^a value (m)
5 (Front)	0.17	1.10	95.98
7 (Front)	0.72	0.11	96.00
F1 (Middle)	0.31	0.44	97.31
F2 (Middle)	0.74	2.28	97.62
			$\Delta Z = 1.74$
RMS = 0.928	$\bar{X} = 0.49$	$\bar{Y} = 0.98$	$\Delta Z \text{ all} = 1.94$
61.8R first sandbar below the Little Colorado River (approx. 100 m long)			
Point number	Error in X (m)	Error in Y (m)	ΔZ^a value (m)
4 (Front)	0.21	0.16	101.29
7 (Back)	0.40	2.26	127.09
RMS = 4.78	$\bar{X} = 0.61$	$\bar{Y} = 1.21$	$\Delta Z = 25.80$
5 (Front)	0.23	0.31	110.17
9 (Middle)	0.00	1.95	128.89
10 (Back)	2.17	6.65	166.06
			$\Delta Z = 55.89$
RMS = 4.68	$\bar{X} = 0.80$	$\bar{Y} = 2.97$	$\Delta Z \text{ all} = 77.14$
81.2L Grapevine Camp (approx. 100 m long)			
Point number	Error in X (m)	Error in Y (m)	ΔZ^a value (m)
3 (Front)	0.95	0.68	95.00
9 (Back)	2.44	1.38	96.97
RMS = 3.9	$\bar{X} = 1.70$	$\bar{Y} = 1.03$	$\Delta Z = 1.97$
2 (Front)	1.61	0.61	95.07
7 (Back)	3.52	0.85	96.40
			$\Delta Z = 1.33$
RMS = 1.83	$\bar{X} = 2.57$	$\bar{Y} = 0.73$	$\Delta Z \text{ all} = 3.40$

^a ΔZ = Difference between minimum and maximum Z values.

1993 (172.3L) with a mean return time of 105 days. The most common morphological change was rapid erosion (complete within 1 day) followed by slow deposition (up to 2 weeks). About 50% of the documented failures followed weekend low flows.

Table 2. Summary error analysis for oblique single-point photogrammetry as used in this study.

A summary of the RMS curves presented earlier is given:

First order	20.39 m
Second order	4.44 m
Third order	0.41 m

Results of point position tests on the second order transforms from three sandbars yield the following values:

	Mean (m)	Standard deviation (m)
$\Delta Z^a < 60.0$ m	1.99	1.81
$\Delta Z < 5.0$ m	1.76	1.08

Compared to the equivalent RMS values for the associated transformation:

	Mean (m)	Standard deviation (m)
$\Delta Z^a < 60.0$ m	4.37	1.73
$\Delta Z < 5.0$ m	2.21	1.52

Applying confidence intervals to the reported RMS values:

Confidence	Order 2 RMS (m)	Order 3 RMS (m)
80% ($\alpha = 0.2$)	6.15	0.75
90% ($\alpha = 0.1$)	7.04	0.92
95% ($\alpha = 0.05$)	7.78	1.07

^a ΔZ = Difference between minimum and maximum Z values.

Figures 6 through 10 illustrate oblique views of two typical sandbar failures. Figure 6 shows 215.7R on 13 March 1993 and Fig. 7 is the same sandbar 1 day later (14 March 1993). Note the loss of several meters. Figure 8 shows 16.4L (Hot Na Na) on 22 October 1992. The same sandbar 1 day later (23 October 1992; Fig. 9) shows seepage failure with water loss in progress. The photograph for 24 October 1992 (Fig. 10) shows the full extent of the failure. Figures 11 (18 June 1991), 12 (19 June 1991), and 13 (1 July 1991) show the sandbar at 172.3L, an active bar as described above. Figures 11 and 12 reflect only 1 day of difference and are indicative of the rapid rate of failure. Two weeks after the 19 June failure, the bar was gradually rebuilding (Fig. 13).

The photogrammetry indicates more active sediment recycling than one would assume from the long term studies only. Data for a number of Grand Canyon sandbar studies (Table 3) show lateral erosion and deposition rates. As



Fig. 6. Sandbar at 215.7R on 13 March 1993, prefailure.

the sampling interval shortens, the maximum instantaneous erosion rates climb in a near-logarithmic increase (Fig. 14).

We have sequenced 200 days of oblique photographs from 68.3R, the large sandbar across the river from the bottom of the Tanner trail, into a 30-s



Fig. 7. Sandbar at 215.7R on 14 March 1993, postfailure.



Fig. 8. Sandbar at 16.4L on 22 October 1992, prefailure.

video loop for demonstration. We need to improve the registration and correction for brightness, but the pilot project allowed us to visualize the changes in an extremely dynamic geomorphic system.



Fig. 9. Sandbar at 16.4L on 23 October 1992, during failure.



Fig. 10. Sandbar at 16.4L on 24 October 1992, postfailure.

Interim Conclusions and Future Work

We conclude that terrestrial photogrammetry is a useful, economical, and minimally intrusive tool for monitoring environmental change and for verification



Fig. 11. Sandbar at 172.3L on 18 June 1991 prefailure.



Fig. 12. Sandbar at 172.3L on 19 June 1991 postfailure.

of theoretical models. Planimetric accuracy using low-oblique, single camera, photogrammetry can approach ± 1 m in a 100-m view. Sandbars in Grand Canyon often change morphology over daily and weekly time scales. Analysis of progres-

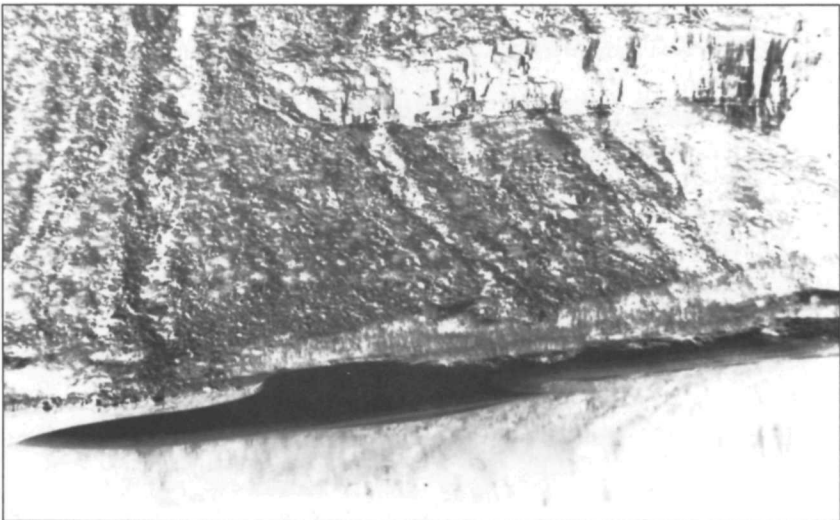


Fig. 13. Sandbar at 172.3L on 1 July 1991, approximately 2 weeks after failure and after rebuilding.

Table 3. Summary of measured lateral erosion rates versus sample frequency.

Reference	Interval	Erosion (m/yr)	Deposition (m/yr)
Beus 1992* ^a	10 years	0.8	1.7
Howard and Dolan 1979	8 years	1.15	0.7
Howard and Dolan 1979	1 year	2.45	0.7
Schmidt and Graf 1990	4.5 months	34.7	26.7
Beus 1992*	2 weeks	520	390
Cluer ^b	2 weeks	780	520
This study	daily	36,500	2,550

^aAsterisk indicates unpublished material.

^bBrian L. Cluer, Northern Arizona University, Flagstaff, personal observation.

sively shorter interval sampling periods revealed a roughly logarithmic increase in short term erosion and deposition rates. The highly dynamic behavior of sandbars in Grand Canyon indicates the need for short-duration sampling intervals.

The remainder of the study will focus on analysis of the effects of interim flows on sandbar stability. What effect did the spring 1993 floods down the Little Colorado River have on the mainstem sandbars? The following are potential research questions that this and future applications of this technique can address:

1. How are the different sandbar types affected by different discharge rates?
2. What is the progression of erosion and deposition both spatially (i.e., downstream) and temporally?
3. Are sandbar dynamics different above and below the Little Colorado River?
4. How do theoretical models of sandbar dynamics compare to reality? and
5. What are the sandbar conditions before and after a human-induced control flood?

Acknowledgments

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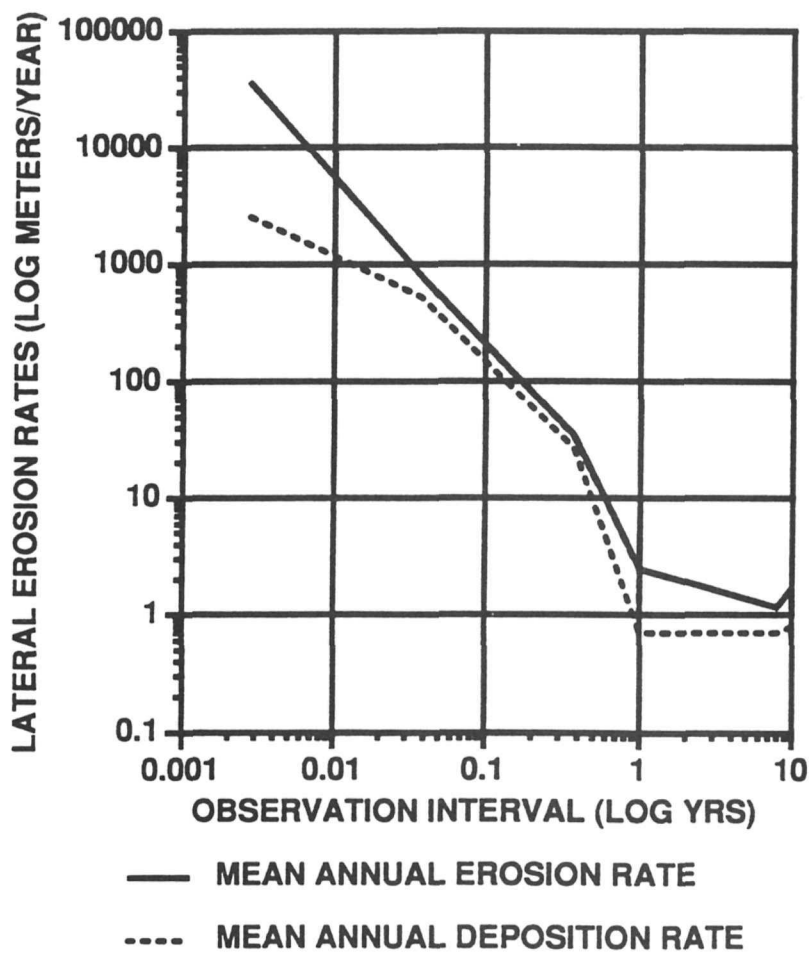


Fig. 14. Log-log scaled plot of measured lateral erosion rates versus sample frequency.

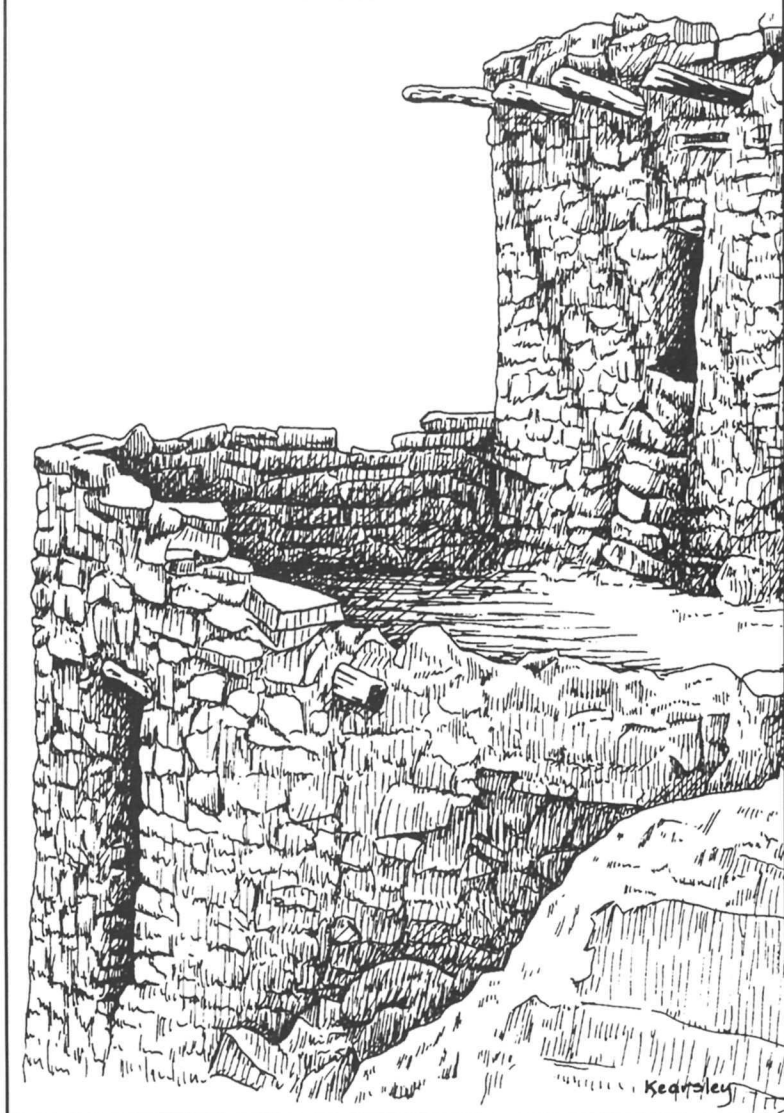
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Cultural Resources



Radiocarbon Record for Archaic Occupation of the Central Colorado Plateau

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Abstract. The traditional view of Archaic hunter-gatherer occupancy of the Colorado Plateau assumes population continuity and gradual evolutionary change. An alternative model contends that the Archaic period was punctuated by regional abandonments and reoccupations resulting in a succession of new lifeways and material culture. The numerous preceramic radiocarbon dates obtained from the central Colorado Plateau in the last 2 decades are tabulated and graphically summarized to provide a context for evaluating these two models. Long-term continuity in occupancy throughout the Archaic period is supported. Adaptive shifts that involved increased residential mobility and changes in settlement pattern probably account for previous gaps in the Colorado Plateau radiocarbon record, such as the 1,000-year interval during the middle Archaic (ca. 6000–5000 B.P. [before the present]). Because of the exceptional preservation of subsistence remains and perishable technology within numerous stratified dry shelters, copious paleoenvironmental data from a variety of sources, and occupation throughout the Archaic period, the central Colorado Plateau emerges as a highly productive area for studying hunter-gatherer adaptations and economic transitions, including the adoption of agriculture.

Key words: Archaic period, chronology, Glen Canyon, hunter-gatherers, Southwest prehistory.

Here I summarize the existing array of preceramic radiocarbon dates of the central Colorado Plateau (Fig. 1) to provide a context for examining two competing models of Archaic occupation. The first, regarded as the traditional concept of southwestern archaeologists, posits long-term continuity in hunter-gatherer occupancy marked by evolutionary changes and other alterations. The second model contends that hunter-gatherer occupancy was discontinuous—that the Archaic period was punctuated by a sequence of population abandonments

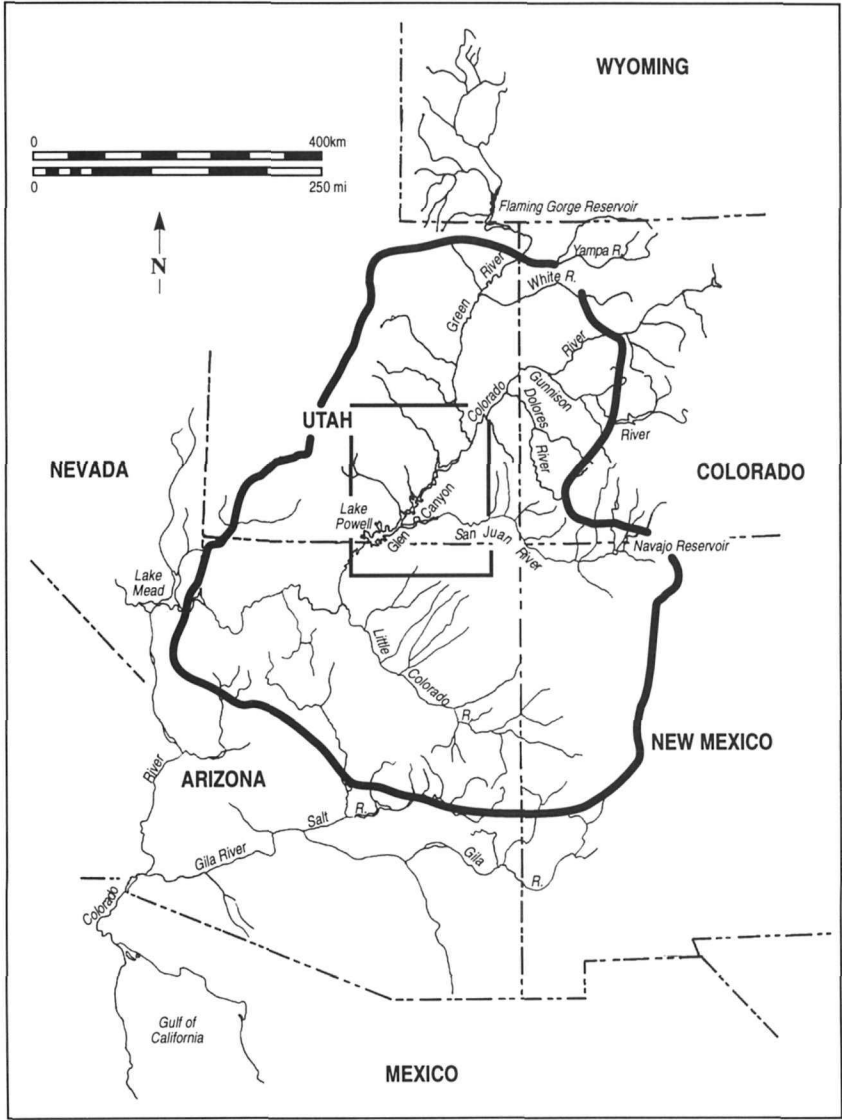


Fig. 1. Location of the central Colorado Plateau study area.

and reoccupations with new lifeways and material culture being introduced by each successive wave of hunter-gatherers (Berry and Berry 1986).

The notion of continuity in occupation during the Archaic period through the introduction of agriculture was implicit in the Pecos classification of the

1920's, which postulated that the Basketmaker II Anasazi were descendants of indigenous hunter-gatherers (Kidder 1924, 1927). This hypothetical stage of preagricultural development was designated Basketmaker I. Irwin-Williams (1967, 1973, 1979) has been the most influential recent advocate of in situ continuity in hunter-gatherer occupancy of the Colorado Plateau. Irwin-Williams (1979:35) claimed that, following abandonment by Paleo-Indians, "the northern Southwest was the focus of a long-term continuous development within the Archaic spectrum, which culminated ultimately in the formation of the central core of the relatively well-known sedentary Anasazi (Pueblo) culture." This model of continuous occupation throughout the Archaic period is so pervasive that many southwestern archaeologists consider it a fact rather than an assumption.

Few have challenged the model, but Berry and Berry (1986), with a strongly stated contrary position, are a notable exception (see Berry and Berry [1976:31–37] for the seedbed of their 1986 argument). In their opinion (Berry and Berry 1986:321),

Its perpetuation in the literature owes more to the model's function as a self-fulfilling prophecy than it does to any consideration of empirical matters. A model that assumes continuity of occupation for millennial periods hardly fosters inquiry into the occurrence and nature of discontinuities. But continuity must be assumed if the primary research objective is "... firmly establishing and understanding an uninterrupted succession of human occupancy of over a dozen millennia in the arid Southwest" (Haury 1983:159–160).

To evaluate the possibility of intermittent rather than continuous Archaic occupation, Berry and Berry (1986) analyzed the patterning of 288 radiocarbon dates before 1400 B.P. (before the present) from 119 southwestern sites. They concluded that the empirical evidence supports the contention that Archaic occupation of the Colorado Plateau was discontinuous.

The Region

The preceramic radiocarbon record we examined provides an excellent opportunity to evaluate the argument for and against continuous occupation. The 132 dates included in this study come from 64 sites scattered throughout a territory of approximately 45,000 km centered on Glen and Cataract canyons (Figs. 1 and

2). This region corresponds mostly with the Canyonlands section of the Colorado Plateau (Hunt 1974:278), a rugged area of renowned scenery—deep labyrinthian canyons bounded by colorful cliffs of mesas and plateaus and with a scattering of small mountain ranges. The region extends from the Rainbow Plateau and Monument Valley on the south to the Fremont River and Orange Cliffs on the north and from Boulder Mountain and Kaiparowits Plateau on the west to the Abajo Mountains and Comb Wash on the east. The patterning of

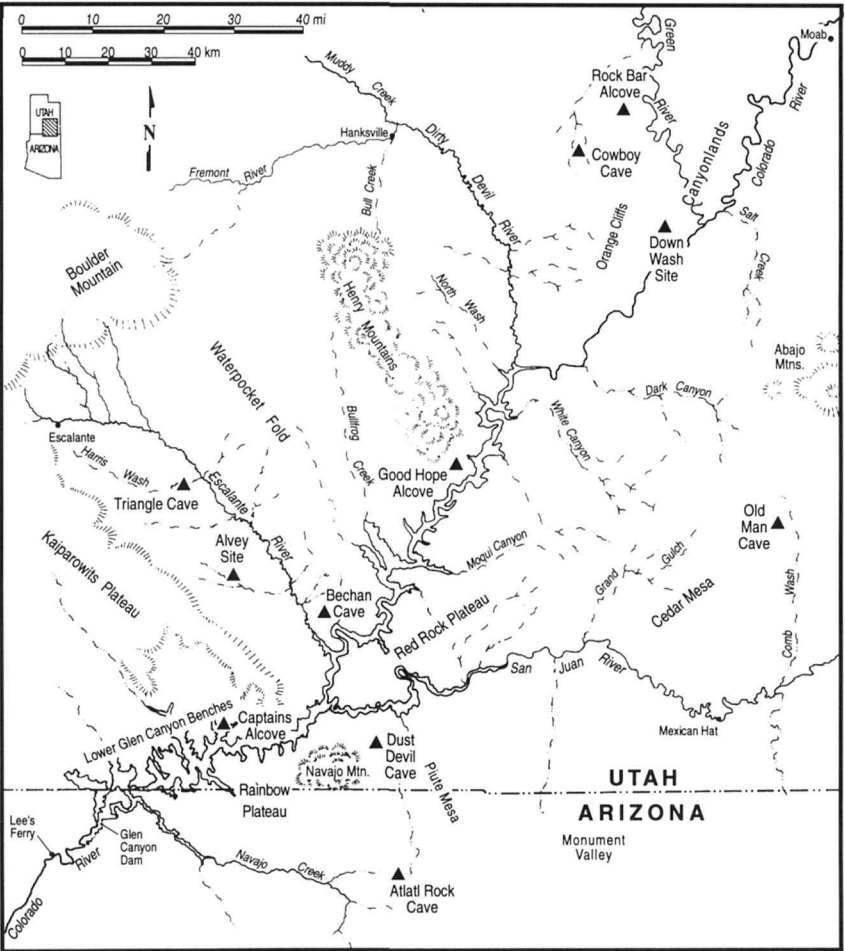


Fig. 2. The central Colorado Plateau showing the location of certain sites mentioned in the text and listed in Table 1.

radiocarbon dates analyzed here reflects human occupancy of a region considerably smaller than that examined by Berry and Berry (1986), yet the record for this central section of the Colorado Plateau should doubtless reflect the general trend on the plateau.

Key Sites

Most Archaic sites of the central Colorado Plateau have only been tested (limited excavation), so their principal contribution to this study is radiocarbon dates. These sites reveal that Archaic populations were residing throughout the region in diverse environmental settings. Two sites that help to flesh out the chronological skeleton with details of material remains and subsistence are Cowboy (north) and Dust Devil (south) caves, sites that geographically bracket the region (Fig. 2). Sandals and projectile points indicate that the Archaic groups using these two shelters had similar material culture inventories. Indeed, it is conceivable that a hunter-gatherer family group could have visited both sites, which, at 150 km apart, are within the potential long-term settlement shifts of human foragers.

Devil Cave and its nearby counterpart Sand Dune Cave¹ yielded the first conclusive evidence of Archaic culture within the central Colorado Plateau during excavations in 1961 (Lindsay et al. 1968). Sandals of previously undocumented style (open-twined) from the completely excavated Sand Dune Cave were radiocarbon dated from 8000 to 7000 B.P. (Lindsay et al. 1968), and identical sandals plus two other distinctive styles (fine warp-faced and plain-weave [coarse warp-faced]) were found during the test of Dust Devil Cave (Fig. 94 of Lindsay et al. 1968; Ambler 1994*). The subsequent total excavation of Dust Devil Cave in 1970 clarified the stratigraphic relation of the Archaic sandals and other remains, extended the range of the Archaic occupation back to almost 9000 B.P. (8830 ± 160 B.P.; Ambler 1994*), and provided much greater detail on subsistence (Van Ness 1986). Cultural deposition was relatively heavy during the early Archaic (stratum IV, ca. 8800–6700 B.P.), but a layer of essentially sterile eolian sand (stratum V) corresponding to the interval of roughly 6600–4000 B.P. reveals a significant alteration in the Archaic occu-

¹The archaeological significance of Sand Dune Cave is considerably less than that of Dust Devil because of excavation by arbitrary levels and the consequent mixing of materials from widely different periods (early Archaic through Pueblo).

pancy of Dust Devil Cave. Sparse late Archaic use of the site is evidenced by the recovery of Gypsum points from stratum VI (Geib and Ambler 1991).

Cowboy Cave (Jennings 1980), more than any other site, has had the most significant influence on our present understanding of Archaic culture—history and lifeways for the central Colorado Plateau. Besides being relatively rich in material remains, this site was excavated by natural rather than arbitrary levels, and the results were published in a timely manner. Furthermore, the changes in projectile point styles for the dated strata of Cowboy Cave were concordant with point style changes at Sudden Shelter (Jennings et al. 1980). On the strength of these results, Holmer (1978, 1980) outlined a chronology for Archaic point types for the northern Colorado Plateau, whereas Schroedl (1976) devised a phase system for the same region.² The depositional history of Cowboy Cave led Jennings to conclude that two significant occupational breaks had taken place during the Archaic use of the site—one ca. 6300–3700 B.P. and the other ca. 3200–2000 B.P. As at Dust Devil Cave, these hiatuses were represented by layers of eolian sand classified as sterile.

Two other sites deserving mention are Bechan Cave (Agenbroad et al. 1989) and Old Man Cave (Geib and Davidson 1995). Test excavations in Bechan Cave documented a single buried cultural layer without any stratigraphic separation (Agenbroad et al. 1989:338). The nine ¹⁴C samples from this deposit ranged from almost 7800 to 1200 B.P., indicating mixed or poorly differentiated cultural deposition from over 6,000 years of site use. In lieu of separable cultural strata, the dates were grouped to form five cultural periods, and artifacts were assigned to each period. Whether or not the cultural periods are real, the dates are useful for this study, and their range reveals that the site holds promise for helping to understand the Archaic period.

Only a preliminary report is currently available on the recent excavations at Old Man Cave (Geib and Davidson 1995), so this site is as yet not well known. Nevertheless, the site provides an important radiocarbon record for the eastern edge of the study area, affords an excellent glimpse of early

²The general applicability of Schroedl's phase system to the central Colorado Plateau is readily acknowledged, especially when contrasted with the Oshara phase system (Irwin-Williams 1973, 1979), which does not accurately represent the chronology and material remains found in and around Glen and Cataract canyons. Nevertheless, until greater detail on Archaic culture history of the study area and surrounding regions has been obtained, temporal subdivisions such as early, middle, and late Archaic provide preferred neutral alternatives for discussing portions of the long Archaic period (see Matson 1991).

Archaic subsistence based on the analysis of human feces (Hansen 1994), and has yielded open-twined sandals, among other perishable remains. As at both Cowboy and Dust Devil caves, a relatively intensive early Archaic occupation of Old Man Cave started drawing to a close during the seventh millennium B.P., terminating before 6,000 years ago. This hiatus or decline in site use ended when Basketmaker II agriculturalists began using the cave for storage and burial shortly after 2000 B.P.

Chronometric Data Base

More than 130 radiocarbon determinations from 64 sites of the central Colorado Plateau predate the use of ceramics and have clear cultural origins (Table 1). I have used 1600 B.P. as an appropriate time line cutoff for this study; it allows inclusion of the first practices of agriculture in the region (the Archaic to Formative transition) but excludes dates from the early Formative period (except perhaps for a few old wood determinations). Most of the dates listed in Table 1 were obtained in the past 10 years, so less than 15% have been included in previous summaries of Archaic radiocarbon dates (e.g., Schroedl 1976; Berry and Berry 1986). All standard dates (beta decay) are gas determinations made on wood charcoal from hearths or on perishable organics like yucca. Some of the dates on perishables are accelerator mass spectrometry (AMS) determinations, where the ratio of $^{14}\text{C}:^{12}\text{C}$ is directly measured. Determinations on materials subject to isotopic fractionation (Stuiver and Polach 1977) were corrected by either calculating actual $^{13}\text{C}:^{12}\text{C}$ ratios or using an assumed delta value.

Though all dates clearly have a cultural origin, in instances such as buried hearths exposed in arroyo cuts there is little or nothing in the way of associated artifacts. Some dates are on materials from multicomponent sites where stratigraphic context was lacking (surface artifacts) or obscured by poor excavation technique or previous disturbances. These dates are nonetheless useful for chronometric analysis because they are on materials of indisputable cultural origin, especially those on artifacts or human feces.

Dates on hearth charcoal can routinely overestimate the age of a cultural event by 200 years, with potential discrepancies of 500 years or more (Smiley 1985). This can lead to spurious conclusions about the chronology, use histories, and depositional rates—among other issues—of single sites and can be particularly confounding when attempting to trace the origin and spread of stylistic,

Table 1. Radiocarbon dates older than 1600 B.P. from the central Colorado Plateau.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
Alvey Site (42KA172)	123	Beta-34942	1690 \pm 80	Maize	-11.1	8.6	Geib (1993). Maize cob (FS 86) from level II (feature 31).
	116	AA-10373	1735 \pm 50	Maize	(-10.0)	22.1	Maize cob (FS 124.1) from level I (feature 47).
	114	AA-10374	1755 \pm 50	Maize	(-10.0)	22.1	Maize cob (FS 126.1) from level I (feature 47).
	107	AA-10375	1830 \pm 50	Maize	(-10.0)	22.1	Maize cob (FS 152.3) from level I (feature 56).
	Rejected	Beta-34944	2260 \pm 90	Maize	-10.8	6.8	Geib (1993). Maize cob (FS 126.2) from level I (feature 47). Rejected based on recently obtained additional maize dates from level I.
Atlatl Rock Cave	9	Beta-633306	7900 \pm 60	Grass	-11.2	15.3	Grass padding (PN2.2 from open-twined sandal; PN2.1).
Beaucoup Alcove (42KA2753)	48	Beta-38342	3900 \pm 60	Human feces	-20.7	15.3	One of 5 human feces collected from surface of alcove during its initial documentation. A rich site with an undoubtedly long history of occupation; this date provides the only evidence so far for a late Archaic component.
Bechan Cave (42KA2546)	93	GX-10501	2080 \pm 140	Charcoal		2.8	Agenbroad et al. (1989:Appendix). Slab-lined hearth assigned to Cultural Period III.
	73	A-3516	2640 \pm 50	Charcoal		22.1	Agenbroad et al. (1989:Appendix). Charcoal from auger test of cave, of uncertain context and associations. Assigned to Cultural Period III.
	42	A-3513	5500 \pm 80	Charcoal		8.6	Agenbroad et al. (1989:Appendix).

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	27	Beta-16025	6750 \pm 120	Yucca	(-25.0) ^d	3.8	Charcoal from auger test of cave, of uncertain context and associations. Assigned to Cultural Period II. Agenbroad et al. (1989:Appendix). Small fragment of open-twined sandal assigned to Cultural Period I; a whole example of this sandal type also recovered.
	17	GX-10502	7525 \pm 220	Charcoal		1.1	Agenbroad et al. (1989:Appendix). Associated with a lower occupational surface near central portion of site and assigned to Cultural Period I. A "squash gourd container" is supposedly associated with the hearth and living surface (Agenbroad et al. 1989:338), but this is well out of line with current evidence for cultigen use in the Southwest. Either the date is wrong or the association is misidentified.
	10	GX-10500	7795 \pm 230	Charcoal		1.0	Agenbroad et al. (1989:Appendix). Charcoal lens or perhaps a hearth (cf. Agenbroad et al. 1989:338 and Fig. 3); assigned to Cultural Period I.
Benchmark Cave (42KA433)	55	AA-10376	3355 \pm 50	Yucca	(-25.0)	22.1	Plain-weave sandal (FS35.1) from feature 17 (Lipe 1960); stratum 10 of the 1962 excavation (Sharrock 1964).
Captains Alcove	76	Beta-1749	2445 \pm 85	Charcoal		7.6	Tipps (1984:Table 31). Hearth 3 of

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
(42KA265)	70	Beta-1750	2720 \pm 205	Charcoal		1.3	occupation B, subarea 2 of shelter. Tipps (1984:Table 31). Hearth 2 of occupation B, subarea 2 of shelter.
	69	Beta-1748	2735 \pm 115	Charcoal		4.2	Tipps (1984:Table 31). Same hearth as sample 64 above; average of these two is given as 2730 \pm 100 B.P. (Tipps 1984:54).
	61	UGa-3254	3145 \pm 105	Small log		5.0	Tipps (1984:Table 31). Log from lowest layer of test pit 8 in subarea 2 of shelter; thought to be associated with occupation A.
	49	Beta-1232	3760 \pm 75	Charcoal		9.8	Tipps (1984:Table 31). Hearth 1 of occupation A, subarea 2 of shelter.
Casa Del Fuego (42GA3132)	40	Beta-35559	5880 \pm 90	Disseminated charcoal in sediment		6.8	Tipps (1992b* ^e). Associated with five unlined pits originating from an old ground surface buried by ca. 1.8 m of dune sand. Overlying sediment component has a burned pithouse dated 1550 \pm 60 (Beta-20671) and 1580 \pm 60 (Beta-35560); this upper component contains both Elko and Rosegate (Rose Springs) points.
Co-op Site (42KA2756)	63	GX-11339	3000 \pm 145	Charcoal	-22.6	2.6	Agenbroad et al. (1989:Appendix). Site and sample provenience documented in Bungart and Geib (1987*). Hearth 2 exposed in arroyo cut. A mano fragment and several chert pressure flakes in association. Hearth is stratigraphically

Table 1. Continued.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
Cowboy Cave (42WN420)	46	Beta-16276	4330 \pm 80	Charcoal		8.6	above a date of 4330 \pm 80 B.P. (sample 41) and below a date of 1290 \pm 75 B.P. (GX-11338; Agenbroad et al. 1989:30) and 1060 \pm 80 B.P. (Beta-16274; Bungart and Geib 1987*). Bungart and Geib (1987*). Hearth 3 stratigraphically below previous sample and buried by ca. 8 m of alluvium. Associated debitage, 2 biface fragments, a mano fragment, but no diagnostics.
	108	Maize cache average	1824 \pm 39	Maize and grass	-12.0 -15.6		Geib and Bungart (1989:42) discuss the dating problems with the Cowboy Cave maize. Stratum of origin is unknown but presumably derived from stratum Vb or Vc and associated with Rose Spring corner-notched arrow points and other remains (see Jennings 1980).
	103	UGa-1053	1890 \pm 65	Charcoal		13.1	Jennings (1980:Table 3). Obtained during original test of cave in 1973; only a probable provenience (stratum Vb) is known.
	57	SI-2495	3330 \pm 80	Grass	-15.6	8.6	Jennings (1980:Table 3). Listed as unproven since recovered during 1973 testing. Presumably from unit IV. The grass (<i>Sporobolus cryptandrus</i>) is from skin bag containing various items.
	53	SI-2998	3560 \pm 75	Wood		9.8	Jennings (1980:Table 3). Stratum IVd; associated with Gypsum points and split-twig figurines, among numerous other

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	52	SI-2715	3635 \pm 55	Charcoal		18.3	items. Jennings (1980:Table 3). Stratum IVc; associated with Gypsum points and split-twig figurines, among numerous other items.
	34	SI-2421	6390 \pm 70	Charcoal		11.3	Jennings (1980:Table 3). Loose charcoal found in sterile red sand layer, stratum IVa. Date used as upper temporal bracket for unit III instead of the date (6675 \pm 75 B.P., SI-2420) from stratum IIIi. No clear associations.
	30	SI-2420	6675 \pm 75	Yucca	-24.3	9.8	Jennings (1980:Table 3). Sandal fragment of unspecified construction technique from stratum IIIi. Expected to provide terminal date of occupation for unit III, but the previous sample was used for the upper temporal bracket of this unit. Associated with Northern side-notched and Elko points, plain-weave sandals, and other remains.
	25	UGa-637	6830 \pm 80	Charred wood		8.6	Jennings (1980:Table 3). Listed as probable from unit III; recovered during 1973 testing. No certain associations.
	21	SI-2419	7215 \pm 75	Charcoal		9.8	Jennings (1980:Table 3). Loose charcoal from midden of stratum IIIId. Associated with a Northern side-notched point, open-twined and plain-weave sandals, and other remains.

Table 1. Continued.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	7	SI-2418	8275 \pm 80	Charcoal		8.6	Jennings (1980:Table 3). Loose charcoal from first thin cultural layer in cave, stratum IIb. Associated with open-twined sandals.
Doughnut Alcove (42KA3384)	79	Beta-30568	2320 \pm 80	Grass	-24.5	8.6	Geib (1990a:268). Basketmaker II cache of three wooden tools wrapped in juniper bark mat fragment and grass (<i>Oryzopsis hymenoides</i>) and placed in a pit. No other associated remains or evidence of alcove use.
Down Wash Site (42WN1666)	130	Beta-34247	1640 \pm 60	Charcoal		15.3	Horn (1990*). Stratum 6, feature 2 (slab-lined hearth) upper fill. Inconsistent with a date of 1440 \pm 100 B.P. from lower fill of same hearth; probably because of burning of "old wood" (cf. Horn 1990*).
	111	Beta-34260	1790 \pm 100	Charcoal		5.5	Horn (1990*). Stratum 6, feature 7 (hearth). No associated diagnostics.
	102	Beta-34253	1890 \pm 70	Charcoal		11.3	Horn (1990*). Stratum 7, feature 10 (hearth). No associated diagnostics.
	100	Beta-21207	1960 \pm 60	Charcoal		15.3	Horn (1990*). Hearth exposed in cutbank of locus C. No associated diagnostics.
	98	Beta-34244	2010 \pm 70	Charcoal		11.3	Horn (1990*). Stratum 6, feature 1 (hearth). No associated diagnostics.
	91	Beta-34254	2140 \pm 70	Charcoal		11.3	Horn (1990*). Stratum 6, feature 12 (hearth). No associated diagnostics.
	87	Beta-34252	2180 \pm 60	Charcoal		15.3	Horn (1990*). Stratum 8, feature 13 (hearth). No associated diagnostics.

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	86	Beta-34259	2200 \pm 80	Charcoal		8.6	Horn (1990*). Stratum 8, feature 15 (hearth). No associated diagnostics. [Note: Table 4–2 of Horn 1990* lists this date as 220 \pm 80 B.P., clearly a typographical error given the calibrated range for the date presented in that table and the plot of the dates in Fig. 4–30 of Horn's report.]
	82	Beta-34251	2280 \pm 90	Charcoal		6.8	Horn (1990*). Stratum 7, feature 9 (hearth). No associated diagnostics.
	62	Beta-34255	3110 \pm 170	Charcoal		1.9	Horn (1990*). Stratum 9, feature 11 (hearth). No associated diagnostics.
	60	Beta-16667	3180 \pm 140	Charcoal		2.8	Agenbroad (1987*:see Figs. 91 and 92 for provenience information). Hearth exposed in arroyo cut of locus C. No associated remains.
	54	Beta-34257	3500 \pm 150	Charcoal		2.5	Horn (1990*). Loose Charcoal from stratum 11A. No associated diagnostics.
	50	Beta-34256	3750 \pm 120	Charcoal		3.8	Horn (1990*). Loose charcoal from stratum 11. No associated diagnostics.
	47	Beta-34258	4070 \pm 140	Charcoal		2.8	Horn (1990*). Stratum 11A, feature 14 (hearth). No associated diagnostics.
Durffey's Kitchen (42GA3133)	44	Beta-35561	4980 \pm 130	Charcoal		3.3	Tipps (1992b*). Hearth at site. No associated diagnostics.
Dust Devil Cave (NA7613)	109	TX-852	1820 \pm 80	Charcoal		8.6	Lindsay et al. (1968:108). Hearth 3 of alcove outside of cave proper. No certain associations.

Table 1. Continued.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	28	TX-1261	6740 ± 110	Charcoal		4.6	Ambler (1994:Table 1) Hearth 35, top of stratum IV.
	26	AA-10379	6785 ± 60	Yucca	(−25.0)	15.3	Plain-weave sandal from top of stratum IV.
	24	TX-1260	6840 ± 130	Yucca	(−25.0) ^d	3.3	Ambler (1994:Table 1). Plain-weave sandal, top of stratum IV.
	23	AA-10378	6890 ± 60	Yucca	(−25.0)	15.3	Plain-weave sandal from top of stratum IV.
	20	TX-1264	7250 ± 110	Charcoal		4.6	Ambler (1994:Table 1). Hearth 37, middle of stratum IV.
	19	TX-1263	7340 ± 110	Charcoal		4.6	Ambler (1994:Table 1). Loose charcoal, middle of stratum IV.
	14	TX-1262	7630 ± 120	Human feces	?	3.8	Ambler (1994:Table 1). Feces from top of stratum IVb. Not corrected for isotopic fractionation; given the C4 and CAM plants consumed during the early Archaic this date could be 100–200 years older.
	3	TX-1265	8730 ± 110	Charcoal		4.6	Ambler (1994:Table 1). Hearth 32, bottom of stratum IV.
	2	TX-1266	8830 ± 160	Yucca	(−25.0) ^d	2.2	Ambler (1994:Table 1). feature 17 (yucca-lined pit), bottom of stratum IV. Chapter 7 of this report discusses context and associations.
Good Hope Alcove (42GA3411)	15	Beta-31191	7560 ± 130	Yucca	−21.4	3.3	Open-twined sandal fragment from buried cultural deposit exposed at front of alcove because of erosion. Other associated remains include a mano, grinding slabs, and flakes but no other diagnostics.

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
The Hermitage (42KA443)	41	AA-10372	5665 \pm 60	Yucca	(-25.0)	15.3	Plain-weave sandal (FS 24) from an aceramic midden deposit (feature 9). Site excavated by Lipe (1960).
	37	AA-10371	5890 \pm 55	Grass	-12.1	18.3	Grass padding of plain-weave sandal (FS 19.1) from an aceramic midden deposit (feature 9).
Horse Canyon Rock Shelter (42GA3138)	80	Beta-39256	2320 \pm 60	Charcoal		15.3	Tipps (1992b*). Hearth, middle of stratum II. No associated shelter diagnostics. Stratum III dates 1380 \pm 70 B.P. (Beta-35318) whereas stratum IV dates 770 \pm 60 B.P. (Beta-20673), so date sequence is internally consistent.
	67	Beta-35319	2760 \pm 100	Charcoal		5.5	Tipps (1992b*). Hearth, bottom of stratum II. No associated diagnostics.
Lone Tree Dune (42SA363)	121	Y-1350	1700 \pm 80	Burned beam		8.6	Jennings (1966:34); also Berry (1982:57). Beam in fill of shallow slab-lined Basketmaker II pithouse with a slab-lined entrance (Sharrock et al. 1963:151-161).
Long Canyon Dune (42GA3122)	83	Beta-20669	2250 \pm 70	Charcoal		11.3	Tipps (1992b*). Hearth at site. No associated diagnostics.
Meister Knapper (42KA2745)	125	Beta-16271	1670 \pm 70	Charcoal		11.3	Bungart and Geib (1987*). Slab-lined hearth at locus B.
Murphy (42SA8500)	117	Beta-20466	1730 \pm 70	Charcoal		11.3	UPAC Newsletter, Vol. 7, No. 2, Table 1, 1989.
	68	Beta-20467	2740 \pm 60	Charcoal		15.3	UPAC Newsletter, Vol. 7, No. 2, Table 1, 1989.

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
Old Man Cave (42SA21153)	112	Beta-47741	1790 \pm 90	Juniper bark		6.8	Geib and Davidson (1995: Table 1). Basketmaker II burial (feature 3) originating from level 2.
	39	Beta-47008	5890 \pm 70	Rodent feces	-24.6	11.3	Geib and Davidson (1995: Table 1). <i>Neotoma</i> feces from level 4, which along with level 3 seems to represent an interval of natural deposition (cultural hiatus?). This date was not used in Figs. 3 and 4 of this report.
	36	Beta-48141	6120 \pm 70	Charcoal		11.3	Geib and Davidson (1995: Table 1). Hearth (feature 5) originating within level 5. Marks the end of early Archaic occupation of the shelter.
	29	Beta-47743	6730 \pm 70	Charcoal		11.3	Geib and Davidson (1995: Table 1). Hearth (feature 10) associated with level 7.
	18	Beta-40116	7440 \pm 100	Yucca	-22.1	5.5	Geib and Davidson (1995: Table 1). Open-twined sandal fragment found on surface of site in looter's backdirt; south-central part of shelter. Remainder of sandal housed at Edge of the Cedars (accession ECPR 84.6).
	16	Beta-47742	7560 \pm 90	Grass	-12.79	6.8	Geib and Davidson (1995: Table 1). <i>Sporobolus</i> sp. chaff from lowest midden deposits (feature 11) in south-central portion of site.
	11	Beta-47007	7790 \pm 80	Charcoal		8.6	Geib and Davidson (1995: Table 1). Basin hearth (feature 12) of level 12 cut into in sterile, calcified dune sand; marks

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
Pantry Alcove (42GA103)	129	Beta-34936	1640 \pm 80	Maize	-12.0	8.6	the start of cultural deposition at the site. Geib (1993). Maize cobs (FS49.1) from fill of cist 7 (feature 3a).
Perfect Ruin (42KA2687)	33	Beta-19920	6480 \pm 70	Charcoal	11.3		Eininger (1987*). Hearth encountered below a Pueblo trash deposit in a 1- \times 1-m test unit; hearth separated from Pueblo trash by only 3-8 cm of sand. Hearth has two separate use episodes; this sample and sample 30.
Pittman (GG-69-18)	32	Beta-19919	6500 \pm 80	Charcoal		8.6	Eininger (1987*). See above.
	122	GX-2142	1695 \pm 90	Charcoal		6.8	Matson (1991:90, sidebar). Slab-lined hearth built in fill of Basketmaker II pithouse. A rerun of this sample obtained a ^{14}C age of 1759 \pm 176 B.P. (Berry 1982:Table 14).
	104	GX-2074	1870 \pm 100	Charcoal		5.5	Matson (1991:92, sidebar). Extramural hearth associated with pithouse. Matson rejects this date as being 200 years earlier than the other ^{14}C dates from site and the tree-ring dates.
Rock Bar Alcove (42WN1779)	6	Beta-31192	8280 \pm 160	Yucca	-22.3	2.2	Open-twined sandal fragments from buried cultural deposits exposed at front of alcove because of erosion. A nearly complete open-twined sandal also recovered.
Rock Creek Alcove (42KA2661)	77	Beta-8264	2420 \pm 100	Organic material	?	5.5	Nickens et al. (1988:240). Partially decomposed soft body parts of a Basketmaker II burial. Not corrected for iso-

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
	4	Beta-8623	8660 \pm 80	Charcoal		8.6	topic fractionation. Nickens et al. (1988:240). Loose charcoal scattered in fill of tested area in alcove. No clear associations but probably cultural.
Salt Pocket Shelter (42SA17092)	56	Beta-21209	3340 \pm 100	Charcoal		5.5	Tipps and Hewitt (1989). Basin hearth within midden deposit; encountered in a 1- \times 1-m test unit. A Sand Dune side-notched point and a Barrier Canyon-style anthropomorph pictograph are present at the site but are not clearly associated with the dated hearth. [Note: On pages 92 and 137 of Tipps and Hewitt 1989, the 1 σ for this date is given as 110 years. I did not notice the discrepancy until after this analysis was finished.]
Sand Dune Cave	22	A-850	7150 \pm 130	Yucca	(-25.0) ^d	3.3	Lindsay et al. (1968:96). A single open-twined sandal fragment, stratum V.
	12	A-848	7740 \pm 120	Grass	(-12.0)	3.8	Lindsay et al. (1968:96). Lining of open-twined sandal, stratum V. Date not corrected for isotopic fractionation in the lab. As the grass was probably <i>Sporobolus</i> , its assumed ¹³ C value is between -11 and -13; consequently, 200 years have been added to the reported date of 7540 \pm 120 B.P.
	13	A-849	7700 \pm 120	Yucca	(-25.0) ^d	3.8	Lindsay et al. (1968:96). Two open-twined sandal fragments, stratum V.

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
Sifted Shelter (42KA2730)	81	Beta-19514	2310 \pm 90	Charcoal		6.8	Agenbroad (1990*); Geib and Fairley (1986*) for site description. Sample came from a layer of burned material (sticks, twigs, and leafy material) that might be the remains of a burned brush structure largely destroyed by looters. A Gypsum point along with other remains was found in looter backdirt.
Square Cist Alcove (42KA2737)	119	Beta-31974	1720 \pm 140	Basketry	-23.5	2.8	Geib (1990b:142); see Geib and Fairley (1986*) for site description. Basket fragment is close coiled, half rod and bundle stacked foundation with stitches intentionally split on both surfaces.
Sunny Beaches (42KA2751)	110	Beta-16272	1800 \pm 100	Charcoal		5.5	Geib and Bungart (1989:Table 1). Basin hearth associated with Rose Spring corner-notched points.
Triangle Cave (42GA288)	132	AA-5224	1600 \pm 50	Maize	-10.3	22.1	Geib (1993). Maize kernels (FS137.19) from cache of five maize ears in stratum 1.
	113	Beta-34941	1770 \pm 90	Maize	-11.2	6.8	Geib (1993). Maize cob (FS161.1) from floor of structure (feature 19) in stratum 1.
Turkey Pen (42SA21153)	99	WSU-3512	1980 \pm 60	Maize	(-10.0)	15.3	Date uncorrected for isotopic fractionation. 250 years have been added to the reported date of 1730 \pm 60 B.P. using an assumed $\delta^{13}\text{C}$ value of ca. -10. Sample from near top of stratum A-6 in Matson's

Table 1. Continued.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
							(1991: Fig. 2.33, 92) stratigraphic test of site; all deposits exposed in this test are Basketmaker II and yielded various materials including cultigens.
	97	WSU-3513	2050 \pm 80	Maize		8.6	Stratum C-4. Date uncorrected for isotopic fractionation. 250 years have been added to the reported date of 1800 \pm 80 B.P. using an assumed $\delta^{13}\text{C}$ value of -10 .
	105	WSU-2750	1860 \pm 45	Charcoal		27.3	Matson (1991:Fig. 2.33). Stratum C, Basketmaker II.
	101	WSU-2751	1925 \pm 55	Charcoal		18.3	Matson (1991:Fig. 2.33). Stratum A, Basketmaker II.
	96	WSU-2759	2065 \pm 50	Charcoal		22.1	Matson (1991:Fig. 2.33). Stratum B, Basketmaker II.
Verres Pithouse (GG-69-1)	127	GX-2072	1655 \pm 80	Charcoal		8.6	Matson (1991:92, sidebar). Burned super-structure of Basketmaker II pithouse.
Walters Cave (42WN421)	1	SI-2416	8875 \pm 125	Yucca	-22.3	3.5	Jennings (1980:Table 3). Sandal of unspecified construction technique. Listed as no provenience by Jennings but field notes reveal that it is from a stratum comparable to stratum IIb of Cowboy Cave, just above a pre-occupation sand layer with oak leaves (stratum IIa).
White Crack (42SA17597)	64	Beta-24478	2990 \pm 70	Charcoal		11.3	UPAC Newsletter, Vol. 7, No. 2, Table 1, 1989.
Willow Seep (42SA415)	88	Beta-20469	2160 \pm 100	Charcoal		5.5	UPAC Newsletter, Vol. 7, No. 2, Table 1, 1989.

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
AZ C-3-2 (NAU)	90	A-3934	2140 \pm 80	Charcoal		8.6	Largely deflated basin hearth of a probable Basketmaker II temporary camp.
42GA3035	128	Beta-28770	1650 \pm 100	Charcoal		5.5	Bungart (1990).
42GA3048	106	Beta-16268	1850 \pm 140	Charcoal		2.8	Bungart (1990).
42GA3084	66	Beta-31185	2850 \pm 70	Charcoal		11.3	Bungart (1990).
42GA3086	59	Beta-32025	3230 \pm 140	Charcoal		2.8	Bungart (1990).
42GA3119	89	Beta-31187	2160 \pm 90	Charcoal		6.8	Bungart (1990).
42GA3202	74	Beta-31189	2530 \pm 70	Charcoal		11.3	Bungart (1990).
42GA3205	71	Beta-28322	2670 \pm 90	Charcoal		6.8	Bungart (1990).
	58	Beta-27897	3240 \pm 60	Charcoal		15.3	Bungart (1990).
42GA3206	65	Beta-32026	2950 \pm 100	Charcoal		5.5	Bungart (1990).
42KA2731	115	Beta-16587	1750 \pm 90	Charcoal		6.8	Agenbroad (1990*); see Geib and Fairley (1986*) for site description and Anderson (1988:Fig. 20) for stratigraphic provenience of date. This determination comes from a thin lens of sparse charcoal buried in alluvium and is consistent with a date of 950 \pm 160 B.P. from charcoal located roughly 1 m higher (see Anderson 1988:Fig. 20). No certain cultural associations.
42KA2771	43	GX-11146	5300 \pm 235	Charcoal	-23.7	1.0	Agenbroad et al. (1989:Appendix); see Geib and Fairley (1986*) for site description and Anderson (1988:Fig. 21) for stratigraphic provenience of date. Sample obtained from a lens of dense charcoal-stained soil within a cultural

Table 1. *Continued.*

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
							stratum buried in dune sand. Flaked lithics and grinding tools in association but no diagnostics.
42KA2773	118	Beta-16277	1730 \pm 70	Charcoal		11.3	Bungart and Geib (1987*); slab-lined hearth.
42SA17107	38	Beta-31790	5890 \pm 70	Charcoal		11.3	Tipps and Schroedl (1990*).
	Rejected	Beta-18737	8340 \pm 290	Charcoal		1.0	Tipps and Schroedl (1990*); not included in Figs. 3 or 4 because of large counting error).
42SA17141	94	Beta-21208	2080 \pm 60	Charcoal		15.3	Tipps and Hewitt (1989:128). Slab-lined hearth at open site. No certain associations, but an Elko side-notched, a Pueblo I-style arrow point, and several other remains recovered from site surface; abundant materials at site.
42SA17215	5	Beta-16596	8330 \pm 110	Charcoal		4.6	Agenbroad (1990*); also Tipps and Schroedl (1990*).
42SA17216	120	Beta-19284	1720 \pm 80	Charcoal		8.6	Agenbroad (1990*); also Tipps and Schroedl (1990*).
	8	Beta-19285	8100 \pm 220	Charcoal		1.1	Agenbroad (1990*); also Tipps and Schroedl (1990*).
42SA17790	31	Beta-18736	6580 \pm 100	Charcoal		5.5	Tipps and Schroedl (1990*).
42SA20292	92	Beta-30484	2120 \pm 60	Charcoal		15.3	Tipps (1992a*); also Tipps and Schroedl (1990*).
	85	Beta-30485	2220 \pm 70	Charcoal		11.3	Tipps (1992a*); also Tipps and Schroedl (1990*).
42SA20256	84	Beta-30482	2220 \pm 90	Charcoal		6.8	Tipps (1992a*); also Tipps and

Table 1. Continued.

Site	Sequence ^a no.	Lab no.	Radiocarbon age (B.P.)	Material dated	$\delta^{13}\text{C}^b$	Weight ^c	References and comments
42SA20301	78	Beta-30487	2330 \pm 90	Charcoal		6.8	Schroedl (1990*); Tipps (1992a*); also Tipps and Schroedl (1990*).
42SA20309	51	Beta-34978	3710 \pm 230	Charcoal		1.0	Tipps and Schroedl (1990*).
42SA21091	95	Beta-31962	2070 \pm 70	Charcoal		11.3	Agenbroad (1990*); also Tipps and Schroedl (1990*).
42SA21095	35	Beta-31963	6290 \pm 110	Charcoal		4.6	Agenbroad (1990*); also Tipps and Schroedl (1990*).
42SA21117	124	Beta-31964	1670 \pm 80	Charcoal		8.6	Agenbroad (1990*); also Tipps and Schroedl (1990*).
(No number)	45	Beta-33355	4510 \pm 130	Charcoal		3.3	Agenbroad (1990*); also Tipps and Schroedl (1990*).
BC-86-1	131	Beta-15640	1600 \pm 60	Charcoal		15.3	Agenbroad (1990*); see also Anderson (1988:64). Charcoal lens buried in allu- vium of Bowns Canyon; no site docu- mentation.
GG-69-20	126	GX-2143	1655 \pm 85	Charcoal		7.6	Matson (1991:90, sidebar). Cist in floor of a Basketmaker II pithouse.

^aSequence number is the temporal order of the date from oldest to youngest within this data set.

^b $\delta^{13}\text{C}$ values in parentheses are assumed, either by the laboratory or by this author.

^cProduct of the squared standard error of each date over the largest squared standard error (235 in this study).

^dSample uncorrected for isotopic fractionation but probably not a problem because all previous measurements of $\delta^{13}\text{C}$ for yucca from early Archaic contexts have obtained values between -21 and -25. For this sample it is reasonable to assume a value of -25, requiring no correction of the reported date.

^eAsterisk indicates unpublished material.

technological, and biological innovations. In a regionally based examination of preceramic radiocarbon dates, age overestimation is not so critical, especially considering the millennial time spans for the Archaic subdivisions. Moreover, the suite of radiocarbon dates for the central Colorado Plateau includes many on organic remains not subject to age overestimation.

Uncalibrated dates are used to structure this discussion for two principal reasons. First, most discussion of Archaic chronology is in terms of uncalibrated dates and to continue so facilitates communication and comparison. Second, all paleoenvironment research is couched in terms of uncalibrated radiocarbon years, and until the various paleoenvironmental data sets and reconstructions are also calibrated, a calibrated Archaic archaeological record would be dislocated from its environmental context. After plotting both the calibrated and uncalibrated dates, and even though the disparity between the laboratory determination and the true age of a sample is about 700 years during the early and middle Archaic, the basic temporal pattern was unchanged. Using uncalibrated dates does not impede our understanding of prehistory until the Christian era, and then chronologies established by radiocarbon dating have to meld with high-resolution tree-ring chronologies tied to the Gregorian calendar.

Two different but complementary techniques are used to graphically summarize the radiocarbon dates (Figs. 3 and 4). The dates are arranged along the horizontal axis from oldest to youngest whereas their one-sigma values in radiocarbon years B.P. are plotted as solid lines on the vertical axis (Fig. 3). This first approach to portraying the radiocarbon record for the region provides substantial detail, but Berry and Berry (1986:284) argue that it can obscure patterning when many dates are graphed. They have developed an alternative technique that provides a relative probability bar chart that equitably accounts for a wide range of standard errors through a method of inverse weighting. The second graphic (Fig. 4) was created from the central Colorado Plateau radiocarbon record using the approach as described by Berry and Berry (1986:284), except that 50-year increments were used for the *x*-axis and a sigma value of 235 years provided the basis for calculating the weights³ assigned to each date. This technique involves plotting each date as a scaled plus-and-minus one-sigma line (as in Fig. 3) and noting its weight. The weights within each 50-year

³Weights are the product of the squared standard error of each date (from 235 to 39 years) over the largest squared standard error (235 years) and ranged from 1.0 to 36.3 in this study.

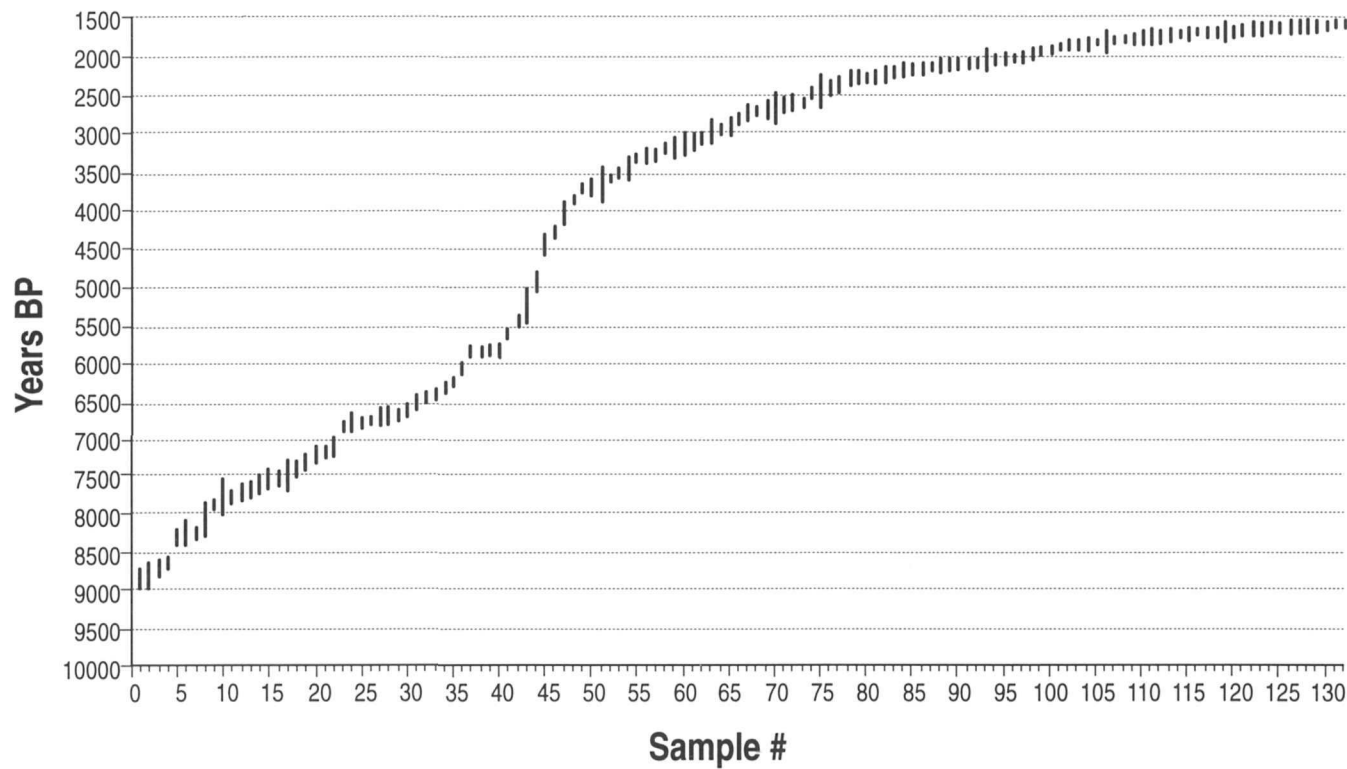


Fig. 3. Array of preceramic (pre-1600 B.P.) radiocarbon dates from the central Colorado Plateau; refer to Table 1.

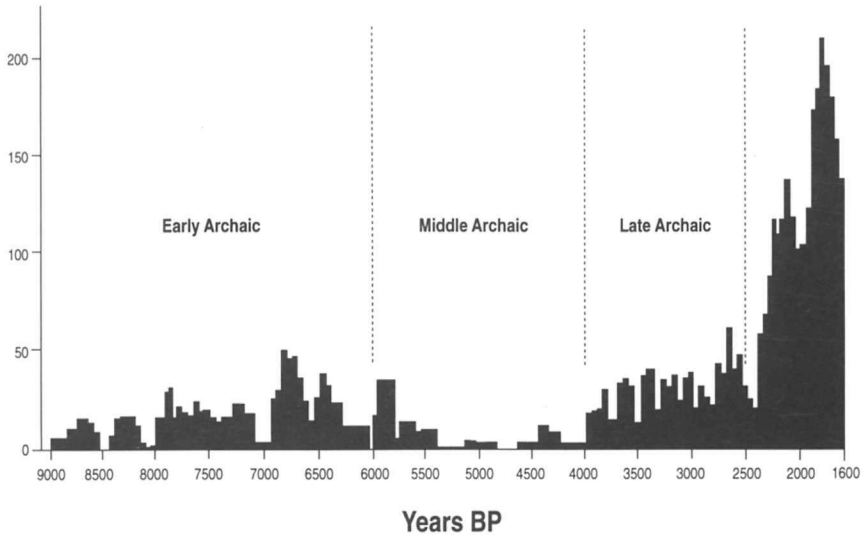


Fig. 4. Weighted preceramic radiocarbon bar chart for the central Colorado Plateau produced according to the method developed by Berry and Berry (1986:284); 50-year intervals for the x -axis.

increment are then summed to provide the ordinate value for that period. Included in Fig. 4 are three approximate cut points of the long Archaic sequence that seem to have adaptive significance.

Results

Because radiocarbon dates represent human activity at points in time and the number of dates may be related to the “magnitude of occupation. . . it is possible to assess and compare, in a relative fashion, the occupation histories within and between regions” (Rick 1987:55). The radiocarbon record for the central Colorado Plateau (Fig. 4) starts abruptly at 9,000 years ago; no radiocarbon dates are yet available for Paleo-Indian remains of the region. During the ensuing 3,000 years, the record is filled in except for a short gap around 8500 B.P. and two dips in the record about 8050 and 7000 B.P. A significant decline exists in dates between 6,000 and 4,000 years ago, as well as a small gap between 4850 and 4650 B.P. After 4000 B.P. the frequency of dates increases and remains fairly high but fluctuating until about 2500 B.P., at which point there is a short dip and then a dramatic increase to an all-time high. The record is

arbitrarily cut off at 1600 B.P., and the short dip just before this is the result of edge effect.

At this point, it is worthwhile to consider the degree to which the patterning of Fig. 4 results from differential preservation related to such postdepositional biases as erosion and burial by recent sediment. First, most early and middle Archaic dates are from natural shelters (caves, alcoves, and rock shelters) that have served to preserve the remains from this early time. A few dates are from deeply buried open sites, but none come from sites exposed on the surface. Surface lithic scatters earlier than about 4,000 years ago may exist, but such sites have been so severely eroded that datable organic material is often absent. Thus, the early portion of the radiocarbon record is the byproduct of both costly excavation of deeply stratified shelters and chance finds of buried hearths or organic remains exposed by erosion.

In contrast, about one-third of the late Archaic dates are from surface hearths at open sites. Sampling these features (Bungart 1990; Tipps and Schroedl 1990*⁴) has increased the frequency of late Archaic dates over preceding periods. These features were not sampled to provide a detailed late Archaic chronology, but this has been the outcome (see Bungart 1990:55). Natural factors have resulted in a greater accumulation of late Archaic dates because sites of this period are more visible (less buried or eroded) and, as hearths are still preserved, they have a greater likelihood to contain datable remains. In short, sites exposed on the surface are more likely to be discovered, and such sites have a greater likelihood to date to the late Archaic period or more recently.

What about the reduction in dates between 6,000 and 4,000 years ago? Could this be a consequence of postdepositional bias? The same sheltered sites that produced numerous early Archaic dates yielded few if any middle Archaic dates, suggesting that differential preservation may not be evoked in this instance. Something apparently happened that prompted humans to abandon or seldom use shelters that were previously important residential bases. Although preservation bias may not be a significant factor in the middle Archaic decline in radiocarbon dates, sampling bias could well play a role. Thus, middle Archaic sites may be located in areas heretofore inadequately investigated.

⁴Asterisk indicates unpublished material.

Discounting preservation bias, the low frequency of middle Archaic dates may be the result of sampling bias related to another visibility problem. The archaeological record produced by foragers with a high degree of residential mobility and variable annual rounds might be so dispersed as to be largely invisible, and thus rarely subject to archaeological treatment. Wills (1988:65) argues that logistically organized hunter-gatherers produce more visible archaeological traces than mobile foragers and consequently their remains are more likely to contribute to regional chronologies. "Interregional variation in radiocarbon chronologies may well be the product of shifts in economic organization and mobility. . . ." and consequently ". . . should not be taken as a direct indicator of prehistoric demographics" (Wills 1988:65). Thus, changes in mobility and subsistence-settlement strategies during the Archaic may be partially responsible for some patterning in the radiocarbon chronology.

Before proceeding, a brief digression about sandals is in order. Many of the Archaic dates listed in Table 1 are on sandals made of yucca leaves. Three different sandal types were produced during the Archaic: open-twined, fine warp-faced, and plain-weave (or coarse warp-faced). Each of these was first described by J. Richard Ambler from his excavations at Dust Devil and Sand Dune caves. He (Lindsay et al. 1968:95-97, 120-121) identified open-twined sandals as a key diagnostic trait of the early Archaic Desha complex northeast of Navajo Mountain. Excavations at Cowboy Cave, however, produced this sandal type from cultural units IV and V (Table 12 of Hewitt 1980) dated about 3700-3300 and 1900-1500 B.P., respectively. Ambler (1984*) suggested that these were present in more recent strata at Cowboy Cave as a result of disturbance of early deposits by later occupants. Berry and Berry (1986:309-310) gave a similar argument to account for the presence of Gypsum points and split-twig figurines in unit V at this cave. Since Ambler's contention, open-twined sandals from five separate sites of the central Colorado Plateau were directly dated, and all are within the early Archaic period: Atlatl Rock Cave at 7900 B.P., Bechan Cave at 6750 B.P., Good Hope Alcove at 7560 B.P., Old Man Cave at 7440 B.P., and Rock Bar Alcove at 8280 B.P. (Table 1). Ambler is therefore probably correct about the upward displacement of open-twined sandals in the deposits of Cowboy Cave into later cultural units. At this juncture there is sufficient justification to state that this type of footwear is restricted to the early Archaic and may be expected anytime after 9000 B.P. but before 6000 B.P.; direct dates confirm that sandals of this type occurred during the interval 8300-6700 B.P. (or 8600-6500 B.P. based on the two-sigma deviations).

Based on current radiocarbon dates, it is evident that plain-weave sandals were initially manufactured during the end of the early Archaic; both plain-weave and open-twined styles overlapped during the first half of the seventh millennium B.P. but open-twined sandals predate plain-weave sandals by at least 1,500 years. Plain-weave sandals continued to be manufactured through the middle Archaic, apparently extending into the late Archaic, up to 3,000 years ago. A sandal technology that began during the end of the early Archaic and persisted into the late Archaic provides convincing circumstantial evidence in itself for cultural continuity over more than 3,000 years of significant paleoenvironmental change and alterations in settlement pattern. Temporal placement of fine warp-faced sandals is not certain because few have been recovered (all extant examples come from Dust Devil Cave), and none have been directly dated; they are probably restricted to the early Archaic.

Archaic Origins

No apparent local antecedents exist for the early Archaic remains of the central Colorado Plateau. It seems doubtful that the point types (Elko Corner Side-notched, Northern Side-notched, Pinto), sandals, close-coiled basketry, and generalist subsistence remains (diverse small seeds, cactus pads, and small mammal bone) that characterize the earliest cultural deposits from sites such as Dust Devil and Cowboy caves were the cultural residue of local Paleo-Indians turned foragers. Though the region apparently had a low-level late Paleo-Indian occupation (Schroedl 1991; Geib 1994), a break in occupation probably occurred before about 9000 B.P., and Archaic hunter-gatherers soon resettled the abandoned rugged canyon landscape. This assumes, of course, that hunter-gatherers would not make an abrupt change in adaptive strategy and that if such a change is evident it represents population replacement. Regarding the first issue, a body of theory exists supporting the notion that change among hunter-gatherers is mainly a conservative process (see Wills 1988:36 for summary of this opinion with regard to hunter-gatherer adoption of agriculture). Regarding the second issue, little is known of the late Paleo-Indian occupation, so the degree to which early Archaic subsistence patterns and material culture vary from earlier patterns and remains is largely conjectural.

Early Archaic

That the Archaic period began almost 9,000 years ago is evidenced by 8800 B.P. dates on yucca leaves from caves in both northern and southern portions of the central Colorado Plateau. The oldest of these dates is on a sandal from the lowest cultural deposit of Walters Cave (Jennings 1980), which is adjacent to Cowboy Cave. Because other organic remains were found near the sandal, additional radiocarbon dates can eventually verify this early determination. Unfortunately, the manufacturing technique for the sandal apparently was not recorded before its destruction. The second early date comes from the lowest portion of stratum IV in Dust Devil Cave (Ambler 1994*). As with the early date from Walters Cave, this one is also on yucca—in this instance leaves lining a storage pit.

Six other dates for the region fall within the ninth millennium B.P., but only one of these is on material that will not result in age overestimation. This is the date of 8280 B.P. on open-twined sandal fragments from Rock Bar Alcove on the Spur, just 14 km northeast of Cowboy Cave (Table 1). The other five dates are on charcoal and provide equivocal evidence for occupation before 8000 B.P. The bulk of early Archaic radiocarbon dates fall within the eighth and seventh millennia B.P., including numerous dates on yucca leaves or other materials not subject to age overestimation.

The end of the early Archaic is problematic but placed sometime during the latter half of the seventh millennium B.P. No clear break exists in the radiocarbon record—just a reduction in the number of dates from 7,000 to 6,000 years ago. Besides fewer dates, a principal reason for identifying an end to the early Archaic is that cultural activity at Cowboy, Dust Devil, and Old Man caves ceased (or was greatly diminished) during the seventh millennium, and over the next several thousand years the sites were seldom if ever used (Jennings 1980:17–26; Ambler 1994*; Geib and Davidson 1995). Several hundred years of apparent gradual change in hunter–gatherer adaptation during the seventh millennium B.P. marks the transition from early to middle Archaic.

Middle Archaic

The middle Archaic is characterized by a significant reduction in radiocarbon dates. This period began during the latter half of the seventh millennium B.P. and lasted over 2,000 years until around 4000 B.P., when there is a marked

increase in dates. The beginning of this interval is not fixed in time, a reflection of the extended transition from the early Archaic as mentioned above. Besides fewer dates, a principal reason for identifying the onset of the middle Archaic is that sites that were once key nodes in an annual subsistence round lost their former significance and were rarely used. This is well exemplified by Cowboy, Dust Devil, and Old Man caves, each of which ceased to function as a residential base during the middle Archaic. This change in site use at both Cowboy and Dust Devil caves is represented by essentially sterile dune sand that accumulated within the caves (strata IVa and IVb at Cowboy Cave and stratum V at Dust Devil Cave; Jennings 1980:20–26; Ambler 1994*). At Old Man Cave, the temporally comparable hiatus deposit consists of small roof spalls, dust, and rat dung, with very little addition of cultural material (Geib and Davidson 1995).

Changes in site use at the onset of the middle Archaic are also exemplified by Rock Bar and Goodhope alcoves and Atlatl Rock Cave. At the former two sites, trashy early Archaic deposits are buried beneath apparently sterile eolian sand layers similar to those reported at Cowboy and Dust Devil caves. The strata are exposed in profile at the front of each alcove because of downslope movement of talus and sediment from drip-line erosion. Goodhope Alcove was reoccupied during the Formative period, but at Rock Bar Alcove the only evidence of occupation is the early Archaic deposit. Atlatl Rock Cave was recently investigated in the wake of serious looting, so dating results are not yet available. Nevertheless, it is clear from extensive stratigraphic exposures that a layer of culturally sterile ceiling rock spalls up to 70 cm thick separates early Archaic deposits from those of Basketmaker II.

The middle Archaic period includes the apparent 1,000-year gap in radiocarbon dates for the northern Colorado Plateau noted by Schroedl (1976: 13–29 and Figs. 2 and 4) and Berry and Berry (1986:Fig. 14). As is evident from Figs. 3 and 4, dates from the central Colorado Plateau are beginning to fill this gap, as are dates from further north along the Colorado River (Barnes 1985). Schroedl's (1976:64) suggestion that population declined to an all-time low relative to other periods may be right, but with the partial filling of the middle Archaic gap in the radiocarbon record, there is good reason to doubt that hunter-gatherers completely abandoned the region 6,000 years ago as Berry and Berry (1986:315) suggested. The small middle Archaic break in the central Colorado Plateau radiocarbon record seems more likely attributable to sampling problems than to a lack of occupation.

Sites interpreted as having been abandoned during the middle Archaic provide some of the most compelling evidence for an overall break in occupation. Nevertheless, there is reason to believe that sites such as Dust Devil and Cowboy caves were used at least on occasion during this interval. An analysis of lithics from Dust Devil Cave showed that almost as many projectile points were recovered from the apparently sterile middle Archaic stratum V as from the early Archaic stratum IV (Geib 1984*). Despite the quantity of projectile points, flake density was reduced, as was the amount of most other debris. Instead of a hiatus, it seems plausible that there was a significant change in cave use: after about 7000 B.P., the cave was used less and less frequently as a base camp and ultimately became a seldom-used way station for small groups of highly mobile hunters who added little debris to the eolian sand accumulating within the cavern (Ambler 1994*). A similar argument might be extended to the middle Archaic hiatus layers of Cowboy Cave (strata IVa and b), which, though supposedly representing an approximate 2,000-year interruption in human use, contained more flaked lithic tools and debitage than any of the early Archaic strata of unit III (Weder 1980:Table 7). Jennings (1980:26) attributes artifacts in the nonoccupation sand layers of Cowboy Cave to intrusion from overlying cultural layers, "varyingly, artifacts were pushed down into the loose upper sand zones by foot traffic when occupancy of the cave was renewed." This would mean that fully 35% of the debitage and 25% of the flaked lithic tools from the stratum of renewed occupation (IVc) were intruded down into the sand of strata IVa and IVb.

The apparent middle Archaic population decline and the abandonment, or drastic reduction in use, of previously inhabited shelters likely results from regional climatic change. Perhaps not by coincidence, the middle Archaic occurs during the period that Antevs (1955) characterized as being warm and dry, his Altithermal drought. This drought episode continues to be a controversial subject (e.g., Martin 1963; Mehringer 1967; Peterson 1981; Davis 1984; Hall 1985; Barnosky et al. 1987; Van Devender et al. 1987), perhaps because the Altithermal episode "was far more variable across space and through time than Antevs ever imagined" (Meltzer 1991:236). Current evidence suggests that the central Colorado Plateau, like certain other places of the western United States, was characterized by a middle Holocene drought (Scott 1980*; Cole 1981; Hall 1985; Karlstrom and Karlstrom 1986; Anderson 1988:98; Karlstrom 1988:69; Withers 1989).

As the climate warmed and dried during the early to middle Archaic transition, hunter-gatherers might have made several adaptive responses. The most extreme response would have been wholesale population movement over long distances to more favorable environments—the Altithermal refuge model. This is what Berry and Berry (1986) advocate. The Colorado Rockies, which have numerous middle Archaic sites, could have served as an Altithermal refuge as Benedict (1979) proposed. The Berrys (1986:317) concur with Benedict's argument but conclude that the eastern Great Basin, with its resource-rich lake margins, could have absorbed many more middle Archaic hunter-gatherers (Berry and Berry 1986:319).

With the recent accumulation of about a dozen radiocarbon dates during the purported middle Archaic date gap, total emigration of hunter-gatherers is not credible. Without completely discounting long-distance movement of some populace, it is more likely that hunter-gatherers made localized adaptive adjustments in settlement-subsistence strategies in response to increasing aridity. One probable adjustment could have been a relocation of base camps to secure water sources. Meltzer (1991:259) relates that “a lack of water, and not food resources or foraging efficiency, is the limiting factor in arid settings.” Settlement patterns may have shifted as sites situated at a distance from reliable (i.e., drought-resistant) water sources became less desirable for residential bases. Two of the sites dated to the middle Archaic are within Bowns Canyon, which has a permanent stream fed from numerous springs. Even during a protracted drought, the Navajo sandstone aquifer of this canyon probably would have maintained its viability.

Even in the worst conditions, the Colorado, San Juan, Escalante, and Dirty Devil rivers would have provided resident hunter-gatherers with a plentiful water supply. Further north along the Colorado River, sites such as DeBeque Rockshelter (Reed and Nickens 1980*) have middle Archaic cultural deposits. Reed and Nickens postulate that this site's proximity to the Colorado River may have made it a more suitable residence relative to other areas of the Colorado Plateau during a time of deteriorating environmental conditions. To investigate this possibility for the central Colorado Plateau, portions of plain-weave sandals from two shelters beside the Colorado River of lower Glen Canyon (The Hermitage and Benchmark Cave; Lipe 1960) were recently submitted for AMS radiocarbon analysis. The dates on these artifacts, a few of which were available in time to include in this analysis (Table 1), confirm that the shelters had previously unsuspected middle Archaic occupations and support the proposition that Archaic populations shifted some residential bases to river corridors.

Besides shifting residential camps to more water-rich lowland settings, some camps could have been moved to the several higher-elevation settings—those above 2,438 m—in and adjacent to the central Colorado Plateau. These include Navajo Mountain in the southern part of the region, the Henry Mountains near the central portion, the Abajo Mountains and associated high mesas (e.g., Elk Ridge) to the east, the Aquarius Plateau (Boulder Mountain) to the west, and the La Sal Mountains to the northeast. The benefit of the high-elevation settings during a protracted drought would have been their greater biotic productivity and faster regeneration rates for foraged resources relative to the lower-elevation benchlands and canyons. The presence of so many high elevation settings, especially those of great areal extent such as the extensive Aquarius Plateau (ca. 2,600 km² above 2,750 m), might have been an important factor in the apparent continual hunter–gatherer occupation of the central Colorado Plateau during the middle Archaic.

In addition to changes in the location of residential camps, middle Archaic populations could have increased the frequency of residential moves, expanded the territory of seasonal rounds, and decreased the periodicity of residential reuses. All of these factors could have led to a substantially diminished and more diffuse archaeological record. In essence, middle Archaic remains might be far more dispersed than those of the early Archaic, and thus less subject to archaeological discovery and investigation. This might sound contrary to the notion of becoming tethered to water sources, which could result in more concentrated accumulations of debris. Nevertheless, if the truly reliable middle Archaic water sources of the central Colorado Plateau were the linear oases of rivers, there would be less chance for point-specific concentrations. Along rivers, hunter–gatherers could have had the option to move camps frequently in response to lowered foraging return rates without having to worry about not finding water elsewhere. Moreover, despite being tethered to secure water sources, expanded foraging territories, shorter stays at residential bases, and longer lapses between residential reuse still would have resulted in a diffuse archaeological record.

Late Archaic

The late Archaic began about 4,000 years ago with a noticeable increase in radiocarbon dates and is temporally correlated with an increase in effective

moisture during what has been termed the sub-boreal interval (Berry and Berry 1986:316–317). The middle–late Archaic transition may have happened at a quicker pace than the early–middle Archaic transition, though this is just an impression. The increase in radiocarbon dates may be partially the result of population growth; in addition, settlement and subsistence strategies might have changed, thereby greatly increasing the archaeological visibility of late Archaic hunter–gatherers. This is basically the reverse of the scenario proffered for the early–middle Archaic transition, though the specifics of late Archaic subsistence and settlement may have varied from earlier patterns owing to the expanded range of the pinyon pine (*Pinus edulis*; see Bungart 1990) and other factors. Moreover, as discussed earlier, late Archaic sites have a greater chance of contributing to the radiocarbon record because of preservation biases with earlier periods.

Berry and Berry (1986:318) hypothesized that a major exodus was responsible for the apparent late Archaic population increase and suggested the Mexican highlands as one possible source region based on similarities between Gypsum points of the Southwest and the earlier constricting stem points of Mexico. Appearing sometime after about 4500 B.P. (Holmer 1986:105), Gypsum points are among the most common temporally sensitive dart-sized point type found over much of the region. The frequency and distribution of Gypsum points alone indicates a rather significant late Archaic occupation of the central Colorado Plateau. Nevertheless, it has yet to be demonstrated that a point style equals a people, and there are many examples of point styles spreading rapidly between different cultural groups.

Starting about 3700 B.P., Cowboy Cave again became an important settlement nexus, but cave sites south and east of the Colorado River in the southern portion of the region continued to be little used. Several Gypsum points are present in stratum VI of Dust Devil Cave (Geib and Ambler 1991), but this layer seems to be predominantly of Basketmaker origin. A few Gypsum points were recovered from Sand Dune Cave (Fig. 23w of Lindsay et al. 1968), but the lack of stratigraphically controlled excavation precludes an accurate assessment of how extensively this site was used during the late Archaic. At Old Man Cave, there is as yet no evidence of a late Archaic presence, though the strata that correspond to this interval were largely disturbed by vandals and have yet to be adequately sampled. Gypsum points are even more rare immediately south of Glen Canyon, with few examples known from the Kayenta region.

The introduction of agriculture marks the end of the late Archaic, a process that on the central Colorado Plateau occurred less than 2,500 years ago. As Berry and Berry (1986:319) observe, "the agricultural influx drastically changed the character of southwestern subsistence systems and altered profoundly the trajectory of evolutionary development. . . . Hence, for all intents and purposes, the Archaic came to a close." Direct dating of maize, cucurbita, and beans from the study region has yet to produce a reliable date before 2,000 years ago. A maize cob from the Alvey Site produced a radiocarbon age of 2260 B.P. (Geib 1993), but additional dating of maize from this site demonstrated that this early date is probably in error (Geib 1994). Cultigens have considerably greater antiquity immediately south of the region (Smiley 1993, 1994).

The end of the late Archaic is coincident with a reduction in the frequency of radiocarbon dates for the central Colorado Plateau. A similar break or dip in the Colorado Plateau radiocarbon record between roughly 3000 and 2500 B.P. was highlighted by Schroedl (1976:Fig. 4) and Berry and Berry (1986:Fig. 14). Despite the apparent break in his plot of radiocarbon dates from about 3000 to 2500 B.P., Schroedl (1976:68–73) saw strong evidence for cultural continuity in points, basketry, and other material remains from dated contexts both sides of this 500-year gap. Thus, he defined the Dirty Devil phase as spanning the possible hiatus. Berry and Berry (1986:309) took issue with his reasoning, characterizing it as "a typical case of phase-stacking to achieve the illusion of continuity." Alternatively, they see significant depopulation because of drought as the reason for the drastic reduction in radiocarbon dates between 3000 and 2500 B.P. and conclude that Archaic hunter–gatherers were subsequently displaced by San Pedro Basketmaker II agriculturalists from some southern source area (Berry and Berry 1986:318–319). Rather than cultural continuity from the Archaic to Formative periods, as maintained by Schroedl (1976:77), Berry and Berry see cultural replacement (see Matson 1991 for a detailed discussion on this issue). Some stratified shelters in and near the region still reveal a break in occupation between about 3000 and 2000 B.P. (e.g., Horn 1990:85*; Janetski et al. 1991:Table 1), but dates on hearth charcoal from open sites throughout the central Colorado Plateau indicate a lack of wholesale abandonment at the end of the late Archaic. The basis for concluding that there was an occupational discontinuity about 3000 B.P. is not, therefore, evident in the chronometric data.

A major point in Berry and Berry's (1986:309–310) argument for a lack of continuity during the late Archaic–Formative transition is placing an upper temporal limit on the production of Gypsum points and split-twist figurines. The

crucial evidence that Berry and Berry must refute comes from Cowboy Cave, where these twin late Archaic diagnostics were recovered from unit V, dated roughly 1900–1500 B.P. Berry and Berry may be right about the displacement of late Archaic artifacts upward from unit IV into unit V at Cowboy Cave and that Gypsum points and split-twigg figurines were not produced much after about 3000 B.P., but their argument cannot account for the basketry sequence at the site, which mirrors the developmental sequence in Utah from Archaic to Fremont (Hewitt 1980:57). Preformative basketry from the Escalante River basin also represents a continuation and elaboration of Archaic basketry technology for Utah and supports the idea of cultural continuity during the agricultural transition north of the Colorado River (Geib 1990b). As Matson (1991) has detailed, the instance south of the Colorado River is substantially different and seems to support the notion of an intrusive agricultural population.

Discussion

Berry and Berry (1986) identified three temporally discrete occupations separated by abandonments for the Archaic occupation of the entire Colorado Plateau. These discrete occupations are not apparent in the central Colorado Plateau radiocarbon record. The purported 1,000-year middle Archaic gap in the Colorado Plateau radiocarbon record is not evident in the record for the central portion of the plateau. Significantly fewer dates exist between 6,000 and 4,000 years ago than either previously or subsequently, but there is good reason to suggest that the central Colorado Plateau was not completely abandoned about 6000 B.P., as Berry and Berry (1986:315) suggested happened for the plateau as a whole. The small middle Archaic gap remaining in the radiocarbon record examined here seems more likely because of sampling problems than to a lack of occupation. The apparent abandonment of previously well used sites provides the most compelling evidence for an occupational hiatus, but this probably reflects a change in settlement pattern, with residential bases relocated close to secure water sources such as rivers and perhaps to the several high-elevation settings near the canyon lowlands. In addition, middle Archaic populations could have increased the frequency of residential moves, expanded the territory of their seasonal round, and decreased the periodicity of residential reuse. These factors would have led to a substantially diminished archaeological record.

In essence, middle Archaic remains might be far more dispersed than those of the early Archaic and thus less subject to archaeological discovery and investigation.

Recall Schroedl's (1976:63) point about the possibility that archaeologists have missed the evidence corresponding to this interval (which he calls the Castle Valley phase) by incorporating middle Archaic remains with those of earlier or later occupations. Based on the Sudden Shelter sequence, he reasoned that greatly reduced depositional rates resulted in thin middle Archaic deposits and that "unless very fine-grained distinctions with tight controls are utilized during excavation of Archaic sites, the occupations associated with this phase [Castle Valley or the middle Archaic] might be completely missed" (Schroedl 1976:64).

The other occupational hiatus recognized by Berry and Berry corresponds to the 500-year interval between 3,000 and 2,500 years ago, just before the introduction of agriculture. This was also the hiatus identified by Madsen and Berry (1975) as evidence for lack of continuity between Archaic and Fremont populations in Utah. In the central Colorado Plateau radiocarbon record, no hiatus is apparent. The date frequency has an obvious dip, but the region was apparently not void of human occupants. Again, certain key sites such as Cowboy Cave and the Down Wash site were apparently abandoned, but dates from open sites throughout the central Colorado Plateau indicate a continued human presence during the Archaic to Formative transition. The occupational records of a few key sites can never vouch for that of a region, no matter how unequivocal the evidence. As Wills (1988:155) put it, "We need to consider individual sites and artifacts as participants in and products of socioeconomic systems, not models for such systems."

At this point, I wonder whether the tripart temporal subdivision of the Archaic period is not too coarse for future research goals? The seven-part framework presented in Table 2 is tentatively advanced as a potentially useful partitioning of the roughly 6,500 years of hunter-gatherer occupation of the central Colorado Plateau to better describe change.⁵ These seven temporal subdivisions of the Archaic period should not be viewed as cultural phases in

⁵In Table 2, the breaks between the seven temporal subdivisions are also listed in calibrated years B.C. This reveals that some of these intervals are relatively longer than indicated by the radiocarbon dates, while a few are slightly shorter. For example, the 1,600-year middle Archaic period actually spanned almost 1,900 years.

Table 2. Synopsis of the Archaic period for the central Colorado Plateau according to seven temporal subdivisions.

¹⁴ C years (B.P.)	Archaic period subdivisions	Descriptive characterization	Important sites and components	Diagnostic projectile points	Diagnostic perishable artifacts	Calibrated years B.C.
2500	Terminal Archaic	Apparent population decline but without an occupational hiatus of entire region. Perhaps an abbreviated version of the middle Archaic period. Introduction of agriculture during end of this period profoundly affects cultural systems. Hunting and gathering was still important, but horticulture became the predominant subsistence mode well before introduction of ceramics.	Hiatus layer at Cowboy Cave (stratum Va), open sites of the Orange Cliffs	Gypsum points (?), Elko points	Perhaps same as previously?	670
3000	Late Archaic	Perhaps greatest population during the entire Archaic period; thick trash accumulations in certain natural shelters and numerous open sites with slab-lined and basin hearths and dense artifact scatters.	Cowboy Cave (unit IV), sparse use of Dust Devil Cave (stratum VI), Bechan Cave, and other sites in same canyon	Gypsum points, Elko Eared, McKean Lanceolate	Split-twig figurines, Morss's problematical objects, plain-weave sandals	1265
3800	Middle-late transition	Apparent population increase or at least greater archaeological visibility over previous period, temporally correlated with climatic amelioration and expansion of pinyon into or beyond current elevational and geographical range.	Down Wash site, Co-op site, and nearby sites in same canyon: Beaucoup Alcove and Beaver Shelter	Replacement of earlier side-notched types by San Rafael side-notched; appearance of McKean Lanceolate	Appearance of split-twig figurines, plain-weave sandals	2235
4400	Middle Archaic	Apparently corresponds to a drought interval; significantly warmer and drier than before or since. Drastic reduction in population but not total abandonment. Fewer people per square kilometer than during previous Archaic periods owing to greatly expanded territories and perhaps some migration. Residential bases perhaps relocated to well watered settings such as along rivers. Local high-elevation settings such as the Aquarius Plateau could have served as additional altithermal refugia. Low archaeological visibility.	Hiatus layers at Cowboy (stratum IVa), Dust Devil (stratum V), and Old Man (levels 3 and 4) caves; occupation of Bechan Cave and site 42KA2771 in same canyon; Benchmark Cave and The Hermitage	Apparent continuation of Sudden side-notched and Hawken side-notched	Continuation of plain-weave sandals as evidenced by recent direct dating of specimens from lower Glen Canyon	3035

Table 2. *Continued.*

¹⁴ C years (B.P.)	Archaic period subdivisions	Descriptive characterization	Important sites and components	Diagnostic projectile points	Diagnostic perishable artifacts	Calibrated years B.C.
6000	Early-middle transition	Apparent population decline, perhaps because of expanded territories and some movement to other regions. Change in settlement patterns and perhaps an increase in residential mobility brought about a decreased use of certain previously well used sites. Overall decline in archaeological visibility over previous period.	Sites previously used rather intensively and frequently were rarely used and some may have been virtually abandoned. All sites previously mentioned contain little evidence of occupation corresponding to this interval.	Replacement of early Archaic point types with various side-notched forms: Sudden (including Rucker) and Hawken	Plain-weave sandals and perhaps a continuation of open-twined sandals	4925
6800	Early Archaic	Increased population from preceding period. Thick trash accumulations in preserved sites indicates frequent reoccupations of favored locales; perhaps relatively low residential mobility.	Cowboy and Walters caves (Unit III), Dust Devil Cave (stratum IV), Sand Dune Cave (lower stratum V), Old Man Cave (levels 7-12), Good Hope Alcove, Rock Bar Alcove (?), and Bechan Cave	Elko Corner side-notched, Northern side-notched, Pinto, and perhaps Sand Dune side-notched	Open-twined sandals and plain-weave sandals (coarse warp-faced)	5645
7800	Initial Archaic	Start of Archaic occupation in the region; sort of a "settling in" period with sparse population. Apparently no continuity with local late Paleo-Indians; rather, Archaic populations intrusive from eastern Great Basin.	Cowboy and Walters caves (Unit II), Dust Devil Cave (lower stratum III), Rock Bar Alcove, and perhaps Sand Dune Cave (stratum III)	Pinto, Elko Corner side-notched, perhaps Sand Dune side-notched	Open-twined sandals, fine warp-faced sandals	6610
9000						8050

the traditional sense, although they do seem to correspond to intervals wherein cultural patterns were relatively similar yet sufficiently different from earlier and later patterns. These intervals also correspond to some degree with the extent of current knowledge. For example, on a scale from 0 to 10, where 10 denotes detailed knowledge, the empirical underpinning for each of the seven subdivisions might be ranked as follows: 5 for the early and late Archaic, 1 for the two transitions and the initial Archaic, 0.5 for the terminal Archaic, and 0.1 for the middle Archaic. Once we have comparable amounts of information for the entire Archaic sequence, more useful temporal partitions might become obvious. If for no other reason, the seven subdivisions serve to emphasize which portions of the Archaic sequence should receive concerted investigation.

Conclusion

Having reviewed the available chronometric dates, I find that the data support the model of long-term continuity in Archaic occupation of the central Colorado Plateau. The radiocarbon record is sufficient to cast doubt on interpreting the Archaic period as a sequence of major population abandonments and intrusions on a pan-regional scale. Despite arguing for occupational continuity, I am unwilling to discount population immigration as a reason for some apparent changes during the Archaic. Migration still has something to offer archaeologists for understanding prehistory (see Anthony 1990) but not to the extent that Berry and Berry (1986:321) believe when they suggest that major population replacement “is the key to understanding Archaic prehistory in the Desert West.” Current knowledge of the Archaic period is still so limited and spotty that we cannot yet critically evaluate the issue of migration during this early interval. I see no necessary linkage between long-term occupational continuity and gradualism (Berry 1982; Berry and Berry 1986:255) but find little evidence for sudden change during the Archaic. Even by examining change during seven temporal subdivisions instead of three, it is difficult to make an argument for anything happening rapidly because the smallest time interval is of 500-year duration—about 20 biological generations.

Future research on the Archaic period of the central Colorado Plateau must attempt to muster evidence for those portions of the Archaic sequence that are still poorly documented. Only by such an effort can we adequately describe the economic and cultural transitions during the roughly 6,500 years and thereby

disentangle the various historical and evolutionary processes that might be involved in culture change. Even for those portions of the Archaic sequence that are more completely understood, the information is derived from a paltry site sample with primary reliance on two sites in largely similar environmental settings—Cowboy and Dust Devil caves. The excavated sample of high-information sheltered sites needs to be expanded to cover a diversity of environmental settings, with particular emphasis placed on well-watered canyon lowlands and on high-elevation settings (ca. 2,625 m). Open sites need to be investigated also, but it seems evident that the sample of absolutely-dated early and middle Archaic open sites available for study is limited. Open sites are potentially assignable to these early periods based on point types, but even if such assignments are correct, the sites are often so deflated and otherwise affected by postdepositional processes that our ability to use them for interpretive purposes is limited.

The central Colorado Plateau emerges as a region of the Southwest with significant evidence of Archaic culture. Indeed, the earliest documented expression of an Archaic lifeway anywhere on the Colorado Plateau is found here. Exceptionally preserved subsistence remains and perishable technology are present within numerous stratified dry shelters. Paleoenvironmental data are rife from a variety of sources (alluvial stratigraphy, packrat middens, cave sediments, etc.) and should eventually enable detailed climatic and biogeographic reconstructions for the entire Holocene. As such, the central Colorado Plateau is one of the highly productive areas for studying Archaic hunter-gatherer adaptations and economic transitions, including the adoption of agriculture. Our understanding of this period is not limited by a lack of potential data sources, though the best of these are in serious danger of being lost to illicit digging. To gain the most benefit from the still-rich archaeological data base, a long-term, regionwide research program is needed, designed to document not just the common lifeway patterns that form the basis of culture-history but also the variability that informs us about the organization of hunter-gatherer societies and how they change.

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⁶Asterisk indicates unpublished material.

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Compositional Analysis of Temper in Emery Gray Ceramics From Central Utah

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Abstract. Emery Gray ceramics of the Fremont culture are characterized by crushed igneous rock temper. Several temper types that appear distinct under the binocular microscope are included in this ceramic type, and the relation of these temper types and the sources of the rocks have been debated. Emery Gray sherds from a site in central Utah were used to address this research question. Analysis with the petrographic microscope and electron microprobe indicates that the composition of feldspars in two distinct temper types is similar. Samples of potential source rocks collected near the site also were analyzed and compared with the temper samples. The feldspar composition of the rocks and the Emery Gray sherd temper are comparable and the mineral assemblages also are similar. Combining the compositional data with the distribution of the several rock types revealed patterns that can be used to determine the location of production and patterns of distribution of Emery Gray ceramics. These patterns provide information on resource use by Fremont peoples. The data may also be useful in refining the classification system for Fremont ceramics.

Key words: Ceramic production, Fremont, Utah prehistory.

Studies of Fremont ceramics have followed the pattern of development that characterizes archaeological analysis of ceramics in most of the New World. Subsumed under Desert Gray Ware (Rudy 1953), several ceramic types have been named, described, and used in the identification of regional variants of the Fremont culture. Recently, however, more intensive analysis revealed problems with the traditional taxonomy, and revisions may be necessary to accurately characterize excavated Fremont ceramic assemblages.

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One potential problem with the classification system is that temper type is heavily emphasized as an attribute, even though few petrographic or compositional analyses of Fremont ceramics have been conducted. This has led to confusion and difficulty in applying the classification, even by analysts familiar with Fremont ceramics. For example, Madsen (1977) described Emery Gray temper as fine gray basalt and Sevier Gray temper as coarser black basalt. Compositional analysis revealed, however, that the temper material in these ceramics is not basalt (Spurr 1993); it was identified as such because of its dark color. Furthermore, Emery Gray has a range of temper color, possibly dependent on where the ceramics were produced (Geib and Lyneis 1993). The difficulty with defining ceramic types based on temper type is compounded by the complexity of the geology of central and southern Utah. A great number and variety of igneous—mainly volcanic—formations crop out in this area. The temper material of Fremont ceramics in this region is mainly igneous rock, and the potential for identifying production locations is great but must be approached with caution.

Perhaps the greatest problem with the current classification of Fremont ceramics is the inaccurate and inconsistent temper designations (Geib and Lyneis 1992*²). The nonspecific nature of most temper descriptions makes their application difficult. The problem is exacerbated by the difficulty with correlating small pieces of rock, such as temper, with hand samples of rock. This step, however, is necessary to identify temper sources. The use of nonspecific terms such as *black basalt* and *gray basalt* to indicate two distinct ceramic types invites inconsistent identification. This is exactly the situation faced by analysts of Sevier Gray and Emery Gray ceramics.

The need for a revision of the Fremont ceramic typology has become evident. The system is not failing; the modification of classification systems as new information becomes available is a normal part of scientific endeavor. In 1992, I completed compositional analyses of Emery Gray sherds from a Fremont site in central Utah. The research project, undertaken at Northern Arizona University, had several goals:

1. to define the variability of temper in sherds from one site;
2. to determine the chemical composition of the temper material in the sherds;

² Asterisk indicates unpublished material.

3. to determine the chemical composition of rocks from the local area;
4. to compare the compositions of the temper and rock to determine a possible source of the temper; and
5. to compare the variability of the sherds to the current type description of Emery Gray.

Although my research focused on both Emery Gray and Sevier Gray ceramics, this paper will concentrate on Emery Gray ceramics. In addition to providing confirmation of local ceramic production, compositional analyses revealed that a single ceramic type cannot adequately describe the variety of temper in Emery Gray.

Round Spring Site and Ceramic Assemblage

The research area is in the San Rafael region of the Fremont culture area, which extends from the east side of the Wasatch Mountains of Utah eastward to the Uncompahgre Plateau in Colorado and from the southern edge of the Uinta Mountains south to the Colorado River in Utah (Fig. 1). In this geographic area, along the tributaries of the Fremont River, Morss (1931) recorded the sites and artifact assemblages that defined the Fremont culture. Gunnerson (1957, 1969) and Rudy (1953) carried out further survey and test excavations of several Fremont sites in a wide area in Utah and helped refine the definition of the Fremont culture. One of the sites that Gunnerson located and tested was the Round Spring site (42SV23), the focus of this project (Gunnerson 1957:102–105).

The Round Spring site is a large San Rafael Fremont pit house village at the confluence of the Round Spring Draw and Last Chance Creek (Fig. 2) on the eastern edge of the Wasatch Plateau. At an elevation of 2,278 m, the site is surrounded by pinyon–juniper forest and sagebrush grassland. The site is on an aggrading colluvial fan deposit that slopes gently to the southeast; the Fremont component of the site is buried by as much as 1.5 m of sediment (Metcalf 1993a). During a survey before the realignment and upgrading of State Highway 72, archaeologists from Brigham Young University evaluated the Round Spring site as eligible for nomination to the National Register of Historic Places (Nielson and Hall 1985). In 1987, Metcalf Archaeological Consultants, Inc. (MAC), conducted excavations to mitigate destruction of the central portion of the site by road construction.

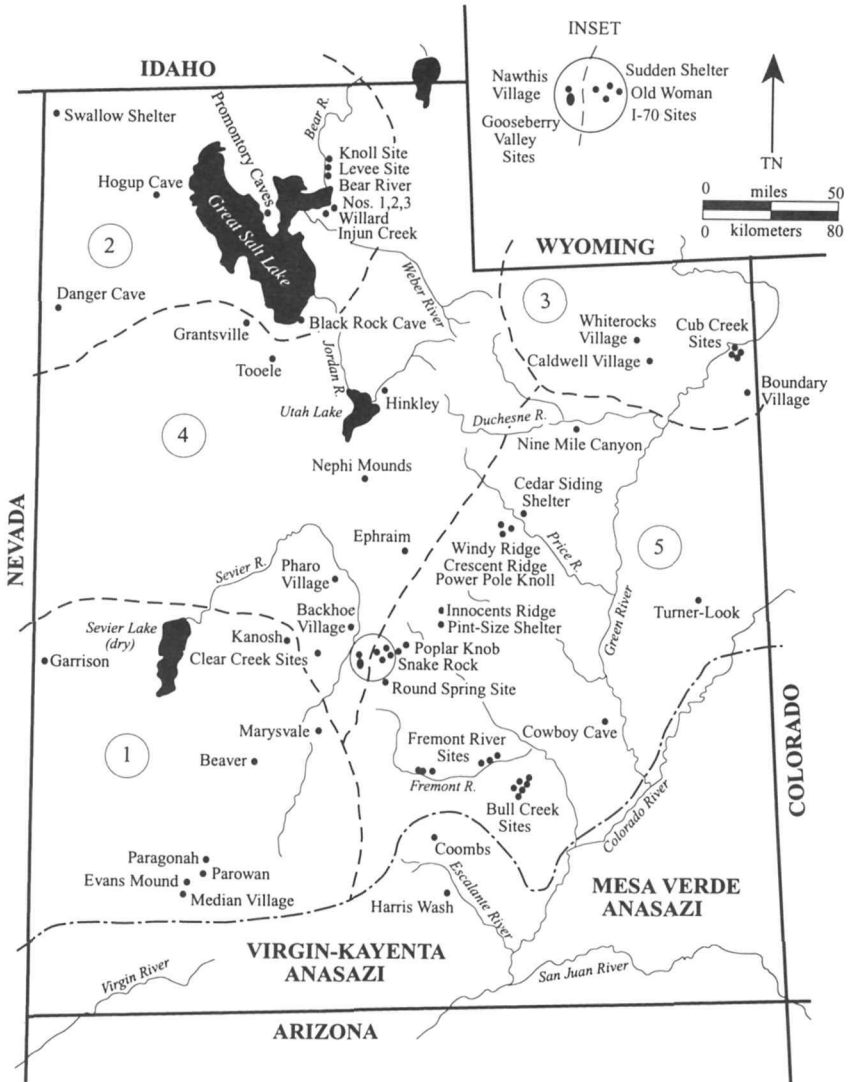


Fig. 1. Map of selected Fremont sites and Fremont regional variants: 1. Parowan Fremont; 2. Great Salt Lake Fremont; 3. Uinta Fremont; 4. Sevier Fremont; and 5. San Rafael Fremont. Redrawn after Marwitt (1970:Figure 84). Courtesy of the University of Utah Press.

The highway corridor, 300 m long and 50 m wide, transects the site. Crews from MAC conducted excavations along this corridor and in an additional 20- × 20-m block along the two-track road that leads to Round Spring. In

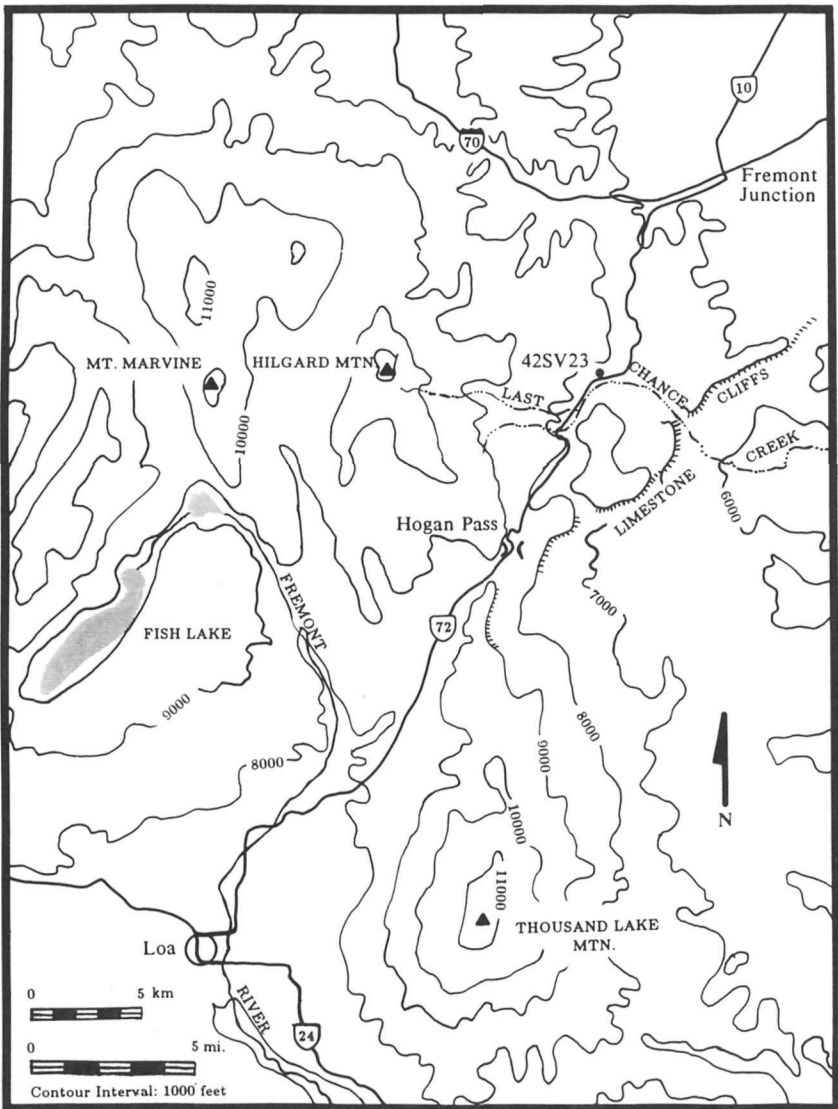


Fig. 2. Map of the project area, showing the location of 42SV23, the Round Spring site. Redrawn after Rood et al. (1988:Fig. 1).

addition to the 2 structures that Gunnerson (1957:102–105) excavated, MAC crews excavated 6 complete and 4 partial structures (mainly pit houses), 1 puddled adobe surface storage unit, a possible jacal structure, at least 3 outdoor

activity areas, and more than 20 hearths (Metcalf 1993a). Several features outside the highway right-of-way were not excavated by MAC. The number of structures on the site probably exceeds 20 and makes the Round Spring site one of the larger Fremont sites in the vicinity. Architecture and artifact assemblages are similar to those of other San Rafael Fremont sites in the area.

Twenty-two radiocarbon dates from the main area of the site range from 1520 ± 80 B.P. to 150 ± 50 B.P. Radiocarbon dates, diagnostic projectile point styles, and ceramic trade wares indicate occupation from about A.D. 650 to 1300. Although the occupation may have been continuous, different areas of the site were used during shorter periods. The period from A.D. 650 to 900 is associated with features from several areas across the site. The second period, A.D. 900–1050, is mainly represented by features in the central section of the site. The third period, A.D. 1050–1150, saw the most intensive use of the site, mainly concentrated in the western area. The final period, represented by only one structure at the southeastern edge of the site, was from A.D. 1150 to 1300. Two late dates— 590 ± 5 and 150 ± 50 B.P.—from features in the eastern section of the site are probably associated with subsequent Numic use of the area (Metcalf 1993b).

Basic ceramic analysis, including classification by ceramic type, was completed on the ceramic assemblage of nearly 30,000 sherds that MAC recovered (Morris et al. 1993). Fremont ceramic types make up more than 99% of the ceramic assemblage from the site, a pattern that is typical in this region. Most Fremont ceramics (89.4%) were classified as Emery Gray. The next most common types at the site were Sevier Gray (3.9%) and Ivie Creek Black-on-white (3.9%). Small quantities of the Snake Valley series (1.7%), a few sherds of Great Salt Lake Gray, and one sherd of Paragonah Coiled also were recovered (Morris et al. 1993:Table 1).

Non-Fremont trade wares composed only 0.2% of the assemblage and included Kayenta Anasazi types such as Tusayan Black-on-red, Tusayan Polychrome, and Dogoszhi Black-on-white and Mesa Verde types such as McElmo–Mesa Verde Black-on-white, Cortez Black-on-white, and Mesa Verde Corrugated. Twelve pieces of brownware also were noted in the collection. These sherds may be Alameda Brown Ware, a Sinagua ceramic type produced in north-central Arizona (Colton and Hargrave 1937).

Ceramic Analysis

Because ceramics are formed from natural materials, ceramic vessels are compositionally linked to the environment in which they are produced. This fact forms the basis of compositional studies of ceramic provenience, production, and distribution. Ceramic composition relates not only to the cultural realm (social and individual patterns of material procurement and preparation), but also to the natural realm (source rocks, weathering, and transportation). Binocular and petrographic microscope analyses allow the archaeologist to address both aspects quickly and inexpensively. Information regarding locations of ceramic production and patterns of distribution can be gained by identifying materials present in the ceramic paste, determining which were added and which were natural inclusions, and then comparing the materials to geologic resources. Provenience studies are the most common use of petrographic analysis in archaeology and have proven to be reliable and useful.

Analysis Methods

I used three successively more detailed methods of compositional analysis to characterize the temper in ceramics from the Round Spring site. For this study, temper is defined as nonplastic material that is deliberately added to clay by the potter (Shepard 1985:24; Rice 1987:406). This distinction is usually made on the basis of particle shape, size range, and frequency (Maggetti 1982:131; Rice 1987:409–411).

I analyzed temper in plain and surface-manipulated graywares, the most common types in the Fremont region; painted ceramics were not included. The majority of the ceramics in the sample were Emery Gray, usually associated with the San Rafael Fremont (Madsen 1970). This ceramic type was originally defined by Wormington (1955; called Turner Gray—variety II), and later revised by Lister (1960; called Turner Gray—Emery variety) and Gunnerson (1960*, 1969). Most recently, R. Madsen (1977:31) characterized the temper as “. . . angular crushed fragments of gray basalt (20–40%) and quartz (10–25%); some mica occasionally present. Inclusions range from 0.1–1.5 mm in size. . . .” Most analysts working in the area agree that there is more variation in the temper than is recognized by the current type description, but systematic studies are needed to quantify the variation.

Because of the large amount of ceramic material recovered from the Round Spring site during MAC's excavation, only a small percentage of the total could be analyzed for this study. I tried to avoid analyzing more than one sherd from a single vessel in order to represent the range of variation in the assemblage as completely as possible. I believed that a simple random sample of the sherds could increase the chances of including more than one sherd from a single vessel (as well as unsuitable sherds), and so I used a more rigorous sampling design.

The sample was limited to rim sherds, which allowed the vessel type to be determined because correlations between specific temper materials and specific types of vessels were considered in the analysis. Sherds smaller than a quarter were not included because of a minimum size limit for petrographic thin sections as well as a concern about accurate temper identification in extremely small sherds. Each structure and activity area in the site was divided into horizontal units based on the cultural stratigraphy. From the total rim sherd collection I selected those from well documented, well controlled contexts, especially from proveniences inside structures under roof fall (floor fill and floor contact). Two hundred seventy-two bags of sherds met all the criteria, and one sherd was chosen randomly from each bag. A fresh break on each sherd was examined under a low power ($\times 30-40$) binocular microscope. The types of inclusions were recorded and identified as temper or natural inclusions. Temper in the Emery Gray sherds was divided into three categories: type A, type C, and a combination of both types.

Petrographic microscope analysis was used to identify more specifically the minerals present in temper particles of sherds analyzed with the binocular microscope. Thirty-two sherds of Emery Gray were included in the petrographic analysis—26 of type C, one of type A, and five with both temper types. This sample reflects the frequency distribution of temper types in the binocular microscope sample. Sherds were chosen from the larger sample using a random number generator and were then inspected for suitability. Those that had a pronounced curve to them were not used in an effort to avoid excessively small thin sections and to ensure a representative sample of temper. Friable sherds were not used because of the large amount of epoxy impregnation required for these specimens, and burned specimens were rejected because of the difficulty in studying dark thin sections.

At each of 300 points on each sherd, the material under the microscope cross-hairs was recorded. This type of point counting, termed *multiple intercept*,

is common in geologic studies and has been determined to be satisfactory for ceramics studies (Middleton et al. 1985). *Multiple intercept* indicates that if a single grain appears under the crosshairs at more than one point, it is counted more than once. The result is actually a measure of the relative area or volume of each type of material in the thin section rather than the number of each grain type.

The third phase of analysis used an electron microprobe. The microprobe is useful for archaeological studies because it is nondestructive; a single sample can be used for repeated analyses and the sample, a thin section, can be curated for future studies. Furthermore, the small size of the thin sections used by the microprobe makes it possible to analyze small pieces of vessels or sherds. The main advantage of the microprobe over X-ray fluorescence, to which it is similar, is that the electron beam can be focused to include only a few cubic micrometers (μm) of material in the analysis. This permits analysis of small portions of the artifact, such as ceramic temper, which would be difficult to mechanically separate from the sample.

The microprobe produces a beam of electrons that, after passing through a series of magnetic lenses, strike the target specimen and interact with the atoms in the specimen. Inner-shell electrons in the atoms are knocked out of their orbits by the impact of the electrons, and as the resulting ion returns to its normal stable energy state it gives off energy in the form of an X-ray characteristic of the element. The X-rays emitted by this process can be detected by either wavelength or energy spectrometers and analyzed. Wavelength dispersive spectrometry, used in this analysis, counts the X-rays emitted by specific elements and provides a quantitative analysis of those elements in the sample. Birks (1963) and Fitzgerald (1973) provide more detailed descriptions of the mechanical aspects of the microprobe. Microprobe analysis operating conditions and detection limits for this analysis are described by Spurr (1993:81–85).

Sherds to be analyzed with the electron microprobe were chosen based on the petrographic microscope analysis and included one sherd with temper type A, five with temper type C, and two with both temper types. Two sherds of Sevier Gray were also included in the microprobe analysis. The goal of the microprobe work was a quantitative compositional analysis of feldspar in the temper in the sherds. Elements analyzed with the microprobe were Na (sodium), Al (aluminum), Si (silica), K (potassium), Ca (calcium), Ba (barium), and Fe (iron). These elements, reported as oxide weight percents of Na_2O , Al_2O_3 , SiO_2 , K_2O , CaO , BaO , and Fe_2O_3 , represent the major constituents of the feldspar group.

Feldspars are the most common rock-forming minerals in the earth's crust and are a major constituent of igneous rocks; the types and associations of feldspars are one of the attributes used to classify rocks (Moorhouse 1959; Deer et al. 1971). The feldspars, which are framework silicates, form two solid solution series in which the chemical composition varies between finite limits whereas the crystalline form remains essentially the same. The standard classification of feldspars approximates a ternary system and is divided into two series, alkali feldspar and plagioclase (Fig. 3). End members of the feldspar system are orthoclase (Or), albite (Ab), and anorthite (An). Rare celsian (Cs) feldspars, in which barium replaces all or most Ca, can exist in the place of anorthite in the system.

Orthoclase (KAlSi_3O_8) and albite ($\text{NaAlSi}_3\text{O}_8$) form the end members of the alkali feldspar group, in which anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) is absent or a minor constituent. Minerals in this group are monoclinic or triclinic. Alkali feldspars are mainly present in felsic igneous rocks such as syenite and granite and their volcanic equivalents. Albite and anorthite are the end members of the plagioclase series, in which orthoclase represents less than 10% of the composition.

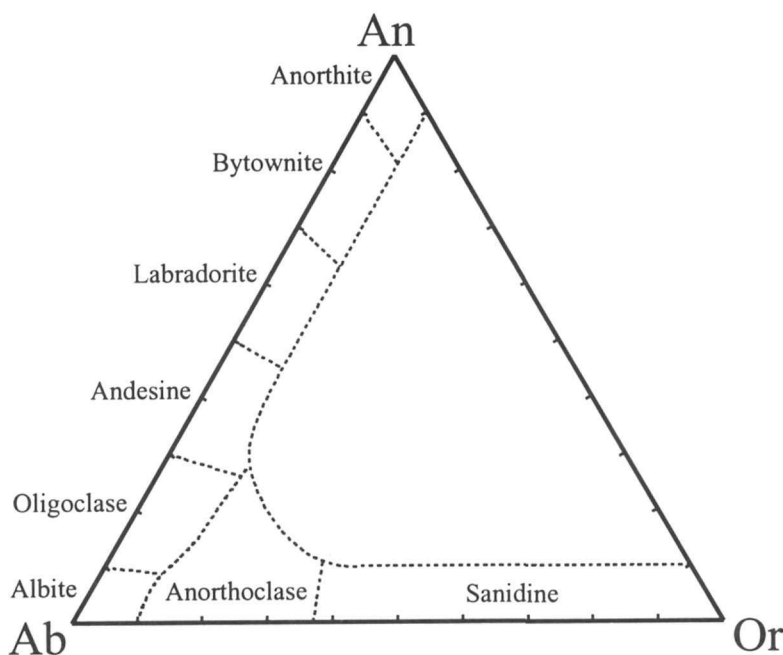


Fig. 3. Ternary diagram of the feldspar system, with conventional nomenclature.

Plagioclase minerals are triclinic. These minerals are found in intermediate and mafic igneous rocks such as andesite and basalt. Plagioclase may comprise both phenocrysts and groundmass of these rocks, and several types of plagioclase are commonly found in a single rock.

The feldspar system is essentially a continuous reaction series involving a gradual change in composition caused by continuous substitution of Na for Ca or K for Na. The crystal structure remains essentially unchanged by these compositional changes. The composition of feldspars represents a closed system, and the elements composing different feldspars are not independent variables. For instance, the amount of Ca is directly proportional to the amount of Na and Al and to a lesser extent K. Because of the closed nature of the feldspar system, statistical methods that treat one or more variables as independent, such as Principle Components Analysis, are not appropriate for modeling the feldspar system. The standard method of presentation is on a ternary diagram, where feldspar composition is presented as a percentage of the end members. For example, $An_{66.0}Or_{0.7}Ab_{33.1}Cs_{0.2}$ represents a feldspar with 66.0% anorthite component, 0.7% orthoclase component, 33.1% albite component, and 0.2% celsian component.

Analysis Results

Binocular microscope analysis of 272 sherds indicated that two types of igneous rock were used as both primary and secondary temper in the Emery Gray ceramics from the Round Spring site. Primary temper is the most abundant type, and secondary temper is a relatively less abundant type. Because the temper particles in each sherd are generally of roughly equal size, the primary–secondary distinction is based on both the number of grains and the volume of each type.

The two temper materials identified with the binocular microscope correspond to types previously identified by Geib and Lyneis (1993) in Fremont sherds. In the interest of consistency, I have continued the designation system used by Geib and Lyneis (1993) in their research. Under the microscope, temper type A is black to dark gray with a glassy groundmass and abundant phenocrysts of plagioclase and dark green to black pyroxene. Based on petrographic analysis, this material was identified by Geib and Lyneis (1993) as basaltic andesite. Temper type C is a microcrystalline intermediate igneous material, light to medium gray in color, with abundant phenocrysts of dark green to black pyroxene and black magnetite. This temper type is generally considered to be the classic Emery Gray

temper. This material was also noted by Geib and Lyneis (1993) and was identified as a possible variation of the basaltic andesite that is type A.

Temper types A and C make up the majority of the ceramic temper at the Round Spring site. In the binocular microscope analysis, temper type A represents 1.8% of the total sample, type C makes up 73.9%, and sherds with both temper types represent 12.9% of the assemblage; only 11.4% of the sherds do not have one or both of these temper types. Crosstabulations indicate that there is no correlation between temper type and vessel form or surface treatment. When temper types A and C are present in the same sherd, it is often difficult to distinguish between them based on mineralogy, lending credence to the possibility that the raw material that produces these two temper types is a gradation of a single igneous formation.

During point counting with the petrographic microscope, each grain was identified as sherd paste, epoxy, feldspar, pyroxene (clinopyroxene or orthopyroxene), opaque minerals (such as magnetite), biotite, olivine, volcanic glass, or rock fragment. Rock fragments are pieces of the source rock groundmass, characterized by very small, tightly bonded crystals of feldspar, pyroxene and some volcanic glass as well as small to large phenocrysts of various minerals. Phenocrysts were recorded as a mineral when they were loose in the sherd paste but as rock fragments when they were within groundmass. This distinction may be an indication of the level of processing of temper in the sherds or of the nature of the raw temper material (e.g., dense vs. porous or fresh vs. weathered). Differences noted in the ratio of feldspar to pyroxene in the groundmass of the rock fragments may correspond to macroscopic differences in temper sources, as discussed below. Petrographic analysis revealed that temper types A and C have similar amounts of feldspars, pyroxenes, and opaque minerals indicating that temper types A and C could be derived from the same rock source. Statistical tests of the frequency of minerals present revealed that temper types A and C are mineralogically similar but are significantly different from temper in Sevier Gray ceramics from the site.

The petrographic point count data were analyzed by cluster analysis using Euclidean distance and the complete linkage (farthest neighbor) method. The cluster analysis yielded three distinct groups, which correspond to the temper types (Table 1; temper type E represents Sevier Gray ceramics). The clusters are differentiated mainly by the amount of volcanic glass, pyroxene, and rock fragments in the temper and to a lesser degree by the amount of opaque minerals (such as magnetite) and feldspar (Table 2). It is plausible that temper types A

Table 1. Distribution of temper groups by cluster for sherd petrographic microscope analysis.

Temper type	Cluster			Total
	1	2	3	
A	1 ^a	—	—	1
	2.8 ^b	—	—	2.8
A & C	5	—	—	5
	13.9	—	—	13.9
C	19	—	7	26
	52.8	—	19.4	72.2
E ^c	—	4	—	4
	—	11.1	—	11.1
Total	25	4	7	36
	69.4	11.1	19.4	100.0

^aFrequency.^bPercent.^cTemper in Sevier Gray ceramics.

and C are derived from the same rock source, as the frequencies of mineral inclusions in clusters 1 and 3 are similar (Table 2). The presence of both temper types A and C in cluster 1 indicates that these temper types are not mineralogically distinct. The main difference between clusters 1 and 3 is the ratio of rock fragments to paste, which only indicates that the sherds in cluster 3 contain more temper than those in cluster 1.

Roughly 20 points were analyzed on each of the 10 sherds selected for electron microprobe analysis. The relative proportions of each analyzed element were used to plot the electron microprobe data on ternary diagrams. Figures 4–11 show the analysis results of the Emery Gray sherds and indicate that the feldspar in all the sherds is similar. The feldspar in temper types A and C straddles the boundary between andesine and labradorite and ranges in composition from $\text{An}_{35.9}\text{Or}_{6.2}\text{Ab}_{55.3}\text{Cs}_{0.3}$ to $\text{An}_{68.6}\text{Or}_{1.4}\text{Ab}_{29.9}\text{Cs}_{0.1}$ (Figs. 4–11). Microprobe analysis data from the sherds indicates that the feldspar in temper types A and C is similar (Fig. 12) but is clearly different from feldspar in sherds with other temper types (Fig. 13). Chemical differences between the feldspars are most apparent in the amount of Fe_2O_3 and BaO. Sherds with temper types A and C contain similar amounts of these oxides (Fig. 14) but differ from sherds with other temper types (Fig. 15).

Table 2. Distribution of minerals by cluster for sherd petrographic microscope analysis.

Cluster	Sherd paste	Feldspar	Volcanic glass	Pyroxene	Opaque	Biotite	Rock frag.	Epoxy
1	140–209 ^a	9–53	0–2	2–18	0–12	0–2	53–103	0–14
<i>n</i> = 25	171.8/170 ^b	32.1/33	0.12/0	8.9/7	4.6/5	0.2/0	76.7/74	5.4/5
	19.5 ^c	12.5	0.4	4.6	3.2	0.5	14.6	3.6
2	130–189	13–35	52–106	0–2	0–6	2–7	0–7	11–21
<i>n</i> = 4	172.5/185.5	24.3/24.5	75.0/71	0.8/0.5	2.3/1.5	4.8/5	2.5/1.5	15.0/14
	28.5	9.2	22.8	1.0	2.6	2.6	3.3	4.2
3	119–156	15–46	0–0	3–10	0–5	0–0	106–142	0–24
<i>n</i> = 7	139.0/143	25.9/25	0.0/0	6.7/6	2.4/3	0.0/0	120.4/116	5.6/1
	13.5	10.3	0.0	3.3	2.1	0.0	11.8	8.6

^aFrequency range.^bMean/median.^cStandard deviation.

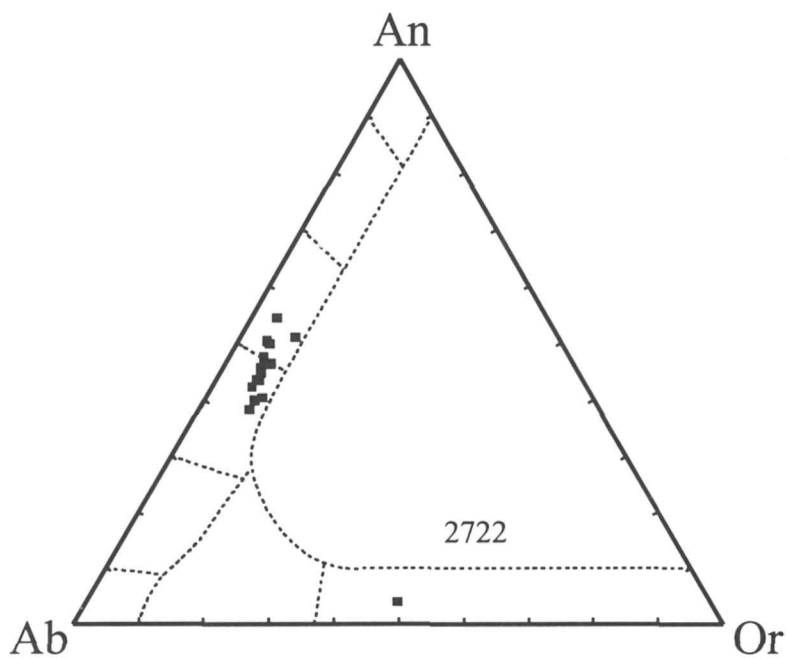


Fig. 4. Results of electron microprobe analysis of sherd 2722.

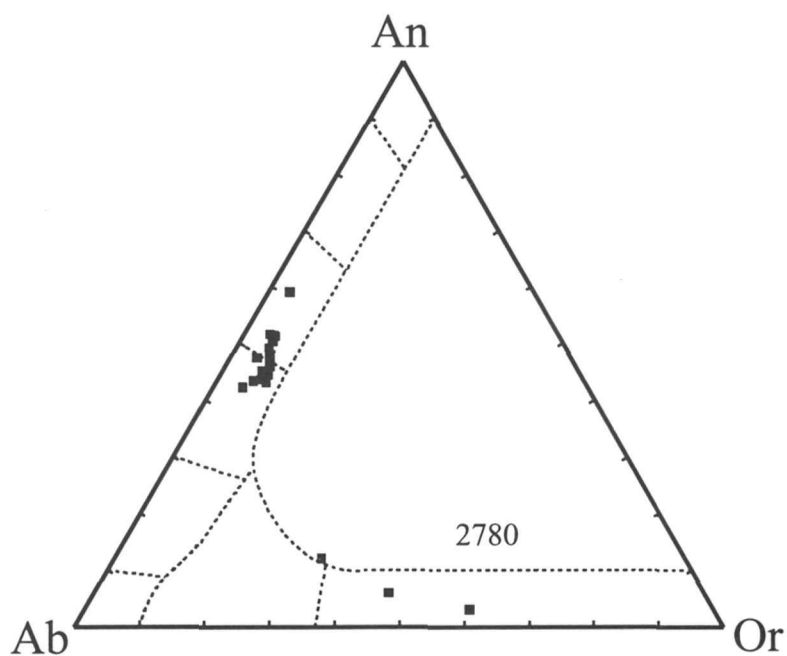


Fig. 5. Results of electron microprobe analysis of sherd 2780.

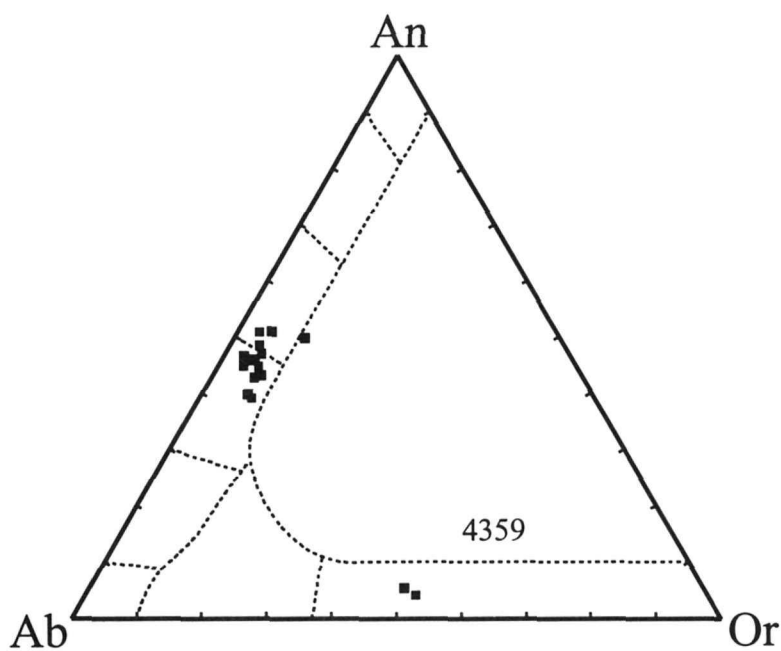


Fig. 6. Results of electron microprobe analysis of sherd 4359.

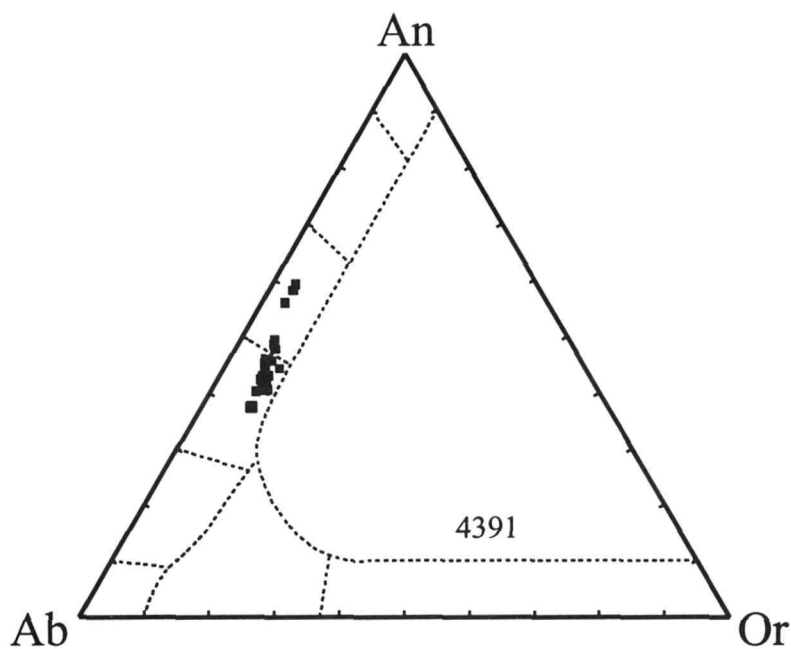


Fig. 7. Results of electron microprobe analysis of sherd 4391.

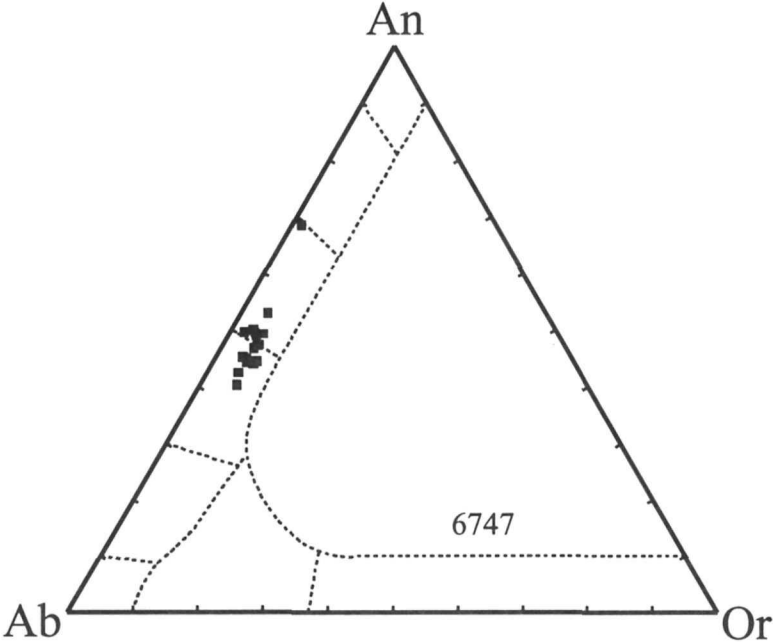


Fig. 8. Results of electron microprobe analysis of sherd 6747.

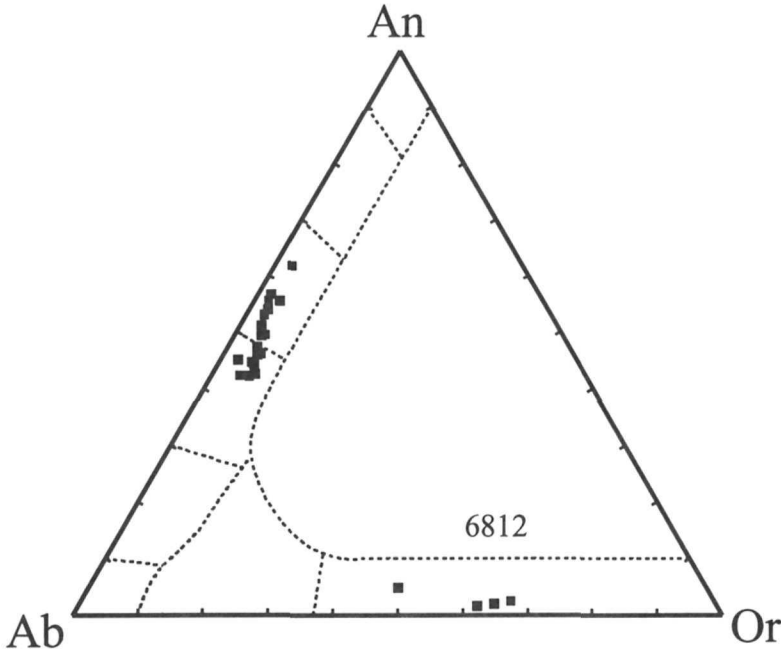


Fig. 9. Results of electron microprobe analysis of sherd 6812.

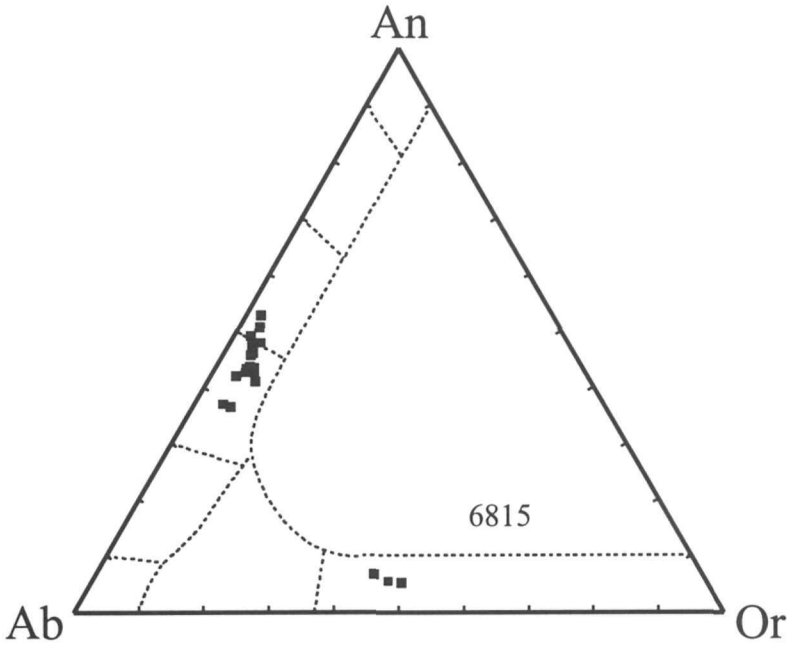


Fig. 10. Results of electron microprobe analysis of sherd 6815.

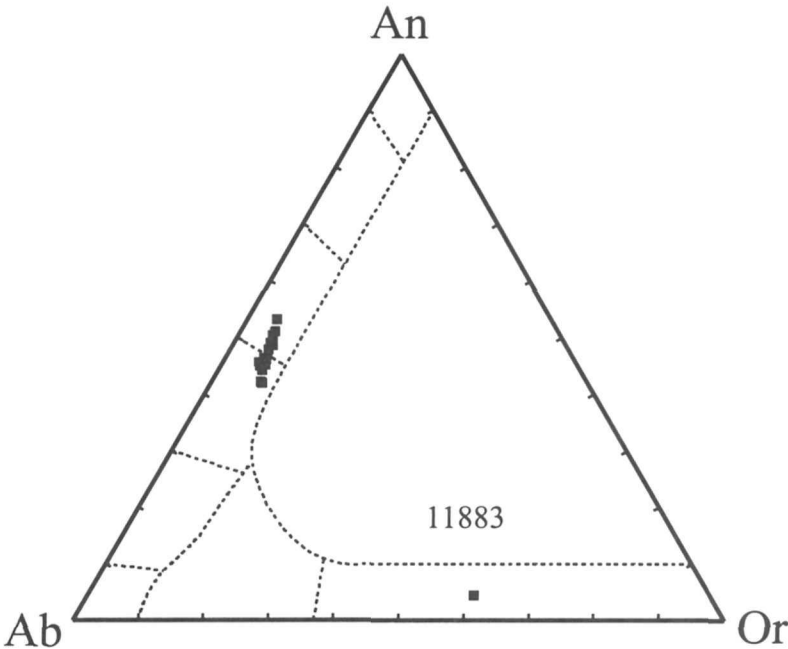


Fig. 11. Results of electron microprobe analysis of sherd 11883.

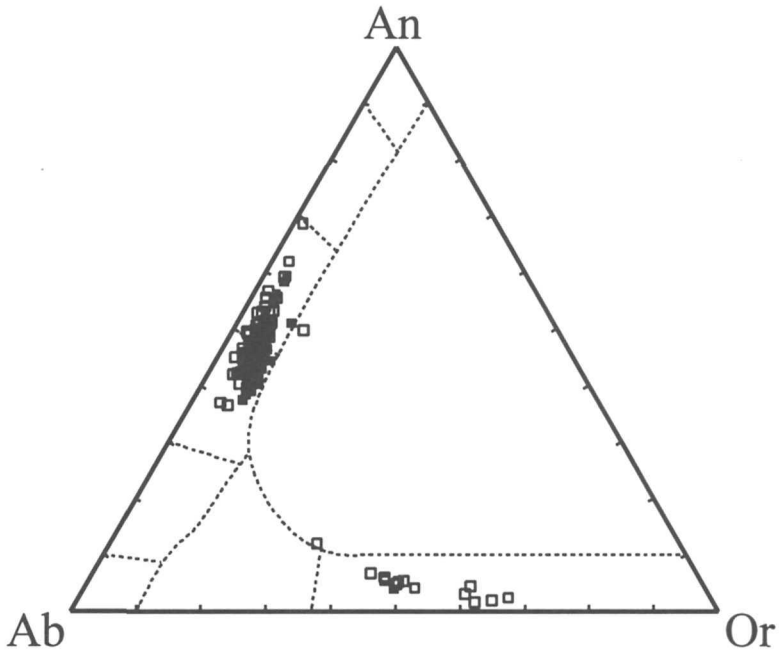


Fig. 12. Comparison of feldspar composition in sherds with temper type A (■) versus temper type C (□).

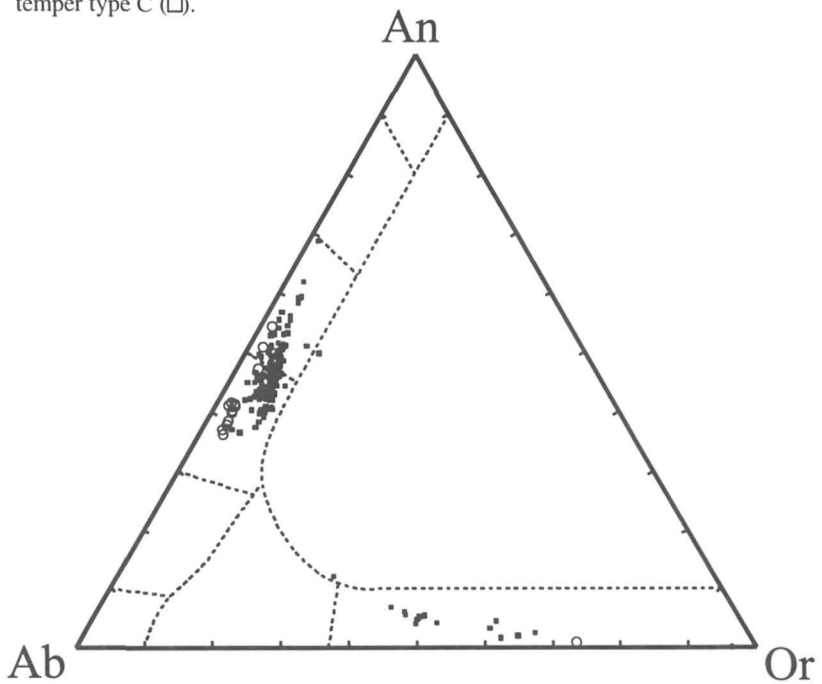


Fig. 13. Comparison of feldspar composition in sherds with temper type E (○) versus temper types A and C (■).

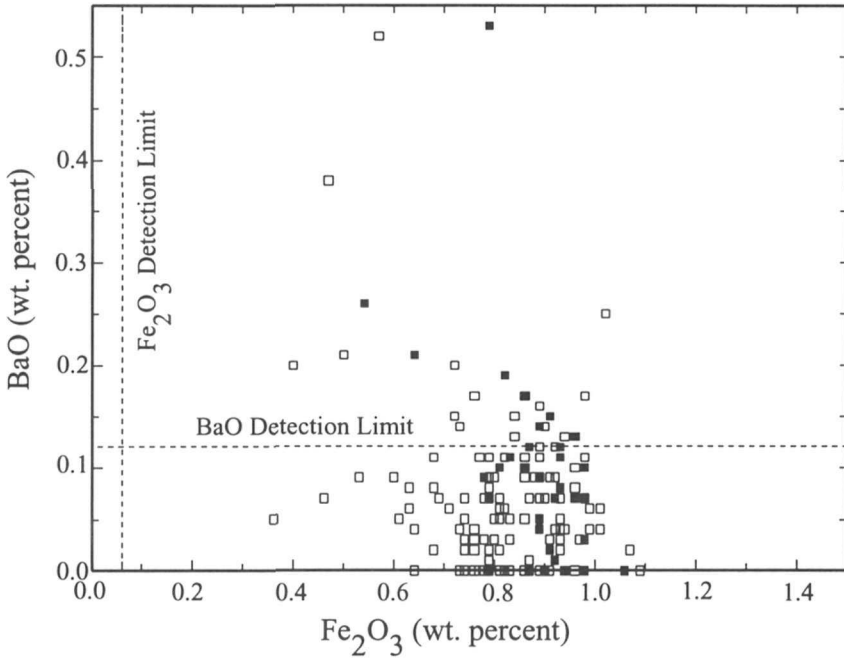


Fig. 14. Plot of Fe_2O_3 versus BaO content in sherds with temper type A (■) versus temper type C (□).

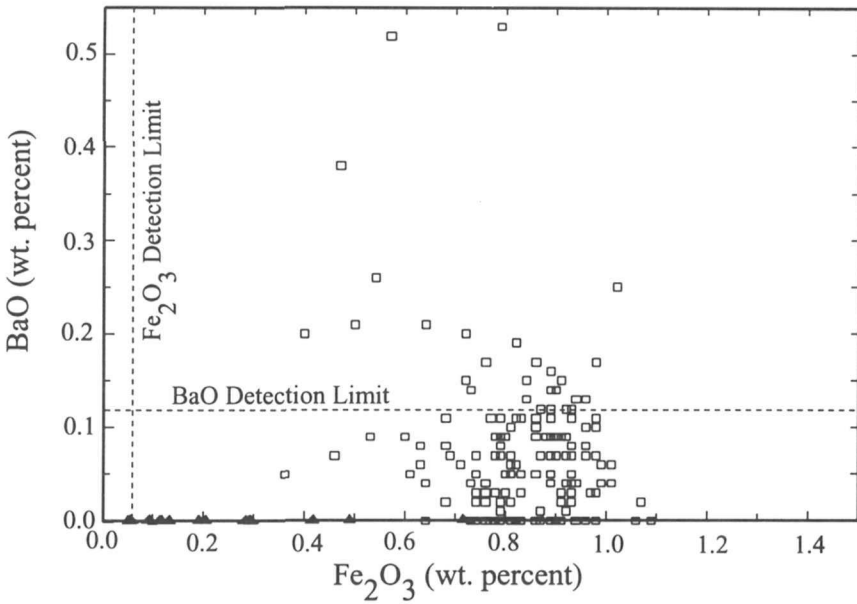


Fig. 15. Plot of Fe_2O_3 versus BaO content in sherds with temper type E (▲) versus temper types A and C (□).

In addition to the feldspar, the mineral assemblages of the temper in sherds with temper types A and C are similar. The microprobe analysis revealed titanomagnetite, ilmenite, and two forms of pyroxene—diopside (or augite) and hypersthene—in all sherds with temper types A or C. Alkali feldspar was also noted in most sherds during the microprobe analysis and may have been residual in the clay (Spurr 1993:124–125).

Geologic Analysis

As additional research on the ceramics at the Round Spring site, rock samples were collected from the vicinity of the site to compare the composition of the temper in the sherds to the geology of the site location and to determine which temper types were local and which were not. Geologic formations surrounding the project area include mainly sedimentary rocks to the east and a combination of sedimentary and igneous rocks to the west. The igneous rocks are of various intermediate types except for the most recent, which are basaltic (Eardley 1963:27; Proctor and Bullock 1963; Williams and Hackman 1983).

Although the hillsides and old terraces upstream from the site are covered with boulders and cobbles from igneous formations that have eroded away, there is little igneous material cropping out in the drainage basin of upper Last Chance Creek. Prehistoric people probably obtained their ceramic temper material from the terraces and the streams. The extreme hardness of the material at outcrops also argues against collection of material from these sources. After transportation down the streams and weathering on the terrace surfaces, the cobbles are smaller, more friable, and more easily broken.

Methods

Samples of possible temper materials, in the form of alluvial cobbles from stream beds and old terraces, were collected from drainages near the Round Spring site. These samples were compared macroscopically and microscopically to temper materials in the ceramics from the site to relate the ceramic temper to the local geology. Geib and Lyneis (1993) were successful in similar efforts to match rock samples with temper in sherds from other Fremont sites.

The collection of the geologic materials used a modified version of the line intercept (or belt intercept) method developed by biologists for sampling plant species (Brown 1954:20–21, 63–71). Transects (1 × 10 m) were placed in

drainage channels and on terraces along the main tributaries of Last Chance Creek to examine the range of igneous materials available and the variation in resource distribution around the site. Transects were placed so all tributaries that contribute material to Last Chance Creek were sampled. Figure 16 shows the location of the transects in relation to the Round Spring site.

Extrapolating from models generated by ethnographic research (Browman 1976:469–471; Arnold 1985:45–46, 51–52), sources of temper used in the manufacture of ceramics at the Round Spring site were expected to be located within 9 km of the site. A representative sample of rocks found within 9 km of the site was collected, crushed, and sieved, and the various size fractions were studied under the binocular microscope. Seven rock samples were analyzed with the petrographic microscope. These included rocks from both macroscopic groups (see next paragraph) as well as intermediate samples. Petrographic thin sections were analyzed in the same manner as the ceramic thin sections. Finally, feldspar in four of the rock samples was analyzed with the electron microprobe for the same elements as the feldspar in the sherds. Methods and operating conditions for the microprobe analysis were the same as for the sherd analysis.

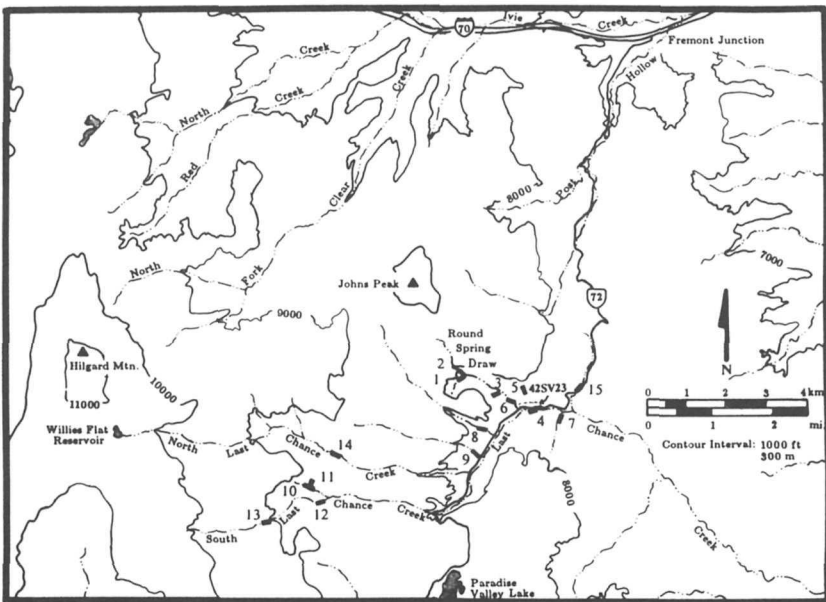


Fig. 16. Location of geologic sampling transects. Base map is Salina, Utah—1:100,000 (1990).

Results

Macroscopic inspection of the rock samples indicates two groups. Rocks in the first group are dense and hard. These rocks have a fine-grained holocrystalline groundmass of feldspar and pyroxene crystals of various sizes. They are generally light gray because of their high feldspar content. Feldspar and pyroxene phenocrysts are abundant. When crushed, the rocks produce a large amount of fine dust and small angular particles. Large pieces of this material are difficult to crush because of their hardness, but smaller pieces are more easily reduced.

Rocks in the second group are vesicular, and relatively large feldspar and pyroxene phenocrysts are common in the glassy to microcrystalline groundmass. These rocks are generally dark gray to black, although they sometimes exhibit a dark red weathering rind. When crushed, they produce rough, angular pieces and loose crystals and less fine dust than rocks in the first group. Because of the vesicular nature of the rocks, it is much easier to crush these rocks than those in the first group. This rock matches that identified by Geib and Lyneis (1993) as the basaltic andesite that is the source of temper type A.

Aside from the dense versus vesicular texture and the variation in color, rocks in the two groups appear to be mineralogically similar and contain similar phenocrysts. Also, several rock samples are intermediate in texture and color. When weathering rinds cover the rocks or when they are wet, it is difficult to differentiate between the two groups. The texture of igneous rocks is largely dependent on the viscosity of the magma and the rate of cooling rather than the composition of the magma. Geologic maps (i.e., Williams and Hackman 1983) and previous research indicate that the rock samples may be part of a discontinuous volcanic formation, Tertiary basaltic andesite (Tba), that is identifiable from the Escalante River drainage to the Ivie Creek drainage (Geib and Lyneis 1993) and from the project area at least to Clear Creek Canyon west of the Sevier Valley (Lane Richens, Brigham Young University, Provo, Utah, personal communication).

Petrographic microscope analysis revealed that the groundmass of all rock samples is composed of fine to microcrystalline feldspar and pyroxene. Even in vesicular samples the groundmass is compact. Phenocrysts of feldspar, pyroxene, and opaque minerals are present in all the samples, although the sizes of the phenocrysts vary greatly. Biotite and altered olivine crystals are present in some samples as well. Cluster analysis indicates that all seven samples are

similar (Table 3), and cluster membership crosscuts the macroscopic divisions of the rock samples.

Although the same mineral assemblages are present in all the rock samples, some differences are apparent. The relative frequency of feldspar and pyroxene crystals in the groundmass differs and, consequently, the groundmass ranges in color from dark to light gray. This variation was observed in both the hand specimens and the petrographic samples and may provide an expedient way to correlate temper with raw material source. In general, designation of temper as dark or light correlates with temper types A and C, respectively.

Another difference among the rock samples is the presence or absence of biotite. The presence of this mineral is often considered an indicator of specific compositions and formation conditions (Moorhouse 1959). Biotite contains relatively large amounts of K and Fe and is generally present in rocks with high K content. The presence of biotite in some of the samples and its absence in others could indicate that the samples are from different formations. The presence of biotite does not seem to be associated with any other characteristics of the samples, however, as biotite is present in samples from both macroscopic groups of rocks. Either the presence of biotite is linked to some variable that has not been considered here or its presence is not significant in the rocks involved in this study. Bulk compositional analysis would be of help in assessing the similarity of the rocks, but this analysis has not yet been completed.

Results of the electron microprobe analysis for the rock samples are shown in Figs. 17–20. Plagioclase compositions in all rock samples range from $\text{An}_{40.4}\text{Or}_{7.4}\text{Ab}_{50.1}\text{Cs}_{0.3}$ to $\text{An}_{66.4}\text{Or}_{2.7}\text{Ab}_{30.9}\text{Cs}_{0.0}$, intermediate between andesine and labradorite. The similarity of the plagioclase in the rock samples supports the hypothesis that the two rock groups are not chemically distinct, at least as regards feldspar composition.

Discussion

In all phases of analysis, Emery Gray temper types A and C are similar, and in the petrographic and microprobe analyses it can be difficult to distinguish between them. With the binocular microscope they can be separated by texture and the types of associated inclusions, such as pyroxene. Mineralogy and elemental composition show strong similarities, however, indicating that the two temper types may be derived from the same or very similar geologic sources.

Table 3. Distribution of minerals by cluster for petrographic microscope analysis of geologic samples.

Cluster	Groundmass	Feldspar	Pyroxene	Opaque	Biotite	Other	Epoxy
1 <i>n</i> = 2	140–141 ^a	67–87	34–54	11–18	0	0	20–28
2 <i>n</i> = 3	139–146	106–133	26–31	5–12	5–10	0–1	3–21
3 <i>n</i> = 2	104–121	103–135	28–33	6–13	2	0–1	7

^aFrequency range.

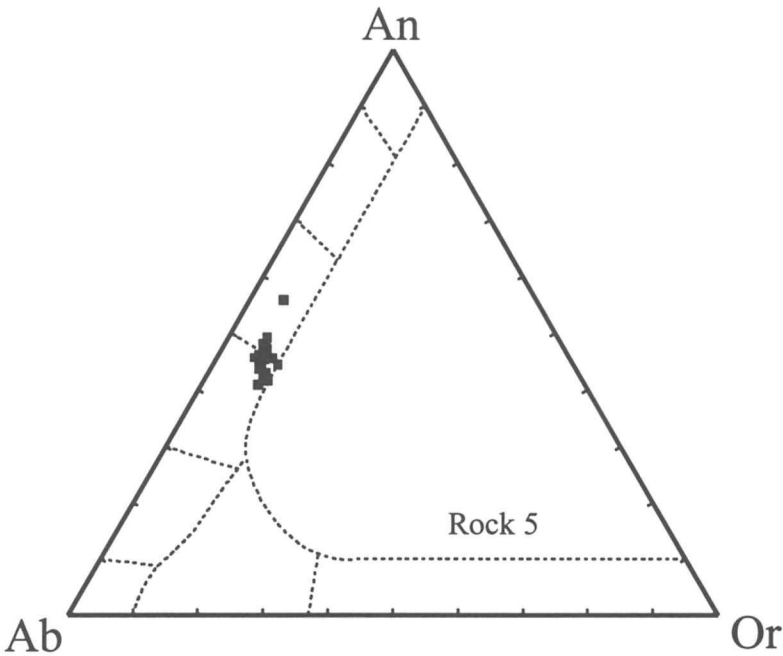


Fig. 17. Results of electron microprobe analysis of geologic sample 5.

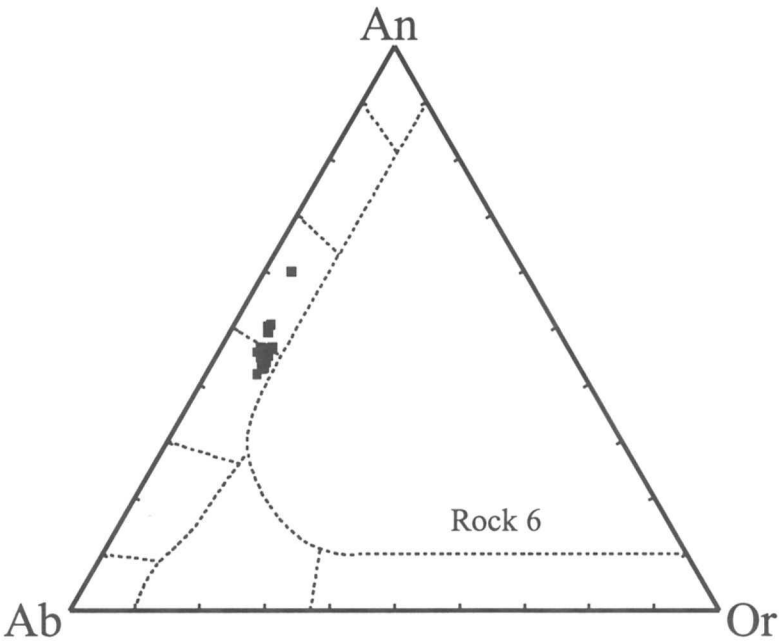


Fig. 18. Results of electron microprobe analysis of geologic sample 6.

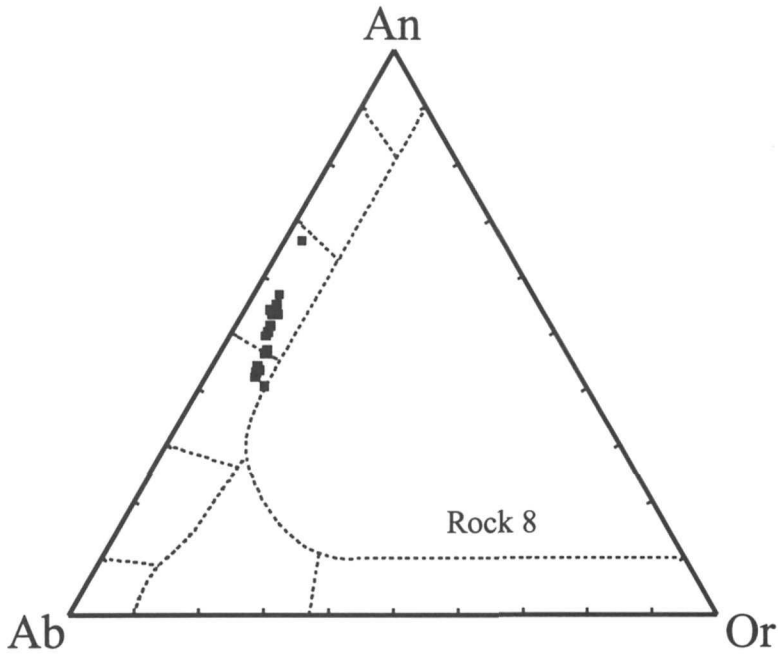


Fig. 19. Results of electron microprobe analysis of geologic sample 8.

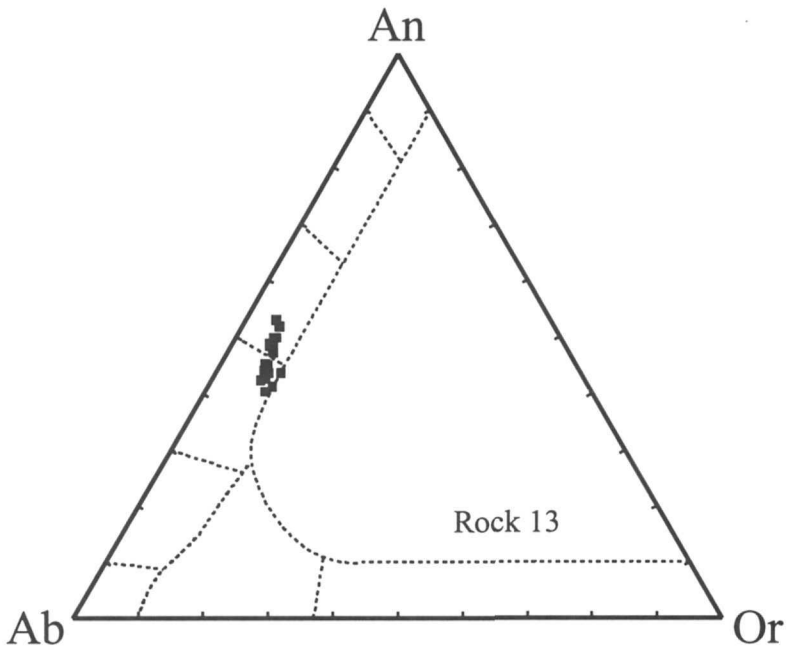


Fig. 20. Results of electron microprobe analysis of geologic sample 13.

Analysis of other minerals in the material—the pyroxenes, for example—is necessary to verify this possibility.

Analysis results of the geologic samples indicate that, despite macroscopic differences in texture, density, and color, all the rocks collected are similar. The major differences among the samples are the amount of biotite and feldspar present as phenocrysts and the absolute frequency of phenocrysts (Table 3). Although it is difficult to prove that several rock samples are the same material based on the analysis of only one mineral, it is plausible that the two rocks, macroscopically different, are related compositionally. The similarity of the rocks in every level of analysis supports the conclusion that both rock groups are basaltic andesite.

Plotting the microprobe analyses of the rock samples and of the sherds with temper types A and C reveals that all contain similar plagioclase (Fig. 21). The plagioclase in the sherds contains slightly less K_2O than plagioclase in the rocks, although the two fields overlap substantially. The amount of Fe_2O_3 and BaO in the rocks also is similar to the amount of these compounds in the temper

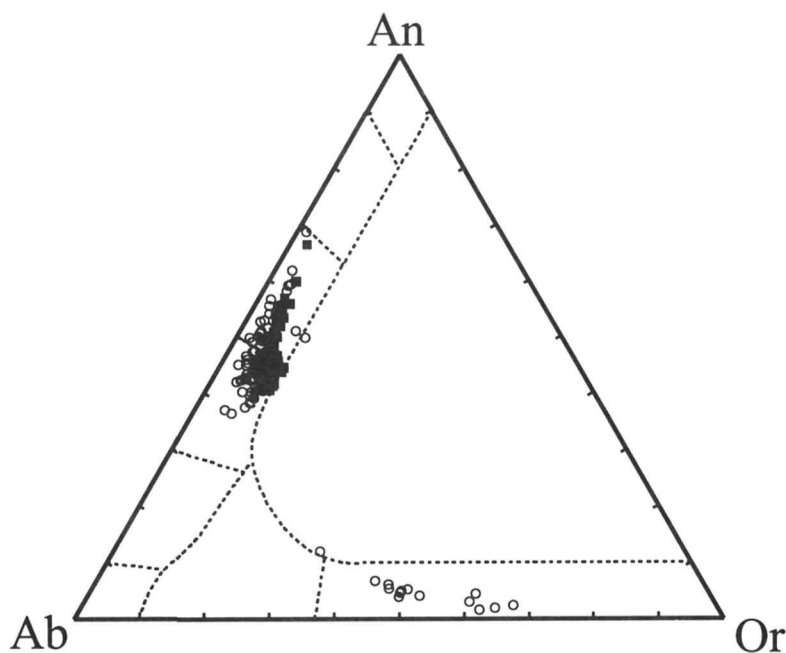


Fig. 21. Comparison of feldspar composition in geologic samples (■) versus sherds with temper types A and C (○).

(Fig. 22). These data indicate that the rocks near the Round Spring site may be the source of temper types A and C. The difference in K_2O content is problematic and needs to be further examined before the rocks can be considered the source of the temper. The process of firing ceramics may affect the K_2O content of the plagioclase.

The rock samples also contain pyroxenes—hypersthene and diopside or augite—that are the same as the pyroxenes in the sherds. Titano—magnetite and possibly ilmenite, noted in the sherds, are present as phenocrysts in the rocks. In the future, pyroxenes and opaque minerals may be analyzed with the microprobe, because they may increase the certainty that temper types A and C are from similar rock sources. Examination of the same minerals in the rock samples would help determine whether these rocks are the sources of the temper.

Although the amount of igneous material in the vicinity of the Round Spring site is large, the variety is limited. The rocks collected for this study are the only types available in any appreciable amount near the site. The frequency of the rock types in the sampling transects is homogeneous, and there is no

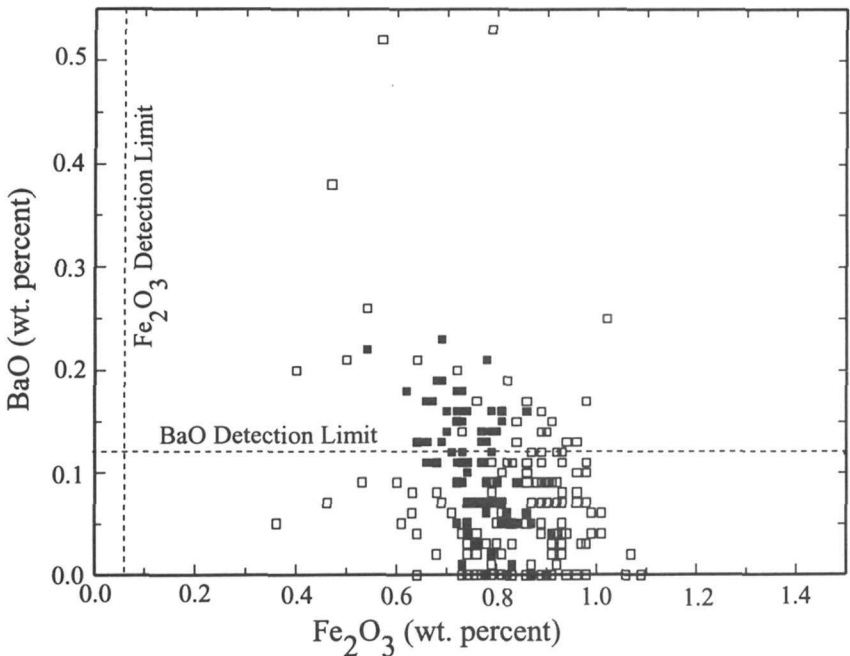


Fig. 22. Plot of Fe_2O_3 versus BaO content in geologic samples (■) and sherds with temper types A and C (□).

indication that these frequencies change systematically in any direction from the site. Igneous material exists in every drainage near the site, and residents of the Round Spring site evidently obtained igneous rock for ceramic temper from the immediate vicinity of the site. Rocks from both macroscopic groups, which seem to be the same or very similar rock, were probably used interchangeably. Several of the rock samples are identical to rocks previously noted by Geib and Lyneis (1992*, 1993) as sources of Emery Gray temper.

The distinctive nature of the temper types under low-power magnification suggests that heavy reliance on temper type is not necessarily a major problem in Fremont ceramic analysis. Instead, accurate and consistent identification of the temper types seems to be a bigger problem. The presence of distinct temper may be the reason that temper became a major criterion of classification in the first place; early researchers may have realized that temper was the only consistent difference among the types, which are mainly graywares with plain or textured surfaces. Unfortunately, few archaeologists have considered the relation of local geology to the distribution of temper types. Assuming local ceramic production, the abundance of igneous rocks in southern and central Utah requires that ceramic types based on igneous temper type have a large amount of variation in the type definitions or a large number of types. This situation is not reflected in the Fremont ceramic typology, and the result is a typology that is difficult to apply.

This is true with regard to Emery Gray ceramics. Temper type C can be considered classic Emery Gray temper and would be easily classified by most analysts. Sherds containing temper type A, however, would not be classified as Emery Gray by some analysts because the temper particles are too dark to be the gray basalt described by Madsen (1977:31). The similar composition of these temper types and their pattern of distribution as noted by Geib and Lyneis (1993) suggest that both belong to the ceramic tradition of the San Rafael Fremont. The Fremont ceramic classification system is in need of revision and, following Geib and Lyneis (1992*), two possibilities present themselves. The first is that a wider range of variation in Emery Gray, including types A and C, be included in the system. Perhaps establishing varieties of Emery Gray, based on temper type, would illustrate distribution patterns of the different tempers. These distribution patterns should reflect production areas of the ceramics. The second possibility is that temper type C defines Emery Gray, and a separate type designation be given to ceramics containing temper type A. As Geib and Lyneis (1992*) noted, however, the addition of new ceramic types is not what Fremont

archaeology needs. Perhaps for now, more careful and consistent descriptions of temper and better correlations of temper with geologic units are the most constructive tasks for Fremont ceramic analysts. As more research is completed on the types and distributions of temper, the Fremont ceramic taxonomy can be refined to provide a more useful and accurate system.

Acknowledgments

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A Model to Study Fire Effects on Cultural Resource Studies of Mesa Verde

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Abstract. On 8 July 1989, lightning struck the dry terrain of Long Mesa in Mesa Verde National Park and ignited a 2-week burn that scorched 1,200 ha. As a result, park management initiated studies of the effects of high-intensity fire on cultural resources. Mesa Verde National Park was established to protect works of prehistoric humans including pit-houses and cliff dwellings of the Anasazi. Later, park management was charged with the preservation of historic buildings and wood structures of 20th-century Americans. Our research will provide the necessary background information to predict specific fire effects on cultural sites. We mapped the vegetation communities, reconstructed the prehistoric fire history of half of Mesa Verde, and will document postfire succession. These data sets, incorporated into spatially explicit layers in the park's Geographic Information System, will be used to model the risk and specific effects of fire as related to particular classes of cultural resources.

Key words: Anasazi, postfire succession, vegetation mapping.

Mesa Verde is a series of north–south mesas in sandstone and shale substrates. Mancos Shale of marine origin is topped by Point Lookout Sandstone, then covered in parts of Mesa Verde National Park by the diverse Menifee Shale. The Cliffhouse Sandstone is exposed above these formations, and it is in this final layer that the most impressive cliff dwellings were built (Griffiths 1990). Water is ephemeral throughout the Mesa system—seeps and springs are infrequently encountered. The Mancos River forms the eastern boundary of the park and provides the only perennial water source.

We focused our postfire succession study on Long Mesa, the site of the 1989 fire that burned 1,200 ha. Long Mesa, one of the western mesas, ranges in elevation from 2,180 m in the south to 2,517 m at the north end. Long Canyon floor is 2,133 m. The vegetation on Long Mesa is a mosaic of mature piñon–juniper woodlands and mountain shrub associations. Shrub associations range from oak (*Quercus gambelii*) and serviceberry (*Amelanchier utahensis*) to sagebrush (*Artemisia nova*) and bitterbrush (*Purshia tridentata*).

Piñon (*Pinus edulis*) and juniper (*Juniperus osteosperma*) woodlands dominate the lower, southern ends of the mesas, whereas mountain shrub communities dominate on the northern ends. Differential fire frequency is hypothesized to be the major factor controlling this pattern (e.g., Erdman 1970). Douglas-fir (*Pseudotsuga menziesii*) forms dense stands on the north escarpment or on steep north-facing slopes. Ponderosa pine (*Pinus ponderosa*) is found in a few limited stands in Morefield and Prater canyons and in isolated pockets elsewhere. Scattered, small deciduous forest communities include aspen (*Populus tremuloides*) and maple (*Acer* sp.).

Methods and Preliminary Results

Mapping of Vegetation and Woody Fuels

The first step in modeling the effects of fire on cultural resources was to compile a digital map to define the vegetation of Mesa Verde to accurately predict the fire potential of each plant community. Landsat TM and SPOT panchromatic scenes from May and June 1990 were used as a spatial and spectral base. An unsupervised classification of the image and initial field surveys showed that 17% of the image was in shadow and that important vegetation characteristics were obscured. To mitigate the topographic effects in the image data, a transformation was used to separate the spectral and illumination

information (Pouch and Campagna 1990). The transformed image was then reclassified. Ground-truth efforts guided by this reclassification were made with relevé stand analyses (Mueller-Dombois and Ellenburg 1974) of more than 300 sites, each located with a Trimble Basic Pathfinder Global Positioning System (GPS). Species cover and abundance ratings were clustered with TWINSpan, a multivariate clustering program (Gauch 1982). This ordination was used to guide the final supervised classification of the image data with training signatures from the mean spectral signatures of the clustered sample points. In this way, the spectral and field information were related to one another.

Woody fuels were assessed in a subsample of the sampling points ($n = 26$). Canopy fuels—dead snags and woody fuels in live trees and shrubs—were measured (Meeuwig and Budy 1981). Downed fuels were sampled on transects with the plane-intercept method (Brown 1974). These data will be used in the fire behavior model BEHAVE (Burgan and Rothermel 1984) to predict the fire potential within the major vegetation communities in Mesa Verde National Park.

Fire History and Fire Effects

Our study of fire history and fire effects at Mesa Verde Park had two objectives (Floyd-Hanna and Romme 1993*¹). First was to document the postfire succession patterns following the 1989 fire on Long Mesa. This large fire affected at least three different vegetation types—piñon-juniper, mountain shrub, and Douglas-fir. Three permanent sampling grids containing 291 sampling points were established to document postfire patterns. Percent cover of plants, litter, or bare substrates was recorded in 1991, 1992, and 1994.

The second objective was to develop and apply a method of dating past fires in Mesa Verde (for background see Arno and Sneek 1977; Romme 1982). Because few fire-scarred trees are in Mesa Verde National Park and no unequivocal fire scars were located, we developed a method to age shrubs, which resprout vigorously after fires, using annual ring counts to determine their time of origin. All dominant shrub species were sampled and aged in the historically documented 1934, 1959, 1972, and 1989 burns. Although there is some variability within an individual plant as to the date of shoot emergence, we determined that by selecting the centermost shoot and restricting ourselves to the species *Quercus gambelii* we could determine reliably the known fire date. In

¹Asterisk indicates unpublished material.

1992 and 1994, we applied this method to sample areas of unknown fire history in the northern portion of Mesa Verde National Park.

Results of the postfire succession sampling indicate that perennial resprouting has returned the cover of the northern sector of the burn to a shrub-dominated community much like the prefire community, whereas the southern burned areas (formerly piñon-juniper) are proceeding through a herbaceous phase of succession. The effects of prefire vegetation have been significant, and previous fire history has also affected the postfire successional patterns since the 1989 fire. Noxious weed invasion of the southern end of the fire is becoming an increasing problem.

Using the technique to age shrubs, we successfully identified and mapped prehistoric fires that occurred between 1850 and the 1920's. The median fire return interval varied from 55 years in the west to greater than 130 years in the eastern portion of the sampling area.

Discussion

Effects of Fire on Cultural Resources

These data will allow us to predict the probability of occurrence and the effect that a fire might have on a given type of archaeological site, depending on its location in the landscape. Data layers, each spatially defined for points or extrapolated to areas, will be as follows (Figure):

1. Median fire interval—expressed as a probability of occurrence: high = 0.02 (from a 50-year fire return interval), medium = 0.01 (from a 100-year fire return interval), and low < 0.01 (for fire return intervals greater than 100 years).
2. Vegetation—fuels and fire intensity potential—expressed as high, medium, or low intensity. High potential occurs in Douglas-fir forests or piñon-juniper woodlands, medium potential occurs in sparse piñon-juniper woodlands, and low potential occurs in mountain shrublands and meadows.
3. Significant and vulnerable cultural resources—Although all cultural resources at Mesa Verde have intrinsic value, some are more vulnerable to fires than other. The following classification was

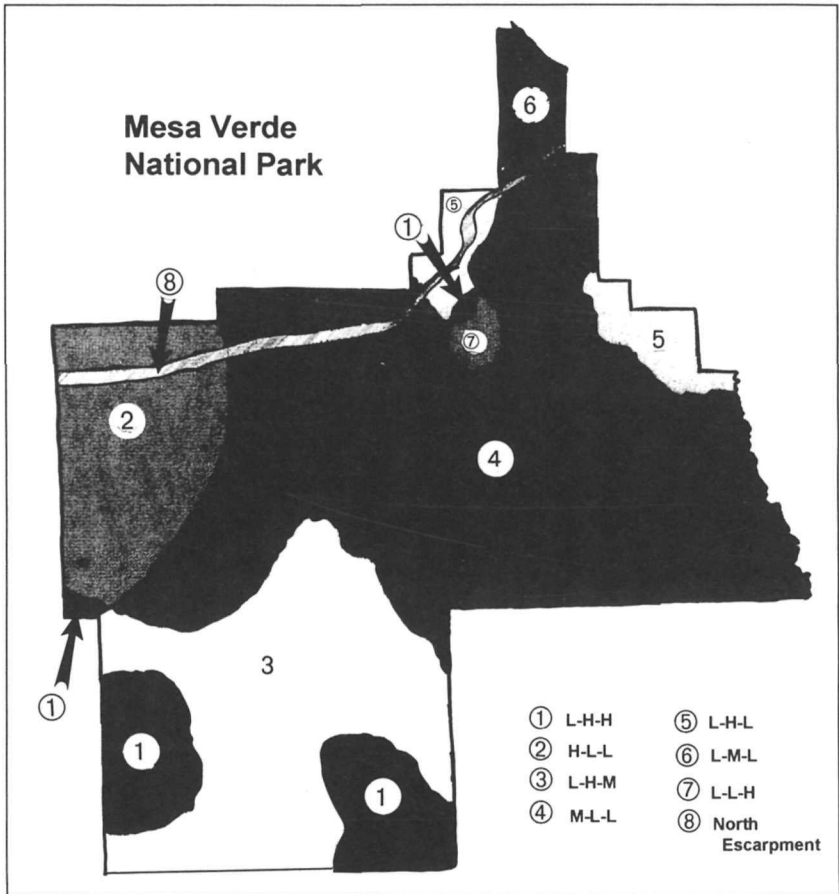


Figure. A fire-risk summary of Mesa Verde National Park showing fire probability–fire intensity–vulnerability of cultural resources; L = low; M = medium; H = high. This is a simplified example of three layers for illustrative purposes.

developed by a group of archaeologists, ecologists, and fire behavior specialists (Romme et al. 1993):

A. Sites with high vulnerability to fire damage:

1. Native American historic structure (e.g., sweat lodges and corrals)
2. Alcoves and cliff dwellings containing organic materials (e.g., packet rat middens, wooden beams, corn cobs)
3. Rock-art panels

4. Culturally-scarred trees
- B. Sites with moderate vulnerability to fire damage:
 1. Euro-American historic structures (e.g., museum and administration buildings)
 2. Lithic scatter and shallow hearth
- C. Sites with low vulnerability to fire damage:
 1. Deeply buried, unexcavated pueblos
 2. Lithic scatter
 3. Check dams

A risk model is being developed by the authors and other National Park Service personnel where these three categories of risk overlap each other (Figure). Although each data layer is not yet complete, we begin to see the pattern of fire risk at Mesa Verde National Park as a mosaic of superimposed risk probabilities. For example, an area with dense fuels and highly valued cultural sites such as Chapin Mesa is at higher risk than an area that has burned frequently and has few archaeological resources (the north end of the park). Many of the most vulnerable sites—and perhaps those on which fire fighting efforts and presuppression-suppression activities such as fuel reduction should focus—are on the southern ends of Chapin and Wetherill mesas. High risk rating occurs there in two categories. Another high risk area is at the head of Prater Canyon where culturally scarred trees and dangerous fuels exist together.

We will continue to improve on the risk assessment for Mesa Verde National Park. The mass and configuration of woody fuels in each vegetation type will be used to predict actual fire behavior under particular sets of weather conditions (e.g., using BEHAVE, a fire behavior model), and this information will add significantly to our modeling potential. Fire history will be determined for the northeastern and southern portions of the park in 1994. Completion of the inventory and mapping of cultural sites in 1994 and combining of these data with the risk model will allow accurate assessment of the vulnerability of archaeological sites to fire.

Acknowledgments

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Public Support for Protecting Grand Canyon Resources

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Abstract. Personnel of the Social Research Laboratory at Northern Arizona University surveyed the adult human population of Arizona to explore public attitudes toward protecting Grand Canyon resources. The telephone survey of 402 adult Arizona residents was conducted between 22 and 28 February 1993. Survey results indicate widespread (74%) support for resource protection at the Grand Canyon. Regardless of the nature of the threat, citizens support a variety of resource protection strategies. The survey also indicates that citizens are willing to incur personal costs to protect Grand Canyon resources.

Key words: Arizona, attitudes, national park, policy, survey.

The Grand Canyon is one of Arizona's most valued resources. Approximately 443.2 km long, 1.6 km deep, and averaging 16 km wide, the Grand Canyon attracts tourists traveling through the Southwest—more than 4 million in 1992. This volume of visitors suggests trouble in the future for such a fragile resource. Arid land, plants, animals, and soils of the canyon are threatened by the sheer number of sightseers that visit each year. Other human endeavors, such as mineral-resource extraction and the generation of electric power, also pose threats.

Early in 1993, personnel of the Social Research Laboratory at Northern Arizona University conducted a survey of Arizona residents' attitudes and opinions concerning the protection of the Grand Canyon resources. The Grand Canyon issue was included as part of the *Arizona Poll*, a biannual statewide public affairs telephone poll conducted by laboratory personnel. The issue was included in the poll as an extension of an ongoing interest among laboratory personnel to ferret out public understanding of trade-offs between protecting the environment and supporting a growing economy. Finally, whereas the Grand Canyon is intensively

studied by biologists, geologists, ecologists, botanists, and other natural scientists, this survey module created an opportunity for social scientists to evaluate public perceptions of the responsibility policymakers have to protect national park resources.

Survey Methods

The *Arizona Poll* was conducted between 22 and 28 February 1993, and 402 adult residents of Arizona were interviewed. The respondents were part of a probability sample selected through random digit dialing techniques to represent the geographic distribution of the Arizona population. Three calls were placed to each sample-point phone number and its backup number. Phone numbers were replaced as needed. The margin of error for the survey was $\pm 5\%$ with a 95% confidence interval.

The survey questions were designed to investigate three specific areas. First, we were interested in gauging usage patterns, and we asked questions about the frequency of Grand Canyon visits and the primary purposes of those visits. Second, the survey examined public concern for protecting Grand Canyon resources. Levels of support for various public policy solutions that attempt to neutralize resource threats were investigated. Third, whereas people can easily establish an intention to resolve abstract public policy problems, we were interested in knowing the extent to which people were willing to endure monetary costs to support these public policies. In more colloquial terms, we wanted to know if people are willing to put their money where their mouths are. Questions were asked in a closed-ended format.

Results

Park Usage

According to the *Arizona Poll*, 76% of Arizonans have visited the Grand Canyon (Fig. 1). One in five Arizonans visited the canyon during calendar year 1992 (Fig. 2). Using 1990 census statistics, this translates into approximately 2 million Arizonans having visited the canyon at some time, and 616,000 Arizonans having visited during 1992.

Age, income, and education are most closely associated with Grand Canyon visits. Whereas almost 9 in 10 older residents (61 years of age and older) have visited the canyon at some time, about 6 in 10 younger residents (18 to 35) have

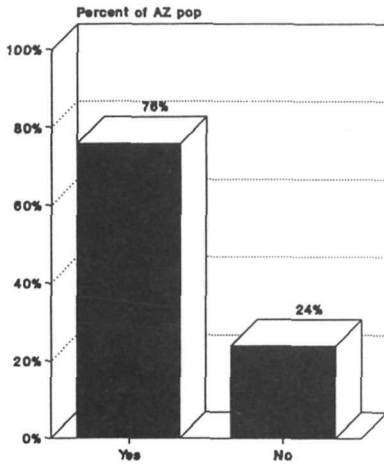


Fig. 1. Percentage of Arizonans who have visited the Grand Canyon at least once.

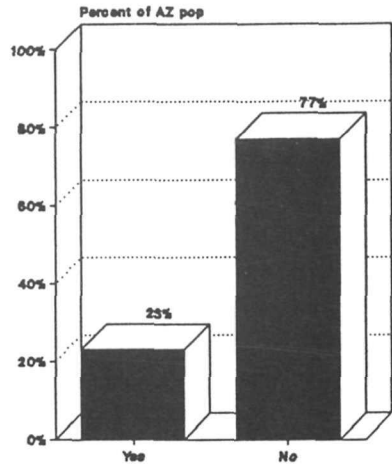


Fig. 2. Percentage of Arizonans who visited the Grand Canyon in 1992.

visited the canyon. Upper income residents (making more than \$60,000 per year) are more likely to have visited the canyon than lower income residents making under \$30,000 a year (87 vs. 68%). Well educated residents are also more likely to have visited the Grand Canyon than less well educated residents. Whereas 85% of residents who graduated from a 4-year college or university have visited the canyon, only 59% of people without a high school degree have visited.

Arizona residents were asked to clarify their primary reason for visiting the Grand Canyon. Three times as many people visit the canyon for sightseeing than to engage in more outdoor types of activities (Fig. 3). Sixty-seven percent of respondents who have visited the canyon say they drive their cars through the park, stop at lookout points, and observe the beauty of the canyon. Twenty-two percent of visitors from Arizona visit to be involved in outdoor activities including hiking, camping, rafting, bird watching, and other, more strenuous ventures. Another 7% say they engage in both sightseeing and outdoor activities.

Support for Policies Designed to Protect Grand Canyon Resources

Respondents to the Arizona Poll were asked to express their support, or lack thereof, for a series of public policies designed to protect Grand Canyon resources. The policy options were in various stages of formulation by national and state policymakers. Whereas some of the policy options discussed have actually been

proposed and debated in various sectors of the federal government, others are currently competing for limited space on the nation's public policy agenda.

Overall, when confronted with a choice between protecting resources of the Grand Canyon at the risk of curbing tourism or protecting tourism and its associated economic benefits even if resources suffer to some extent, most people choose the former (Fig. 4). Three out of four respondents (74%) prefer protecting resources. Only 18% said they prefer protecting tourism. Another 5% said the choices were of equal value. Strong support for protecting Grand Canyon resources was evident, as was support expressed for specific policy options designed to protect Grand Canyon resources.

Respondents were first polled for their reactions to the imposition of federal regulations that prohibit sightseeing planes and helicopters from flying over the most popular portions of the Grand Canyon. Twice as many people agreed with prohibiting flights rather than the option of maintaining or increasing existing flights (Fig. 5). The final numbers for supporting prohibitions on flying over designated areas of the Grand Canyon were 32% very supportive, 32% somewhat supportive, and 31% no support (6% did not know; percentages do not equal 100% because of rounding).

Next, *Arizona Poll* respondents were asked about their level of support for uranium mining in and near Grand Canyon National Park. Mining for uranium has taken place outside the boundaries of Grand Canyon National Park, and resources

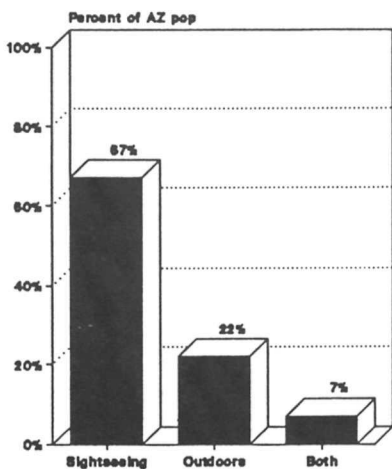


Fig. 3. Percentage of Arizonans involved in sightseeing, hiking, or both during visits to Grand Canyon National Park.

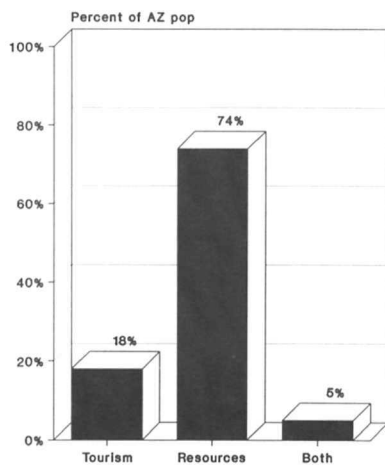


Fig. 4. Percentage of Arizonans who support protecting the resources, promoting tourism, or a compromise between the two.

within the park have been affected. One in five respondents (20%) expressed support for uranium mining in the vicinity of Grand Canyon National Park (Fig. 6). Two-thirds of respondents (65%) did not support uranium mining in the region. Another 15% were unsure of their position on this issue.

Willingness to Incur Personal Costs

Survey researchers often find respondents willing to "do the right thing" when it comes to supporting policies that promote social and economic justice. Support for environmentalism, in particular, generally cuts across age, education, income, and ideological cleavages. One way of moving beyond the ease with which people offer abstract support for environmentally conscious policies is to examine willingness to incur personal costs to promote individual goals. Support for specific policy options must be considered somewhat skeptically if people are simultaneously unwilling to back that support with a personal commitment albeit financial, emotional, or otherwise. To more fairly gauge public support for protecting Grand Canyon resources, the spring 1993 *Arizona Poll* included a series of questions regarding policy options that incur personal costs.

Concerning the Glen Canyon Dam, some argue that sudden and massive flows of water released into the Colorado River from the Glen Canyon Dam affect the Grand Canyon. Some argue that this practice can only be curbed at the expense

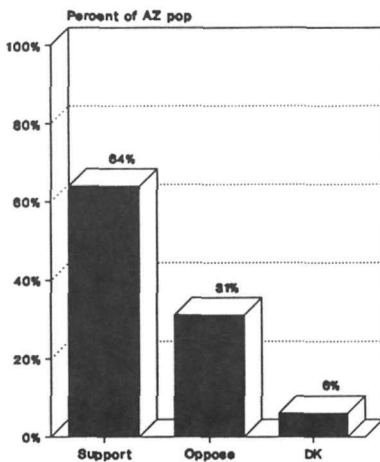


Fig. 5. Percentage of Arizonans for and against regulation of aircraft over the Grand Canyon.

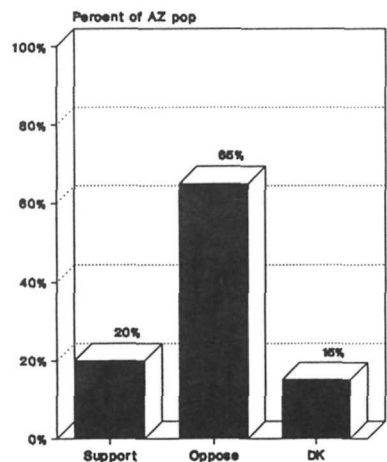


Fig. 6. Percentage of Arizonans for and against regulation of uranium mining in and around the Grand Canyon.

of higher electric rates. Accepting the validity of that proposition, the *Arizona Poll* asked respondents specifically if they would be willing to pay higher electric rates to help curb the sudden flows of water. More than half of the respondents (52%) said they would be willing to pay higher electric rates in the name of protecting Grand Canyon resources (Fig. 7). Another 13% said they would possibly support this policy option. Twenty-nine percent indicated they would not support this policy option.

Air pollution from a variety of sources affects visibility at the Grand Canyon. One of the sources of air pollution is the Navajo generating station near Page, Arizona. Equipment to clean emissions and thereby reduce air pollution is said to cost a substantial sum of money, and this sum would be passed on to consumers through their utility bills. When asked if they would pay higher utility rates to reduce the amount of pollution emitted over the Grand Canyon, a majority (67%) of respondents again said they would support this strategy (Fig. 8). Fifty-six percent of respondents said they would support paying higher utility rates and another 11% said they would possibly support this strategy. Twenty-nine percent of respondents said they would definitely not support paying higher utility rates to reduce air pollution over the Grand Canyon.

In addition, people were asked whether or not they would support restricting the number of vehicles allowed to enter the Grand Canyon National Park at any

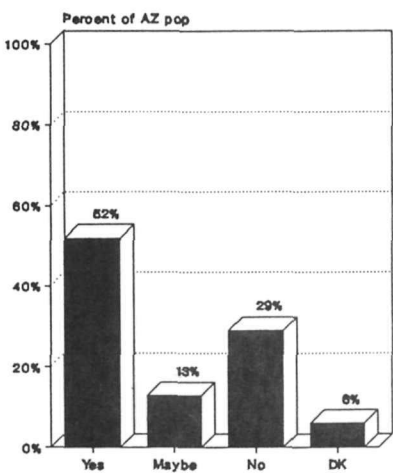


Fig. 7. Percentage of Arizonans willing to pay higher electricity rates to protect Grand Canyon's environment from sudden and massive flows of water.

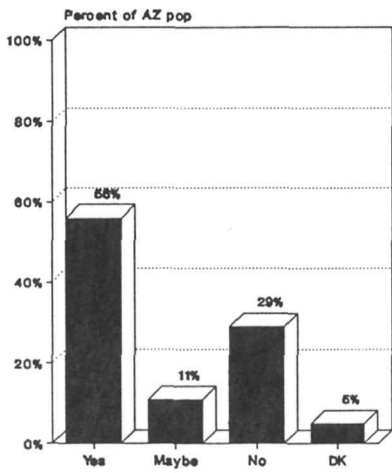


Fig. 8. Percentage of Arizonans willing to pay higher utility rates to help reduce air pollution as it affects the Grand Canyon.

one time. Seventy-eight percent of respondents said yes (Fig. 9). Another 6% answered maybe to this question. Twelve percent opposed the strategy.

Finally, people were asked about their own willingness to pay higher entrance fees if those fees went directly to protecting the Grand Canyon. A majority (79%) of respondents said they would support this option (Fig. 10). Twelve percent of the public said they would not support paying higher entrance fees to protect Grand Canyon resources.

Conclusions

The spring 1993 *Arizona Poll* results make it clear that Arizonans have high regard for Grand Canyon National Park. People in Arizona are familiar with and regularly visit the park and support a wide variety of policy options that are intended to protect the park's resources. Support ranges from a bare majority to a resounding mandate of support. Furthermore, there is much support for policy options that impose personal costs on the Arizona public. This is significant because many policy options designed to protect Grand Canyon resources would inflict a disproportionate burden on residents of Arizona.

The survey results presented here suggest the need for additional attitudinal research of residents of Colorado, Utah, and New Mexico and other citizens

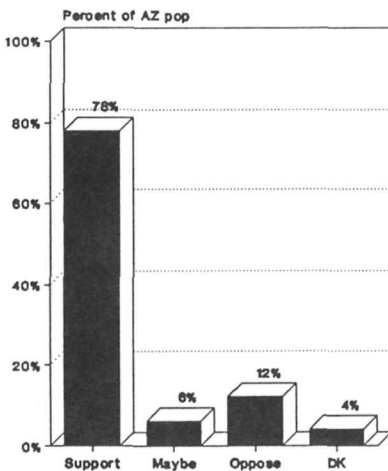


Fig. 9. Percentage of Arizonans willing to restrict vehicular traffic into Grand Canyon National Park to help reduce pollution.

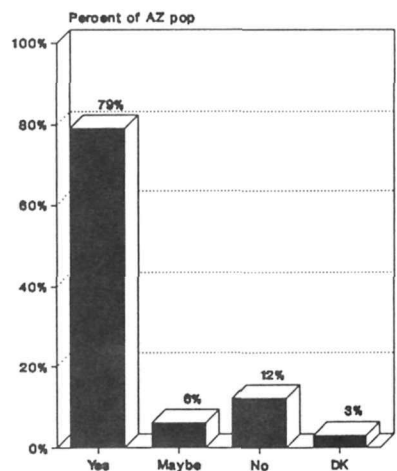


Fig. 10. Percentage of Arizonans willing to pay higher entrance fees at Grand Canyon National Park to help protect resources.

(including tourists) who would be asked to pay a disproportionate share of the costs of protecting the Grand Canyon.

Public support for the Grand Canyon is strong. The Arizona public support is unyielding regardless of whether the costs are borne more generally by economic establishments that thrive on tourist dollars or whether the costs are borne more personally in the form of higher utility rates.

Appendix. Spring 1993 Arizona Poll Questionnaire and Responses ($n = 402$)

As you know, the Grand Canyon is a very popular tourist attraction in Arizona. Have you ever visited the Grand Canyon?

Have visited	76%
Never visited	24
	<u>100%</u>

How many times did you visit the park during calendar year 1992?

Visited park in 1992	23%
Visited park, but not in 1992	53
Never visited park	24
	<u>100%</u>

Do you typically visit the Grand Canyon National Park for sightseeing, or do you get involved in outdoor activities such as hiking, camping, or river rafting?

Sightseeing	67%
Outdoor activities	22
Both	7
Don't know	4
	<u>100%</u>

Controversy exists over some uses of the Grand Canyon's resources, and I would like your opinion on two of these issues. First, how supportive are you of federal regulations that prohibit sightseeing planes and helicopters from flying over the most popular portions of the Grand Canyon? Are you very supportive, somewhat supportive, or not supportive?

Very supportive	32%
Somewhat supportive	32
Not supportive	31
Don't know	6
	<u>101%¹</u>

Second, are you very supportive, somewhat supportive, or not supportive of uranium mining in the region in and around Grand Canyon National Park?

Very supportive	7%
Somewhat supportive	13
Not supportive	65
Don't know	15
	<u>100%</u>

¹Frequencies do not total 100% because of rounding.

Grand Canyon National Park receives between 4 and 5 million visitors each year, and whereas these visitors bring tourist dollars to the region, they also place a considerable strain on park resources such as the environment, historic buildings, and park ruins. Which of the following statements comes closer to your own point of view?

Statement one: Protection of the Grand Canyon’s resources should be given priority, even at the risk of curbing tourism.

Statement two: Tourism should be given priority, even if the resources suffer to some extent.

Protect resources	74%
Protect tourism	18
Both	5
Neither/don’t know	3
	<hr/> 100%

The environment in Grand Canyon National Park is affected by sudden and massive flows of water released from Glen Canyon Dam to keep electricity rates low. Would you be willing to pay higher electricity rates to protect the Grand Canyon’s environment?

Yes	52%
Maybe/it depends	13
No	29
Don’t know	6
	<hr/> 100%

Air pollution from a variety of sources affects visibility at the Grand Canyon. Would you be willing to pay higher utility rates to reduce air pollution that restricts visibility at the Grand Canyon?

Yes	56%
Maybe/it depends	11
No	29
Don’t know	5
	<hr/> 101% ²

To reduce pollution and protect the park’s many resources, would you accept restrictions on the number of vehicles allowed into Grand Canyon National Park on any given day?

Yes	78%
Maybe/it depends	6
No	12
Don’t know	4
	<hr/> 100%

²Frequencies do not total 100% because of rounding.

Would you be willing to pay higher entrance fees when you visit Grand Canyon National Park to protect resources?

Yes	79%
Maybe/it depends	6
No	12
Don't know	3
	<hr/> 100%

Natural Resources



A Preliminary Vegetation Classification for the Colorado Plateau

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Abstract. A new vegetation classification is developed and applied to the Colorado Plateau. The Spence–Romme–Floyd–Hanna–Rowlands (SRFR) classification is loosely based on the Brown–Lowe–Pase system. The SRFR classification is hierarchical and open-ended and can be adapted to any region of North America. The levels in the hierarchy, from broad scale to fine scale, are biogeographic realm, floristic province, climate–elevation zone, plant formation, series, and association. A preliminary classification of the vegetation of the Colorado Plateau is presented to the series level.

Key words: Biome, climate zone, formation, plants, series.

We examine vegetation classification in the region of the Intermountain West known as the Colorado Plateau (Figure) as defined physiographically by

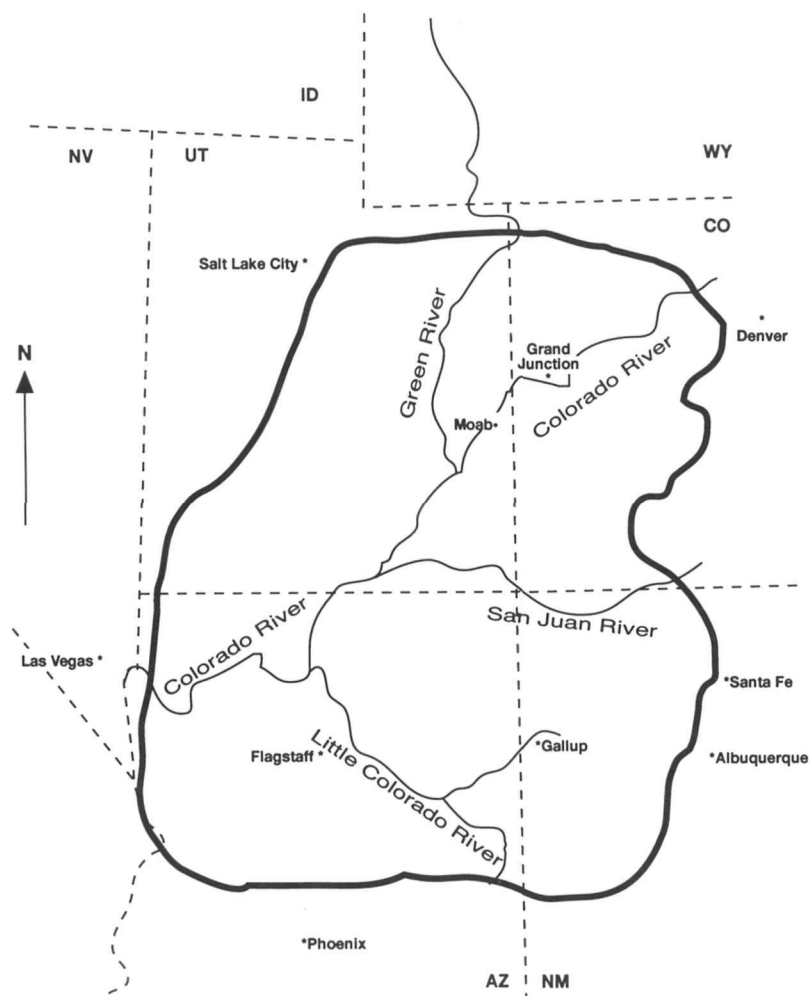


Figure. The Colorado Plateau physiographic province (after Hunt 1967).

Hunt (1967) and floristically by McLaughlin (1989). After a preliminary review of various classifications, some of which have been used or suggested for the region, we concentrate on a new vegetation classification based in part on the Brown–Lowe–Pase (BLP) classification (Brown et al. 1980). We provide a preliminary classification of the vegetation on the Colorado Plateau to the series level and present criteria and methods for classification of field data.

Literature Review

Classification of vegetation can be done at various scales of resolution. The detailed classifications of the U.S. Forest Service habitat and community types represent fine levels of resolution. Forest vegetation is classified by series and habitat–community types (associations) but is not incorporated into an explicit, higher-level classification. Above the level of series, several world and North American vegetation classifications have been applied, or could potentially be applied, to the Colorado Plateau. These include the classifications of Fosberg (1961), Holdrige (1967), Küchler (1964), UNESCO (United Nations Educational, Scientific, and Cultural Organization; 1973), and Brown et al. (1980; Brown 1982). Other, less widely used systems exist as well (Dansereau 1957; Krajina 1965). These classifications vary in the criteria used in their construction. Primary plant criteria include flora, physiognomy (structure), function, dynamics, and biogeography. Some are pure plant-based classifications, whereas others incorporate climate and elevation. Published work using at least three of the above criteria exist for portions of the Colorado Plateau–BLP (Brown et al. 1980), Holdrige (MacMahon and Wieboldt 1979; MacMahon 1988), and Küchler (1964; see also MacMahon 1988; West 1988).

The classification of Fosberg (1961) is simple, hierarchical, and predominantly plant-based. The main features used are dominant life-form (tree, shrub, herb, etc.) and density (spacing; e.g., open, closed). It is cumbersome because of the large numbers (31) of formations. Also, some of the differences between formations seem to be arbitrary (e.g., scrub savanna vs. low savanna).

The floristic classification of Küchler (1964) has been widely applied in the United States (Barbour and Major 1988; West 1988). The classification has many vegetation types (mapping units) and is nonhierarchical. Potential natural vegetation rather than actual vegetation is used. The primary criterion used is floristic (the dominant species present).

Holdrige (1967) developed a classification based on control of life zones by latitude, elevation, and climate. Each unique combination of biotemperature, precipitation, and evapotranspiration describes a particular life zone that is reflected in a particular kind of vegetation. The vegetation terms are largely structural–functional (i.e., steppe, desert scrub). Much climate information is needed to apply this system to a region. MacMahon and Wieboldt (1979; see also MacMahon 1988) have applied the classification to Utah.

The UNESCO system uses a hierarchical classification of primarily physiognomic features, within floristic provinces (UNESCO 1973; Mueller-Dombois and Ellenberg 1974). Forest, woodland, shrub land, and grassland are characteristic formations, with finer groupings detailed based on height, leaf size, and leaf duration. Fewer nonplant features are incorporated than with many systems. This classification is extensively used and is worldwide in scope. A modification of the UNESCO system was developed for use in the United States by Driscoll et al. (1984). Their classification differs from the original in the incorporation of the concept of potential natural vegetation (or climax vegetation), as in the classifications of Küchler and U.S. Forest Service.

The BLP system (Brown 1982) incorporates vegetation, flora, topography, and climate. It is the most explicitly hierarchical and open-ended of the systems detailed. Although used primarily in the western United States, the system may be adaptable to the world level, as noted in Brown et al. (1980). This system was the one chosen for use in National Park Service units on the Colorado Plateau (Spence 1993; Bennett and Kunzmann 1991^{*1}). Spence (1992^{*}) analyzed the structure of the BLP system with reference to the Colorado Plateau.

The BLP system as currently described is inadequate to classify the vegetation of the Colorado Plateau. In particular, several problems were encountered that required solutions before the classification could be applied to the Colorado Plateau. Below, we examine these problems within each of the levels in the BLP hierarchy and discuss our solutions.

Upland–Wetland

Vegetation exists across a continuum of moisture availability, and, although the endpoints may be distinct, any attempt to differentiate wetlands and uplands is arbitrary. Classifying vegetation into these categories is both unnecessary and redundant. The plants, especially at the formation and series levels, already reflect site differences in available moisture. The upland–wetland level is therefore dropped from our classification.

Formation

Formations are traditionally named after the physiognomy of the vegetation (e.g., forest, grassland, etc.). In the BLP system, however, logically unre-

¹Asterisk indicates unpublished material.

lated concepts are mixed. Two formations are climate–landscape terms (tundra and desert land), whereas the rest are true plant structural formations (e.g., forest, grassland). This produces some problems in classification (e.g., grass-dominated vegetation could be classified under both grassland and tundra). We have removed tundra from the system because tundra vegetation can be classified as shrub land, grassland, or forb land.

The BLP formation desert land (sometimes called desert scrub) is redefined and named thorn scrub. Subtropical and tropical arid thorn scrub vegetation, consisting of drought deciduous thorny trees and large succulents, is different in origin, function, and structure from the simpler shrub lands and forests in the southwestern United States and Mexico (cf. Brown 1982).

We added two formations, tall and low-shrub lands, based on height and growth form of shrubs. Tall-shrub land is equivalent to scrub in the BLP system. Low-shrub land was necessary to classify some shrub vegetation on the Colorado Plateau. In the original BLP system, shrub vegetation was classified under either scrub (tall-shrub land) or desert land (desert scrub). Much low shrub vegetation on the Colorado Plateau and elsewhere in western North America, however, is neither scrub nor desert land.

To classify certain communities on the Colorado Plateau, a formation was needed that represented broad-leaved forbs, both annual and perennial. This vegetation included certain subalpine forb communities (very common in the central-northern Rockies) dominated by *Lupinus*, *Mertensia*, various Asteraceae, *Thalictrum*, etc., and in which grasses are generally unimportant. Also, some badland communities on heavy clays and shales are dominated by annual species of *Atriplex*, *Eriogonum*, and *Phacelia* (nomenclature follows Welsh et al. 1993). We added a forb land formation to the classification. Formations are defined below.

Forest and woodland—Vegetation dominated by trees (usually or potentially 10 m high). Forests have closed (interlocking or touching) canopies whereas woodlands have open canopies.

Thorn scrub (desert scrub or desert land of BLP in part)—Tropical–subtropical arid land formation dominated by a mix of microphyllous trees and shrubs, and tall succulents, often spiny or thorny (e.g., Sonoran Desert).

Savanna—Tropical–subtropical formation of grasses with an open canopy of widely spaced trees, dominated by tall seasonal grass layer. Savanna is not found on the Colorado Plateau.

Tall-shrub land (scrub of BLP)—Vegetation dominated by shrubs, mostly less than 5 m high, usually multistemmed, open (shrub land or scrub), or densely interlocked (thickets). Tall-shrub land is traditionally called scrub in many parts of the world.

Low-shrub land (desert scrub or desert land of BLP in part)—Vegetation dominated by woody, single, or multistemmed dwarf or mat shrubs that are generally less than 1 m high.

Grassland—Vegetation dominated by perennial or annual species of grasses.

Marshland—Vegetation dominated by herbaceous obligate wetland species of sedges, rushes, and cattails.

Forb land—Vegetation dominated by herbaceous perennial and annual species of broad-leaved dicots, ferns, or nongraminoid monocots (e.g., lilies, irises).

Aquatic—Vegetation dominated by herbaceous species that are supported by water and are either rooted with their structures underwater or floating on the surface or plants free-floating on the surface.

Cryptogamic—Vegetation dominated by cryptogams, either lichens or bryophytes (includes *Sphagnum* bogs).

Nival—Permanent snow and ice with some exposed rock, dominated by cryptogams, with vascular plants rare. Nival probably is not found on the Colorado Plateau, except perhaps in the La Sal Mountains.

Barren—Areas essentially bare of vegetation. These can include salt barrens, shale barrens, or slickrock. Plants can be present but only as scattered individuals with low cover.

Climate Zone

The climate zonation used in BLP is difficult to apply to the Colorado Plateau because it does not properly reflect the complexity of climate-controlled vegetation zonation. Two aspects of climate need to be considered, regional climate and orographic effects. For regional climate, Walter (1985) provides a useful classification with two zonobiomes in the region; subtropical-arid and arid-temperate with cold winters. Although there are latitudinal and longitudinal differences in climate on the Colorado Plateau at similar elevations, orographic effects predominate. The division of BLP zones into boreal-arctic, cold and warm temperate, and subtropical is largely controlled by elevation on the Colorado Plateau and in the southwestern United States in general. We have redrawn the

climate zones as elevationally controlled zones, based largely on traditional zonation schemes. These zones are shown in Table 1 with defining and controlling factors identified. Climate zonation remains difficult to use because it can vary locally depending on aspect and topography. We have drawn zonal boundaries broadly and provide vegetation criteria (Tables 2 and 3) that help identify each zone. As climate data are scarce for much of the Colorado Plateau, no attempt is made here to provide climatic definitions and characteristics for each zone. Some zonal boundaries remain poorly understood (e.g., the montane–subalpine boundary). Also, riparian vegetation, because it consists of linear strips cutting across zones, will be more difficult to place into zones than most other kinds of vegetation. Future work addressing these problems, and also in providing a climatic characterization for each zone, is needed.

We recognize that vegetation is rarely found as discrete elevational bands on the Colorado Plateau. An alternative system could be envisioned in which landscape elements (based on topography, elevation, soils, etc.) are the building blocks of a vegetation classification. Such a system, however, would be far more difficult to use because of its increased complexity. Climate–elevation zones, although less realistic, provide a necessary tradeoff between accuracy of vegetation classification and practicality.

Biome

Many definitions of biomes exist, but a standard is “a grouping of terrestrial ecosystems on a given continent that are similar in vegetation structure or physi-

Table 1. Elevational limits and controlling factors of climate–elevation zones defined for the Colorado Plateau.

Zone	Elevational limits (m)	Controlling factors
Alpine	Upper: 3,862 Lower: 3,440–3,600	Highest point on plateau Snowpack, cold air drainage
Subalpine	Upper: 3,440–3,600 Lower: 2,750–3,050	50° C July isotherm, wind Fire?
Montane	Upper: 2,700–3,100 Lower: 1,900–2,700	Winter snow, temperature? Drought (arid–humid boundary)
Cold–Temperate lowland	Upper: 1,900–2,200 Lower: 900–1,200	Competition, winter temperatures Summer temperatures, drought
Warm–Temperate lowland	Upper: 900–1,500	Winter temperatures

Table 2. Characteristic vegetation features and species on upland or dry sites for each climate–elevation zone on the Colorado Plateau.

Zone	Vegetation	Characteristic species
Alpine	Meadows	<i>Geum rossii</i>
	Fell-field	<i>Erigeron vagus</i> <i>Silene acaulis</i>
Subalpine	Coniferous forest	<i>Abies lasiocarpa</i> ^a <i>Picea engelmannii</i>
Montane	Coniferous forest	<i>Abies concolor</i>
	Montane scrub	<i>Pinus ponderosa</i> <i>Pseudotsuga menziesii</i> <i>Acer grandidentatum</i> <i>Artemisia nova</i> <i>Cercocarpus ledifolius</i> <i>Juniperus scopulorum</i> <i>Quercus gambelii</i>
Cold–Temperate lowland	Pinyon–Juniper woodland	<i>Juniperus osteosperma</i>
	Semiarid shrub land	<i>Pinus edulis</i>
	Galleta–three awn steppe	<i>Atriplex confertifolia</i> <i>Atriplex corrugata</i> <i>Coleogyne ramosissima</i> <i>Hilaria jamesii</i> <i>Stipa comata</i> <i>Stipa hymenoides</i>
Warm–Temperate lowland ^b	Desert scrub	<i>Acacia greggii</i> <i>Encelia farinosa</i> <i>Ferrocactus</i> sp.
		<i>Fouquieria splendens</i> <i>Larrea divaricata</i> <i>Yucca brevifolia</i>

^a*Abies bifolia* in Flora of North America Editorial Committee 1993.
^bThis zone is not present on the Colorado Plateau per se. Some component species, however, do exist in closely adjacent areas, such as in extreme western Grand Canyon National Park, and penetrate some distance (Havas Creek) into the plateau along the Colorado River corridor.

ogonomy, in the major features of environment to which this structure is a response, and in some characteristics of their animal communities” (Whittaker 1975:135). Whittaker’s list of North American biomes is instructive; broad-leaved deciduous forest, grassland, tundra, coniferous forest, etc. Clearly, these are close to the definition of the formation in the BLP system, differing largely by including animals in the biome and by incorporating some geographic restrictions and associated climate (e.g., temperate). In the BLP system, the biome seems to be

Table 3. Characteristic vegetation features and species in wetland sites for each zone on the Colorado Plateau.

Zone	Vegetation	Characteristic species
Alpine	No data available	No data available
Subalpine	Fen, carr ^a	<i>Salix glauca</i>
Montane	Marshland	<i>Populus angustifolia</i>
	Riparian forest and scrub	<i>Alnus tenuifolia</i>
	Aspen	<i>Cornus sericea</i>
		<i>Salix boothii</i>
		<i>Salix geyeriana</i>
Cold-Temperate	Marshland	<i>Acer negundo</i>
lowland	Riparian forest and scrub	<i>Populus fremontii</i>
	Hanging garden	<i>Salix exigua</i>
		<i>Cirsium rydbergii</i>
		<i>Mimulus eastwoodiae</i>
		<i>Primula specuicola</i>
Warm-Temperate	Mesquite bosque	<i>Prosopis glandulosa</i>
lowland	Riparian forest and scrub	<i>Baccharis sarothroides</i>
		<i>Fraxinus pennsylvanica</i>
		<i>Juglans major</i>
		<i>Platanus wrightii</i>

^aLow-lying wetland willow complexes at high (2,500 m) elevations.

more narrowly defined (compare *Rocky Mountain subalpine conifer forest* [BLP] with *temperate evergreen forest* [Whittaker]).

The last 30 years of paleoecological research (Betancourt et al. 1990) in the southwest has completely invalidated the Clements–Weaver biome concept (i.e., a coevolved vegetation unit with a center of origin migrating in unison). Because of the problems with definition of the biome and the unfortunate connotations of the name itself, we have completely revised this level. Rather than use the biome concept, we use floristic provinces. We are impressed by the statistically robust and intensive floristic analyses of McLaughlin (1986, 1989, 1992). Our classification uses his subprovinces (but names them provinces for convenience). McLaughlin recognized a distinct Colorado Plateau unit, which he named the Colorado Plateau subprovince of the Intermountain Province. The province level in our new classification logically follows biogeographic realm in the hierarchy, so it is placed second. We prefer to use McLaughlin's subprovinces rather than provinces because the former are more likely to conform to climatic, physiographic, or geological classifications in use in the west (Hunt 1967). Also, any extensions of McLaughlin's system to other parts of North

America could produce changes in the higher levels in his hierarchy. His subprovinces comprise one of the fundamental building blocks of his system and should remain unaffected by more extensive analysis.

Series

Series is a widely used term throughout the western United States, as used by the U.S. Forest Service in their extensive vegetation classifications. A series is defined and named by the dominant species in a community, or codominant species if more than one is present. Currently, no set of rules has been formulated for defining a series. We incorporated published series from a wide variety of sources into our classification.

Association

Associations have traditionally been difficult to define, and we do not attempt to provide a definition here. A consistent method of naming them is available, however (e.g., U.S. Forest Service). The name is based on the dominants in all recognizable important strata. For example, under ponderosa pine series are the following associations (community-habitat types sensu U.S. Forest Service): *Pinus ponderosa*–*Muhlenbergia virescens*, *P. ponderosa*–*Festuca arizonica*, *P. ponderosa*–*Arctostaphylos pungens*, etc. (Hanks et al. 1983). Although the emphasis on classifying Colorado Plateau vegetation is not on the association, this method of recognizing and naming associations is probably the best system to use to prevent confusion with other work and to be consistent with classifications of the U.S. Forest Service.

Spence–Romme–Floyd–Hanna–Rowlands Classification

The classification presented here differs in several respects from the BLP classification, although they share strong philosophical and logical similarities. We believe that it is inappropriate to continue to use the BLP name, and have used the first letters of our surnames (Spence, Romme, Floyd–Hanna, and Rowlands; SRFR) to name the new classification.

The hierarchical structure of the SRFR system follows. Each letter in the series ABCDEF.GHIJ is associated with one of the six levels in the hierarchy:

- A = Biogeographic realm (1 for Nearctic realm; not shown in classification)
- BC = Floristic province (first number in sequence is 01 because more than 10 provinces exist)
- D = Climate–elevation zone
- EF = Plant formation
- GH = Series (first two numbers to the right of decimal)
- IJ = Association

In actual named vegetation, the letters are replaced by numbers, hence the sequence 101201.01 represents the *Picea engelmannii*–*Abies lasiocarpa* series in the subalpine zone, forest and woodland formation, on the Colorado Plateau Province in the Nearctic realm (no association is indicated).

A preliminary classification of the Colorado Plateau to the series level is presented in Table 4. This listing highlights the many gaps in our knowledge of the vegetation on the Colorado Plateau. In particular, high-elevation, treeless vegetation and wetlands are poorly understood.

How to Identify Vegetation

Once vegetation data are collected and analyzed (Rowlands 1994), a series level determination can usually be made. The dominant or codominants (i.e., two or more dominants) are used to define the series. Placement of the series into the classification is usually routine after this stage. Three questions need to be answered.

1. What is the floristic province?

Some problems may arise if the site in question is on a province boundary. The best solution is to determine the floristic affinities of the subdominant herbaceous flora—dominant plant species, especially woody species, tend to be widespread and often do not conform to floristic provinces—and whether the area is considered geological or physiographical.

2. In which climate–elevation zone does the vegetation exist?

Because climatic zonation is highly variable from area to area, problems will be encountered in making a decision. We attempted to provide boundaries that relate to biologically important limits, such as treeline, the arid–humid boundary, frost-free climates, etc. Many plant species, particularly the dominants, are limited in distribution by some aspect of climate. Many subdominant species of flora (as well as fauna) will also conform to the limits defined by the

Table 4. Preliminary Spence–Romme–Floyd–Hanna–Rowlands (SRFR) vegetation classification for the Colorado Plateau.^a

01 Colorado Plateau Province (0 not listed below)

11 Alpine zone (3,440 m)

1101 Grassland formation

1101.01 *Carex elynoides* series

1101.02 *Festuca ovina* series

1101.03

1102 Forb land formation

1102.01 *Erigeron vagus* series

1102.02 *Geum rossii* series

1102.03

1103 Low-shrub land formation

1103.01

1104 Marshland formation

1104.01

1105 Aquatic formation

1105.01

1106 Barren formation

12 Subalpine zone (2,750–3,600 m)

1201 Forest and woodland formation

1201.01 *Picea engelmannii*–*Abies lasiocarpa* series

1201.02 *Picea engelmannii* series

1201.03 *Abies lasiocarpa* series

1201.04 *Populus tremuloides* series

1201.05 *Pinus longaeva* series

1201.06

1202 Tall-shrub land formation

1202.01

1203 Low-shrub land formation

1203.01 *Juniperus communis* series

1203.02 *Ribes montigenum* series

1203.03 *Potentilla fruticosa* series

1203.04 *Salix wolfii* series

1203.05

1204 Grassland formation

1204.01 *Festuca ovina* series

1204.02 *Festuca thurberi* series

1204.03

1205 Marshland formation

1205.01

1206 Forb land formation

1206.01

1207 Aquatic formation

1207.01

1208 Barren formation

1208.01

Table 4. *Continued.*

01 Colorado Plateau Province (0 not listed below)

13 Montane zone (1,900–3,100 m)

1301 Forest and woodland formation

- 1301.01 *Pseudotsuga menziesii* series
- 1301.02 *Abies concolor* series
- 1301.03 *Pinus ponderosa* series
- 1301.04 *Pinus flexilis* series
- 1301.05 *Populus tremuloides* series
- 1301.06 *Juniperus scopulorum* series
- 1301.07 *Picea pungens* series
- 1301.08 *Acer grandidentatum* series
- 1301.09

1302 Tall-shrub land formation

- 1302.01 *Cercocarpus ledifolius* series
- 1302.02 *Quercus gambelii* series
- 1302.03 *Amelanchier utahensis* series
- 1302.04 *Robinia neomexicana* series
- 1302.05 *Chrysothamnus nauseosus* series
- 1302.06 *Betula occidentalis* series
- 1302.07 *Alnus tenuifolia* series
- 1302.08 *Cornus stolonifera* series
- 1302.09 *Salix boothii* series
- 1302.10 *Salix bebbiana* series
- 1302.11

1303 Low-shrub land formation

- 1303.01 *Artemisia nova* series
- 1303.02 *Purshia tridentata* series
- 1303.03 *Arctostaphylos patula* series
- 1303.04

1304 Grassland formation

- 1304.01 *Poa fendleriana* series
- 1304.02

1305 Marshland formation

- 1305.01 *Eleocharis palustris* series
- 1305.02

1306 Forb land formation

- 1306.01 *Pteridium aquilinum* series
- 1306.02 *Eriogonum panguicense* series
- 1306.03

1307 Aquatic formation

- 1307.01

1308 Barren formation

14 Cold-Temperate lowland zone (900–2,200 m)

1401 Forest and woodland formation

- 1401.01 *Pinus edulis* series
- 1401.02 *Juniperus osteosperma* series
- 1401.03 *Juniperus monosperma* series

Table 4. *Continued.*

01 Colorado Plateau Province (0 not listed below)

1401.04	<i>Populus angustifolia</i> series
1401.05	<i>Populus fremontii</i> series
1401.06	<i>Salix goodingii</i> series
1401.07	<i>Acer negundo</i> series
1401.08	<i>Elaeagnus angustifolia</i> series
1401.09	<i>Ostrya knowltonii</i> series
1401.10	<i>Rhamnus betulifolia</i> series
1401.11	<i>Pinus edulis</i> – <i>Juniperus osteosperma</i> series
1401.12	
1402	Tall-shrub land formation
1402.01	<i>Artemisia tridentata</i> series
1402.02	<i>Quercus gambelii</i> series
1402.03	<i>Sarcobatus vermiculatus</i> series
1402.04	<i>Tamarix ramosissima</i> series
1402.05	<i>Salix exigua</i> series
1402.06	<i>Amelanchier utahensis</i> series
1402.07	<i>Salix lutea</i> series
1402.08	<i>Salix goodingii</i> series
1402.09	<i>Atriplex canescens</i> series
1402.10	<i>Cerotoides lanata</i> series
1402.11	
1403	Low-shrub land formation
1403.01	<i>Coleogyne ramosissima</i> series
1403.02	<i>Artemisia spinescens</i> series
1403.03	<i>Artemisia pygmaea</i> series
1403.04	<i>Artemisia filifolia</i> series
1403.05	<i>Grayia spinosa</i> series
1403.06	<i>Atriplex confertifolia</i> series
1403.07	<i>Zuckia brandegei</i> series
1403.08	<i>Atriplex corrugata</i> series
1403.09	<i>Atriplex gardneri</i> series
1403.10	<i>Ephedra viridis</i> series
1403.11	<i>Ephedra cutleri</i> series
1403.12	<i>Poliomintha incana</i> series
1403.13	<i>Gutierrezia sarothrae</i> series
1403.14	<i>Vanclevea stylosa</i> series
1403.15	<i>Eriogonum corymbosum</i> series
1403.16	<i>Fallugia paradoxa</i> series
1403.17	<i>Quercus harvardii-undulata</i> series
1403.18	<i>Parryella filifolia</i> series
1403.19	<i>Toxicodendron rydbergii</i> series
1403.20	
1404	Grassland formation
1404.01	<i>Hilaria jamesii</i> – <i>Aristida purpurea</i> series
1404.02	<i>Stipa hymenoides</i> series
1404.03	<i>Stipa comata</i> series

Table 4. *Continued.*

01 Colorado Plateau Province (0 not listed below)

1404.04	<i>Hilaria jamesii</i> series
1404.05	<i>Bouteloua gracilis</i> series
1404.06	<i>Sporobolus cryptandrus</i> – <i>Sporobolus contractus</i> series
1404.07	<i>Sporobolus airoides</i> series
1404.08	<i>Bromus tectorum</i> series
1404.09	<i>Distichlis spicata</i> series
1404.10	<i>Elymus salinus</i> series
1404.11	<i>Calamovilfa gigantea</i> series
1404.12	<i>Phragmites australis</i> series
1404.13	<i>Panicum virgatum</i> series
1404.14	
1405	Marshland formation
1405.01	<i>Typha latifolia</i> series
1405.02	<i>Typha domingensis</i> series
1405.03	<i>Scirpus pungens</i> series
1405.04	<i>Scirpus validus</i> series
1405.05	<i>Scirpus acutus</i> series
1405.06	<i>Juncus arcticus</i> series
1405.07	<i>Eleocharis palustris</i> series
1405.08	<i>Cyperus erythrorhizos</i> series
1405.09	<i>Carex nebrascensis</i> series
1405.10	<i>Juncus arcticus</i> – <i>Equisetum hyemale</i> series
1405.11	
1406	Forb land formation
1406.01	<i>Adiantum capillus-veneris</i> series
1406.02	<i>Platyschukhria integrifolia</i> – <i>Cleome palmeriana</i> series
1406.03	<i>Eriogonum flexum</i> series
1406.04	<i>Eriogonum inflatum</i> series
1406.05	<i>Salsola australis</i> series
1406.06	<i>Melilotus officinalis</i> series
1406.07	<i>Solidago occidentalis</i> series
1406.08	<i>Oxytenia acerosa</i> series
1406.09	<i>Solidago canadensis</i> series
1406.10	
1407	Aquatic formation
1407.01	<i>Zanichellia palustris</i> series
1407.02	
1408	Barren formation

^aNumbers without designated series are available for the incorporation of new series.

dominant species. This observation forms the basis for life zone classifications such as that of C. H. Merriam. Information helpful in determining the proper climate–elevation zone can be found in Tables 1, 2, and 3. Zonal boundaries are broadly drawn to reflect real differences in climate, available flora, and history in different parts of the Colorado Plateau.

3. To which plant formation does the series belong?

Generally this is easy to do, but certain exceptions do exist on the Colorado Plateau. Mixed shrub–grass vegetation, traditionally called shrub–steppe in the United States, may be difficult to place. If shrubs dominate in terms of cover and biomass, the series can be classified as a shrub land. If shrubs are less common than the grasses, however, the best placement is grassland. When the mix seems to be even, a new formation, shrub–steppe, may be needed.

Discussion

We have defined the vegetational Colorado Plateau as those areas on the geologic–physiographic Colorado Plateau above the elevation of the hot desert flora as defined principally by the presence of creosote bush, *Larrea divaricata*, although other species could be named (Tables 2 and 3). Along the southwestern and southern edges, this elevation varies from 900 to 1,500 m. Boundaries elsewhere are more difficult to determine. To the west and northwest, the western slope of the High Plateau section of the Colorado Plateau grades into the Great Basin. The high Uinta Mountains define the northern edge. The eastern and southeastern edges form an indefinite and complex boundary with the central and southern Rocky Mountains. The White Mountains and Mogollon Rim form the boundary between the Colorado Plateau and the Madrean and Sonoran regions to the south. Classification of vegetation into surrounding McLaughlin subprovinces (provinces in SRFR), including the Great Basin, central Rocky Mountains, southern Rocky Mountains, Madrean, and Sonoran, may be more appropriate depending on where the vegetation work is being accomplished.

Because the classification of the region into floristic groups is relatively new, little work has been done on delimiting floristic province boundaries. We believe the work of McLaughlin (1992) could provide a useful starting point for fruitful research into the nature of floristic boundaries and the evolution and dispersal of floristic elements. We emphasize that the floristic Colorado Plateau

is not the same as a Colorado Plateau floristic element. The former is defined by boundaries, albeit not well understood yet; the latter consists of species that presumably originated on the plateau but in many instances extend into surrounding provinces (McLaughlin 1986, 1989). Furthermore, provinces can be fragmented, with more or less intact outlier regions embedded within other provinces. McLaughlin (1992) illustrates this with his central Rocky Mountain subprovince, which includes a large disjunct fragment in northeastern Nevada surrounded by McLaughlin's Great Basin subprovince. On the Colorado Plateau, a likely candidate for disjunction is the La Sal Mountains, which harbor at higher elevations a large number of species characteristic of the central Rocky Mountains.

The problem of disjuncts also exists at the climate–elevation level in the classification. Relict patches of vegetation exist on the Colorado Plateau well below or above their usual elevational limits. For example, patches of Douglas-fir (*Pseudotsuga menziesii*) are present at elevations as low as 1,500 m, well within the cold–temperate lowland zone. Vegetationally, these patches are related in composition to higher-elevation montane forests. Although not yet investigated, it is probable that these patches are present in microclimates that mimic climates at higher elevations. We suggest that classification of relict communities like these should reflect their origins. In the instance of the Douglas-fir relicts, we would classify them as montane rather than cold–temperate lowland communities.

Because the classification name (e.g., series, formation names) does not necessarily convey all information about the vegetation, we suggest a series of descriptors that could provide additional information. First, we recommend adding data on the Raunkiaer life-form system (Raunkiaer 1934) for the species in the vegetation classification (shown in Table 5). This system provides information on the functional responses of plant species to climate and has been widely used throughout the world. For example, the *Pinus ponderosa* series (Table 4, 1301.03) is dominated by megaphanerophytes (Pg) and mesophanerophytes (Pm), whereas the *Artemisia tridentata* series (1402.01) is dominated by nanophanerophytes (Pn) and hemicryptophytes (H). Combined with data on leaf duration and size (for at least the dominants), vegetation cover, landforms, soils, and other physical data, a much clearer picture of the vegetation in question can be obtained.

Several aspects of vegetation classification will need to be addressed in the future. First, a standardized list of the flora with identification keys needs to

Table 5. Suggested Raunkiaer life form classification (Raunkiaer 1934) for use with the SRFR vegetation classification.^a

Life form	Code ^b	Characteristics
Vascular plants		
Megaphanerophytes	Pg	Buds 25 m, large trees
Mesophanerophyte	Pm	Buds 10–25 m, trees
Microphanerophyte	Pp	Buds 2–10 m, trees, tall shrubs
Nanophanerophyte	Pn	Buds 0.5–2 m, shrubs
Chamaephyte	Ch	Buds 0–0.5 m, dwarf shrubs
Hemicryptophyte	H	Buds at ground level, forbs, graminoids
Geophyte	G	Buds buried, bulb forbs
Therophyte	Th	Annuals
Stem succulent ^c	SS	Cacti
Liana	Li	Supported by other plants, rooted in ground
Epiphyte	E	On other plants, not rooted in ground
Parasite	Pa	Parasitic or saprophytic on other plants
Hydrophyte	HH	Structures supported by water
Nonvascular plants^d		
Lichens	L	Lichens (composite alga–fungus)
Bryophyte	Br	Mosses, liverworts, hornworts
Algae	Al	Mostly aquatic, includes <i>Chara</i>

^aRaunkiaer's classification system is based on the position of the regenerative parts (perennating buds) relative to the substrate.

^bWith some modification, the codes are based on Dansereau (1957).

^cLeaf succulents are included as either chamaephytes or hemicryptophytes by some authors (Mueller-Dombois and Ellenberg 1974).

^dNonvascular plants are generally classified into one or more of the above categories as specialized members. For example, Mueller-Dombois and Ellenberg (1974) classify foliose lichens as thallo-hemicryptophytes using the abbreviation Li H fol. For our classification we recommend a simpler system using L, Br, and Al. The interested reader looking for a more intensive life-form classification system should consult Mueller-Dombois and Ellenberg (1974).

be developed for the Colorado Plateau. Second, objective ways of classifying complex vegetation data at the series and association levels needs to be implemented. We recommend the use of relatively objective multivariate classification and ordination techniques (Causton 1988) for vegetation classification work at or below the series level. Such techniques are readily available as commercial software and take the form of either divisive; polythetic (e.g., TWINSpan, developed by Hill 1979); or various agglomerative, polythetic methods (e.g. the several forms of cluster analysis described in Pielou 1984). Finally, until research on floristic boundaries is completed, a set of rough guidelines based on characteristic vegetation series or floristic criteria will need

to be developed so these boundaries can be determined for classification of vegetation.

The SRFR classification should be adaptable to any floristic region in North America, although it may not work at all levels in tropical vegetation (series level classifications are difficult and often impossible to use in the species-rich tropics). Although McLaughlin analyzed the flora of only the western United States, his techniques and philosophy may be extended to other parts of the country. Currently, enough vegetation work has been done in the United States and Canada to formulate climate–elevation zonation for most areas. As our classification is open-ended and flexible, it can be modified to fit most situations that we can foresee elsewhere in North America. Currently, we are adapting the SRFR classification to the central Rocky Mountain region and the Sonoran Desert.

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Level of Endemism in Hanging Gardens of the Colorado Plateau

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Abstract. Infrequent seeps and springs along xeric canyon walls of the Colorado Plateau support hydrophytic habitats called hanging gardens. We surveyed the level of endemism among vascular plant taxa of hanging gardens in three National Park Service units: Zion and Capitol Reef national parks and the Glen Canyon National Recreation Area. The number of hanging-garden endemics per hanging garden was significantly higher in the Glen Canyon National Recreation Area than in Zion National Park or in Capitol Reef National Park ($F = 8.640$, $P = 0.001$). This higher level of endemism was not because of larger hanging gardens or higher richness of vascular plant species per garden. Community importance of endemic plant taxa as measured by species canopy coverage has a range of 0–52%. The canopy coverage of hanging-garden endemics did not differ among the three parks ($F = 1.740$, $P = 0.189$).

Key words: Capitol Reef, Glen Canyon, species richness, vegetation community, Zion.

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Hanging gardens are small, hydrophytic, herbaceous plant communities (Malanson 1980; Welsh and Toft 1981; Tuhy and MacMahon 1988^{*3}; Welsh 1989; Heil et al. 1991*) on canyon walls in the entrenched drainage system of the Colorado Plateau. The microclimate at larger hanging gardens contrasts sharply with the surrounding high desert—water is abundant, soils are moist, and canyon walls offer periodic shade. Several plant taxa that are endemic to hanging gardens have been found in Utah and Colorado (Loope 1977; Welsh and Toft 1981; Welsh 1989; Naumann 1990*). We compared levels of endemism in vascular plant taxa among hanging gardens in Zion National Park (ZION), Glen Canyon National Recreation Area (GLCA), and Capitol Reef National Park (CARE).

Methods

Hanging-garden vegetation was sampled for species richness and the species community importance in Zion National Park, Capitol Reef National Park, and Glen Canyon National Recreation Area during the summers of 1991 and 1992. We define a hanging-garden community as an area that is dominated by hydrophytic, herbaceous vegetation on canyon walls at perennial, broad-based seeps or springs that originate from a sandstone aquifer. Key physical parameters are permanently wet rock surfaces or subirrigated colluvial soils. Woody plants occasionally become established on drier islands and are often in the mesophytic ecotone around a hanging garden. The boundary with surrounding desert vegetation is where the more mesic-xeric vegetation begins. The boundary with the riparian community is placed where colluvial soils stop and alluvial soils begin. Colluvial soils develop on deposits that accumulated by gravitational downslope movement, whereas alluvial soils develop on water-transported deposits as in a floodplain (Brady 1974).

Vegetation was systematically sampled (Krebs 1989; Manly 1989*) with 20- × 50-cm quadrat frames to estimate herbaceous canopy cover by species. The major axis of the hanging garden was divided into 10 equal segments. Beginning with a random start in the initial segment and systematically thereafter, widths were measured and a second random point chosen (Manly 1989*) to determine placement of the lower left corner of the sampling frame. Edge

³Asterisk indicates unpublished material.

quadrats were proportionally weighted to include only the portion inside the hanging garden. Hanging-garden area was calculated from the width and major axis measurements. The Daubenmire method (1959) was used for visually estimating and analyzing the following canopy cover classes: 1 = 0–5%, 2 = 5–25%, 3 = 25–50%, 4 = 50–75%, 5 = 75–95%, 6 = 95–100%. Voucher specimens of each species were collected and deposited at the Rocky Mountain Herbarium of the University of Wyoming (Laramie). Nomenclature followed Welsh et al. (1993). Plant species distributions were taken from Weber (1987), Albee et al. (1988), Atwood et al. (1991), and Welsh et al. (1993). Colorado Plateau endemic taxa included species found in other habitats as well as on hanging gardens. Hanging-garden endemics are restricted to that habitat, or nearly so. Our data were analyzed with the least-squares ANOVA program MGLH in SYSTAT (1992), which adjusts mean square and probability for unbalanced designs. Hanging-garden area data were log transformed and canopy-coverage data were arcsine transformed before analysis (Zar 1974).

Results

In 48 hanging gardens, we found 144 species, of which 11 were taxa endemic to the Colorado Plateau and 7 were taxa endemic to hanging gardens (Table 1). The level of plant endemism differed among the three parks (Tables 2, 3, and 4): the number of Colorado Plateau endemics per hanging garden was significantly higher in the Glen Canyon National Recreation Area than in Capitol Reef National Park (one-way ANOVA, $F = 6.371$, $P = 0.004$, Bonferroni post hoc test GLCA vs. CARE, $P = 0.009$) and had a trend to be higher than in Zion National Park (Bonferroni post hoc test GLCA vs. ZION, $P = 0.064$). When the focus of endemism was narrowed to the seven taxa endemic to hanging gardens (Table 1), the trend became significant. The Glen Canyon National Recreation Area is richer in hanging-garden endemics than Zion National Park or Capitol Reef National Park (one-way ANOVA, $F = 8.640$, $P = 0.001$; Bonferroni post hoc test, GLCA vs. CARE, $P = 0.008$ and GLCA vs. ZION, $P = 0.005$).

The community importance of endemic plant taxa was measured in 40 hanging-garden communities (Tables 2, 3, and 4). Thirty-five communities had endemic plant taxa that may make up as much as 52% of the canopy. In eight hanging gardens, canopy coverage of hanging-garden endemics was less than 5% (Tables 2, 3, and 4; Figure). The Horseshoe hanging garden, for example, had

Table 1. Endemic plant taxa found in hanging gardens where they make up small proportions (trace–0.05) of canopy coverage.

Endemic plant taxa ^a	Park ^b	Hanging garden
<i>Mimulus eastwoodiae</i> (HGE) ^a	CARE	Horseshoe
	GLCA	Pyro
	GLCA	Hardwood
	GLCA	Rattlesnake
<i>Primula specuicola</i> (HGE)	GLCA	Hardwood
	GLCA	Pyro
<i>Zigadenus vaginatus</i> (HGE)	GLCA	Fence
<i>Aquilegia micrantha</i> (HGE)	GLCA	Graffiti
	GLCA	Rattlesnake
<i>Cirsium rydbergii</i> (HGE)	GLCA	Pyro
	GLCA	Hardwood
<i>Habenaria zothecina</i> (CPE)	GLCA	Rattlesnake
<i>Jamesia americana zionis</i> (CPE)	ZION	Canyon Overlook I
	ZION	Falling Water
	ZION	Grotto
<i>Erigeron sionis</i> (CPE)	ZION	Canyon Overlook II
<i>Sphaeromeria ruthiae</i> (CPE)	ZION	Falling Water
<i>Carex haysii</i> (HGE)	ZION	Menu Falls
	ZION	Weeping Rock
<i>Dodecatheon pulchellum zionense</i> (HGE)	ZION	Weeping Rock

^aHGE = Hanging garden endemic; CPE = Colorado Plateau endemic.
^bCARE = Capitol Reef National Park; GLCA = Glen Canyon National Recreation Area; ZION = Zion National Park.

small clumps of the Eastwood monkeyflower, *Mimulus eastwoodiae* (Tables 1 and 4). The three parks showed no difference in canopy coverage for either Colorado Plateau endemic plant taxa (one-way ANOVA, $F = 1.807$, $P = 0.178$) or for hanging-garden endemic plant taxa (one-way ANOVA, $F = 1.741$, $P = 0.189$). Zion National Park and the Glen Canyon National Recreation Area have large populations of endemic plant taxa in some hanging gardens (Tables 2 and 3), and all three parks had hanging-garden communities with small populations of hanging-garden endemics (Table 1; Figure).

Discussion

The higher level of endemism in the hanging gardens of Glen Canyon National Recreation Area was not an artifact of different patterns of species

Table 2. Number of endemic vascular plant taxa in hanging gardens of Zion National Park (ZION), Utah, by site.

Hanging garden	R ^a	HGE ^b	CPE ^c	Area(m ²) ^d	CC ^e
ZION total	95	2	5		
Upper Emerald	33	2	2	1,170	0.23
Kaye's	29	1	1	124	0.16
Weeping Rock	28	2	2	812	0.03
Grotto	28	1	2	628	0.24
Narrows Trail	26	1	1	383	0.22
Canyon Overlook II	26	0	1	70	T ^f
Menu Falls	23	1	1	190	T
Falling Water	21	0	2	420	T
Court Patriarchs	20	0	0	99	0
Fall	14	1	1	274	0.49
Canyon Overlook I	14	0	1	4	T
Hailstone	13	1	2	28	NA
Snail	13	0	0	61	0
Trail's End	13	1	1	226	0.12
Lower Emerald	12	1	1	131	0.29
Pine Creek	6	1	1	72	0.32

^aTotal species richness.

^bNumber of taxa endemic to hanging gardens.

^cNumber of taxa endemic to Colorado Plateau.

^dArea of hanging garden.

^eSum of canopy coverage proportions for all hanging-garden endemic taxa.

^fT < 0.005 of canopy coverage.

richness because the total vascular plant species richness per hanging garden was not significantly higher (one-way ANOVA, $F = 6.940$, $P = 0.002$; Bonferroni post hoc test GLCA vs. ZION, $P = 0.118$, GLCA vs. CARE, $P = 0.053$, CARE vs. ZION, $P = 0.002$). Nor does Glen Canyon National Recreation Area's larger number of endemic taxa in hanging gardens seem to be related to hanging garden area. Hanging garden areas were significantly larger in Zion National Park and in the Glen Canyon National Recreation Area than in Capitol Reef National Park but were not significantly different from each other (one-way ANOVA, $F = 10.889$, $P = 0.000$; Bonferroni post hoc test, GLCA or ZION vs. CARE, $P = 0.000$, GLCA vs. ZION, $P = 1.000$). The small hanging-garden area and low level of endemism in Capitol Reef National Park may have been because of the absence of an adequate sandstone aquifer (May et al. 1995).

The higher level of endemism in hanging gardens of the Glen Canyon National Recreation Area may have been due to stronger microclimatic isolation

Table 3. Number of endemic vascular plant taxa in hanging gardens of the Glen Canyon National Recreation Area (GLCA), Utah, by site.

Hanging garden	R ^a	HGE ^b	CPE ^c	Area(m ²) ^d	CC ^e
GLCA total	82	5	6		
Zigy	30	5	5	1,215	0.43
Hardwood	29	3	3	1,177	0.01
Hook	27	4	4	351	0.52
Crossbed	22	2	2	115	0.18
Pyro	21	3	3	37	T ^f
Fence	21	2	2	344	T
Rattlesnake	20	3	4	836	0.04
Ice	18	4	5	893	0.43
Dune	18	2	2	173	0.12
Zephyr	16	3	3	81	0.29
Stone Basin	16	0	0	115	0
Camp	15	2	3	341	0.29
Pedestal	15	2	2	269	0.13
Upper Three	15	3	3	825	0.42
Lower Cow	14	1	1	86	0.15
Corner	13	2	2	249	0.27
Hawk	12	4	4	193	0.49
Channel	11	4	4	714	0.27
Swallow	11	4	5	52	0.13
Boondoggle	11	0	0	17	0
Wrong	11	0	0	35	0
Baby Too	10	1	1	38	NA
Baby	10	0	0	35	NA
Surprise	9	0	0	150	NA
Ivy	7	0	0	70	NA
Graffiti	7	1	1	44	T
Lower Three	6	2	2	162	0.28

^aTotal species richness.
^bNumber of taxa endemic to hanging gardens.
^cNumber of taxa endemic to Colorado Plateau.
^dArea of hanging garden.
^eSum of canopy coverage proportions for all hanging-garden endemic taxa.
^fT < 0.005 of canopy coverage.

effects. The visual contrast between hanging garden vegetation and the surrounding xeric habitats was more abrupt in the Glen Canyon National Recreation Area with its predominance of slickrock and narrow riparian zones. More mesic habitats surrounded hanging gardens within Zion Canyon. Alternatively, the higher level of endemism in the Glen Canyon National Recreation Area may have been due to its more central geographic location between the Rocky

Table 4. Number of endemic vascular plant taxa in hanging gardens of Capitol Reef National Park (CARE), Utah.

Hanging garden	R ^a	HGE ^b	CPE ^c	Area (m ²) ^d	CC ^e
CARE total	22	1	1		
Sidewall	12	0	0	42	0
Beaver Dam	9	0	0	2	0
Horseshoe	8	1	1	25	T ^f
Fort	4	0	0	3	0
Meander	3	0	0	9	0

^aTotal species richness.
^bNumber of taxa endemic to hanging gardens.
^cNumber of taxa endemic to Colorado Plateau.
^dArea of hanging garden.
^eSum of canopy coverage proportions for all hanging-garden endemic taxa.
^fT < 0.005 of canopy coverage.

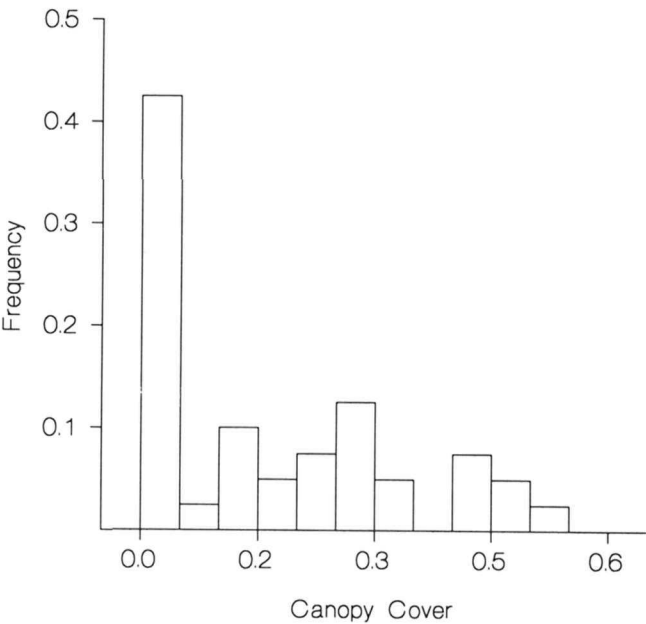


Figure. Community importance values of endemic plant taxa measured as the total amount of endemic taxa in the herbaceous canopy in each of 48 hanging gardens in Zion National Park, in the Glen Canyon National Recreation Area, and in Capitol Reef National Park during summers of 1991 and 1992.

Mountain and Great Basin floras. These hypotheses are testable and will be the subject of future analysis.

Some hanging gardens in Zion National Park and in the Glen Canyon National Recreation Area have large populations of endemic plant taxa (Tables 2 and 3; Figure). These are primarily large, dense patches of Rydberg's thistle, *Cirsium rydbergii*, in the Glen Canyon National Recreation Area and many smaller, scattered clumps of Zion shooting star, *Dodecatheon pulchellum zionense*, in Zion National Park.

Eleven hanging gardens had small proportions of endemic species in the canopy coverages (Tables 2, 3, and 4; Figure). The trace—5% class (Figure) may be used to identify hanging gardens with small endemic-species populations that are more susceptible to local extinction. Among the endemic taxa of hanging gardens (Table 1), *Cirsium rydbergii*, *Aquilegia micrantha*, *Zigdenus vaginatus*, and *Dodecatheon pulchellum zionense* are more abundant in other hanging gardens from Zion National Park and the Glen Canyon National Recreation Area (Stanton et al. 1992*, 1993*). *Mimulus eastwoodiae*, *Primula specuicola*, and *Carex haysii* populations, however, were usually only a small part of each hanging-garden community (i.e., a trace to 8% of the hanging-garden vascular plant canopy cover; Stanton et al. 1992*, 1993*). Although these species are not threatened with regional extinction, monitoring these small populations for local extinction is desirable for the early detection of hanging-garden disturbance; for example, groundwater depletion. The same rationale applies to the Colorado Plateau endemics *Erigeron sionis* and *Habenaria zothecina* (Table 1) because hanging-garden habitats make up a significant part of their range.

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Tissue Culture of Mature Ponderosa Pine: Callus Induction and Differentiation

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Abstract. Callus was induced from needle segments of mature ponderosa pine (*Pinus ponderosa* Doug. ex Laws.). Callus formation was significantly affected ($P \leq 0.01$) by four growth-regulator treatments and the position along needle segments. The highest frequency of callus formation (57%) was obtained with Murashige-Skoog (MS) medium containing 0.5 mg/L BAP (benzylaminopurine) and 1.0 mg/L 2,4-D (2,4-dichlorophenoxyacetic acid). The needle segments located in the middle part of the axis responded best, as measured by callus formation, to the tested treatments. Three callus lines were grown by applying two subcultures for subsequent study of callus differentiation. Semithin sections of callus tissue from the second subculture revealed a vascular nodule (tracheid masses with cambiumlike structure), and meristematic tissue had formed in the lower part of callus cultured in MS medium containing 0.03 mg/L NAA (naphthalene acetic acid) + 0.5 mg/L BAP. Among three callus lines, only line 2—treated with 0.5 mg/L 2,4-D + 1.0 mg/L BAP—developed a vascular nodule and meristematic tissue after transfer to two subculture media.

Key words: Callus formation, meristematic tissue, needles, phytohormones, *Pinus ponderosa*, vascular nodule.

Callus culture is a method by which a mass of unorganized tissue—callus—is induced. Callus can then be transferred to new medium to obtain differentiated callus that would develop into organs or somatic embryos and eventually obtain plantlets (Geissbühler and Skoog 1957; Halperin 1969; Pierik 1987). Callus culture is considered a potential tool to achieve tree regeneration via embryogenesis or organogenesis. Aboel-Nil (1987) estimated that 247,100 ha could be reforested with plantlets produced from 100 L of callus in only 3 months. Callus induction is a first step to achieve tree regeneration. Since 1934, when the first callus was obtained from cambial explants of *Pinus pinaster* Ait. trees 15–50 cm in diameter (Gautheret 1943), many gymnosperms have been successfully

induced to form callus (Harvey and Grasham 1969; Brown and Sommer 1975; John 1983; Tuskan et al. 1990).

Callus differentiation, the second step of callus culture, is critical for achieving regeneration. Vascular nodule and meristematic tissue formation are the two major types of callus differentiation in vitro (Gautheret 1966; Gresshoff 1978). Many studies have been done in angiosperm species (Sterling 1950; Steward et al. 1958; Gautheret 1966; Fosket and Torrey 1969; Meada and Thorpe 1979). In gymnosperms, callus differentiation involved in vascular nodule and meristematic tissue formation is only documented in *Pinus eldarica* Medw. (Wagley et al. 1987), *Pinus radiata* D. Don (Washer et al. 1977), and *Sequoia sempervirens* (D. Don) Endl. (Ball 1950).

Capacity of callus differentiation varied in plant species, organs, and tissues (Halperin 1973). Aging of a plant can also influence the capacity for callus differentiation. The older the plant or tissue is, the more difficult it is to obtain differentiated callus (Mehra-Palta and Thompson 1987). In most instances mentioned above, however, the sources used in the experiments were either from embryos or juvenile materials. Because some superior characteristics are not expressed until trees reach maturity, regeneration from tissues of mature trees is highly desired. For instance, resistance of ponderosa pine to some insects may be recognized only when the trees reach maturity.

With the development of a callus initiation protocol and the study of callus differentiation, we may be able to produce plantlets from resistant, mature ponderosa pine. Our interest in callus culture for mature ponderosa pine and the lack of available information on callus culture for mature gymnosperms prompted our study. In this paper we report the successful induction of callus and the study of callus differentiation of mature ponderosa pine.

Materials and Methods

Callus Induction

Ten current-year branches were collected from each of four open-pollinated mature ponderosa pines (trees 2, 3, 12, and 14, ranging from 20 to 29 years of age) on 15 July 1988. The trees are located south of Parks, Arizona, in the Kaibab National Forest (R4E, T21N, Sections 3, 4, 9, and 10). The trees were a subset of 20 trees used for the past 3 years in a rooting experiment (M. R. Wagner, unpublished data). The branches, including needles that were half-

elongated, were stored along with a wet paper towel in plastic bags inside a refrigerator (0–2° C) for 2 days before the experiments.

The branches with needles were disinfected on the surface by a five-step procedure that included soaking in 1% (w/v) Alconox for 2 min, soaking in 10% (v/v) Clorox for 15 min, soaking in 5% (v/v) H₂O₂ for 15 min, soaking in 2% (w/v) Benlate for 2 min, and finally rinsing with sterilized distilled water.

Difco bacto–agar media were sterilized in an autoclave at 1.4 kg²/cm² and 120° C for 20 min. All media were adjusted to pH 5.8 with 1N NaOH and 1N HCl before autoclaving.

Needles were removed from the branches and were transversely cut into 8 segments 8–10 mm long. Segments were numbered from 1 to 8 along the needle axis from proximal to distal and were placed horizontally in petri dishes containing MS nutrient medium with growth regulators. Needle explants were grown in a growth chamber at 25 ± 1° C. Fluorescent white lights (82 µmol/cm²/s) were used with a 16-h photoperiod.

Four growth-regulator treatments were applied to test the effect of auxin-to-cytokinin ratios on callus formation:

1. 0.1 mg/L 2,4-D + 2.5 mg/L BAP (benzylaminopurine);
2. 0.5 mg/L 2,4-D + 1.0 mg/L BAP;
3. 1.0 mg/L 2,4-D + 0.5 mg/L BAP; and
4. 1.0 mg/L 2,4-D + 0.1 mg/L BAP.

The first and second treatments were designed to have auxin-to-cytokinin ratios less than 1. The last two treatments were designed to have the ratio greater than 1.

The effects of phytohormone, positions along needle axes, genotypes (represented by the four trees), and their interactions on callus formation were assessed with three-way ANOVA (Zar 1984). Twenty needles were cultured for each combination of the three factors. Because there were significant differences among the treatments, the Newman–Keuls multiple comparison test (Zar 1984) was used to compare the differences among treatments. Frequency of callus formation was calculated by recording the number of callused explants divided by the total number of callused and noncallused explants for each combination of the three factors after the explants had grown for 4 weeks.

Callus Differentiation

The calli derived from three growth-regulator treatments—MS media containing 1.0 mg/L 2,4-D + 0.5 mg/L BAP; 0.5 mg/L 2,4-D + 1.0 mg/L

BAP; or 1.0 mg/L 2,4-D + 0.1 mg/L BAP—were used in the callus differentiation study and were named callus lines 1, 2, and 3.

After calli grew for 7 weeks, approximately same-sized calli were used for subculturing. Two subculture lines were developed. In the first subculture, 5 calli from each of the four genotypes of all the three callus lines were cultured in two treatments: 2.5 mg/L BAP + 0.03 mg/L NAA (naphthalene acetic acid) and 0.5 mg/L BAP without NAA. After 14 weeks of growth in the above media, the calli were transferred into the second subculture medium containing 0.5 mg/L BAP + 0.03 mg/L NAA. The culture condition was the same as that in callus induction.

Callus tissue was collected after growing for 10 weeks in the second subculture media. The callus was fixed in formalin-aceto-alcohol (FAA) solution, then gradually dehydrated and embedded in paraffin as described by Jensen (1962). The embedded materials were serially sectioned at 10 μ m using a rotary microtome. The sections were stained with safranin and fast green and mounted with resin (Jensen 1962).

Results and Discussion

Callus Induction

Growth Regulator Effect

Vigorous, light green, and fragile callus started forming on the 10th day. The average frequency of callus formation by the four trees (Fig. 1) was taken after 4 weeks.

Three-way ANOVA showed there was a significant difference among the phytohormone treatments ($F = 43.59$, $df = 3, 127$, $P < 0.01$). The Newman-Keuls multiple comparison test categorized four treatments into four groups (A, B, C, and D; Table). In terms of the effect, the most effective treatment for callus formation was treatment 3 (group A; 57% callus formation) containing 1.0 mg/L 2,4-D + 0.5 mg/L BAP; followed by treatment 4 (group B; 39% callus formation) with 1.0 mg/L 2,4-D + 0.1 mg/L BAP; then treatment 2 (group C; 29% callus formation) with 0.5 mg/L 2,4-D + 1.0 mg/L BAP; and finally treatment 1 (group D; 18% callus formation) containing 0.1 mg/L 2,4-D + 2.5 mg/L BAP.

An exogenous supply of auxin alone or auxin combining cytokinin is often required to induce callus formation (Pierik 1987). Different species, organs, or tissues have a wide range of growth-regulator requirements (Pierik 1987).

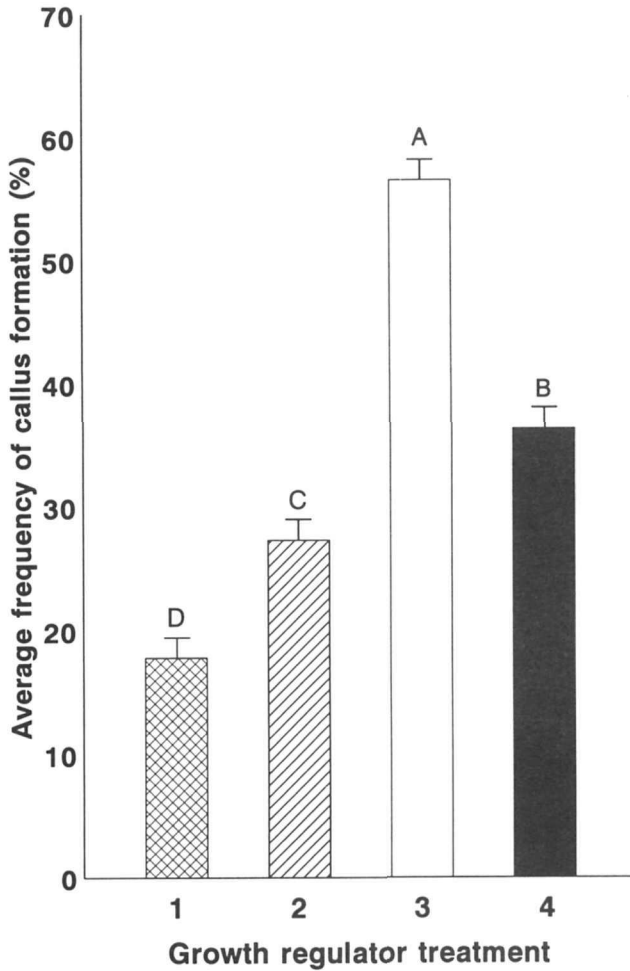


Fig. 1. Effect of phytohormone treatments on callus formation in mature ponderosa pine (*Pinus ponderosa*). The average frequency of callus formation of each treatment was taken after 4 weeks of growth. Bars represent the standard errors. The letter above the bar represents groups categorized by Newman-Keuls test. 1 = 0.1 mL/L 2,4-D + 2.5 mL/L BAP (benzylaminopurine); 2 = 0.5 mg/L 2,4-D + 1.0 mL/L BAP; 3 = 1.0 mL/L 2,4-D + 0.5 mL/L BAP; 4 = 1.0 mL/L 2,4-D + 0.1 mL/L BAP.

Tissues from *Pinus sylvestris* and *Pinus nigra* formed callus when stimulated by auxins (Bogdanovic 1968; Bogdanovic and Jelenic 1968). Harvey and Grasham (1969) reported that 0.5 mg/L NAA was the best treatment for callus

Table. Response of three callus lines to the callus subculture media of mature ponderosa pine (*Pinus ponderosa*).

Callus line	First subculture		Second subculture
	Treatment A ^a	Treatment B ^b	Treatment C ^c
1	Dead	Dead	
2	Slow growing	Dead	Differentiated
3	Slow growing	Dead	Dead

^a2.5 mg/L BAP (benzylaminopurine) + 0.03 mg/L NAA (naphthalene acetic acid).

^b0.5 mg/L BAP.

^c0.5 mg/L BAP + 0.03 mg/L NAA.

growth of stem cortex of ponderosa pine seedlings. Among six growth regulator treatments, Tuskan et al. (1990) found that the combination of 1.0 mg/L BA + 1.0 mg/L NAA gave the best growth of callus initiated from cotyledons of ponderosa pine embryos. In other species, such as *Pinus eldarica* and *Pinus strobus*, callus was induced by applying both auxin and cytokinin (Kaul 1985; Gladfelter and Phillips 1987). Generally, when using both auxin and cytokinin, a ratio of greater than 1 auxin:cytokinin is recommended for callus induction (Sharp and Larsen 1977). In our experiment, the ratio of auxin:cytokinin was less than 1 in the least- and second-least effective growth-regulator treatments, including treatments 1 and 2, whereas treatment 3, the most effective treatment, and 4, the second most effective treatment, had a ratio greater than 1. Our result agrees with Sharp and Larsen's (1977) argument. The callus formation in treatment 4 (39%) with the ratio 10:1, however, was significantly lower than the one in treatment 3 (58%) with the ratio 2:1, which suggests that the ratio of auxin:cytokinin may be critical for callus induction of mature ponderosa pine. Too high an auxin:cytokinin ratio resulted in reduced callus yield.

Position Effect

The position effect along the needle axis on callus formation was significantly different ($F = 27.46$, $df = 7, 127$, $P = 0.000$). The segments (1–8 presenting the needle positions from the proximal to the distal) were categorized into four major groups by Newman–Keuls test (Fig. 2). Segment 4, in the middle part of needles, was determined to callus best. Segment 1, at the bottom of needles, rarely produced callus. The position had no interaction with the other two factors.

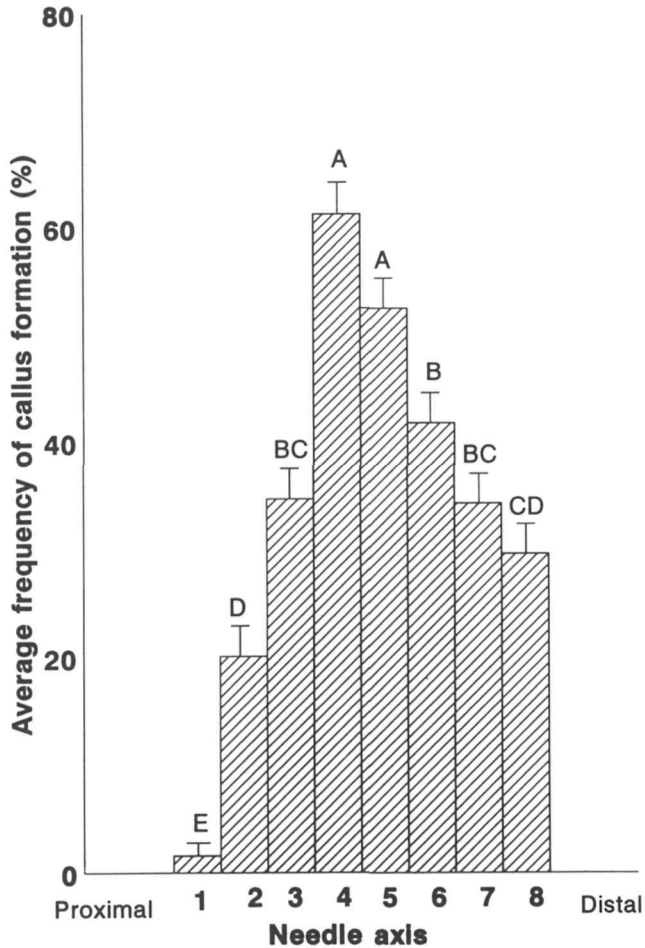


Fig. 2. Effect of explant positions along needle axis on callus formation in mature ponderosa pine (*Pinus ponderosa*). The average frequency of callus formation was taken from each individual segment of four growth-regulator treatments. The bars represent the standard errors. The letter above the bar represent groups categorized by Newman-Keuls test.

The morphogenetic response of explants varies among plants, organs within a plant, and positions within an organ (Minocha 1987). In an in vitro study of *Populus* species, Douglas (1984) found that a gradient of morphogenesis developed along stem internodes cultured on a hormone-free medium. The fourth through seventh internodes produced the most buds and shoots. This

suggests that the morphogenesis gradient may reflect the endogenous plant hormone gradients along the stem. Bornman (1987) reported that the position on the leaf axis of *Picea abies* strongly affected the morphogenesis of needle explants. Organogenesis decreased gradually along the needle axis from the proximal to the distal, which implies increasing age. This phenomenon, he deduced, may be associated with a gradually decreasing level of endogenous auxin from proximal to the distal part of needles. Minocha (1987) indicated that different effects of the same exogenous hormone level on different tissues may be the result of the different physiological zones of tissues. Different positions along a developing needle represent different ages that increase from proximal to distal (Kozlowski 1971; Bornman 1987). Auxin level usually is the highest at leaf base of young expanding leaves (Goodwin and Erwee 1983). The best callus production in the middle part of the needle may be the result of the exogenous phytohormone supply being appropriate for the middle part of the needle. In contrast, the exogenous phytohormone might be too high at the proximal end so that it suppressed callusing and might not be sufficient to induce large-quantity callus at the distal end.

Genotype Effect

Significant genotypic variation with respect to percentage callus formation ($F = 8.1$, $df = 3, 127$, $P = 0.0001$) was present. Genotypes 2 and 14 produced less callus than genotypes 3 and 12 (Fig. 3). Genotype is known to be critical for successful tissue culture of woody plants. In a protoplasts culture of *Malus × domestica*, one genotype regenerated into whole plantlets, whereas the other remained in callus stage although many parameters had been tested (Russell 1993). Dunstan et al. (1989) reported that shoot production of explants from 17-year-old Douglas-fir (*Pseudotsuga menziesii*) varied significantly between provenances and within a provenance. In an in vitro culture experiment of mature *Pinus radiata*, the percentage rooting of micropropagated shoots were greatly influenced by plant genotypes (Horgan and Holland 1989). Callus production from cotyledons of ponderosa pine embryos varied among different genotypes (Tuskan et al. 1990). By recognizing genotypic variation, selection of the most responsive genotype would greatly improve success in tissue culture of woody plants.

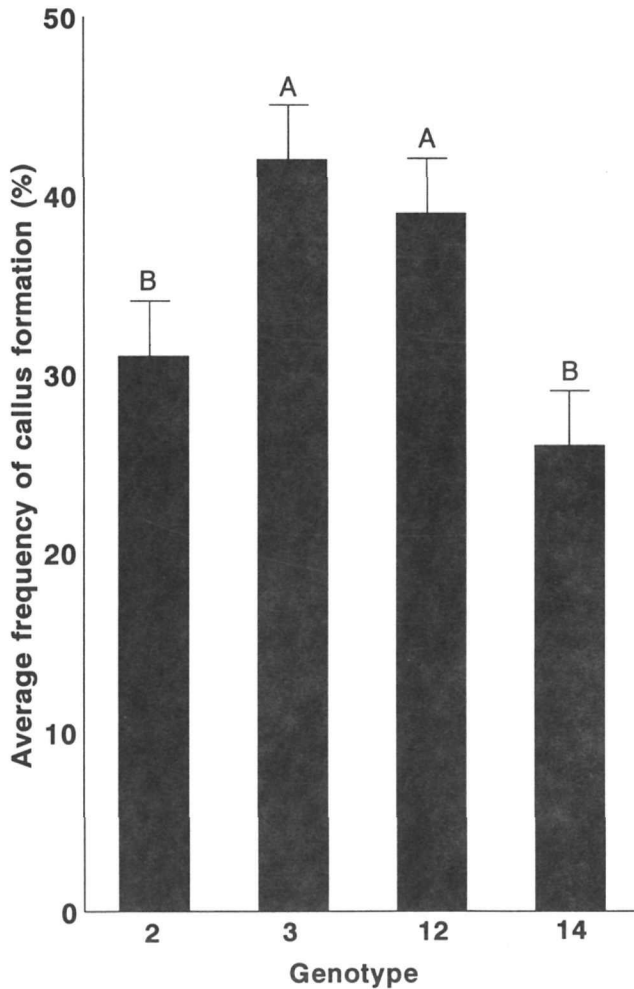


Fig. 3. Effect of genotypes on callus formation in mature ponderosa pine (*Pinus ponderosa*). The average frequency of callus formation of each genotype was taken after 4 weeks of growth. The bars represent the standard errors. The letter above the bar represents groups categorized by Newman-Keuls test.

Callus Differentiation

The external features of callus from the three treatments of the callus initiation media were slightly different. Callus induced from treatment 3 appeared light green and fragile. Callus induced from treatment 1 was yellowish and less proliferated. The color and proliferation of callus from treatment 2 was

intermediate to treatment 1 and 3. The calli were less fragile or more compact than the one initiated from treatment 3.

After transfer into the first subculture media for 2 weeks, the three callus lines showed different responses in color and feature. All callus lines in treatment B, containing only BAP, turned dark brown in 2 weeks in the first subculture (Table). The browning was an indication of phenolics, which often results in dead callus (Gresshoff 1978). These calli were discarded. Only the calli in treatment A with 0.03 mg/L NAA + 0.5 mg/L BAP continued growth.

The three callus lines had different characteristics in treatment A (Table). Calli from line 1 turned brown and were discarded. The growth of callus lines 2 and 3 were significantly reduced as compared to the induction medium. The calli showed a compact, smooth surface with some protrusion and became light brown. After the fourth week in the second subculture media, only three calli were alive, of which two were from genotype 14 and one was from genotype 3. Callus of genotype 3 was initiated from MS media containing 1.0 mg/L 2,4-D + 0.1 mg/L BAP (callus line 3). The other two were from the media with 0.5 mg/L 2,4-D + 1.0 mg/L BAP (callus line 2).

In the serial sections of callus from the final subculture of three surviving calli, callus differentiation only developed in callus line 2. A distinctive vascular nodule was located at the bottom of the callus tissue. The vascular nodule was composed of a tracheid mass and cambiumlike structure formed by rows of flattened cells surrounding the tracheid mass that appeared similar to the cyclic nodules described by Gautheret (1966). In the cross section of callus, next to the vascular tissue, a mass of meristematic cells occupied nearly a quarter of the callus cross section, mainly at the bottom and middle of the tissue. The meristematic cells were characterized by small cells, larger nuclei, and a high density of cytoplasm densely stained by fast green.

Several factors, including genotypes, may have influenced the callus differentiation in our experiment. Among the four genotypes, only genotype 14 showed differentiation. Because of the small sample size, however, we hesitate to conclude that callus differentiation was genotype dependent in our study although genotypes have been demonstrated as having a major influence on plant regeneration (Ernst 1993; Russell 1993).

In this experiment, growth regulators affected callus differentiation in two ways: callus differentiation only developed in the callus line 2 initiated in 0.5 mg/L 2,4-D + 1.0 mg/L BAP; and callus differentiation developed in subculture media containing both BAP and NAA.

Previous studies on the effect of growth regulator on callus differentiation have primarily concentrated on the growth regulator effect on callus subculture media (Sterling 1950; Fosket and Torrey 1969; Bonga and Fowler 1970; Torrey and Fosket 1970; Maeda and Thorpe 1979; Mehra and Annand 1983). The effect of growth-regulator concentrations in callus initiation media, however, is rarely documented in reference to subsequent differentiation. In Christianson and Warnick's study (1983), callus induction media containing different growth-regulator balances had no effect on organogenesis capacity of leaf explants of *Convolvulus arvensis*. In the current study, we found that growth-regulator concentrations in callus initiation medium can be important in determining callus differentiation. Murashige and Skoog (1962) reported that tissue grown in a lower ratio of cytokinin:auxin produced fragile callus, whereas a higher ratio of cytokinin:auxin tended to produce compact callus, which may be considered as the initial step in callus differentiation. The external morphology of callus among the three treatments of initiation media demonstrated this effect. In other words, growth regulators in callus-induction stage may affect the capability of organogenesis of callus during the callus-induction stage.

The result of callus differentiation developing in the second subculture media containing both auxin and cytokinin indicates that the auxin is necessary for callus differentiation. Minocha and Halperin (1974) suggested that differentiation must be involved in cell division that requires auxin. The need for both auxin and cytokinin for vascular nodule formation has been demonstrated (Gautheret 1966; Fosket and Torrey 1969; Torrey and Fosket 1970; Maeda and Thorpe 1979; Wagley et al. 1987). Torrey and Fosket (1970:1072) reported that auxin and cytokinin are necessary for the "initiation of DNA synthesis. . . for the subsequent division, and finally for their specific cytodifferentiation."

Gresshoff (1978) suggested vascular nodule formation was the initial phase of organogenesis and that further development of vascular nodules would result in organogenesis, such as roots and buds, although Gautheret (1966) indicated that vascular nodule formation would not necessarily result in organogenesis instead of new tissues. Some studies have supported Gresshoff's (1978) suggestion, however. Maeda and Thorpe's (1979) study on tobacco callus culture showed a series of histogenesis events before shoot initiation. They indicated that the developmental sequence of shoots involved "occurrence of meristematic center near the tracheary elements" (Maeda and Thorpe 1979:423), which was similar to our study. In a callus differentiation study of *Sequoia sempervirens*, Ball (1950) observed tracheid cells surrounded by cambium after

the fifth transfer and, after subsequent cultures, adventitious buds were obtained. The same event was also observed by Wagley et al. (1987) in *Pinus eldarica* and Washer et al. (1977) in *Pinus radiata*. Steward et al. (1958) found that before roots formed from callus, vascular nodules with lignified elements surrounded by cambiumlike elements were obtained. The callus development process in our study was similar to the above studies suggesting that the callus derived from needles of mature ponderosa pine may have organogenesis potential.

Acknowledgments

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Preliminary Survey of Leopard Frogs in Glen Canyon National Recreation Area

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Abstract. Collection records and published reports indicate that the northern leopard frog (*Rana pipiens*) was formerly widely distributed along the Colorado River corridor in the area that is now Glen Canyon National Recreation Area. This species has experienced serious declines over much of its range in western North America. We report on a newly discovered population along the Colorado River in Glen Canyon National Recreation Area, and two new populations in tributaries of Lake Powell. Recent surveys suggest that the river site supports the sole remaining leopard frog population between Glen Canyon Dam and Lake Mead. This population is vulnerable because of its small size (80–100 individuals), its isolation, and because of possible effects from planned increased high flows from Glen Canyon Dam.

Key words: Amphibian decline, Colorado River, conservation, *Rana pipiens*.

Recent reviews and conferences have focused attention on serious declines of anuran amphibians from Australia to North and South America (Barinaga 1990; Blaustein and Wake 1990; Wyman 1990; Tyler 1991; Blaustein 1994a). In western North America, populations of frogs (*Rana* spp.) and toads (*Bufo* spp.) have suffered significant declines (Hayes and Jennings 1986; Fellers and Drost 1993; Corn 1994). Despite speculation and an increasing number of careful studies (e.g., Bradford et al. 1993; Carey 1993; Blaustein 1994b), the cause of many of the declines remains an enigma.

The northern leopard frog (*Rana pipiens*) and related species (*R. chiricahuensis*, *R. onca*, *R. yavapaiensis*) are among the North American species that have experienced serious declines (Corn and Fogleman 1984; Clarkson and Rorabaugh 1989; Bishop and Petit 1992). Northern leopard frogs were formerly widespread and abundant across much of the western United States and Canada.

Since the 1970's, however, declines of northern leopard frogs have been reported from Arizona, Colorado, Wyoming (Hammerson 1982; Corn and Fogleman 1984; Clarkson and Rorabaugh 1989; Vial and Saylor 1993) and large areas in Canada (Bishop and Petit 1992; Vial and Saylor 1993). Clarkson and Rorabaugh (1989) surveyed 13 sites in Arizona that previously supported northern leopard frog populations but did not find the species at any of the sites.

In 1992, National Park Service personnel found leopard frogs at Horseshoe Bend on the Colorado River in Glen Canyon National Recreation Area (GLCA). They had previously found small numbers of frogs in two tributaries of Lake Powell, also within GLCA. Based on these discoveries, we proposed an intensive survey for leopard frogs along the Colorado River in GLCA. Our objectives were to (1) survey the Horseshoe Bend site and assess the population size and condition of the frogs there, (2) search the remainder of the Colorado River corridor from Glen Canyon Dam to Lees Ferry and the tributary canyons of Lake Powell for additional leopard frog populations and potential leopard frog habitat, and (3) compare the current distribution of leopard frogs in the area with reconstructed distributions from historical records.

Methods

We searched published literature and unpublished agency reports for information on leopard frogs in the Glen Canyon area. In addition, we examined 7.5-minute U.S. Geological Survey maps and color aerial photographs of the area to locate springs, marshes, and tributary streams that might provide suitable habitat for frogs. Fieldwork on the river had three components: (1) census and habitat survey of the Horseshoe Bend site; (2) surveys by boat along the river corridor from the base of Glen Canyon Dam to Lees Ferry to search for additional potential leopard frog habitat; and (3) searches on shore for leopard frogs at all sites having suitable habitat (see Fig. 1).

We searched wetland areas adjacent to the shore by carefully walking along and through all wetland habitat while looking for frogs sitting or jumping along the water's edge or in adjacent marsh or meadow vegetation. Leopard frogs are relatively conspicuous and are usually found sitting out in the open. We also turned boulders and logs to look for frogs or other amphibians hiding underneath. We searched areas of still or slowly flowing water for tadpoles, which we captured with a dip net and examined and identified in the hand. We

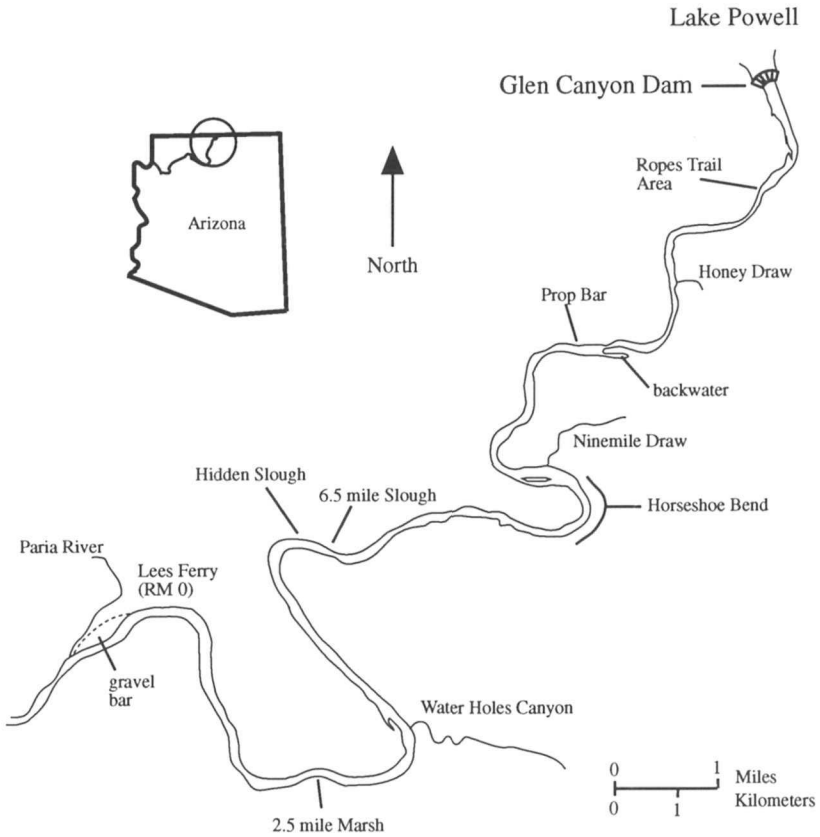


Fig. 1. The Colorado River in Glen Canyon National Recreation Area, from Glen Canyon Dam to Lees Ferry, indicating areas intensively searched for leopard frogs (*Rana* sp.) in 1993. The one site where frogs were found was Horseshoe Bend.

recorded body length (snout–urostyle) and general condition for all frogs captured. We recorded a general description of the habitat at each site that supported leopard frogs, including basic topography of the area, type and size of surface water (if any), and dominant plant species. We began surveys well upriver of apparently suitable leopard frog habitat and continued downriver beyond the last frogs seen and the last areas of apparently suitable habitat.

On the second survey of the Horseshoe Bend site, a three-person crew conducted a careful census of the frogs by walking slowly through the habitat in a line perpendicular to the river. The crew stayed abreast of each other, approximately 2 m apart, while sweeping the ground ahead with a staff or large branch.

Each person recorded separately the frogs seen in their path so the counts were stratified by distance from the river's edge (0–2, 2–4, 4–6, 6–8, 8–10, and >10 m). Frogs were noted as large, medium, or small, judged with reference to a sample of frogs captured by hand before the count was begun. These size classes were based on measurements of 21 frogs at the Horseshoe Bend site and 29 from Lake Powell tributaries, which show distinct groups of small (42 mm body length) and large (>60 mm) frogs with few individuals of intermediate size.

In the boat and shore portion of the survey, we searched for potential habitat by looking for obvious standing or running water, large side canyons, and areas of wetland vegetation such as sedges (*Carex* spp.), common reed (*Phragmites communis*), bulrushes (*Scirpus* spp.), and cattails (*Typha* spp.). We noted the location of all seemingly suitable areas on a topographic map and either surveyed the site when it was first noted, or on a later day. The shore surveys included side canyons along the river corridor, where these side canyons offered possible habitat.

Along tributary canyons of Lake Powell, a three-person team hiked the canyon bottom from lake's edge up toward the head of the canyon, searching for amphibians in areas of standing and running water and marsh and meadow vegetation. Boulders and logs were turned to look for amphibians underneath, and we scanned and used dip nets in streams and pools for tadpoles. General character of the canyon—including substrate type, vegetation, and surface water—were recorded, and detailed notes were made for areas with leopard frogs.

Surveys along the river were conducted on 1–4 June and 2–3 August 1993 to allow for seasonal variation in numbers or activity among the frogs and to obtain information on the phenology of the frogs in this area. Tributaries of Lake Powell were searched on 4–5 August. Total time spent actively searching for amphibians was 105 person-hours: 57 person-hours over 4 days on the first week; 25 person-hours on 2 different days during the second week; and 23 person-hours searching tributary canyons of the lake.

Results

Previous Records

Before the discovery of the population described here, the only recent (subsequent to dam construction) report of leopard frogs from the Colorado River corridor below Glen Canyon Dam was from Cardenas Marsh, 114 km below Lees Ferry (Tomko 1975; Miller et al. 1982). Biologists working at Cardenas Marsh in

1992 and 1993 did not find any frogs at this site, however, and recent sediment deposits have resulted in marked drying of the marsh (M. K. Sogge, unpublished data). From this we conclude that this population of frogs has been lost. Leopard frogs are not otherwise known from the entire reach of the Colorado River from Glen Canyon Dam to Lake Mead (Miller et al. 1982; C. Pinnock, 1993, personal communication). In the Lake Mead area, leopard frogs are widely distributed, but a substantial number of these frogs may be nonnative—descended from introduced individuals (Schwartz et al. 1978).

In the region of the Colorado River above Glen Canyon Dam, leopard frogs were formerly common (Woodbury 1958). There were a few reports of leopard frogs from pools along the main course of the river, but most occurrences were in tributary streams from at least Trachyte Creek near Hite, Utah, downriver to Warm Creek (Table). Most of the sites above the dam were inundated by the creation of Lake Powell (Table). Leopard frog populations persist, however, along some of the tributary streams of the lake (J. Spence, Glen Canyon National Recreation Area, personal communication).

Horseshoe Bend Site

We surveyed the Horseshoe Bend area on 2 June and 2 August. The shoreline on both sides of this sharp bend in the river were scanned from the water, and we searched the stretch from river mile (RM) -8.6 to -9.4 on foot (RM 0 is at Lees Ferry; negative RM values indicate upstream distances). Leopard frogs were restricted to the area from about RM -8.9 to -8.75 L. Habitat for the frogs is centered on a small, spring-fed stream and marsh perched above river level at the foot of a large talus slope. The pool and marsh area contains meandering, interconnected, U-shaped channels, about 0.5 m deep with a thick silt bottom. Tall, dense vegetation fringing these channels consists of *Carex*, *Phragmites*, *Scirpus*, and *Typha*. The pool-marsh area drains to a boulder and cobble shallows area along the river, which has two additional pools just above river level. The lower pools are small and shallow, 4–5 m across and up to 10 cm deep. The pools have a moderate amount of green algae and rooted *Chara*. Sparse vegetation around the pools and scattered across the low boulder bar consists of small *Carex* sp., *Juncus* spp., *Polypogon semiverticillata* (= *Agrostis viridis*) and watercress (*Rorippa nasturtium-aquaticum*). *Carex*, *Juncus*, and other elements of this wetland vegetation extend along the river's edge both upstream and downstream from the spring area for a total distance of approxi-

Table. Historical locations of northern leopard frogs (*Rana pipiens*) along the Colorado River through Glen Canyon National Recreation Area and Grand Canyon National Park.^a

Location ^b	Source	Date	Present status ^c	Notes
Lower Trachyte Creek	Woodbury	1958	Flooded	1,050 m elevation
Below mouth of				
Ticaboo Creek	Woodbury	1958	Flooded	
River mile -109	Woodbury	1958	Flooded	In small side
River mile -101.5	Woodbury	1958	Flooded	
Lower Long Canyon	Woodbury	1958	^d	
Hole-in-the-Rock	Woodbury	1958	Flooded	In pond on river
Hidden Passage	Woodbury	1958	Flooded	
Rainbow Bridge Canyon				
Below Rainbow Bridge	Eaton	1935	Flooded	1,525 m elevation
Above Rainbow Bridge	AES	1936	Unknown	
Rock Creek	Woodbury	1958	Flooded	
West Canyon Creek	Woodbury	1958	Flooded	
Lower Kane Creek	Woodbury	1958	Flooded	River mile 40.6
Padre Creek	Woodbury	1958	Flooded	Numerous near mouth (of creek)
Warm Creek	Woodbury	1958	Flooded	Near mouth of creek
Cardenas Marsh	Tomko	1975	Extirpated?	Not seen during field work in 1991-93

^aMost records are from surveys conducted by the American Exploration Society from 1936 to 1938 and from a survey conducted by the University of Utah in 1957-58 before the construction of Glen Canyon Dam (Woodbury 1958).

^bSites are listed from upriver to downriver. River mile references are from Woodbury (1958) and are based on Lees Ferry = 0.

^cFlooded means the site was inundated by Lake Powell.

^dOriginal site flooded. Population still present in upper canyon (J. Spence, Glen Canyon National Recreation Area, 1993, personal communication).

mately 200 m. The leopard frogs at the site also use, to a lesser extent, the adjacent band of grasses, goldenrod (*Solidago* sp.), and other herbaceous species on drier ground just upslope from the marsh vegetation. Estimated total area of marsh and adjacent habitat for frogs is 0.3 ha.

On 2 June we counted approximately 60 leopard frogs, primarily in marsh vegetation along the river and along two small streams that drain the spring and the pool-marsh area. The frogs were identified as northern leopard frogs by the conspicuous white halo surrounding the large dorsal dark spots, complete white lip stripe, unbroken dorsolateral folds, and light-colored, unmarked posterior surface of the thighs. No specimens were taken, but photos are on file at the Colorado Plateau Research Station in Flagstaff, Arizona, and at the GLCA offices in Page, Arizona. The June count was not complete, but based on the proportion of the marsh that was thoroughly searched, we estimated that approximately 80 to 100 frogs were in the available habitat. These ranged from juvenile (transformed last year) to adult.

All observed frogs were active and alert. We captured and measured 15 frogs, and these individuals appeared healthy, with clear eyes and skin and no unusual outward appearances. Body length (snout-urostyle) of most of the measured sample fell into small (30–40 mm) and large (60–70 mm) size classes, with few intermediate (Fig. 2). One 42-mm-long individual was probably the same age as the 30–40-mm size class, so the only distinctly intermediate frog was one individual that measured 54 mm. Based on this, we recorded frogs of less than 40 mm as small, those greater than 40 and less than 60 mm as medium-sized, and those greater than 60 mm as large.

We noted several leopard frog tadpoles in the deep channels of the upper pool. One individual measured had a body length (snout-vent) of 24 mm, and a total length (including tail) of 54 mm. All tadpoles were approximately the same size and were presumed to be from eggs produced during spring 1993.

On 2 August we counted 81 leopard frogs at the Horseshoe Bend site, including 29 large, 3 medium, and 49 small frogs. We surveyed 185 m of shoreline (up- and downstream from the marsh), encompassing the entire area where frogs had been seen in previous visits. The width of suitable habitat over most of this length was 10–12 m. Upslope, suitable habitat was limited by hot, dry ground and dense brush. On the up- and downstream ends, the area suitable for frogs was apparently limited by the lack of open marsh vegetation, as woody cover extended to the edge of the water.

Most of the frogs noted in the August count were immediately adjacent to the river. Of the frogs not along the river, most were along the outflow stream below the spring pool or around a marshy overflow area just upriver of the spring outflow. The high river level at the time of this second survey (19,500 cfs) seemed to have crowded the frogs into this narrow area. Whereas most of the

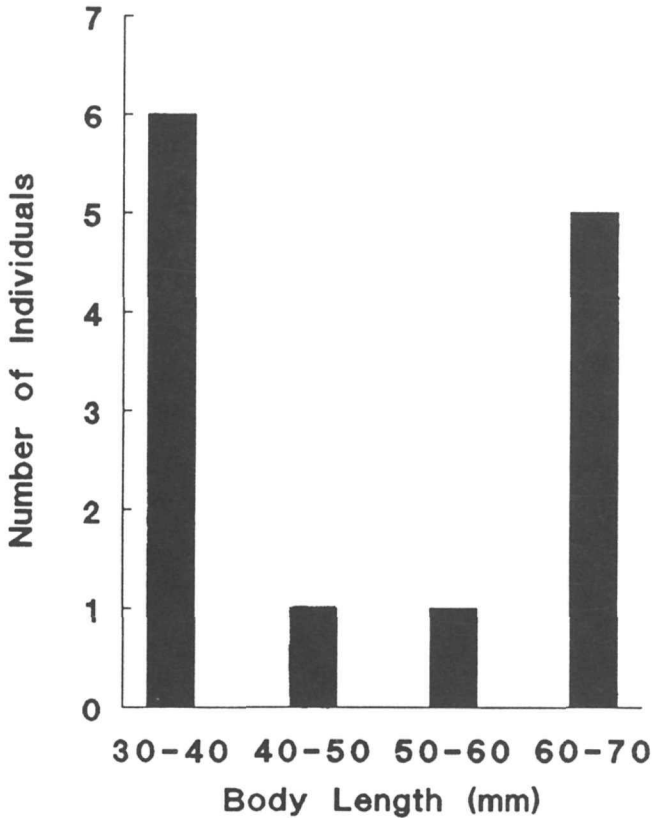


Fig. 2. Size (snout-urostyle) distribution of a sample of 13 northern leopard frogs (*Rana pipiens*) caught at Horseshoe Bend on the Colorado River in Glen Canyon National Recreation Area in June 1993. The 30–40 mm size class represents 1-year-old frogs.

marsh vegetation was inundated, the grassland and desertscrub vegetation upslope from the river at this level were dry and hot. At the lower levels of the river that prevailed during the June count, the areas of marsh vegetation and moist ground were broader, and the frogs were distributed over a greater area.

Large and small frogs also showed different distribution patterns in relation to the river's edge (Fig. 3). Eighty percent of the small frogs were in the 2-m band immediately adjacent to the river. Large frogs, in contrast, were more evenly distributed across the different bands. This difference was significant (χ^2 test of homogeneity comparing the distribution of large and small frogs; $\chi^2 = 11.72$, $P < 0.025$, $df = 4$).

Other Areas

During the 2-week survey, we searched all areas that seemed to offer potential habitat for leopard frogs from the base of Glen Canyon Dam (RM -15.6) downstream to Lees Ferry and the Paria River. No leopard frogs were found at any of these sites. Specific areas searched are listed in the Appendix; detailed descriptions of the sites and results of our surveys are given in Drost and Sogge (1993*¹).

Surveys on Lake Powell were limited to the Bowns Canyon and Ribbon Canyon tributaries to the lake. We found scattered northern leopard frogs in

¹Asterisk indicates unpublished material.

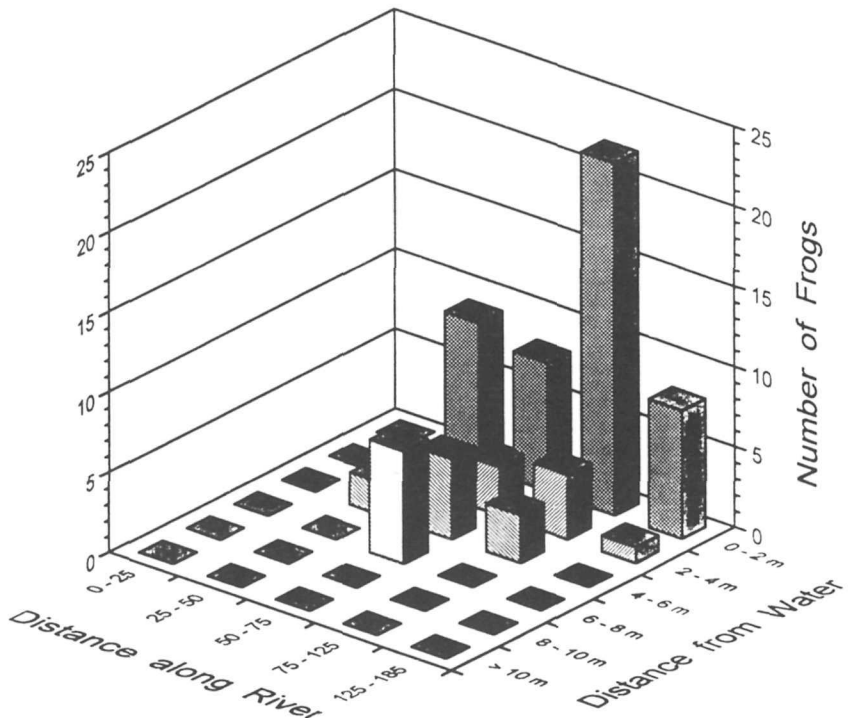


Fig. 3. Distribution of small (30–40 mm) and large (>60 mm) leopard frogs (*Rana* sp.) with respect to river's edge at Horseshoe Bend along the Colorado River in Glen Canyon National Recreation Area. From 0 to 2 m is adjacent to the water, and greater than 10 m is farthest upslope.

Bowns Canyon in parts of the stream and in streamside vegetation from about 1 km up from the lake to at least 2 km farther upstream. We counted 35 juvenile, subadult, and adult frogs, plus 3 large leopard frog tadpoles in the stream at the upper end of the area searched (2.5–3 km upstream from the lake). Most of the frogs found in Ribbon Canyon were in a large plunge pool in a hanging garden alcove at the head of the north arm of the canyon 2 km above the lake. At the time of our survey, the pool was approximately 20×40 m and as deep as 1.5 m. Nine large and 28 small northern leopard frogs were counted in the pool. The small frogs were recently transformed and ranged in length from 24 to 31 mm. Nine large tadpoles were observed—6 alive and 3 dead. Cause of death could not be determined.

Discussion

Leopard Frog Census

We estimated the number of northern leopard frogs at Horseshoe Bend to be 80–100. Some tadpoles were just metamorphosing at the August count (one 25-mm [total length] individual was noted, still with tail nub), so the August–September population was probably higher. The August count was conducted as a single sweep through the habitat. The observers worked together and kept track of individual frogs as they flushed, so there was little or no recounting. Without having marked individuals, we cannot be sure of the number of frogs that escaped being counted. Leopard frogs, however, are typically conspicuous and easy to find, particularly in the open habitat present at the Horseshoe Bend site. Also, we made a concerted effort to search the available habitat thoroughly as we moved through it, and we found few frogs under cover or that remained motionless.

The presence of tadpoles and two size classes of frogs indicates that the population is reproducing. We saw only a few tadpoles; however, we did not make a thorough search of the pool area to avoid damage to the small area of breeding habitat or directly to the larval frogs. Large tadpoles were present in early June, and five transforming and recently transformed frogs were present in early August. Reported larval periods of leopard frogs in this region range from 70 to 90 days (Stebbins 1951; Corn 1981), so mating and egg-laying probably occurred during April or early May (in surveys in 1994, egg masses were noted in March and April).

Conservation Concerns

The northern leopard frogs at the Horseshoe Bend site are apparently a highly isolated remnant population. Other than the 1970's record at Cardenas Marsh, this is the only recent report of northern leopard frogs along the Colorado River corridor's 300-mile course from northern Arizona to Lake Mead. Three intensive multiyear studies were conducted along the river corridor in the last 15 years; most were associated with Glen Canyon Environmental Studies and centered on the wetland areas along the river including Cardenas Marsh. No other leopard frog populations were found.

Historical collections and observations indicate that northern leopard frogs formerly existed as scattered populations along the Colorado River through southern Utah and northern Arizona. The construction of Glen Canyon Dam radically altered the river system both up- and downstream of the dam. Above the dam, the river and its tributaries were inundated for more than 250 km along the river. Below the dam, the river was changed from a warm, heavily silt-laden stream with a highly seasonal flow, to a much colder stream with a highly-regulated, nonseasonal flow. These changes affected northern leopard frog distribution and numbers by eliminating river populations above the dam and by isolating the populations that persisted in tributary streams above lake level. Downstream, the physical barrier presented by the dam and the cold temperature of the river water have combined to isolate the population at Horseshoe Bend. The dam presents an absolute barrier to any interaction with populations in Lake Powell tributaries, and the cold water probably prevents significant dispersal from the Horseshoe Bend population.

Is an isolated population like the one at Horseshoe Bend worth serious concern and management attention? Although there are still scattered populations of northern leopard frogs in southern Utah (such as the populations in Lake Powell tributaries), there is serious concern about the status of the species in Arizona. In addition to the losses reported by Clarkson and Rorabaugh (1989), recent surveys in northern Arizona have failed to find any northern leopard frogs. The northern leopard frog is currently a candidate for the Arizona state list of threatened wildlife (Arizona Game and Fish Department 1988), and southwest populations of the species have recently been proposed for addition to the federal candidate list of threatened and endangered species. In light of widespread declines of the species, both locally and regionally, a healthy population definitely merits attention.

Several other aspects of the Horseshoe Bend site are also of specific conservation concern. The spring-fed marsh habitat of the site is unique in the Glen Canyon area and is rare along the Grand Canyon stretch of the river. The site supports plant species that are rare along the central Colorado River corridor, including one grass species (rice cutgrass, *Leersia oryzoides*) not found anywhere else in Glen Canyon and Grand Canyon.

The greatest immediate threat to the Horseshoe Bend site is from planned "habitat maintenance" flows from Glen Canyon Dam, which are intended to limit bank erosion downstream and achieve a more normal pattern of sediment transport along the river. At the moderately high river levels present during the August survey (20,000–21,000 cfs), the lower pools at the Horseshoe Bend site were inundated, and most of the marsh area was at or barely above river level. At the much higher habitat maintenance flows planned for 1995 (45,000 cfs or greater), the river would wash over most or all of the frog habitat. This may directly or indirectly kill most of the frogs at the site. Tadpoles are restricted to the lower pools and marsh and, at a minimum, the projected high flows would sweep all of the tadpoles downstream and eliminate the current year's recruitment. Many of the frogs may also be swept into the cold waters of the main channel where they would be vulnerable to fish. High flows would probably also degrade the habitat at the site by stripping or drowning marsh vegetation and altering the slope that supports the marsh.

A proposed alternative management action for Glen Canyon Dam is to release warm water from the surface of Lake Powell, rather than the cold bottom water currently released. The resulting rise in the temperature of the river water may benefit some of the warmwater-adapted endangered fish species. This action might benefit the leopard frog population as well, allowing the frogs to use additional shore habitat immediately along the river and perhaps to disperse to other sites in the warmer river waters.

The Colorado River in this region has been profoundly altered and is subject to extensive management. This management must balance many often-conflicting demands and mandates, ranging from power production to limiting or mitigating negative effects of dam operations on physical, cultural, and biological resources, including endangered species. The marsh site at Horseshoe Bend—and the populations of northern leopard frogs and other species that it supports—must be added to this complex mix of demands. Within the context of the other physical, biological, and economic considerations in the management of the river, all reasonable efforts should be taken to protect this unique site.

Acknowledgments

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Appendix. Areas Surveyed for Northern Leopard Frogs

Areas surveyed on foot for northern leopard frogs (*Rana pipiens*) in the Glen Canyon National Recreation Area during 1993. River sites are areas along the Colorado River between Glen Canyon Dam and Lees Ferry; lake sites are areas off Lake Powell. River mile (RM) references are based on Lees Ferry = 0; negative values indicate upstream site. Survey week 1 was 1–4 June; week 2 was 2–5 August.

River sites

1. Ropes Trail area (RM -14.3 R; week 1)
2. Honey Draw (RM -13.2 L; week 1)
3. Backwater above Prop Bar (RM -12.2 L; week 1)
4. Ninemile Draw (RM -9.6 L; week 1)
5. Horseshoe Bend area (RM -8.6 to -9.4 L; weeks 1 and 2)
6. 6½-mile Marsh (RM -6.5 R; weeks 1 and 2)
7. Hidden Slough (RM -6.2 R; weeks 1 and 2)
8. Water Holes Canyon (RM -3.8 L; week 2)
9. 2½-mile Marsh (RM -2.5 L; week 2)
10. Lees Ferry (shoreline and small tributary stream, above boat ramp, RM -0.2 R; week 2)
11. Lees Ferry (boulder-gravel bar just upstream of mouth of Paria River, RM +0.2 R; weeks 1 and 2)
12. Lower Paria River (Paria River N of road at Lees Ferry; week 1)

Lake sites

1. Bowns Canyon (tributary of Lake Powell, RM -78 R; week 2)
 2. Ribbon Canyon (tributary of Lake Powell, RM -69 L; week 2)
-

Temperature Patterns of Rattlesnakes at Natural Bridges National Monument, Utah

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Abstract. We implanted 12 western rattlesnakes (*Crotalus viridis*) with temperature-sensitive radios; 4 each in 1989 and 1990 and 7 in 1991 (3 snakes were tracked for 2 years). Individual snakes were tracked for 1 to 2 years and were located daily while active. Average body temperature for this population was $22.5^{\circ}\text{C} \pm 6.98^{\circ}$ (range $18.4\text{--}26.7^{\circ}\text{C}$). Body temperatures were low relative to body temperatures reported for *C. viridis* and other species of rattlesnakes. Substrate temperature best predicted body temperature, but air temperature played a role in determining body temperature for many snakes. In 1990, an incubating female maintained a higher and more constant body temperature than any other snake in the study during the 3 years, including her own temperature in 1989. Except during gestation, western rattlesnakes at Natural Bridges apparently will accept lower body temperatures to meet other physiological needs.

Key words: Body temperature, *Crotalus*, radiotelemetry, reproductive ecology, thermoregulation.

Body temperature (T_b) plays a critical role in snake ecology, regulating behavioral and physiological responses to the environment. As ectotherms, snakes must rely on external heat to raise body temperatures above the activity threshold and thus are tightly coupled to their physical environment. Body temperature results from interactions between physiological, behavioral, and

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physical factors in ectotherms. Behavior determines the particular physical microenvironment of the snake and is the most important (Lillywhite 1987).

Metabolic processes are temperature dependent with maximum rates occurring at specific temperatures (Huey 1982). This pattern has generated predictions that ectotherms have an optimum T_b for metabolic activity, and that they thermoregulate to keep T_b 's as near optimum as possible (Huey and Stevenson 1979; Pough 1980; Huey 1982). It is often assumed that the mean of a range of observed activity T_b 's represents this optimum T_b for the species (Huey and Slatkin 1976; Huey et al. 1977; Magnuson and Beitingner 1978; Greenwald and Kanter 1979; Huey 1982; Pough and Gans 1982). An alternative hypothesis is that each metabolic process (e.g., digestion, locomotion, gestation, etc.) has its optimum temperature (Bustard 1967; Pough 1974, 1980; Lang 1979; Gier et al. 1989). Observed T_b 's represent either a compromise among various needs optimized at different temperatures or optimization of one process at the expense of other activities (Gibson et al. 1989; Huey et al. 1989; Peterson et al. 1993).

Whereas research into thermoregulation by reptiles has increased over the past 20 years, more work has been done with lizards than with snakes (Lillywhite 1987). Body temperatures have been reported for over 100 species of snakes, but there are few studies where T_b has been collected systematically along with ecological and physiological characteristics (Avery 1982; Lillywhite 1987). Thermal relations of rattlesnakes (*Crotalus* spp.) are poorly known (Cowles and Bogert 1944; Brattstrom 1965; Cunningham 1966; Hirth and King 1969; Moore 1978; Brown et al. 1982; Beck 1991), and studies of free-ranging rattlesnakes are rare (Brown et al. 1982; Beck 1991).

Western rattlesnakes (*Crotalus viridis*) are frequently seen at Natural Bridges National Monument (NABR), especially near the residence area (including the visitor center). Safety concerns for employees and visitors resulted in funding for a study of rattlesnakes in the residence area. We designed the study to learn more about the ecology of western rattlesnakes at NABR and to determine what attracts snakes to the residence area. We considered their thermal relations important. Two objectives were to correlate snake T_b with ambient conditions (e.g., air and substrate temperatures at snake locations and microhabitat characteristics of snake locations) and physiological events (e.g., feeding, shedding, gestation). We report on some aspects of the thermal ecology of *C. viridis* at NABR.

Methods

Natural Bridges is about 2,000 m in elevation on the lower slopes of the Abajo Mountains in southeastern Utah. The habitats occupied by snakes were predominantly piñon–juniper woodland, and ledgy, rocky slopes along upper canyon edges.

Temperature-sensing radios were surgically implanted in snakes (4 each in 1989 and 1990 and 7 in 1991—3 were tracked for 2 years for a total of 12 individual snakes). Snakes were released where captured and located once daily in 1989 and 1991 and twice daily in 1990. At each location, T_b was determined from radio pulse frequency (Beck 1991). Air temperature (T_a) was measured in the shade at a height of 1 m within 2 m of the snake. Substrate temperature (T_s) was measured with the thermometer tip barely below the soil or litter surface, in the same thermal environment as the snake (e.g., full sun, vegetation-filtered sun, under rock, etc.), and as near the snake as possible (usually within 0.1–0.5 m). Taylor digital thermometers and Schultheis thermometers were used for T_a and T_s . Minimum (T_{min}) and maximum (T_{max}) daily temperatures were recorded near the visitor center at the NOAA weather station.

Analyses of variance were performed on the data to compare mean temperatures of individual snakes. Tukey's multiple means comparisons were used to test for significant differences between pairs of means (Sokal and Rohlf 1981; Minitab, Inc. 1991). Stepwise multiple regressions (Minitab, Inc. 1991) were run using T_s , T_a , date, and time of observation to learn which environmental factors regulate T_b . One female (12) tagged in 1989 and 1990 was gravid in 1990 and incubated her young 24 May to 10 August. Snake T_b 's were compared during this period using analysis of variance and Tukey's tests.

Results

Snake 32 was killed 9 days after release—its T_b data were excluded from these analyses. Mean T_b for all snakes in the study was $22.5^\circ\text{C} \pm 6.98^\circ$. Snakes in 1989 and 1990 (except 12 in 1990) had lower T_b 's than any snake in 1991 (Fig. 1). Figure 2 shows T_b 's for each snake in 1989 plotted with T_{min} and T_{max} (at visitor center) and T_s for each snake location. Figure 3 has similar plots for snakes in 1990, and the T_b 's for snakes in 1991 are plotted with environmental temperatures in Fig. 4. Results of stepwise multiple regression for individual snakes are shown in

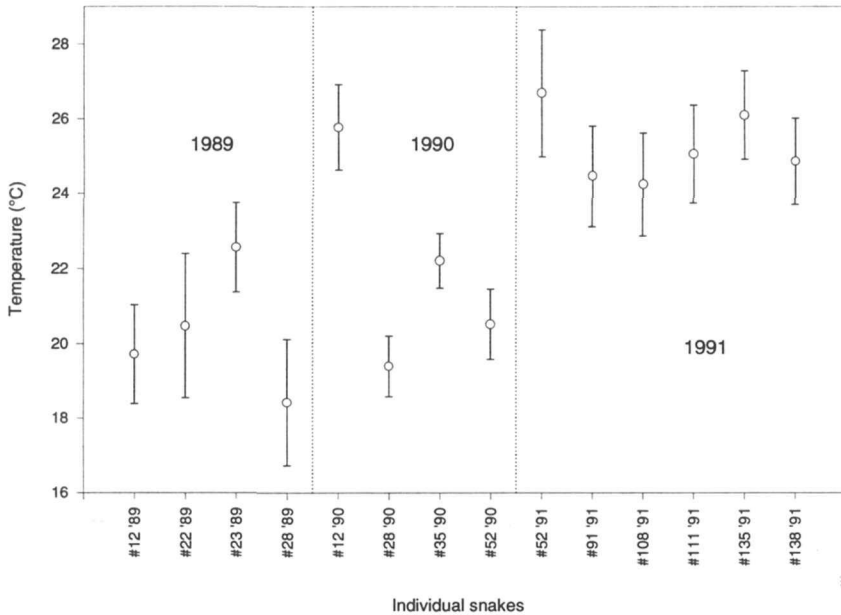


Fig. 1. Body temperature ($\bar{x} \pm 95\%$ CI) of 11 snakes measured during each individual's entire observation period in 1989, 1990, or 1991. Three snakes were each monitored in 2 consecutive years. Mean snake T_b 's (body temperatures) in 1991 were significantly warmer than all snakes in 1989 or 1990 except snake 12 in 1990; mean T_b 's of snakes in 1989 and 1990 did not differ except for snake 12 in 1990.

the Table. Substrate temperature accounted for most of the variation in T_b in 11 snakes, T_a was most important in 2 snakes, and the T_b of 1 snake correlated best with date.

Average T_{min} and T_{max} measured at the visitor center were warmer in 1989 than 1991, but temperatures in 1990 did not differ from either 1989 or 1991. Results of Tukey's multiple means comparison tests for T_a and T_s from all snakes over all their observation periods for each year showed that average T_s for 28 in 1989 differed from all 1990 snakes and from snakes 91, 108, and 111 in 1991. Mean T_a comparisons found that snake 35 in 1990 differed from snake 28 in 1989 and snake 52 in 1991.

During incubation in 1990, snake 12's T_b was significantly higher than all other snakes in the study (Fig. 5). Variation in T_b was significantly smaller for snake 12 than any other snake as well. The coefficient of variation (CV) of snake 12's T_b was 6.33%—CVs ranged from 11.4 to 39.8% for the other snakes.

Comparing snake 12's T_b in 1989 and 1990 emphasizes the difference in T_b between nongravid and gravid snakes. Snake 12's average T_b 's in 1989 and 1990 for the entire observation period (15 June to 6 October 1989, 16 April to 17 August 1990) were different (Fig. 1), but variation about the means was similar in both years ($CV_{1989} = 30\%$, $CV_{1990} = 33\%$). During the time snake 12 was incubating (24 May to 10 August 1990), average temperatures were again different between years (Fig. 5), but T_b in 1990 was more constant ($CV_{1989} = 27\%$, $CV_{1990} = 6\%$).

No differences in T_{min} or T_{max} existed during the incubation period for the 3 years. Average T_s at locations for snake 28 in 1989 differed from all four snakes in 1990, and from snakes 91 and 108 in 1991. Snake 28 in 1990 had T_s 's that differed from all snakes in 1989 and from snake 138 in 1991. Means for both T_a and T_s for snake 12 in 1990 differed from snake 28 in 1989, and from snakes 108, 135, and 138 in 1991. Average T_s 's for both snakes 35 and 52 in 1990 were different from snakes 23 and 28 in 1989, and from snakes 135 and 138 in 1991. Mean T_a differed between snake 28 in 1989 and all snakes in 1990. Both snakes 35 and 52 in 1990 T_a 's differed from snakes 135 and 138 in 1991; snake 108 T_a 's were also different from those of snake 35.

Discussion

Mean T_b 's for active *C. viridis* reported in the literature range from 25.4 to 31.7° C (Cowles and Bogert 1944; Brattstrom 1965; Cunningham 1966; Hirth and King 1969; Moore 1978; Brown et al. 1982; Charland and Gregory 1990; Beck 1991). At NABR, individual mean T_b 's ranged from 18.4 to 26.7° C; the average T_b was 22.5° C \pm 6.98°. The low mean T_b 's in this study could result from including cool days in spring and fall, but Hirth and King (1969) reported warmer spring (25.5° C) and fall (29° C) T_b 's for *C. v. lutosus* in northeastern Utah. Snakes at NABR tracked only during summer (e.g., 22, Fig. 2B; and 111, Fig. 4D) also had low mean T_b 's. Whereas these data represent only daily snapshots of snake activities, we believe the large number of observations for each snake provides a realistic range of T_b 's. Most published T_b 's are single measurements of one or more individual snakes, not extended series of daily measurements of the same snakes, and thus may not be directly comparable to results of this study.

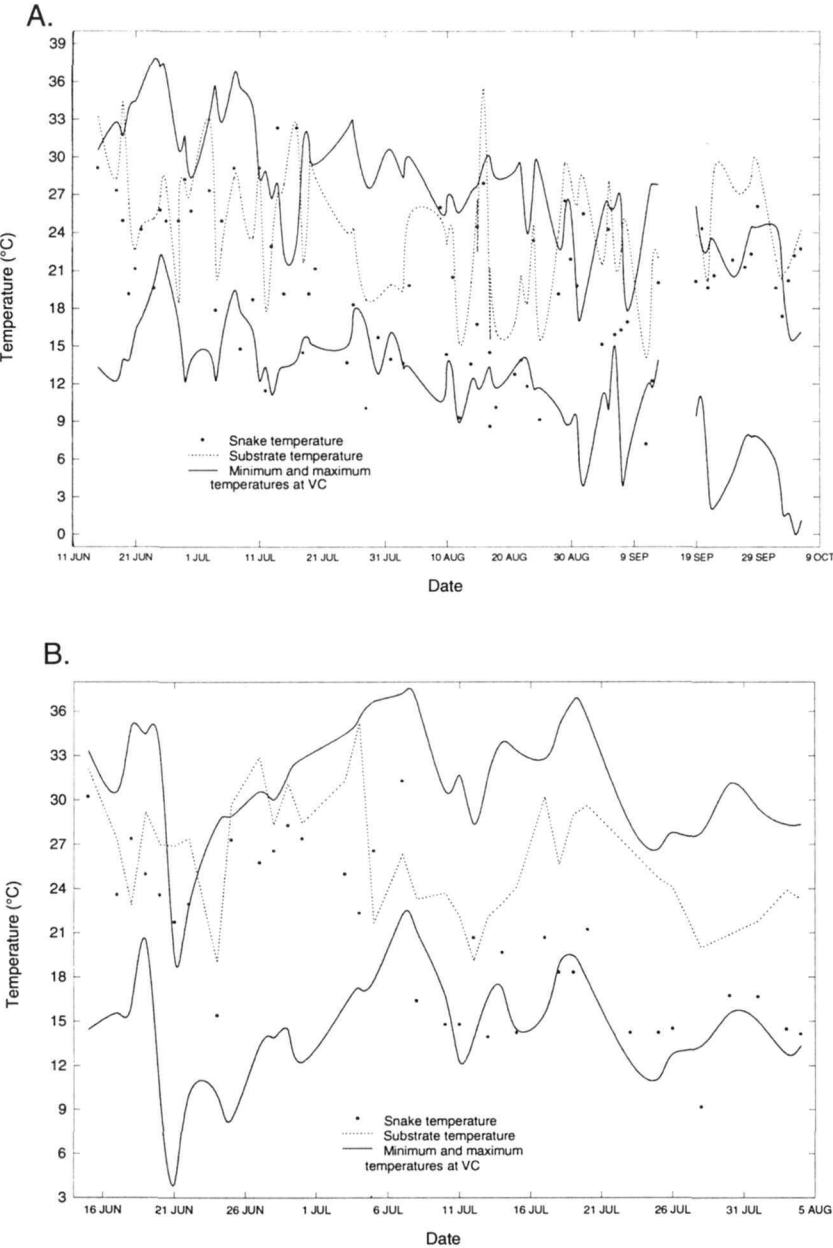


Fig. 2. Daily body temperatures of four snakes monitored in 1989, plotted with T_{min} and T_{max} (minimum and maximum daily temperatures) at the visitor center, and T_s (substrate temperature). Breaks in the data are due to surgeries to implant new radios. A. snake 12, B. snake 22, C. snake 23, and D. snake 28.

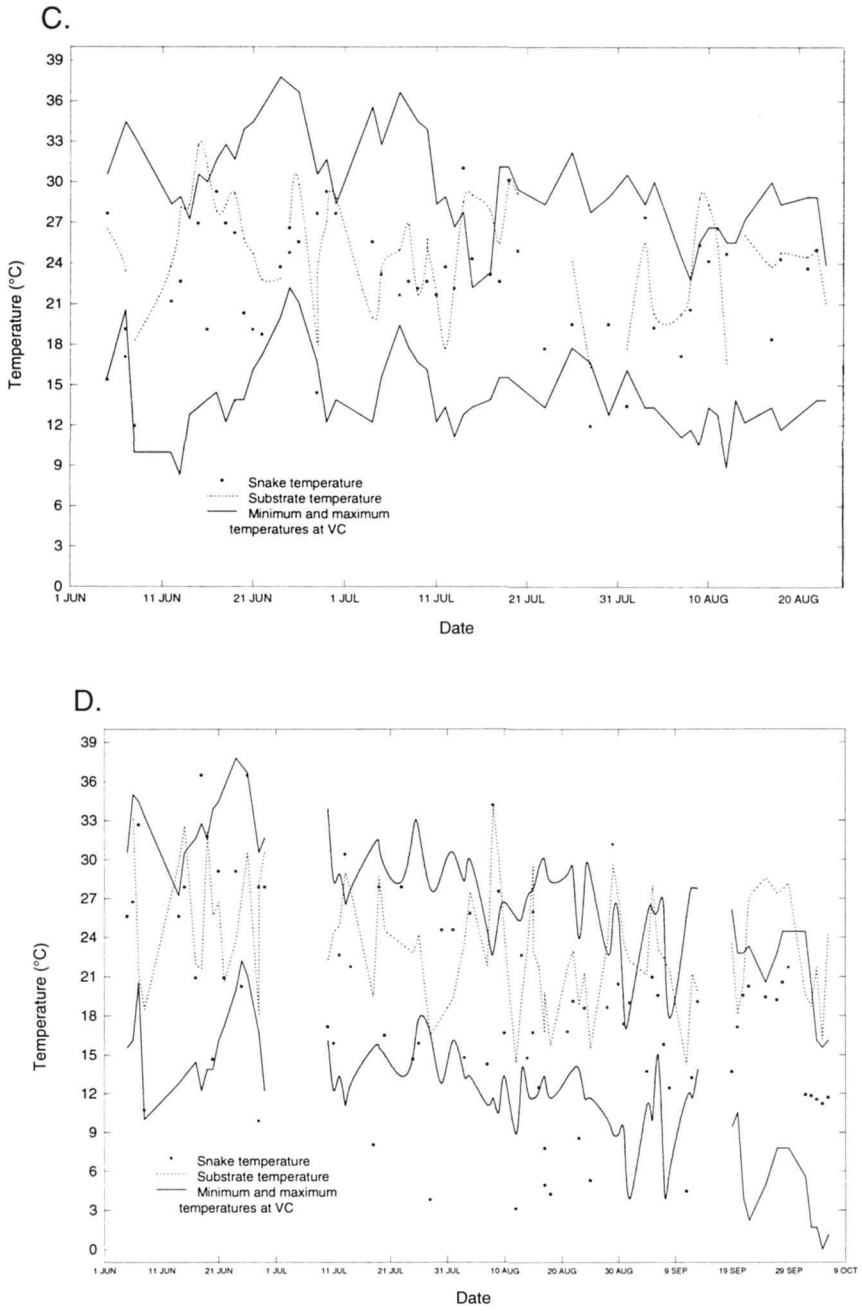


Fig. 2. Continued.

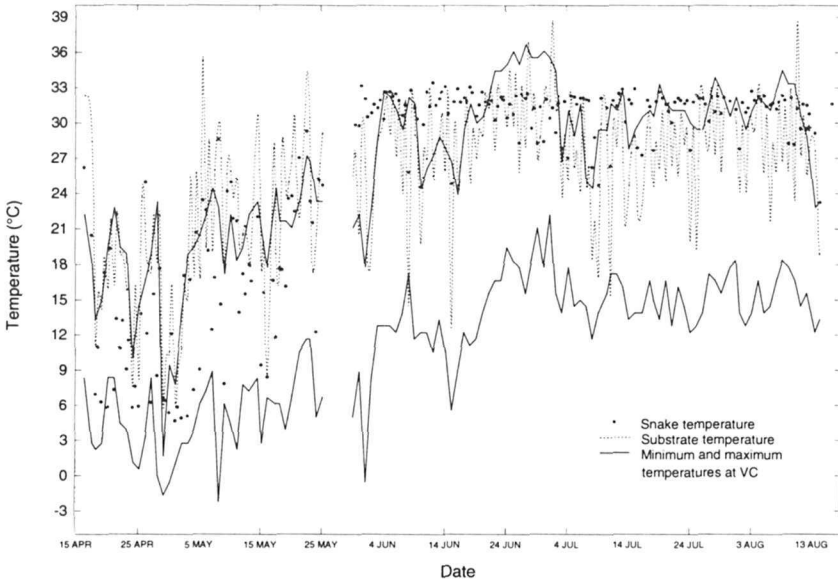
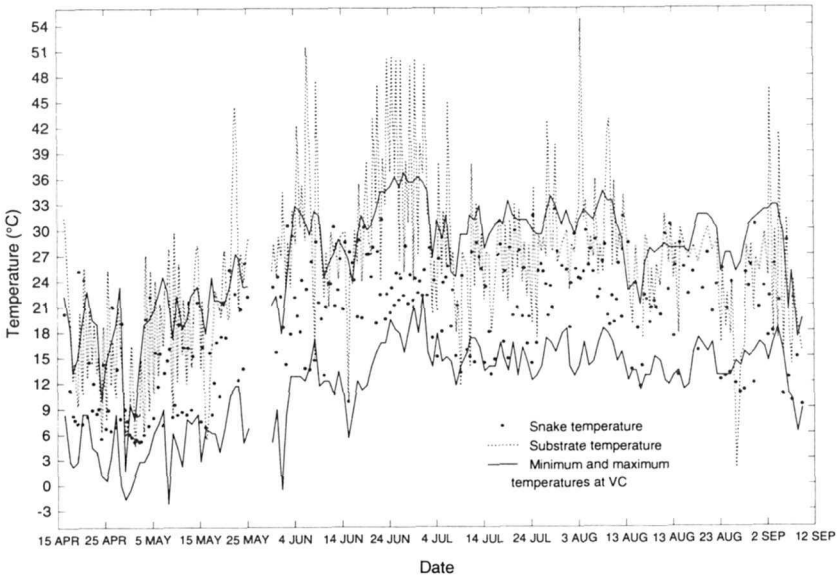
A.**B.**

Fig. 3. Daily body temperatures of four snakes monitored in 1990, plotted with T_{min} and T_{max} (minimum and maximum daily temperatures) at the visitor center, and T_s (substrate temperature). Breaks in the data are due to surgeries to implant new radios. A. snake 12, B. snake 28, C. snake 35, and D. snake 52.

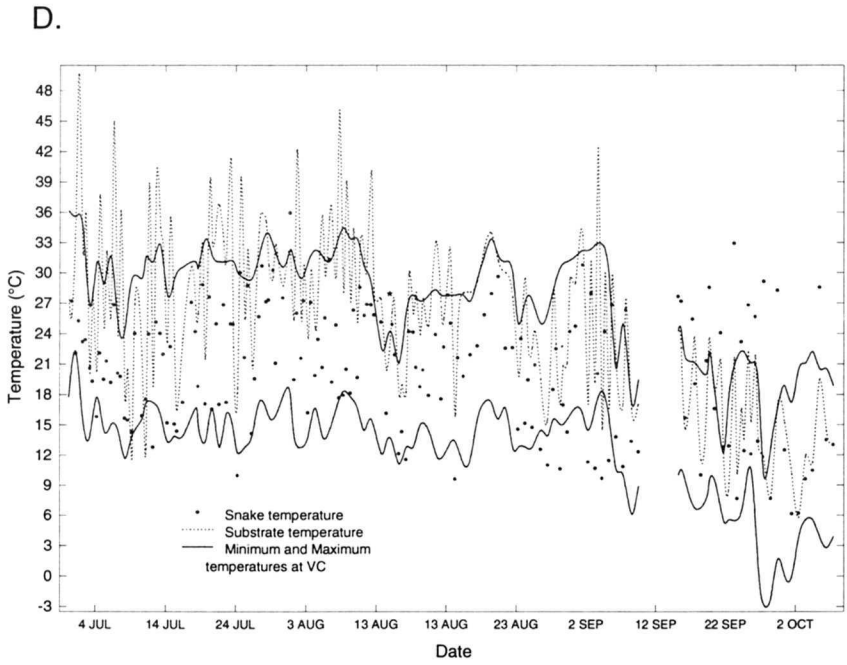
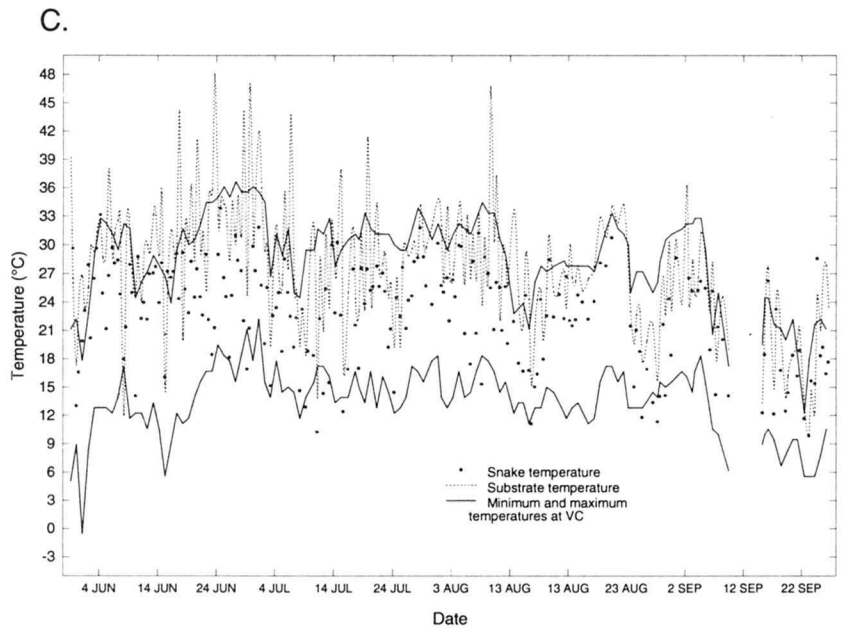


Fig. 3. Continued.

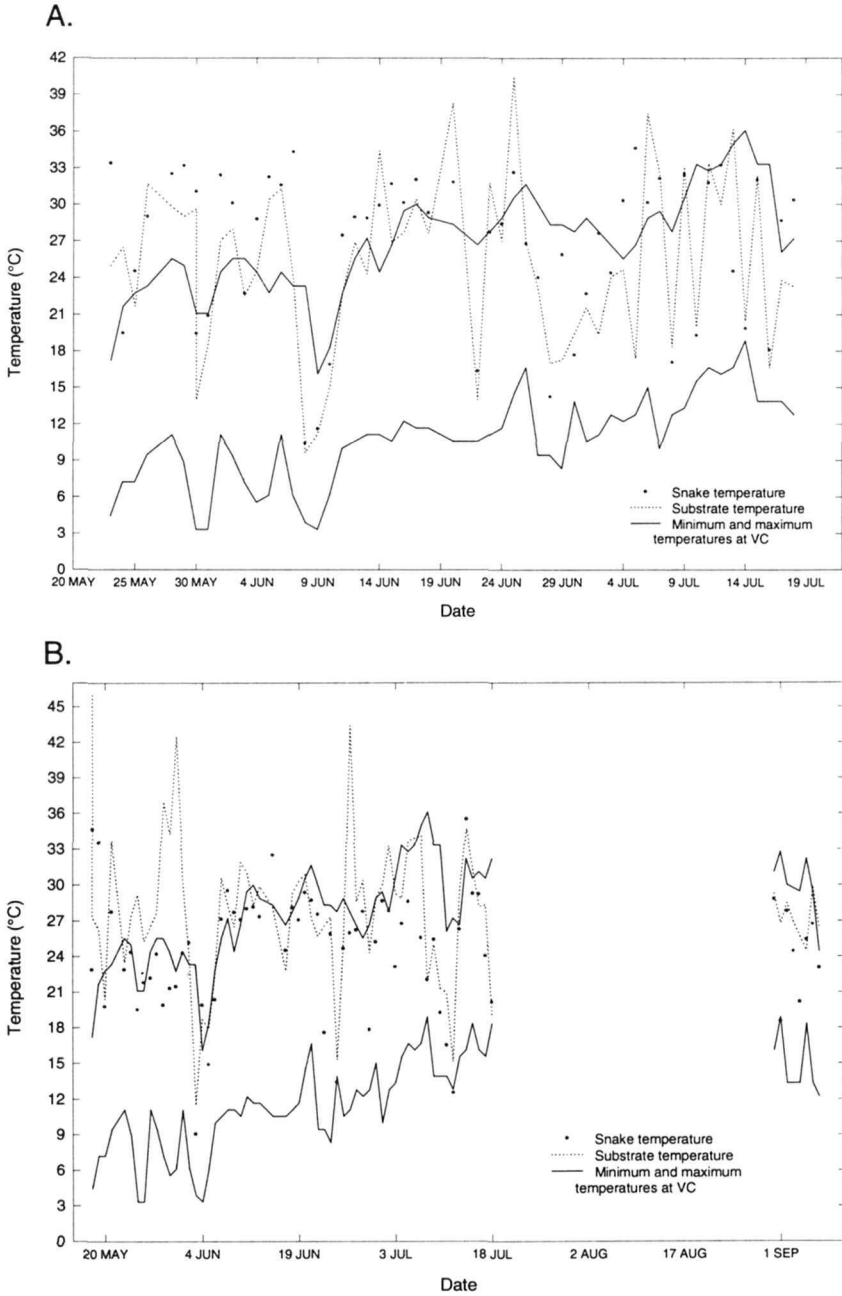


Fig. 4. Daily body temperatures of six snakes monitored in 1991, plotted with T_{min} and T_{max} (minimum and maximum daily temperature) at the visitor center, and T_s (substrate temperature). Breaks in the data are due to surgeries to implant new radios, or equipment failure. A. snake 52, B. snake 91, C. snake 108, D. snake 111, E. snake 135, and F. snake 138.

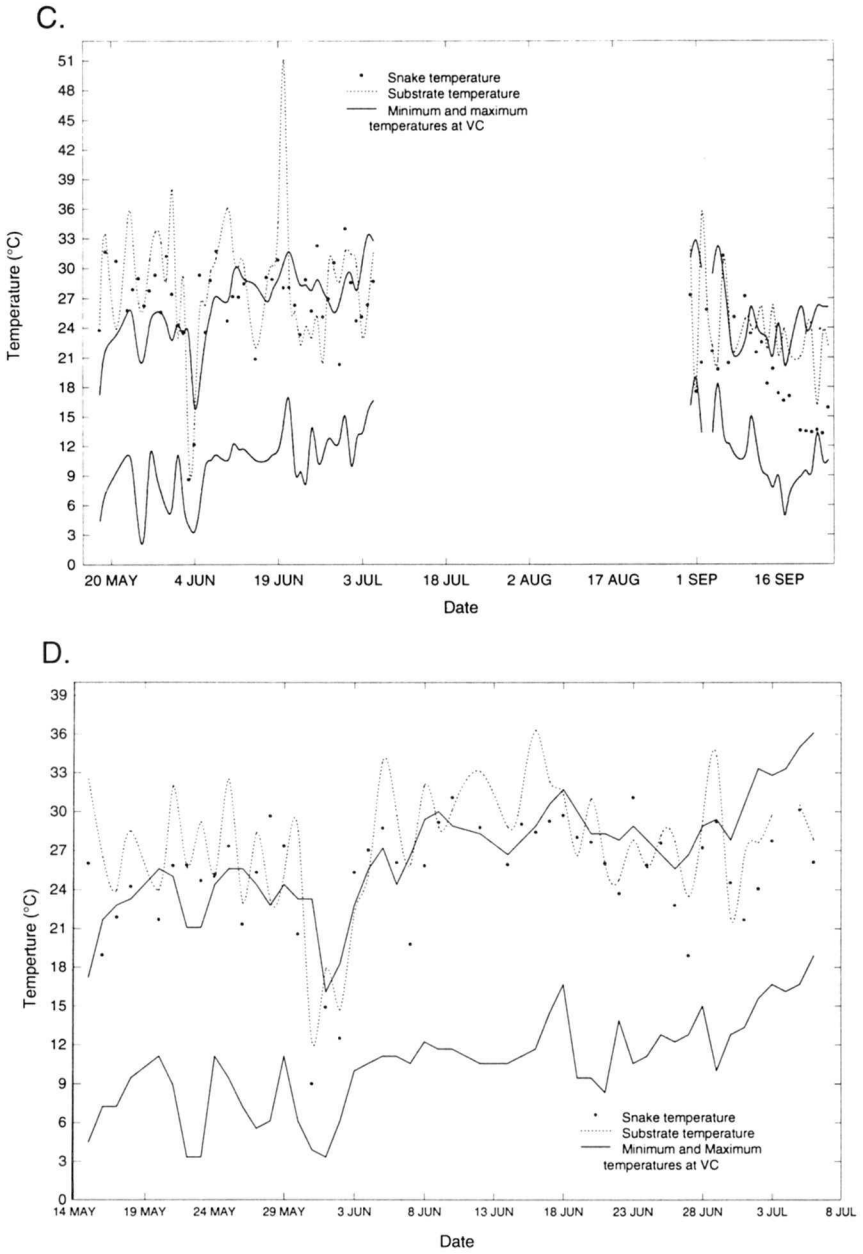
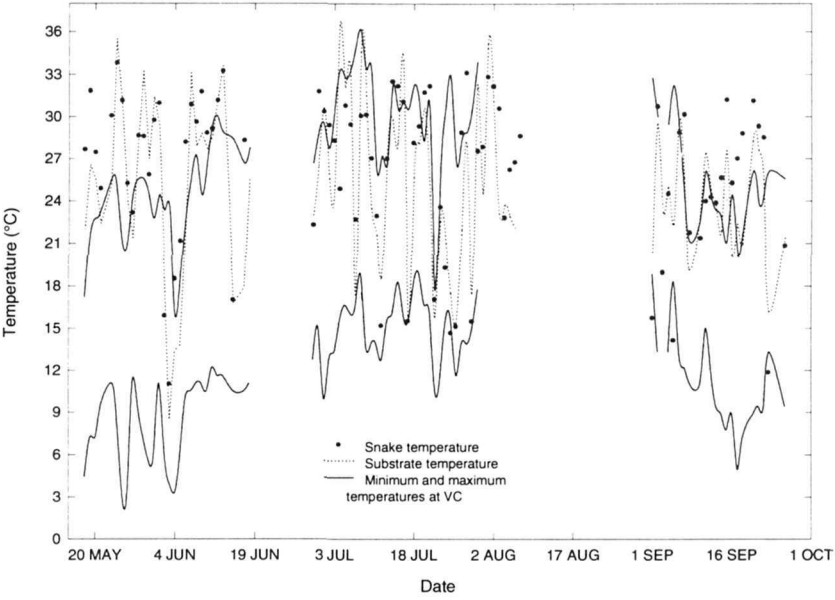


Fig. 4. Continued.

E.



F.

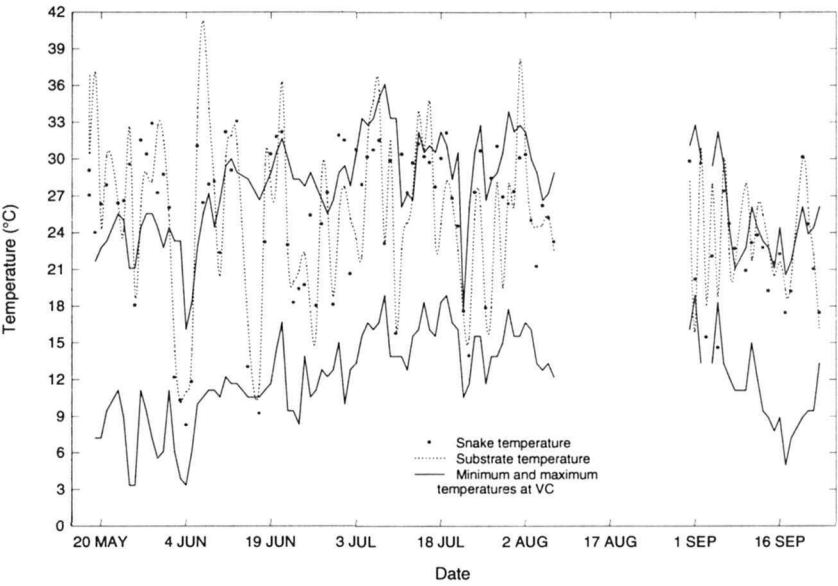


Fig. 4. Continued.

Table. Regression coefficients for stepwise multiple regression analysis of western rattlesnake body temperature (T_b) on substrate temperature (T_s), air temperature (T_a), date,^a and time^b of observation for 14 snake observation periods. Only significant regression coefficients ($P < 0.05$) are shown.

Snake	Year	T_s	T_a	Date	Time	Total
12	1989	69.11			2.80	73.02
22	1989		19.59	52.63		77.81
23	1989	40.02				47.57
28	1989	21.67	14.91	4.58		41.91
12	1990	61.98		16.79		79.93
28	1990	1.41	60.49	1.48	2.22	68.24
35	1990	1.62	50.68	1.54		55.37
52	1990	41.62			4.99	49.15
52	1991	50.02				50.73
91	1991	39.53	10.51		4.92	56.76
108	1991	40.32	6.01	13.50		66.44
111	1991	60.22	6.67			67.67
135	1991	60.76			5.89	70.17
138	1991	61.82	9.16	2.71		74.43

^aDate = stepwise multiple regression of the date of observation.

^bTime = stepwise multiple regression of the time of observation.

Intraspecific variation in temperature preferences does occur in reptiles (Dawson 1975; Huey 1982). Western rattlesnakes at NABR could have lower preferred temperatures than other populations, and they may have cooler T_b 's than many other rattlesnake populations because they live in a cooler thermal environment. Keeping T_b 's above ambient temperature at NABR may require so much active thermoregulation that other needs can't be met. As a result, snakes operate at lower T_b 's. Data from a population in Wyoming support this hypothesis. Graves and Duvall (1993) found gravid females had higher T_b 's than nongravid females in this population but that gravid females engaged in active thermoregulation at the expense of almost all other activities, whereas nongravid females spent their time in long-distance foraging moves during summer.

Body temperatures were similar between snakes within years but differed between years, even for the same snakes. This suggests that snake T_b 's were determined by some component(s) of the physical environment that differed between years, or that thermoregulatory signals differed consistently between years, or that different snakes had different preferred T_b 's. Examination of Figs. 2–4 reveal that in 1989 and 1990, T_b 's were between the daily maximum

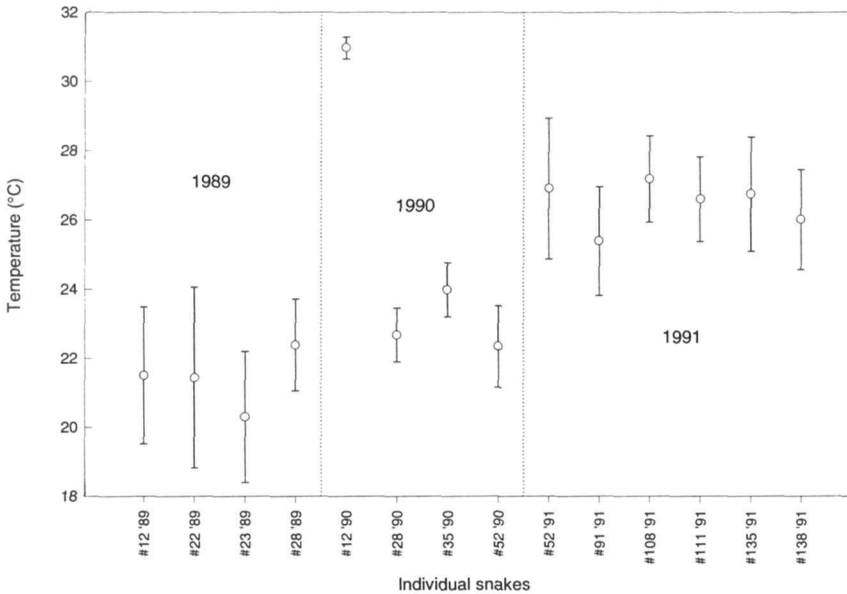


Fig. 5. Body temperature ($\bar{x} \pm 95\%$ CI) of 11 snakes during the incubation period of 12 in 1990 (25 May to 10 August) 1989, 1990, or 1991. Three snakes were each monitored in 2 consecutive years. In 1990, snake 12 had a higher mean T_b (body temperature) for this period than any other snake, including its own T_b in 1989.

and minimum temperatures (measured at the visitor center), and were spread throughout the range. In 1991, most T_b values were still within the visitor center maximum–minimum temperature range but were clustered near the maximum line much more than in 1989 or 1990. In 1991, snake T_b 's followed T_s more closely than in 1989 or 1990 (Figs. 2–4). This is also evident from the results of regression analyses where T_s accounted for most of the explained variation in T_b 's in all snakes followed in 1991 (Table). Body temperatures of snakes tracked more than 1 year (12, 28, 52) all differed between years. Differences in T_b between years were due to differences each year in snake thermoregulatory behavior.

Snakes radio-tagged in 1989 were first captured in the residence area. In 1990, two snakes tagged in 1989 (12 and 28) were tracked from their dens, and two were captured in the residence area and tagged. All of the snakes followed in 1989 and 1990—except snake 12 in 1990—had home ranges in or near the residence area. In 1991, we captured snakes at the den, implanted radios, and

released them at the den. Five of these snakes moved southeast and did not visit the residence area. One (32) was killed a few days after release. The only snake to include the residence area in its home range in 1991 was 52, first captured and tagged in the residence area in 1990.

In 1991, snakes occupied habitat that was subjectively different from habitat near the residence area used by snakes tracked in 1989 and 1990. Habitat used in 1991 was rockier and more open with less tree-and-shrub cover and more exposed bedrock. Microhabitats selected in 1991 probably received more solar radiation than the area around the residences. Whereas air and substrate temperatures in 1991 were comparable to 1989 and 1990, snakes in more open habitats could reach high T_b 's more rapidly in the morning and keep T_b 's higher during the day with less effort and perhaps fewer costs (Lillywhite 1987). The warmest snake in 1989 (23) spent most of his time in the open locations bordering parking lots in the residence area. Snake 35 had the warmest average T_b of any nongravid snake in 1990. This snake, a male, was more active than the three females tracked in 1990, and spent more time in the open in full sun than the other three snakes (unpublished data from authors' observations—not part of this study). Snake 12 selected similar rocky, open habitat for incubation instead of more densely vegetated habitats available nearby.

Snake 12 carried a radio from 15 June 1989 to 17 August 1990. She was gravid in 1990, providing an opportunity to contrast T_b and behavior of the same snake under different physiological constraints. We had radios in males and nongravid females—including snake 28—both years, with data encompassing the entire period that snake 12 was tracked. Because of this, we can compare snake 12's behavior and resulting T_b to the other snakes to assess whether there were deviations from the normal range by snake 12 in either year. Figures 1 and 5 indicated that snake 12's T_b in 1989 did not differ from the other snakes monitored in 1989 nor from nongravid snakes in 1990, but in 1990 her T_b was much higher. The differences between snake 12's T_b during incubation in 1990 and all other snake T_b 's emphasize the importance of thermoregulating to keep T_b high, even at the expense of other physiological needs.

The behavior of snake 12 in 1990 was different from her own behavior in 1989 and different from that of all other snakes observed during the 3 years. Her behavior was similar to gravid female rattlesnakes in other studies (Brown et al. 1982; Reinert 1984; Graves et al. 1986; Reinert and Zappalorti 1988; Graves and Duvall 1993; Peterson et al. 1993). The few differences between environmental temperatures at snake 12's locations in 1990 and at other snake locations

indicate that snake 12's T_b was maintained by active thermoregulation rather than thermoconformity with the microhabitats each snake selected.

Moves by snake 12 in 1989 were extensive. She was first captured on 5 June 1989 in the residence area, and her home range in 1989 was estimated to be more than 5 ha (unpublished data from authors' observations—not part of this study). In 1990, she moved only approximately 325 m (straight line distance) from the den and remained in a 30-m² area for 79 days until parturition. In 1989, snake 12 ate at least twice—we did not detect her feeding at all in 1990. Even during the spring migration from the den in 1990, snake 12 maintained a higher T_b than snake 28 ($T_{b12} = 15.15 \pm 6.96$, $T_{b28} = 12.43 \pm 5.91$, $t_{139} = 2.54$, $P = 0.012$).

Charland and Gregory (1990:1090) identify "at least two factors that influence thermoregulatory behavior of a free-ranging snake: its preferred T_b and the priority it places on thermoregulation (i.e., thermoregulation may conflict with other activities)." The difference in T_b between 1989 and 1990 for snake 12 reflects a shift in the priority the snake placed on thermoregulation between the 2 years; this shift was generated by pregnancy. In 1989, snake 12's priorities were probably related primarily to foraging, whereas in 1990, maintaining a high T_b superseded other needs. Maintaining a high T_b at Natural Bridges is apparently not compatible with other activities. Graves and Duvall (1993) suggested foraging conflicts with efficient thermoregulation in the cool Wyoming environment of the population they studied. Gravid females do not undergo the extensive vernal migrations in search of dense populations of small rodents that males and nongravid females do (Duvall et al. 1985, 1990).

Gravid female snakes have been documented to aggregate in rookeries in some populations (Brown et al. 1982; Reinert 1984; Reinert and Zappalorti 1988; Graves and Duvall 1993). We did not observe this at Natural Bridges. No other snakes were observed near snake 12's rookery at any time during 1990. We believe this difference reflects a greater abundance of thermally suitable microhabitats for gestation at Natural Bridges relative to these other studies.

An organism's maximum metabolic rate occurs at a specific temperature, considered to be its optimum or preferred temperature (Dawson 1975; Huey 1982). Ectotherms thermoregulate to maintain body temperature as near optimum temperatures as possible (Huey and Stevenson 1979; Pough 1980; Huey 1982). Various metabolic processes (e.g., digestion, locomotion, gestation, etc.), however, could have different temperature optima (Regal 1966; Pough 1980; Slip and Shine 1988; Peterson et al. 1993). Ectotherms may regulate T_b to

optimize one process at the expense of other activities or compromise efficiency among a variety of metabolic needs (Dawson 1975).

Environmental constraints, physical and biological, can prevent ectotherms from maintaining their T_b 's near optimum temperature (DeWitt 1967; Muth 1977; Magnuson and Beiting 1978; Magnuson et al. 1979; Peterson 1987; Gier et al. 1989). Body temperatures may also deviate from optimum because thermoregulatory behavior is too costly in terms of predation risk, loss of foraging time, energetic costs, competition, or social interactions (Regal 1967; Huey 1974; Huey and Slatkin 1979; Huey 1982; Charland and Gregory 1990).

Snakes have needs (e.g., thermoregulation, food, shelter, mates) that must be balanced in a heterogeneous environment. Beck (1991) found that thermoregulatory response varied with time of year; basking occurred only when ambient temperatures were low. Basking is not without costs because snakes are more exposed to predators, are not able to actively forage, and can't search for mates. In fact, snakes may bask only when the need to raise T_b is greater than other physiological needs (Huey 1974; Beck 1991).

Western rattlesnakes at NABR are capable of maintaining high, constant T_b 's, at least in summer. Ambient temperatures at NABR are high enough for snakes to be active without basking but not high enough to maintain high T_b 's without basking. At NABR, males and nonincubating females sacrifice high T_b 's to perform other necessary activities. Pregnant females such as snake 12 in 1990 must maintain a high, constant T_b for normal development of embryos and do so at the expense of other needs.

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Cowbird Concentrations at Livestock Corrals in Grand Canyon National Park

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Abstract. Brown-headed cowbirds (*Molothrus ater*) at Grand Canyon National Park parasitize broods of many neotropical migrants including the southwestern willow flycatcher (*Empidonax traillii extimus*). We conducted surveys from 16 May through 28 July 1993 for brown-headed cowbirds at horse and mule corrals at five sites in the Grand Canyon, noting presence, abundance, sex, and foraging habits of cowbirds. Brown-headed cowbirds were detected at three of five pack stations where they foraged on grain, hay, mule dung, and insects. Cowbird numbers were lowest in the morning (before 1000 h) and increased thereafter. Brown-headed cowbirds are known to spend mornings in breeding areas and concentrate at foraging centers during midday. Corrals along the rim are providing important foraging centers for cowbirds and may be allowing these cowbirds to brood parasitize nests of other bird species in local forest and riparian areas.

Key words: Brood parasitism, brown-headed cowbird, monitoring, neotropical migrants.

The brown-headed cowbird (*Molothrus ater*) is a small passerine bird found throughout most of the United States and southern Canada. It is one of only three obligate brood parasites in North America (Brittingham and Temple 1983). Brood parasitism occurs when one species (the parasite) lays its eggs in the nest of another species (the host). The host species incubates the egg and raises the young of the parasite.

Before the arrival of European settlers, the cowbird was largely confined to the grasslands of the midcontinent. The cowbird followed grazing animals and ate the insects they stirred up (Wilcove et al. 1986). By the late 1800's, cowbirds were apparently widespread but not abundant in eastern North America and were found primarily in cultivated areas (Brittingham and Temple 1983).

The range of the brown-headed cowbird continued to increase in association with agricultural development and urbanization, and numbers still seem to be increasing in the West (Robinson et al. 1993).

Brown-headed cowbirds lay their eggs early in the day—usually before sunrise (Scott 1991). Female cowbirds usually lay 14–16 eggs per nesting season but in captivity are capable of laying up to 77 eggs in a season (Jackson and Roby 1992; Holford and Roby 1993). The incubation period of cowbirds is usually shorter (11–12 days) than the incubation period of the host, giving the cowbird nestling a distinct advantage over the host species nestlings (Friedmann 1963). Cowbird nestlings develop faster and demand more food and attention from the host parents (Friedmann 1929; Ortega and Cruz 1991).

Brown-headed cowbirds typically demonstrate a pattern of daily movement between separate foraging and breeding areas. Radio-tracking of cowbirds in the eastern Sierra Nevada of California showed that females and males spent mornings in host-rich habitat such as riparian zones and then commuted 2–7 km in the late morning and afternoon to one or more prime feeding sites such as horse corrals and pack stations (Rothstein et al. 1984).

Cowbirds regularly parasitize nests along the Colorado River corridor in the Grand Canyon—often nests of rare or declining species. For example, nest parasitism of southwestern willow flycatchers (*Empidonax traillii eximius*) is well documented (Brown 1988; Sogge et al. 1993*¹). Cowbird parasitism affects willow flycatcher populations through reduced nesting success, reduced productivity, and delayed successful fledging of young (Sanders and Flett 1989; Whitfield 1990; Harris 1991; Sogge et al. 1993*). Nests of many other species of neotropical migrants, including Bell's vireos (*Vireo bellii*), yellow warblers (*Dendroica petechia*), and yellow-breasted chats (*Icteria virens*), were parasitized in the park (Brown et al. 1987; Johnson and Sogge 1993*).

The Grand Canyon National Park management and the park concessionaire (Fred Harvey Co.) maintain horse and mule corrals at five sites in the Grand Canyon. As demonstrated in the Sierra Nevada, such stations may provide foraging centers for brown-headed cowbirds (Rothstein et al. 1984; Beedy and Granholm 1985; Gains 1988). Brown et al. (1987) provide anecdotal records of brown-headed cowbirds foraging at park corrals. The food sources could attract cowbirds that might parasitize bird nests in adjacent areas and along the river

¹ Asterisk indicates unpublished material.

corridor (<10 km away). Grand Canyon National Park resources management staff requested that we develop a monitoring program to determine if park corrals were serving as foraging centers for brown-headed cowbirds. We designed the project to determine abundance and foraging activity of brown-headed cowbirds at the livestock corrals.

Methods

The project was coordinated by the Cooperative Park Studies Unit at Northern Arizona University (CPSU/NAU; currently the National Biological Service, Colorado Plateau Research Station). Surveyors included personnel from the CPSU/NAU and the National Park Service Grand Canyon Division of Resources Management. We conducted surveys at four sites along the south rim of the Grand Canyon (referred to as rim sites): Grand Canyon Village corral, Grand Canyon landfill, Yaqui Point corral, and Sunset Drive mule and horse corral (Fig. 1). The Phantom Ranch corral located along the river corridor was also surveyed weekly, and two surveys were conducted at two north-rim mule corrals.

Brown-headed cowbirds were detected by sight and song. We conducted surveys at least once per week from 16 May through 28 July 1993. Survey times varied between 0600 and 1600 h and were staggered each week to arrive at each major site at varying times throughout the day. Surveys began on the hour and lasted for 40 min.

Every 10 min throughout each survey period, we recorded the number, sex, and foraging behavior of the cowbirds observed. We noted the specific foraging within the site, and what the cowbirds were consuming (e.g., grain, dung, insects).

To determine the general abundance and distribution of brown-headed cowbirds in riparian areas along the Colorado River corridor, we summarized the cowbird data collected during CPSU/NAU-coordinated southwestern willow flycatcher and breeding bird surveys in 1992 and 1993 (Sogge and Tibbitts 1992*; Sogge et al. 1993*). These data included the location (by river mile), date, and time and the number, sex, and age of each cowbird observed during surveys of willow flycatcher and other breeding birds.

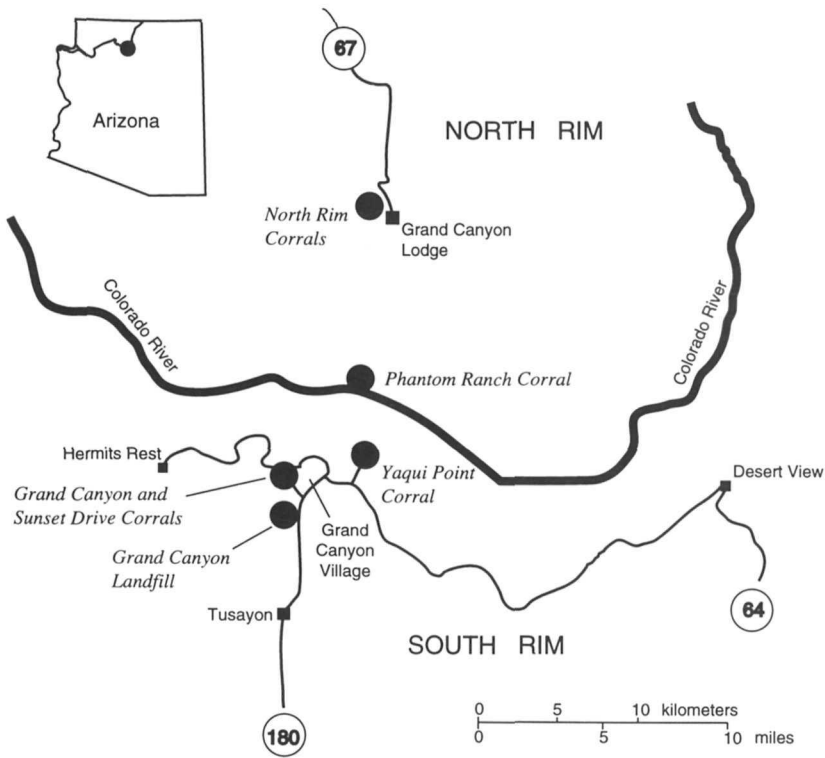


Fig. 1. Brown-head cowbird (*Molothrus ater*) survey sites (●) in Grand Canyon National Park.

Results

We conducted 64 surveys (Table 1) and made 449 observations of brown-headed cowbirds at the Grand Canyon Village, Yaqui Point, and Sunset Drive corrals. Some of the individuals probably were detected in more than one survey. No cowbirds were detected at Phantom Ranch, the Grand Canyon landfill, or the North Rim corral. At the three sites where they were observed, cowbirds foraged on feed grain, mule dung, insects, and other materials. Occasionally, cowbirds rested in trees or structures near the corrals, or males were seen courting females.

Where brown-headed cowbirds were observed in 35 surveys, we detected significantly more males than females ($n_m = 268$, $n_f = 167$, $\bar{x}_m = 7.65$, $SD_m =$

Table 1. Summary of 1993 brown-headed cowbird (*Molothrus ater*) surveys at livestock corrals in Grand Canyon National Park (GRCA).

Survey	GRCA Village	Yaqui Point	GRCA landfill	Phantom Ranch	North rim	Sunset Drive
Number	16	16	16	7	6	3
Total hours	10.6	10.6	10.6	4.6	4.0	2.0

4.85, $\bar{x}_f = 4.8$, $SD_f = 3.4$, $P = 0.001$). The ratio of males to females was 1.6:1. We detected 14 immature (young-of-the-year) cowbirds.

We recorded the most observations of cowbirds at Grand Canyon Village corral, followed by Yaqui Point (Table 2). The difference in cowbird detections between these two sites, however, was not significant. Sunset Drive and the north rim corrals were not surveyed until late July; cowbirds were detected at Sunset Drive but not at the north rim.

Juvenile brown-headed cowbirds first appeared at corrals in late July. Cowbird abundance was maintained throughout the survey period, with a slight (but insignificant) decline in numbers later in the season (Fig. 2).

Cowbird numbers varied by time of day. Numbers were lowest in early morning (0600–0900 h) then increased after 0900 h (Fig. 3). The daily pattern remained constant through all 3 months of surveys.

We found 117 records of brown-headed cowbird sightings along the Colorado River corridor during the southwestern willow flycatcher and breeding bird surveys in 1992–93. These sightings included 135 males, 78 females, 60 unknown sex or age, and 6 juveniles. Two possible male bronzed cowbirds (*Molothrus aeneus*) were noted in 1992. Cowbirds were detected throughout the

Table 2. Number of brown-headed cowbirds (*Molothrus ater*) observed per 40-min survey.^a

Cowbirds	GRCA ^b Village	Yaqui Point	Sunset Drive	GRCA landfill	Phantom Ranch	North rim
Observed	13.8 ± 8.1	11.7 ± 6.9	10.7 ± 3.2	0	0	0
Foraging	11.2 ± 6.7	8.9 ± 5.3	10.3 ± 3.1	0	0	0

^aNumbers given mean ± 1 standard deviation.

^bGRCA = Grand Canyon.

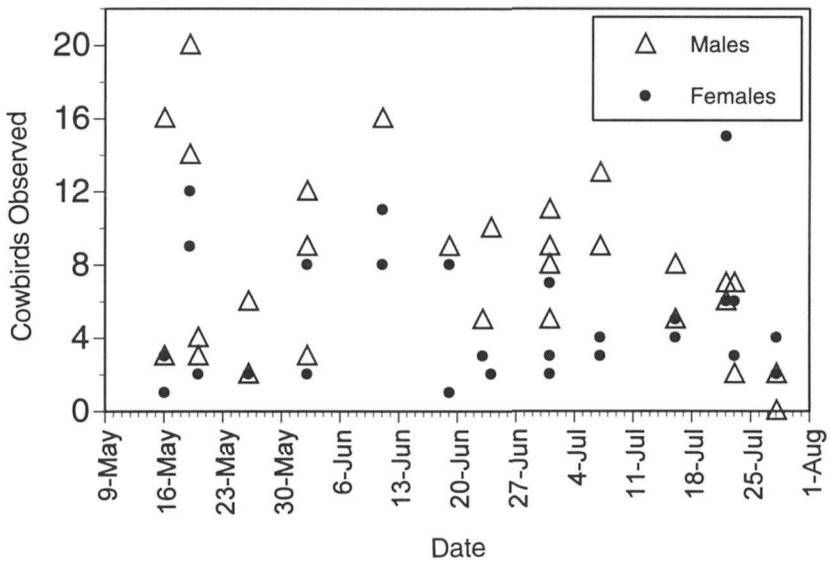


Fig. 2. The number of male (triangles) and female (circles) brown-headed cowbirds (*Molothrus ater*) detected, by survey date, at livestock corrals along the south rim of Grand Canyon National Park.

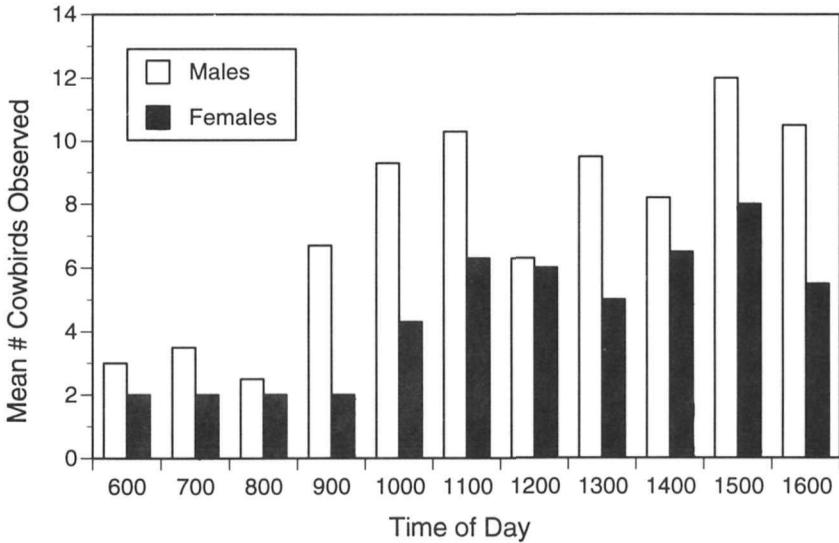


Fig. 3. The mean number of male (white bars) and female (shaded bars) brown-headed cowbirds (*Molothrus ater*) detected each hour during different hours of the day at corrals along the south rim of Grand Canyon National Park.

entire river corridor in Grand Canyon. In addition, we found records of cowbird eggs in nests of Bell's vireos, yellow warblers, common yellowthroats (*Geothlypis trichas*), yellow-breasted chats, and blue grosbeaks (*Guiraca caerulea*). We observed fledgling cowbirds being fed by adult yellow-breasted chats, yellow warblers, and southwestern willow flycatchers.

Discussion

We found brown-headed cowbirds at three of the five sites surveyed (Yaqui Point, Grand Canyon Village, and Sunset Point). At these sites, cowbirds are using corrals as foraging centers. Each corral provided food, water, and presence of stock animals, all important attractants for cowbirds.

At the three foraging centers, we noted significantly more males than females, a situation common with this species (Robinson et al. 1993). The extra males were usually immature and unmated 1-year-old birds that arrive later in the season (Wetmore 1920). Friedmann (1929) also observed males outnumbering females, with a ratio of 3:2, similar to the 3.4:2 ratio that we found.

The largest numbers of actively foraging brown-headed cowbirds were observed at Grand Canyon Village and Yaqui Point corrals. We were unable to determine why these two corrals were the most frequented. These corrals are the largest, are used consistently for horses, and relatively large amounts of cowbird food are always present as attractants (Glahn and Otis 1986).

Contrary to our original expectations, no brown-headed cowbirds were detected at the Grand Canyon landfill. The mule manure deposited at the landfill is a potential source of food for cowbirds, but it is spread throughout the landfill and buried. Burying the manure makes the potential food source inaccessible to cowbirds, thus eliminating cowbird concentration.

Cowbirds were absent from Phantom Ranch corral. We do not know why, particularly given historic concentrations at this site (Brown et al. 1987). Mules at Phantom Ranch are fed the same items as mules on the rim (R. Clayton, Fred Harvey Co., personal communication), thus availability of differing foods is not a factor. Other factors such as presence of hikers or extreme environmental conditions (e.g., heat) at the site may play a role.

Cowbirds were not detected during several opportunistic surveys conducted at the concession and park corrals on the north rim. Mules at these corrals are provided the same food as at south rim corrals; therefore, availability of food

is not responsible for the absence of cowbirds. In the Sierra Nevada of California, cowbirds are uncommon above 2,440–2,590 m (Gaines 1988), thus the high elevation of the north rim (2,680 m) corrals may inhibit cowbird use.

Cowbird numbers varied throughout the day but were lowest during the early mornings when cowbirds are known to frequent riparian and woodland areas where females parasitize host nests. The greatest number of cowbirds was detected between 1100 and 1400 h (Fig. 3). Rothstein et al. (1984) observed similar patterns.

The abundant and widespread cowbird sightings noted along the river corridor reflect the general magnitude of cowbird parasitism. Some cowbirds could move between the river corridor and the corrals, a distance of less than 10 km at the river's nearest point (cowbirds commuted 2–7 km daily in the Sierra Nevada [Rothstein et al. 1984] and are capable of moving greater distances [S. I. Rothstein, personal communication]). Cowbird parasitism of locally breeding neotropical migrant birds is pervasive, not only along the river but in virtually every habitat within the park (Brown et al. 1987). In addition to the warbler species parasitized in our study, cowbirds also parasitize mountain chickadees (*Parus gambeli*), blue-gray gnatcatchers (*Poliophtila caerulea*), and black-throated gray warblers (*Dendroica nigrescens*; Brown et al. 1987).

Reduced productivity associated with cowbird nest parasitism may have detrimental effects on bird communities within Grand Canyon. Loss of productivity for extremely rare species, such as the proposed-endangered southwestern willow flycatcher, can have devastating effects. For example, all three willow flycatcher nests found in the park in 1993 were parasitized by brown-headed cowbirds, and all three nests failed to produce fledgling flycatchers. One pair did successfully rear a cowbird chick (Sogge et al. 1993*).

Nest parasitism by cowbirds may reduce the productivity of many of the neotropical migrant bird species found in the park and may be responsible for the decline of rare species such as the southwestern willow flycatcher. The conservation, protection, and management of avian resources is of concern to managers of Grand Canyon National Park. The park provides breeding areas for a variety of avian species, including many neotropical migratory birds. Parasitism by brown-headed cowbirds is a leading cause of decline of many neotropical migrant birds species (Mayfield 1977; Brittingham and Temple 1983).

General and specific resource-protection mandates exist that support control of cowbirds to reduce effects on bird species within the park. We recommend active management of cowbirds through continued monitoring,

population reduction, and research using radiotelemetry to determine movement of individuals within the park.

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Observations of a Great Blue Heron Colony From 1987 to 1993

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Abstract. Great blue herons (*Ardea herodias*) have nested near Gunnison, Colorado, for at least 40 years. Since 1970, city expansion has forced the birds west; the colony is now located adjacent to Curecanti National Recreation Area in cottonwoods (*Populus angustifolia*) on private land. Observations of population size and reproductive success were made each year since 1987. Occupied nests more than doubled over the past 5 years, and the population seems to have stabilized at about 80 active nests. No immediate threats exist to the colony or to foraging areas, but the long-term survival of the colony is a concern. Cattle grazing under trees within the colony prevents recruitment of cottonwoods. Absence of regeneration will limit the colony as existing trees die. Future changes in land ownership or land uses could affect the colony as well.

Key words: *Ardea herodias*, land use, reproduction, threats.

Many great blue herons (*Ardea herodias*) are colonial breeders, building bulky stick nests in the crowns of large trees (Bent 1926; Hancock and Kushlan 1984; Butler 1992). In the Southwest, most colonies are located in mature cottonwoods (*Populus* spp.) in riparian gallery forests. Colonies are conspicuous and commonly attract birding enthusiasts. Despite this interest, there have been few long-term studies of the breeding biology of great blue herons (Palmer 1962; Pratt 1970; Pratt and Winkler 1985).

Heron nests have been found along the Gunnison River for at least 40 years (Cook 1979*²). This colony has moved twice in the past 26 years, seemingly in response to expansion of the town of Gunnison, Colorado (Cook 1979*; Hyde 1979). The colony is currently located on private land approximately 9 km

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²Asterisk indicates unpublished material.

southwest of Gunnison in a large stand of cottonwoods surrounded by hay meadows. This site (Fig. 1), adjacent to Curecanti National Recreation Area (NRA), has been occupied since 1968 (Cook 1979*).

Observations of the Gunnison colony were made sporadically from 1975 to 1986, but quantitative data on breeding behavior, reproductive effort and success, and population size were not collected (Cook 1979*; Shaw 1982*). Volunteers observed the colony each year since 1987. Observers and methods differed in 1987 and 1988, but one of us (R.W.M.) has observed the colony since 1989. We summarized data from each year to evaluate the stability of the colony.

Methods

The colony was visited approximately once a week from March through July 1987 and in 1989–93. Observations were made from vantage points at least 100 m from the colony. Dates when great blue herons were first seen at the colony and when any courtship behavior (as described in Butler 1992) was first observed were recorded. We also recorded the dates when incubating adults were first seen, when hatchlings were first observed in nests, and when juveniles left the nests. The number of nests attended by at least one adult great blue heron

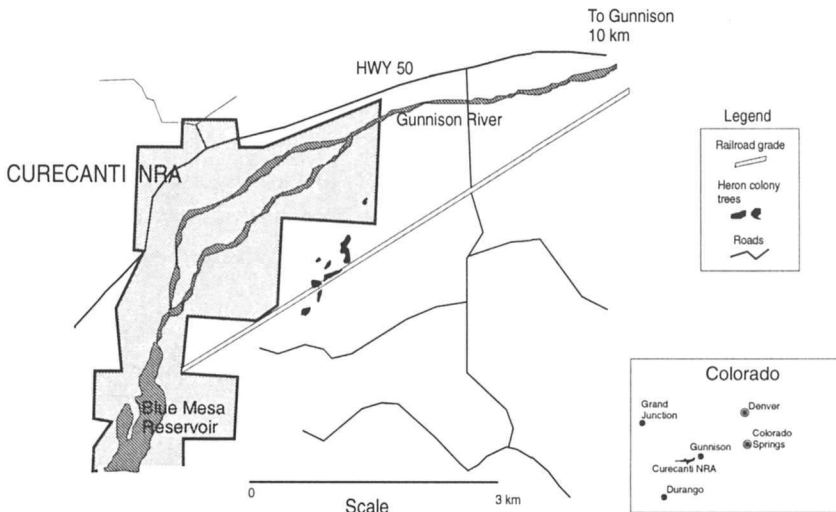


Fig. 1. Great blue heron (*Ardea herodias*) colony and surrounding land along the Gunnison River near Gunnison, Colorado.

was recorded as occupied each day of observation. The largest number of occupied nests each year was used in this analysis. This could overestimate the number of nests actually fledging young because the larger counts were often in early spring and some nests failed later. Monitoring of all nests without disturbing the birds is not possible after the trees leaf out.

Data for 1988 consist of counts of occupied nests and great blue herons on 8, 10, 15, and 19 April. Because the number of active nests was usually established by 20 April in the other 6 years of observations, we believe the maximum number of occupied nests estimated for 1988 is comparable to data from other years.

Results

Observations of breeding phenology are reported for 1989–93. Great blue herons were first seen at the colony in early- to mid-March. Courtship and nest selection began shortly thereafter. Little courtship behavior occurred after 1 April. Most birds seemed to be incubating by early April, although it was impossible to determine whether eggs were actually present. Nestlings were first seen between 7 and 18 May. Young from most nests fledged in late June or early July. Two–four young fledged each year from most nests in the colony.

The colony increased steadily between 1987 and 1990 and stabilized at about 80 active nests by 1990 (Fig. 2). In October 1989, 216 nests were counted in the colony. Occupancy of available nests varied from 12.5 to 42%; use of individual nests was inconsistent from year to year.

Discussion

Phenology of breeding activities at the colony in 1989–92 matched dates for this colony reported by Cook (1979*). Breeding phenology in the Gunnison colony was consistently 30 days later than that reported for a colony in California (Pratt 1970) and 1–2 weeks later than colonies in north-central Ohio (Burkholder and Smith 1991) but was similar to colonies in British Columbia and Nova Scotia. The Gunnison colony, at 2,300 m above sea level, may be one of the highest colonies in North America (Butler 1992). Herons arrive before winter ends and often must endure severe snowstorms through April incubation. Reproduction is difficult under these conditions. The high quality foraging

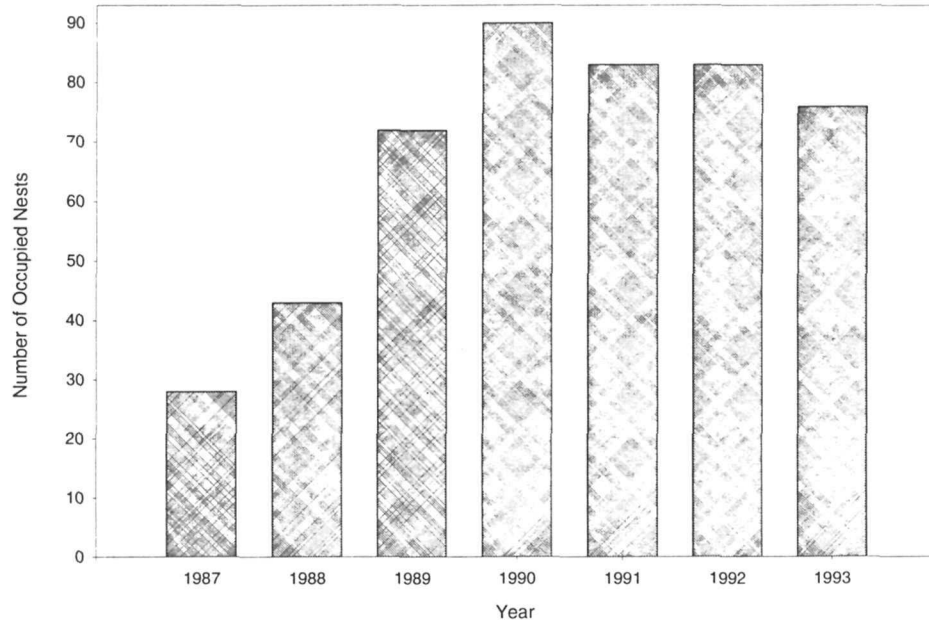


Fig. 2. Nests occupied by great blue heron (*Ardea herodias*) in the Gunnison River, Colorado, colony from 1987 to 1993.

habitat of irrigated hay meadows and Blue Mesa Reservoir may be what enables the herons to nest successfully.

The great blue heron colony on the Gunnison River grew rapidly from 1987 to 1990, and has remained fairly stable since then with about 80 occupied nests. The increase in colony size could be due to successful recruitment of offspring into the breeding population. Fledglings were not marked, thus we cannot determine whether the rapid increase in active nests was because of recruitment of offspring.

Southwestern Colorado was experiencing a drought during this study. The proximity of this colony to the vast foraging habitat of Blue Mesa Reservoir at Curecanti NRA probably ameliorated the effects of drought on the herons. Herons may have concentrated near Blue Mesa Reservoir during this time because it provided reliable foraging at a time when water levels were low elsewhere in the region. The increased number of occupied nests may have been from an influx of birds abandoning colonies because their foraging had been adversely affected by the drought rather than from recruitment of offspring into the breeding population.

Data from 1987 and especially 1988 do not reflect the same level of effort as from 1989 to the present. The low counts of active nests in these years may be a result of fewer or less systematic observations. Numbers of active nests have remained relatively constant since 1989 (72–90). Continued and consistent monitoring is needed to determine natural fluctuations in great blue heron numbers at the colony.

Data on the colony are sparse before 1987. Cook (1979*) counted herons in the colony in spring 1977 and 1978. The largest number of herons seen during a single day in each year was 52 (30 April 1977 and 14 April 1978). In 1987, when 28 active nests were observed, 52 was the largest number of herons seen during a single day. By contrast, on 18 April 1990, with 90 active nests, 88 birds were seen.

Herons are susceptible to human disturbance, especially during the breeding season (Werschkul et al. 1976; Shaw 1982*; Vos et al. 1985). The Gunnison River population was disturbed in the 1960's by expansion of the city of Gunnison (Cook 1979*; Shaw 1982*). Since becoming established at its current location in 1968, the colony has remained relatively undisturbed. No major threats to the great blue heron colony are apparent at this time, but an increase in human activity in the area could cause the herons to abandon the location.

The herons have apparently acclimated to occasional intrusions by ranch or National Park Service personnel, but the birds are still sensitive to certain types of disturbance, such as humans on foot (personal observation). Park and ranch activities near the colony during the heron breeding season are restricted to a few short visits. Should management of the area become more intensive, especially early in the season, the colony could be disrupted. The colony is probably safe in the short-term, but the future is doubtful.

Development of the Gunnison valley is increasing rapidly, and land values are rising. Ranching may not be economically viable in the near future, even in the privately owned bottom lands. The current owner of the land where the colony resides is sensitive to the herons' needs, but if uses change, or if the land were sold, activities near the colony could force the herons to leave. A change in land use of nearby meadows could alter foraging habitat and negatively affect reproductive success.

Cattle graze within the colony area from fall to spring each year and prevent recruitment of new cottonwood trees. Nests are located in stands of even-aged, mature-to-senescent cottonwoods. When these trees die, few options remain for relocation of the colony in the Gunnison Valley. To the west, large trees are sparse, are about the same age as the existing nest trees, and will probably die about the same time. Younger cottonwoods are numerous near the Gunnison River, but there is heavy year-round fishing in the area, and U.S. 50, a heavily traveled highway, is adjacent to the river near these trees. Humans on foot and motor vehicle traffic disturb nesting herons (Vos et al. 1985; Kelly et al. 1993). Expansion of this colony into trees near the Gunnison River has been limited; only one tree near the river contains nests.

In 1993, one large tree in the colony had many dead branches. This tree held about 20 active nests early in the breeding season (nests are selected before leaves emerge) but young fledged from only 3 nests. The absence of canopy cover may have prompted the herons to abandon nests in this tree. More nests than breeding pairs exist in the colony, so some expansion is possible within the colony. We do not know how many of these unused nests are acceptable to the herons. Attrition of suitable nest sites because of the death of all or part of the mature trees may have already begun. Future observations will include an assessment of tree health.

The long-term survival of the colony in its present location depends on protection of the site and a change in land use to allow establishment of new cottonwood trees. The National Park Service has expressed interest in acquiring

the colony and adjacent property. Cottonwood cuttings were planted in Curecanti NRA adjacent to the colony, and grazing was eliminated in that area in 1989 to try to establish new trees for the future. The initial plantings were largely unsuccessful, so more attempts are needed. Natural recruitment of cottonwoods may augment restoration efforts. Cottonwoods have become established near the high water level of Blue Mesa Reservoir within 1 km of the colony during the past 10 years, and they may eventually provide nest trees for the colony.

Other immediate threats to the colony are not apparent. There is time to pursue long-term protection of habitat by acquiring the colony land or by obtaining a protective easement. We plan to continue monitoring the population, to assess nest tree health, and to document tree and nest use. Other studies are needed and should include identification of the following:

1. critical foraging habitat,
2. food habits,
3. interactions between herons and shoreline fishermen at Blue Mesa Reservoir (Curecanti),
4. the relative effects of pre- and postfledging deaths on the colony's population,
5. the fidelity of individuals to the colony,
6. how the aging characteristics of the trees influence nest use, and
7. the effects of fluctuating water levels in the reservoir on reproductive success in the colony.

Acknowledgments

We thank M. Reynolds for generating Fig. 1.

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Abert's Squirrels of the Colorado Plateau: Their Reproductive Cycle

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Abstract. Results of a morphological and histological analysis of Abert's squirrels (*Sciurus aberti aberti*) killed on the road are presented. Resolving either the sex or the age of the animals on the basis of body measurements is not possible. Plotting testis weight against body length, however, seems to differentiate between juvenile and adult animals. Testicular activity, as judged from weight increases and histological analyses, displays a broad pattern that begins in October and ends in May–June when testicular regression ensues. Testicular regression is not complete because some residual meiotic activity is retained even through September and October. This maintenance meiosis serves to preserve the testes in a state of preparedness from which rapid recrudescence can be implemented. Evidence for dual gestation in Abert's squirrels is indicated by actual embryos and the presence of lactating nipples.

Key words: Embryos, gestation, reproduction, spermatogenesis, testis.

Ponderosa pine (*Pinus ponderosa*) forests of Arizona provide habitats for Abert's squirrels. These animals make extensive use of the pine trees for shelter, nest material, and food (e.g., inner bark of pine shoots and seeds from ovulate cones; Keith 1965; Patton 1975; Allred 1989). Although inner bark is available year-round, its caloric content varies seasonally from 2,454 cal/g in December to 4,999 cal/g in May (Pedersen et al. 1987) and may determine the use of alternate food sources. Abert's squirrels also act as spore-dispersing agents when feeding on ectomycorrhizal fruiting bodies growing in association with ponderosa pine roots (Kotter and Farentinos 1984; States et al. 1988). Dispersal of trees may be aided by these animals when they bury ovulate cones that are then left untouched (Bailey 1932).

Abert's squirrels are food for goshawks (Reynolds 1963; Reynolds et al. 1992) and therefore serve as important intermediates in the food chain of the

ponderosa pine forest. Although the density of squirrel populations is influenced by food resources (Keith 1965) and climate (Stephenson and Brown 1980), the reproductive mechanisms responsible for maintaining population levels are still elusive. Some authors suggest that these animals have only a single reproduction period (Farentinos 1972, 1980; Brown 1984), whereas others propose that, under certain circumstances, two gestations in one season are possible (Hall and Kelson 1959; J. Hall, 1992, personal communications). We present morphological and histological data that provide a comprehensive view of the reproductive cycle in Abert's squirrels. Tangible evidence for two periods of gestation in one season is also offered.

Methods

Carcasses were recovered from roads and kept frozen until examined. Most animals were obtained from the immediate Flagstaff vicinity that varied by no more than 61 m in elevation (average 2,164 m) over a 129-km² area. Animals were thawed at room temperature overnight and weighed. Measurements included total length, hind foot, tail, ear, and tassel length. Male sexual organs (testes and attached epididymides) were removed from the carcasses, weighed, and fixed in Bouin's fluid for 24 h. Tissues were then processed for histological examination using standard methods of dehydration through alcohols, paraffin infiltration, sectioning, and staining with haematoxylin and eosin. Female tissues were similarly excised and processed. When possible, the ovaries, oviducts, and the upper segment of the uterus were included.

All photographs were obtained with Plus X film through a Zeiss microscope equipped with an automatic camera system (MC 63). The negatives were developed in D76 (1:1) and printed on Ilford RC multigrade paper.

Results

We present data from 2 years of a continuing collection that began in February 1992. Morphological parameters plotted in a variety of combinations yield only scatter diagrams that cannot be resolved either into the sexes or the ages of the squirrels (Fig. 1). Adult and juvenile squirrels, however, may be distinguishable from each other on the basis of total body weight (Fig. 2). For any one body length, the right testis can either be heavy (probably mature) or

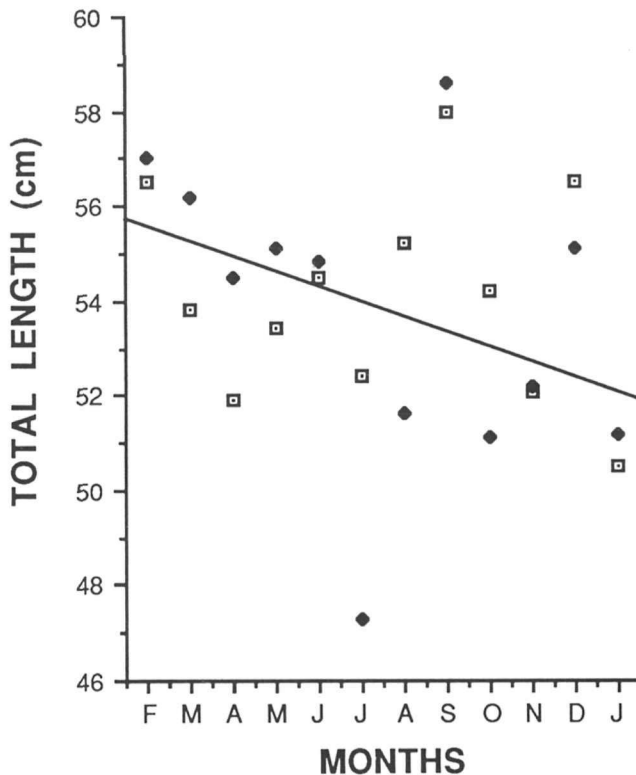


Fig. 1. Total length of squirrels plotted against the month of collection. Months are represented by the first letter beginning with February (F). *Open squares* represent males and *diamonds* represent females. The *line* represents the best-curve fit.

light (possibly from a juvenile). Therefore, body length alone does not provide information on the age or sex of squirrels. A similar plot can be obtained if testis weight is plotted against total body weight (not shown).

If testicular activity is correlated with increases in weight then our data reveal a broad peak of testicular enlargement and activity extending from September–October to June (Fig. 3). Testicular regression occurs during July and August. During that time, meiotic divisions and spermatogenic elements such as primary spermatocytes are seen within the germinal epithelium (Fig. 4). Resumption of spermatogenesis is synchronized with the emergence of second-

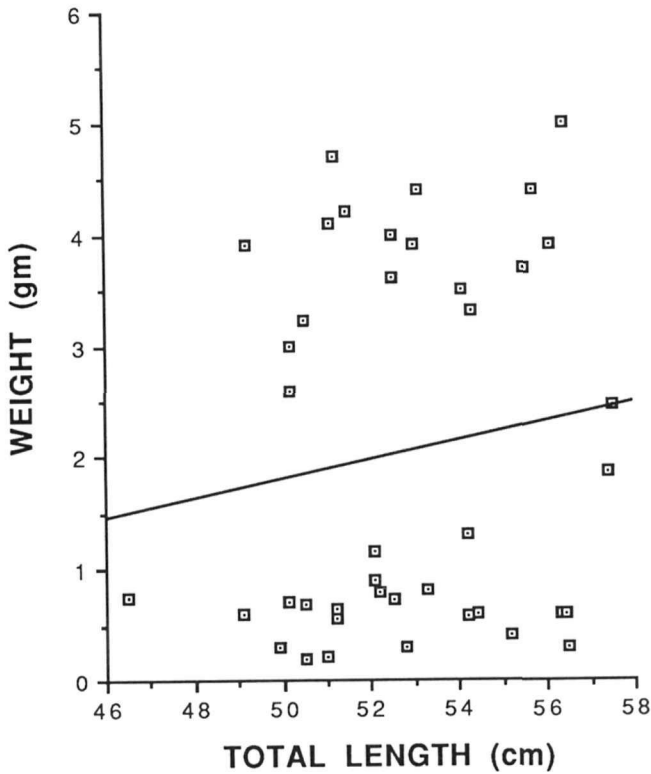


Fig. 2. Distribution of the weight of the right testis plotted against total length. The line represents the best-curve fit.

dary gonial elements such as secondary spermatocytes and spermatids. Maximal spermatogenic activity occurs through March and April (intermediate months not shown) and is indicated by the production of mature sperm, their release into the lumen of seminiferous tubules (Fig. 5a), and their accumulation within the vas deferens (Fig. 5b). The presence of large numbers of sperm within the vas deferens in June (Fig. 6) is interpreted as the latest time in the season when males can impregnate.

Testicular regression occurs abruptly and is already manifest in July. At that time, collapsed seminiferous tubules, devoid of sperm, are visible (Fig. 7). Both the thickness and the cellular complexity of the germinal epithelium in

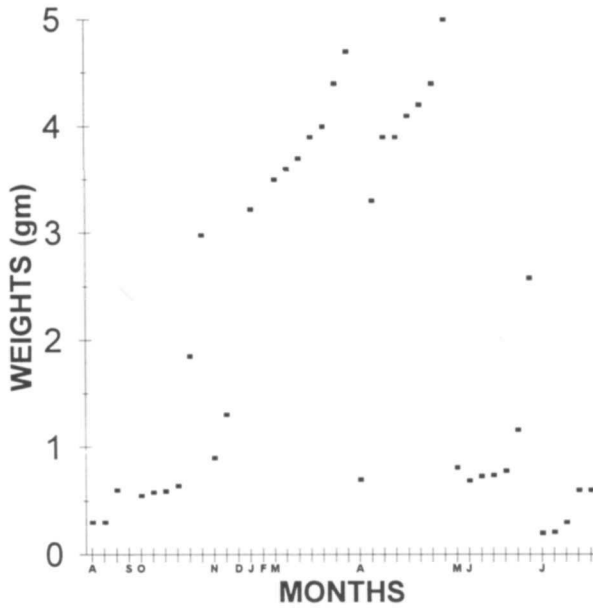


Fig. 3. Right testicular weights plotted against the month of collection. The months are represented by the first letter beginning with August (A).

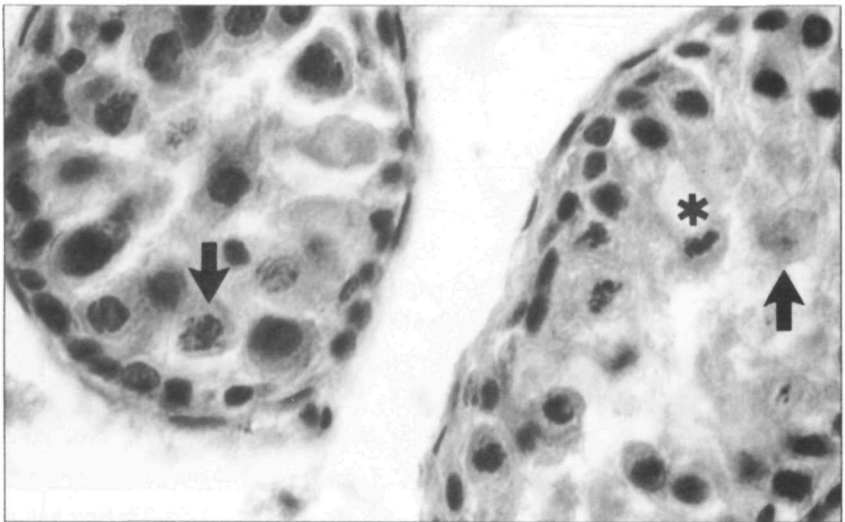


Fig. 4. Cross section ($\times 400$) of a testis from a male recovered in October 1992. *Small arrows* point to spermatogonia. *Large arrows* identify primary spermatocytes in the pachytene stage. The *asterisk* shows chromatin of a dividing primary spermatocyte. A spermatid can also be seen toward the center of the tubule (*arrow point*).

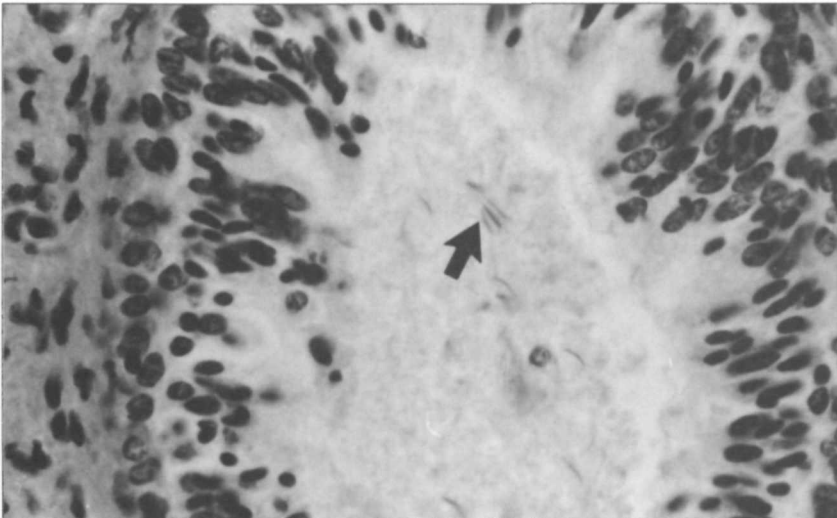
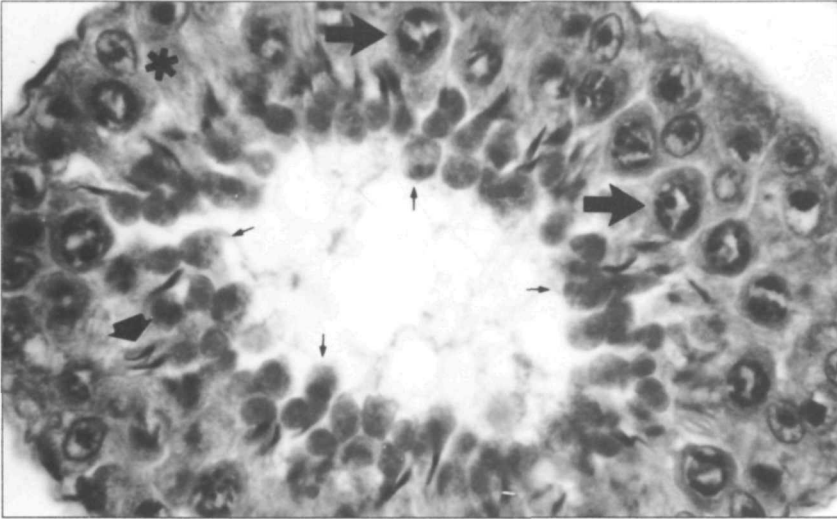


Fig. 5. (Top) An active testis ($\times 400$) from a male recovered in March 1993. The large lumen is bordered by spermatids (*small arrow*) and sperm (*arrow point*). Primary spermatocytes in pachytene stage are identified (*large arrow*). Sertoli cells are also visible (*asterisk*). (Bottom) Cross section ($\times 160$) of the vas deferens in the same male as above showing that mature sperm are stored (*arrow*).

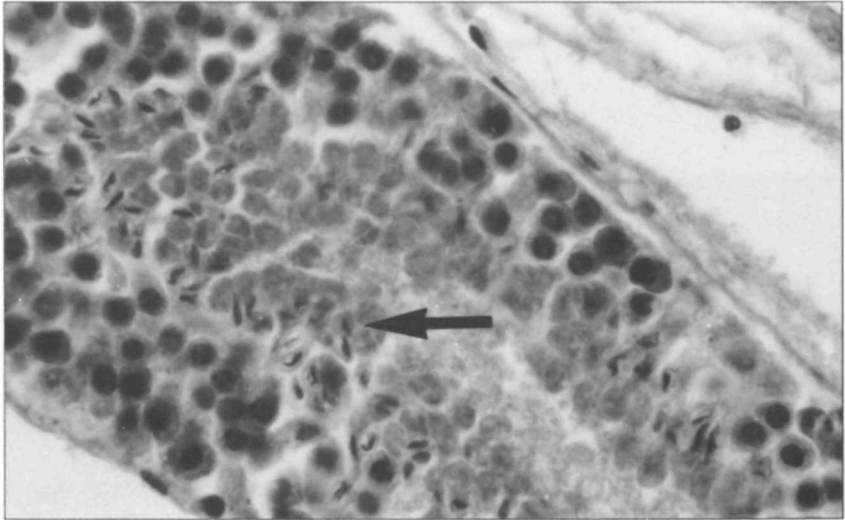


Fig. 6. Cross section ($\times 160$) of the testis of a male recovered in June 1992. Mature sperm are visible within the lumen (arrow).

July are much reduced, and no secondary spermatogenic elements are seen. A number of primary spermatocytes, however, mainly in zygotene, are observed in males in both July (Fig. 7) and August (Fig. 8).

Sexual activity of female Abert's squirrels can be deduced from the presence of well developed embryos obtained in June and July 1992 and March 1993 (Fig. 9). Because of their precarious state of decomposition, the embryos were immediately preserved in alcohol. Crown-rump lengths were determined at a later date. Lactation was indicated by nipples being surrounded by conspicuous and partially depilated areolae. Although no embryos were found in carcasses of June and July 1993, nine lactating females were noted. The contiguous evidence gathered from 1992 and 1993 samples suggests that Abert's squirrels can undergo two gestation periods in any one season. These dual periods of gestation are made possible by the prolonged spermatogenic activity of males.

Discussion

Tight synchrony between the sexual cycles of male and female Abert's squirrels does not seem to be a prerequisite for two periods of gestation within the same season. Instead, the prolonged spermatogenic activity of males ensures

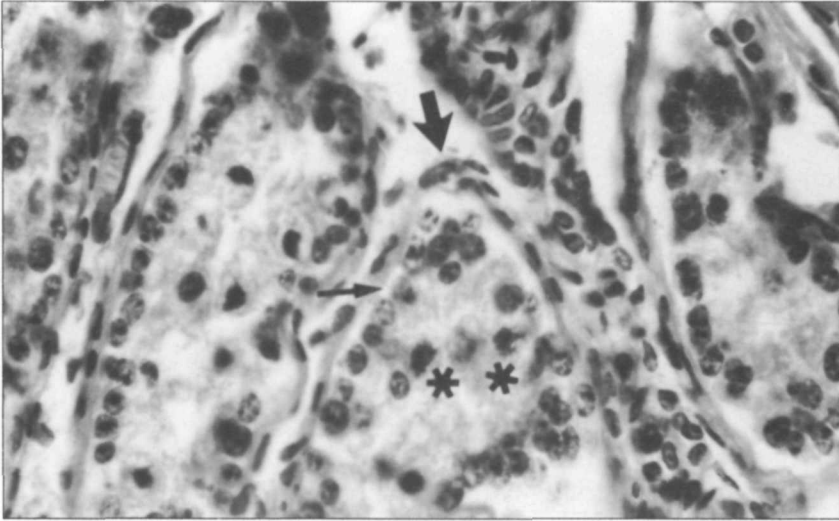


Fig. 7. Regressed testis from a male recovered in July 1992. Tubules are collapsed, and no lumen is present. Leydig cell clumps are small and dispersed (*large arrow*). Numerous spermatogonia are visible (*small arrow*) and chromatin from a dividing primary spermatocyte is identified (*asterisk*).

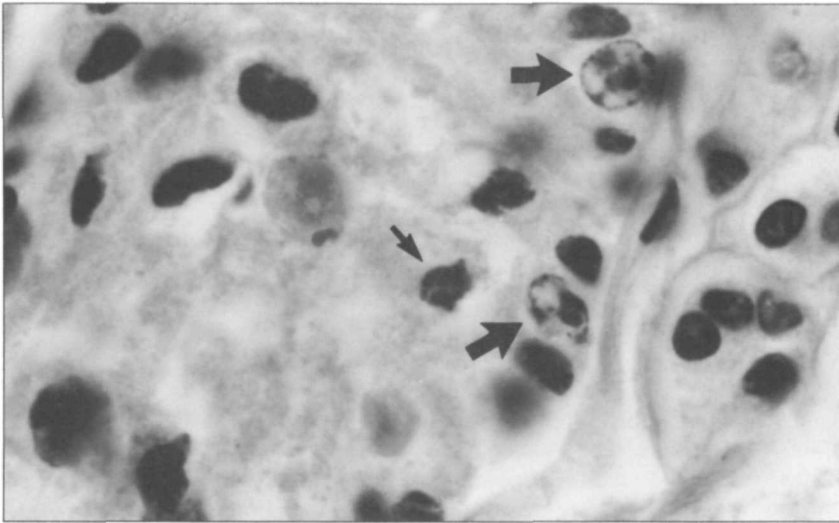


Fig. 8. Regressed testis ($\times 1,000$) in the same male as in Fig. 7. Zygotene cells (*small arrows*) and Sertoli cells (*large arrows*) are visible.



Fig. 9. A representative embryo from a female recovered in March 1993.

the likely insemination of females at most times of the year. Based on previous approximations of the length of gestation in Abert's squirrels (38–46 days; Keith 1965), we estimate that some females may have been inseminated as early as mid-February.

In this paper, we reconstruct the reproductive cycle of male Abert's squirrels from testicular tissues obtained monthly. Similarly, the female cycle was deduced from the presence of embryos or of lactating nipples. Active spermatogenesis is maintained from October to June. Similar results are seen in the grey squirrel (*Sciurus carolinensis*; Dubock 1979) and in the fox squirrel (*Sciurus niger*; Kirkpatrick 1955). Testicular regression is initiated suddenly in July and is of short duration. Recrudescence of the testes is already evident by October as germinal epithelia resume active meiotic divisions and spermatogenesis.

Males maintain a prolonged regimen of spermatogenesis even during the winter months. This reproductive strategy is presumably sustained in an effort to keep males in mating readiness. Energy to maintain this extensive cellular activity is probably provided by their use of alternative food sources such as the inner bark of clipped tree branches and hypogeous fungi (States et al. 1988). Even when testicular regression ensues, primary spermatogenic elements are still retained. This is contrary to the hamster (*Cricetidae*) where the epithelium

regresses to Sertoli cells and premeiotic spermatogonia (Bergman 1987) thus ceasing spermatogenesis completely. We refer to this residual spermatogenic activity in Abert's squirrels as maintenance meiosis. In times of need, full spermatogenesis can be rapidly recovered by merely completing the second meiotic division and generating the needed spermatozoa, obviating the need to start from premeiotic spermatogonia. The prospect of early insemination during February is a condition that demands rapid sexual preparedness by the males.

A bimodal spermatogenic pattern has been described for the grey squirrel in England (Dubock 1979) where peaks of testicular activity (weights) are separated by periods of recrudescence. These peaks coincide with litter production during March–April and July–August, respectively. This pattern is not, however, consistent over a 5-year period. In some years, a single, prolonged, spermatogenic-activity peak is observed. Hence, the consistency in reproductive pattern exhibited by male Abert's squirrels will have to be ascertained by continued sampling and analysis of additional collections.

The two gestation periods we observed in females coincide well with those published for the red-bellied tree squirrel (*Callosciurus erythraeus*; T'sui et al. 1982) in which the authors also reported two active reproductive periods—one from January to March and the other from June to August. A similar dual reproduction in Abert's squirrels has previously been suggested (Gurnell 1987) as occurring only under favorable conditions of weather (Heany 1984) and food availability (Gurnell 1987). Neither Brown (1984) nor Nash and Seaman (1977), however, support the hypothesis that individual Abert's squirrels can have two litters in a year. The possibility exists that the two periods of gestation we observed may be transient and characteristic only of certain years when conditions are appropriate. Our evidence of two periods of gestation in 2 consecutive years, however, strongly suggests that the phenomenon may not be unusual.

The inherent mechanism behind the reproductive strategy of Abert's squirrels on the Colorado Plateau may embrace three assumptions. The first assumes that males are consistent from year to year in having a prolonged period of sexual activity extending for most of the year. In this instance, females could control the incidence of gestation by regulating their own cycle according to environmental cues. This female-driven system would, therefore, be instrumental in regulating the yearly frequency of gestation. The second presumes the reverse situation in which females are consistent while males respond to environmental stimuli. In this male-driven system, economy and control of reproduction would be vested in male Abert's squirrels. This contention may be

supported by evidence for weather-induced delays in male sexual preparedness reported by Webley and Johnson (1983). The third strategy suggests that both sexes synchronize their reproduction in terms of fluctuating environmental circumstances.

Our data are more consistent with the first strategy because of the prolonged spermatogenic activity in male squirrels. Hence, the two periods of gestation we observed in 1992 and 1993 could have been the consequence of environmental circumstances favorable to females in promoting timely ovulation and subsequent pregnancies. The decisive pattern (or patterns) existing in Abert's squirrels is uncertain as yet, however, and will require further observations and data. An initial attempt to correlate environmental parameters such as snow, temperature, and total moisture with the dual gestation in Abert's squirrels has not identified a single factor responsible for this reproductive pattern. Dual gestation could be implemented by the animals when climatic factors (such as snow cover) are minimal and temperature is mild (Stephenson and Brown 1980). Reproduction could be limited to one period of gestation when environmental conditions are severe. Similarly, ovulate cone productivity and availability (Allred et al. 1994) could be factors in either promoting or discouraging a biannual reproductive pattern.

Our data do not suggest that individual females go through two gestations in a season. The possibility exists that distinct groups of females become pregnant in winter and in spring, depending on their respective sexual maturity. Similarly, the consistency in the yearly frequency of gestations in females represents a fundamental population parameter that needs to be resolved. These questions are important because they will likely affect management practices related to hunting of Abert's squirrels. Recommendations for habitat management will also be influenced by the frequency of reproduction in these squirrels. The inherent capability of these squirrels to breed either once or twice a year may, in fact, represent an effective means of regulating their population density under differing environmental conditions.

Histological results obtained from animals killed on the road must be interpreted with extreme care because of the postmortem necrosis of the tissues. At present, there are no standards against which to assess these postmortem changes. We have therefore initiated a detailed histological analysis in mice of the effects of necrosis on the testicular histology after death (Pogany and Allred, in preparation). Our preliminary data suggest that the integrity of the seminiferous epithelium is remarkably stable to 12 h after death. Obvious necrotic

changes are only detectable 24 h after euthanasia. The analysis of similar effects on ovaries is presently being undertaken (Pogany and Allred, in preparation). We ultimately hope to provide a scale of injuries (in mice) against which the squirrel histological data can be interpreted.

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